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Article

Legacy mercury, reservoir dynamics, and dredging effects on methylmercury in San Francisco Bay

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SUMMARY

Legacy methylmercury (MeHg) contamination is a critical environmental concern within the San Francisco (SF) Bay water system. While historical mining sources have been identified as legacy MeHg inputs, the specific pathways through which this pollutant cycles via upstream reservoirs and human activities remain unclear. This study investigates the influence of legacy mining, reservoir dynamics, and sediment dredging on regional MeHg concentrations to better understand these ongoing environmental risks. To evaluate these dynamics, we analyzed extensive historical datasets from the SF Bay Regional Monitoring Program spanning 1999 to 2022, comparing MeHg concentrations against Stevens Creek Reservoir releases, river flow patterns, and annual dredging volumes. Our analysis reveals that MeHg levels in Stevens Creek Reservoir are notably elevated—likely due to runoff from the nearby New Almaden Mining District—and exhibit strong seasonal peaks during late summer and fall. Furthermore, we identified a statistically significant correlation between monthly river flows and SF Bay MeHg levels when lagged by nine months, indicating a delayed environmental response. Contrary to some existing literature, we also found that total annual dredging volumes and sediment disposal practices are significantly associated with higher MeHg concentrations across the Bay Area. These findings elucidate the complex cycling dynamics of MeHg in impacted watersheds, demonstrating how legacy mining continuously impacts upstream waterbodies. Ultimately, this research showcases the significant effect of human activities on pollutant distribution, giving insight to inform future reservoir management and dredging policies in the SF Bay Area and beyond.

INTRODUCTION

The San Francisco (SF) Bay-Delta estuary ranks among the largest and most ecologically significant estuaries on the West Coast of North America (1). It provides crucial habitat for a diverse array of fish, birds, and invertebrates, supports important commercial and recreational fisheries, and serves as a vital resource for millions of Californians (1). Nevertheless, the estuary faces many environmental challenges, including contamination from various pollutants that have accumulated over decades of industrial, agricultural, and urban activity (2).

Among the contaminants of concern is mercury (Hg), particularly its organic form, methylmercury (MeHg). Known as a potent neurotoxin, MeHg poses significant risks to wildlife and human health, primarily because it biomagnifies up the food web, reaching its highest concentrations in predatory fish and the wildlife and humans that consume them (3). Microbes, especially sulfate-reducing bacteria, form MeHg through processes in aquatic sediments under anaerobic conditions, converting less toxic inorganic mercury into this more readily assimilated form, which then becomes especially concentrated in predatory species (4). As a result, the public health relevance of this issue in SF Bay is typified by long-standing fish consumption advisories related to elevated mercury levels in certain species (5).

Multiple factors that may promote MeHg generation are evident in the SF Bay region. Firstly, due to the presence of extensive historical mercury mining operations in the New Almaden Mining District, formerly one of the largest mercury mines in North America, the SF Bay Area is significantly at risk for ongoing Hg and MeHg contamination (6). Furthermore, both seasonal swings in the surface temperatures of water bodies and seasonal patterns of stratification in the SF Bay itself provide the potential for anoxic conditions in which sulfate-reducing bacteria thrive. Finally, with extensive dredging activities and one of the largest wetland restoration efforts in the continent, the SF Bay has the potential to see impacts in areas directly affected by such dredging due to resuspension of MeHg previously trapped in sediment during both sediment dredging and related disposal activities, as has been indicated in other studies (7).

Monitoring programs have collected data on MeHg concentrations, river flows, reservoir levels, and dredging activities within the Bay system over the period from approximately 1999 to 2022 (5). Still, the interplay between legacy sources, reservoir dynamics, seasonal hydrology, and in-bay activities like dredging requires specific investigation. While methylmercury (MeHg) dynamics within the New Almaden Mining District have been well studied, a gap remains in understanding how this legacy pollution affects proximate, downstream, and distant regional water bodies, particularly regarding the influence of seasonal reservoir releases and dredging activities. We hypothesized that mining runoff from former mining sites in upstream regions of the Stevens Creek watershed causes seasonally-dependent, elevated MeHg in the downstream Stevens Creek Reservoir, that subsequent seasonal releases from this reservoir correlate with downstream San Francisco (SF) Bay MeHg levels, and that regional dredging activities do not significantly elevate MeHg across the broader area. To test these hypotheses, we analyzed MeHg concentrations alongside Stevens Creek Reservoir discharge data and SF Bay dredging volumes across 347 monitored locations. Our results supported the first two hypotheses but contradicted the third, revealing that dredging and upland sediment disposal actually correlate

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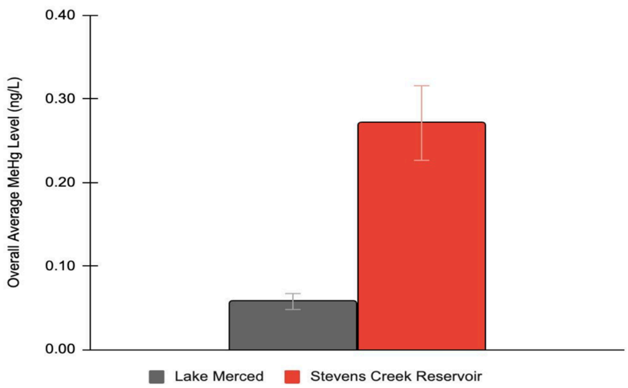

Figure 1. Comparison of overall average methylmercury (MeHg) levels across all data points for Stevens Creek Reservoir and Lake Merced. Data obtained from all sources referenced across years 1999-2022. The grey bar shows MeHg Levels for Lake Merced and the red bar shows MeHg levels for Stevens Creek Reservoir. Error bars represent ± 2 standard errors of the mean.

strongly with MeHg pollution levels across SF Bay waters. Ultimately, these findings provide critical insight into regional MeHg cycling and will directly inform future reservoir management and sediment disposal policies in any location dealing with legacy mercury pollution.

RESULTS

LEGACY MINING AND MeHg CONCENTRATION

Our analysis of reservoir MeHg concentrations from 1999 to 2022 revealed distinctly elevated levels in the Stevens Creek Reservoir compared to the levels found in SF Bay Area water bodies not impacted by legacy mining operations, as well as strong seasonality, peaking in the summer. Average MeHg concentrations from all available data for Stevens Creek Reservoir yielded 0.271 ng/L (95% confidence interval (CI) 0.227–0.316 ng/L), far higher than Lake Merced, an SF Bay Area lake with no history of mining in its watershed, which yielded 0.058 ng/L (95% CI 0.048–0.067 ng/L) (**Figure 1**). Further exploring the dynamics of elevated MeHg in Stevens Creek Reservoir, we noted a highly statistically significant seasonal cycle using monthly average data (one-way ANOVA, $F(11,77) = 5.022$, $p = 0.0000075$) with variable, but discernibly elevated concentrations peaking sharply in summer through early fall (monthly averages ± standard deviation: July: 0.35 ± 0.37 ng/L, August: 0.65 ± 0.71 ng/L, September: 0.52 ± 0.86 ng/L, October: 0.24 ± 0.58 ng/L) and reaching minimums during winter/early spring (monthly averages ± standard deviation: February: 0.09 ± 0.06 ng/L, March: 0.09 ± 0.07 ng/L, April: 0.12 ± 0.09 ng/L) (**Figure 2a**). On visual inspection we found no evidence for dependence of this seasonal peak in reservoir MeHg levels on monthly reservoir volume (**Figure 2b**). However, it coincided with the period of lowest average reservoir flow (**Figure 2c**). Furthermore, our comparison between monthly average MeHg concentrations in Stevens Creek Reservoir and SF Bay showed a somewhat correlated logarithmic relationship, which, interestingly, tended to cluster seasonally, especially during fall, winter, and summer months (logarithmic regression, $R^2 = 0.314$, $F(1,10) = 4.57$, $p = 0.058$) (**Figure 3a**). Finally, we determined a strong, significant correlation between annual MeHg levels measured in Stevens Creek Reservoir and levels detected in the SF Bay (linear regression, $R^2 = 0.584$, $F(1,7) = 9.829$, $p = 0.016$) (**Figure 3b**).

Stevens Creek Reservoir MeHG Levels Impact the SF Bay

To investigate the hypothesis that seasonal reservoir releases influence downstream Bay MeHg levels, we examined the relationship between SF Bay monthly MeHg concentrations and monthly average river flow at Stevens

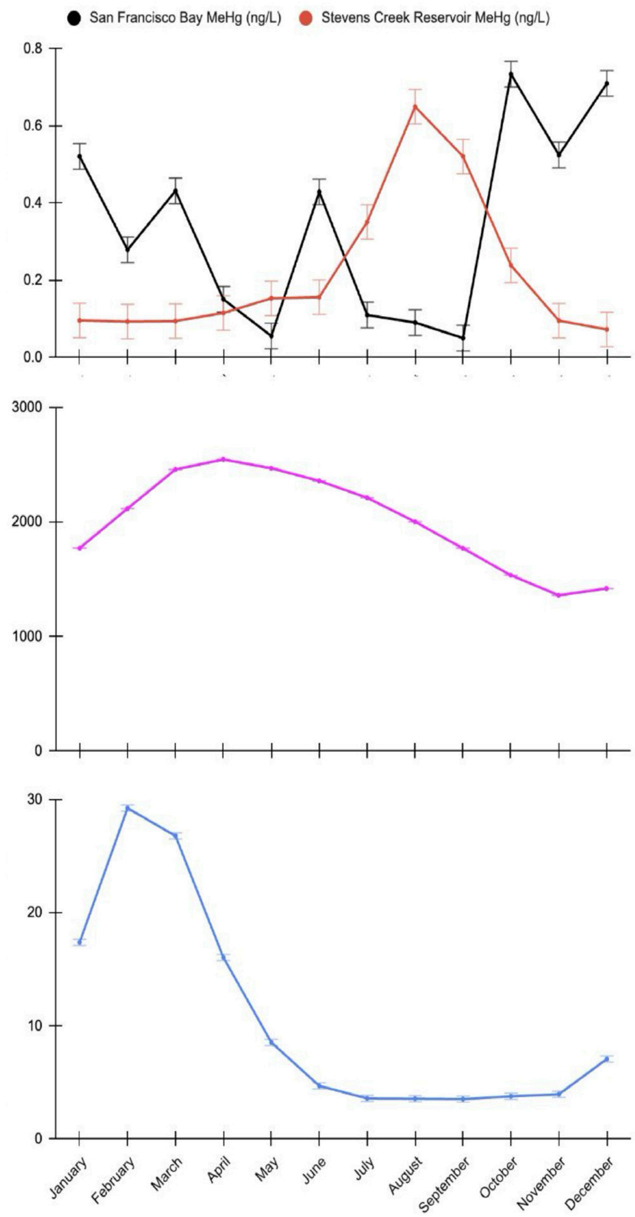

Figure 2. Seasonal patterns in methylmercury (MeHg) concentrations, reservoir conditions, and hydrologic variables in Stevens Creek Reservoir. (A) Monthly average MeHg concentrations in Stevens Creek Reservoir plotted by calendar month. (B) Average monthly Stevens Creek Reservoir storage volume. (C) Average monthly discharge flow below Stevens Creek Reservoir measured by Valley Water stream sensor 5044 (Stevens Creek below Stevens Creek Reservoir). Data represent monthly averages from the 1999–2022 monitoring period; error bars indicate ±2 standard errors of the mean.

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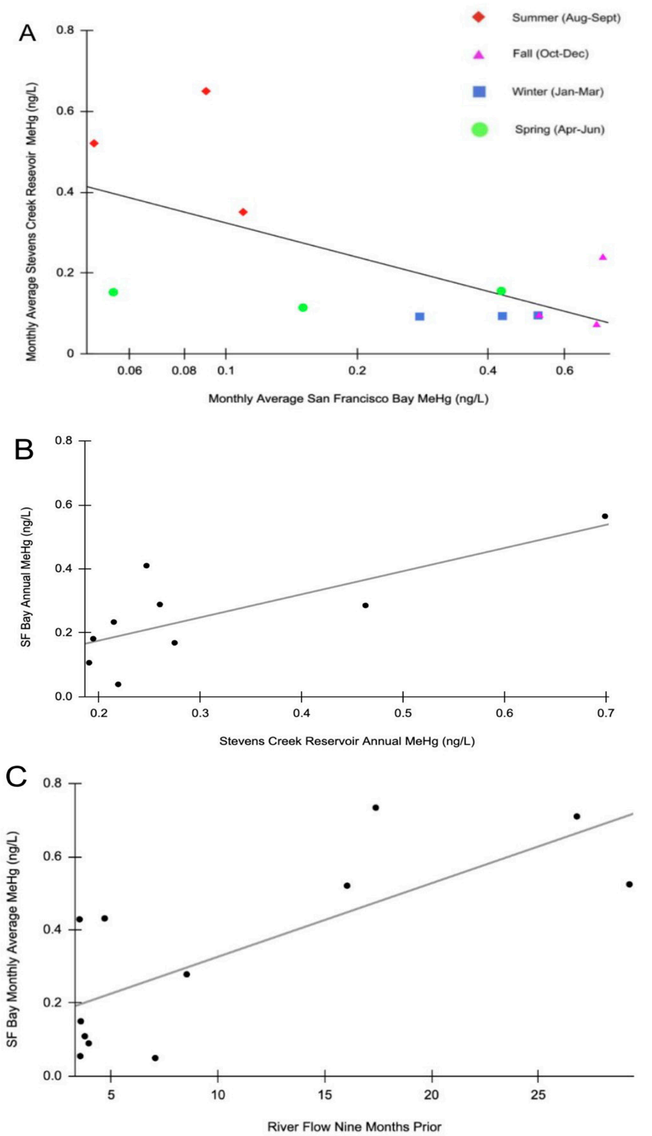

Figure 3. Relationships between methylmercury (MeHg) concentrations and discharge rates in Stevens Creek Reservoir and MeHg concentrations in San Francisco Bay. (A) Monthly average MeHg concentrations in Stevens Creek Reservoir versus monthly average MeHg concentrations in San Francisco Bay. Data represent monthly averages calculated from the 1999–2022 monitoring period (n = 12). The fitted logarithmic regression model was Bay MeHg = −0.1907 ln(Reservoir MeHg) − 0.0026 (R^2 = 0.314, F(1,10) = 4.57, p = 0.058). Points are colored by season: winter (January–March), spring (April–June), summer (July–September), and fall (October–December). (B) Annual average methylmercury (MeHg) concentrations in Stevens Creek Reservoir versus annual average MeHg concentrations in San Francisco Bay. Each point represents one year with available data (n = 9). The fitted linear regression model was Bay MeHg = 0.7236(Reservoir MeHg) + 0.0312 (R^2 = 0.584, F(1,7) = 9.829, p = 0.0165). The positive slope indicates a significant relationship between annual average MeHg concentrations in Stevens Creek Reservoir and the San Francisco Bay. (C) Monthly average San Francisco Bay MeHg concentrations versus Stevens Creek Reservoir discharge flow lagged by nine months. Data represent monthly averages from the 1999–2022 monitoring period (n = 12). The fitted linear regression model was Bay MeHg = 0.0201(Flow) + 0.1255 (R^2 = 0.568, F(1,10) = 13.14, p = 0.0047).

Creek just beneath the Stevens Creek Reservoir, an outflow proxy used by the reservoir's controller. SF Bay MeHg concentrations also exhibited seasonality, although the pattern showed less pronounced variation than in Stevens Creek Reservoir. Monthly average MeHg levels in the SF Bay displayed a broader peak in fall through early winter (October-January), approximately nine months after the peak average flow period occurring in January-April (**Figure 2a,c**). Visual inspection of the monthly time series showed that the broad peak in SF Bay MeHg concentrations during fall through early winter occurred approximately six to seven months after the peak average flow period. However, our correlation analysis between the monthly average flow at Stevens Creek beneath Stevens Creek Reservoir and monthly average SF Bay MeHg concentrations found the strongest statistically significant relationship occurred when the river flow nine months prior was correlated with MeHg levels in the Bay (linear regression, R^2 = 0.561, p = 0.005) (**Figure 3c**).

Impacts of Dredging Activity and Sediment Disposal on Methylmercury Concentrations

Addressing the hypothesis that dredging activity does not affect MeHg levels in the Bay, we examined the relationship between annual dredging activity and average annual MeHg concentrations in SF Bay waters for the years 2000-2022. Yearly average MeHg concentrations, as based on overall SF Bay system averages, fluctuated during this period, with averages ± standard deviation ranging from 0.058 ± 0.008 ng/L in 2022 to 6.90 ± 16.7 ng/L in 2005. A visual inspection suggested apparent correlation between some aspects of dredging activity and SF Bay MeHg levels (**Figure 4**). Further parsing the data, comparison of average MeHg versus total annual dredging volume showed a moderate-to-strong non-linear relationship (polynomial regression, R^2 = 0.683) according to the fitted polynomial trendline (**Figure 5a**). On the other hand, our analysis comparing annual in-Bay disposal volume specifically to annual average SF Bay MeHg levels via scatter plot revealed only a very weak positive linear relationship (linear regression, R^2 = 0.064), and we found a statistically insignificant linear correlation between these variables (linear regression, p = 0.257) (**Figure 5b**). Upland reuse of dredged sediments also correlated strongly with SF Bay MeHg levels according to a second-order polynomial regression model (R^2 = 0.567) (**Figure 5c**).

DISCUSSION

Our study investigated the potential linkages between legacy mining inputs, reservoir dynamics, dredging activities, and MeHg concentrations within the SF Bay system using monitoring data from approximately 1999–2022. We hypothesized that (1) runoff from legacy mining causes seasonally elevated MeHg in Stevens Creek Reservoir, (2) seasonal releases from this reservoir correlate with downstream Bay MeHg levels, and (3) regional dredging activity does not detectably elevate Bay-wide MeHg concentrations. The results provide insights into the complex factors influencing MeHg levels in this ecologically sensitive estuary. Elucidating these key drivers is critical for predicting contamination dynamics, protecting the health of the Bay›s wildlife, minimizing human exposure through fish consumption,

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and informing effective management strategies.

Consistent with the premise that upstream legacy mercury sources impact local water bodies, Stevens Creek Reservoir exhibited distinct MeHg dynamics. First, while the connection to mining sources remains somewhat speculative and is based mainly on geographic proximity, our comparison to Lake Merced strengthens this idea. Lake Merced is a similarly sized lake in the San Francisco Bay region but does not have a history of mercury mining. This comparison therefore suggests that inputs from legacy mining may be a primary factor behind the statistically elevated MeHg levels observed in Stevens Creek Reservoir, although this control carries with it the important limitation that Lake Merced is part of a coastal watershed, not one connected to the San Francisco Bay. Additionally, the strong seasonality observed, with pronounced peaks in late summer/fall coinciding with periods of low inflow and minimum water volume, suggests internal reservoir processes (e.g., enhanced methylation in warmer, stratified, anoxic bottom waters) likely play a significant role in MeHg production, potentially fueled by accumulated mercury from the watershed (4) (**Figures 2-3**). Although our calculation yielded a lower average MeHg concentration ± standard deviation (0.22 ± 0.18 ng/L) from the provided monthly summary data than might be expected, given the high peaks (up to 0.65 ± 0.71 ng/L), the overall seasonal pattern supports the idea of the reservoir being a site of significant MeHg presence. The marginally significant linear relationship we found between monthly Stevens Creek Reservoir and SF Bay MeHg levels suggests that processes within the reservoir do influence downstream SF Bay concentrations, although other factors are also clearly important.

Additionally, our analysis supports the hypothesis that reservoir dynamics influence downstream SF Bay MeHg levels, particularly revealing a strong seasonal component with a significant time lag (Figures 2 and 3). While SF Bay

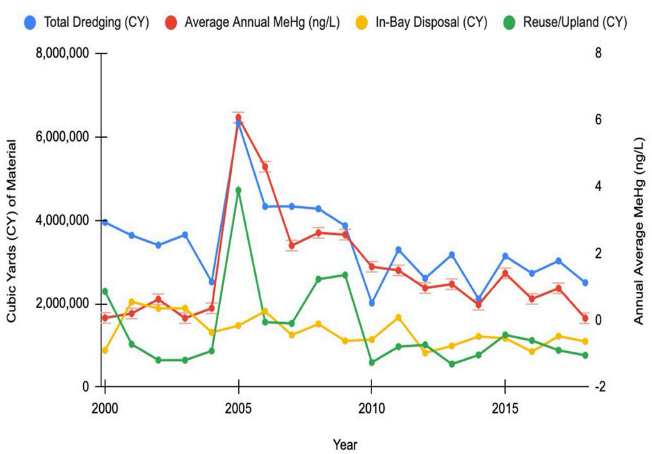

Figure 4. Annual total dredging volume, in-bay disposal volume, reuse/upland disposal volume, and annual average methylmercury (MeHg) concentrations versus calendar year (2000-2022). Dredging data are from Army Corps of Engineers Dredged Material Management Office (DMMO) and are recorded totals for each year. Average annual MeHg concentrations are from the San Francisco Bay Regional Monitoring Program averaged across all monitoring locations in the broader San Francisco Bay area. Error bars representing ± 2 standard errors of the mean are shown.

MeHg concentrations exhibited a less pronounced seasonal pattern than those observed in Stevens Creek Reservoir, Bay concentrations peaked during late fall through early winter, approximately nine months after the period of highest average discharge flow from Stevens Creek Reservoir. This cyclical pattern suggests a hysteresis effect caused by a decoupling of MeHg production and transport. Stevens Creek Reservoir may act as a seasonal production hotspot during the warm, low-flow summer months, when conditions favorable for methylation are most prevalent, while hydrologic transport is limited. Subsequent winter and spring flows may then mobilize and transport MeHg downstream, contributing to elevated concentrations observed later in the Bay. The statistically significant relationship between discharge flow and SF Bay MeHg concentrations lagged by nine months provides quantitative support for this delayed response. Such a lag could reflect the combined effects of watershed transport, sediment storage and remobilization, in situ methylation processes within the Bay, and incorporation into lower trophic levels monitored by regional sampling programs (3, 8). Taken together, our findings indicate that monthly average MeHg concentrations in Stevens Creek Reservoir are associated with monthly average MeHg concentrations in the SF Bay and that Bay MeHg concentrations are strongly related to Stevens Creek discharge flow when flow is lagged by nine months. These results support the possibility that seasonal reservoir dynamics contribute to downstream MeHg patterns in the SF Bay, although our reliance on discharge data as a proxy for managed reservoir releases remains an important limitation.

Finally, we investigated dredging in the bay to address the hypothesis that dredging and related activities did not affect MeHg levels. Interestingly, the results did not support our hypothesis, especially when disposal patterns were parsed more fully. We found a statistically significant positive linear correlation and a strong non-linear relationship between total annual dredging volume and average annual MeHg concentrations across sites sampled throughout the study region (**Figures 4 & 5a**). This non-linear, polynomial relationship suggests a potential ‹threshold effect.› At lower volumes, the estuary›s natural sedimentation dynamics might buffer resuspended contaminants. However, as dredging volumes increase, the disturbance may overwhelm the buffering capacity, possibly exposing deeper, concentrated legacy mercury deposits and keeping them suspended in the water column for longer. This suggests that overall sediment disturbance from dredging activities is statistically associated with higher MeHg levels in the water column year to year, contradicting our general hypothesis. As part of the investigation, we also examined the specific component of in-bay disposal volume. Our analysis revealed that the linear correlation between annual in-bay disposal volume and annual average MeHg levels proved very weak and statistically non-significant (**Figure 5b**). This finding implies that, based on this analysis of yearly averages, the volume of material specifically disposed within the SF Bay did not have a strong linear relationship with average SF Bay-wide MeHg levels. However, we were able to demonstrate a strong linear correlation between upland disposal and beneficial reuse of dredged sediments (**Figure 5c**). Since ‹beneficial reuse› in the SF Bay region generally means wetland restoration, this

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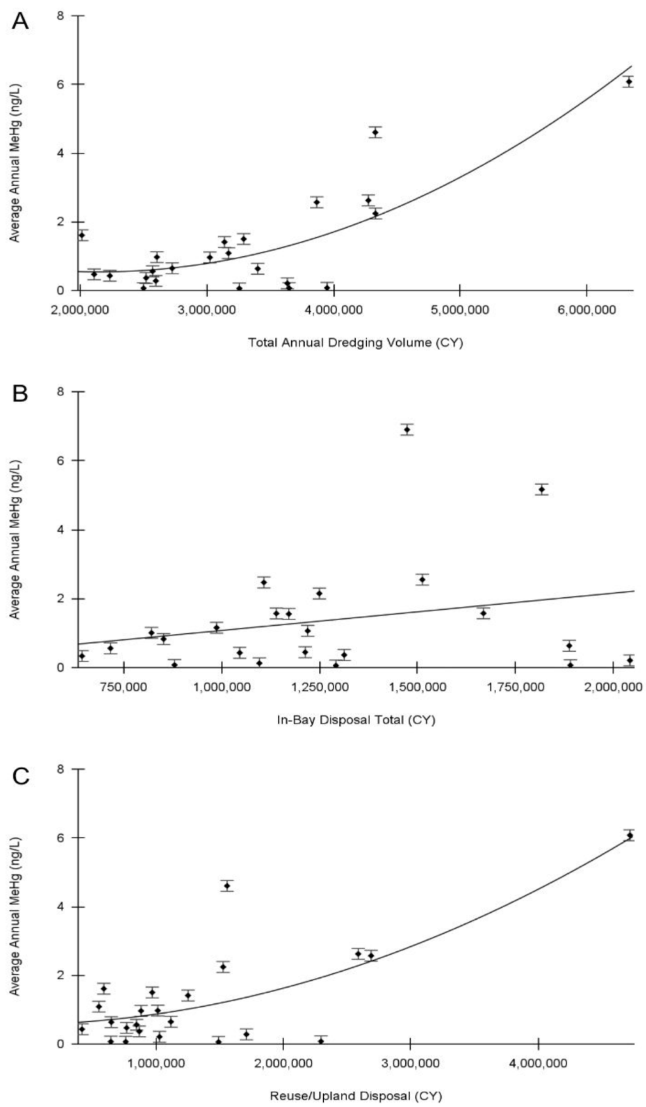

Figure 5. Relationships between annual average methylmercury (MeHg) concentrations and sediment management activities in San Francisco Bay (2000–2022). (A) Annual average MeHg concentrations versus total annual dredging volume (ADV). A second-order polynomial regression model is shown: MeHg = $3.404 \times 10^{-13}ADV^2 - 1.467 \times 10^{-6}ADV + 2.121$ ($R^2 = 0.683$, n = 23 years). (B) Annual average MeHg concentrations versus annual in-bay disposal volume (IDV). The fitted linear regression model was MeHg = $9.794 \times 10^{-7}IDV + 0.0457$ ($R^2 = 0.064$, $F(1,21) = 1.435$, $p = 0.244$, n = 23 years), indicating a weak and statistically non-significant relationship. (C) Annual average MeHg concentrations versus annual reuse/upland disposal volume (RUDV). Each data point represents one year during the 2000–2022 study period. A second-order polynomial regression model is shown: MeHg = $2.283 \times 10^{-13}RUDV^2 + 7.150 \times 10^{-8}RUDV + 0.567$ ($R^2 = 0.567$, n = 23 years). Trendlines illustrate the fitted relationships between MeHg concentrations and sediment management volumes, and error bars represent ± 2 standard errors of the mean.

correlation may be due to the role of newly restored wetlands as methylation reactors. By relocating dredged sediment into these environments, we may be providing the raw ingredients to the zones with the highest methylation rates, leading to the subsequent export of MeHg back into the wider estuary. This suggests that, regardless of potential lag times, watershed dynamics are sufficient to return MeHg from these reused sediments to the SF Bay within months of their disposal. Such a result could indicate that the primary drivers related to dredging consist of resuspension during excavation, perhaps better reflected in total volume, and the transport of sediments containing MeHg via watershed dynamics, likewise possibly better reflected in upland disposal / reuse, rather than a more specific disposal location–or that any effects of in-bay disposal are perhaps non-linear, localized, short-lived, or obscured by other factors in this aggregated dataset (9). We must also acknowledge the inherent limitation that correlation does not prove causation, as well as the possibility of confounding variables other than dredging that may have played a role in these patterns.

This paper relies on summarized and publicly available data, carrying inherent limitations. As noted, flow data served as a proxy for reservoir releases, and we based hydrological connections on stated premises, namely that seasonal rainfall might mobilize MeHg only or primarily during times of peak precipitation. Our analysis primarily used yearly and monthly averages and did not parse data based on specific locations of sampling, both of which can mask shorter-term events or localized hotspots. Furthermore, our correlation analyses identify associations, but controlled studies or source-tracking methods would be needed to confirm causal relationships between mining inputs, reservoir management, dredging, and MeHg levels. Future research could benefit from data of higher spatiotemporal resolution, especially around dredging events and reservoir releases, incorporation of sediment MeHg data, using more sophisticated hydrological and water quality models, and potentially employing mercury isotope analysis to better trace sources. Controls involving possible, confounding hydrological influences such as precipitation and tidal data would be especially desirable and beneficial.

Our results suggest that MeHg concentrations in the SF Bay system are influenced by a combination of factors, including seasonal reservoir dynamics possibly linked to legacy mercury inputs, and overall dredging activity. We also observed a significant time-lagged relationship between seasonal flow and Bay MeHg levels. While total dredging volumes showed a significant association with Bay MeHg, our specific analysis of in-bay disposal volume showed only a weak linear relationship, suggesting greater complexity in these interactions. These findings highlight the ongoing challenges in managing mercury contamination within the Bay. Such complexity suggests that future efforts to lower MeHg levels and protect ecosystem and human health must account for both seasonal hydrological drivers originating in the watersheds and the multifaceted impacts of in-bay activities such as dredging.

MATERIALS AND METHODS

Data Sources and Selection

Datasets for this study were obtained from publicly available California environmental monitoring databases located via web search and state Geographic Information System (GIS) portals (10). Exploring the data involved locating suitable datasets, extracting relevant parameters,

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filtering specifically for MeHg entries, converting units where necessary, and organizing the data for analysis. The final datasets covered approximately 1999 to 2022 and included three primary categories: time-series data of MeHg concentrations (ng/L) for 347 locations across the SF Bay Area (**Figure 6**); annual dredging summaries for 2000–2022 detailing total volume in cubic yards and disposal methods, sourced from the SF Bay Dredged Material Management Office (11); and monthly average river flow and reservoir water volume data for Stevens Creek Reservoir, sourced from the Santa Clara Valley Water District (12). A notable limitation of the MeHg data is that sampling frequencies and protocols varied across locations (10). This MeHg data was compiled from numerous sources, including the Aquatic Pesticide Monitoring Program, Bay Area Stormwater Management Agencies Association (BASMAA) Regional Monitoring Coalition, California Department of Transportation National Pollutant Discharge Elimination System (NPDES) Permit, Delta Regional Monitoring Program, Environmental Protection Agency (EPA) Environmental Monitoring & Assessment Program, H Street Green Street Improvements Project, PRISM Grant Program, Proposition 13, Proposition 84, Santa Clara Valley Water District (SCVWD) Impaired Waterbodies Improvement: Mercury Studies, SF Bay Regional Monitoring for Water Quality, SF Bay Stormwater Treatment Levels (STLS) Monitoring, San Francisco Estuary Institute (SFEI) Green Infrastructure Monitoring Program, Special Protections for Areas of Special Bio Sig, Suisun Bay Monitoring Project, and the Surface Water Ambient Monitoring Program.

Data Processing

All datasets were screened to retain only entries reporting MeHg concentrations in water (ng/L). Records with missing concentration values or incomplete date information were excluded and units were standardized to ng/L where necessary. No explicit outlier removal was performed;

Figure 6. Map of sampling locations at which our data were collected. Red circles show individual locations, all of which are bodies of water, including lakes, reservoirs, streams, creeks, wetlands, bay, and ocean.

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rather, variability was quantified using appropriate statistical methods as discussed below. In calculating monthly and annual averages, data were grouped by calendar month and year for each water body. Yearly averages were used for long-term trend and dredging analyses, while monthly averages and hydrological data served for seasonal and reservoir-bay linkage analyses. Place names were assigned to each location in the dataset using Google Maps to manually verify the landmark located at each associated longitude and latitude provided in the original data sets.

Data Aggregation and Statistical Analysis

To investigate the study's hypotheses, we performed several analyses. First, we explored the premise linking legacy mining to reservoir contamination by plotting and examining the time series of MeHg concentrations using yearly and monthly averages for Stevens Creek Reservoir and looking for temporal patterns, including seasonality. We calculated summary statistics (mean, median, range, standard deviation, and standard error) and qualitatively compared average reservoir concentrations to average SF Bay concentrations. Importantly, while we reported averages ± standard deviations in-text, we chose to use doubled standard error calculations as error bars on graphs in order to reflect the precision of estimated means rather than the full variability of the data. Second, we assessed the potential impact of reservoir releases on Bay MeHg levels, which required investigating monthly patterns. We plotted a time series of monthly flow data averaged across all years 1999-2022 alongside monthly MeHg concentrations in SF Bay averaged across those same years. Correlation analyses were used to explore relationships between outflow proxies and potentially lagged Bay MeHg concentrations, and we calculated seasonal averages. Third, we evaluated potential dredging impacts by analyzing yearly data using time series plots and correlation analyses comparing the annual total dredging volume, specifically annual in-bay disposal volume, against the yearly average MeHg concentrations for SF Bay waters. Throughout, linear, logarithmic, and polynomial regression models were used to evaluate relationships among variables and estimate coefficients of determination (R^2). Correlation analyses were used to identify statistical associations but did not establish causation. We noted that general flow/reservoir volume data served as indirect proxies for specific reservoir release events, and correlation analyses identified statistical associations, but did not confirm causation. We used Google Sheets with XLMiner Analysis Tool Pak Extension to facilitate all data visualization and statistical analyses.

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