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Evaluation of PCB Concentrations, Masses, and Movement from Dredged Areas in San Francisco Bay

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CONTRIBUTION #938 / March 2019

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Final Report
March 28 2019

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SFEI Contribution #938

This work was funded as a result of settlement of
San Francisco Bay Water Board enforcement actions

Suggested citation: Yee, D. Wong, A. 2019. Evaluation of PCB Concentrations, Masses, and Movement from Dredged Areas in San Francisco Bay. SFEI Contribution #938. San Francisco Estuary Institute, Richmond, CA.

EXECUTIVE SUMMARY

Dredged materials from San Francisco Bay undergo chemical analysis to determine appropriate disposal options, but the data were previously accessible primarily as standalone reports to the Dredged Materials Management Office (DMMO). The DMMO has undertaken an ongoing effort in recent years to compile dredging project testing data since approximately 2000 into a DMMO database to allow data to be more readily searched and downloaded. The database is available to the public (https://www.dmmosfbay.org "Data Search" page) and the data content as of April 2017 was downloaded for this study and a recent RMP dioxin synthesis report (Yee et al., 2019).

This report is a product of a Regional Monitoring Program for Water Quality in San Francisco Bay (RMP) project funded to analyze sediment PCB data in the DMMO database to address priority management questions for PCBs. The first goal was to characterize the PCB concentrations in sediment from dredged areas. Data reported for the DMMO include individual congener results, but none were reported by the highest sensitivity methods used in the RMP (EPA 1668 variants), so there were extensive non-detects (NDs) in the DMMO data that resulted in substantial uncertainty about the distribution of concentrations found. The lower and upper bounds of estimates (using substitution by zero or method detection limits (MDL)~~)~~ for the DMMO results bracket the RMP-measured ambient concentrations for the habitats most comparable (i.e., RMP margins versus dredged nearshore areas; and RMP open-Bay ambient concentrations versus dredging in open-Bay areas). The upper and lower limit estimates were often significantly different from the RMP results, but some variants of their central tendencies (e.g., NDs substitute at half of the MDL) were not significantly different from the corresponding ambient data.

Estimates of PCB masses in dredged nearshore areas derived from the DMMO data suggested these areas added relatively modest masses to the overall mass of PCBs in the Bay (about 1% to 2.5% or less of the Bay-wide inventory, depending on the convention used for estimating non-detects). Maximum concentrations in dredged nearshore sites are higher than those in the ambient open-Bay and often similar to ambient RMP margin sites, but are still one to two orders of magnitude less than the most contaminated sites found to date in the Bay. Thus although they are likely to have a small influence on contaminant exposure for wide-foraging sport fish, birds, and other wildlife, some areas may have presented or still present elevated risk to localized biota.

Estimates of PCB masses transferred from dredged areas in various Bay segments to disposal sites were also highly sensitive to the assumptions for handling NDs, but ND handling did not greatly alter the relative proportions allocated to in-Bay versus ocean or upland disposal. Overall, sediment volumes sent to ocean or upland/reuse disposal sites represent a net loss of PCBs from the Bay, as described in the San Francisco Bay PCB TMDL. For dredging projects with reported PCB data, this report estimates that just over 50% of the PCB mass encountered is removed from the Bay, independent of the method for handling NDs. However, these net transfers via dredging were relatively small (but not negligible) compared to PCB external loads and other internal cycling processes in the Bay; annual PCB export from the Bay and transfers within the Bay were equal to about 20% to 40% of present day local watershed loadings to the Bay.

This effort has provided a good initial assessment of PCB distributions, masses, and transfers from dredged areas. Efforts to more consistently populate some database fields (e.g. to exactly match project names with those in DMMO annual reports), and inclusion of some project metadata such as dredged volumes provided in the DMMO reports would improve the usability of the DMMO database for other purposes and help future efforts to more precisely estimate the contribution of dredging to overall PCB fate and transport in the Bay.

SECTION 1: BACKGROUND

PCB contamination in the San Francisco Bay region is spread widely across the land surface and mixed deep into the sediment, resulting in contamination of the Bay food web and health risks to humans and wildlife, a legacy of poor management practices of this group of contaminants. In 2008, the San Francisco Bay Regional Water Quality Control Board (Water Board) 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 reductions in external loadings of PCBs to the Bay (mainly from the stormwater pathway), control of internal sources of PCBs within the Bay (including dredging), and management of risks to consumers of fish from the Bay.

Every year, millions of cubic yards of sediment are dredged in and around San Francisco Bay to maintain safe navigation in open-Bay channels and operations in ports and harbors. The Dredged Materials Management Office (DMMO) is an interagency group responsible for approving economically and environmentally sound dredging projects. The group is comprised of the US Army Corps of Engineers (USACE), US Environmental Protection Agency Region 9 (USEPA), San Francisco Bay Conservation and Development Commission, Water Board, State Water Resources Control Board, and the California State Lands Commission. Dredged sediment are analyzed for PCBs and other contaminants on either an ongoing or periodic basis, and compared to ambient sediment concentrations in the Bay measured by the Regional Monitoring Program for Water Quality in San Francisco Bay (RMP). Remaining residual sediment (post-dredge surface sediment) are analyzed for PCBs and other contaminants on an as-needed basis if the results of overlying material warrants such analysis. Testing is required at sites where there are no recent data or past testing has shown highly contaminated sediment. At sites where past data suggest low risk of contamination (“Tier 1” sites), sample testing is required at a lower frequencies (e.g., every 3 to 5 years). The analysis of dredged material is used to determine the suitability for disposal at specific sites within the Bay, for reuse at upland sites around San Francisco Bay, or for open-ocean disposal.

The physical, chemical, and biological testing data for dredging projects were previously reported annually in standalone documents for each project. These data were recently compiled into a database on the DMMO website, providing the first opportunity to analyze and synthesize the results of dredged materials testing throughout the Bay. These analyses may provide valuable insights into the mass of contaminants from or moved around the Bay by dredging projects. This information can help us verify and refine our conceptual understanding of contamination in the Bay, contribute to answering management questions, and identify ways in which DMMO data can be more closely integrated with management strategies.

This effort focused on PCB testing results from dredged sediment. Sediment PCB data from the DMMO database were downloaded in April 2017. In addition to these data, each annual report published by DMMO specifies the total volume of dredged sediment from each project in the Bay and the destination of the dredged sediment (e.g., San Francisco Deep Ocean Disposal Site, in-Bay disposal sites, or upland for disposal or reuse). The DMMO database downloaded in early 2017 included complete physical, chemical, and biological testing data from sediment dredging projects from 2000 to 2016. Combining the relevant PCB sediment concentration testing data (i.e., for the dredged volumes, excluding data on the residual "z-layers" left post-dredging) with the project-specific dredged volumes and disposal sites as reported in the DMMO annual reports, we estimated the amount of PCBs in dredging projects moved out of the Bay or to other areas within the Bay.

The data from the DMMO database were also used to evaluate the spatial distribution of PCB concentrations in dredged sediment around the Bay. Dredging generally occurs at sites where sediment is accreting in depositional zones, so it was expected that these sediment pollutant concentrations would be similar to ambient concentrations in surrounding subtidal sites or nearby shallow water or intertidal margin sites. Comparisons among these groups of sites were used to help confirm our conceptual models of sediment and pollutant processes in the Bay (Jones et al., 2012). Where our conceptual model expectations were contradicted, we can begin to identify the factors involved and modify our conceptual models and management approaches.

By addressing these topics, the statistical and spatial analysis of dredged sediment testing data will help better inform the overall management of PCBs in the Bay Area. The comparison of sediment dredging data and RMP ambient data on a regional and local basis can inform understanding of appropriate management options for the dredged sediment, and evaluate opportunities for beneficial reuse. Rising sea level and a current deficit of sediment for wetland restoration projects (Goals Project, 2015) suggest a desire for increased beneficial reuse of dredged material where possible. The distribution of sediment PCB concentrations from dredging sites relative to nearby ambient sites can also help us evaluate whether there are more PCBs than expected from simple redistribution of nearby ambient sediment, suggesting unaccounted or unexpected nearby legacy or current sources. Lastly the estimates of net PCB movement via dredging and disposal activities allow us to evaluate whether or not dredging activities can have substantial impacts on PCB mass balances and the long-term recovery of the Bay from PCB contamination. Although dredging can sometimes bring up PCBs that were already settled below a biologically active zone, PCBs in dredged sediment largely represent a mass already present in the Bay, so dredging and disposal within the Bay is considered to have no net effect on the PCB inventory in the TMDL Staff Report (SFBRWQCB 2008). Although a small proportion of sediment contaminants disposed of in the ocean or at upland/reuse sites potentially could find their way back into the Bay, ocean and upland disposal mostly results in net removal of PCBs from San Francisco Bay.

Although this report focuses on sediment concentrations of PCBs, the DMMO database also contains results for other matrices, such as sediment elutriate (water) PCBs and concentrations in tissue from bioaccumulation testing. These matrices and methods are not used in RMP monitoring, and thus we have no appropriate sample group to which we could compare these results. A separate RMP special study evaluating bioaccumulation results in the DMMO database was proposed and will be considered for future RMP or Supplemental Environmental Projects (SEP) funding.

SECTION 2: CURRENT STATUS AND INVENTORY OF SEDIMENT PCBs

PCB Spatial Distributions

The DMMO database at the time of download in April 2017 included PCB concentrations for 391 samples obtained from 293 sites in 111 project studies from the years 1998 to 2016. Samples from “z-layers,” located below the planned dredging depth, and meant to represent residual concentrations exposed as the surface after dredging, were excluded. These dredging data most directly address one of the RMP management questions for PCBs, namely: MQ2. What is the spatial pattern of impairment?

We focused our data analysis on the 40 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, with the intent to quantify PCBs most likely to be present at ambient concentrations. Therefore, the RMP dataset typically has relatively few non-detects (NDs); any non-detects that do occur in RMP data reported since 2002 are typically for only the least abundant of the historically reported congeners.

One challenge of interpreting the PCB data in the DMMO database was the frequent occurrence of non-detects for individual congeners (Table 1). The minimum and maximum MDLs for non-detects are shown as <MDL values (in units of ug/kg dw). The MDLs varied among studies, with minimum and maximum MDLs within about a factor of 100 for most congeners. The primary goal of chemical analysis for dredged materials is to determine appropriate disposal, so non-detects are acceptable, so long as the detection limits are below disposal thresholds. However, non-detects introduce uncertainties in efforts to more generally characterize chemical distributions, as concentrations below detection limits are not quantified. Although the RMP data also had occasional non-detects for individual congeners, there were no samples where all of the targeted 40 congeners were non-detects. In contrast, of the nearly 400 samples with PCB concentrations reported in the DMMO database, 89 had non-detects on all congeners. The disparity in the prevalence of non-detects reflects the different goals for the analyses; RMP data are collected to characterize the overall distribution of concentrations, including relatively clean ambient locations. However, given that more sensitive analytical methods typically cost more, quantification at low concentrations below disposal thresholds may be seen as an unnecessary additional expense for projects reporting to the DMMO.

The RMP reporting convention is to substitute zero for the concentration of congeners not detected because there are generally relatively few, and they are usually among the least abundant congeners even when detected. For the DMMO dataset, despite the much higher prevalence of non-detects, we primarily reported PCB concentrations using the RMP convention of substituting zero for non-detects. We also explored some alternative assumptions or substitutions and the possible impacts to inferences or conclusions that might be drawn from the data. Substituting the MDL or half the MDL as the estimated concentrations for congeners not detected could sometimes grossly overestimate their abundance relative to the detected congeners, particularly when the detected (usually more abundant) congeners are only slightly above MDL. For example, two congeners might typically have a 3:1 ratio in a high concentration samples (due to relative abundances in source Aroclors). If the first congener is reported just above its MDL in a low concentration sample, and the second is reported ND with approximately the same MDL, substitution of MDL for the latter concentration may create an artifact of a 1:1 relative abundance.

Table 1 Reported congeners in the downloaded DMMO data (391 samples) with their minimum and maximum MDLs (shown as <MDL, often differing by ~100x among studies) and maximum values (in ug/kg dw). The total count of results (Tcount) varies, as some congeners were not reported in all studies. The percent of reported results that were ND (%ND) was over half the samples for many congeners. The average percentage contribution to reported Sum of 40 PCBs in DMMO data (Avg%ofSum) indicates which congeners were detected consistently at higher concentrations. Only samples with at least 28 of the 40 congeners reported were included to derive the Avg%ofSum.

AnalyteName	<MDL Min	<MDL Max	Max Value	TCount	% ND	Avg%ofSum
PCB 008	<0.055	<4.3	2	335	88.7	0.4%
PCB 018	<0.044	<5	12.6	391	83.6	1.9%
PCB 028	<0.013	<5	12.7	391	74.2	1.1%
PCB 031	<0.0335	<5	5.4	340	78.5	1.0%
PCB 033	<0.039	<5	1.9	344	84.6	0.5%
PCB 044	<0.065	<5	18.8	391	71.6	1.8%
PCB 049	<0.058	<5	12.7	391	64.7	2.4%
PCB 052	<0.059	<5	30.5	391	57.5	4.1%
PCB 056	<0.03	<2.2	3.1	330	82.1	1.0%
PCB 060	<0.039	<2.2	2.4	319	94.7	0.1%
PCB 066	<0.035	<5	19.6	391	65.2	1.0%
PCB 070	<0.051	<5	30.8	391	52.2	2.7%
PCB 074	<0.044	<5	11.3	391	84.1	0.9%
PCB 087	<0.038	<5	8.7	389	76.9	2.7%
PCB 095	<0.049	<7.1	8.6	344	42.4	3.7%
PCB 097	<0.053	<5	5.5	344	63.4	2.0%
PCB 099	<0.045	<5	7.8	391	47.3	2.7%
PCB 101	<0.049	<5	34	390	33.3	7.5%
PCB 105	<0.033	<5	8	391	61.9	2.8%
PCB 110	<0.035	<5	16.2	391	34.3	6.1%
PCB 118	<0.031	<5	12.5	389	34.2	5.4%
PCB 128	<0.031	<5	3.5	391	75.2	1.6%
PCB 132	<0.075	<5	2	280	91.8	0.4%
PCB 138	<0.064	<8.45	16	389	33.7	9.1%
PCB 141	<0.035	<5	3.1	344	72.1	1.2%
PCB 149	<0.067	<5	18.4	390	33.1	6.2%
PCB 151	<0.043	<5	3.2	391	68	1.7%
PCB 153	<0.038	<5	29	388	30.2	8.4%
PCB 156	<0.042	<5	2.1	391	81.6	0.7%
PCB 158	<0.028	<5	7	195	75.4	0.7%
PCB 170	<0.026	<5	5	391	54.2	2.4%
PCB 174	<0.03	<2.1	3.8	326	50	2.1%
PCB 177	<0.052	<5	2.4	388	72.2	1.4%
PCB 180	<0.053	<5	24.6	391	37.9	5.0%
PCB 183	<0.062	<5	2.6	389	64.3	1.5%
PCB 187	<0.047	<5	13.5	391	39.4	3.3%
PCB 194	<0.043	<5	2.9	386	75.9	1.2%
PCB 195	<0.031	<3.8	1.3	335	89	0.3%
PCB 201	<0.041	<7.85	0.7	391	93.9	0.2%
PCB 203	<0.039	<1.8	3.2	330	79.4	0.7%

Although the ND=0 substitution is used by the RMP, the bias on sums of PCBs relative to other substitution conventions is generally relatively small because few individual congeners are reported as ND, and the congeners substituted account for a small percentage of the sum. In contrast, for cases where many or all of the individual reported congeners are ND, which occurred frequently in the DMMO data, estimated concentrations can differ greatly between substituting conventions, so care must be taken to not over-interpret apparent differences that may be artifacts of the substitutions selected.

Concentrations of the sum of the 40 RMP-reported congeners (“SumOf40PCBs”) reported from various dredging projects in the DMMO database are shown in Figure 1, including data from the Bay Protection and Toxic Cleanup Program (BPTCP), RMP sampling of deeper open-Bay subtidal areas (RMP Bay), and more recent sampling of intertidal and very shallow (above 1 ft below mean lower low water) subtidal areas (RMP Margins) plotted on the same scale. For all the plotted data, non-detects were substituted with zero, so any samples where the sum of PCBs was zero (i.e., all congeners were ND, which only occurred in the DMMO data) do not appear at all on the map. For any given area within the Bay, the BPTCP reported concentrations were among the highest, which was expected, as the intention of that program was to characterize and remediate the most contaminated areas within the Bay.

Conversely, RMP open-Bay sampling sites usually had the lowest PCB concentrations, with DMMO reported samples taken from similar deep-water areas (i.e., channel maintenance dredging activities) also similarly low in PCB concentrations. RMP Margins sampling and DMMO data from nearshore sites generally fell into a middle range of concentrations, with some very low concentrations similar to open-Bay sites, and others nearly as high as some of the BPTCP sites.

The DMMO data also display north to south patterns in concentrations comparable to those from other programs. DMMO sites in the RMP Central Bay segment (from the southern edge of San Pablo Bay, to the area roughly between San Francisco and Oakland International Airports) have higher maximum concentrations than in sites of more northern (Suisun and San Pablo) or southern (South and Lower South) Bay segments, which is similar for the BPTCP and RMP Margins sites.

These distributions are in line with the RMP’s current conceptual model of PCBs sources and fate processes (Jones et al., 2012). The majority of PCBs originate from use and disposal at terrestrial sites, with loading to the Bay occurring primarily through stormwater conveyances carrying contaminated water and sediment from upland areas in watersheds to the edges of the Bay, or leaching and runoff from poorly contained landfills and other sites located along the shoreline. The generally higher concentrations in sites from nearshore areas within the database are consistent with this expectation. The higher maximum concentrations found in Central Bay sites within the DMMO database also fit the current conceptual model. Many areas of Central Bay watersheds were more extensively developed and industrialized during the peak of PCBs usage in the 1960s and 1970s, so especially higher concentrations near the shorelines of Central Bay areas would be expected.

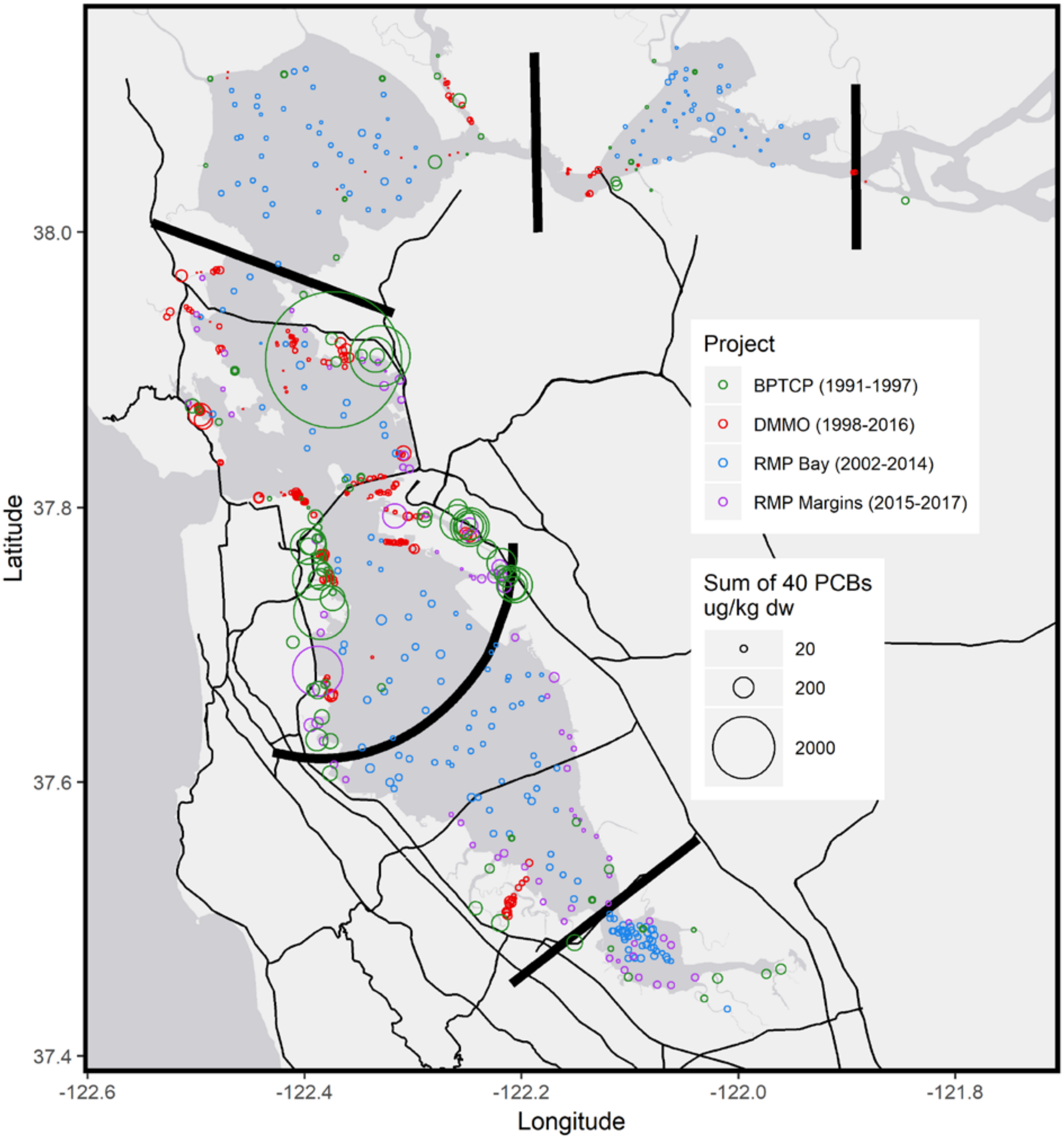

Figure 1 Sediment PCB concentrations reported by DMMO (dredging projects) and other San Francisco Bay projects. Concentrations are for the sum of 40 congeners reported routinely by the Bay RMP (Regional Monitoring Program), with non-detects substituted with zeros. Open-Bay RMP sites have generally lower PCB concentrations, with BPTCP (Bay Protection and Toxic Cleanup Program) sites usually the highest, and RMP Margins and DMMO data generally in a middle range. Bold black lines indicate boundaries of RMP Bay segments and fine black lines denote major (numbered) highways in the San Francisco region.

Although DMMO projects were not expected to be unbiased or spatially and temporally uniformly distributed, we generated empirical cumulative distribution functions (ECDFs) to explore the general distribution of PCB concentrations in the dataset, and considered whether they were significantly different from RMP open-Bay or Margins ambient concentrations. Our expectation was that dredged areas are likely to sediments similar to nearby ambient habitats, and the distributions of concentrations would therefore be not significantly different.

In generating the ECDFs, we assumed each of the DMMO reported values had equal weight, as the surface area that each individual reported sample was meant to represent was not pre-defined or constant; some projects may have more or fewer samples taken for a given surface area. Conceivably, a scheme for defining the areas of individual dredging projects, and adjusting for the sample counts and surface areas for sub-sections of each of the projects could be devised in a future analysis effort to assign an area weight to each sample individually. However, given the large number of studies in the DMMO database, compiling that level of detailed information is beyond the scope of this report.

Given the large percentage of samples that had non-detects for all congeners (i.e., with zero for sum of PCBs when non-detects are substituted with zero), we explored alternative substitution methods for non-detects, both for plotting the data in ECDFs and for PCB mass estimates of sediment inventories and transfer between or within areas of the Bay due to dredging activities. In addition to using the RMP convention of substituting zero for congener results not detected, we also generated estimates for sums of PCBs substituting values at the MDL for non-detects (ND=MDL) of each congener individually, or substituting the lowest detected value (ND=MinStudy) for the same congener within the study, or the lowest value detected in any DMMO study when a congener was never detected within its own study. These alternative substitutions represent upper bound worst case estimates for non-detects; the actual concentration in any given sample likely falls below these upper limits but above zero.

Because the sediment dredged in nearshore areas appeared to differ greatly from channel maintenance and other open-Bay areas, we plotted them separately against their comparable RMP margins and open-Bay samples, respectively. In designing the RMP open-Bay and margins sampling frames, port and marina areas were intentionally excluded. Any DMMO samples taken from subtidal areas excluded from both RMP sampling areas were designated as “nearshore” areas for this study, with the remaining DMMO samples characterized as “open-Bay” locations.

RMP margin data spanned much of the same range as reported for sampled nearshore sites in the DMMO sampling (Figure *2*). The handling of non-detects biased the estimated distribution of DMMO data high or low depending on the substitution used, with the ND = 0 substitution resulting in a majority of samples being far below RMP-reported ambient margin concentrations. However, for the top quartile of DMMO sites, results were still sometimes about the same or higher than the same quartile within the margins data. This is likely because those samples have relatively few or no non-detects, so the ND = 0 substitution only biases low a small portion of their sums.

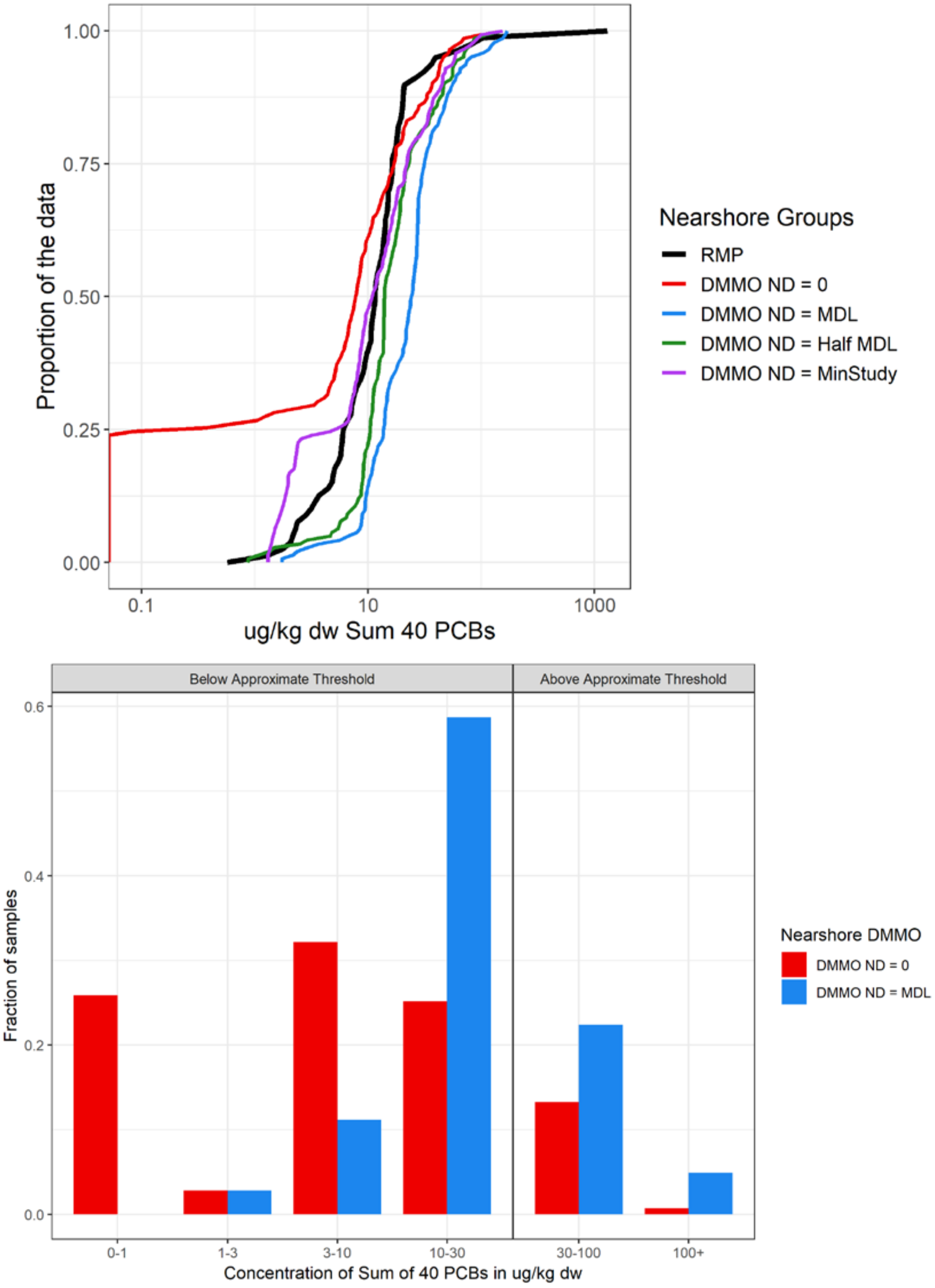

Figure 2 Distributions of RMP Margins Data Compared to DMMO Nearshore Data Using Different Handling for Non-Detects. Upper graph shows distributions as empirical CDFs, lower graph as histograms with fraction of samples in size bins grouped above and below the approximate in-Bay disposal threshold. Substituting zero for non-detects (ND = 0) yields the lowest estimates for DMMO-reported data due to extensive non-detects, with most results below ambient concentrations reported by the RMP. Substituting the MDL (ND = MDL) yields much higher estimates, mostly above RMP ambient values. Actual concentrations in DMMO data likely fall between these lower and upper limits. Substituting at the lowest concentration reported in the same study (ND = MinStudy) or at half the MDL (ND = Half MDL) yields distributions similar to the RMP samples.

Conversely, substituting ND = MDL for non-detects resulted in the highest distribution of PCBs in DMMO data compared to RMP ambient open-Bay and margins samples over most of the range. Similar to the case for ND = 0 substitution, the introduced bias of the ND = MDL substitution method decreases in importance as more of the individual congeners are detected. For the median DMMO concentrations and higher, the difference between the ND = 0 and ND = MDL substitutions diminishes.

Substituting ND = MinStudy or ND = Half MDL yielded distributions between the lower and upper limits that were similar to RMP margins concentrations. Although the RMP open-Bay and margins data are both reported using only the ND = 0 substitution method, the impact of the substitution is very small, as MDLs reported are typically less than those for most of the DMMO data, and very few congeners are reported as ND within each sample. For example, within the South Bay RMP Margins report (Yee et al., 2019 draft) PCB data, of the 40 historically reported RMP congeners, only one congener (PCB 151) was ever reported ND, in only 4% of samples.

Similarly, distributions for open-Bay sites in the DMMO data (Figure *3*) fell mostly below RMP open-Bay results for ND = 0 substitution, above for ND = MDL, and overlapping RMP ambient distributions for ND = MinStudy and ND = Half MDL substitutions. Care should therefore be exercised in interpreting plots of data with extensive non-detects, as estimates often differed by more than two-fold between the substitution methods. Again, although RMP open-Bay data are reported using the ND = 0 substitution, for the 40 historically reported RMP congeners, NDs are rare. For example, in 2014 RMP Status & Trends sediment sampling, no samples had any NDs for those 40 PCB congeners.

Methods for conducting statistical tests with left-censored data—such as non-detects—without using substitution have been developed, and we used such a method for comparing the DMMO data to ambient concentrations reported by the RMP. We used the cendiff function from the NADA R-statistical package (Lee 2016) to compare the ECDFs between the DMMO and RMP data from open-Bay areas, and between the DMMO and RMP data from margins (nearshore) areas. The package inverts approaches used for comparisons of survival studies with right censored data (e.g., with indeterminate survival times for some individuals past the end of a study), to apply to datasets that are typically left-censored, such as environmental concentrations with non-detects below one or more thresholds. The null hypothesis tested is that the compared groups (with either or both groups left-censored) originate from a single distribution. Despite the design of this statistical package explicitly to handle left-censored datasets, the substitutions for NDs still had an effect, because the functions are primarily designed for individual measured parameters rather than aggregated results, such as sums of PCBs, where with a single detected component, the sum is no longer censored. We explored treating samples where more than 12 congeners were NDs as also being censored (as unknown values below their reported sums) but the results suggested extremely low p-values (e.g., probabilities of $1x10^{-30}$ and lower that the RMP and DMMO sets originated from the same distribution), likely an artifact of the distribution of the very few values remaining uncensored in the DMMO sets (typically about 10% to 20% of the samples when using that handling).

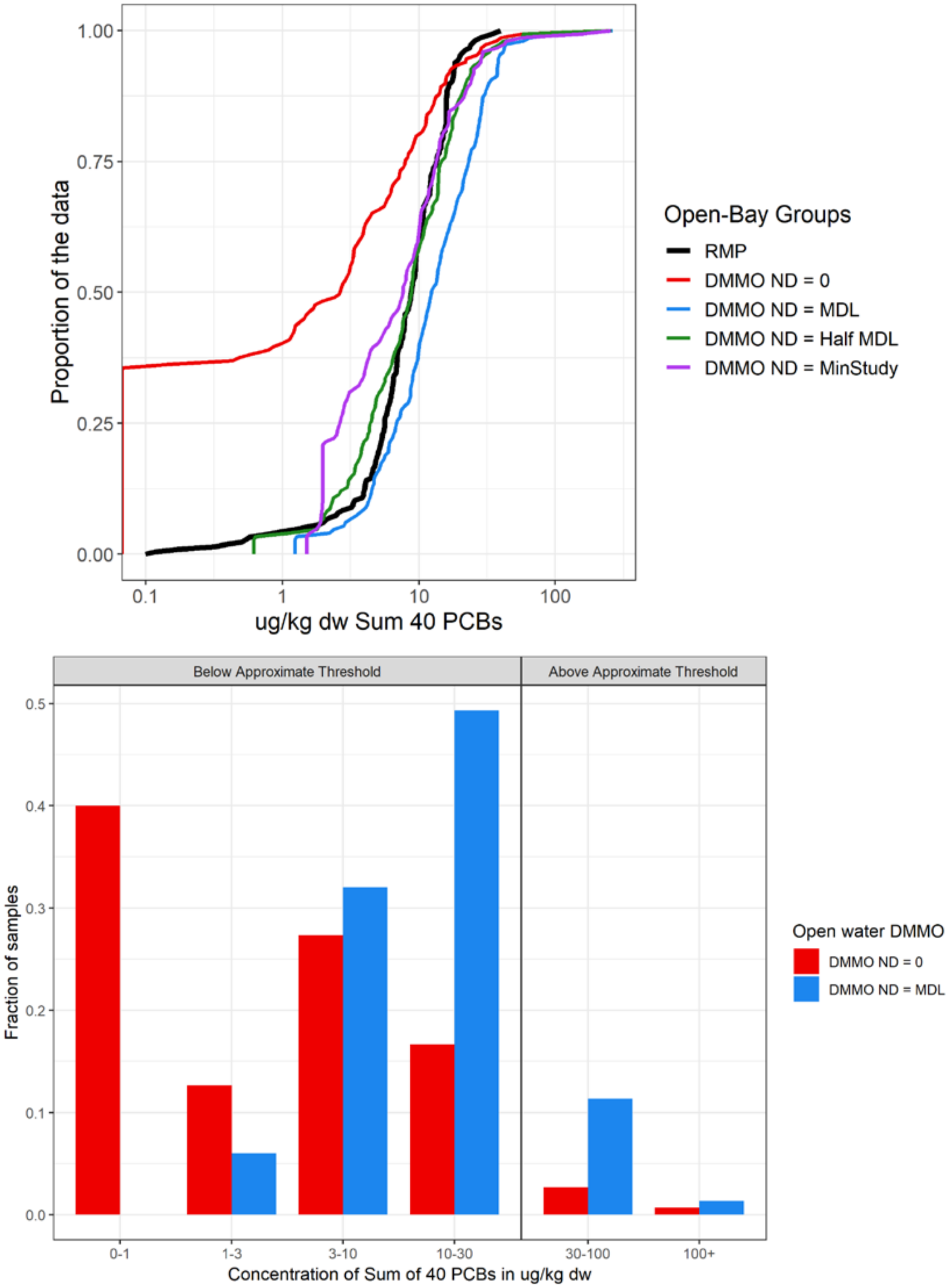

Figure 3 Distributions of RMP Open-Bay Data, and DMMO Open-Bay Data Using Different Handling for Non-Detects. Upper graph shows distributions as empirical CDFs, lower graph as histograms with fraction of samples in size bins grouped above and below the approximate in-Bay disposal threshold. Substituting zero for non-detects (ND = 0) yields the lowest estimates for DMMO-reported data due to extensive non-detects, with most results below ambient concentrations reported by the RMP. Substituting the MDL (ND = MDL) yields much higher estimates, mostly above RMP ambient values. Actual concentrations in DMMO data likely fall between these lower and upper limits. Substituting at the lowest concentration reported in the same study (ND = MinStudy) or at half the MDL (ND = Half MDL) yields distributions similar to the RMP samples.

Where some of the individual congeners were detected, a sum of PCBs can be reported, but the sum may be highly biased depending on the handling of the remaining NDs. With the ND = 0 substitution, the subset of samples with a zero sum of PCBs (the proportion where the ECDFs intersect the vertical axis in Figure 2 and Figure 3) were handled as unknown values less than their sum of MDLs. However, values above that threshold (with detections of one or more congeners, and thus an uncensored sum) were handled by the function as though they were fully quantitative values.

The distributions for the ND substituted DMMO nearshore data were statistically significantly different ($p < 0.05$), lower throughout nearly the whole range for ND = 0 substitution, when compared to the RMP margins group (Figure *2*). For the ND = MinStudy and ND = Half MDL substitutions for DMMO nearshore sites, the sums of PCBs largely overlapped with values reported for the RMP margins, and the groups were not significantly different ($p > 0.05$). Both these substitutions for DMMO nearshore sets yield wide variances, and the ECDFs cross the RMP nearshore distribution at multiple points across the range, increasing the probability that they appear to originate from the same distribution. Although we would expect the results to be entirely biased high, we also compared the DMMO data with NDs substituted by the MDLs for each congener (ND = MDL) for the sake of exploring the upper bound of possibilities. Sums for all samples with any non-detects were biased to their highest possible values, and the distribution was significantly higher for DMMO nearshore areas compared to RMP margins ($p < 0.05$). Because the ND = 0 and ND = MDL substitutions bias the DMMO set lower and higher than the RMP margins respectively, the apparent significant differences are likely just an artifact of the substitutions.

For the open-Bay areas, the ND = 0 substituted DMMO data (Figure *3*) were also lower and significantly different from the RMP open-Bay PCB results. For both the ND = MinStudy and ND = Half MDL substitutions (Table 2, Figure 3) for the DMMO open-Bay set, these substituted distributions were also significantly different from the RMP open-Bay data. It should be noted that cendiff and other comparative methods for ECDFs compare not only the central tendencies, but also the spread and tails of distributions. Thus although visually the open-Bay RMP data appears to cross the DMMO results for the ND = MinStudy and ND = Half MDL distributions around their medians, they significantly differ. The RMP Bay data is nearly always higher than the DMMO MinStudy and Half MDL substitutions below the median and lower than those DMMO cases above the median (indicating a smaller variance), thus appearing significantly different. Only the open-Bay DMMO results compared to open-Bay RMP samples were not significantly different ($p > 0.05$). Again, ECDF comparisons are not always as visually intuitive as means or median tests, but multiple intersections of the ECDFs between the RMP and ND = MDL substituted values for DMMO data suggest relatively little differentiation. Again, these outer bound distributions can be largely artifacts of their elected substitutions, so we should not dwell on their significant differences (or lack thereof) for each of the substitutions too much. Inferences derived are only robust if both substitution methods yield the same conclusion (e.g., that upper and lower bound substitutions are either both higher or both lower than the corresponding RMP distribution, i.e., significantly different in the same ways independent of the substitution method).

Table 2 Statistical comparison between DMMO and RMP PCBs Sample sets using different substitutions assumptions– ND = 0, ND = MinStudy, ND = Half MDL, and ND = MDL indicate different substitutions for non-detect results. For the nearshore data, the significant differences between RMP and DMMO sets for the lowest (ND=0) and highest (ND=MDL) substitutions appear to be an artifact of the substitution method, as the intermediate substitutions are not significantly different. However, for the open-Bay comparisons, there are stronger indications of a real difference, as three of the substitution methods for the DMMO data are significantly different from the RMP set, and in similar ways based on the ECDFs (higher concentrations than the RMP data for their top ~10% of samples, regardless of the substitution, and median and bottom quartile concentrations below corresponding values for the RMP data.

Comparison	DMMOSumGroup	p
RMP vs DMMO, Nearshore	DMMO ND = 0	0.0095
	DMMO ND = MinStudy	0.81
	DMMO ND = Half MDL	0.069
	DMMO ND = MDL	9.8E-06
RMP vs DMMO, Open-Bay	DMMO ND = 0	2.60E-16
	DMMO ND = MinStudy	0.00020
	DMMO ND = Half MDL	0.010
	DMMO ND = MDL	0.175

PCB Inventories

Another PCB management question of interest to the RMP concerns the existing inventory within the Bay: MQ3. What is the mass of PCBs in Bay sediment from DMMO reported areas compared to the mass in the rest of the open-Bay?

PCBs already in the Bay present a risk to resident biota and represent a persistent exposure that extends the time for recovery of the ecosystem. PCB inventories in open-Bay and margins sediment can be estimated using the concentration data obtained from RMP sampling in those areas. Similarly, PCBs in dredged nearshore areas may also cause exposure to biota, or be exported to other areas in the Bay and be mixed with cleaner sediment. An estimate of total PCBs in dredged nearshore areas relative to other inventories is of interest to evaluate the risk presented relative to other Bay inventories. Although PCB concentrations for open-Bay areas are also available in the DMMO database, such locations largely occur within areas already monitored in the RMP Status & Trends program, and thus are not an inventory separate from that already estimated for the RMP open-Bay areas.

In contrast, dredged nearshore areas are not sampled by the RMP in either the Status & Trends or Margins characterization efforts. Using the concentrations reported in DMMO samples, PCB inventories in dredged nearshore areas were estimated. The total surface area of nearshore areas in each of the RMP defined Bay segments was calculated and multiplied by the active layer depth (15 cm) used for the PCB mass budget inventory (Davis 2004). The same concentration of solids in sediment value of 0.5 kg/L as used by Davis (2004) was then applied to calculate a mass of sediment in dredged nearshore areas, and multiplied by the PCB concentration in DMMO port sites averaged by Bay segment to obtain an inventory estimate.

Based on the large differences in distributions depending on the handling of non-detects, the expected PCB inventories in DMMO dredged nearshore areas could also potentially vary by a large amount depending on the assumptions applied for the expected concentrations of congeners not detected, especially for samples where all or most congeners were NDs. Substitution of NDs by zero (ND = 0) or MDL (ND = MDL) provided lower and upper bounds of port inventories that differed by about a factor of two (Table 3). The ND = half MDL and ND = MinStudy substitution alternatives yield estimates between those lower and upper limits.

The mass of PCBs present in the active layer in DMMO nearshore areas was small relative to the estimated Baywide inventory of around 2500 kg, assuming a mixed layer depth of 15 cm (Davis 2004). Even in the upper limit case (ND = MDL), only about 2.5% of the Bay inventory is estimated to be present in DMMO nearshore areas. This is not surprising given the relatively small area of that stratum.

Table 3 Estimated Mass of PCBs (kg) Present in Port Areas by Segment, Using Different ND Substitution Methods

Region	ND = 0	ND = MDL	ND = Half MDL	ND = MinStudy
Central Bay	34.06	58.73	46.39	38.90
San Pablo Bay	0.73	2.63	1.68	1.14
South Bay	1.52	6.44	3.98	2.27
Suisun Bay	0.06	0.45	0.26	0.12

SECTION 3: PCB MOVEMENT VIA DREDGING

The dredged volumes and disposal sites for various projects listed in the DMMO annual report can be used with the reported sediment concentration data to estimate movement of PCBs within the Bay and exported outside of the Bay. These estimates are useful for partially addressing the following RMP management questions:

- MQ5. What is the relative contribution of each loading pathway as a source of PCBs impairment in the Bay?
- MQ6. What future impairment is predicted for PCBs in the Bay?

Dredging is not tracked as a “loading” pathway to the Bay because the dredged sediment is considered to already be in the Bay. However, this study presents an opportunity to assess the movement of PCBs via dredging, relative to loading pathways, and loss processes in PCB fate.

Tables 5 and 6 show the expected mass of PCBs moved in the period 2006 to 2017 for all projects reported in the DMMO database. Sediment PCB masses moved were calculated by taking the reported dredge volumes for each project, multiplying by the concentration of solids in sediment of 0.5 kg/L used in a PCB mass budget for San Francisco Bay (Davis 2004) to get a mass of sediment moved, and multiplying that mass by average PCB concentration for that project period. This value is likely to vary between dredge locations depending on the composition and degree of consolidation in the dredged sediment, but represents a reasonable starting point that makes estimates based on assumptions on a similar basis as those used in the Bay PCB TMDL and other RMP reports estimating PCB inventories and loads.

Table 4 Mass of PCBs (kg) Redistributed by Dredging from Bay Regions to Disposal Areas 2006-2017 (assuming ND=0)

Region	SF-10 San Pablo	SF-11 Alcatraz	SF-16 Suisun	SF-9 Carquinez	Total In-Bay	SFDODS Ocean	Upland/ Reuse	Total Out of Bay
Central Bay	2.72	16.57		0	**19.3**	9.64	10.05	**19.7**
San Pablo Bay	0	0		0.04	**0.04**		0.63	**0.6**
South Bay	0.62	16.57			**17.2**	2.65	14.22	**16.9**
Suisun Bay		0.15	0	0.39	**0.5**	0.08	1.07	**1.2**
Total Received	**3.34**	**33.29**	**0**	**0.43**	**37.1**	**12.37**	**25.96**	**38.3**

Table 5 Mass of PCBs (kg) Redistributed by Dredging from Bay Regions to Disposal Areas 2006-2017 (assuming ND=MDL)

Region	**SF-10 San Pablo**	**SF-11 Alcatraz**	**SF-16 Suisun**	**SF-9 Carquinez**	**Total In-Bay**	**SFDODS Ocean**	**Upland/ Reuse**	**Total Out of Bay**
Central Bay	7.89	57.62		0.01	**65.5**	30.91	47.89	**78.8**
San Pablo Bay	3.64	0.23		3.13	**7.0**		2.83	**2.8**
South Bay	0.85	26.11			**27.0**	3.39	22.55	**25.9**
Suisun Bay		0.45	1.25	2.01	**3.7**	0.15	4.06	**4.2**
Total Received	**12.38**	**84.41**	**1.25**	**5.15**	**103.2**	**34.45**	**77.33**	**111.8**

The mean DMMO reported concentration for each study location was determined for each year in which testing occurred and applied to the entire dredged volume in that year. Some projects were granted “Tier 1” status, for concentrations not above thresholds of concern in previous rounds of testing, so they did not have reported concentrations associated with dredged volumes reported in some years. For those projects, average results from the last previously tested year were applied to dredged sediment volumes. The database was downloaded in early 2017, so the testing data included in the DMMO database would be from 2016 and prior at the time of download. However, similar to the method we applied to sites with “Tier 1” status and only periodic chemistry data, we still calculated masses moved in 2017 projects, assuming that PCBs in sediment dredged in 2017 would equal their average concentrations from the last previous year tested (i.e., 2016 or prior) for that project. About half of the total reported dredged volumes in the DMMO Annual Reports did not have associated PCBs data.

The total PCB masses dredged for all Bay segments combined differ by nearly a factor of three between the ND = 0 and ND = MDL substitutions (Table 5, Table 6). Most dredging activity occurred in Central Bay, with about half the disposed PCB masses remaining in the Bay for both substitution methods. About 50-60% of the remaining PCBs were sent for upland disposal or reuse, with the remaining portion (about one-fourth of the total) sent to ocean disposal. South Bay, with the next greatest masses of PCBs moved, also had disposal about equally split between disposal inside the Bay and outside the Bay (upland/reuse or ocean). For in-Bay disposal, the vast majority from South Bay went to the Alcatraz disposal site in Central Bay. The majority of PCBs in South Bay sediment sent for disposal outside of the Bay went to upland and reuse sites. For dredging in the Suisun and San Pablo Bay regions, the PCB masses estimated for in-Bay versus upland/reuse differed greatly between the ND substitution methods, so the true net movement is highly uncertain.

This net movement of sediment PCBs, between about 80 to 200 kg (depending on the assumptions for NDs) over the course of 12 years, with about half of that mass (about 40 to 100 kg) disposed outside of the Bay, represents a moderate loss pathway for PCBs. An average removal rate of about 4 to 8kg per year is about 20% to 40% of the estimated yearly local stormwater input (approximately 20 kg annually), and higher than the net PCB movement via dredging for 2001 to 2005 (4.6 kg disposed in-Bay, 6.1 kg sent out (upland/ocean), approximately 1 kg per year for each), previously estimated in the San Francisco Bay PCB

TMDL Final Staff Report (SFBRWQCB 2008). Although the movement of sediment PCBs via dredging is moderate to small relative to loading from the largest loading pathways at a Bay-wide scale, it may be important to account for this pathway, especially in considering contaminant fate at a localized scale, e.g. for margin areas adjoining dredged nearshore sites or channels. In Bay disposal may also transfer some of the nearshore exposure risk to biota in open-Bay habitats, spreading and diluting somewhat more contaminated sediment over a wider area. However, the most contaminated sediment cannot be disposed of in-Bay, so the potential increase in exposure is not likely to be large.

SECTION 4: CONCLUSIONS AND FUTURE NEEDS

Qualitatively, PCB concentrations in dredged sediment reported by the DMMO follow general patterns seen in other data sets reported for the Bay. PCB concentrations were highest in Central Bay, particularly in nearshore and port areas. One of the greatest challenges in working with this dataset was the high frequency of non-detects, with around one-quarter of all the samples non-detect for all congeners. Data distributions were highly sensitive to handling of non-detects, with substitution by zero or MDL greatly skewing results, yielding distributions significantly different from RMP margins and open-Bay samples for the most part. Other substitutions such as half the MDL resulted in distributions often more similar to results from prior margins or open-Bay sampling, and may provide more realistic concentration estimates.

The uncertainties arising from extensive NDs extended to estimates of PCB inventories in port areas and the transfers of PCBs between regions. Minimum (ND = 0) and maximum estimates (ND = MDL) differ by about a factor of two. Due to the relatively small areas and volumes of sediment compared to overall Bay inventories, even the maximum estimate is only about 20 to 40% of Bay-wide PCB loading via watersheds. However, in some locations, the dredged areas may represent a larger proportion of the local habitat, and thus potentially a large fraction of local PCB loads and transport. However, regardless of the method used for handling non-detects, when evaluated at a Bay-wide scale, about half of the PCBs present in dredged sediment are removed from the Bay, via net export to ocean or upland/reuse disposal sites.

Although the existing methods used for analyzing dredged sediment may suffice for determining disposal options and evaluating needs for bioaccumulation testing and other regulatory needs, their usability for other applications will be limited or highly uncertain due to the high frequency of NDs. Use of more sensitive analytical methods for samples from areas that have demonstrated low concentrations in past analyses (especially those with NDs for all congeners) would make data more useful for applications beyond compliance testing for disposal. Approaches such as providing supplemental funding to composite archived material and reanalyze them with more sensitive analytical methods (e.g., batched with RMP samples in later analysis or reanalysis) to address more critical data gaps may help provide more useful information while incurring minimal additional costs.

Other challenges of working with the database included the lack of standardization in site or project naming conventions between database entries and published documents, such as the annual reports. Even slight mismatches prevented linking fields in database tables, requiring manual investigation of the reasons for seemingly missing data. Although many of these discrepancies were eventually resolved by consulting various sources (e.g., hardcopy reports, staff for involved agencies), the usability of the data would be improved by ensuring consistent naming and reporting conventions between reporting products, especially within a project. Other projects included ND data with reported MDLs of 0, impossible as an MDL of 0 would suggest never needing to report something as not-detected (for continuous data such as chemical concentrations). Although for our reporting here we substituted the MDLs of zero with the lowest non-zero MDL for the given congener reported from the same project (or the lowest non-zero MDL for any project in the DMMO data where there were no valid MDLs for the congener within the project)

Although an ultimate goal may be to make the data comparable to California Environmental Data Exchange Network (CEDEN) datasets from other providers, some accommodations to make entries to the database easier and more hands-on assistance in data entry and upload may help DMMO stakeholders make more accurate and complete reporting entries going forward. SFEI will be taking over the maintenance and management of the DMMO database moving forward, so we hope to play a role in developing and implementing methods to resolve some of these challenges. Despite the challenges, this exploration of the DMMO data has provided insights on the characteristics of this component of Bay ecosystem which has not been examined in much depth previously. We recommend continuing efforts to continue to report data from dredging projects digitally (beyond just PDFs or other hardcopy equivalents), as it ensures that the data are provided with sufficient detail and backing metadata to make them useful beyond just their immediate needs for documenting permit compliance.

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