FINAL

PCBs in San Francisco Bay:

Impairment Assessment/Conceptual Model Report

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EXECUTIVE SUMMARY

This report has been produced for the Clean Estuary Partnership (CEP). The CEP is a collaboration of the Bay Area Clean Water Agencies, Bay Area Stormwater Management Agencies Association, the San Francisco Bay Regional Water Control Board, and other participants. This cooperative partnership facilitates efforts to improve water quality in San Francisco Bay by providing financial and staff support for technical studies, discussion of management questions and strategies, and stakeholder outreach activities.

Several Conceptual Model/Impairment Assessment (CM/IA) reports have been commissioned by the CEP for pollutants that have been identified in the past as possible causes of impairment to beneficial uses in San Francisco Bay. These CM/IA reports have several objectives:

- Evaluate the current level of impairment of beneficial uses, including description of standards or screening indicators and relevant data;
- Develop a conceptual model that describes the current state of knowledge for the pollutant of concern, including sources, loads, and pathways into and out of the Bay and its water, sediment, and biota; and
- Identify potential studies that might reduce uncertainties associated with the report's conclusions.

This report on PCBs is intended to facilitate public participation in the PCB TMDL process by providing a concise overview of available information on PCBs in San Francisco Bay.

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.

The phaseout of PCBs during the 1970s and the 1979 federal ban on sale and production appear to have led to relatively rapid declines in Bay PCBs during the 1970s and early 1980s, followed by a slower trajectory of decline from 1982 to the present. Without further management action it appears that the general recovery of the Bay from PCB contamination will take many more decades. 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 TMDL development. 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.

Impairment Assessment

PCB concentrations in sport fish were a primary cause of the consumption advisory for the Bay and the consequent classification of the Bay as an impaired water body. Median concentrations in two important indicator species in 2003 were 342 ng/g wet weight in white croaker and 217 ng/g wet in shiner surfperch, over an order of magnitude higher than the 10 ng/g threshold of concern for human health (Figure ES-1). 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. Several recent studies of PCBs in Bay birds have found concentrations that were at or near the threshold for embryo mortality. PCB concentrations in Bay harbor seals (*Phoca vitulina*) are elevated in comparison to other parts of the world and cause for concern for seal health. Concern for the potential effects of PCBs and other pollutants on fish has been heightened by recent sharp declines in fish populations in the San Francisco Estuary and several recent studies suggesting that pollutant impacts on survival of early life stages of fish are possible. 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.

PCB contamination in the Bay is primarily associated with urban areas along the shoreline and in local watersheds (Figure ES-2). Strong spatial gradients in PCB concentrations persist decades after the release of these chemicals to Bay Area waterways.

Conceptual Model

The conceptual model presented in this report (Figure ES-3) provides a framework for optimizing management decisions and actions for reducing contamination by PCBs in San Francisco Bay. The conceptual model summarizes present understanding of:

- sources, pathways, and loadings of PCBs to the Bay;
- the present rate of decline of PCBs; and
- fate processes and recovery forecasts.

The conceptual model also identifies information gaps that limit our ability to evaluate management alternatives and estimate recovery rates.

Urban runoff from local watersheds is a significant pathway for PCB entry into the Bay (Figure ES-4). A recent study on the Guadalupe River has confirmed that urban runoff carries significant quantities of PCBs and other contaminants to the Bay, with PCB loads of 1.2 kg in water year 2003 and 0.7 kg in water year 2004. This study suggests that the overall load of PCBs from local watersheds in 2003 and 2004 was in the range of 9 – 15 kg per year. Higher flow years would likely increase the estimate of long-term average loading. 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. Annual loads from Delta outflow for 2002 and 2003

Figure ES-1. PCB concentrations (as Aroclors) in San Francisco Bay sport fish, 2003. Bars show medians, points are individual samples representing composites of multiple fish. Line indicates screening value of 10 ng/g. Unpublished data from the RMP.

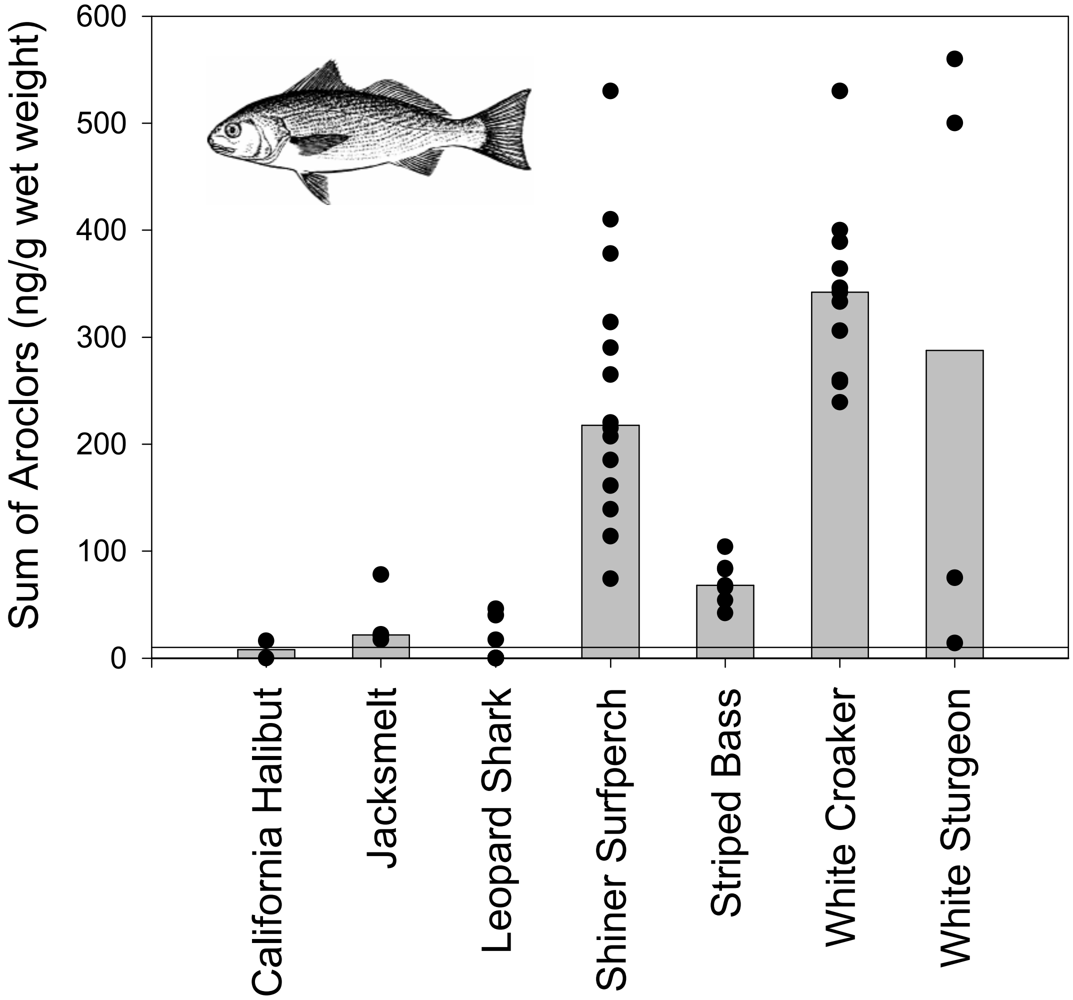

Figure ES-2. Average PCB concentrations in Bay Area sediment. Data compiled from RMP monitoring (e.g., SFEI 2002), the 2000 and 2001 NOAA-EMAP survey (e.g. NOAA, 2001; U.S. EPA, 2001), Hunt et al. (1998), Daum et al. (2000), KLI (2001), and Salop et al. (2002). Urban area in 1954 from the USGS Urban Dynamics Research Program (2000). In-Bay "hotspots" were identified by SFBRWQCB (2004).

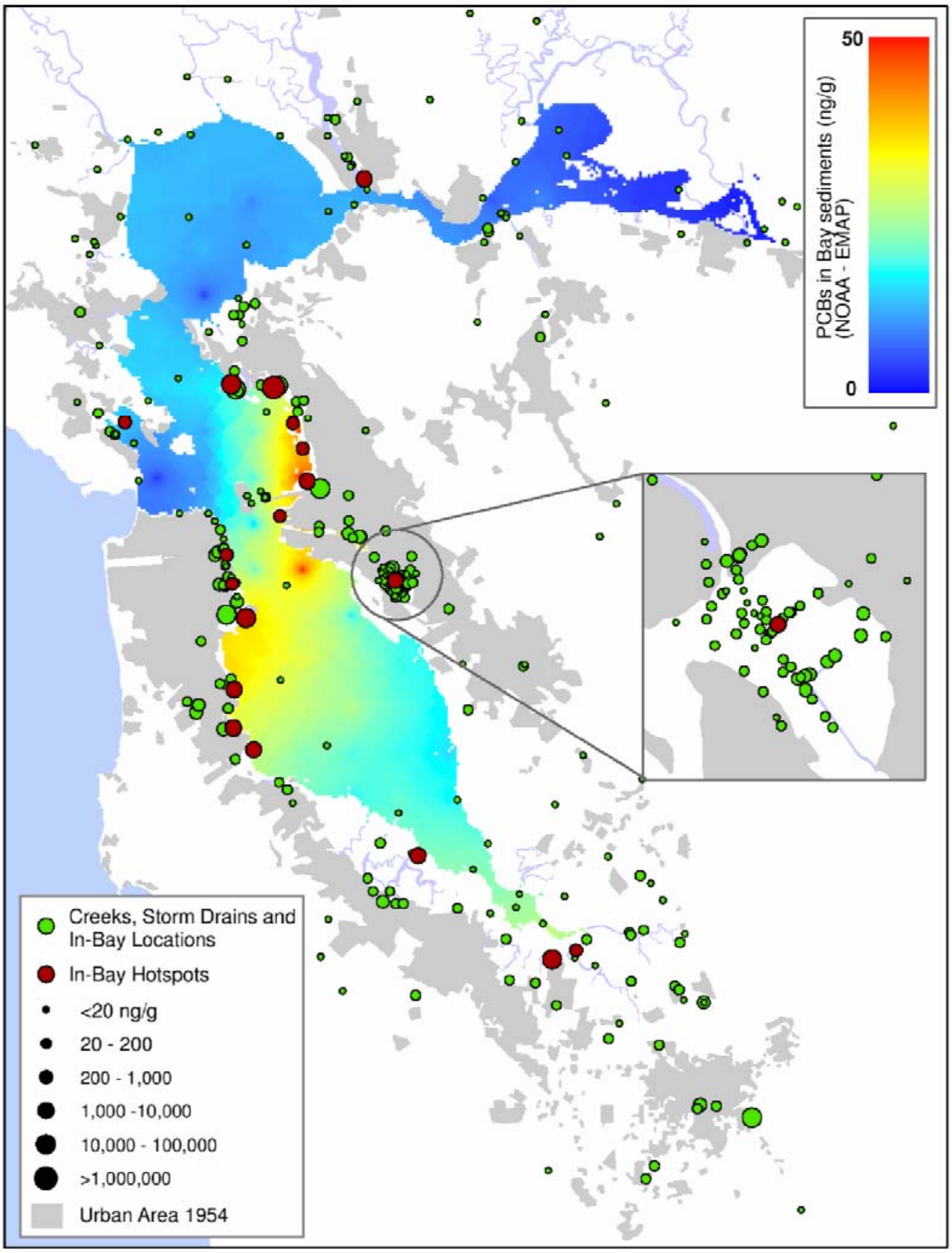

Figure ES-3. Conceptual relationships of important PCB sources, pathways, compartments and fate processes, and impairment. Bold text and arrows indicate the most critical elements. Creeks and storm drains are really pathways, but are included in the "source" column for completeness.

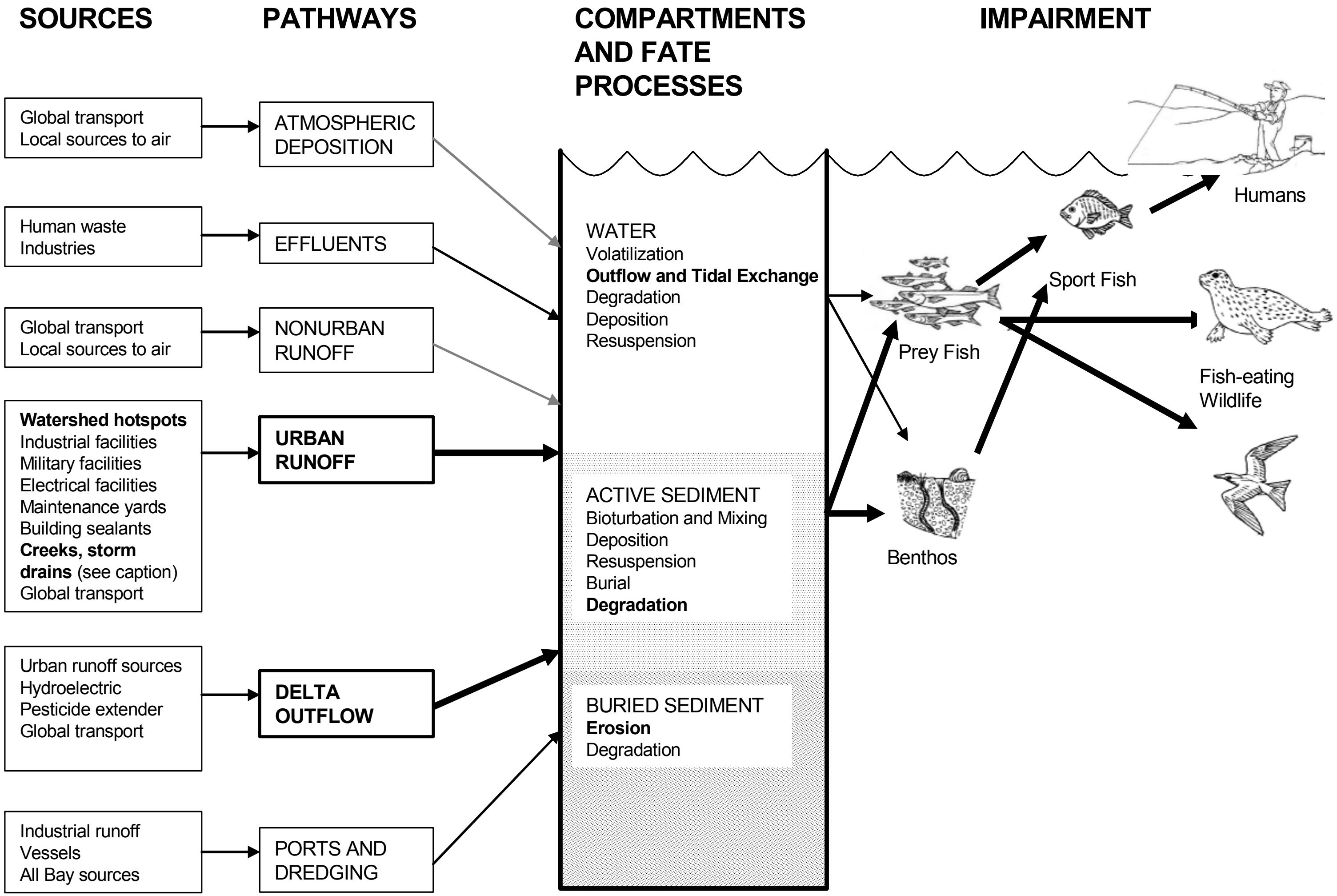

Figure ES-4. **PCB pathways to the Bay:** 1) urban runoff; 2) Central Valley (Delta outflow); 3) buried sediment; 4) in-Bay PCB hot spots; 5) dredging and dredged material disposal; 6) wastewater effluent; and 7) nonurban runoff. Not shown: atmospheric exchange. The size of each arrow indicates the relative magnitude of the load. The color of each arrow indicates how concentrated the input stream is (darker colors more concentrated). Urban runoff, the Central Valley, erosion of buried sediment, and in-Bay hot spots likely represent the largest pathways.

were 6.0 and 23 kg PCBs, respectively. As for 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. Recent studies have shown that erosion of buried sediment is occurring in large regions of the Bay. This poses 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. The magnitude of this pathway is likely to be relatively large, and may become larger as the Bay's sediment deficit increases, but is not well quantified at present. PCB hot spots in the Bay are likely a major contributor of PCBs to the Bay food web and are also not well quantified. These hot spots are known to cause increased PCB bioaccumulation on a local scale, and are suspected to contribute to bioaccumulation on a regional scale. Dredged material disposal, wastewater effluent, and atmospheric deposition are relatively minor pathways for PCB loading to the Bay.

Understanding present rates of increase or decrease in concentrations is an essential element of a conceptual model, crucial in evaluating the need for management action and in attempting to predict probable trends in the future. The database on temporal trends over the past 40 years is very fragmented. PCB concentrations in shiner surfperch, a key indicator species, declined from 832 ng/g wet in 1965 to 217 ng/g wet in 2003. Regular sport fish monitoring conducted from 1994 to 2003 has shown no clear pattern of decline. Transplanted mussels at northern Estuary locations have shown declines from approximately 4000 ng/g lipid in 1982 to 1000 ng/g lipid in 2003. For the southern Estuary locations, concentrations have declined from approximately 6000 ng/g lipid in 1982 to 2000 ng/g lipid in 2003. Data from the top of the Bay food web also indicate that PCB concentrations have declined over the past 20 years. Only two cores from the Bay representing long-term time series have been analyzed for PCBs, indicating that PCB concentrations in the Bay appear to have peaked around 1970, coinciding with peak PCB production, and declining from 32 – 34 ng/g dry weight at depth to 13 – 14 ng/g dry in the surface layer.

A one-box mass budget for PCBs in the Bay has been developed and works well enough to crudely 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 polychlorinated biphenyls in San Francisco Bay. A multi-box mass budget model is currently in development. The multi-box 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 the multi-box model include a more realistic treatment of sediment mixing, sediment erosion and deposition, and a quantification of the aggregate uncertainty of the model estimates. Another recently completed modeling effort describes PCB movement from water and sediment through the food web.

Information Needs

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 hotspots; 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 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 ecosystem.

ACKNOWLEDGMENTS

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Appendix 1 (Prioritized List of PCB Information Gaps) was developed through discussion and communication of the authors with Jon Konnan, EOA, Inc.; Dan Cloak, Dan Cloak Environmental Consulting; Betsy Elzufon, Larry Walker Associates; Paul Salop, Applied Marine Sciences; and Andy Jahn, Port of Oakland.

The hand-drawn illustrations were prepared by Steve Curtis (curtises@comcast.net). Jennifer Hunt and Linda Wanczyk of SFEI assisted with production of graphics. Max Delaney of SFEI assisted with preparation of the final report.

Andy Gunther (Applied Marine Sciences) also deserves particular thanks for managing this project and assisting with defining the scope of the report.

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1. INTRODUCTION

A major effort is underway to tackle one of San Francisco Bay's most challenging water quality problems. Polychlorinated biphenyls (PCBs) are extremely persistent synthetic chemicals that were heavily used from the 1930s to the 1970s in electrical equipment and a wide 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 we are left with a legacy of PCBs spread across the land surface of the Bay-Delta watershed, mixed deep into the sediment of the Bay, and contaminating the Bay food web. Twenty-five years after a ban on PCB sales and production, PCB concentrations in Bay sport fish are still more than ten times higher than a threshold of concern for human health. The San Francisco Bay Regional Water Quality Control Board (Regional Board) has initiated a process to establish a PCB Total Maximum Daily Load (TMDL) and an implementation plan to accelerate the recovery of the Bay from decades of PCB contamination. In short, the PCB TMDL is a plan of action to cleanse the Bay of PCBs.

The federal Clean Water Act requires states to identify water bodies that do not meet water quality standards and to develop TMDLs to achieve attainment of water quality standards. The process for establishing a TMDL includes the following elements:

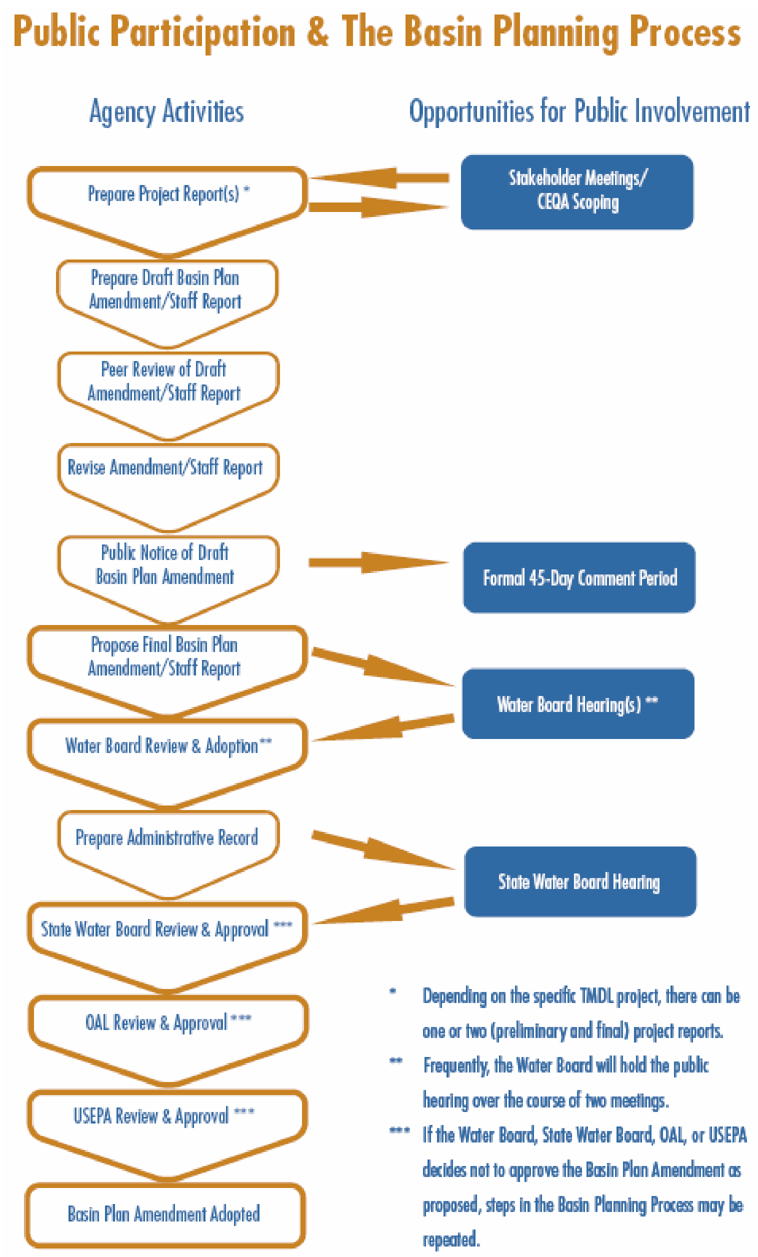
- compiling available data and information,
- defining the water quality impairment,
- identifying and quantifying sources of contamination, and
- determining the maximum load that can enter the water body without unacceptable impacts.

In addition, the State of California requires the development of an implementation plan to eliminate the impairment.

To initiate the TMDL process, Regional Board staff has prepared a draft PCB TMDL Project Report that includes all of these elements (SFBRWQCB 2004). Public participation (or "stakeholder involvement") is considered a vital part of the process of TMDL development. The TMDL development process provides several opportunities for public involvement, including public meetings and opportunities to review and submit comments on draft reports (Figure 1). Public comments on the TMDL Project Report have been received. A revised TMDL Project Report and draft Basin Plan Amendment are being prepared that will address these comments and incorporate any new information. The Basin Plan is the primary policy document that describes the legal, technical, and programmatic bases for regulation of water quality in the Bay. The end product of the PCB TMDL process will be a Basin Plan Amendment that legally establishes the TMDL and specifies regulatory requirements.

This report has been produced for the Clean Estuary Partnership (CEP). The CEP is a collaboration of the Bay Area Clean Water Agencies, Bay Area Stormwater Management Agencies Association, and the San Francisco Bay Regional Water Quality Control Board. Other important participants include the San Francisco Estuary Institute, Clean Water Fund, San Francisco Bay Keeper, Port of Oakland, and the Western States

Figure 1. Public participation and the Basin Planning process. From CEP (2004).



Petroleum Association. This cooperative partnership facilitates efforts to improve water quality in San Francisco Bay by providing financial and staff support for technical studies, discussion of management questions and strategies, and stakeholder outreach activities. Several Conceptual Model/Impairment Assessment (CM/IA) reports have been commissioned by the CEP for pollutants that have been identified as possible causes of impairment to beneficial uses in San Francisco Bay. The general objectives of these CM/IA reports are:

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This introduction describes the San Francisco Bay setting, provides background information on PCBs, and provides background on the management and regulation of PCBs in San Francisco Bay.

1.1 San Francisco Bay

San Francisco Bay is located on the central coast of California (Figure 2). It is the largest estuary on the west coast of the United States, draining a watershed of 60,000 square miles. Much of the Bay is shallow: the median depth is only about six feet and the average depth is only about 14 feet. At its deepest, however, the Bay is more than 300 feet deep. The federal and state regulatory bodies divide San Francisco Bay into eight segments: Sacramento /San Joaquin River Delta, Suisun Bay, Carquinez Strait, San Pablo Bay (including Castro Cove), Richardson Bay, Central San Francisco Bay (including Oakland Harbor and San Leandro Bay), Lower San Francisco Bay, and South San Francisco Bay. The Bay is a popular fishing location, visited by thousands of anglers every year. The Bay is also important habitat for wildlife, including birds and marine mammals. The Bay is a staging and wintering area for approximately one million migratory waterfowl and one million shorebirds and also provides breeding habitat for many bird species. The Bay also supports a significant resident breeding population of Pacific harbor seals (Grigg 2003). The Water Quality Control Plan for the region (SFRWQCB 1995) lists the beneficial uses for the Bay (Table 1).

1.2 Polychlorinated Biphenyls (PCBs)

PCBs, or polychlorinated biphenyls, are a family of chemicals that were widely used for many decades, are extremely stable in the environment, have a strong tendency to accumulate in living organisms, and continue to pose health risks to humans and wildlife. The term "polychlorinated biphenyl" refers to a family of 209 individual

Figure 2. Map of San Francisco Bay showing locations mentioned in this report.

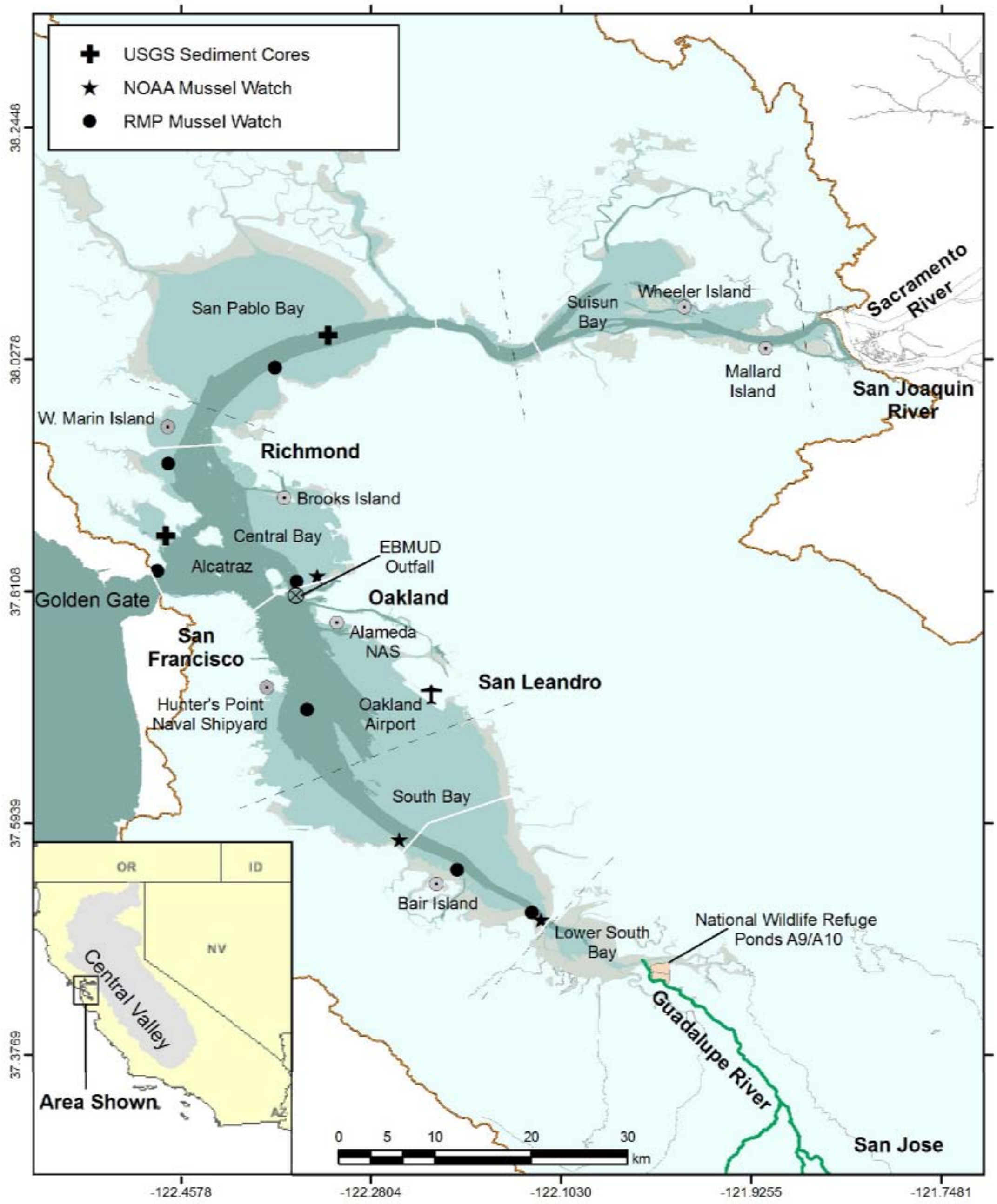
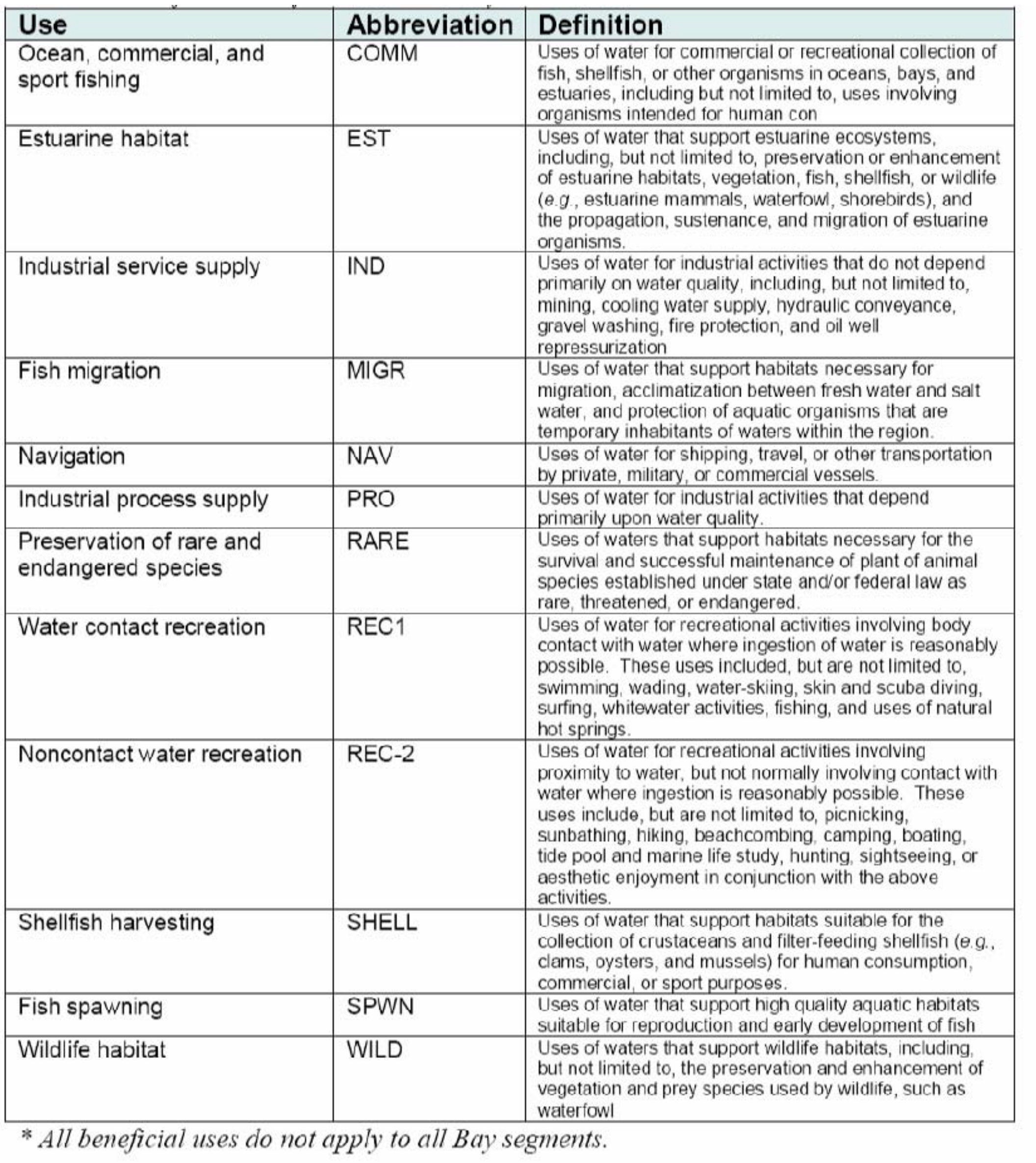


Table 1. Beneficial uses of San Francisco Bay (SFRWQCB 1995).



Use	Abbreviation	Definition
Ocean, commercial, and sport fishing	COMM	Uses of water for commercial or recreational collection of fish, shellfish, or other organisms in oceans, bays, and estuaries, including but not limited to, uses involving organisms intended for human con
Estuarine habitat	EST	Uses of water that support estuarine ecosystems, including, but not limited to, preservation or enhancement of estuarine habitats, vegetation, fish, shellfish, or wildlife (*e.g.*, estuarine mammals, waterfowl, shorebirds), and the propagation, sustenance, and migration of estuarine organisms.
Industrial service supply	IND	Uses of water for industrial activities that do not depend primarily on water quality, including, but not limited to, mining, cooling water supply, hydraulic conveyance, gravel washing, fire protection, and oil well repressurization
Fish migration	MIGR	Uses of water that support habitats necessary for migration, acclimatization between fresh water and salt water, and protection of aquatic organisms that are temporary inhabitants of waters within the region.
Navigation	NAV	Uses of water for shipping, travel, or other transportation by private, military, or commercial vessels.
Industrial process supply	PRO	Uses of water for industrial activities that depend primarily upon water quality.
Preservation of rare and endangered species	RARE	Uses of waters that support habitats necessary for the survival and successful maintenance of plant of animal species established under state and/or federal law as rare, threatened, or endangered.
Water contact recreation	REC1	Uses of water for recreational activities involving body contact with water where ingestion of water is reasonably possible. These uses included, but are not limited to, swimming, wading, water-skiing, skin and scuba diving, surfing, whitewater activities, fishing, and uses of natural hot springs.
Noncontact water recreation	REC-2	Uses of water for recreational activities involving proximity to water, but not normally involving contact with water where ingestion is reasonably possible. These uses include, but are not limited to, picnicking, sunbathing, hiking, beachcombing, camping, boating, tide pool and marine life study, hunting, sightseeing, or aesthetic enjoyment in conjunction with the above activities.
Shellfish harvesting	SHELL	Uses of water that support habitats suitable for the collection of crustaceans and filter-feeding shellfish (*e.g.*, clams, oysters, and mussels) for human consumption, commercial, or sport purposes.
Fish spawning	SPWN	Uses of water that support high quality aquatic habitats suitable for reproduction and early development of fish
Wildlife habitat	WILD	Uses of waters that support wildlife habitats, including, but not limited to, the preservation and enhancement of vegetation and prey species used by wildlife, such as waterfowl

** All beneficial uses do not apply to all Bay segments.*

chemicals (called "congeners") based on combination of a two-ringed carbon skeleton with varying numbers of chlorine atoms (Figure 3). In the U.S., PCBs were sold as mixtures of many congeners known as "Aroclors".

Due to their resistance to electrical, thermal, and chemical processes, PCBs were used in a wide variety of applications from the time of their initial commercial production in 1929 (Brinkmann and de Kok 1980). PCBs were most commonly used as insulators in electrical equipment such as transformers and capacitors. Electrical utilities and industries consuming large quantities of electricity used the greatest quantities of PCBs. PCBs were also used in many other applications, including hydraulic fluids, lubricants, inks, and as a plasticizer. One example of a common use of PCBs was in one billion ballasts installed in fluorescent light fixtures throughout the U.S. The estimated total commercial production of PCBs in the United States ranged from 610 million to 635 million kilograms (kg). U.S. production peaked in 1970 at 39 million kg (Figure 4). Trends in PCB release to the environment, including San Francisco Bay, approximately matched trends in PCB production.

The production of PCB-containing capacitors and transformers ended in January 1979. However, the use of PCBs in some totally enclosed applications remains legal to this day. The life expectancy of capacitors and transformers is decades. In-place capacitors, transformers, and other PCB-containing equipment may still be significant potential sources of PCBs to the environment. 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).

PCBs are extremely persistent in the environment. Leakage from or improper handling of PCB-containing equipment over many decades has led to contamination of urban areas that persists today, and stormwater continues to wash contaminated soils from these sites into the Bay. Contaminated industrial sites are present in the watershed and along the shoreline of the Bay. Remediation and control of PCBs releases from these sites may help to achieve the loadings reductions necessary to attain the Bay's beneficial uses. In addition, implementation actions will likely need to address releases associated with widespread open-ended historical PCB uses.

The 1979 ban resulted from a growing appreciation of the health risks of PCBs. In spite of the fact that their use has been restricted for almost two decades, PCBs remain among the environmental contaminants of greatest concern because they are potent toxicants that are resistant to degradation and have a strong tendency to accumulate in biota. PCBs can cause toxic symptoms including developmental abnormalities and growth suppression, disruption of the endocrine system, impairment of immune function, and cancer. U.S. EPA classifies PCBs as a probable human carcinogen. PCBs and other similar organochlorines reach higher concentrations in higher levels of aquatic food chains in a process known as "biomagnification". Consequently, predatory fish, birds, and mammals (including humans that consume fish) at the top of the food web are particularly vulnerable to the effects of PCB contamination (Figure 5).

Figure 3. Structure of the PCB molecule. Chlorines can be attached at any of the positions numbered 2 through 6.

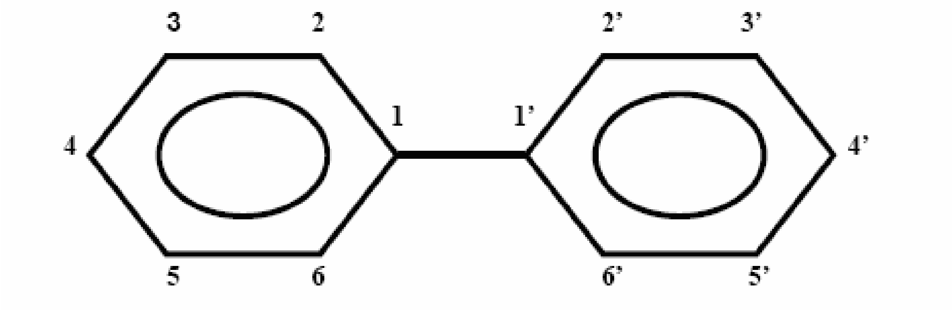


Figure 4. PCB production in the U.S., 1957 – 1975 (Brinkmann and deKok 1980).

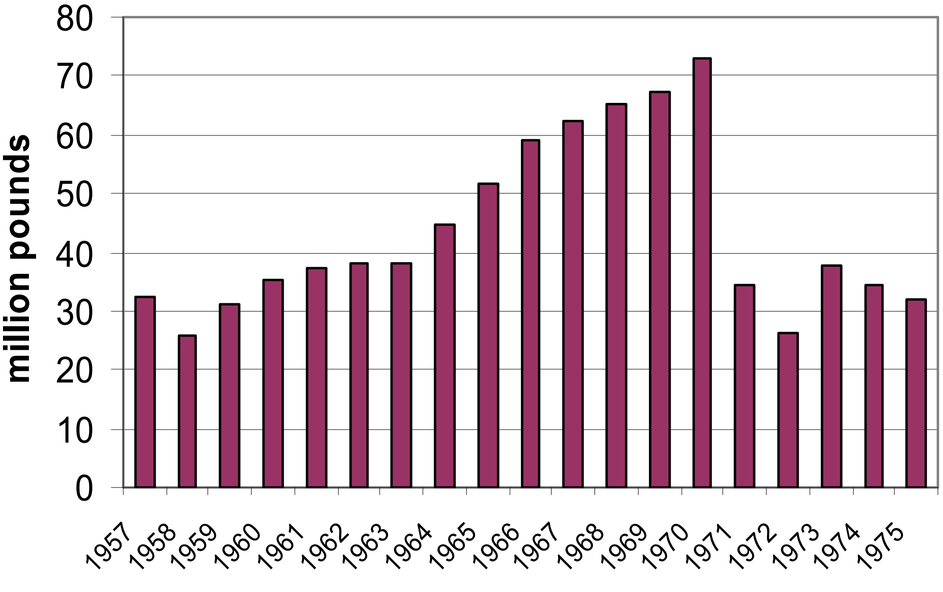
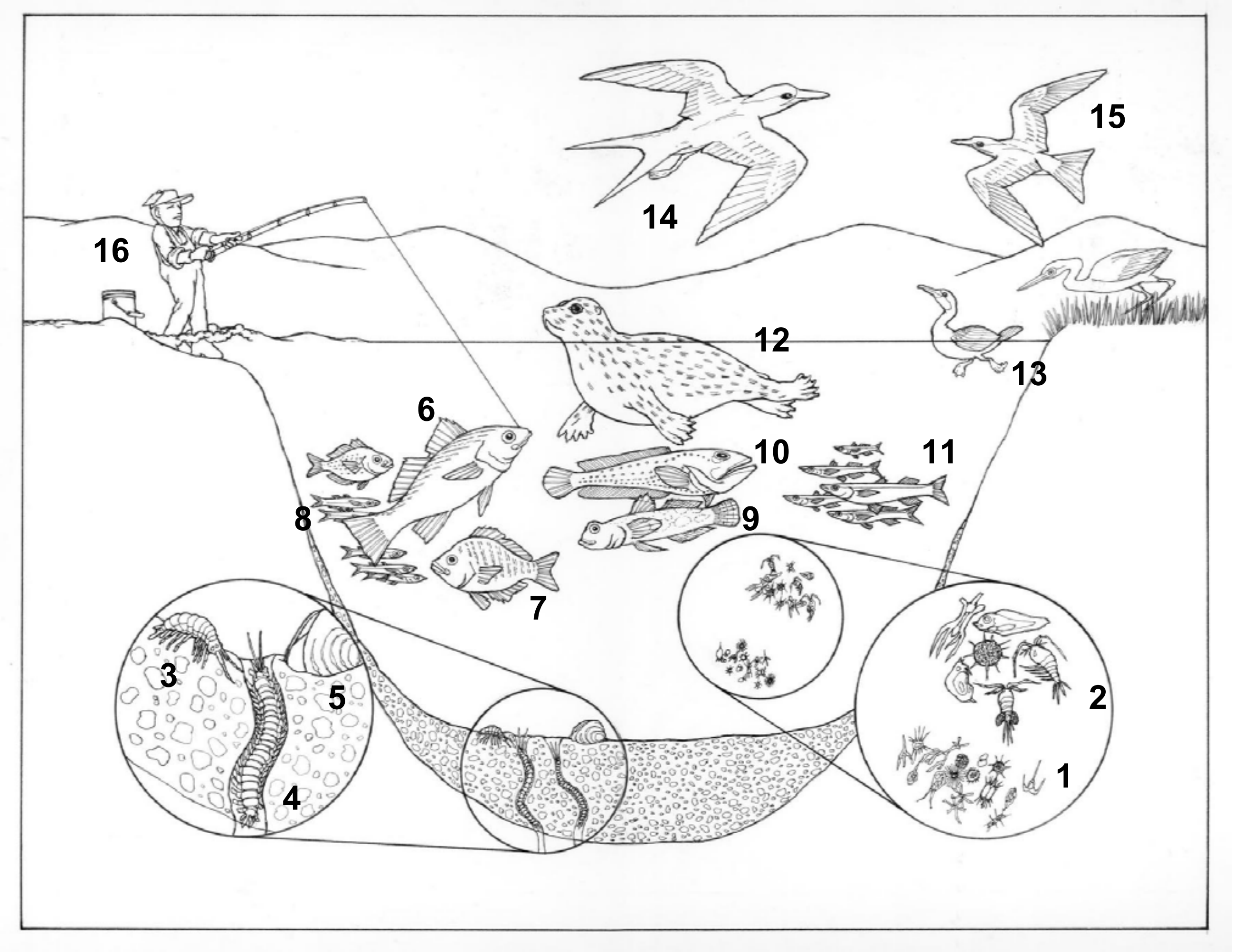


Figure 5. **The Bay food web impacted by PCBs.** PCBs enter the food web primarily through accumulation by phytoplankton (1) at the base of the food web. PCB concentrations then increase with each step up the food web, in a process known as "biomagnification," reaching maximum concentrations and posing the greatest health risks in species that consume Bay fish. Phytoplankton (1) are consumed by small animals including zooplankton (2) and invertebrates such as amphipods (3), worms (4), or clams (5). Invertebrates in the sediment also accumulate PCBs directly from sediment through ingestion of particles and from contact with sediment porewater. Fish consume the zooplankton and invertebrates and receive a higher dose of PCBs. People (16) and wildlife species consume the fish and receive an even higher dose. Wildlife consume smaller fish species such as yellowfin goby (9), plainfin midshipmen (10), and anchovy (11). People prefer larger species such as white croaker (6), shiner surfperch (7), and jacksmelt (8). The wildlife species most sensitive to PCB accumulation and effects include harbor seals (12), cormorants (13), Forster's terns (14), and the endangered least tern (15).



Some PCB congeners closely mimic the potency and mechanism of toxicity of 2,3,7,8-tetrachlorodibenzo-p-dioxin ("dioxin", one of the most toxic compounds known). Other toxicologically active PCB congeners and their metabolites exert toxicities through different mechanisms than the dioxin-like congeners. The dioxin-like PCB congeners can cause toxic symptoms similar to those caused by dioxin exposure, including developmental abnormalities and growth suppression, disruption of the endocrine system, impairment of immune function, and cancer promotion. The PCBs that most closely mimic the potency of dioxin are three congeners, PCB 77, PCB 126, and PCB 169. PCB 126 is the most potent PCB congener by far, one-tenth as potent as dioxin, and is the congener of greatest concern in aquatic environments. In Bay fish, PCB 126 and the other dioxin-like PCBs actually account for more dioxin potency than do the dioxins themselves. While the dioxin-like PCBs resemble dioxin in their *effects* on consumers of Bay fish, their *sources* are very different from dioxins. The dioxin-like PCBs are associated with the same sources as the other PCBs (electrical equipment, etc.), while contemporary sources of dioxins in the Bay Area are believed to be primarily associated with combustion (fireplaces, diesel exhaust, and natural fires). The same cleanup actions that will address PCBs as a whole will also clean up the dioxin-like PCBs. Since TMDLs are focused on control of sources, the dioxin-like PCBs are included in the PCB TMDL.

PCBs are complex mixtures of chemicals, and analysis of minute amounts of these mixtures in environmental samples is challenging. Analytical methods have evolved over the years, with a trend toward finer resolution of the components of the mixtures. In addition, slight variations in methods among laboratories performing contemporaneous analyses can lead to differences in measured PCB concentrations. Long-term trend signals for PCBs in the Bay are obscured to some extent by the use of different analytical methods and laboratories and methods. One major advance in PCB analysis was the switch from low resolution, "Aroclor" methods common in the 1970s and 1980s to methods that measure individual congeners in the late 1980s. PCBs measured as Aroclors are not strictly comparable to PCBs measured as congeners. Furthermore, different studies analyze different suites of congeners. These factors should be considered when making fine-scale comparisons between studies.

1.3 Background on Management and Regulation of PCBs in San Francisco Bay

The History of PCB Management in the Bay

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 sale and production of PCBs (Figure 4) (Brinkmann and deKok 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 dataset 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 MGD or more 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 in 1970. Concentrations dropped by an order of magnitude in 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 (Figure 6).

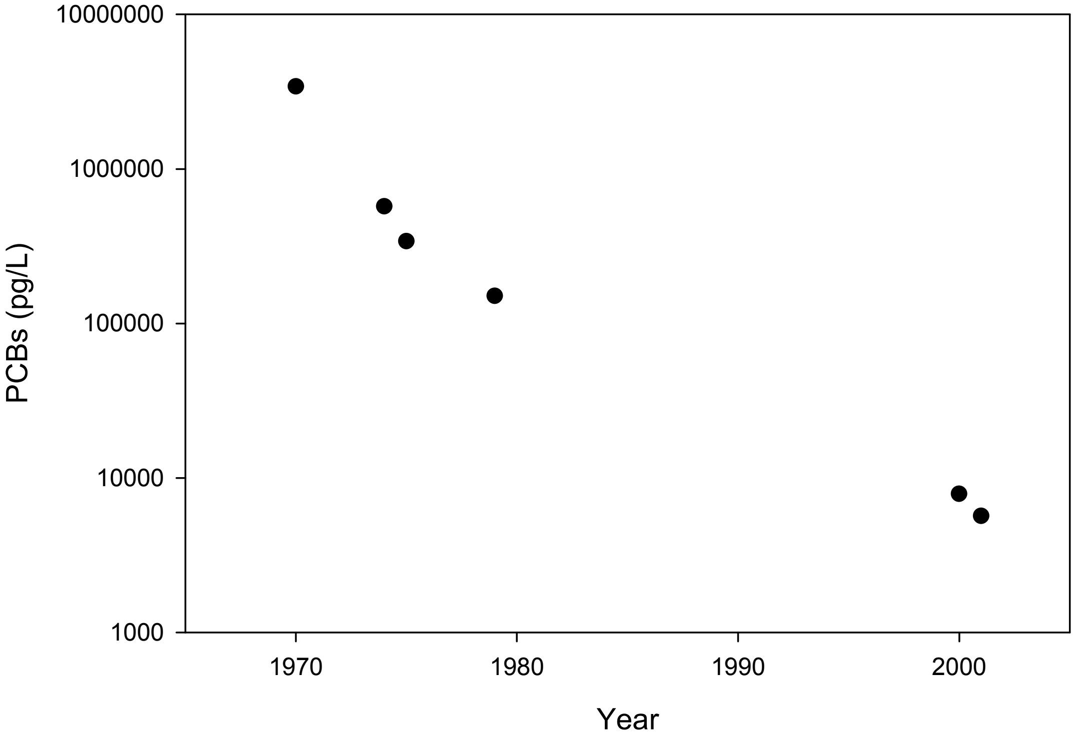
PCB concentrations in Bay bivalves, the only temporal trend monitoring conducted in the1980s, appeared to improve in response to the phaseout and ban by showing rapid declines in the early 1980s, perhaps as a result of the decline in open-ended applications. An alternative hypothesis put forth by Phillips (1987), is that a spill occurred in the Bay in the early 1980s, temporarily increasing concentrations at the onset of long-term bivalve monitoring. The rapid declines in the early 1980s were followed by a slower trajectory of decline from 1982 to the present, probably driven by the gradual reduction in sources of more persistent PCBs in the watershed.

Despite the 1979 ban, a considerable amount of PCBs remains in use today – a voluntary reporting initiative by USEPA documented approximately 200,000 kg still in use in Bay Area transformers in 1999 (SFBRWQCB 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 hotspots in the watershed have been remediated under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), or “Superfund”. Cleanup of these hotspots undoubtedly reduced PCB loading to the Bay, but the magnitude of this reduction cannot be quantified.

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 hot spots, and develop strategies to prevent creation of new toxic hot spots or the perpetuation of existing ones. BPTCP program 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 hot spots primarily through studies of sediment chemistry and toxicity. This study screened 127 sites in the Bay, and identified several hotspots of PCB contamination with PCB concentrations in surface sediment exceeding 200 ng/g dry weight (Hunt et al. 1998).

Figure 6. PCB concentrations in treated wastewater effluent from the East Bay Municipal Utilities District, 1970 - 2001. Data from Risebrough (1997) and SFEI (2002a).



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. The interim advisory remains in place today. Based on the existence of the Bay-wide consumption advisory, the entire Bay was classified as a toxic hot spot.

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 prevented implementation of much of the recommended action.

The History of PCB Regulation in the Bay

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. The federal Clean Water Act (CWA) provides protection to the surface waters of the United States. Section 101(a)(2) of the act establishes a national goal of "water quality which provides for the protection and propagation of fish, shellfish, and wildlife, and recreation in and on the water, wherever attainable." In California, Section 13001 of the California Water Code identifies the California State Water Resources Control Board (SWRCB) and Regional Water Quality Control Boards (RWQCBs) as the principal agencies responsible for controlling water quality.

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 1995a):

> "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 in water. This criterion is deemed protective of a human health cancer risk for fish consumers from waters meeting these PCB concentrations. This newly promulgated 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 2005). This criterion remains in effect at present.

A major shift in the regulatory approach to managing Bay water quality began in 1998. The new approach is based on the development and implementation of total maximum daily loads (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 Total Maximum Daily Load 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 and wildlife prey. 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.

2. IMPAIRMENT ASSESSMENT

The Clean Water Act requires California and the federal government to adopt and enforce water quality standards to protect the Bay. The Basin Plan and the California Toxics Rule delineate these standards. The standards include beneficial uses of the Bay, numeric and narrative water quality criteria to protect those uses, and provisions to enhance and protect existing water quality. Section 303(d) of the Clean Water Act requires states to compile a list of "impaired" water bodies that do not meet water quality standards (the "303(d) List"). All segments of San Francisco Bay appear on the 303(d) List because PCBs impair the Bay's established beneficial uses (Table 1), including sport fishing, preservation of rare and endangered species, and estuarine and wildlife habitat.

2.1 Ocean, Commercial, and Sport Fishing (COMM)

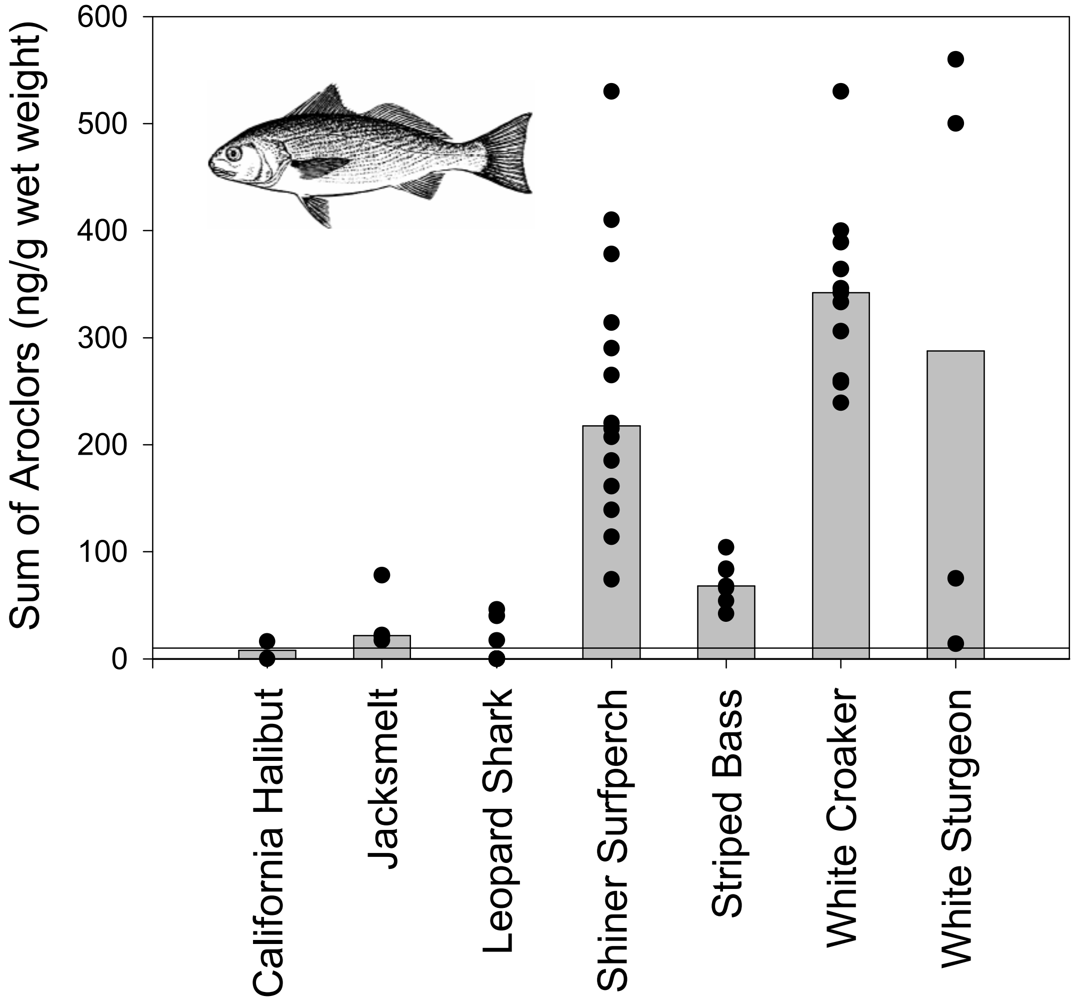
One of the designated beneficial uses of the Bay is for "ocean, commercial, and sport fishing" (abbreviated as "COMM"). The use of the Bay for sport fishing is impaired by the existence of a consumption advisory. The advisory was issued in 1994 by the Office of Environmental Health Hazard Assessment (OEHHA) after a study that year found concentrations of mercury, PCBs, and other chemicals in popular sport fish species that posed a potential human health risk. PCB concentrations in sport fish were, along with mercury, a primary cause of the consumption advisory and the consequent classification of the Bay as an impaired water body. PCBs 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 three-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 a 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. Fetuses and young children are most sensitive to the effects of PCBs, mercury, and other food web contaminants.

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). The most recent data (from 2003) show that PCB concentrations vary among species (Figure 7). 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 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 Figure 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.

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

Figure 7. PCB concentrations (as Aroclors) in San Francisco Bay sport fish, 2003. Bars show medians, points are individual samples representing composites of multiple fish. Line indicates screening value of 10 ng/g. Unpublished data from the RMP.



PCBs was 39%, with a range of 11% to 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.

PCB concentrations in water are another indicator of impairment of COMM. 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 – 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.

2.2 Preservation of Rare and Endangered Species (RARE), Estuarine Habitat (EST), Wildlife Habitat (WILD), and Fish Spawning (SPWN)

A narrative water quality objective for the Bay states that "…controllable water quality factors shall not cause a detrimental increase in toxic substances found in bottom sediments or aquatic life." The existing level of PCB contamination in the Estuary is considered to be a violation of this narrative standard with regard to the RARE, EST, and WILD beneficial uses. Only the narrative objective applies to the EST, RARE and WILD beneficial uses, as there is no numerical criterion for the protection of wildlife and estuarine beneficial uses.

Several sources of information (reviewed in detail by Thompson et al. submitted) 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 (Figure 5). Populations residing in PCB hotspots also face relatively high risks.

Birds

Studies of PCBs in eggs of the endangered California clapper rail, the endangered California Least Tern, and Double-crested Cormorants have found concentrations that are near the threshold for embryo mortality.

One study in the 1980s 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 ppm 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 night herons, with average PCB concentrations in San Francisco Bay Caspian and Forster's Tern eggs of 4.85 ppm and 5.65 ppm 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 embryo mortality (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 3800 ppb 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 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 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 ppm fresh wet weight (fww) in Caspian Terns, 2.0 ppm fww in Forster's Terns, and 2.7 ppm fww in Least Terns. The Least Terns forage in an area near one of the Bay's PCB hotspots, 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 3.69 and 3.61 ppm fresh wet weight, 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 (1.30 ppm fww) had not declined from the mean concentration observed in 1986 (0.82 ppm fww). The authors concluded that PCBs in 1992 may still have been high enough in some 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 herons and egrets 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 night heron eggs from Alcatraz Island in 1991 had a geometric mean of 6.1 ppm fww, higher than that observed at Bair Island in 1983 when an association between PCB concentrations and embryo weight was observed.

Seals

PCB concentrations in Bay harbor seals (*Phoca vitulina*) are elevated in comparison to 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 ug/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 co-workers (Kopec and Harvey 1995, 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 50.5 ppb 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 and co-workers (Neale 2004, 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 determined 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 ppb wet to 18 ppb 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.

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 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 – 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. 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 a new study in 2005 that will include field and laboratory studies to evaluate the effects of exposure to realistic mixtures of pollutants. Shiner surfperch has been selected as the indicator species for this work. Surfperch in the Bay accumulate relatively high concentrations of PCBs and other organics, have high site fidelity, and possess other qualities that make this species a good indicator. This pilot study will attempt to establish surfperch as a model to build the capacity for long-term contaminant effects monitoring in a Bay fish species. The study plan for 2005 includes collection of surfperch from contaminated and uncontaminated sites in the Bay and measurement of contaminant concentrations, reproductive output (number and size of embryos in females), and biological markers of chemical exposure. The study plan for 2006 includes collection of surfperch from an uncontaminated site for use in laboratory tests. Growth rates and body conditions of adult fish exposed to contaminant mixtures collected from Bay waters will be studied.

Summary of Impairment of RARE, EST, WILD, and SPWN

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, the degree of impairment of RARE, EST, and WILD does not appear to be as severe as the impairment of COMM. 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. Consistent with this, a screening value for protection of wildlife calculated by USEPA for the Great Lakes is 16 times higher than the human health screening value. Consequently, the reduction in PCB concentration needed to protect human health should also result in protection of wildlife health.

2.3 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 – 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 contamination. In 2000 and 2001, the National Oceanic and Atmospheric Administration (NOAA) National Status and Trends Program and the U.S. 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 (Lowe et al. 2005). Another significant study of PCBs in sediment at 170 locations in Bay Area creeks and storm drains was performed in 2000 and 2001 (Salop et al. 2002, CCCCWP 2002, KLI 2001, KLI 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 (Figure 8).

PCB contamination in the Bay is primarily associated with urban areas along the shoreline. Numerous in-Bay hotspots in the nearshore zone have been identified downstream of industrial areas. Creeks ands storm drains upstream of the in-Bay hotspots are similarly elevated. Hotspots along the western shoreline south of San Francisco and the eastern shoreline from Richmond through Oakland and south to San Leandro have resulted in 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 hotspots in the Bay and adjoining watersheds.

3. CONCEPTUAL MODEL

3.1 SOURCES, PATHWAYS, AND LOADINGS

Urban Runoff

Urban runoff from local watersheds is a significant pathway for PCB entry into the Bay (Figure 9). The mass of PCBs entering the Bay through this pathway is

Figure 8. Average PCB concentrations in Bay Area sediment. Data compiled from RMP monitoring (e.g., SFEI 2002), the 2000 and 2001 NOAA-EMAP survey (e.g. NOAA, 2001; U.S. EPA, 2001), Hunt et al. (1998), Daum et al. (2000), KLI (2001), and Salop et al. (2002). Urban area in 1954 from the USGS Urban Dynamics Research Program (2000). In-Bay "hotspots" were identified by SFBRWQCB (2004).

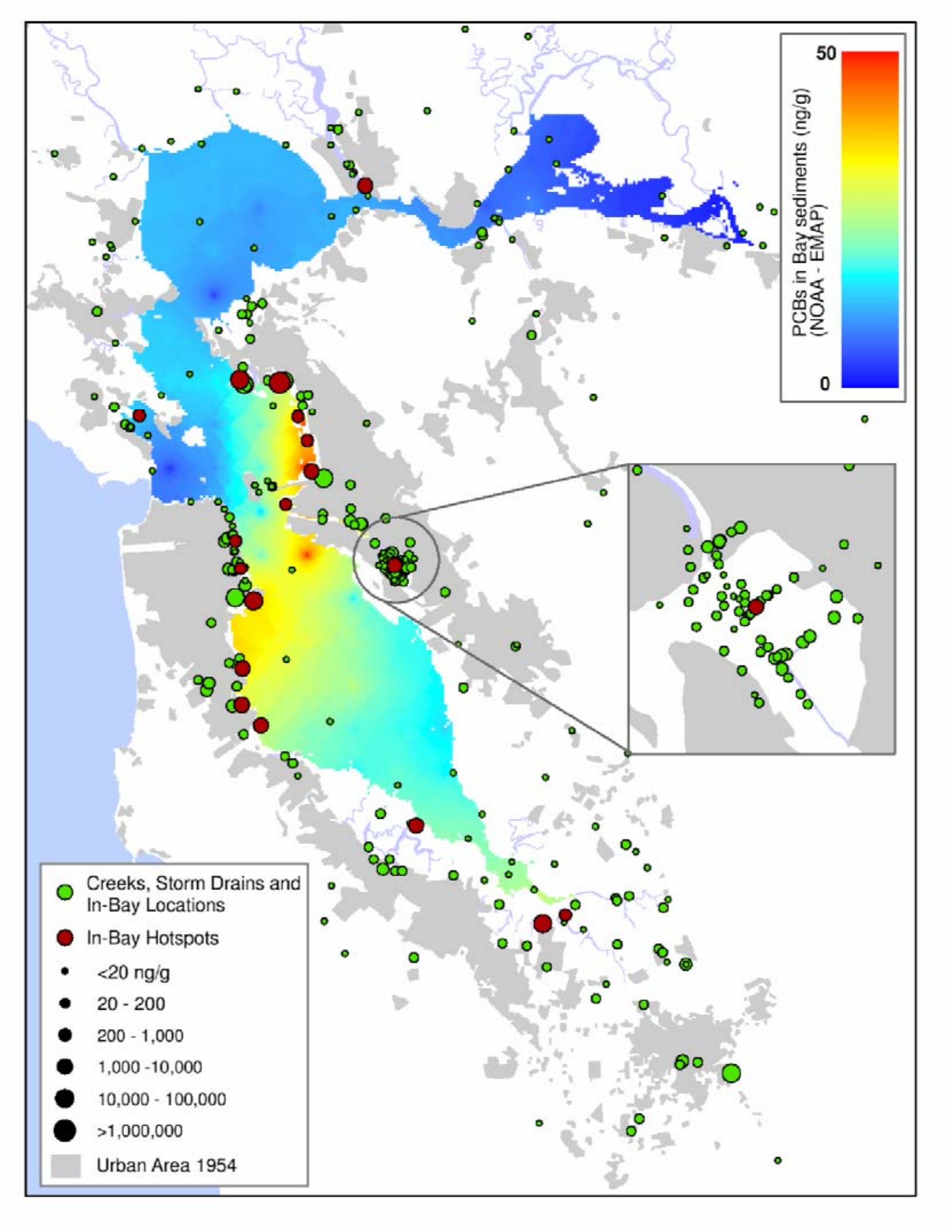


Figure 9. PCB pathways to the Bay: 1) urban runoff; 2) Central Valley (Delta outflow); 3) buried sediment; 4) in-Bay PCB hot spots; 5) dredging and dredged material disposal; 6) wastewater effluent; and 7) nonurban runoff. Not shown: atmospheric exchange. The size of each arrow indicates the relative magnitude of the load. The color of each arrow indicates how concentrated the input stream is (darker colors more concentrated). Urban runoff, the Central Valley, erosion of buried sediment, and in-Bay hot spots likely represent the largest pathways.

relatively large. In addition, PCBs from urban runoff enter the Bay in relatively concentrated streams that are probably 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.

Bay Area watersheds generally consist of a non-urban upper watershed that begins in the Coast Range hills surrounding the Bay and a highly urbanized lower watershed (Figure 10). PCBs are ubiquitous worldwide due to their capacity to enter the atmosphere, so small quantities are found throughout Bay Area watersheds. However, the lower, urbanized portions of the watersheds are where the industrial activities associated with PCB contamination were concentrated, and are where the PCBs present in urban runoff predominantly originate. Industrial sites where PCBs were used in electrical equipment or where such equipment was stored or salvaged are important sources of PCBs in urban runoff from the local watersheds. With each rainstorm, contaminated soils from these sites are gradually washing into creeks, storm drains, and the Bay.

Watershed hotspots and contaminated creeks and storm drains are considered to be significant contributors to PCBs in urban runoff. A survey of PCBs in sediments of creeks and storms drains in Alameda County found particularly high concentrations at the Ettie Street pump station in West Oakland (Salop et al. 2002) and led to a followup investigation to identify sources within the drainage area of the pump station (Applied Marine Sciences 2002, Kleinfelder Inc. 2005). This is a $460,000 project funded by Proposition 13 and being conducted by the City of Oakland. The project includes inspections of industrial facilities, targeted sampling and analysis, abatement activities, and targeted public outreach. The highest concentrations of PCBs in the Ettie Street drainage were found in sediment near sites occupied by hazardous waste contractors, vacant lots, automobile and metal salvage companies, trucking facilities, and paint contractors (Kleinfelder Inc. 2005).

The Ettie Street investigation also yielded information suggesting that episodic release of large masses of PCBs from watersheds remains a distinct possibility. Inspectors for this project entered one property where they discovered chemical storage barrels, including one that apparently contains PCBs based upon the label. This barrel, if the label is accurate, contains an estimated 320 kg of PCBs. In comparison, an estimated 2,500 kg of PCBs are present in the active sediment layer of all of San Francisco Bay. Other watersheds in the Bay Area have not yet been investigated, but it seems reasonable to assume that there are similar situations in other watersheds. This suggests that there could be more PCB mass in the watershed, in forms that can easily be mobilized, than in the Bay itself. If not disposed of properly, this mass could be released due to spills (accidental or intentional), resulting in large loads that could impact PCB dynamics in San Francisco Bay for decades.

Other recently published information indicates that more diffuse watershed inputs from PCBs in sources like building sealants (Herrick et al. 2004, Kohler et al. 2005) and

Figure 10. **PCB transport from urban watersheds.** Bay Area watersheds generally consist of a non-urban upper watershed that begins in the hills surrounding the Bay and an urbanized lower watershed. The non-urban upper watersheds in the Bay Area are minor sources of PCBs, with small amounts present mainly due to the long-range atmospheric transport and deposition of these chemicals. The lower parts of the watersheds are predominantly urban and are where activities associated with PCB use were concentrated, including industrial and military sites, electricity consumption, and waste disposal sites and scrapyards. Urbanized lower watersheds in the Bay Area are significant sources of PCBs and other priority contaminants.

fluorescent light ballasts may also be important. The relative importance of different PCB sources to urban runoff is one of the highest priority PCB information gaps.

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 through 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 two 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 per 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 "hotspots" on land, in storm drains, and in the vicinity of storm drain outfalls, and capture, detention, and treatment of highly contaminated runoff. However, there is presently insufficient data to determine which approaches are best. 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 presently is limited information that can be used to estimate the likelihood of success in achieving urban runoff load reductions.

Gradual reductions in urban runoff loads can also expected without further management action due to several processes. This phenomenon is referred to as "attenuation" of these loads. Since PCB use in the watersheds is on the decline, loads can also be expected to continue to decline. It is also likely that PCB inventories at hotspots in the watershed are generally on the decline from historic maxima due to erosion and transport. The most contaminated soil and sediment particles from these hotspots in general have probably already been washed into the Bay. Volatilization of PCBs from contaminated areas leads to some degree of atmospheric transport out of local watersheds. Degradation is another process that is probably occurring at a slow, but perhaps tangible rate. As time passes, volatilization and degradation rates are likely to become even slower as inventories of the more volatile and reactive PCB congeners (those with fewer chlorines) are reduced. All of these processes are difficult to quantify. It should be noted that accidental release of PCBs that are still in use or stored in the watersheds could temporarily reverse the expected attenuation of urban runoff loads. Expected trends in PCB loads from urban runoff with and without further management actions is a high priority information gap.

A $1.3 million study to evaluate the feasibility of achieving load reductions from urban runoff is currently underway. SFEI will soon begin this Proposition 13-funded project that will help develop methods to quantify and control stormwater loads of PCBs, mercury, and other pollutants to the Bay. It will include reviewing current methods used to reduce stormwater pollutant loadings in the Bay Area and, when data are available, the effectiveness and implementation costs of the methods. In addition, the project will quantitatively evaluate the efficiency of selected stormwater pollutant controls through modeling and field monitoring.

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 (Figure 9). 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 portion of the PCB load may wash immediately through the Bay and out into the Pacific Ocean. Ongoing studies presently funded by the RMP through 2009 are addressing the need for a better understanding of the magnitude and fate of PCB loads from Delta outflow.

Sediment PCB loads from the Central Valley are expected to be difficult to control. Still, the PCB concentration of suspended sediments coming from the Central Valley is greater than the sediment PCB target for the Bay. Eventual reductions of this load are expected as these concentrations on suspended sediment naturally attenuate over time, due to the same processes described above for urban runoff.

Three major questions exist with regard to PCB loads from the Central Valley. First, the magnitude of loads during a high flow year is not known. Sampling has been performed in the past few years, but these have not been high flow years and loads during high flow cannot simply be extrapolated from low flow data. Second, the long-term fate of the PCBs attached to sediment particles carried in from the Central Valley is not known. If these PCBs stay adsorbed to particles over the long-term, then sediment from the Valley may help dilute sediment concentrations in the Bay. Third, the fate of Central

Valley loads during high flow events is a question. It is possible that a large portion of the large loads that are expected to occur during high flows may wash right through the Bay to the ocean.

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 (Figure 9). 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). This is an unusual phenomenon for an estuary. In typical estuaries, existing sediments are buried as additional layers of sediment are deposited every year. The Bay, however, is experiencing a sediment deficit, largely due to reduced sediment inputs from the Central Valley (McKee et al. 2002). 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.

In-Bay Hotspots

PCB hot spots in the Bay are likely a major contributor of PCBs to the Bay food web (Figure 9). These hot spots 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 hot spots to impairment is hard to quantify.

Twenty locations around the edge of the Bay have been identified as PCB hot spots, 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 PCB hot spots (SFBRWQCB 2004). Hot spot contamination 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 addition to the clear local impacts of hot spots on food web accumulation, it is possible that PCB export from these locations has an influence on PCB contamination at a regional scale.

PCB hot spots are one of the pathways that is relatively controllable. At some of the hot spots 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 hot spot sediments 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 PCB hot spots 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.

Dredged Material

In terms of the mass of PCBs involved, dredged material disposal in the Bay is a moderately significant pathway for PCB transport (Figure 9). However, this transport actually moves sediment from one location to another within the Bay, and does not increase the total mass in the ecosystem. Concern does exist over the localized impacts on PCB bioaccumulation near the disposal sites.

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 likely 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. Disposal of dredged materials at in-Bay dispersive sites is likely to spread the disposed sediments across the surface of the active sediment layer. Dredged material disposal does not increase the mass of PCBs in the Bay, and therefore is not anticipated to contribute to delayed recovery of the ecosystem as a whole. Increased PCB accumulation in the local food webs around disposal sites may result from the dispersal of the dredged material on the surface sediment layer in the Bay. These increases may occur if the disposed dredged material has higher PCB concentrations than the sediment it is depositing on.

The average annual input of PCBs from disposal at in-Bay sites from 1998 to 2002 was 12 kg, a moderate amount relative to other pathways. It should also be noted that an average of 11 kg per year was removed from the Bay through disposal of dredged material in the ocean and at upland sites. The voluntary reduction of in-Bay sediment disposal put forth in the Long Term Management Strategy for the Disposal of Dredged Material in the San Francisco Bay Region (LTMS) Program would reduce the input of PCBs at in-Bay disposal sites. The LTMS seeks to reduce the total volume of in-Bay disposal from the 2,100,000 cubic yards per year to approximately 1,000,000 cubic yards per year within about 10 years.

Continued tracking of dredged material disposal both in and out of the Bay is needed as well as reporting of disposed dredged material PCB concentrations and mass. Source identification and control should be undertaken when elevated PCB concentrations are detected during dredged material testing. A literature review to assess the question of the significance of in-Bay dredged material disposal on PCB entry into the food web is being performed by the RMP in 2005.

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 (Figure 9). The current total annual loads from municipal and industrial dischargers are estimated at 2.3 and 0.012 kg/yr, 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.

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.

3.2 HISTORIC TRENDS

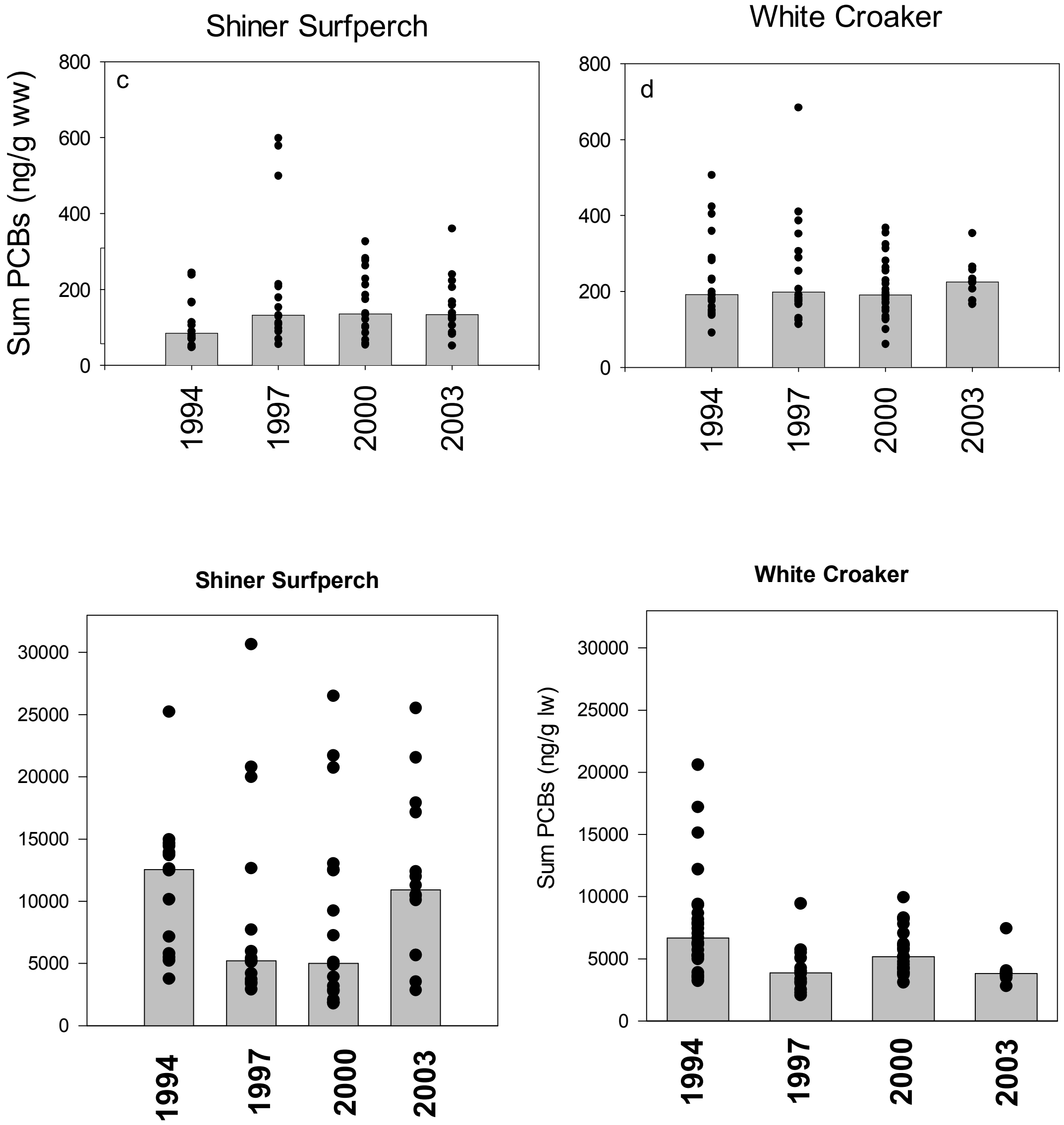
Understanding present rates of increase or decrease in concentrations is an essential element of a conceptual model, crucial in evaluating the need for management action and in attempting to predict probable trends in the future. Available information suggests that PCB concentrations peaked around 1970, 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 1980s 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 coherent picture does begin to emerge when all of the available lines of evidence are considered.

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 three 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 832 ng/g wet (as Aroclors). In comparison, the Bay-wide median concentration measured in 2003 was 217 ng/g wet (as Aroclors), suggesting a reduction of approximately 74% over this 38 year span. Concentrations in shiner surfperch over the past nine years have shown no clear pattern of decline (Figure 11 – 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 (Figure 11). 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 (12600 and 10900 ng/g lipid, respectively), and exhibited considerable interannual variation with much lower concentrations 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 191 ng/g wet to 225 ng/g wet (sum of congeners), with the highest median observed in 2003 (Figure 11). Lipid weight medians have been more variable, ranging from 3800 ng/g lipid in 2003 to 6700 ng/g lipid in 1994 (Figure 11). 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.

Figure 11. PCB trends in shiner surfperch and white croaker, expressed as sum of congeners on a wet weight basis (upper plots) and a lipid weight basis (lower plots).



Mussels

PCB concentrations measured annually in transplanted mussels from the early 1980s to the present represent the best dataset available on trends 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 to 100 day deployment period. Using transplants allows for dependable sampling at specific locations. Seven Bay locations have been sampled consistently since the early 1980s (Figure 12). 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 – this indicates the magnitude of reduction in PCBs in the Bay needed to eliminate PCB impairment. 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 for southern Estuary locations indicate that a twenty-fold reduction in concentration (to 100 ng/g lipid) will take approximately another 40 years 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 datasets 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 approximately 50% over the 15 year period of record (Figure 13). On the other hand, a negligible decrease was observed at Dumbarton Bridge and a slight increase was suggested at San Mateo (Figure 13). These time series suggest slower rates of decline than suggested by the transplanted mussels.

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 (Figure 14). 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

Figure 12. PCB concentrations 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).

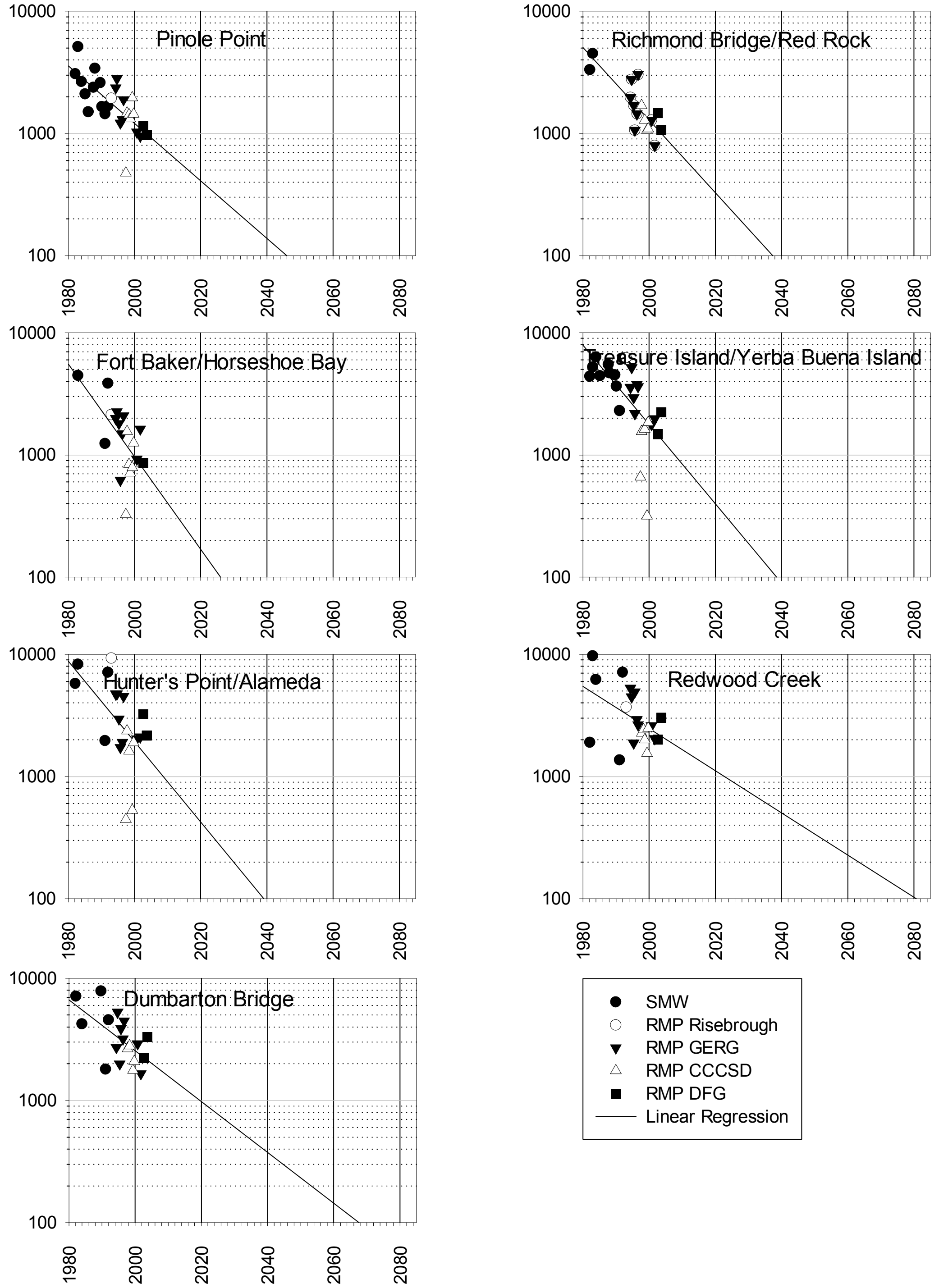


Figure 13. PCB concentrations (sum of 18 congeners) measured by the NOAA National Mussel Watch Program. Data from NOAA National Status and Trends Team (2005).

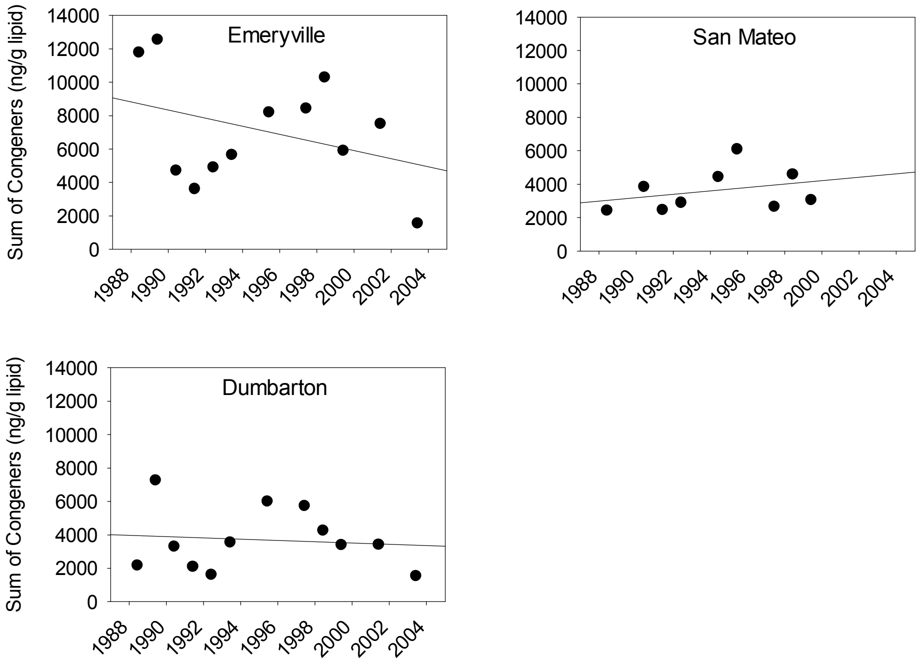


Figure 14. Total PCBs (sums of congeners) in double-crested cormorant eggs collected from Richmond Bridge, Wheeler Island (2002 only), and Don Edwards Ponds A9 and A10 in the San Francisco Bay National Wildlife Refuge. Data for 1999 – 2001 from Davis et al. (2004) and from 2002 and 2004 are unpublished data from the RMP.

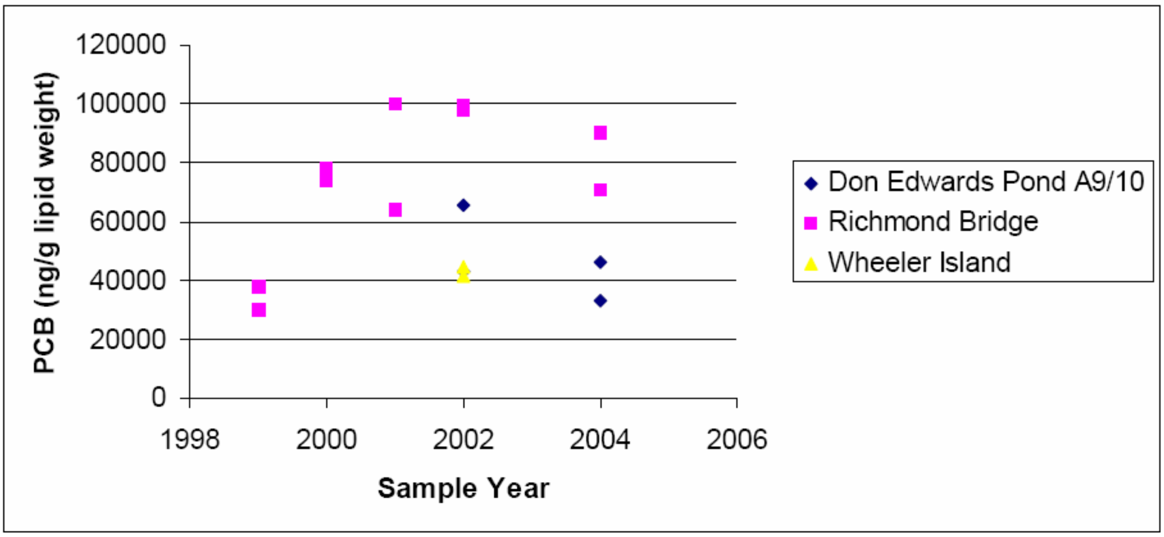


Table 2. PCB concentrations (ppm wet weight) in Bay wildlife, 1975 – present. Means in first row, number of individuals represented in the second. Data sources cited in text.

		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	2005
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 terns	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																		27										18			
	whole blood, wet weight, sum of 6 congeners																		14										35			

Bridge were relatively low in 1999 (1.4 ppm fresh wet weight), then ranged between 3.3 and 4.5 ppm fww during the later rounds of sampling. Concentrations at two other locations ranged from 1.8 to 2.2 ppm fww. These recent observations are similar in magnitude to concentrations measured in several studies of piscivorous bird eggs from 1982 to 2001 (Table 2).

Recent avian egg data are also available for Caspian, Forster's, and Least terns, which averaged 1.6, 2.0, and 2.7 ppm in 2001 (Table 2) (Adelsbach et al. 2003). These concentrations (averages of several Bay locations) in Caspian 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 ppm fww) were about 30% lower than measured by Hothem and Zador (1995) at the same location in 1987 (3.7 ppm fww).

PCB concentrations in Clapper Rails have not been measured recently, but were measured in samples spanning a 17 year period from 1975, 1986, and 1992 (Table 2) (Schwarzbach et al. 2001). Concentrations in 1992 (1.3 ppm fww) were 45% of the mean measured in 1975 (2.9 ppm fww). Concentrations in 1986 were lower than in the other two years sampled. These concentrations were surprisingly high for this non-piscivorous species.

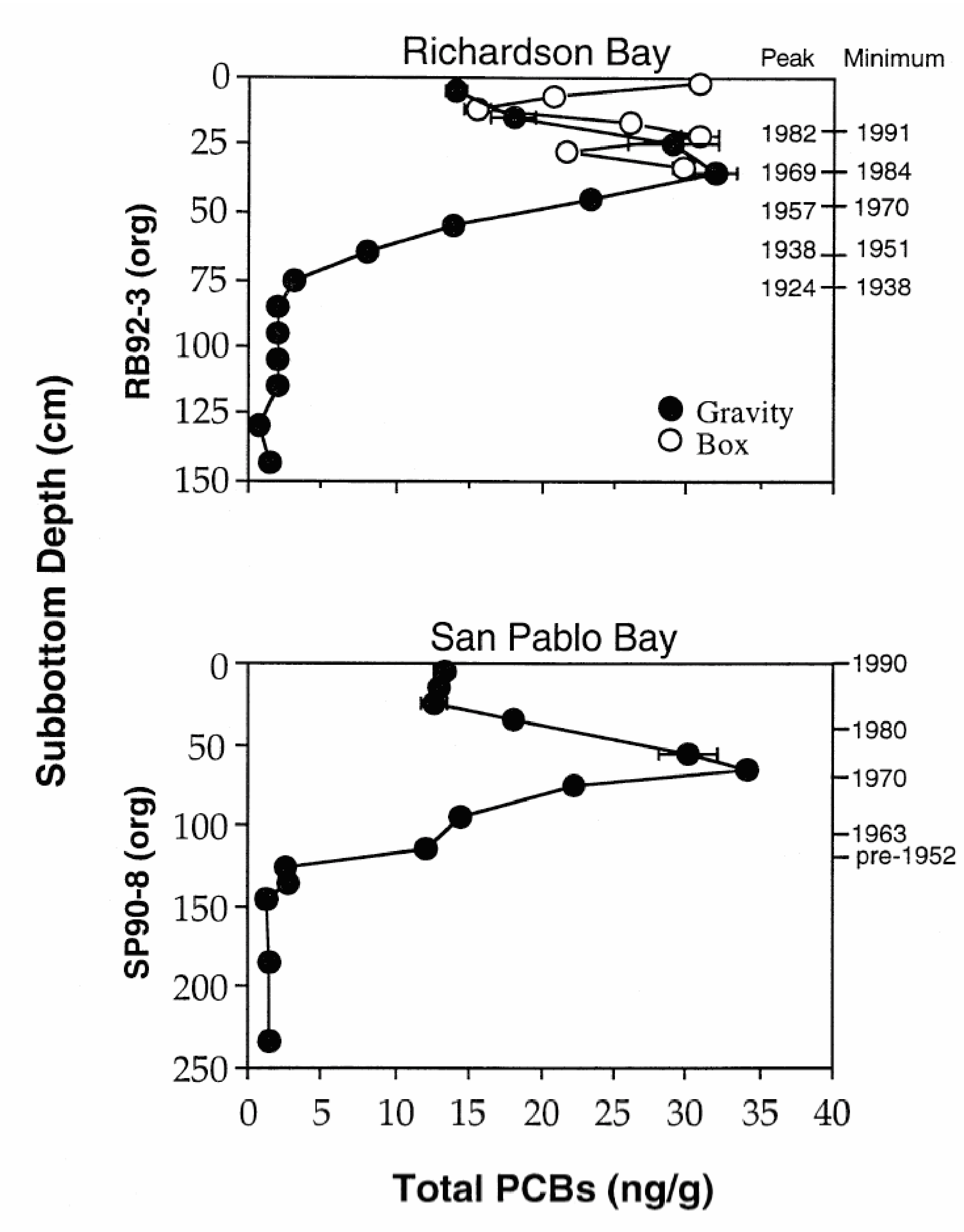
PCBs have also recently been measured in harbor seals. Harbor seal blood in 2001 averaged 18 ppm (sum of six congeners) (Neale et al. 2005), approximately 30% lower than observed in 1992 by Young et al. (1998) (Table 2).

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.

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 (Figure 15), coinciding with peak production (Figure 4). 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 the 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.

Figure 15. PCB concentrations in sediment cores from San Francisco Bay. From Venkatesan et al. (1999). “Gravity” and “Box” refer to types of cores.



3.3 FATE PROCESSES AND RECOVERY FORECASTS

Water and Sediment Processes

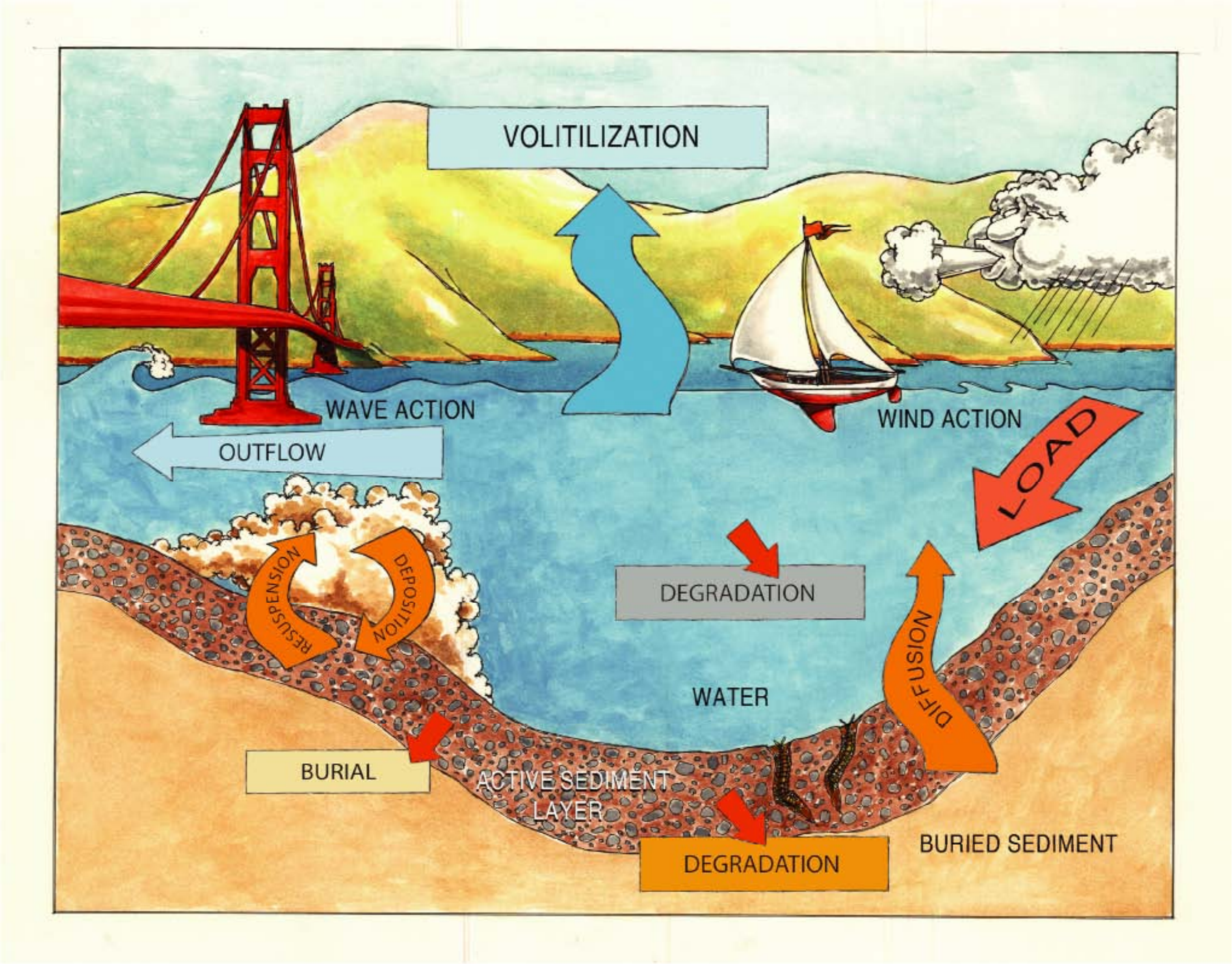
A typical PCB molecule enters the Bay from one of the many pathways described above, then becomes trapped in the ecosystem for decades. During its long residence in the Bay, the molecule will spend most of the time in the sediment, with brief episodes of suspension into the water column. Most PCB molecules end up eventually leaving the Bay through outflow to the ocean, volatilization to the atmosphere, burial in deep sediment, or metabolic degradation by bacteria (Figure 16). Some PCB molecules in sediment and water become incorporated into phytoplankton or detritus at the base of the food web, and are passed up to organisms at higher trophic levels, including humans and sensitive wildlife species. Understanding fate processes in the Bay is essential to discerning which pathways have the greatest influence on accumulation in the food web (the driver of water quality impairment) and to forecasting the recovery of the Bay over the long-term.

PCBs are carried into the water column of the Bay from various pathways, then mostly settle out along with sediment particles and enter the top layer of sediment (the “active sediment”) on the bottom of the Bay (Figure 16). PCBs in the active sediment have the potential to enter the Bay food web either through uptake by benthic organisms or through resuspension into the water column and uptake into a pelagic food web. Waves driven by tides, winds, and storms periodically sweep sediment up from the Bay floor and into the water column, and then the sediment settles back down, completing a recurring cycle of resuspension and deposition. Wave action and bioturbation cause mixing of the active sediment. The degree of mixing gradually diminishes at greater depths, until a point is reached at which sediments are out of reach of waves and bioturbation – this is the buried sediment layer. The mixing of PCBs into the vast pool of active sediment is one of the factors causing the Bay to respond so slowly to changes in loads.

The amounts of PCBs that can be lost from the Bay each year through outflow, volatilization, burial, or degradation are small relative to the mass in the active sediment layer, and this is another factor that makes the Bay slow to respond. The Bay is presently undergoing net erosion rather than burial, so the most important loss pathways for PCBs are outflow, degradation, and volatilization. Outflow of PCBs and sediment particles through the Golden Gate and degradation rates of PCBs under real-world estuarine conditions are both processes that are difficult to measure, where information is lacking, and that have a large influence on the recovery of the Bay from PCB contamination.

A one-box mass budget for PCBs in Bay water and sediment (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.

Figure 16. **PCB cycling in Bay water and sediment.** A typical PCB molecule enters the Bay from one of the many pathways described above, then becomes trapped in the ecosystem for decades. During its long residence in the Bay, the molecule will spend most of the time in the active sediment layer, with brief episodes of suspension into the water column. Most PCB molecules end up eventually leaving the Bay through outflow to the ocean, volatilization to the atmosphere, or degradation by bacteria. The rates of these processes govern the potential rate of recovery of the Bay. Burial is not a pathway for net loss over the long term, as the Bay is currently undergoing net erosion.



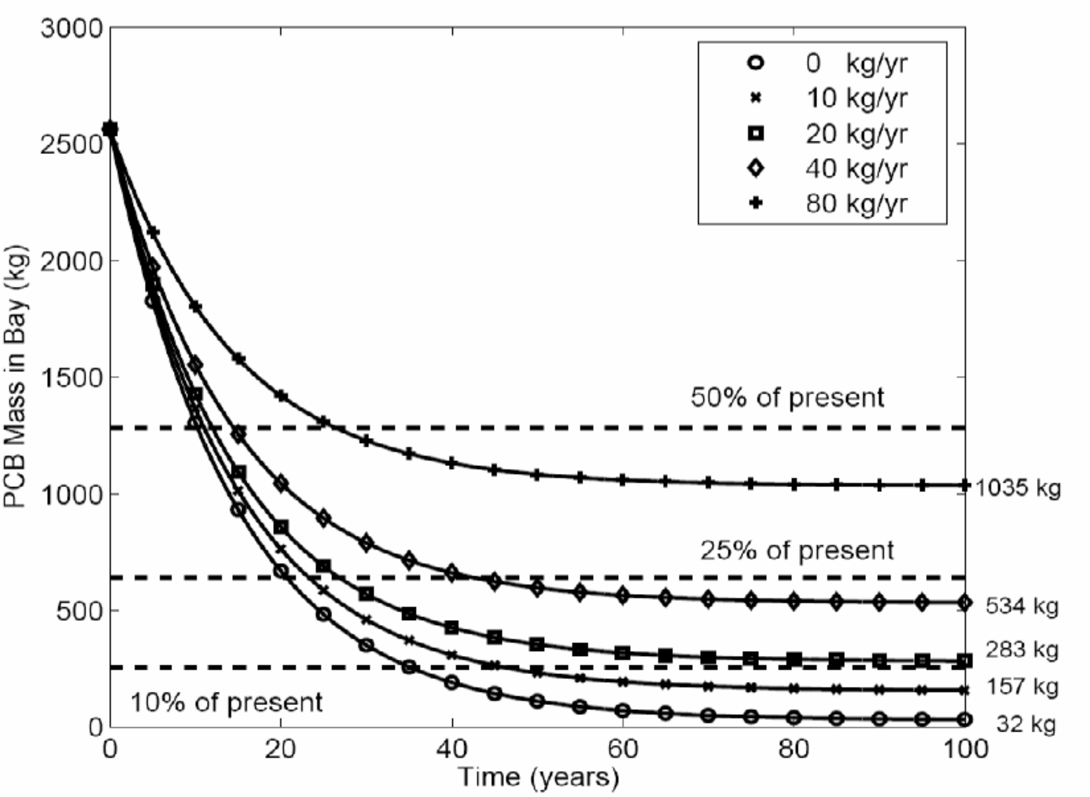
The model was also used to provide a preliminary evaluation of different loading scenarios. With the elimination of external loading, the mass of PCBs in the Bay was predicted to drop to half of the present value in 20 years. The model predicted that sustained loading of 10 kg/year would prevent the 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.

Tidal exchange is an important process that was not initially included in the one-box model (Connolly et al. 2005). 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 (Figure 17). The recovery curves in Figure 17 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 Figure 17. 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 helps 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/yr 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/yr. The transplanted bivalve data (Figure 12) 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% per 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 polychlorinated biphenyls 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 are 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

Figure 17. Predicted masses of polychlorinated biphenyls (PCBs) in San Francisco Bay (USA) 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.



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 by the end of 2005. 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 total maximum daily load development and implementation.

Food Web Processes

PCB impairment of Bay water quality is related to the exposure of humans and wildlife that eat Bay fish. In order to implement the most effective load reductions, it is critical to understand the linkage between PCB sources and pathways and bioaccumulation in fish.

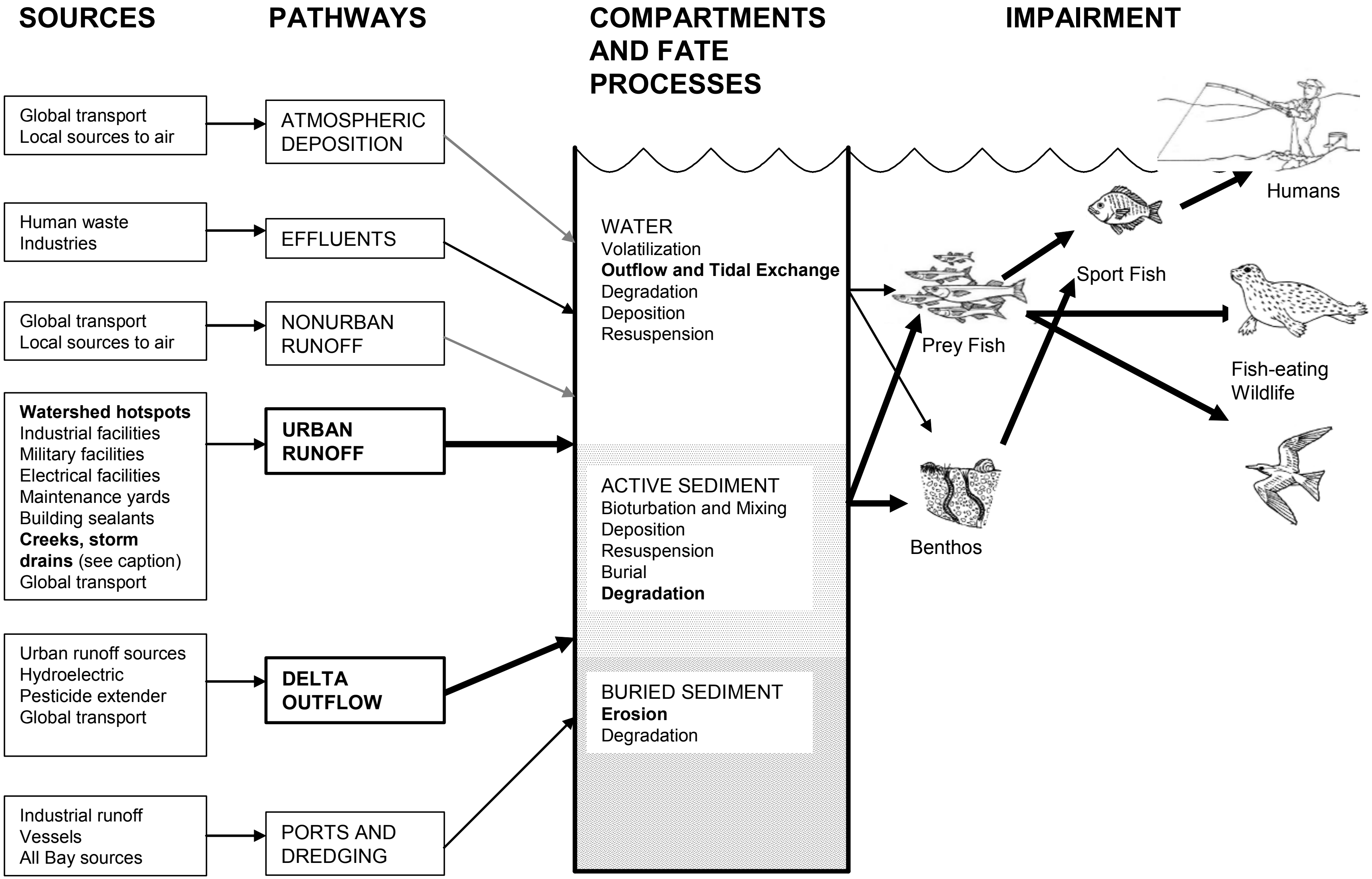
PCBs enter the food web primarily through accumulation by phytoplankton at the base of the food web (Figure 5). PCB concentrations then increase with each step up the food web, in a process known as “biomagnification,” reaching maximum concentrations and posing the greatest health risks in species that consume Bay fish, including people, harbor seals, and several bird species. Humans and wildlife consume different fish species. Wildlife consume smaller fish species such as yellowfin goby, plainfin midshipmen, and anchovy. People prefer larger species, including three (white croaker, shiner surfperch, and jacksmelt) that have relatively high fat content and accumulate correspondingly high concentrations of PCBs.

Benthic invertebrates, including amphipods, worms, clams, and other organisms, are the major source of food for many of the fish species consumed by humans and wildlife. Concentrations in the food web therefore frequently closely parallel those in sediments. Hot spots with contaminated sediments typically also exhibit higher concentrations in the food web. In the Bay, there is a strong linkage between PCBs in the active sediment layer and PCBs in the food web.

The structure of the Bay food web varies from place to place and over time as populations rise and fall and as new species are introduced to the ecosystem. Since PCB concentrations at the top of the food web depend on the number of steps it takes to reach the top, this variation in food web structure can lead to variation in concentrations in the fish-consuming species of concern. The RMP and the CEP have funded the development of a food web model to predict concentrations in fish and wildlife based on concentrations in sediment. The model can also be used to estimate sediment concentrations that would be safe for wildlife and humans – this is one approach to developing TMDL targets. The reliability of these predictions depends on the accuracy with which the structure of the food web is known. The model also provides a tool for quantifying the effect of variation in food web structure on PCB concentrations in sensitive species.

A 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.

Figure 18. 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.



4. 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 (Figure 18). Sources, pathways, and processes of particular importance are highlighted in the diagram. A detailed listing of information gaps relating to PCBs in the Bay was developed with input from the CEP PCB Workgroup. The most critical information gaps are listed below. The complete listing, along with some brief explanation of Regional Board priorities, is provided in Appendix 1.

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. Watershed hotspots and contaminated creeks and storm drains 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 hotspots and remobilization of buried sediment deposits is also in an early stage of development. Priority information gaps related to sources, pathways, and loading include:

- The relative importance of different PCB sources to urban runoff;
- 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 hotspots on PCBs in the food web and the benefits of hotspot cleanup; 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 multi-box model will provide a basis for more realistic representation of the ecosystem and more accurate predictions. Application of the multi-box model will also highlight information needed to generate more reliable predictions. Incorporation of a quantitative treatment of uncertainty in the multi-box 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 and soils in the Bay and its watershed.

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. 2002, 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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APPENDIX 1: UNCERTAINTIES RELATING TO PCBs

IMPAIRMENT

Topic	Uncertainty	Studies Needed	Priority for TMDL[1]	Technical Priority	Technical Practicality	Existing Effort
Human health	Actual human health risks	Blood study	Low	High Understanding actual risks to human health would provide sharper focus on the problem or lack thereof	High	None
	Habitats used by sport fish	Field collections or tagging?		High Knowing where the fish pick up PCBs will help focus cleanup	?	DFG Surveys
Birds	Effects possible in sensitive species in hot spot areas?	Effects on development and survival of embryos	Low	Medium Human health risks are driving the regulations, impacts probably localized	Medium Species at greatest risk (least tern) is endangered	USFWS tern study
	Cumulative impacts of contaminant mixtures and other stressors	Literature review, Lab and field studies	Low	High Potential for significant impact	Medium Egg injections of realistic mixtures challenging, but possible	RMP shiner surfperch study
Seals	Effects on juvenile survival	Lab and field studies	Low	Medium Human health risks are driving the regulations, impacts probably localized	Low	Jennifer Neale, UC Davis
Fish	Lingering effects on reproduction, especially in hot spot areas?	Lab and field studies	Low	Medium Human health risks are driving the regulations, impacts probably localized	High	RMP shiner surfperch study

	Cumulative impacts of contaminant mixtures and other stressors	Literature review, Lab and field studies	Low	High Potential for significant impact	Medium Exposures of realistic mixtures challenging, but possible	RMP shiner surfperch study

[1] Provided by the Regional Board
Regional Board Comment: Although an understanding of actual effects of PCBs in the food web is scientifically important, it will have little effect on the short term need to finalize the TMDL staff report and to get a Basin Plan amendment approved.

SOURCES, PATHWAYS, AND LOADINGS

Topic	Uncertainty	Studies needed	Priority for TMDL[1]	Technical Priority	Technical Practicality	Existing Work
Rivers	Magnitude during high flows	Field sampling	High/medium	High Large mass input	High Just need a high flow year	RMP Mallard Island Study
	Fate of PCBs in high flow events (how much immediate outflow)	Field sampling, modeling	High/medium	High Much of mass may pass right through	Med Modeling is easy, field study difficult	RMP Multi-box model
	Sources	Literature review, field studies	High/medium	Medium	Medium A very large watershed	None
	Effectiveness of control options	Literature review, field studies	High/medium	Medium	Medium Have to find key sources first	None
Nonurban Runoff			Low	Low		None
Dredging	Significance of dredging and disposal to food web accumulation	Literature review, modeling	Low	Medium Relatively small mass	High	RMP Special Study
Harbors	Magnitude of loads from stormwater	Field studies	High	Medium Relatively small part of budget	High	None
	Effectiveness of control options	Literature review, field studies	High	High	High	None

Atmospheric Deposition	Rates of direct and indirect deposition	Field studies	Low	Low Relatively small part of budget		
	Rates of volatilization	Field studies	Low	Low		
	Redeposition of volatilized PCBs in the watershed	Modeling	Low	Low		
In-Bay hot spots	Local benefits of cleanup	Modeling, field studies	Medium	High Influence on fish accumulation potentially large	High	Reg Bd, DTSC, USEPA
	Regional influence of these	Modeling, field studies	Medium	High	High	
	Effectiveness of remediation options (removal, burial, sequestration)	Literature review, field studies, adaptive implementation	Medium	High	High	CEP Nearshore coring
Urban runoff	Magnitude of loads from local watersheds	Field studies	High	High Large mass input	High	RMP, SCVWD
	Magnitude during high flows	Field studies	High	High Loads may increase in nonlinear fashion	High Just need a high flow year	RMP, SCVWD
	Effectiveness of control options	Literature review, field studies, adaptive implementation	High	High	High	SWRCB Prop 13, CEP 4.28
	The attenuation of urban runoff loads with no action	Lit review? Marsh coring studies?	High	High Multi-box predictions	High? A marsh core may	CEP coring study?

		Others?		sensitive to this parameter	work	
	Sources and pathways	Literature review, field studies (storm drain surveys, building chronologies, loads from catastrophic events, etc.)	High	High	High	BASMAA, Prop 13
Buried Sediment	Erosion/deposition trends in the past 15 years	Comparative bathymetry	High	High Potentially large influence on recovery	High Just need bathymetry	SBSP (South Bay only)
	Accurate quantification of loads from this pathway	Modeling	High	High	High	RMP Multi-box
Effluents			Low	Low	High	

[1] Provided by the Regional Board

Regional Board Comment: Continued refinement of our understanding of significant sources of PCBs to the Bay and its food web is necessary. This will continue to inform on implementation actions needed and the potential for load reductions that can be reasonably achieved.

PROCESSES

Topic	Uncertainty	Studies needed	Priority for TMDL[1]	Technical Priority	Technical Practicality	Existing Work
Interplay of all processes	Aggregate uncertainty, reduction in uncertainty by specific studies	Uncertainty analysis	High	High	High	CEP – Tetra Tech
Burial and Erosion	Burial/erosion over the past 15 years	Comparative bathymetry	High	High Potentially large influence on recovery	High	SBSP (South Bay)
	Projected burial/erosion	Model projections of impacts of wetland restoration, sediment budget	High	High	High	SBSP (South Bay)
	Subsurface inventory of PCBs	Coring study	High	High Potentially large influence on recovery, paucity of data	High	CEP/RMP
	Erosivity of sediment	Field studies	High	Medium Moderate influence in multi-box model	Medium	None
Sediment mixing	Representative mixing models for each segment	Mixing studies (cores, isotope work, other approaches)	High	Medium Moderate influence in multi-box model	Medium Resource intensive to characterize heterogeneous ecosystem	CEP/RMP? May be part of coring study

Outflow and tidal exchange	Magnitude	Field studies, modeling	High	High A primary loss pathway	Low Measurements at Golden Gate very challenging	None
Degradation	In situ degradation rates for the Bay for congeners	Field, microcosm, or lab studies	High	High A primary loss pathway, poorly known	Medium?	None
Sediment to Biota Transfer	Sediment concentrations protective of beneficial uses	Food web modeling, site-specific bioaccumulation factors, associated field studies	High	High	High	CEP – Gobas and Arnot

[1] Provided by the Regional Board

Regional Board Comment: There is a great need to have the ability to reasonably model the long term fate of PCBs under different loading scenarios. Any data that will improve this ability falls in the high needs category. However, I leave it to the experts in this field to prioritize the needs listed in the Table above.

INVENTORY

Topic	**Uncertainty**	**Studies needed**	**Priority for TMDL**[1]	**Technical Priority**	**Technical Practicality**	**Existing Work**
Near shore concentrations	Representative average near shore concentration	Randomized sampling of near shore stratum?	Medium	High Much of PCB mass is in near shore zone	High	CEP/RMP
Mass in watershed	Accurate estimate of mass in watershed	Storm drain sediment sampling, targeted sampling of soils and sediments	Medium	High Essential to understanding future inputs	Medium	Counties – storm drain sediment PCB surveys
Mass in Bay sediments	Accurate estimate of mass in subsurface sediments	Cores	Medium	High Potentially large influence on recovery, paucity of data	High	CEP/RMP

[1] Provided by the Regional Board

Regional Board Comment: Refinement of these numbers will certainly be useful. However, current estimates are likely good enough to inform selection of implementation actions needed to help attain beneficial uses of the Bay with respect to impairment by PCBs.

TRENDS

Topic	**Uncertainty**	**Studies needed**	**Priority for TMDL**	**Technical Priority**	**Technical Practicality**	**Existing Work**
Past trends	Recovery trajectory since PCB ban	Cores	Medium	High The best available indicator of future trends	High	CEP/RMP
Present trends	Current rate of decline	Avian eggs	High	High Excellent indicator for long-term regional trends in the Bay food web	High	RMP
	Current rate of decline	Bivalves	High	High Excellent indicator for interannual trends and spatial patterns	High	RMP
	Current rate of decline	Sport fish	High	High Noisy trend signal due to fish life history variation, but essential for evaluating impairment	High	RMP

[1] Provided by the Regional Board

Regional Board Comment: Past rates of decline are likely to have been high due to the phase out of PCBs that began in the late 1970s and clean-up of on-land PCB contaminated sites in the 1980s. Biodegradation rates and atmospheric losses of PCBs have also decreased over time due to the change of congener distribution from weathering. I therefore rank past trends as medium. Future trends are important to know and therefore a high priority. However, before we embark on this type of work, it would be useful to know the power of the proposed work to observe a trend.