Temporal Trends and Spatial Distributions of Polynuclear Aromatic Hydrocarbons (PAHs) in the San Francisco Estuary 1993-2001

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Abstract Polynuclear aromatic hydrocarbons (PAHs) can be generated through combustion of fossil fuels, forest fires, and are found in raw petroleum. Some are know to be carcinogenic and mutanegenic. This study was conducted to assess the temporal trends, spatial distributions, seasonal variation, and sediment quality guideline violations of PAHs in surface sediments between 1993 and 2001 in the San Francisco Estuary, CA. Surface sediment samples were collected biannually during the wet and dry seasons from 26 sampling stations and were separated and quantified using gas chromatography-mass spectrometry technique to determine PAH contaminant levels for 14 PAHs. Contaminant levels at some stations consistently violate the National Oceanic and Atmospheric Administration's (NOAA) sediment quality guidelines. Multiple PAH contaminants were found to be significantly (alpha <0.05) increasing or decreasing at various sites during the study period. Hydrodynamically similar Bay segments South Bay and Central Bay differ significantly in PAH levels from the Estuary Interface, San Pablo Bay, Suisun Bay, and the Rivers. Seasonal variation is detected and shows that the wet season has higher total PAH contaminant loads than the dry season, which is most likely due to atmospheric deposition of airborne PAH from combustion sources into watersheds that get washed into the Estuary. A multivariate model describes total PAH loadings using the dependent variables segment and percent fines (R^2=0.64). The overarching results reveal that some areas of the Estuary have consistent contamination and need more proactive management to confront higher levels of contamination, whereas other parts are showing improvements.

Introduction

The San Francisco Estuary is roughly 1,600 square miles and receives freshwater through rivers and tributaries that drain a watershed constituting 40 percent of California's surface area. Twenty million people receive their drinking water from the estuary and 4.5 million acres of farmland are dependent on the water for irrigation. Thirty species of threatened or endangered organisms live in the estuary; while countless other species of fauna, flora, and migratory birds depend on it (SFEI 1999). Large human populations around the San Francisco and Sacramento regions, extensive agriculture in the central valley, and numerous industries lie within the watershed that drains to the estuary. These create a range of pollution problems, as a variety of chemical compounds originating from urban and agricultural runoff, atmospheric deposition, and industrial discharge find their way into marine estuaries (Soclo *et al.* 2000, Pilar *et al.* 2003, Tsapakis *et. al.* 2003).

The Regional Monitoring Program (RMP) for Trace Substances monitors concentrations of select toxic trace elements and organic contaminants in the estuary at 26 independent sampling stations (SFEI Fact sheet) (Figure 1). Polycyclic aromatic hydrocarbons (PAHs) are one of the chemical groups that RMP has monitored for 10 years in both surface waters and sediment within the estuary. PAHs are generated through high temperature processing and incomplete combustion of fossil fuel, as well as wood burning (Boehm *et al.* 1997, Ou *et al.* 2004). PAH are of special interest because they are persistent organic pollutants that exhibit toxicity, mutagenicity, and carcinogenicity (Oanh *et al.* 1999, Pilar *et al.* 2003).

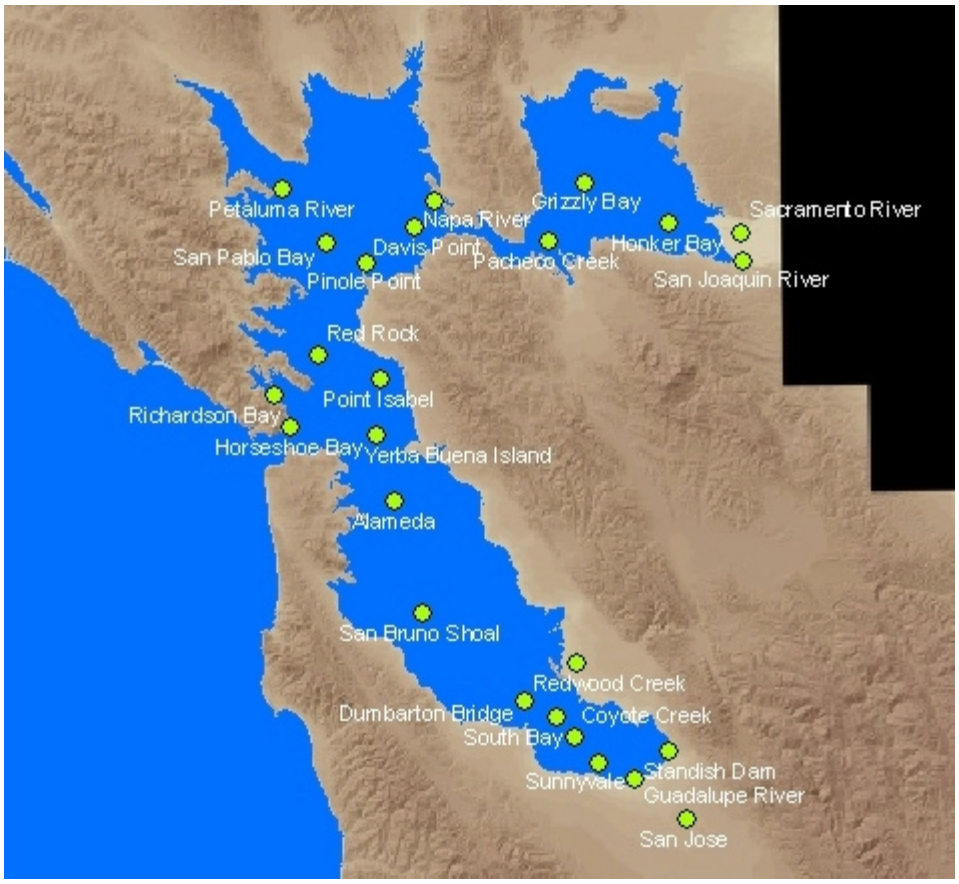

Figure 1 (. Map generated using ArcMap showing approximate locations of the Regional Monitoring Program's sediment sampling locations in the San Francisco estuary.)

Sediment is a typical "sink", where PAH has a tendency to accumulate and concentrate. Intensive industrial activity and dense traffic patterns consistently correlate with high concentrations of PAH in sediments (Ogunfowokan *et al.* 2003), both of which are present in the SF Bay area. Vehicle emissions contain PAH that become airborne (Dunbar *et al.* 2001, Marr *et al.* 2004). One of the principle pathways that PAHs use to enter the estuary is atmospheric deposition, which can occur on the water surface and enter via gas exchange or deposit within watersheds where storm waters convey the contaminants to the estuary (Tsai *et al.* 2002, Tsapakis *et al.* 2003). Once in sediment, benthic organisms tend to accumulate PAHs that can be passed up the food web. (Ferguson and Chandler 1998, SFEI 2000, Vinturella *et al.* 2004).

One of the objectives of the RMP is, "to describe patterns and trends in contaminant concentration and distribution" (SFEI 1999). Previous statistical analyses of RMP sediment PAH data have failed to look at changes over time (Daniel Oros 2003, pers. comm.), and were limited

to the nonparametric Kruskal-Wallis one-way ANOVA and the Tukey-Kramer multiple comparisons on ranks of aggregate PAH data (Leatherbarrow *et al.* 2002).

Studies using other sediment data sets have found evidence of increasing levels of PAH in certain areas of the Estuary. Stehr *et al.* (1997) found total PAH concentrations were increasing at a sampling station near Hunter's Point in San Francisco between 1984 and 1991, but didn't uncover any significant trends at five other sampling sites within the estuary. Analyzing the sedimentary record of San Pablo and Richardson Bay, Pereira *et al.* (1999) determined PAH levels have been increasing since the late 1800's and that the dominant origin contributing to the current contamination is anthropogenic combustion processes.

PAH concentrations in the RMP sediment data are typically compared to National Oceanic and Atmospheric Administration (NOAA) National Status and Trends Program's sediment quality guidelines effects range low (ERL) and effects range median (ERM) values PAH in sediment and displayed using *Delta Graph* in publications from the San Francisco Estuary Institute (SFEI 1999, 2000, 2002). NOAA's sediment quality guidelines relate to the 10th and 50th percentile of concentrations that elicit adverse biological effects in marine organisms (Long *et al.* 1996).

My research focuses on describing PAH contamination in the San Francisco estuary sediment. I seek to identify which stations are consistently violating NOAA's sediment quality guidelines. Understanding how sediment concentrations of PAH are changing over time (trend analysis) can help shed light on how to manage PAH sources in order to meet the recommended guidelines. My objective is to detect significant changes in individual PAH levels at each station over time. This will help identify contaminant problem areas, as well as those that are improving within the estuary. In 2001 the RMP Design Integration Workgroup divided the sampling stations into segments: the Estuary Interface, Southern Sloughs, Lower South Bay, South Bay, Central Bay, San Pablo Bay, Suisun Bay, and Rivers (Leatherbarrow *et al.* 2002) (Figure 2). To understand the spatial distribution and seasonal variation of PAH in the Estuary I compare the contaminant levels between the segments and test for seasonal variability.

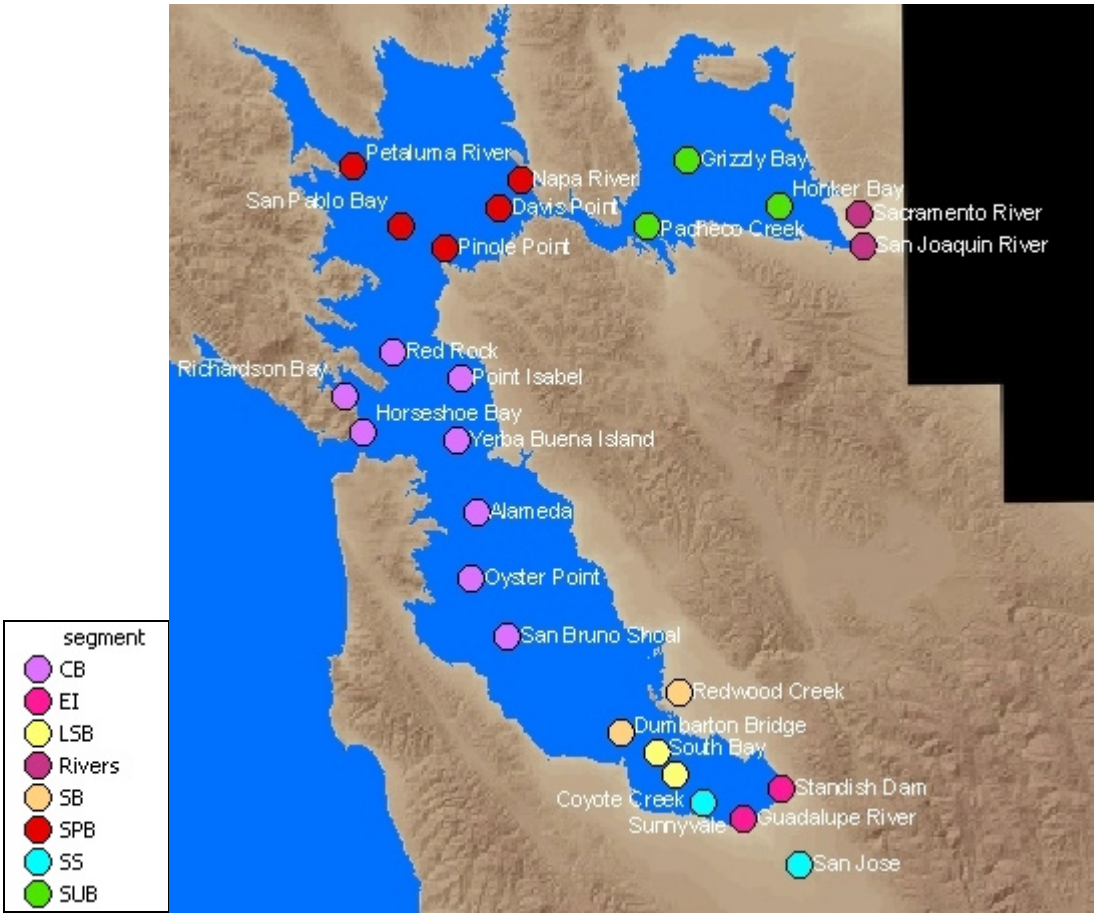

Figure 2. (Bay segments of RMP sampling stations exhibiting similar hydrodynamic characteristics. Central Bay (CB), Estuary Interface (EI), Lower South Bay (LSB), Rivers, South Bay (SB), San Pablo Bay (SPB), Southern Sloughs (SS), Suisun Bay (SUB).)

Methods

Sediment samples were collected by the RMP biannually between 1993 and 2001 from 26 sampling stations within the San Francisco estuary (Figure 1). The data collection procedure for surface sediments and the methods of analysis using gas chromatography-mass spectrometry is described in David et. al 2001. Data is available from the San Francisco Estuary Institute in micrograms per kilogram of sediment or ppb dry weight for the following PAHs: Anthracene, Benz(a) anthracene, Benzo(a) pyrene, Benzo(b) fluoranthene, Benzo(e)pyrene, Benzo(ghi) perylene, Benzo(k) fluoranthene, Chrysene, Dibenz(a,h) anthracene, Fluoranthene, Indeno(1,2,3-cd) pyrene, 1-Methylphenanthrene, Phenanthrene, and Pyrene. Total organic carbon was

determined for each sample and sediment composition data containing percent fines, percent clay, percent sand, and percent gravel summated with shell were measured.

The data tables for PAH compositions and sediment characteristics were joined and scrutinized for accuracy of sampling dates. Nominal data corresponding to the wet (w) and dry (d) seasons was created based on sampling dates and bay segmentations were added based on the findings of the 2001 RMP Design Integration Workgroup. Nonpolar contaminants like PAH preferentially partition with organic material in sediments (Kim, *et. al.* 1999, Venturini and Tommasi 2004), thus PAH data were normalized to the TOC content before conducting statistical analysis using the following equation (Michelsen and Bragdon-Cook 1993):

$$\frac{\text{ug PAH/kg dry sediment}}{\text{kg TOC/kg dry sediment}}$$

Data were further normalized using a log transformation so that a more normal distribution was achieved.

PAH concentrations were compared to the National Oceanic and Atmospheric Administration's (NOAA) sediment quality guidelines effects range low (ERL) and effects range median (ERM) to see if particular stations have been consistently exceeding the guidelines during the study period. The effects ranges are established based on 10% (low) and 50% (median) observed effect threshold in marine organisms for carcinogenic PAHs (NOAA 1999).

JMP IN™ statistical analysis software was used to analyze the normalized data. All analyses of variance had a significance level (α) = 0.05. To check for seasonal variation in contaminant loads of the surface sediment within sites the paired sample t-test was used. To detect differences in individual PAH concentrations between the Bay segments ANOVAs and the Tukey-Kramer honestly significant difference test were utilized. Linear regression analysis was used to detect increases or decreases for each type of PAH for each site during the duration of the study (Sall *et al.* 2001).

Multiple regression analysis was utilized to build a multivariate model that describes aggregate PAH concentrations. One of the goals while conducting modeling is to use as few independent variables (inputs) as possible to determine the independent variable (output), which is total PAH in this case. A simple model can be quite useful to estimate the total PAH loads in

various parts of the estuary where the independent variables (e.g., bay segment, season, year, percent fines, etc.) are known, while avoiding costly sediment sample gathering and analysis.

Results

Numerous stations violated NOAA's sediment quality guidelines ERL, but none violated the ERM. Figure 3 shows the total amount of ERL violations at each site during the study period.

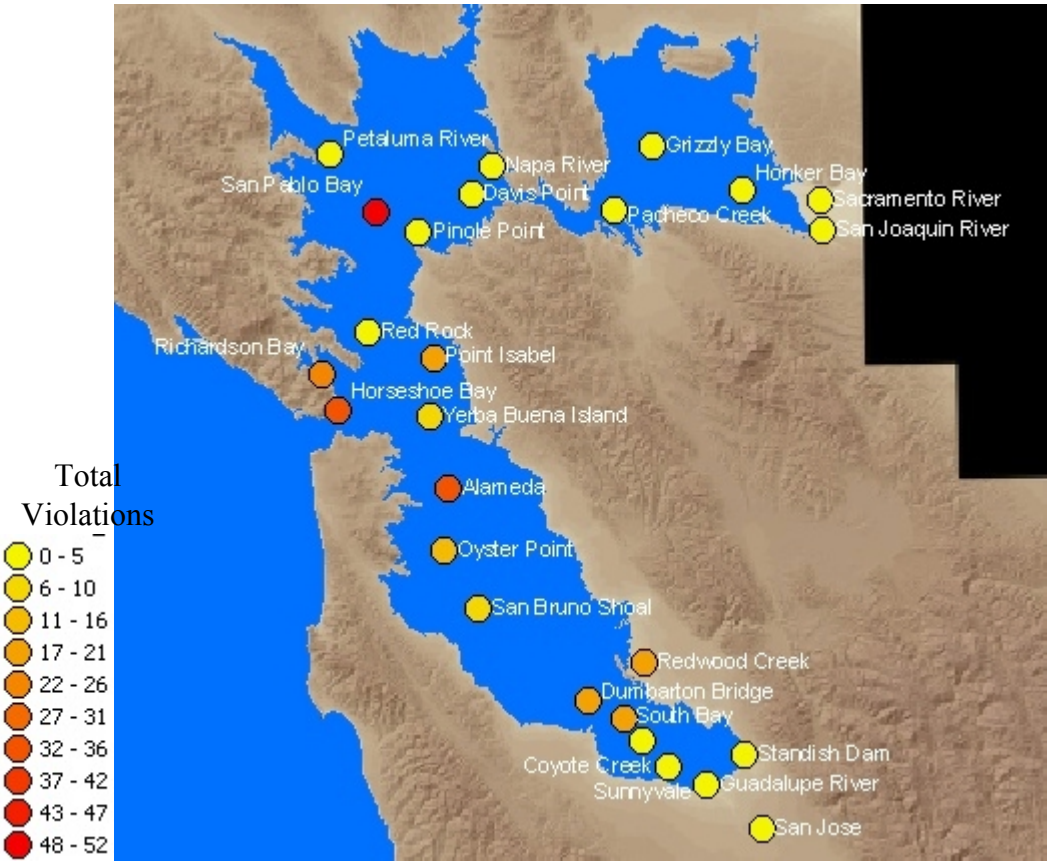

Figure 3. (GIS generated map showing number of total ERL violations at each site during the study period.)

Table 1 shows total violations and the percentage of times that effects range low quality thresholds were violated for individual PAHs, total PAH, sum of high molecular weight PAH (HPAH), and low molecular weight PAH (LPAH) during the study period.

Site	Anthracene	Phenanthrene	Benz(a) anthracene	Chrysene	Fluoranthene	Pyrene	Benzo(a) pyrene	Dibenz(a,h) anthracene	Sum of LPAH	Sum of HPAH	Total PAH	Total violations
Alameda	36	27	18	*	14	29	14	*	29	86	14	**36**
Coyote Creek	*	*	*	*	*	*	*	*	*	8	*	**1**
Davis Point	*	*	*	*	*	*	*	*	*	*	*	**0**
Dumbarton Bridge	*	*	*	*	*	13	6	*	*	94	6	**19**
Grizzly Bay	*	*	*	*	*	*	*	*	*	6	*	**1**
Guadalupe River	*	*	*	*	*	*	*	*	13	13	*	**2**
Honker Bay	*	*	*	*	*	*	*	*	*	*	*	**0**
Horseshoe Bay	25	33	14	*	13	13	6	*	31	69	19	**34**
Napa River	*	*	*	*	*	*	*	*	*	17	*	**3**
Oyster Point	6	*	*	*	*	7	*	*	*	50	6	**11**
Pacheco Creek	*	*	*	*	*	*	*	*	*	*	*	**0**
Petaluma River	*	*	*	*	*	8	7	*	*	14	7	**5**
Pinole Point	*	*	*	*	*	*	*	*	*	*	*	**0**
Point Isabel	6	8	7	*	7	6	7	*	6	63	6	**18**
Red Rock	*	*	*	*	*	*	*	*	*	*	*	**0**
Redwood Creek	*	8	*	*	6	6	6	*	6	63	6	**16**
Richardson Bay	6	8	8	*	13	13	6	*	6	88	6	**25**
Sacramento River	*	*	*	*	*	*	*	*	*	*	*	**0**
San Bruno Shoal	*	*	*	*	*	*	*	*	*	57	*	**8**
San Joaquin River	*	*	*	*	*	*	*	*	*	*	*	**0**
San Jose	*	*	*	*	*	*	*	*	10	10	*	**2**
San Pablo Bay	17	17	24	6	22	33	38	6	17	78	39	**52**
South Bay	6	8	8	6	6	6	6	*	6	63	6	**19**
Standish Dam	*	*	*	*	*	*	*	*	*	*	*	**0**
Sunnyvale	*	*	*	*	*	*	*	*	*	*	*	**0**
Yerba Buena Island	*	*	*	*	6	*	*	*	6	25	6	**7**

Table 1. (Percentage of times that NOAA's effects range low sediment quality guidelines were violated throughout the study. * indicates no violations. Total violations are not in percent.)

ANOVA rejects the null hypothesis that there is no difference in total PAH between bay segments. Table 2 shows the results of the Tukey-Kramer honestly significant difference test. The highest mean was selected (Rank 1) and the means that were not significantly different are listed as the subsequent ranks in order of decreasing means, thus all other Bay segments not listed are significantly different than the highest rank shown for each PAH.

Rank of Mean	Benzo(b) flouranthene	**Flouranthene**	**Pyrene**	Benzo (e) pyrene	Benzo(k) flouranthene	**Chrysene**	**Benzo (a) pyrene**	Benzo(g,h,i) perylene	Indeno(1,2,3-cd) pyrene	**Benzo(a) anthracene**	**Dibenz(a,h) anthracene**	1-Methylphenanthrene	**Phenanthrene**	**Anthracene**
1	SB	SB	SB	SB	SB	SB	SB	SB	SB	CB	CB	CB	CB	CB
2	CB	CB	CB	CB	CB	CB	CB	CB	CB	SB	SB	SB	SB	SB
3	LSB	LSB	LSB	LSB	LSB	LSB	LSB	LSB	LSB	LSB	LSB	SS		
4	SS	SS	SS	SS	SS									

Table 2. (Results of the Tukey-Kramer honestly significant difference test. The ranks correspond to the contaminant mean in a Bay segment for the entire study period, with one being highest. All segments shown for each PAH are not significantly different from the first ranking segment. All segments not shown are significantly different than the first ranking segment. The segments are Central Bay (CB), Estuary Interface (EI), Lower South Bay (LSB), Rivers, South Bay (SB), San Pablo Bay (SPB), Southern Sloughs (SS), Suisun Bay (SUB) See figure 2. PAHs shown in bold are known carcinogens or mutagens.)

The wet season has higher total PAH values than the dry (paired sample t-test, $p = 0.002$)

Each PAH was analyzed at each site to see if there were significant changes in contaminant load during the duration of the study. Linear regression analysis revealed significant increases and decreases for multiple PAHs at numerous sites through time. Table 3 shows which sites had significant changes during the study period.

Site	**Anthracene**	**Benzo(a) anthracene**	**Benzo(a) pyrene**	Benzo(b) flouranthene	Benzo(e) pyrene	Benzo(g,h,i) perylene	Benzo(k) flouranthene	**Chrysene**	**Dibenz(a,h) anthracene**	**Flouranthene**	Indeno(1,2,3-cd) pyrene	**Pyrene**	**Phenanthrene**	1-Methylphenanthrene
Alameda				(+)										
Coyote Creek			(-)	(-)	(-)	(-)		(-)	(-)		(-)			
Guadalupe River		(+)												
Honker Bay							(-)							
Pinole Point								(+)		(+)				
Richardson Bay												(-)		
San Bruno Shoal		(-)			(-)	(-)	(-)	(-)			(-)	(-)	(-)	(-)
San Pablo Bay			(-)		(-)	(-)	(-)	(-)		(-)	(-)	(-)		
Sunnyvale	(+)													
South Bay														(-)

Table 3. (Results of linear regression analysis. (+) sign denotes significant increase and (-) sign denotes significant decrease in contaminant level during the study period. Sites not shown had no PAHs exhibiting significant changes (a = 0.05). PAHs shown in bold are known carcinogens or mutagens)

Figure 4 shows the amount of significantly changing PAHs at each site during the study period.

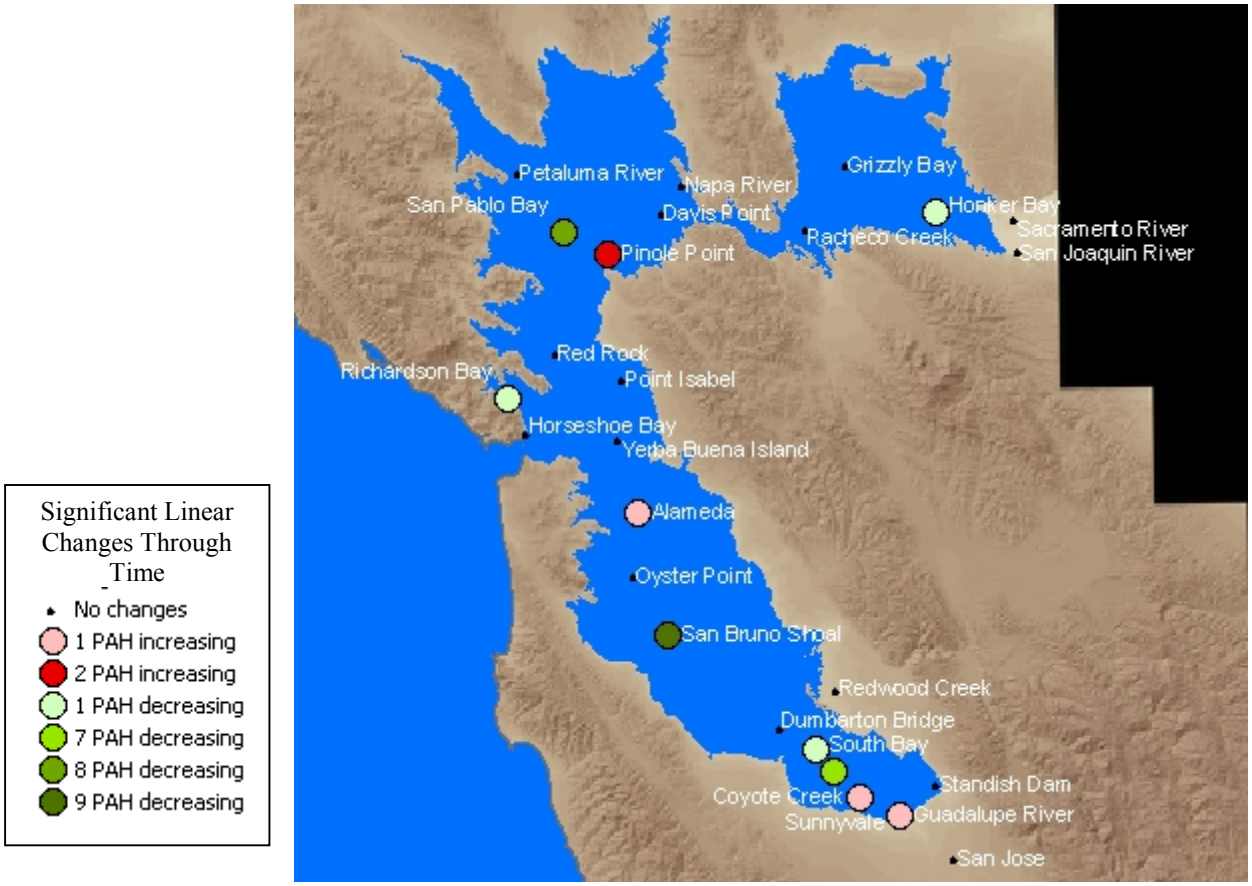

Figure 4. (Spatial representation of linear regression analysis results. Black location dots correspond to no PAHs exhibiting significant linear change throughout the study period, whereas green and red correspond to decreases and increases respectively. The numbers in the legend correspond to the number of contaminants exhibiting significant change.)

Building a multivariate model to describe the log of total PAH (independent variable) using the dependent variables segment and percent fines yields an R^2 value of 0.64, a p-value of <0.0001, and a root mean square error of 0.8056. All parameters are significant except for San

Pablo Bay and the Estuary Interface, which both have a p-value of 0.11. The form of the model is the following:

Log Total PAH = 4.91 + 0.0260 (% fines <63 um) + Segment Input

Segment	Segment Input
Central Bay	0.727
Estuary Interface	-0.279
Lower South Bay	0.334
Rivers	-1.166
San Pablo Bay	-0.148
South Bay	0.635
Southern Sloughs	0.603
Suisun Bay	-0.706

To utilize the model to estimate the log of total PAH, which can be transformed to total PAH, you merely need to input the amount of fine sediment in the sample and the bay segment that it came from. This allows you to calculate with 64 percent accuracy the total PAH load in a sediment sample during the study period using only the two aforementioned variables.

Discussion

Certain PAHs are known carcinogens and mutagens, and it is very common to find high levels of PAH in Estuaries surrounded by human development (Ogunfowokan et al. 2003). Typical sources of PAH in sediment are combustion of fossil fuels, wood burning, and raw petroleum (Boehm *et al.* 1997, Doong *et al.* 2004, Ou *et al.* 2004). PAH can enter the San Francisco Estuary via urban runoff, atmospheric deposition, and industrial discharge (Pereira, *et al.* 1999, Tsai *et al.* 2002). Sediment is a sink for PAHs (Ogunfowokan *et al.* 2003), where they partition with TOC (Michelsen and Bragdon-Cook 1993, Kim, *et. al.* 1999, Venturini and Tommasi 2004). Once in sediments, certain PAHs can be acutely toxic to benthic organisms (Boehm *et al.* 1998, Woodhead *et al.* 1999), or can be accumulated by them and passed up the food web (Ferguson and Chandler 1998, SFEI 2000, Vinturella *et al.* 2004). PAHs in sediment have been known to induce neoplastic liver disease in fish (Stehr *et al.* 1997, Woodhead *et al.* 1999), and fish consumption contributes a significant amount to total carcinogenic PAH

exposure in the "normal" human diet (Phillips 1999). The problem that widespread PAH contamination can have in an Estuary is clear.

Few studies have addressed the temporal trends and spatial distribution of surface sediment contamination in the San Francisco Estuary (Stehr *et al.* 1997, Leatherbarrow *et al*. 2002, Pereira *et al.* 1999). The percentage of violations of NOAA's sediment quality guidelines ERL shown in Table 1 reveals that there is an underlying problem of PAH pollution in the Estuary as a whole. A majority of sites consistently violate the guidelines. Alameda, Dunbarton Bridge, Richardson Bay, and San Pablo Bay have violated the ERL guideline for HPAH more that seventy-five percent of the time and numerous other stations have violated the guidelines numerous times for specific PAHs. Hartmann *et al.* (2004) found that samples from Narragansett Bay in Rhode Island were consistently violating the ERL guidelines, and states that it may have significant impacts on the Bay ecosystem. We must remember that the guidelines are aimed directly at the more dangerous (i.e. carcinogens and mutagens) PAHs.

Incorporating the statistical data into a spatial model can aid in understanding of the distribution and sources of PAH, as well as help to make policy decisions (Levy et al. 2001). Figure 3 confirms this notion, as the spatial representation allows us to see that violations occurred less frequently in the northern and southern parts of the Bay where the adjacent watersheds are less developed than where higher amounts of violations occurred. Huggett, R. J. *et al.* (1988) found PAH sediment contamination levels in Chesapeake Bay to be elevated at sampling stations nearer to higher human densities. This idea applies the San Francisco Estuary as well, where Coyote Creek, Guadalupe River, and the Sunnyvale sampling sites all reside at drainage points originating from Santa Clara County, which is less densely developed than the city of San Francisco and the east Bay region encompassing Oakland, Berkeley, San Pablo, and Richmond. The Santa Clara Valley Urban Runoff Pollution Prevention Program (SCURPPP) that was organized in response to both the federal Clean Water Act and the Water Quality Control Plan for the San Francisco Bay Region (1986) may help to explain why these sites exhibit lower contamination levels (SCURPPP elect. comm.).

The results may be misleading however, because of the positive correlation that PAHs have with fine sediments and TOC (Venturini and Tommasi 2004) and the spatial dynamics of the Estuary. When comparing PAH levels in the Estuary to NOAA's guidelines, the data was not normalized to the aforementioned correlates, thus the violations may only be an indication of the

amount fine sediment and TOC at the stations during the sampling period. Furthermore, Hartmann *et al.* (2004) argue that PAH concentrations are generally higher in coves than in open bays because of their proximity to potential sources like urban runoff, sewers, and marinas, and because there is less mixing and dilution they tend to be more anaerobic and have more TOC, therefore preserving PAHs.

When analyzing the Bay segments however, the contaminant levels were normalized to TOC, yet the South Bay and Central Bay are still consistently higher in PAHs than the other segments (Table 2). The south bay has generally been more polluted in terms of PAH because of higher concentrations of permitted industrial dischargers in these areas (Daniel Oros 2003, pers. comm.). Woodhead *et al.* (1999) discovered that PAH deriving primarily from nearby combustion sources within the Milford Haven estuary in the United Kingdom were at very high concentrations, and numerous other studies have attributed high levels of PAH contamination in surface sediments to combustion processes of nearby industries (Kim, *et al.* 1999, Doong and Lin, 2004, Ou *et al.* 2004). This notion may help to explain why certain stations like San Pablo Bay, which is located nearby permitted industrial dischargers (Chevron oil refinery in Richmond and the C&H Sugar Refinery in Crockett), exhibit high levels of contamination. Chevron treats its wastewater at the site by passing it through a treated wetland (Cole 1998), but never-the-less airborne PAH may be depositing into the estuary near the sampling station from both sources (Greenfield and Davis date unknown, elect. comm.).

The difference between wet season and dry season is significant and needs to be taken into further consideration in management plans that aim to reduce PAH loadings to the Estuary. Surface sediments can be exchanged and transported relatively quickly, thus introducing entirely new contaminant loads between seasons (Ogunfowokan *et al.* 2003). Bouloubassi and Saliot (1993) report that PAH in surface sediments originating from fossil fuel combustion show slight increases during the late summer period in surface sediments of the Rhone Delta in the northwest Mediterranean. This does not correspond to my findings that the wet season has higher values. It is known that combustion engines, especially diesel, emit high amounts of PAHs that enter the atmosphere (Oanh, N. T. et al. 1999, Dunbar *et al.* 2001 Marr *et al.* 2004). This is a non-point source of PAH that can deposit within watersheds draining to the Estuary, or deposit directly onto the water surface and enter the water column via gas exchange (Dunbar *et al.* 2001, Pilar *et*

al. 2003).My findings suggest that runoff during the rainy season may significantly contribute to PAH loadings to sediments.

Linear regression analysis reveals that Coyote Creek, San Bruno Shoal, and San Pablo Bay have had significant decreases in multiple PAHs during the study period, whereas numerous other stations have had one or two significant increases or decreases (Table 3). The fact that sixteen stations have shown no significant changes in PAH levels is a good indication that loadings, as well as contaminant levels, have remained consistent during the study period in a majority of sites. The Coyote Creek watershed lies within Santa Clara Valley, thus indicating that active management strategies like SCURPPP may play an integral role in decreasing the loading of the PAHs. It is a good sign that San Pablo Bay, a site showing high contamination, has also had significant decreases in PAHs. Change in industrial practice may have also contributed to these decreases, as cleaner technology like scrubbers and wastewater treatment wetlands have become more widely adopted (Cole 1998).

The linear regression results share some commonalities with past PAH time dynamics research, as well as suggest some improvements in contaminant loadings. Stehr *et al.* (1997) found that only one sampling station near Hunter's Point in San Francisco showed significant increases between 1984 and 1991. Oyster Point is the RMP sampling location that most closely corresponds to the geographical position of Hunter's Point and it shows no evidence of changing contaminant levels. The stations immediately north (Alameda) and south (San Bruno Shoal) show and increase in one type of PAH and a decrease in nine PAHs respectively. Stehr *et al.* (1997) also sampled in San Pablo Bay, but found no evidence of change in contaminant loads, thus suggesting that a change occurred post 1991 that reduced contaminant loads. Please keep in mind that the comparison may not be applicable because of the varying hydrodynamic properties between sites and that the fact that sampling sites of the RMP do not correspond directly to Stehr *et al.*'s (1997) study, but never the less the comparison provides some insight to the problem.

Venturini and Tommasi (2004) argue that organic matter content is commonly associated with fine sediment particles and that sediment distribution is principally related to hydrodynamic conditions, thus it would make sense that a multivariate model using these parameters would describe the PAH contamination levels. The R^2 value for my model of 0.64 signifies that 64 percent of the variation in the log of total PAH can be described by the model using percent fines and Bay segment as input parameters. Conducting gas chromatography-mass spectrometry

analysis is very costly and time consuming. The model may serve as a very useful tool in the future to get a generalized estimate of total PAH loadings in sediment where there is no time or money to conduct costly analysis. This is assuming that PAH loadings remain constant in the future; otherwise the model may not be accurate as time passes. It can be further calibrated once new data sources become available.

If contaminant sources could be curbed for a brief period of time, then it is possible that drastic improvements in sediment quality could be made. Greenfield and Davis (Date Unknown, elect. comm.) report in a manuscript submitted to Chemosphere that in the absence of loading, the time required to lose one-half of the mass of PAHs in the Estuary range from twenty days for naphthalene to five years for benzo (b) flouranthene.

My research has shown that PAH contamination of surface sediment in the San Francisco estuary is a problem. Although some specific areas have shown improvements, there are others that show consistently high levels of contamination. There appears to be a generalized trend of higher contaminant levels, and thus loadings, in areas surrounded by human development and industries, but this may be due to the distribution of fine sediments within the Estuary. The variety of pathways that PAHs enter the Estuary by, and the hydrodynamic variation that they are subjected to once entering, makes it difficult to determine the exact location of sources. Despite this, non-point sources from combustion processes appear to entering the atmosphere, depositing on surfaces, and washing into the Estuary during the rainy season. Active management strategies and pollution reduction by industry may be playing an active role in reducing loading to the bay. Further sampling and research is needed to better describe trends and distribution of PAH contamination in the surface sediment of the Estuary. If loading could be drastically reduced we would most likely observe wonderful improvements in the overall health of the Estuarial ecosystem.

Sources

Boehm, P. D., *et al.* 1998. Study of the Fates and Effects of the Exxon Valdez Oil Spill on Benthic Sediments in Two Bays in Prince William Sound, Alaska. Environmental Science and Technology 32: 567-576

Bouloubassi I. and Saliot A. 1993. Investigation of anthropogenic and natural organic inputs in estuarine sediments using hydrocarbon markers (NAH, LAB, PAH). Oceanologica Acta. 16: 145-161

Cole, S. 1998. The emergence of treatment wetlands. Feature Article in Environmental Science and Technology. 32: 218-223

David, N., *et al.* 2001. Field Sampling Manual for the Regional Monitoring Program for Trace Substances. San Francisco Estuary Institute. http://www.sfei.org/progprojhome.html accessed 01-11-04

Doong, R., and Lin, Y. 2004. Characterization and distribution of polycyclic aromatic hydrocarbon contaminations in surface sediment and water from Gao-ping River, Taiwan. Water Research 38: 1733-1744

Dunbar, J. C., *et al.* 2001. Estimating the contributions of mobile sources of PAH to urban air using real-time PAH monitoring. The Science of The Total Environment 279: 1-19

Ferguson, P., and Chandler, G. 1998. A laboratory and field comparison of sediment polycyclic aromatic hydrocarbon bioaccumulation by the cosmopolitan estuarine polychaete *Streblospio benedicti*. Marine Environmental Research. 45: 387-401

Greenfield, B. K, and Davis, J. A. Date Unknown. A PAH fate model for San Francisco Bay. A manuscript submitted to Chemosphere. San Francisco Estuary Institute http://www.sfei.org/rmp/reports/PAH/PAHfatemodel_BG.pdf Accessed 05-01-04

Hartmann, P. C., *et al.* 2004. The distribution and sources of polycyclic aromatic hydrocarbons in Narragansett Bay surface sediments. Marine Pollution Bulletin 48: 351-358

Huggett, R. J., *et al.* 1988. Organic compounds in Chesapeake Bay sediments. Marine Pollution Bulletin 19: 454-458

Kim, G. B., *et al.* 1999. Distribution and sources of polycyclic aromatic hydrocarbons in sediments from Kyeonggi Bay, Korea. Marine Pollution Bulletin 38: 7-15.

Law R.J. and. Biscaya J.L. 1994. Polycyclic aromatic hydrocarbons (PAH)-Problems and progress in sampling, analysis and interpretation. Marine Pollution Bulletin 29: 235–241.

Leatherbarrow, J. E. *et al.* 2002. Results of the Estuary Interface Pilot Study. San Francisco Estuary Institute. SFEI contribution 50

Levy, J. I., *et al*. 2001. Fine Particulate Matter and Polycyclic Aromatic Hydrocarbon Concentration Patterns in Roxbury, Massachusetts: A Community-Based GIS Analysis. Environmental Health Perspective 109: 341-347

Long et al. 1996. Sediment Quality Guidelines. National Oceanic and Atmospheric Administration, http://spo.nos.noaa.gov accessed 10-10-03

Marr, L. C., *et al.* 2004. Vehicle Traffic as a Source of Particulate Polycyclic Aromatic Hydrocarbon Exposure in the Mexico City Metropolitan Area. Environmental Science and Technology 38: 2584 -2592

Michelsen, T.C. and Bragdon-Cook, K. 1993. Organic Carbon Normalization of Sediment Data. Technical Information Memorandum. Washington Department of Ecology Sediment Management Unit.

NOAA 1999. Sediment Quality Guidelines developed for the National Status and Trends Program. Available at: http:// response.restoration.noaa.gov/cpr/sediment/SQGs.html. accessed 02-14-04

Oanh, N. T., *et al.* 1999. Emission of Polycyclic Aromatic Hydrocarbon and Particulate Matter from Domestic Combustion of Selected Fuels. Environmental Science and Technology 33: 2703-2709

Ogunfowokan, A. O., *et al.* 2003. Isolation and Determination of Polycyclic Aromatic Hydrocarbons in Surface Runoff and Sediments. Water, Air, and Soil Pollution 147: 245-261

Oros, Daniel. Environmental Scientist, San Francisco Estuary Institute, Oakland CA, 2003. personal communication.

Ou, S., *et al.* 2004. Petroleum hydrocarbons and polycyclic aromatic hydrocarbons in the surficial sediments of Xiamen Harbour and Yuan Dan Lake, China. Chemosphere 56: 107-112

Pereira, W. E., *et al.* 1999. Sedimentary record of anthropogenic and biogenic polycyclic aromatic hydrocarbons in San Francisco Bay, California. Marine Chemistry 64: 99-113

Phillips, D. 1999. Polycyclic aromatic hydrocarbons in the diet. Mutation Research/Genotoxic Toxicology and Environmental Mutagenisis 443: 139-147

Pilar, F, *et al.* 2003. Factors governing the atmospheric deposition of polycyclic aromatic hydrocarbons to remote areas. Environmental Science and Technology 37: 3261-3267

Sall, J., A., Lehman, and L., Creighton 2001. JMP® Start Statistics. A Guide to Statistics and Data Analysis Using JMP®. SAS institute, Duxbury Canada. 489 pp.

Santa Clara Urban Runoff Pollution Prevention Program Website 2004. http://www.scvurppp-w2k.com/History.htm Accessed 05-01-04.

SFEI, Monitoring and Managing Contamination in the San Francisco Estuary. Pulse Publications 1999, 2000, and 2002.

SFEI Regional Monitoring Program Fact Sheet 1999. San Francisco Estuary Institute.

Soclo, H. H., *et al.* 2000. Origin of Polycyclic Aromatic Hydrocarbons (PAHs) in Coastal Marine Sediments: Case Studies in Cotonou (Benin) and Aquitaine (France) Areas. Marine Pollution Bulletin. 39: 387-396

Stehr, C. M., *et al.* 1997. Chemical contamination and associated liver diseases in two species of fish from San Francisco Bay and Bodega Bay. Ecotoxicology 6: 35-65

Tsai, P, *et al.* 2002. Atmospheric Concentrations and Fluxes of Organic Compounds in the Northern San Francisco Estuary. Environmental Science and Technology 36: 4741 –4747

Tsapakis**,** M., *et al.* 2003. Evaluation of atmospheric transport as a nonpoint source of polycyclic aromatic hydrocarbons in marine sediments of the Eastern Mediterranean. Marine Chemistry. 80: 283-298

Venturini, N. and Tommasi, L. R. 2004. Polycyclic aromatic hydrocarbons and changes in the trophic structure of polychaete assemblages in sediments of Todos os Santos Bay, Northeastern, Brazil. Marine Pollution Bulletin 48: 97-107

Vinturella, A. E., *et al.* 2004. Use of Passive Samplers To Mimic Uptake of Polycyclic Aromatic Hydrocarbons by Benthic Polychaetes. Environmental Science and Technology 38: 1154 -1160

Woodhead, R. J., *et al.* 1999. Polycyclic Aromatic Hydrocarbons in Surface Sediments Around England and Wales, and Their Possible Biological Significance. Marine Pollution Bulletin 38: 773-790