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Polychlorinated biphenyls (PCBs) in San Francisco Bay[☆]

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Abstract

San Francisco Bay is facing a legacy of polychlorinated biphenyls (PCBs) spread widely across the land surface of the watershed, mixed deep into the sediment of the Bay, and contaminating the Bay food web to a degree that poses health risks to humans and wildlife. In response to this persistent problem, water quality managers are establishing a PCB total maximum daily load (TMDL) and implementation plan to accelerate the recovery of the Bay from decades of PCB contamination. This article provides a review of progress made over the past 15 years in managing PCBs and understanding their sources, pathways, fate, and effects in the Bay, and highlights remaining information needs that should be addressed in the next 10 years. The phaseout of PCBs during the 1970s and the 1979 federal ban on sale and production led to gradual declines from the 1970s to the present. However, 25 years after the ban, PCB concentrations in some Bay sport fish today are still more than ten times higher than the threshold of concern for human health. Without further management action it appears that the general recovery of the Bay from PCB contamination will take many more decades. PCB concentrations in sport fish were, along with mercury, a primary cause of a consumption advisory for the Bay and the consequent classification of the Bay as an impaired water body. Several sources of information indicate that PCB concentrations in the Bay may also be high enough to adversely affect wildlife, including rare and endangered species. The greater than 90% reduction in food web contamination needed to meet the targets for protection of human health would likely also generally eliminate risks to wildlife. PCB contamination in the Bay is primarily associated with industrial areas along the shoreline and in local watersheds. Strong spatial gradients in PCB concentrations persist decades after the release of these chemicals to Bay Area waterways. Through the TMDL process, attention is being more sharply focused on the PCB sources that are controllable and contributing most to PCB impairment in the Bay. Urban runoff from local watersheds is a particularly significant pathway for PCB entry into the Bay. Significant loads also enter the Bay through Delta outflow (riverine input). Recent studies have shown that erosion of buried sediment is occurring in large regions of the Bay, posing a significant problem with respect to recovery of the Bay from PCB contamination because the sediments being eroded and remobilized are from relatively contaminated buried sediment deposits. In-Bay contaminated sites are likely also a major contributor of PCBs to the Bay food web. Dredged material disposal, wastewater effluent, and atmospheric deposition are relatively minor pathways for PCB loading to the Bay. Priority information needs at present relate to understanding the sources, magnitude of loads, and effectiveness of management options for urban runoff; the regional influence of in-Bay contaminated sites; remobilization of PCBs from buried sediment; historic and present trends; in situ degradation rates of PCBs; reliable recovery forecasts under different management scenarios; the spatial distribution of PCBs in soils and sediments; and the biological effects of PCBs in interaction with other stressors. The slow release of pollutants from the watershed and the slow response of the Bay to changes in inputs combine to make this ecosystem very slow to recover from pollution of the watershed. The history of PCB contamination in the Bay underscores the importance of preventing persistent, particle-associated pollutants from entering this sensitive ecosystem.

Keywords: PCBs; San Francisco Bay; Sources; Trends; Effects; Sport fish; Sediment

1. Introduction

Polychlorinated biphenyls (PCBs) are extremely persistent synthetic chemicals that were heavily used from the 1930s to the 1970s in electrical equipment and a wide

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variety of other applications. Awareness of their presence in the environment and their toxicity to humans and wildlife grew in the 1960s and 1970s, leading to a 1979 federal ban on their sale and production. Today San Francisco Bay (Fig. 1) is left with a legacy of PCBs spread widely across the land surface of the watershed, mixed deep into the sediment of the Bay, and contaminating the Bay food web. Twenty-five years after the ban, PCB concentrations in Bay sport fish are still more than ten times higher than the threshold of concern for human health. In response to this persistent problem, the San Francisco Bay Regional Water Quality Control Board (SFBRWQCB) has recently initiated a process to establish a PCB total maximum daily load (TMDL) and implementation plan to accelerate the recovery of the Bay from decades of PCB contamination (SFBRWQCB, 2004).

Understanding of PCBs in San Francisco Bay has improved tremendously in the past decade. In 1990, the only significant sources of information available on PCBs were some trend data from the State Mussel Watch Program, a study of effects on starry flounder reproduction, and a study suggesting an impact on black-crowned night heron reproduction (Davis et al., 1991). PCB impairment of beneficial uses had not even been established. Today, we have a wealth of data on PCB impairment, in addition to growing data sets on loads, cycling in the Bay, long-term trends, and forecasts of how long it will take for the Bay to recover from PCB contamination. In spite of these advances, significant questions remain and need to be resolved in order to allow management of the PCB problem to proceed in an effective and efficient manner.

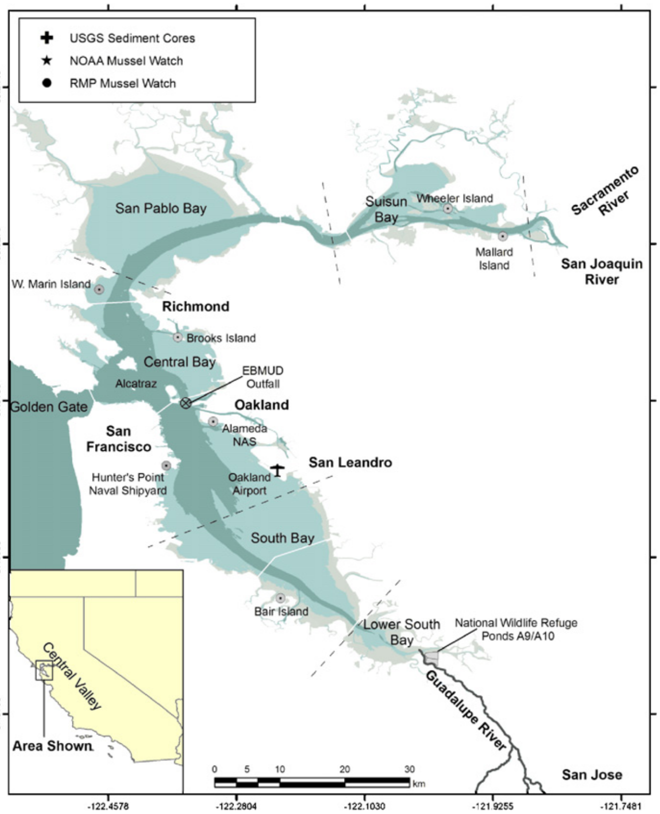

Fig. 1. Location map.

This article provides a review of progress made since the last broad review by Davis et al. (1991) in managing PCBs and understanding their sources, pathways, fate, and effects in the Bay, and highlights remaining information needs that should be addressed in the next 10 years.

2. Developments in management

The most important management actions ever taken to reduce PCB contamination in the Bay were the phaseout during the 1970s and the 1979 federal ban on sales and production (Fig. 2) (Brinkmann and de Kok, 1980). These actions led to a rapid decline in the open-ended uses of PCBs (e.g., as a pesticide and paint additive, in carbonless copy paper), and a gradual decline in the inventory of PCBs used in electrical equipment and other applications in the watersheds. Annual monitoring of PCBs in the Bay did not begin until 1980, so trends during the critical period of the 1970s are unclear. Monitoring in other California locations during the early 1970s indicated that PCBs declined by up to an order of magnitude in the early 1970s after the cessation of open-ended applications. One relevant Bay Area data set that is available from the early 1970s describes trends in PCB concentrations in effluent from a major POTW, East Bay Municipal Utility District, which has discharged 80 million gal/day of effluent from 1970 to the present. Risebrough (1997) provided a summary of concentrations reported from three studies in the 1970s, and data are also available from a recent (2000–2001) study (SFEI, 2002a). The voluntary phaseout in the early 1970s appeared to have a considerable impact on loads from POTWs. PCB loads from EBMUD alone were 2 kg/day (730 kg/year) in 1970. Concentrations dropped by an order of magnitude from 1970 to 1975. By the time of the ban in 1979 they had already dropped 1.5 orders of magnitude. Interestingly, the recent data fall right on a line of exponential decay from the historic concentrations (Fig. 3). Since the early 1980s PCBs in the Bay have

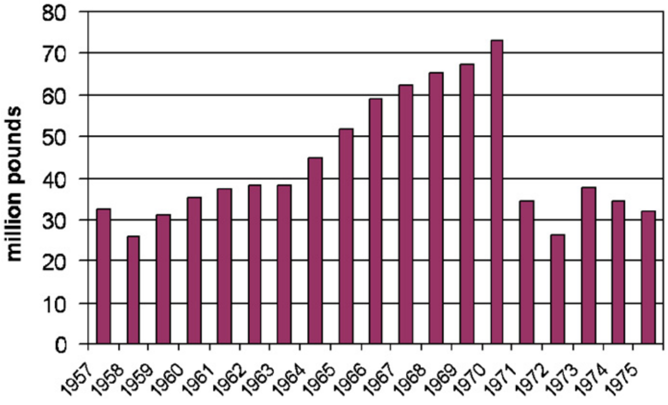

Fig. 2. PCB sales in the US, 1957–1975 (Brinkmann and de Kok, 1980).

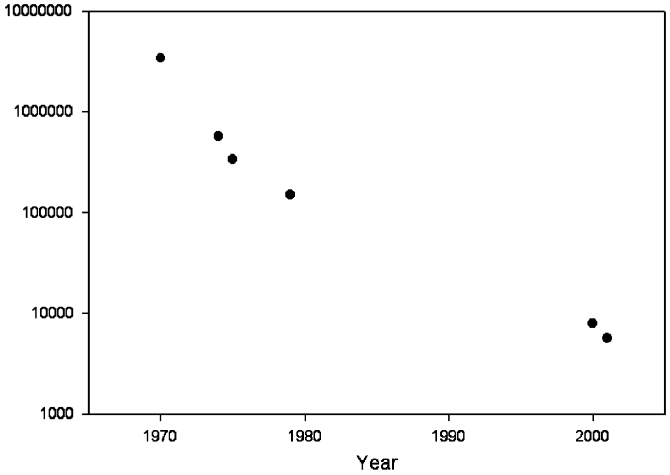

Fig. 3. PCB concentrations (pg/L) in treated wastewater effluent from the East Bay Municipal Utilities District, 1970–2001. Data from Risebrough (1997) and SFEI (2002a).

followed a gradual trajectory of decline, indicated by trends in bivalves (discussed further below).

Despite the 1979 ban, a considerable amount of PCBs remains in use today. A USEPA voluntary transformer registration database showed significant ongoing use, almost 200,000 kg, in the San Francisco Bay Area (the entries in the database were reported between 1998 and 2001) (USEPA, 2004). The life expectancy of transformers and capacitors is decades. The PCB ban has had a significant positive long-term impact, but without further action it appears that the general recovery of the Bay from PCB contamination will take many more decades.

In the 1980s and 1990s, additional management of PCBs in the Bay was largely driven by regulations pertaining to the cleanup of highly contaminated sites in the watershed. Some PCB-contaminated sites in the watershed have been remediated under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), or "Superfund". Cleanup of these sites undoubtedly reduced PCB loading to the Bay, but the magnitude of this reduction cannot be quantified. In many cases, cleanup targets at these sites were in the range of 25,000–50,000 ng/g, approximately 1000 times higher than concentrations that must be reached (in the range of 1 ng/g) in order to reduce concentrations in Bay fish below thresholds for concern.

In 1989, the California State Legislature established the Bay Protection and Toxic Cleanup Program (BPTCP), a statewide program to provide protection of present and future beneficial uses of bay and estuarine waters, identify and develop cleanup plans for toxic hotspots, and develop strategies to prevent creation of new toxic hotspots or the perpetuation of existing ones. BPTCP activities in the San Francisco Bay Region included initiating the Regional Monitoring Program for Trace Substances in the San Francisco Estuary (RMP), conducting studies of fish tissue contamination, and implementing regional monitoring studies to identify toxic hotspots primarily through studies of sediment chemistry and toxicity. This study screened 127 sites in the Bay, and identified several in-Bay PCB-contaminated sites with concentrations in surface sediment exceeding 200 ng/g dry weight (Hunt et al., 1998).

In 1994, the BPTCP performed the first major study to measure concentrations of contaminants in sport fish in San Francisco Bay (Fairey et al., 1997). In response to this study, in 1994 the California Office of Environmental Health Hazard Assessment (OEHHA) issued an interim fish consumption advisory for all of San Francisco Bay (OEHHA, 1994). PCB and mercury concentrations in the fish were the primary drivers of this interim health advisory, which remains in place today. Based on the existence of the Bay-wide consumption advisory, the entire Bay was classified as a toxic hotspot.

As a last step in the BPTCP, cleanup plans for PCBs and other pollutants in the Bay were developed (SWRCB, 1999). The plan called for cleanup of some of the contaminated sites, further study and risk communication on fish contamination, further monitoring of specific sites, and further investigations into ongoing sources of PCBs and development of remediation plans for those sources. Some of these actions have been taken, but a lack of funding has prevented implementation of much of the recommended action.

Management of PCBs through water quality regulations has progressed considerably in the past few years, including an evolution of applicable water quality objectives, and a recent shift toward an emphasis on an active TMDL development effort. From 1986 to 1995, the applicable water quality objective for PCBs was limited to a narrative water quality objective (SFBRWQCB, 1986):

> All waters shall be maintained free of toxic substances in concentrations that are lethal to or that produce other detrimental responses in aquatic organisms. Detrimental responses include, but are not limited to, decreased growth rate and decreased reproductive success of resident or indicator species and/or significant alterations in population or community ecology or receiving water biota…Additionally, effects on human health due to bioconcentration will be considered.

Prior to the inception of the RMP in 1993, there were very few PCB data available to evaluate whether this objective was being met for PCBs, and consequently limited action by the SFBRWQCB (the agency with primary authority to regulate water quality in San Francisco Bay) to address PCB contamination.

In 1995, the Water Board updated the Basin Plan with a specific narrative water quality objective to protect wildlife and human health from bioaccumulative substances, including PCBs (SFBRWQCB, 1995):

> Many pollutants can accumulate on particles, in sediment, or bioaccumulate in fish and other aquatic organisms. Controllable water quality factors shall not

> cause a detrimental increase in toxic substances found in bottom sediments or aquatic life. Effects on aquatic organisms, wildlife, and human health will be considered.

In May 2000, USEPA promulgated numeric water quality standards for the State of California commonly referred to as the California Toxics Rule (USEPA, 2000). In this rule, USEPA derived a human health criterion for PCBs, as total Aroclors, of 0.00017 μg/L (170 pg/L, or parts per quadrillion) in water. This criterion is deemed protective of human cancer risk for fish consumers from waters meeting these PCB concentrations. This PCB criterion for water was exceeded most of the time at all San Francisco Bay Regional Monitoring Program (RMP) sampling locations between 1993 and 2001 (SFEI, 2006). This criterion remains in effect at present.

A major shift in the regulatory approach to managing San Francisco Bay water quality began in 1998. The new approach is based on the development and implementation of TMDLs to address the Bay's remaining water quality problems. This process began with the inclusion of the Bay on the 1998 California 303(d) list of impaired water bodies due to the existence of the Bay-wide fish consumption advisory. The most recent, 2002 version of the 303(d) list contains the same listing for PCBs (SFBRWQCB, 2003). Under the Clean Water Act, TMDLs—cleanup plans based on evaluation and reduction of loads—must be developed in response to inclusion of a water body on the 303(d) list. Development of the PCB TMDL by the Regional Board began shortly after the 1998 303(d) listing, with reports being issued on sources and loadings, impairment, and a TMDL Project Report (SFBRWQCB, 2004). Development of this TMDL has included extensive stakeholder involvement, information gathering, and the improvement of analytical tools to predict the response of the Bay to load reductions. In the PCB TMDL process the emphasis is shifting away from enforcement of water quality objectives and toward enforcement of targets that are more directly linked with impairment, particularly PCB concentrations in sport fish. Through the TMDL process, attention is being more sharply focused on the PCB sources that are controllable and contributing most to PCB impairment in the Bay.

3. Present status of the Bay

3.1. Human health concerns

3.1.1. Sport fish

PCB concentrations in sport fish were, along with mercury, a primary cause of the consumption advisory for the Bay and the consequent classification of the Bay as an impaired water body. PCB concentration in sport fish is therefore a fundamentally important index of PCB contamination in the Bay. Sport fish monitoring in the Bay has been conducted on a 3-year cycle since the initial effort in 1994 (Fairey et al., 1997, Davis et al., 2002, Greenfield et al., 2005). Sport fish sampling in later years has generally confirmed the 1994 findings, and OEHHA has left the advisory in place. The advisory recommends maximum consumption of two meals per month of Bay sport fish, with more restrictive limits (one meal per month) for pregnant women, women that may become pregnant or are breastfeeding, and children under six.

PCB concentrations in sport fish can be compared to "screening values", or thresholds for potential human health concern. For PCBs, a screening value of 10 ng/g wet weight is being applied by the SFBRWQCB (calculated for a 70 kg adult, a cancer risk of 10^{-5}, and a consumption rate of 32 g/day) in the PCB TMDL. PCB concentrations vary among species (Fig. 4). Two sport fish species (white croaker and shiner surfperch) are key indicators of PCB impairment because they accumulate relatively high concentrations and are commonly found in nearshore areas easily accessed by subsistence fishers. These high concentrations are largely a function of the relatively high lipid content in these species. Median concentrations in these two species in the latest round of sampling in 2003 (Davis et al., 2006) were 342 ng/g wet in white croaker and 217 ng/g wet in shiner surfperch, well over an order of magnitude higher than the 10 ng/g threshold of concern for human health. Other species with median concentrations consistently above the screening value across the four rounds of sampling were white sturgeon, striped bass, and jacksmelt. Overall, in 2003, 44 of 51 measured samples (86%) for the species shown in Fig. 4 had concentrations higher than the screening value. The data for white croaker indicate that approximately a 97% reduction in PCB concentrations will be needed to eliminate the impairment.

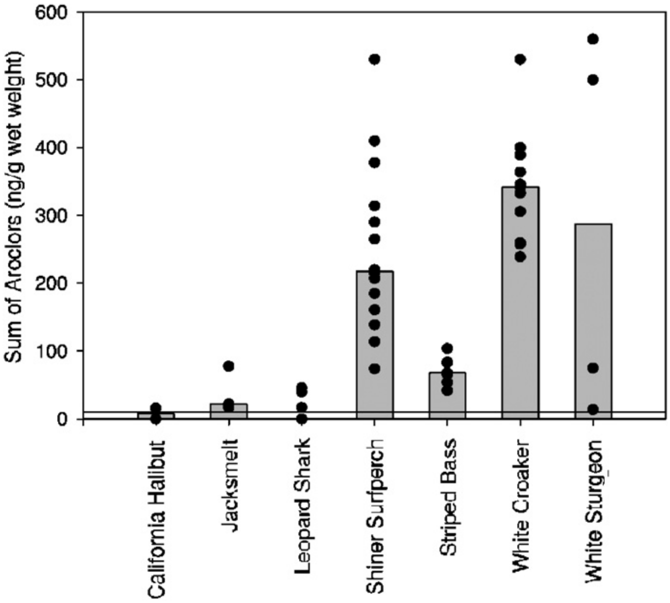

Fig. 4. PCB concentrations (as Aroclors) in San Francisco Bay sport fish, 2003 (Davis et al., 2006). Bars show medians, points are individual samples representing composites of multiple fish. Line indicates TMDL sport fish target of 10 ng/g.

In 1997, a study was conducted to evaluate the effect of removing skin from white croaker fillets (Davis et al., 2002). Substantially lower concentrations of trace organics were measured in the fillets with the skin removed. The average percent reduction for PCBs was 39%, with a range of 11–53%. These reductions were associated with decreased amounts of lipid in the fillets without skin. Lipid content was reduced by an average of 33% in the fillets without skin.

3.1.2. Water

PCB concentrations in water are another indicator of human health risks and impairment of the fishing beneficial use. PCBs in Bay water frequently exceed the 170 pg/L water quality objective established by the California Toxics Rule (USEPA, 2000). This objective was established to protect human health from exposure to PCBs through consumption of contaminated seafood from marine waters. From 1993 to 2003, the PCB water quality criterion was exceeded in 325 of 361 (90%) of samples collected at all San Francisco Bay monitoring stations. Three monitoring stations had typical concentrations that were more than ten times higher than the water quality objective.

3.2. Wildlife health concerns

Several sources of information (reviewed in detail by Thompson et al., 2007) indicate that PCB concentrations in the Bay may be high enough to adversely affect wildlife, including rare and endangered species. Fish-eating species at the top of the food web generally face the greatest risks. Populations residing in PCB-contaminated sites also face relatively high risks. The following sections begin by summarizing information from Davis et al. (1991), then provide a review of information generated since 1991.

3.2.1. Birds

As of 1991 (Davis et al., 1991), there was one study that suggested that PCBs were adversely affecting Bay birds. Hoffman et al. (1986) found a negative correlation between PCB concentrations in eggs and embryo weights in Black-crowned Night Herons collected from Bair Island in 1983. PCB concentrations in these eggs ranged from 0.75 to 52 μg/g wet weight. In the South Bay in 1982 three species, Caspian Tern (*Sterna caspia*), Forster's Tern (*Sterna fosteri*), and Snowy Egret (*Egretta thula*), showed organic contaminant concentrations similar to those of the Black-crowned Night Herons, with average PCB concentrations in San Francisco Bay Caspian and Forster's eggs of 4.8 and 5.6 μg/g wet weight, respectively (Ohlendorf et al., 1988).

Several more recent studies of PCBs in Bay birds have found concentrations that were at or near the threshold for embryo mortality. Davis (1997) and Davis et al. (2004) studied Double-crested Cormorants as an indicator of PCB accumulation and effects in the open waters of San Pablo Bay. In samples collected in 1995, PCB concentrations in embryo yolk sacs from this colony were correlated with reduced egg mass, reduced embryo spleen mass, and induced cytochrome P450 in embryo livers (Davis 1997). The degree of cytochrome P450 induction in these embryos appeared to be just above the threshold for causing embryomortality (Davis et al., 1997). Davis et al. (2004) measured PCB concentrations in freshly laid eggs. Concentrations observed in this study overlapped the lower end of the effects range for this species, with a maximum of 3.8 μg/g fresh wet weight (fww) observed in a composite sample from 2001. Consistent with the earlier study, these results indicated that PCB concentrations in San Pablo Bay were high enough to cause low rates of mortality and deformity in Double-crested Cormorant embryos. These studies indicated that PCB concentrations in the 1990s were still high enough to elicit measurable effects, but probably not high enough to have a significant impact on the viability of the Bay Double-crested Cormorant population.

Recent work on Caspian Terns (*Sterna caspia*), Forster's Terns (*Sterna forsteri*), and the endangered California Least Tern (*Sterna antillarum browni*) have found concentrations that approach thresholds for effects in these species (Adelsbach et al., 2003). Average PCB concentrations in eggs collected in 2001 from colonies distributed throughout the Bay were 1.6 μg/g fww in Caspian Terns, 2.0 μg/g fww in Forster's Terns, and 2.7 μg/g fww in Least Terns. The Least Terns forage in an area near one of the Bay's PCB-contaminated sites, and probably represent a worst-case scenario (high concentrations in the local habitat, high trophic level, threatened population) for possible PCB impacts on an avian population in the Bay. Earlier work on PCBs in Least Tern eggs in the Bay was reported by Hothem and Zador (1995). In this study, geometric mean total PCB concentrations in least tern eggs collected from the Alameda Naval Air Station and the Oakland Airport between 1981 and 1987 were 3.7 and 3.6 μg/g fww, respectively.

Schwarzbach et al. (2001) examined organochlorines and eggshell thickness in California Clapper Rail eggs collected from South Bay marshes in 1992. PCBs, while elevated in one egg, were generally below effects thresholds, but the mean concentration observed in 1992 (1.3 μg/g fww) had not declined from the mean concentration observed in 1986 (0.82 μg/g fww). The authors concluded that PCBs in 1992 may still have been high enough in some Clapper Rail eggs to produce embryotoxic effects.

Hothem et al. (1995) measured PCBs and other contaminants in eggs of Black-crowned Night Herons and Snowy Egrets collected between 1989 and 1991 at locations in South Bay, Central Bay, and San Pablo Bay. Concentrations in both species at the two South Bay locations, Mallard Slough and Bair Island, were similar in magnitude to those measured at these locations in earlier studies (Ohlendorf et al., 1988; Ohlendorf and Marois, 1990). Concentrations in ten Black-crowned Night Heron eggs from Alcatraz Island in 1991 had a geometric mean of 6.1 μg/g fww, higher than that observed at Bair Island in

1983 when an association between PCB concentrations and embryo weight was observed.

3.2.2. Seals

PCB concentrations in Bay harbor seals (*Phoca vitulina*) are elevated in comparison to harbor seal populations in other parts of the world and a cause for concern for seal health. Risebrough et al. (1980) were the first to investigate the potential impacts of contaminants on Bay seals. PCB concentrations in some of the seals they analyzed were considerably elevated (up to 500 μg/g lipid in blubber) and comparable to concentrations that were later observed to cause reproductive problems in controlled feeding studies (Reijnders, 1986). Risebrough et al., however, without the feeding study information available, concluded that pollution was not having a significant impact on the seal population.

In response to the slow recovery of the Bay harbor seal population, Kopec and Harvey (1995) and Young et al. (1998) reexamined the potential influence of pollutants on this species. PCB concentrations (sum of congeners) in whole blood of 14 seals sampled in South Bay in 1991–1992 (averaging 50 ng/g wet weight) were higher than the concentrations observed in the feeding studies of Reijnders (1986) and high relative to concentrations observed in harbor seals in other locations around the world. Data from this research suggested the possibility of contaminant-induced anemia, leukocytosis, and disruption of vitamin A in the Bay seal population.

To further explore the possibility of contaminant-induced health alterations in this population, Neale (2004) and Neale et al. (2005) measured blood concentrations of PCBs and other pollutants in Bay seals, examined relationships between pollutant exposure and several key natural blood parameters, and compared PCB concentrations in 2001–2002 with concentrations measured in Bay seals in the early 1990s. PCBs in harbor seal blood (defined as the sum of six congeners measured in both studies) declined significantly between the early 1990s and 2001–2002 (from 27 to 18 ng/g wet), but remained high enough that reproductive and immunological effects were considered possible. PCB concentrations in the Bay were higher than concentrations in Alaska and Monterey Bay. A positive association was found between leukocyte counts and PBDEs, PCBs, and DDE. The authors concluded from these studies that individual seals with high contaminant burdens could experience increased rates of infection and anemia.

3.2.3. Fish

The most intensive study of PCB effects in Bay fish to date was performed in the 1980s (Spies and Rice, 1988), and showed a negative correlation between PCB concentrations and survival of starry flounder embryos based on specimens collected in 1983–1985. No additional significant work was conducted on the possible effects of PCBs on Bay fish was conducted until the late 1990s. Striped bass in San Francisco Bay in general spend much of their lives in the Bay, but also migrate upstream for spawning and to the ocean. From 1999 to 2001 Ostrach and co-workers (SFEI, 2005a) collected adult female striped bass from the Sacramento River (just upstream from the Bay) in order to evaluate contaminant burdens in eggs and larval development. The study compared eggs and larvae from striped bass reared in a hatchery with others caught in the Sacramento River. In similar studies in other ecosystems, larvae from the wild are usually healthier than larvae from hatcheries. In this study, eggs of River fish had significantly higher concentrations of many pollutants, including PCBs, PBDEs, and chlorinated pesticides, than fish from the hatchery. Under identical rearing conditions in the lab, the larvae from the River were of poorer quality and exhibited developmental alterations (including reduced growth, more rapid yolk sac depletion, reduced brain growth, and altered liver development) that would result in reduced survival in the field.

Recent sharp declines in fish populations in the San Francisco Estuary, particularly in the landward portion of the Estuary, and several recent studies suggesting that pollutant impacts on survival of early life stages of fish are possible have heightened concern for the possible effects of PCBs and other pollutants on fish. In response to these concerns, the RMP initiated studies of pollutant effects on fish in 2005 and 2006.

3.2.4. Summary

PCB concentrations in some Bay wildlife species appear to be above or near thresholds for effects. Given the long-term general trend of slow decline in PCBs in the Bay, concentrations should gradually fall below these thresholds. However, a major uncertainty with regard to PCB effects on wildlife is the extent to which PCBs combine with other stressors, such as other contaminants, diseases, or food shortage, to impair sensitive life-history processes such as reproduction, development, sexual differentiation, and growth. It is possible that the effects of PCBs on wildlife, in combination with other stressors, may be significantly greater than currently realized.

At present, risks to wildlife do not appear to be as high as risks to human health. PCB concentrations in wildlife seem to be just at the threshold for effects on embryo survival. In contrast, PCB concentrations in sport fish are more than ten times higher than the threshold for concern for human health. Consequently, the reduction in PCB concentration needed to protect human health should also result in protection of wildlife health.

3.3. Spatial patterns in impairment

Concentrations of PCBs in surface sediments are the best indicator of the spatial distribution of PCB impairment in the Estuary. Extensive sediment sampling has been performed in the Estuary over the past 25 years. The Bay Protection and Toxic Cleanup Program (BPTCP) sampled

127 sites from 1989 to 1998, with a primary emphasis on identification of hotspots of contamination (Hunt et al., 1998). From 1993 to 2001, the RMP conducted annual sampling of sediment at a set of 26 fixed stations along the central channel of the Bay. In 2002, the RMP switched to a spatially stratified random sampling regime that provides more information on spatial distribution and a more representative characterization of conditions in the Bay. In 2000 and 2001, the National Oceanic and Atmospheric Administration (NOAA) National Status and Trends Program and the US Environmental Protection Agency's Environmental Monitoring and Assessment Program (EMAP) performed coordinated sampling of PCBs and other contaminants in Bay sediments at 200 sites in a stratified random design (unpublished data—I. Hartwell, NOAA, personal communication). Another significant study of PCBs in sediment at 170 locations in Bay Area creeks and storm drains was performed in 2000 and 2001 (ACCWP, 2001; CCCWP, 2002; KLI, 2001, 2002). Collectively, these studies, along with other smaller ones, have provided a high-resolution depiction of the distribution of PCBs in sediments of the Bay and its local watersheds (Fig. 5).

PCB contamination in the Bay is primarily associated with industrial areas along the shoreline. Numerous in-Bay contaminated sites in the nearshore zone have been identified downstream of industrial areas. Creeks and storm drains upstream of the in-Bay contaminated sites are similarly elevated. Contaminated sites along the western shoreline south of San Francisco and the eastern shoreline from Richmond through Oakland and south to San Leandro have contributed to elevated concentrations at a regional scale. Concentrations are also consistently elevated across a large portion of the watershed surrounding lower South Bay. Strong spatial gradients in PCB concentrations persist decades after the release of these chemicals to Bay Area waterways. These data illustrate the persistence and slow dispersion of PCBs from contaminated sites in the Bay and adjoining watersheds.

4. Long-term trends

Understanding past trends is essential to predicting probable trends in the future. Available information suggests that PCB concentrations peaked around 1970, declined rapidly during the 1970s, and then began a phase of gradual decline that continues to the present. The trajectory of this gradual decline since the 1970s is likely to continue into the future, so information on trends during this period is particularly valuable in forecasting.

The database on trends over the past 40 years is very fragmentary. Differences in analytical methods employed (most notably Aroclor-based methods were replaced by congener-based methods) also obscure comparison across the decades. In spite of these difficulties, however, a somewhat coherent picture does begin to emerge when all of the available lines of evidence are considered.

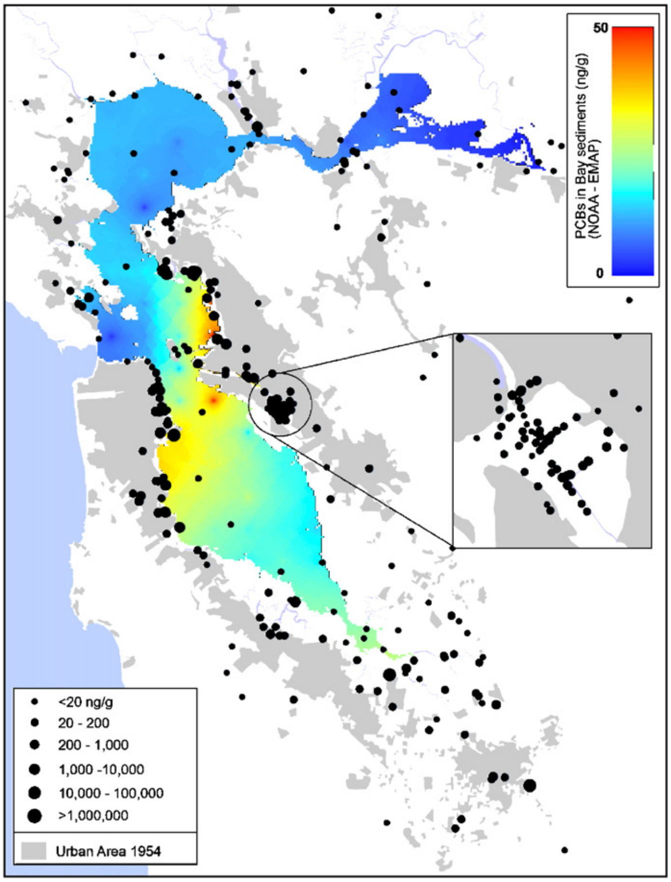

Fig. 5. Average PCB concentrations in Bay Area sediment. Shading in the Bay based on the 2000 and 2001 NOAA-EMAP survey (USEPA, 2001). Data for circles compiled from RMP monitoring (e.g., SFEI, 2005a, b), Hunt et al. (1998), Daum et al. (2000), KLI (2002), and Salop et al. (2002). Urban area in 1954 from the USGS Urban Dynamics Research Program (2000).

4.1. Sport fish

The first measurements of PCBs in samples from the Bay were made by Risebrough in shiner surfperch collected in 1965 (Risebrough, 1997). Regular sampling of this species on a 3-year cycle has been conducted in recent years by the RMP. The mean concentration measured in three composite samples (10–15 fish in each) in 1965 was 830 ng/g wet (as Aroclors). In comparison, the Bay-wide median concentration measured in 2003 (Davis et al., 2006) was 220 ng/g wet (as Aroclors), suggesting a reduction of approximately 74% over this 38-year span. Concentrations in shiner surfperch over the past 9 years have shown no clear pattern of decline (Fig. 6—expressed as sums of congeners). Expressed on a wet weight basis—most appropriate as an indicator of the status of impairment—Bay-wide medians were nearly identical in 1997, 2000, and 2003 (Fig. 6). Expressed on a lipid weight basis—providing a better index of trends in PCB concentrations in the Bay—Bay-wide medians were highest in 1994 and 2003 (13,000 and 11,000 ng/g lipid, respectively), and exhibited considerable interannual variation with much lower concentrations

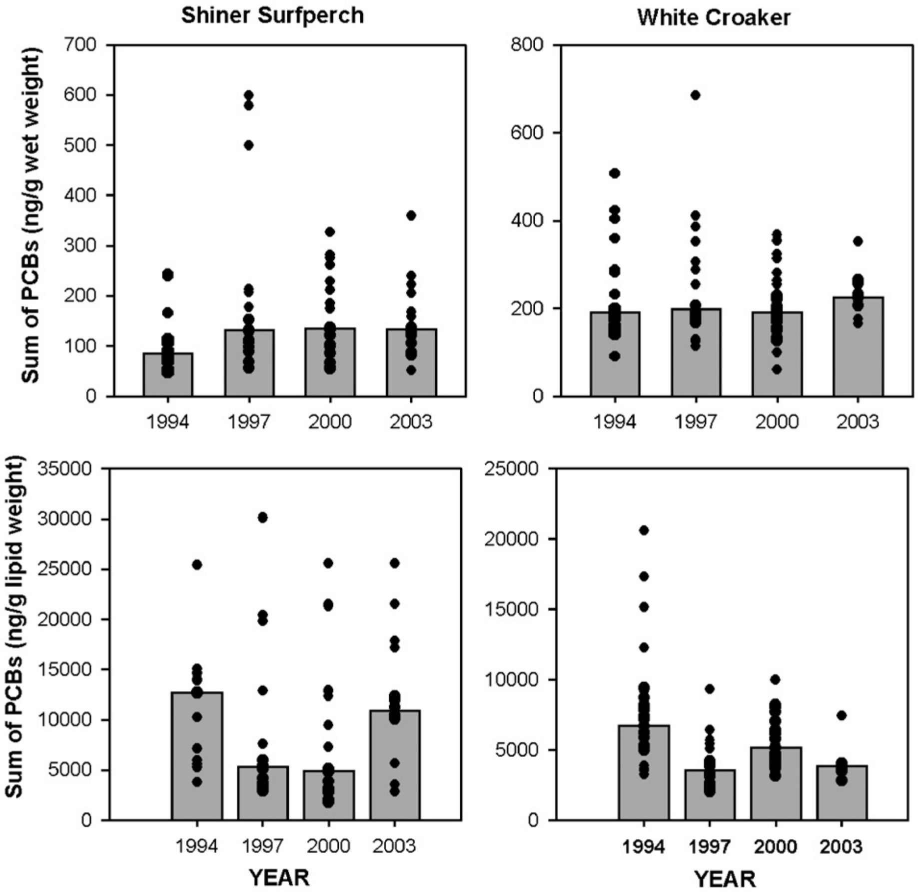

Fig. 6. PCB trends in shiner surfperch and white croaker, 1994–2003 (Davis et al., 2006), expressed as sum of congeners on a wet weight basis (upper plots) and a lipid weight basis (lower plots).

in 1997 and 2000 (5200 and 5000 ng/g lipid, respectively). A relatively long time series (data not shown) also exists for white sturgeon in the Bay (1986–2003), but sample sizes have been small and relatively high concentrations were observed in the 2003 sampling. Time series for other sport fish species are limited to the 1994–2003 period. Concentrations in white croaker, another key indicator species, have also shown no clear pattern of decline from 1994 to 2003. On a wet weight basis, concentrations in white croaker have been quite consistent since 1994, ranging from 190 to 220 ng/g wet (sum of congeners), with the highest median observed in 2003 (Fig. 6). Lipid weight medians have been more variable, ranging from 3800 ng/g lipid in 2003 to 6700 ng/g lipid in 1994 (Fig. 6). Trends in sport fish are a crucial indicator of trends in impairment, but seasonal and interannual variation in fish physiology make them a somewhat unreliable indicator of general trends in Bay contamination, as suggested by the high interannual variance in the lipid-normalized data.

4.2. *Mussels*

PCB concentrations measured annually in transplanted mussels from the early 1980s to the present represent the best dataset available on long-term trends in the Bay over the past 20 years (Stephenson et al., 1995; Gunther et al., 1999; SFEI, 2005b). Transplanted mussels provide an integrative index of concentrations in the water column over their 90-day deployment period. Using transplants allows for dependable sampling at specific locations. Seven Bay locations have been sampled consistently since the early 1980s (Fig. 7). The trend signals are obscured to some extent by the use of different analytical laboratories and methods. PCB concentrations (as Aroclors) in white croaker in 2003 were 34 times higher than the 10 ng/g wet screening value. Plotting the mussel trend data on a log scale indicates the length of time that, based on these data, may be expected for a reduction of this magnitude. Two distinct general patterns are evident in these data. For the northern Estuary locations (Pinole Point, Richmond Bridge/Red Rock, and Fort Baker/Horseshoe Bay), concentrations have declined from approximately 4000 ng/g lipid in 1982 to 1000 ng/g lipid in 2003. For the southern Estuary locations (Treasure Island/Yerba Buena Island, Hunter's Point/Alameda, Redwood Creek, and Dumbarton Bridge), concentrations have declined from approximately 6000 ng/g lipid in 1982 to 2000 ng/g lipid in 2003. Regression lines on log-scale plots for southern Estuary locations indicate that a 20-fold reduction in concentration (to 100 ng/g lipid) will take approximately another 40 years

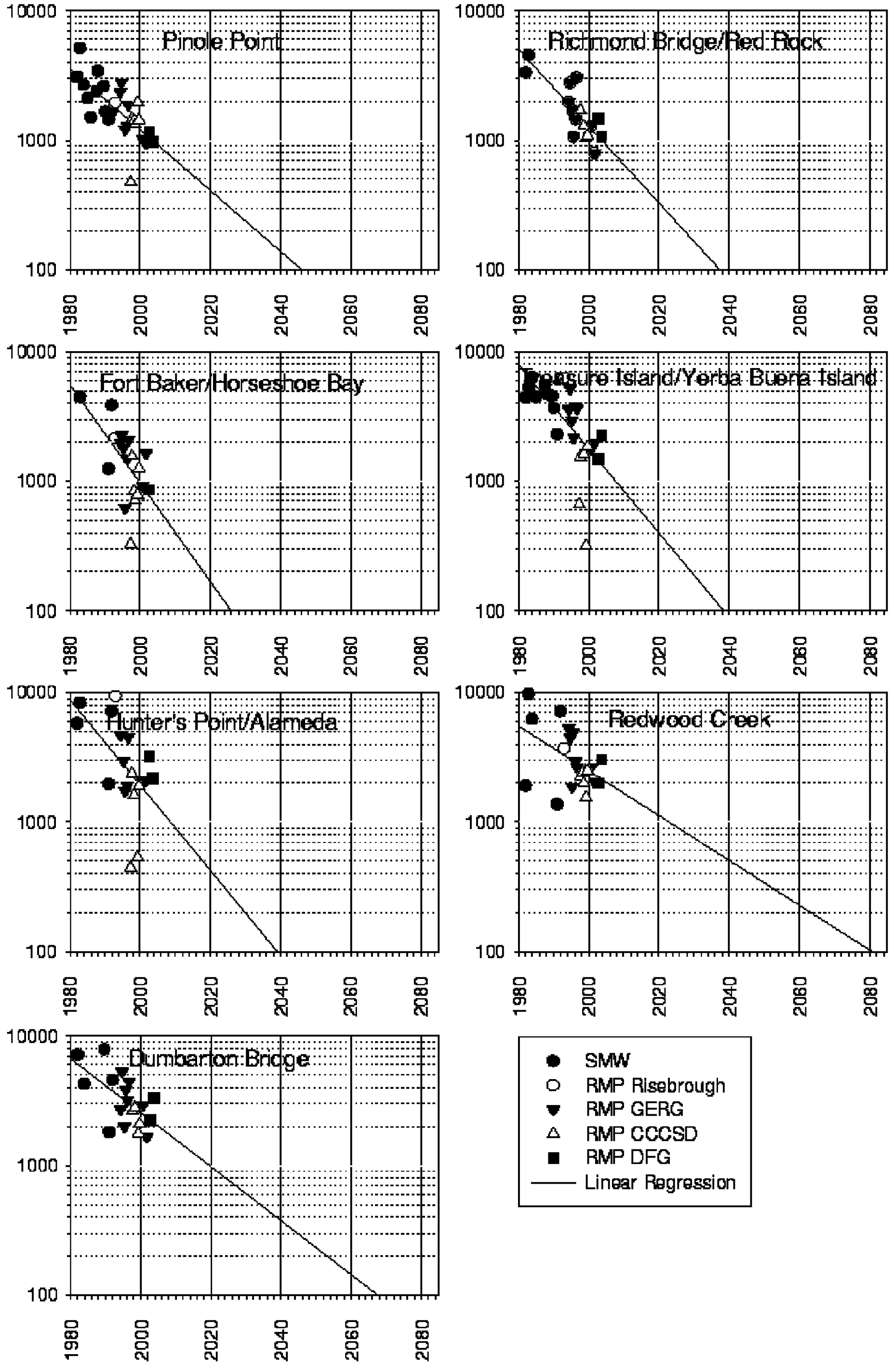

Fig. 7. PCB concentrations (ng/g lipid) in transplanted mussels, 1982–2003. Data from the State Mussel Watch Program as sum of Aroclors and the RMP as sum of congeners. The RMP has used four different analytical labs: Bodega Bay Institute (BBI), Geochemical and Environmental Research Group at Texas A&M (GERG), Central Contra Costa Sanitation District (CCCSD), and Department of Fish and Game (DFG).

at Yerba Buena Island and Alameda, 80 years at Redwood Creek, and 70 years at Dumbarton Bridge. For the northern Estuary locations where present concentrations are lower, it will take approximately 45 years at Pinole Point, 40 years at Richmond Bridge/Red Rock, and 25 years at Fort Baker/Horseshoe Bay to reach 100 ng/g lipid. These are uncertain estimates, based on extrapolation of noisy data sets far into the future. Nevertheless, this is perhaps the best trend information presently available for PCBs in the Bay.

The National Oceanic and Atmospheric Administration (NOAA), as part of their Mussel Watch Program, has also generated a valuable time series of PCB concentrations in resident mussels (*Mytilus edulis*) from three Bay locations (NOAA National Status and Trends Team, 2005). At one location (Emeryville), the data suggest a decline of

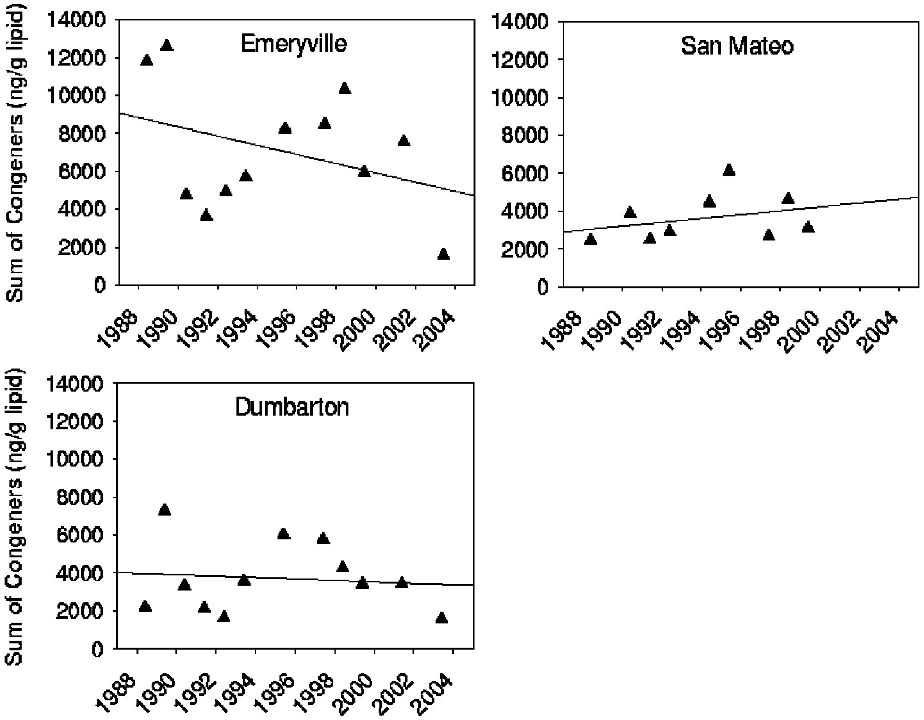

Fig. 8. PCB concentrations (sum of 18 congeners) measured by the NOAA National Mussel Watch Program. Data from NOAA National Status and Trends Team (2005).

approximately 50% over the 15-year period of record (Fig. 8). On the other hand, a negligible decrease was observed at Dumbarton Bridge and a slight increase was suggested at San Mateo (Fig. 8). These time series suggest slower rates of decline than suggested by the transplanted mussels.

4.3. Wildlife

Eggs of piscivorous birds can provide an easily sampled, integrative, and easily measured (due to the high concentrations accumulated) index of PCB contamination in aquatic food webs. The RMP measured PCBs in composite samples of Double-crested Cormorant (*Phalacrocorax auritus*) eggs from three locations in 2002 and 2004 (Fig. 9). At one of these locations (Richmond Bridge) data from 1999, 2000, and 2001 are also available from a previous study (Davis et al., 2004). Concentrations at Richmond Bridge were relatively low in 1999 (1.4 μg/g fww), then ranged between 3.3 and 4.5 μg/g fww during the later rounds of sampling (Table 1). Concentrations at two other locations ranged from 1.8 to 2.2 μg/g fww. These recent observations are similar in magnitude to concentrations measured in several studies of piscivorous bird eggs from 1982 to 2001 (Table 1).

Recent avian egg data are also available for Caspian, Forster's, and Least Terns, which averaged 1.6, 2.0, and 2.7 μg/g in 2001 (Adelsbach et al., 2003). These concentrations (averages of several Bay locations) in Caspian Terns and Forster's Terns were about 70% lower than those measured at Bair Island (in the South Bay) in 1982. In Least Terns, concentrations at Alameda Naval Air Station in 2001 (2.7 μg/g fww) were about 30% lower than measured by Hothem and Zador (1995) at the same location in 1987 (3.7 μg/g fww).

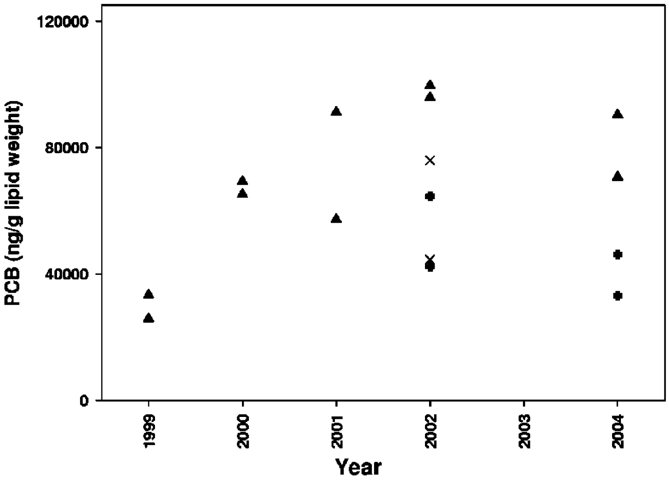

Fig. 9. Total PCBs (sums of congeners) in Double-crested Cormorant eggs collected from Richmond Bridge (triangles), Wheeler Island (crosses—2002 only), and Don Edwards Ponds A9 and A10 in the San Francisco Bay National Wildlife Refuge (circles). Data for 1999–2001 from Davis et al. (2004) and for 2002 and 2004 are unpublished data from the RMP.

PCB concentrations in California Clapper Rails have not been measured recently, but were measured in samples spanning a 17-year period from 1975, 1986, and 1992 (Schwarzbach et al., 2001). Concentrations in 1992 (1.3 μg/g fww) were 45% of the mean measured in 1975 (2.9 μg/g

Table 1
PCB concentrations (μg/g wet weight) in Bay wildlife, 1975–2004

	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Black-crowned night heron																														
Mallard slough									1.6						2.0	2.5														
									12						10	5														
Bair Island								3.0	4.1						2.7	4.0														
								24	12						10	5														
Alcatraz																1.0	6.1													
																10	10													
Brooks																2.7	2.0													
																10	10													
W. Marin															0.6	0.7	1.8													
															16	5	5													
Snowy Egret																														
Mallard Slough																2.5														
																5														
Bair Island								3.3							1.2	5.4														
								10							5	5														
W. Marin															2.2	0.8	1.6													
															5	5	5													
Caspian Tern																														
Bair Island								4.9																						
								22																						
SF Bay																											1.6			
																											?			
Forster's Tern																														
Bair Island								5.7																						
								10																						
SF Bay																											2.0			
																											?			
Least Tern																														
Alameda Naval Air Station													3.7														2.7			
													8														?			
Oakland Airport													3.6																	
													5																	
Double-crested Cormorant																														
Richmond Bridge																									1.4	3.5	3.3	4.5		3.6
																									20	20	20	20		20
Wheeler Island																												1.8		
																												20		
SFBNWR																												2.2		2.0
																												20		20
Clapper Rail																														
South Bay	2.9											0.8						1.3												
	9											13						22												
Harbor seal																														
South Bay whole blood, wet weight, sum of 6 congeners																		27										18		
																		14										35		

Means in first row, number of individuals represented in the second. Data sources cited in text. Locations shown in Fig. 1.

fww). Concentrations in 1986 were lower than in the other 2 years sampled. These concentrations were surprisingly high for this non-piscivorous species.

PCBs have also recently been measured in harbor seals. Harbor seal blood in 2001 averaged 18 µg/g (sum of six congeners) (Neale et al., 2005), approximately 30% lower than observed in 1992 by Young et al. (1998).

Overall, the data from the top of the Bay food web indicate that PCB concentrations have declined over the past 20 years. These declines are consistent with the rates of decline indicated by the transplanted bivalve data. Declines are not apparent in the time series of shorter duration (sport fish and resident mussels), indicating that the general rate of PCB decline is low relative to the interannual variance in the data and long-term time series are needed to firmly establish this important parameter.

4.4. Sediment

Sediment cores from aquatic ecosystems are often analyzed to examine historic trends, as deposited sediment layers provide a chronology of contamination. Unfortunately, only two cores from the Bay representing long-term time series have been analyzed for PCBs (Venkatesan et al., 1999). Based on the limited information available from these cores, PCB concentrations in the Bay appear to have peaked around 1970 (Fig. 10), coinciding with peak production (Fig. 2). Concentrations in the San Pablo Bay core declined from a peak of 34 ng/g dry at a depth of 60–70 cm to 13 ng/g dry in the 0–10 cm layer. Concentrations in a gravity core taken from Richardson Bay declined from a peak of 32 ng/g dry at 30–40 cm to 14 ng/g dry in the 0–10 cm layer. These reductions in concentration of approximately 60% at these locations over a 20-year period probably underestimate the decline in concentrations of deposited sediments because of sediment mixing.

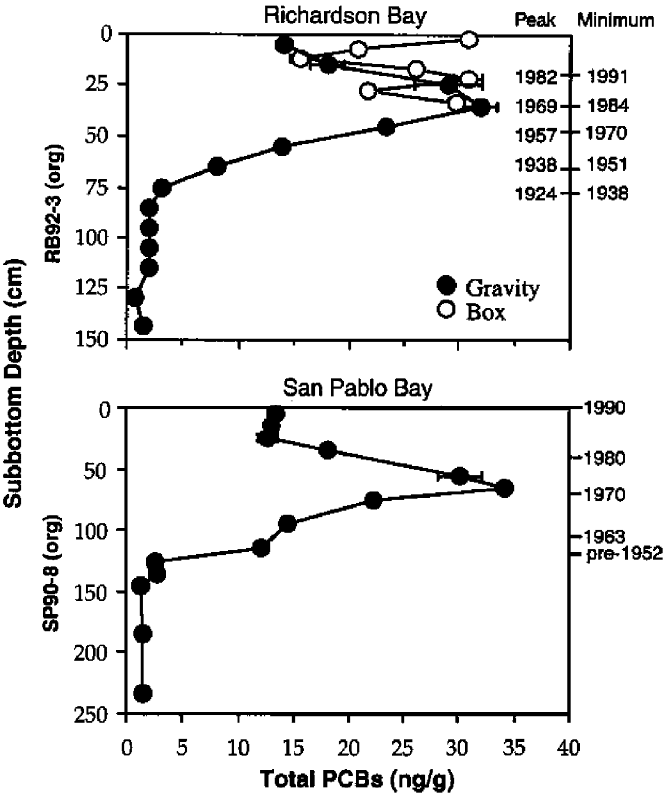

Fig. 10. PCB concentrations in sediment cores from San Francisco Bay. From Venkatesan et al. (1999). RB92-3 from Richardson Bay (near Alcatraz) and SP90-8 from San Pablo Bay.

5. Sources, pathways, and loadings

5.1. Urban runoff

Urban runoff from local watersheds is a significant pathway for PCB entry into the Bay. The mass of PCBs entering the Bay through this pathway is relatively large. In addition, PCBs from urban runoff enter the Bay in relatively concentrated streams that are trapped along the Bay margins, where they are more likely to contribute to food web contamination. The PCB TMDL is calling for relatively large reductions in loads from urban runoff.

Stormwater flow and PCB transport in the Bay Area vary tremendously during the course of a storm, between storms, and from wet season to wet season. The Bay Area has a mild Mediterranean style (dry summer subtropical) climate typified by dry, warm summers and cool, wet winters. About 90% of the annual precipitation occurs during the November–April period (McKee et al., 2003). Rainfall in the region also varies considerably from year to year, from 40% of normal to 200% of normal (McKee et al., 2003). Stormwater in the Bay Area flows rapidly from urban soils and paved surfaces into storm drains and flood control channels that carry water and contaminants to the Bay. The largest storms of the rainy season account for the majority of contaminant loading. In a recent study on the Guadalupe River, for example, over half of the total annual PCB load for 2003 occurred during the storms in the second half of December (McKee et al., 2005). The diffuse and fleeting nature of urban runoff makes it difficult to measure and manage.

The recent study on the Guadalupe River has confirmed that urban runoff carries significant quantities of PCBs and other contaminants to the Bay (McKee et al., 2005). In this study, event-based sampling of contaminant concentrations during storms has been combined with continuous measurement of suspended sediment concentrations and flow to generate estimates of loads of PCBs and other pollutants. In water year (WY, October—September) 2003 the estimated load of PCBs was 1.2 kg. In WY 2004, the estimated load was 0.7 kg. The difference in loads between the 2 years is attributed to a greater first flush and one large intense storm event in WY 2003, in contrast to multiple smaller storms in WY 2004. Water discharge from the Guadalupe watershed during these years was close to average (111% of the 1971–2000 average in WY 2003, and 96% of this average in WY 2004). It is expected that PCB transport in years with higher flows and more intense storms would increase in magnitude in a nonlinear manner relative to flow, following a power function (Davis et al., 2000).

The Guadalupe River watershed is the fifth largest watershed in the Bay Area (McKee et al., 2003), and has the basic elements (non-urban upper watershed, urban lower watershed) that are typical of Bay Area watersheds. As a first approximation (in the absence of better information), total loads from Bay Area watersheds can be estimated by assuming that other watersheds contribute roughly comparable PCB loads. The Guadalupe River watershed encompasses 8% of the watershed area directly adjacent to the Bay, suggesting that the overall load of PCBs from local watersheds in 2003 and 2004 was in the range of 9–15 kg/year. Two considerations suggest that this estimate is probably too low. First, higher flow years would likely increase the long-term average loading, but the magnitude of this effect has not yet been measured. Second, tributaries that drain historically industrial watersheds, even if they have small flows, may contribute relatively large loads. How representative the Guadalupe River watershed is of Bay Area watersheds in general is an important information gap that could either increase or decrease the estimated loading. An annual PCB load of 9–15 kg would be a significant input relative to both other inputs and the total estimated input.

For several reasons, inputs of PCBs from urban runoff are more likely to contribute to accumulation in Bay food webs (and water quality impairment) than loads from Delta outflow. Several characteristics of urban runoff inputs are likely to lead to virtually complete trapping of these materials in the Bay. First, loads from urban runoff enter the Bay at many points, spreading the input all around the edge of the water body, including many locations in South Bay, which undergoes much less flushing than the North Bay. These locations along the margin are also where key fish species forage. Second, during high flows urban runoff inputs are carried by a multitude of relatively small flows spread throughout the Bay, and these flows do not carry contaminants directly out to the ocean even during the very largest of storms.

Proposed control measures specific to PCBs include cleanup of contaminated sites on land, in storm drains, and in the vicinity of storm drain outfalls, and capture, detention, and treatment of highly contaminated runoff. However, there are currently insufficient data to determine which approaches are most effective. Loads of PCBs and other contaminants are being reduced through continued implementation of urban runoff management practices and controls, such as vegetative buffers around paved surfaces and street sweeping programs. Although it is known that these measures have an impact on contaminant loads, there is currently limited information that can be used to estimate the likelihood of success in achieving urban runoff load reductions. Expected trends in PCB loads from urban runoff with and without further management actions is a high-priority information gap. A primary objective of a current \$1.3 million study in the region is to evaluate the feasibility of achieving load reductions from urban runoff.

5.2. *Delta outflow*

Delta outflow is the primary source of freshwater input to the Bay. Delta outflow is also one of the most significant pathways of PCB input to the Bay. However, this relatively large mass input is due to a combination of very large flows with dilute concentrations of PCBs. Loads from the Delta may have a smaller impact on water quality than suggested by the large mass load. Sources of PCBs in Delta outflow are distributed throughout the Bay-Delta watershed, which includes an area of 154,000 km^2 (approximately 37% of the land area of California).

A multi-year field study is currently underway to accurately measure PCB loads from Delta outflow (Leatherbarrow et al., 2005). PCB transport via Delta outflow is highly variable during storms, between storms, and from wet season to wet season, though not quite to the same degree as urban runoff. Annual loads for 2002 and 2003 were 6.0 and 23 kg PCBs, respectively. Contaminant and sediment monitoring in this study occurred during flow years with relatively low annual discharge and relatively small floods ($<$2-year return interval). Similar to urban runoff, it is expected that PCB transport in years with higher flows and more intense storms would increase in magnitude in a nonlinear manner relative to flow, following a power function. The RMP is prepared to measure PCB transport via Delta outflow when the next high flow year occurs.

For two reasons, PCB inputs from Delta outflow may have less impact than those from urban runoff. First, the low concentration inputs from the Delta may dilute or bury more highly contaminated sediment in the Bay. Second, during large storms, when mass loads from the Delta are greatest, a significant portion of the PCB load may wash immediately through the Bay and out into the Pacific Ocean. Ongoing studies presently funded by the RMP are addressing the need for a better understanding of the magnitude and fate of PCB loads from Delta outflow.

5.3. *Erosion of buried sediment*

PCBs mobilized from erosion of previously buried Bay sediments may have an impact on food web contamination that is comparable to urban runoff or Delta outflow. Bay sediments can be divided conceptually into two categories: active and buried. Active sediments are those that are at or near the surface and that are actively exchanging with the water column, actively mixing by physical or biological processes, and in contact with benthic organisms. Buried sediment is below the active layer, and out of circulation with the water column or food web. The vast majority of the mass of PCBs in the Bay resides in the active and buried sediment layers. The upper layer of buried sediment is largely composed of sediment deposited during the era of the most severe contamination of the Bay in the 1950s and 1960s (Venkatesan et al., 1999).

Recent studies have shown that erosion of buried sediment is occurring in large regions of the Bay (Jaffe et al., 1998; Cappiella et al., 1999; Foxgrover et al., 2004). The Bay is experiencing a sediment deficit, largely due to reduced sediment inputs from the Central Valley (McKee et al., 2006). In the future, large-scale floodplain and wetland restoration projects in the Bay and its watershed are likely to further reduce the sediment supply to the Bay and increase the rate of erosion (SFEI, 2005a). This poses a significant problem with respect to recovery of the Bay from PCB contamination because the sediments being eroded and remobilized are from the relatively contaminated upper buried layer. Erosion of buried sediment has the same effect as other PCB inputs: increasing the mass of PCBs in circulation in the active sediment layer, the water column, and the food web, and delaying recovery of the Bay from PCB contamination.

Erosion of PCBs from buried sediment is a pathway that is not easily controlled. However, it is important to understand the magnitude of this pathway so that reasonable expectations for recovery can be established. The magnitude of this pathway is likely to be relatively large, and may become larger as the sediment deficit increases, but is not well-quantified at present. Long-term patterns of erosion and deposition are a critical piece of information needed to predict the rate of improvement of Bay water quality in decades to come. The best information on erosion and deposition is derived from comparisons of bathymetric maps of the Bay floor. The most recent maps available for most Bay segments are from 1990. A new bathymetric survey of the entire Bay and an improved understanding of the distribution of PCBs in buried sediments are needed to evaluate the latest trends in PCB remobilization by erosion.

5.4. *In-bay contaminated sites*

Contaminated sites in the Bay are likely a major contributor of PCBs to the Bay food web. These contaminated sites are known to cause increased PCB bioaccumulation on a local scale, and are suspected to contribute to bioaccumulation on a regional scale. However, the relative contribution of in-Bay contaminated sites to impairment is hard to quantify.

Twenty locations around the edge of the Bay have been identified as contaminated sites, having PCB concentrations in sediment approximately ten times higher than average. These sites are generally associated with runoff from industrial and military facilities. Some of the sites are Superfund sites (e.g., Hunter's Point Naval Shipyard and Seaplane Lagoon at the Alameda Naval Air Station). Organisms that dwell in the contaminated sediment (benthic organisms) and their predators have elevated tissue PCB concentrations at these sites (SFBRWQCB, 2004). Contaminated sites may have a disproportionately large influence on food web contamination because the nearshore areas where they occur also serve as habitat for the sport fish species (white croaker and shiner surfperch) that accumulate high PCB concentrations. PCBs from both the active sediment layer and buried sediment are a concern at these locations.

In-Bay contaminated sites are one of the pathways that is relatively controllable. At some of the sites that have been identified, remedial investigations and feasibility studies are already underway. Remedial actions are anticipated that will greatly reduce food web contamination at a local scale, and possibly accelerate recovery of the Bay at a regional scale. It is expected that sediments at contaminated sites will be remediated according to site-specific clean-up plans as required by the Regional Board and other regulatory agencies.

The major uncertainties associated with in-Bay contaminated sites include the anticipated benefits of cleanup at the local and regional scales and the cost-effectiveness of various remediation options, such as removal, burial, or sequestration.

5.5. *Dredged material*

In terms of the mass of PCBs involved, dredged material disposal in the Bay is a moderately significant pathway for PCB transport. Maintenance dredging of Bay sediments is an ongoing activity where sediment is removed from navigation channels and is disposed of at either in-Bay disposal sites, upland sites, or at a deep-ocean disposal site. The sediment in these channels is usually identical to sediment in the active layer. In less than 5% of the samples tested for in-Bay dredged material disposal, PCB concentrations in these sediments are higher than average due to their proximity to contaminated nearshore areas.

The average annual input of PCBs from disposal at in-Bay sites from 1998 to 2002 was 12 kg, a similar amount relative to other pathways. However, this transport moves sediment from one location to another within the Bay, and does not increase the total mass in the ecosystem. Disposal of dredged materials at in-Bay dispersive sites is likely to spread the disposed sediments into the water column and across the surface of the active sediment layer. Concern exists over the localized impacts on PCB bioaccumulation near the disposal sites.

5.6. *Wastewater effluent*

There are 41 municipal and 27 industrial wastewater discharges in the San Francisco Bay region (SFBRWQCB, 2004). Available data indicate that these wastewater discharges account for a small fraction of the total input of PCBs to the Bay. The current total annual loads from municipal and industrial dischargers are estimated at 2.3 and 0.012 kg/year, respectively (SFEI, 2001, 2002a, b; SFBRWQCB, 2004). These discharges are not expected to contribute disproportionately large masses to the Bay food web, although this is an area where more information is needed.

5.7. Atmospheric deposition

Since PCBs are somewhat volatile and tend to enter the atmosphere, atmospheric transport and deposition can be important processes. In San Francisco Bay, exchange between the water and the atmosphere results in an estimated net loss of 7 kg/year (Tsai et al., 2002). A fraction of the PCBs lost by this pathway may return to the Bay via deposition in the watershed and subsequent runoff.

6. Conceptual models and critical remaining uncertainties

6.1. Models

In the past few years, efforts to articulate understanding of PCB dynamics in the Bay through modeling have complemented the extensive data gathering on status, trends, and loading. The ultimate goal of this model development is to develop a capacity to reliably forecast the recovery of the Bay from PCB contamination under a variety of possible management scenarios. Modeling efforts to date have included a one-box mass budget model for Bay sediment and water, a food web model, and a multi-box model for sediment and water. An overarching conceptual model of sources, pathways, loading, fate, and impairment has also been articulated.

6.1.1. Water and sediment models

A one-box mass budget (Davis, 2004) was a simple first step toward developing a capacity to forecast the recovery of the Bay. This model was based on a highly simplified representation of a heterogeneous and dynamic estuary, but was useful in illustrating some general concepts. Sensitivity analysis identified some of the most influential input parameters, including degradation rates, K_{ow}, outflow, average PCB concentration in sediment, and depth of the active sediment layer. The model was also used to provide a preliminary evaluation of different loading scenarios. With the elimination of external loading, the mass of PCBs in the Bay was predicted to drop to half of the present value in 20 years. The model predicted that sustained loading of 10 kg/year would prevent the total PCB mass in the Bay from ever dropping below 10% of the present mass. With a sustained loading of 20 kg/year, the model predicted that the total PCB mass would never fall below about 25% of the present mass.

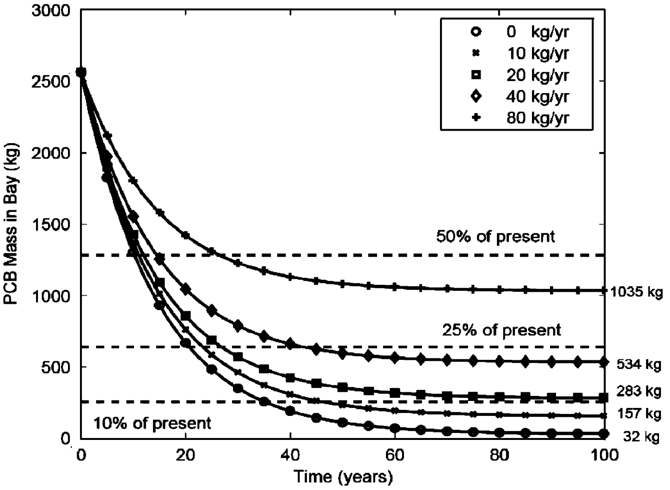

Fig. 11. Predicted masses of polychlorinated biphenyls (PCBs) in San Francisco Bay in the next 100 years with varying amounts of constant annual external loading, based on a one-box model including tidal exchange. Values to the right of the graph indicate masses for each scenario at the end of the 100-year simulation.

After this work was published, Connolly et al. (2005) pointed out a significant omission. Tidal exchange is an important process that was not included in the one-box model presented in Davis (2004). Inclusion of this process increases the estimated rate of loss of PCBs to the ocean through the Golden Gate, and yields predictions of more rapid recovery (Fig. 11). The recovery curves in Fig. 10 were generated using the formulation of Connolly et al. (2005), with one exception. As described by Davis (2004), PCB concentrations in water in Central Bay near the Golden Gate are consistently lower than those measured in other, more landward parts of the Estuary. Davis (2004) used this information to scale losses through outflow, in recognition of the fact that the water column concentrations near the Golden Gate and available for loss through outflow are lower than the Bay average. This approach was considered more realistic and was followed in generating the curves in Fig. 11. Connolly et al. (2005) used a simple Bay-wide average in calculating loss to the ocean, resulting in greater outflow and faster predicted recovery.

Inclusion of tidal exchange does help to bring model predictions into better agreement with existing information on trends in PCB concentrations in the Bay and the loading of PCBs to the Bay. Recent empirical studies of two of the major inputs (Delta outflow and small tributary loads) indicate that average external PCB inputs of 40 kg/year from these inputs alone are plausible. Input from erosion of buried sediment probably adds a relatively significant, but presently unquantified, amount to the total annual input to the Bay. The total annual input to the Bay therefore appears to be greater than 40 kg/year. The transplanted bivalve data (Fig. 7) indicate that concentrations in the Bay have declined by an average of 75% in the past 22 years, corresponding to an annual decline of approximately 6%/year. This rate of decline is faster than the rate of decline predicted by the original one-box model, even with zero loading. In contrast, the loading curves for the one-box model with tidal exchange do overlap this rate of decline—specifically, this rate of decline corresponds to a loading of 0–10 kg/year.

The one-box model with tidal exchange seems to roughly approximate observed trends in recovery. The one-box model was intended as a “first step toward a quantitative understanding of the long-term fate of PCBs in San Francisco Bay" (Davis, 2004). The model served its purpose in this regard and provided some basic insights despite its many simplifications, uncertainties, and the omission of tidal exchange. The one-box model was unquestionably an overly simplified representation of fate processes in the Bay ecosystem. Among the important features of the Bay that were not captured at all in the one-box model were differences in residence time of water and sediment in the different segments of the Bay, the spatial distribution of inputs with the largest inputs toward the landward ends of the Bay, and erosion of buried sediment and associated loading of PCBs into the circulating pool. Perhaps the most significant oversimplification in the one-box model is the assumption that PCB inputs are available for export to the ocean immediately after their entry into the Estuary. In reality, PCBs entering the Estuary generally are transported gradually toward the ocean in a process involving many cycles of deposition, mixing into bedded sediment, and resuspension. This divergence from reality causes the one-box model to inherently overestimate rates of loss to the ocean and recovery of the Bay.

The attention of water quality managers and scientists in the region has now shifted to the next generation of fate model for the bay. In work funded by the RMP and the Clean Estuary Partnership, a multi-box mass budget model is in development. The multi-box model builds on a model developed by Uncles and Peterson (1995) to interpret daily to decadal variability in salinity concentrations in the Bay and includes a sediment transport component developed by Lionberger (2003) to simulate decadal patterns of bathymetric change. The Bay is represented by 50 boxes composed of two layers representing the channel and the shallows. The model accounts in a spatially explicit manner for external inputs of PCBs from various major transport pathways: runoff from the Central Valley via the Sacramento-San Joaquin River Delta, runoff from local tributaries, atmospheric deposition, and municipal wastewater effluent. Other improvements to be incorporated in this version of the model include a more realistic treatment of sediment mixing, sediment erosion and deposition, and a quantification of the aggregate uncertainty of the model estimates. The model is being developed by the San Francisco Estuary Institute and others. A manuscript based on this work is anticipated in 2007. This work will represent a major step forward in modeling the fate of persistent, particle-associated contaminants in the Bay in support of the RMP and TMDL development and implementation.

6.1.2. Food web model

Another recently completed modeling effort examined PCB movement from water and sediment through the food web (Gobas and Arnot, 2005). The purpose of this model was to estimate concentrations of PCBs in a set of key indicator species, including the Double-Crested Cormorant, the Forster's Tern, and the harbor seal, as well as three sport fish species that are frequently caught by fishermen in the Bay (shiner surfperch, jacksmelt, and white croaker). The model can be used to determine what concentrations of PCBs in the water and sediments of the Bay need to be reached to allow an adequate margin of safety in wildlife and humans exposed to PCBs in the Bay Area. This information will be used as part of the TMDL process to formulate remedial actions to achieve desired water quality goals. The model was also used to propose preliminary estimates of the total PCB sediment concentrations that are protective of the health of humans and wildlife consuming San Francisco Bay fish and shellfish. Sensitive variables in the model include particulate organic carbon content in the water and water temperature; lipid content (and organic carbon content in phytoplankton), lipid absorption efficiency, non-lipid organic matter absorption efficiency, and growth rates in biota. Model performance analysis showed that predicted biota-sediment accumulation factors were well within the range of the observed values. The model can be applied in a forwards manner to calculate estimates of PCB concentrations in the San Francisco Bay food web based on current concentrations of PCBs in San Francisco Bay, or in a backwards manner to calculate recommended target PCB concentrations in the sediment that can be expected to meet various human health and ecological risk criteria. The model predicts that sediment concentrations need to average 0.75 ng/g dry weight in order to achieve the fish PCB concentration target of 10 ng/g wet weight for white croaker.

6.2. Overall conceptual model and critical remaining uncertainties

Important processes and priority information gaps can be illustrated with a conceptual model linking sources, pathways, Bay compartments and fate processes, and impairment (Fig. 12). Sources, pathways, and processes of particular importance are highlighted in the diagram.

Studies of sources, pathways, and loadings of PCBs over the past 10 years have focused attention on urban runoff and Delta outflow as the primary pathways of entry of PCBs into the Bay. Field studies initiated in the past few years have provided information affording preliminary estimates of average inputs from these pathways and confirmed that their magnitude is potentially large enough to delay recovery of Bay segments or possibly the Bay as a whole. Contaminated sites, creeks, and storm drains in Bay Area watersheds are considered to be significant contributors to PCBs in urban runoff. More diffuse inputs from PCBs in sources like building sealants (Herrick et al., 2004; Kohler et al., 2005) and fluorescent light ballasts may also be important. Understanding of the influence of in-Bay contaminated sites and remobilization of buried sediment deposits is also in an early stage of development. Priority

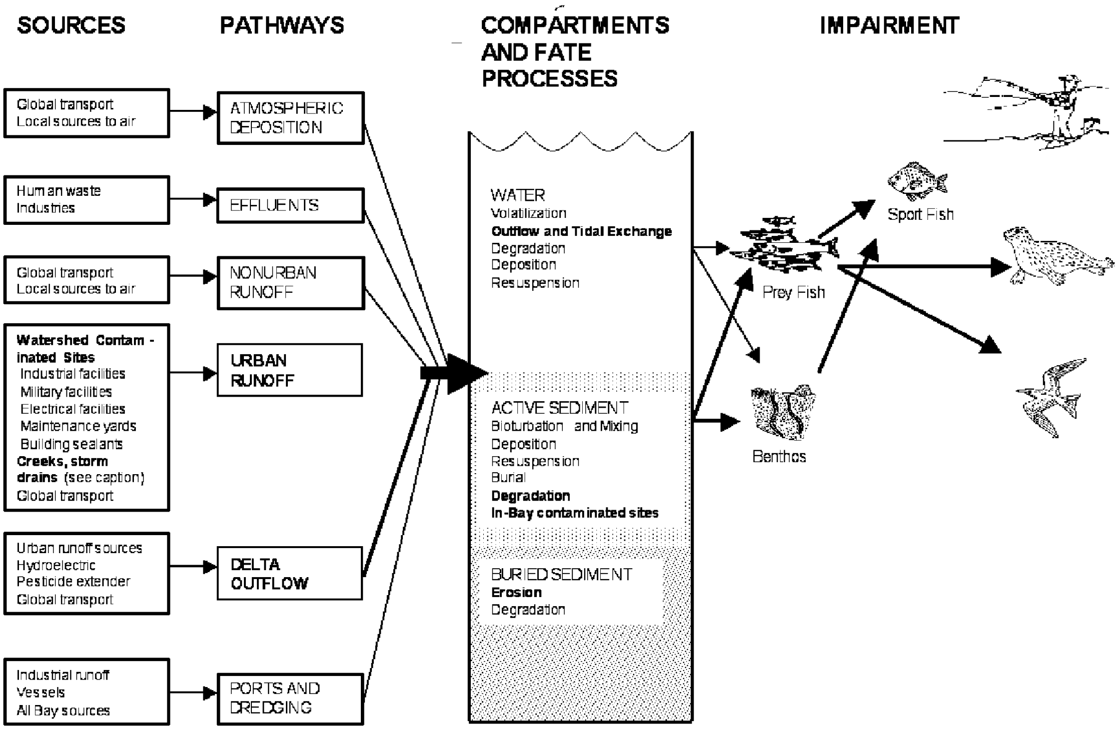

Fig. 12. Conceptual relationships of important PCB sources, pathways, compartments and fate processes, and impairment. Bold text and arrows indicate the most critical elements. Creeks and storm drains are really pathways, but are included in the "source" column for completeness.

information gaps related to sources, pathways, and loading include:

- the relative importance of different PCB sources to urban runoff;
- the distribution of PCBs in soils and sediments of industrial areas;
- the magnitude and fate of loads from urban runoff and Delta outflow during high flow years;
- variation in loads from urban runoff from different local watersheds;
- expected trends in urban runoff loads with and without further management actions;
- the effectiveness of urban runoff source and treatment control options;
- the influence of contaminated sites on PCBs in the food web and the benefits of cleanup of these sites; and
- the anticipated rates of remobilization of PCBs from buried sediment over the next several decades.

Development of fate models and a capacity to forecast the recovery of the Bay from PCB contamination began with a simple one-box mass budget model (Davis, 2004). This model was useful in illustrating some general concepts but was based on a highly simplified representation of a heterogeneous and dynamic ecosystem. Continued development and refinement of the multibox model will provide a basis for more realistic representation of the ecosystem and more accurate predictions. Application of the multibox model will also highlight information needed to generate more reliable predictions. Incorporation of a quantitative treatment of uncertainty in the multibox model will allow an explicit focus on obtaining information that increases confidence in model predictions. Some of the information needs that are already apparent in relation to recovery forecasts include:

- the subsurface inventory of PCBs in different parts of the Bay;
- the historic trajectory of recovery on regional and local scales;
- present trends in concentrations in sport fish and other integrative indicators of interannual variation in food web PCBs;
- the loss of PCBs and sediments to the ocean through the Golden Gate; and
- in situ degradation rates of PCBs.

In the past 15 years, great progress has been made in characterizing the magnitude and spatial distribution of impairment of San Francisco Bay by PCBs. Continued refinement of this characterization is needed to ensure that the degree of reduction needed to eliminate the impairment is clearly defined. High priority information gaps related to PCB impairment presently include:

- the adverse impacts of PCBs in the context of the many stressors affecting humans and wildlife exposed through the Bay food web; and

- more complete characterization of the spatial distribution of PCBs in surface sediments in the Bay.

Persistent, particle-associated pollutants in the San Francisco Bay-Delta watershed are slowly transported from their sites of origin through storm drains, creeks, and rivers toward the Bay in a recurring cycle of mobilization, deposition, and resuspension. Patterns of lead and mercury contamination in the watershed indicate that timescale for this process is decades or centuries (Steding et al., 2000; Conaway et al., 2004). The distribution of PCBs in local watersheds around the Bay is also consistent with this observation. Once these polluted particles wash into San Francisco Bay, especially the southern reach, they become mixed into the bedded sediment and trapped in the ecosystem for many more decades, seeping into the base of the food web and becoming concentrated in sensitive life stages of humans and wildlife. The slow release of pollutants from the watershed and the slow response of the Bay to changes in inputs combine to make the Bay very slow to recover from pollution of the watershed. The history of PCB contamination in the Bay underscores the importance of preventing persistent, particle-associated pollutants from entering this sensitive Bay-watershed system.

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