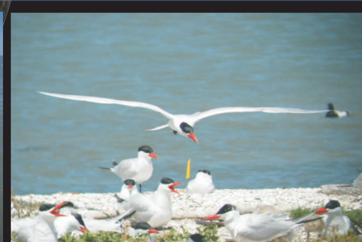
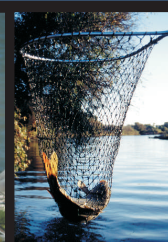
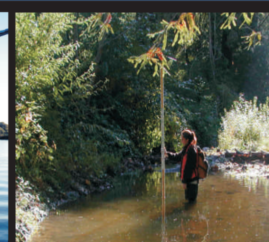
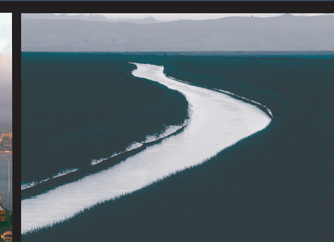
PULSE OF THE ESTUARY 2004



monitoring & managing water quality in the san francisco estuary

San Francisco Estuary Institute

About This Report

In this eleventh year of the San Francisco Estuary Regional Monitoring Program for Trace Substances (RMP), synthesis of findings from the Program since its inception in 1993 continues to provide a general theme. Last year's *Pulse* highlighted lessons learned from long term monitoring of basic water quality parameters and sediment dynamics by the U.S. Geological Survey (USGS). This *Pulse* includes further review of developments in Bay water quality over the past ten years. Thanks primarily to long term monitoring by the RMP and USGS, San Francisco Bay is one of the best-studied estuaries in the world with regard to trace metal contamination. This *Pulse* features articles by Russ Flegal and colleagues from UC Santa Cruz, who have measured metal concentrations in water and sediment of the Bay for the RMP, and Cindy Brown, Sam Luoma, and colleagues from USGS who have generated a remarkable dataset on metals in clams stretching from the 1970s to the present.

Short on time? Just look at the figures and captions. They provide key findings in a nutshell.

Each year the *Pulse* includes articles that provide broad overviews of topics of current interest in water quality management and science. With the imminent release of the draft Basin Plan amendment associated with the mercury TMDL, water quality management in the Bay is entering a new phase. Two articles by San Francisco Bay Regional Water Quality Control Board staff, Tom Mumley and Karen Taberski, describe the importance of science, particularly the RMP, in adaptive implementation of TMDLs and other water quality attainment efforts. The Clean Estuary Partnership (CEP) is complementing the RMP to provide further scientific support for TMDLs. An overview of a series of reports on our present understanding of priority contaminants developed by the CEP is provided in an article by Mike Connor of the San Francisco Estuary Institute (SFEI). Other articles addressing scientific topics include summaries of the present understanding of urban runoff based on the work of Lester McKee and colleagues at the SFEI and a water quality report card for the Bay by Anitra Pawley of the Bay Institute.

The *Pulse* is designed to make the wealth of available information on water quality in the Estuary accessible. The Table of Contents provides a thumbnail overview of each item in the report so readers can readily find topics of greatest interest. In addition, the figure captions have been written in simple language that conveys the basic take-home messages of each article. Readers that are pressed for time can glean many of the important findings from the *Pulse* by simply reviewing the figures and captions. The Status and Trends Monitoring Update is presented entirely as a graphical summary.

The *Pulse of the Estuary* is one of three types of RMP reporting products. The second product, the *Annual Monitoring Results*, is distributed via the SFEI web site <www.sfei.org> and includes narrative summaries and comprehensive data tables and charts of the most recent monitoring results. The third product is the *RMP Technical Reports* series. *RMP Technical Reports* each address a particular RMP study or topic relating to contamination of the Estuary. A list of all RMP technical reports is available at www.sfei.org.

Comments or questions regarding the *Pulse* or the Regional Monitoring Program can be addressed to Dr. Jay Davis, RMP Manager, (510) 746-7368, jay@sfei.org.

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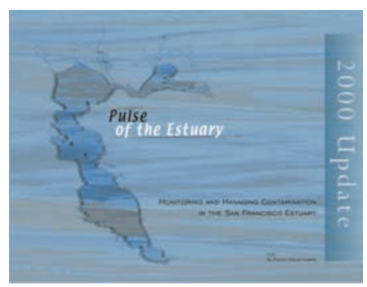
Table of Contents

Feature Articles

2001

Feature articles:
- Using the RMP to Help Manage the Estuary
- Unidentified Contaminants: Hidden Threat?
- Tracking Down Contaminant Sources
- Analyzing Contaminant Movement and Storage
- Improving Contaminant Effects Monitoring
- Fitting the RMP into the Monitoring Milieu

2002



Feature articles:
- The Five Decade Forecast for PCBs in the Bay
- Measuring the Adverse Effects of Contaminants: A New Emphasis
- Closing in on Unidentified Contaminants
- A New Approach to Sampling Water and Sediment

2003

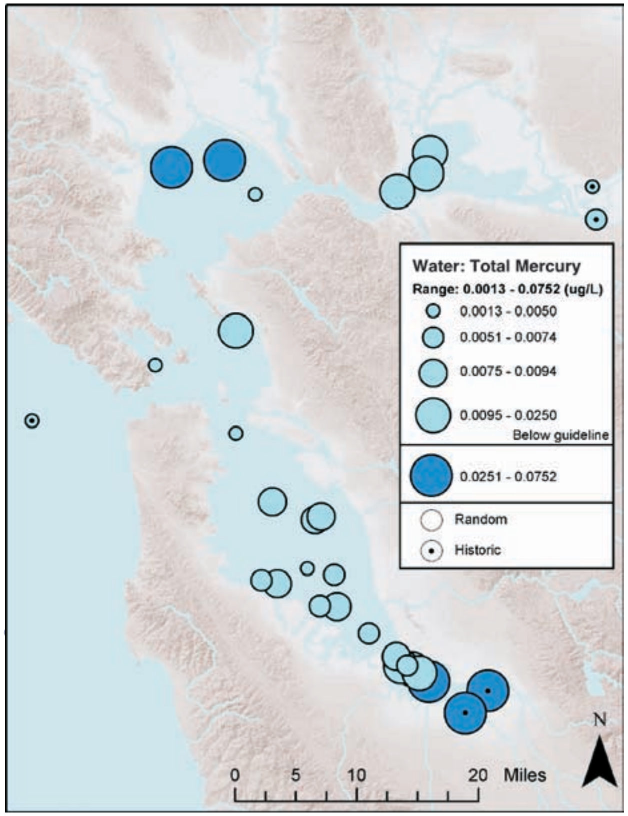
Feature articles:
- Lessons from Monitoring Water Quality in San Francisco Bay
- Sediment Dynamics Drive Contaminant Dynamics
- Ten Years of Testing for the Effects of Estuary Contamination
- Ten Years of Pilot and Special Studies: Keys to the Success of the RMP

latest findings from
contaminant monitoring and research

monitoring update

including
findings from the
RMP and other
programs

Status and Trends update



Total Mercury in Water

Mercury contamination is one of the top water quality concerns in the Estuary and mercury clean-up is a high priority of the Regional Water Quality Control Board. Mercury is a problem because it accumulates to high concentrations in some fish and wildlife species. The greatest health risks from mercury are faced by humans and wildlife that consume fish. The water quality objective for total mercury is designed to prevent unacceptable concentrations in fish.

The new RMP sampling design has provided some new insights into the distribution of mercury in waters of the Estuary. In 2002 the concentrations of total mercury exceeded the water quality objective in 9 of 28 (32%) samples. The highest concentrations were observed in the Lower South Bay and San Pablo Bay. This pattern was also observed in past sampling, but the spatial extent of these high concentration areas is now being defined. All samples collected from the Central Bay and South Bay segments were below the water quality objective.

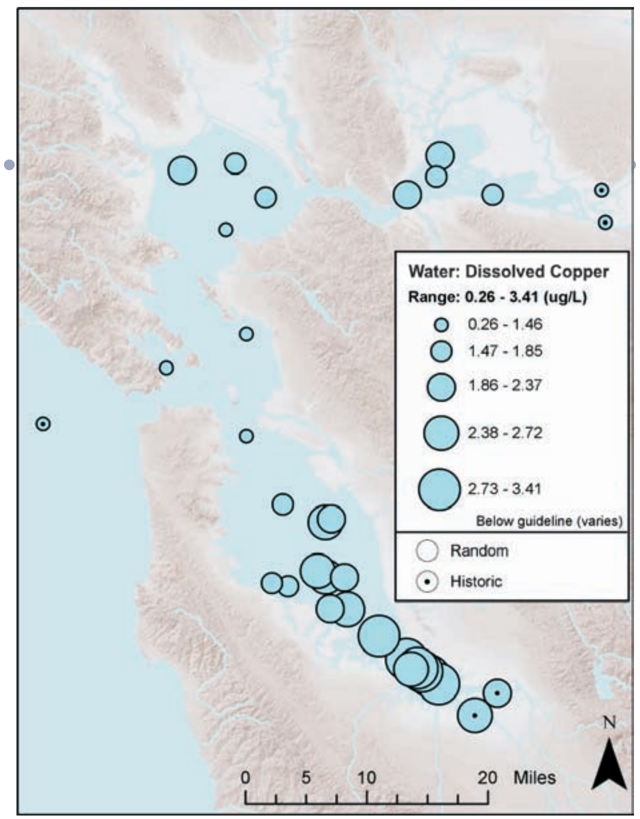
2002

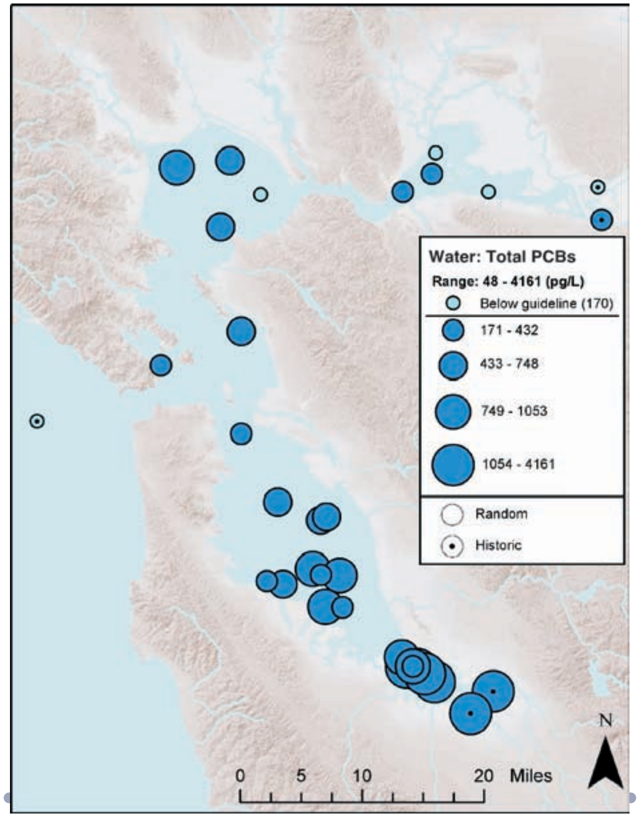
Dissolved Copper in Water

Copper was a major concern in the Estuary in the 1990s, as concentrations were frequently above the water quality objective. A focused evaluation of this issue, with participation by the regulated industries and municipalities, environmental groups, scientists, and the Regional Board, led to:

- new water quality objectives for copper and nickel in the Lower South Bay, south of the Dumbarton Bridge, less stringent but still considered fully protective of the aquatic environment;
- a Water Quality Attainment Strategy featuring pollution prevention and monitoring activities; and
- the removal of copper from the 303(d) list of problem contaminants.

Copper concentrations in Bay waters in 2002 were all below the water quality objective. The Lower South Bay had concentrations that were closest to the guideline.





Total PCBs in Water

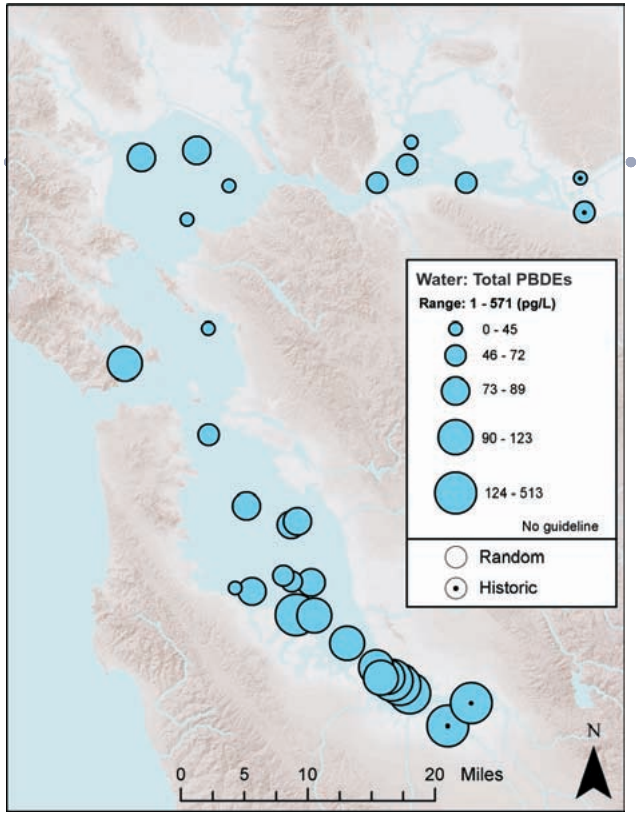
PCB contamination remains one of the greatest water quality concerns in the Estuary, and PCB clean-up is a primary focus of the Regional Water Quality Control Board. Like mercury, PCBs are a problem because they accumulate to high concentrations in some Estuary fish and pose health risks to consumers of those fish. The water quality objective for PCBs in water is designed to prevent unacceptable accumulation of PCBs in humans who consume Estuary fish. **In 2002, the PCB water quality objective was exceeded in 27 of 31 samples (87%) collected from the Estuary.** PCB contamination is greatest in the South Bay; all samples from the South Bay exceeded the objective, with maximum concentrations measured at the southern end of the South Bay. The few samples that did not exceed the objective were from the northern Estuary.

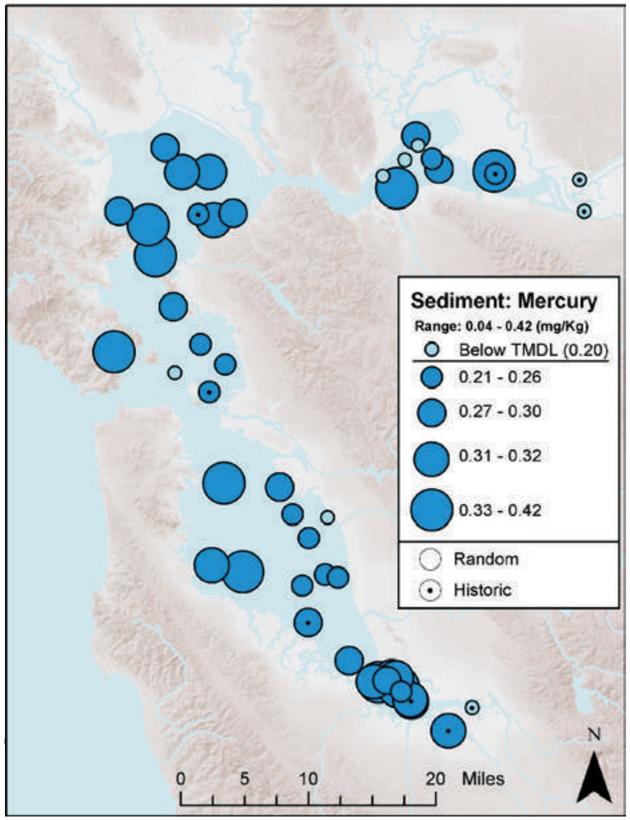
2002

Total PBDEs in Water

PBDEs, a class of flame retardants that were practically unheard of ten years ago, are now found in waters throughout the Estuary. PBDEs are currently on the 303(d) watch list due to increasing concentrations in the Estuary (see page 14) and concerns about their possible effects at the top of the food web. A 2003 California law banned the use of two types of PBDE technical mixtures by 2008.

Tracking the trends in these chemicals is extremely important to determine what effect, if any, the ban will have and if further management actions are necessary. The highest PBDE concentrations in 2002 were measured in waters in the Lower South Bay. Elsewhere, they were present but uniformly low relative to the lower South Bay.

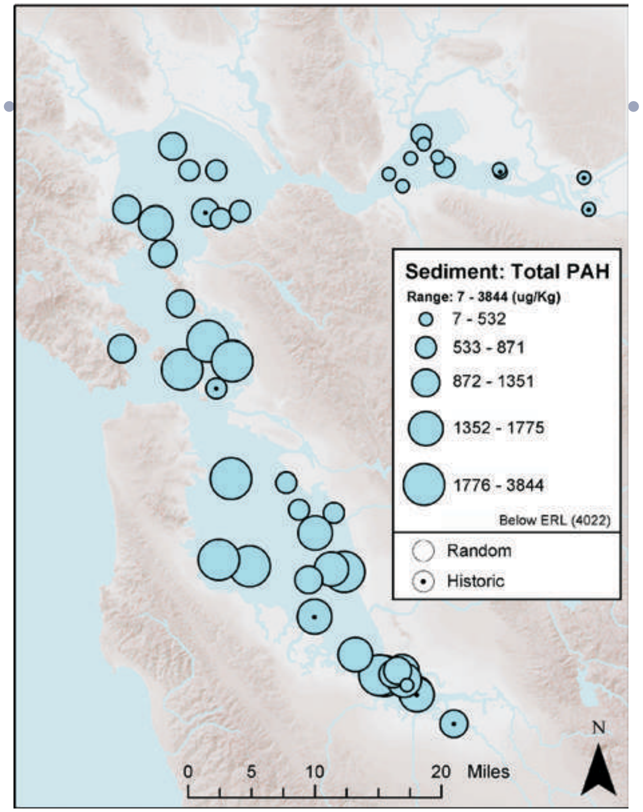




Mercury in Sediment

In 2002, 41 of 49 (84%) of Estuary sediment samples had concentrations higher than the mercury TMDL target of 0.2 mg/kg. Concentrations throughout the Estuary were rather uniform. As expected, low concentrations were measured at sites with more coarse sediment (see related figure on page 10).

2002

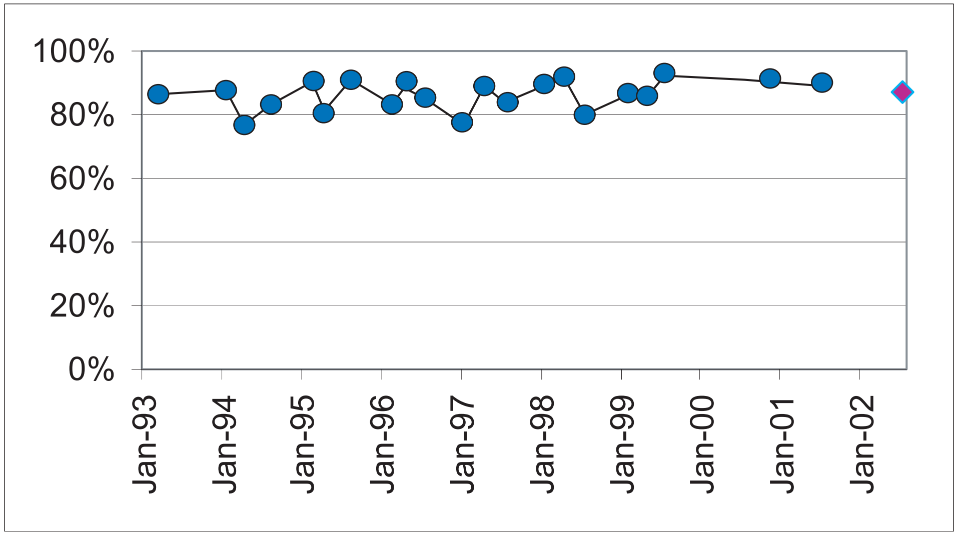


Total PAHs in Sediment

Continuing inputs of polycyclic aromatic hydrocarbons (PAHs) to the Estuary and improved understanding of PAH effects led to their inclusion on the 303(d) watch list. **PAH concentrations in Bay sediments in 2002 were variable,** with the highest concentrations in the South Bay and Central Bay regions. All samples had concentrations below the ERL. Concentrations in the northern Estuary, especially Suisun Bay, were consistently low.

Progress Toward Meeting Guidelines: 1993-2002

Water

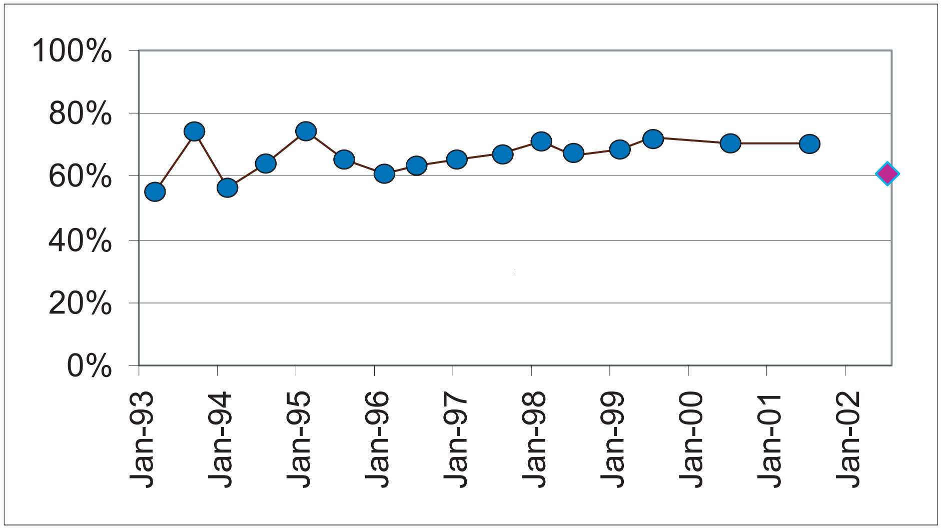


Tracking the overall proportion of measurements that met guidelines

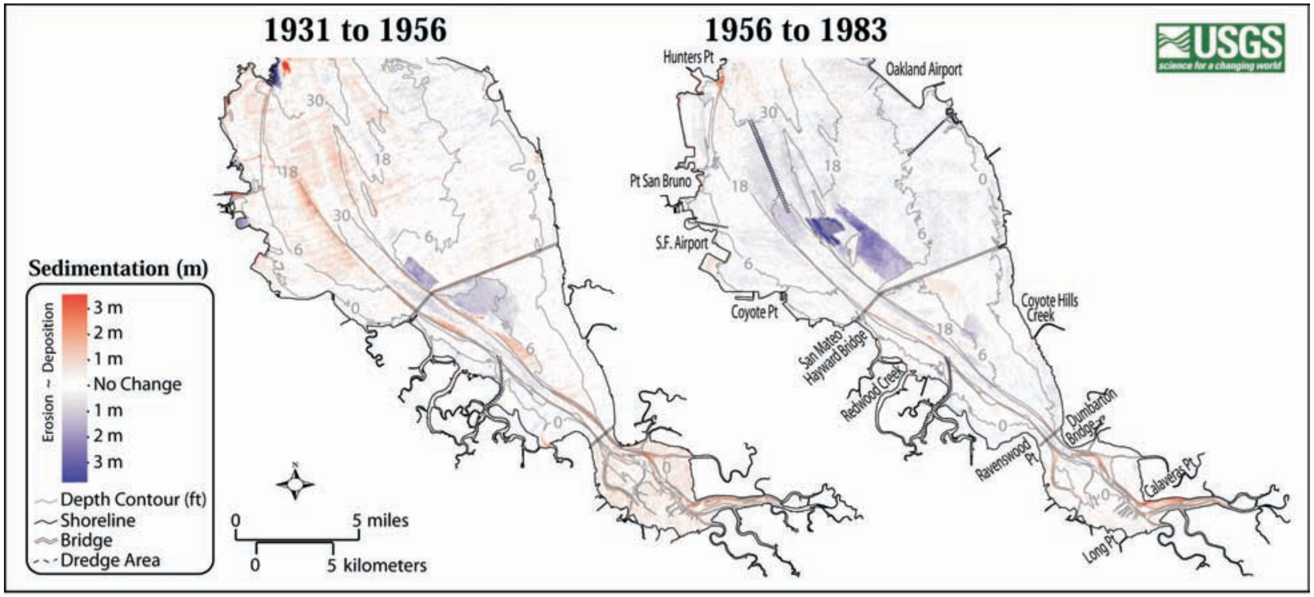
Most contaminant guidelines are being met. A relatively small number of problem contaminants make it rare to find water or sediment in the Estuary that is completely clean. Achieving greater compliance with water and sediment guidelines poses a great challenge, largely because the Estuary is inherently slow to respond to reductions in inputs of persistent contaminants and because many problem contaminants are found throughout the Estuary and its watershed. The 2002 value shown is based on the new sampling design and should not be compared to previous years. **The switch to a new set of sampling locations did not markedly change the overall proportion of measurements that met guidelines.**

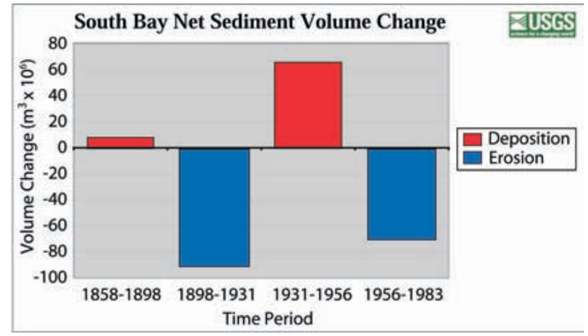
1993-2002

Sediment



A value of 100% would mean every water or sediment sample met guidelines for all contaminants. These charts were created by calculating, for each sampling period, for a consistent set of locations, the proportion of contaminant measurements that met the applicable guideline.





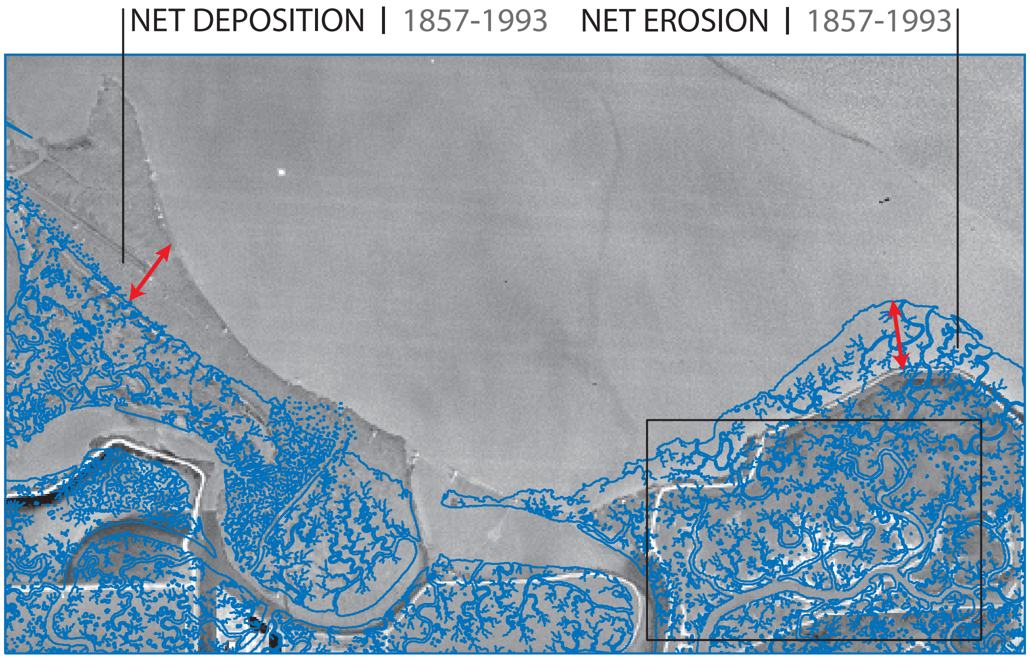
Eroding Sediments in the South Bay

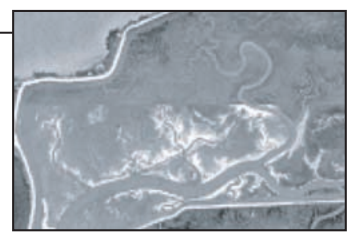
Eroding bottom sediments are a threat to Bay water quality. Sediments on the bottom of the Bay contain an enormous quantity of legacy contaminants such as mercury and PCBs. In typical estuaries, existing sediments are buried as additional layers of sediment are deposited every year. Recent analyses by U.S. Geological Survey (USGS) scientists, however, indicate that the Bay is unusual in this regard: sediment deposits in the Bay are eroding, largely due to a lack of sediment coming in from the watershed. This poses a significant problem with respect to recovery of the Bay from mercury and PCB contamination because the layers of sediment that are being uncovered were originally laid down in earlier decades and are more contaminated. The most recent analysis by USGS examined erosion and deposition in the South Bay (Foxgrover et al., 2004). This type of analysis depends on the availability of bathymetric survey data, which are collected periodically by the National Oceanic and Atmospheric Administration. Bathymetric surveys conducted in 1931, 1956, and 1983 are the basis for the figures shown here. From 1931 to 1956 (a period with rapid urbanization, industrialization, and little wastewater treatment), the South Bay had widespread deposition of relatively contaminated sediment. From 1956 to 1983 (a period including an era of peak contamination in the 1960s and marked improvements with the onset of wastewater treatment in the 1960s and 1970s), the South Bay experienced net erosion. The erosion and deposition varied by location, with erosion dominating in the northern part of South Bay and deposition dominating in southern South Bay. **These 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.** A new bathymetric survey of the Bay is sorely needed to evaluate the latest trends in erosion.

Reference:

Foxgrover, A.C., Higgins, S.A., Ingraca, M.K., Jaffe, B.E., and Smith, R.E., 2004, Deposition, erosion, and bathymetric change in South San Francisco Bay: 1858-1983: U.S. Geological Survey Open-File Report 2004-1192, 25 p. [URL: http://pubs.usgs.gov/of/2004/1192]

Contact: Bruce Jaffe, U.S.G.S., bjaffe@usgs.gov



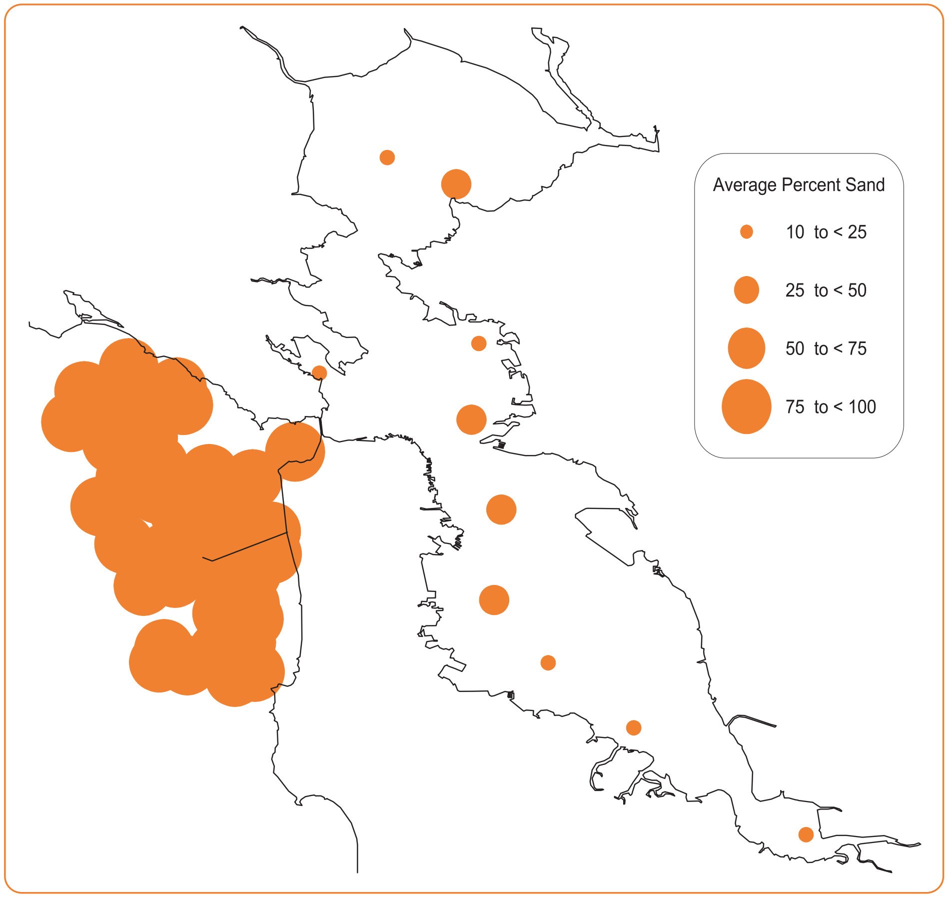


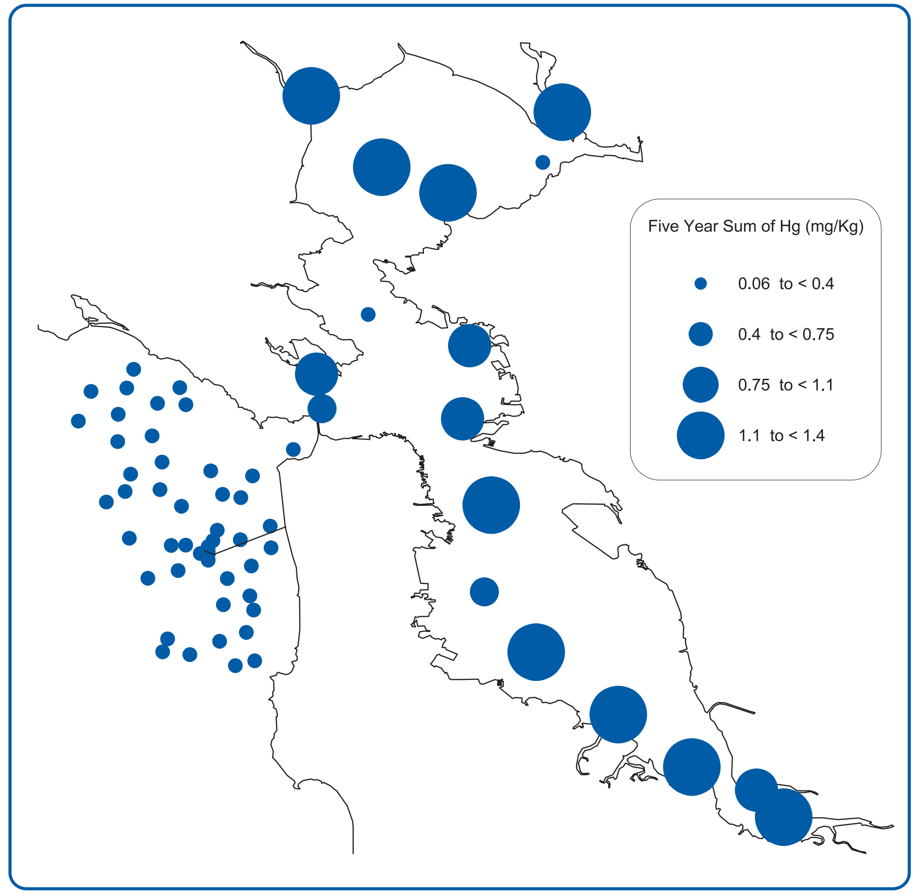
Shoreline changes at Ravenswood Point (above). Inset view (right) shows remnant channel patterns in a diked former marshland.

Erosion and Deposition in Bay Marshes

Like bottom sediments in the Bay, tidal marshes can store large amounts of contaminants. Tidal marshes can also act as sources of contaminants, as contaminated marsh sediment erodes. The Bay's marshes are also a potential source of information about the timing and degree of contaminant input from local watersheds. For example, the extensive marshes adjacent to the mouth of Guadalupe River—now mostly converted to salt ponds—may contain a record of mercury contamination from mining activities at New Almaden. SFEI is studying the historical changes in the South Bay marshes and shoreline in the Historical Tidal Marsh Mapping project, funded by the Santa Clara Valley Water District, City of San Jose, Alameda County Flood Control and Water Conservation District, and others. This work may reveal additional information on Bay contaminant history. Shown is a figure overlaying marshland hydrography circa 1857 on modern marsh and diked baylands at Ravenswood Point. The accuracy of the historical data can be seen by the close correspondence of "ghost channels" to the original mapping. We expect the distribution of contaminants in now-diked marshlands to be related to the pattern of historical tidal channels, which controlled the deposition of Bay sediment. Similar to the bathymetric studies, shoreline change investigation can help gauge patterns of contaminant exposure and release in the Estuary's marshes.

Contact: Robin Grossinger, San Francisco Estuary Institute, robin@sfei.org

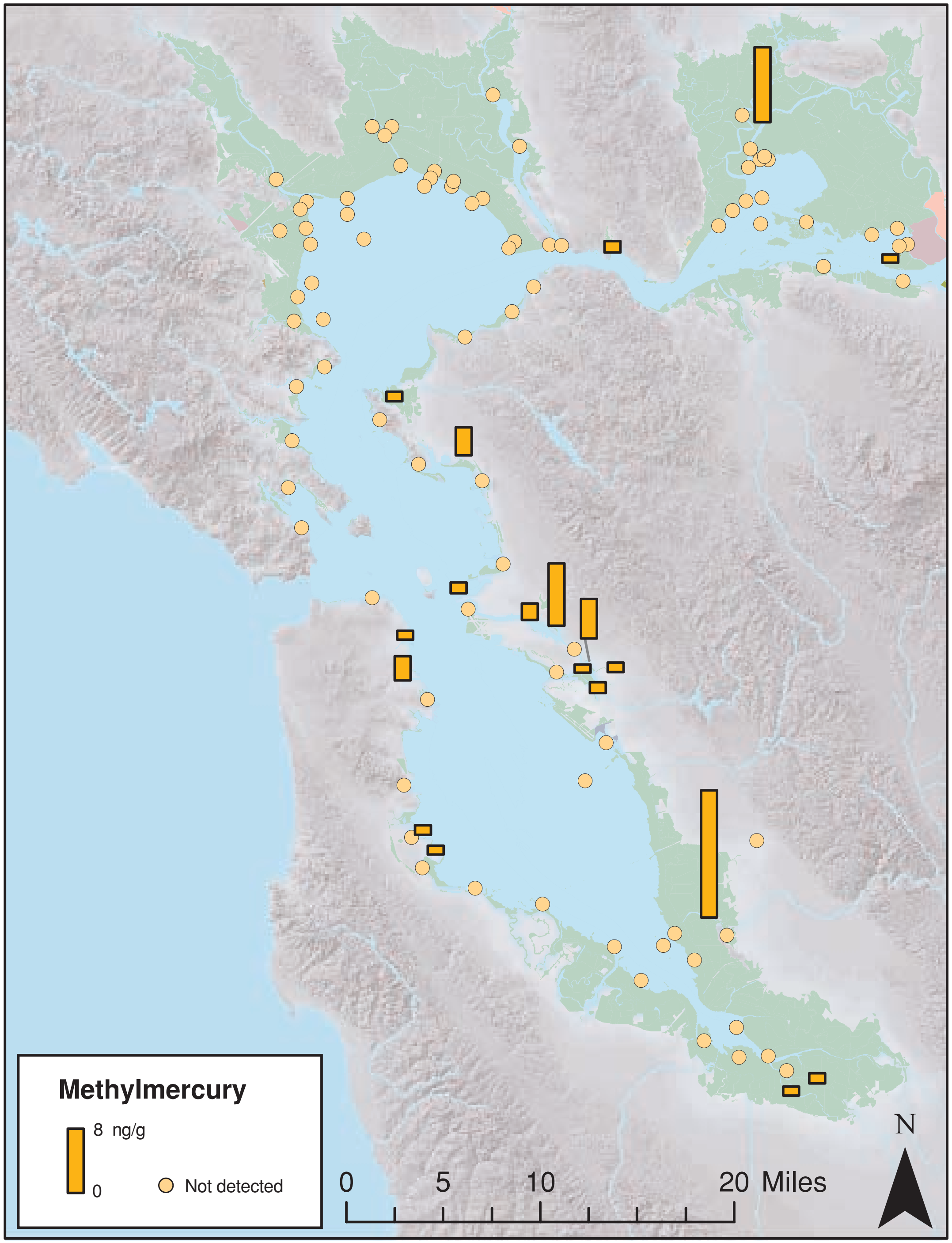




Ocean Monitoring Complements RMP

Sediment contamination in the Bay is greater than in the adjacent ocean. Long term (1997-2001) monitoring data collected by the City and County of San Francisco for their ocean wastewater outfall can be combined with RMP data to provide a view of patterns across the Bay and adjacent ocean. The size of sediment grains has a great influence on contaminant concentrations. Sandy (larger-grained) sediments tend to have lower concentrations than sediments dominated by silt or clay (smaller grains) because they have less overall surface area and fewer binding sites for contaminants. Sampling sites in the Bay include a mixture of sandy and finer-grained sediments (left). Sandy sites in the Bay have lower contaminant concentrations, as illustrated with mercury (right). Outside the Bay, the sediments are uniformly sandy and have low concentrations of mercury and other contaminants. Finer sediments don't settle out near the mouth of the Estuary because the currents are too strong.

Contact: Michael Kellogg, City and County of San Francisco, mkellogg@sfwater.org

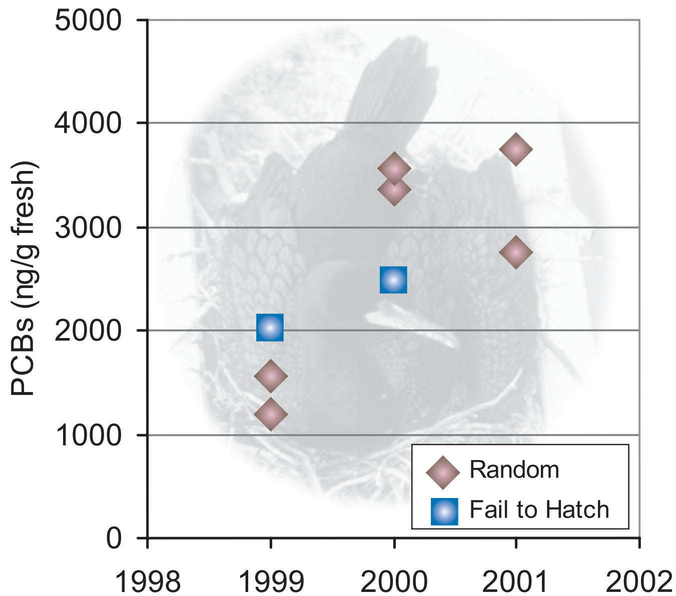


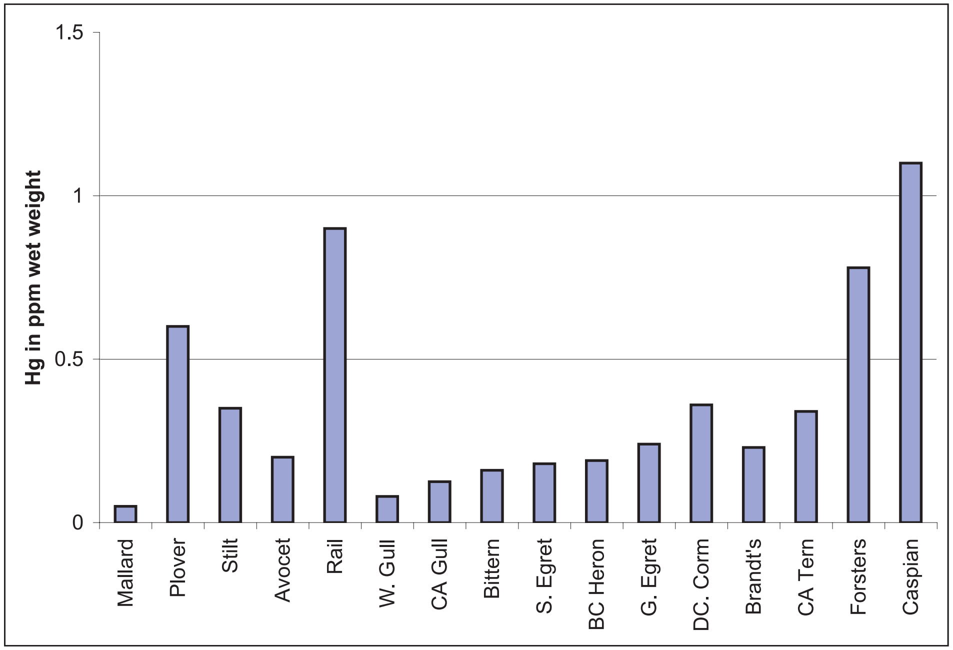
A Snapshot of Methylmercury

Mercury is converted to its most hazardous form, methylmercury, primarily by bacteria in sediment. The rate of this conversion is dependent on a complex combination of factors that can vary tremendously by location and over time. Wetlands are generally sites of relatively high methylmercury production. As part of the CALFED Mercury Project, researchers at Moss Landing Marine Laboratory performed a survey of mercury and methylmercury concentrations in Bay sediment in 1999. Relatively high methylmercury concentrations were observed: one in the lower South Bay, Oakland Harbor, and Suisun Marsh. Since methylmercury production is so variable, this should be considered a snapshot of conditions in the Bay at the time of this survey.

Reference: Heim, W. et al. 2003. Methyl and Total Mercury Spatial and Temporal Trends in Surficial Sediments of the San Francisco Bay-Delta. http://loer.tamug.tamu.edu/calfed/FinalReports.htm

Contacts: Wes Heim, Moss Landing Marine Laboratory, wheim@mlml.calstate.edu
Mark Stephenson, Moss Landing Marine Laboratory, mstephenson@mlml.calstate.edu





PCBs in Cormorant Eggs

PCB concentrations in the Bay food web appear to be just below the threshold for toxic effects on bird embryos. Sampling of double-crested cormorant eggs was conducted by SFEI from 1999-2001. Some PCB concentrations were greater than an apparent threshold for toxic effects in this species (3600 ppb). A maximum of 3800 ppb was observed in a multi-egg sample from 2001. The results from this study indicate that PCB concentrations in San Pablo Bay may be high enough to cause low rates of mortality and deformity in cormorant embryos. Analyzing concentrations of PCBs and many other food web contaminants in cormorant eggs provides, in addition to information on possible toxic effects, an indication of long-term contaminant trends. Concentrations of PCBs and other contaminants were lower in cormorant eggs in 1999 than in 2000 and 2001 – the cause of this variation is unclear. Fail-to-hatch eggs collected in 1999 and 2000 did not have higher concentrations than randomly selected eggs.

Reference: Davis et al. 2003. CISNET Technical Report: Contaminant Accumulation in Eggs of Double-crested Cormorants and Song Sparrows in San Pablo Bay. San Francisco Estuary Institute, Oakland, CA.

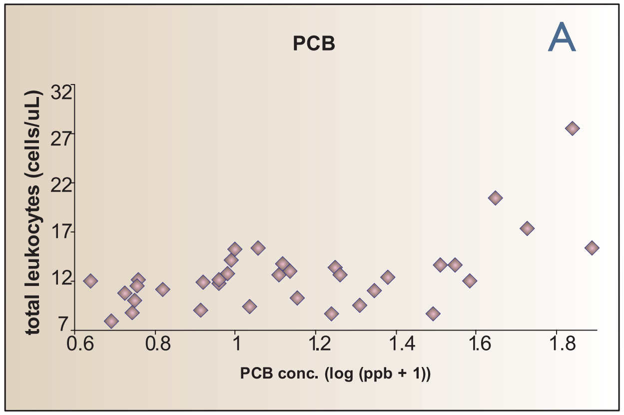
Contact: Jay Davis, San Francisco Estuary Institute, jay@sfei.org

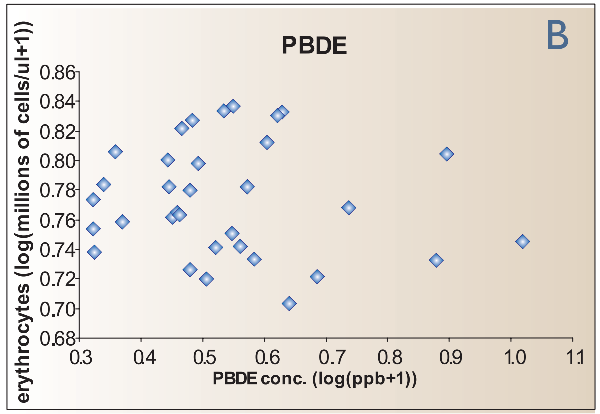
Mercury in Bird Eggs

Mercury concentrations in the Bay food web may be high enough to impair reproduction in the endangered California clapper rail and other bird species. A study in 2000 and 2001 by the U.S. Fish and Wildlife Service (USFWS) examined mercury concentrations in eggs of many species of birds from the Estuary. Studies indicate mercury starts to become toxic to bird embryos at egg concentrations between 0.5 to 0.8 ppm. Eggs of clapper rails, Forster's terns, and Caspian terns exceeded these concentrations. Laboratory studies have shown that clapper rail embryos are relatively sensitive to mercury, leading USFWS to conclude that the concentrations measured in the rail eggs were likely toxic. Rates of reproduction in San Francisco Bay rails are lower than in other locations, and it is quite plausible that mercury toxicity to rail embryos is a significant contributing factor. Forster's and Caspian tern eggs also had concentrations above the toxic level. Embryos and young of these species appear to be at significant risk of mercury toxicity as indicated by levels detected in their eggs and observed reproductive rates.

Reference: Schwarzbach, S. and T. Adelsbach. 2003. CALFED Bay-Delta Mercury Project – Subtask 3B: Field Assessment of avian mercury exposure in the Bay-Delta ecosystem.

Contacts: Steve Schwarzbach, U.S. Geological Survey, steven_schwarzbach@usgs.gov
Terry Adelsbach, U.S. Fish and Wildlife Service, Terry_Adelsbach@fws.gov





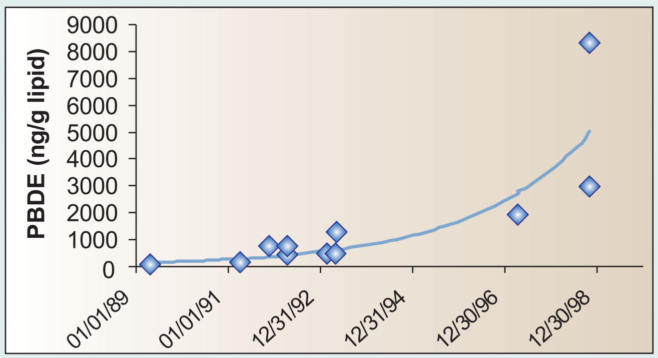
Links to Seal Health

Contaminant concentrations in the blood of Bay harbor seals are high enough to warrant concern for effects on their reproduction and immune systems. PCBs and other priority contaminants reach their highest concentrations at the top of the Bay food web, so fish-eating wildlife such as seals, terns, and cormorants face the highest exposures and greatest health risks. The Bay's harbor seal population has suffered from habitat loss and degradation, including decades of environmental contamination. To explore the possibility of contaminant-induced health alterations in this population, UC Davis researchers measured blood levels of PCBs, DDE, and PBDEs in Bay seals, examined relationships between contaminant exposure and several key natural blood parameters, and compared PCB levels in the present study with levels determined in Bay seals a decade ago. PCBs in harbor seal blood declined slightly during the past decade, but remain high enough that reproductive and immunological effects are possible. A positive association was found between leukocyte counts and PBDEs, PCBs, and DDE in seals (Figure A), and a negative relationship between PBDEs and red blood cell count (Figure B). Although not necessarily detrimental, these responses serve as sentinel indications of contaminant-induced alterations in Bay seals, which in individuals with relatively high contaminant burdens could include increased rates of infection and anemia.

Reference: Neale, Jennifer C. C. 2004. Persistent organic contaminants and contaminant-induced immune alterations in the harbor seal, Phoca vitulina. Ph. D. Dissertation, U.C. Davis, Davis, California.

Contact: Jennifer Neale, University of California Davis, jcneale@ucdavis.edu

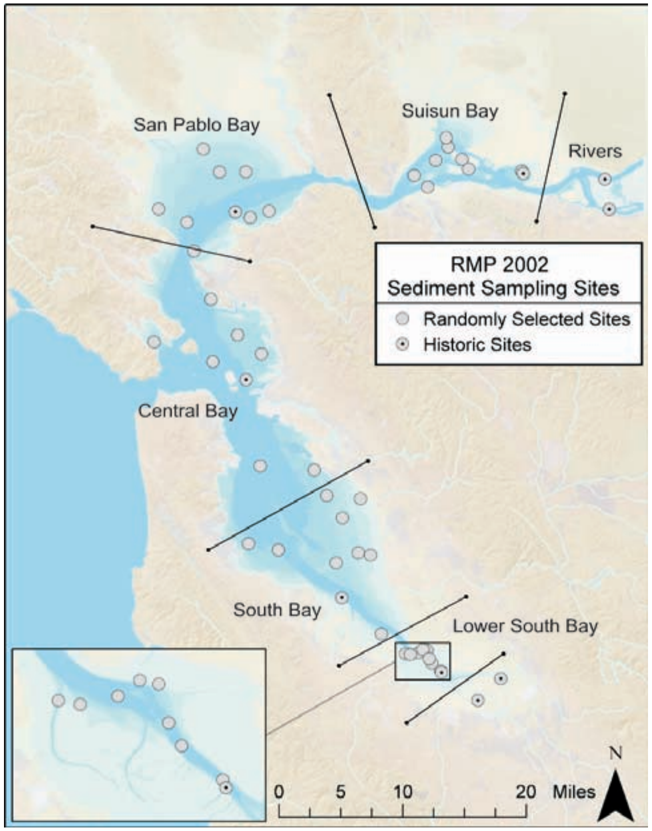
PBDEs in Seal Blubber

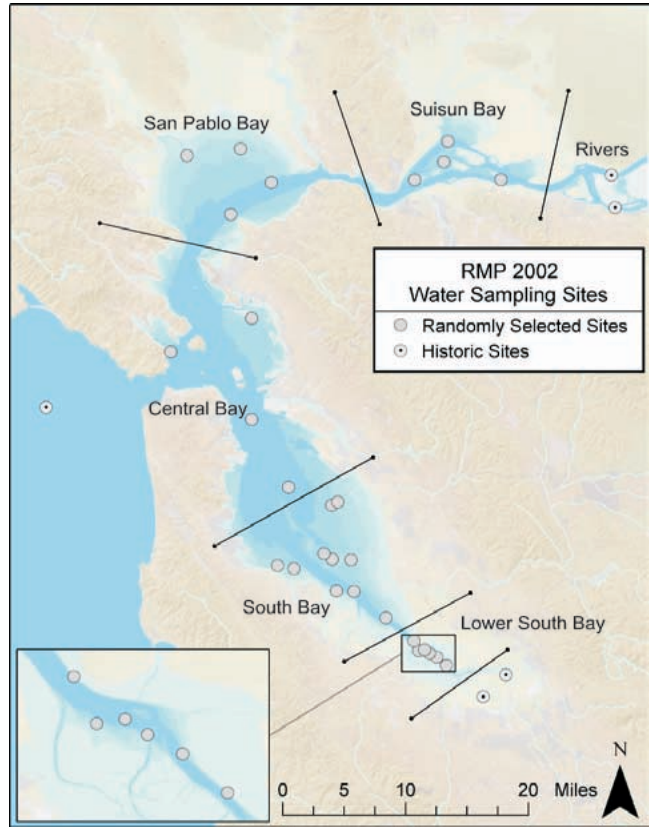


PBDE concentrations appear to be rising rapidly in the Bay, raising concern that another legacy contamination problem is developing. Virtually undetectable in samples during the 1980s, over the course of the past 10 years PBDEs have become common in the water, sediments, and food web of the Bay, and concentrations in some samples rival those of other major organic contaminants such as PCBs and DDT. Perhaps the best record of PBDEs over time is from the analysis of harbor seal blubber by the Hazardous Materials Laboratory of the California Department of Toxic Substances Control. These data illustrate the rapid increase in the Bay food web in the 1990s. In the past few years, significant concentrations of PBDEs have also been measured in terns, cormorants, and fish from the Bay. Furthermore, studies of PBDE concentrations in human blood, fat, and breast milk from the Bay Area have found some of the highest concentrations measured in the world. **Concerns about PBDEs led to legislation in 2003 that will ban two PBDE formulations ("penta" and "octa") in California starting in 2008.** Another major formulation ("deca"), however, has not been banned. The RMP now measures PBDEs in water, sediment, bivalves, fish, and bird eggs, and is establishing a database that can be used to track the success of the PBDE ban and other management efforts.

Reference: She, J.; Petreas, M.; Winkler, J.; Visita, P.; McKinney, M., and Kopec, D. PBDEs in the San Francisco Bay Area: measurements in harbor seal blubber and human breast adipose tissue. Chemosphere. 2002 Feb; 46(5):697-707.

Contacts: Seal work - Jianwen She, California Department of Toxic Substances Control, jshe@dtsc.ca.gov
PBDEs in general - Kim Hooper, California Department of Toxic Substances Control, khooper@dtsc.ca.gov
Tom McDonald, California Office of Environmental Health Hazard Assessment, TMCDONAL@oehha.ca.gov





Water and Sediment Monitoring locations for 2002

Most RMP monitoring locations are now chosen at random. In this scheme, the Estuary is divided into five regions and random locations are chosen in each of the regions. For sediment, eight random locations are chosen in each region each year. Some of these locations will be revisited in future years, to provide a consistent basis for measuring change over time. For water, four to ten random locations are chosen in each region each year. Choosing random rather than fixed locations means the results are representative of each region, rather than just particular locations within each region. A few historical fixed-site stations remain, for tracking long-term trends at those locations. Each site is sampled once each year, during the dry season.

recent developments in water quality
management in the Estuary

management update

PG. 16

PG. 23

PG. 27

Adaptive Implementation of TMDLs – The Mercury Example

Thomas E. Mumley (TEM@rb2.swrcb.ca.gov) and Richard Looker,
San Francisco Bay Regional Water Quality Control Board

Key Points

- ***Adaptive implementation will be a key to the success of Total Maximum Daily Loads (TMDLs) to improve water quality in the Bay***
- ***Application of the scientific method is an integral part of adaptive implementation***
- ***The mercury TMDL for the Bay is a groundbreaking example of how adaptive implementation is being accomplished in the TMDL process***

The Regional Monitoring Program (RMP) has opened the door of opportunity to tackle San Francisco Bay's water quality challenges. The RMP provides valuable data and insight to improve our understanding of complex pollutant fate, transport, and effects processes. Meanwhile, we are challenged with TMDL requirements that call for actions to attain water quality standards. These requirements and underlying public interest reflect the desire and will to repair impairment of the San Francisco Bay-Delta Estuary. Adaptive implementation provides the way. The San Francisco Bay Mercury TMDL is the example.

Adaptive Implementation is the Way

A National Research Council (NRC) review of the TMDL program strongly suggested that adaptive implementation is the key to improving the application of science in the TMDL program.

"Adaptive implementation is, in fact, the application of the scientific method to decision making. It is a process of taking actions of limited scope commensurate with available data and information to continuously improve our understanding of the problem and its solutions, while at the same time making progress toward attaining water quality standards" (NRC 2001).

Concerns with uncertainties and risks associated with potentially costly actions are usually behind the call for "sound science." However, calls to make policy decisions based on "the science," or calls to wait until "the science is complete" reflect a misunderstanding of science. Science is the process of continuing inquiry, and the ultimate way to improve the scientific foundation of the TMDL program is to incorporate the *scientific method*, not simply the results from analysis of particular data sets or models, into TMDL planning. The scientific method starts with limited data and information from which a tentatively held hypothesis about cause and effect is formed. The hypothesis is tested, and new understanding and new hypotheses can be stated and tested. Adaptive implementation simultaneously makes progress toward achieving water quality standards while relying on monitoring and experimentation to reduce uncertainty (NRC 2001).

For a TMDL, applying the scientific method involves:

1. taking immediate actions commensurate with available information;
2. defining and implementing a program for refining the information on which the immediate actions and possible additional actions are based;
3. evaluating additional actions that show promise, with consideration of recognition of emerging and innovated strategies; and
4. a process for adding, modifying, or eliminating actions as necessary based on new information.

Taking actions that have a high degree of certainty associated with their water quality outcome and technical and economic feasibility allows the Bay to make progress toward attaining water quality standards while we simultaneously improve our understanding of the ecosystem through research and by observing how it responds to the actions.

The draft state TMDL development and implementation guidance embraces and builds upon the adaptive implementation approach recommended by the NRC (SWRCB 2003). The guidance recommends consideration of implementation issues as soon as possible in the process. With limited resources it is important to consider and weigh implementation opportunities and constraints along with impairment and source assessments.

The success of implementation, particularly adaptive implementation, is dependent on appropriate monitoring and tracking. Use of multiple monitoring and tracking techniques can help evaluate progress on a continuous basis, from the procurement of funding resources, to the initiation of management actions until water quality standards are achieved. Multiple levels of tracking can diagnose problems and guide actions in an adaptive implementation approach. The monitoring and surveillance techniques used will depend on numerous factors including the type, size, location, and sources of impairment, management practices (MPs), funding availability for management, time constraint or requirements, and monitoring resources. A schematic of implementation monitoring and surveillance and the adaptive implementation approach is shown in Figure 1. This schematic describes the relationships between various levels of tracking, the multiple opportunities for evaluation of progress, and the potential for adjustment.

TMDL Process

The TMDL process involves multiple decisions.

- What is the problem; what water quality standard is not attained?
- What is an appropriate numeric target (or targets) that reflects attainment of water quality standards (solution of the problem)?
- What are sources of concern and their relative significance?
- What are relevant and important pollutant fate, transport, and effect processes that link sources to the impairment?
- What reduction in pollutant loading and other actions are necessary to attain numeric targets?

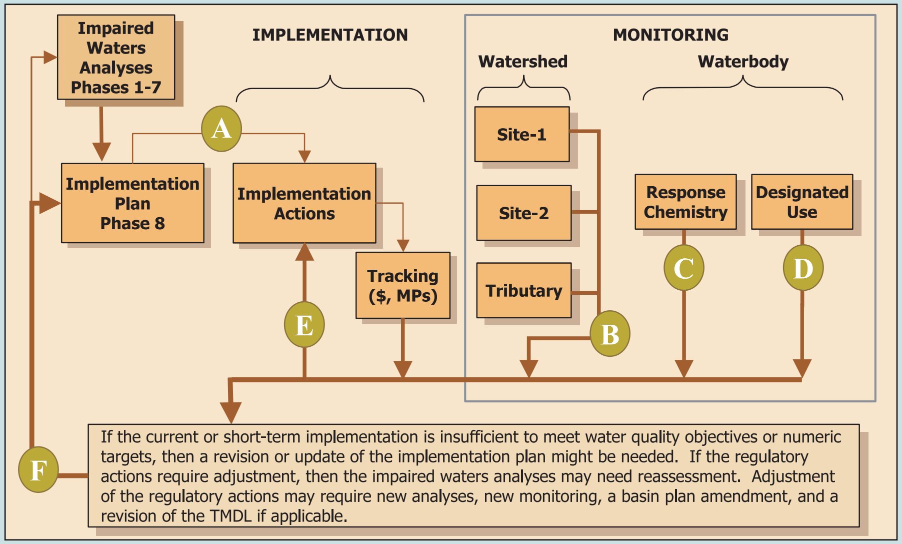


Figure 1. Monitoring and Adaptive Implementation Approach. The adaptive implementation approach to TMDLs—taking action now based on available data, while preparing to revise action when more is known—is key to successfully and efficiently ending the impairment of the Estuary. This flowchart illustrates the details of the approach.

A. Regulatory actions are identified and implemented through appropriate local, state, and federal authorities. Management activities can include nonpoint source management measures, permits, urban runoff management, compliance, and abatement activities. Financial or stakeholder resources are required to put management plans in place. Typically, procurement of these resources must be in place before the management activities can proceed.

B. Response can be most easily measured closest to the management action. Selected monitoring locations can be used to directly evaluate the localized benefit of various management practices.

C. Chemical/biological response to management can be measured in the impaired waterbody to evaluate improvement or trends relative to water quality objectives. As the distance from management activities and size of the watershed increase, the direct immediate benefit of management is harder to discern and depending on the pollutant there may be a considerable delay between management actions and measurable receiving water response. For example, phosphorus load reductions in the watershed may not immediately result in improved lake quality based on measures of summer chlorophyll-a.

D. Direct measurement of the beneficial use impairment can identify positive trends and desirable response. For example, if the lake is impaired for aquatic life due to eutrophication, direct measure of fish population and recreational use may identify an improvement in use support.

E. Monitoring at multiple scales (B, C, D) can also lead to a re-evaluation of the rate of implementation (are practices being installed?), the type of practices used (some practices might be demonstrated as highly effective), or the need for maintenance of existing management practices (e.g., periodic clean-out of stormwater ponds). In an adaptive implementation approach, initial short- term actions may not result in meeting standards. Limited or pilot-scale monitoring can be used to test techniques and support revision or expansion of implementation techniques as appropriate. This re-evaluation may indicate a readjustment of the implementation plan is necessary within the context of the identified regulatory actions.

F. If current actions are insufficient, the implementation plan could be revised or updated based on information gathered during monitoring and tracking (A-E). If adjustment of the implementation plan is insufficient, a reassessment of the regulatory actions and potentially the associated project analyses is indicated. This update could result in new data collection, project analyses, revised regulatory actions, additional basin plan amendments and/or re-submittal of the TMDL if applicable.

The Clean Water Act and TMDLs

The Clean Water Act recognizes that every body of water provides benefits that are valuable and worth protecting. The beneficial uses of a particular water body might include, for example, catching and eating fish, swimming, and drinking. Such uses require good water quality. Traditional management of water quality centers on maintaining standards for the cleanliness of wastewater. In some places this approach successfully protects the uses of a water body, but in others it does not. Water bodies that continue to lack the water quality necessary for supporting their designated uses are considered "impaired waters." Each state is required to develop a list of impaired waters and the contaminants that impair them (known as the "303(d) list," after the corresponding section of the Clean Water Act). Under the Clean Water Act, cleanup plans known as Total Maximum Daily Loads (TMDLs) must be developed for all impaired waters. The TMDL process takes a more comprehensive view of water quality by identifying all contaminant inputs to the water body, determining the total input the water body can handle, and designating particular inputs that need reduction.

- What is the optimum scheme to allocate load reductions and actions to sources and responsible parties?
- What are appropriate mechanisms and associated regulatory actions to ensure implementation of actions and to track and evaluate them?

These decisions are interconnected and are associated with required elements of the TMDL process. Figure 2 illustrates the TMDL process and its key elements. The arrows between the boxes indicate the interconnection of the elements. The outer dashed box implies that all the elements are interconnected, the process is not linear, and the process may be conducted in an iterative and adaptive manner.

It is important to remember that a TMDL is not an end in itself; it is a means to an end, which is to solve a water quality problem. A complete TMDL must account for each of the process elements. However, the level of attention and detail applied to each element requires weighing its significance and relevance to solving the problem. The main challenge is to identify and implement actions that will solve the problem. All the other elements are associated with establishing a scientific basis for actions and considering the regulatory and economic and other non-technical constraints. So the TMDL process is an adaptive implementation process that involves balancing application of resources and knowledge towards multiple interconnected decisions leading to actions that will attain water quality standards.

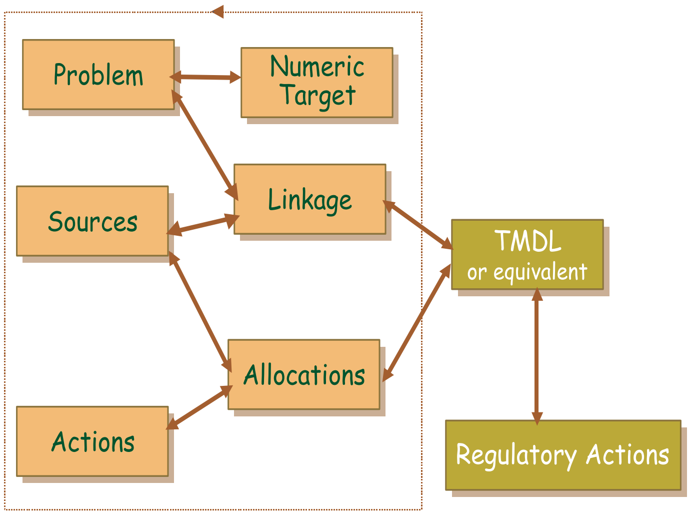


Figure 2. TMDL Process Elements. The TMDL Process is being followed to address water quality problems that persist despite past efforts. A TMDL is a clean-up plan that looks at the big picture—all the sources to the problem—calculates the source reductions needed to restore water quality, and determines where to take action.

The San Francisco Bay Mercury TMDL

The San Francisco Bay Mercury TMDL, although a work in progress, illustrates the application of adaptive implementation and the scientific method to decision making. Certainly the TMDL process raises very challenging questions when applied to excess mercury in a complex estuary like the San Francisco Bay-Delta. We are faced with not only physical and biological science challenges, but also social science challenges associated with decision-making. The decision making challenge requires balancing the need to simplify the science appropriately to allow broad participation of informed decision makers with the need to retain enough scientific complexity to ensure the decisions will lead to actions that will solve the problem. Fortunately, data and knowledge generated by the RMP and the collaborative efforts of the Clean Estuary Partnership allow application of the scientific method and adaptive implementation to the mercury TMDL.

The mercury problem is that methylmercury accumulates in fish to levels that pose risk to humans and wildlife that consume them. The San Francisco Bay Mercury TMDL Project Report (SFBRWQCB 2003) and the proposed Basin Plan Amendment and supporting staff report that will establish the TMDL and implementation plan (SFBRWQCB 2004) describe all the TMDL elements and associated analyses and rationale. In the spirit of simplicity, the key TMDL elements are described below.

Numeric Targets

A 0.2 ppm (wet weight) fish tissue target is intended to protect human consumers. A 0.5 ppm (wet weight) bird egg target is intended to protect wildlife consumers. A 0.2 ppm (dry weight) sediment target is intended to define the assimilative capacity of the system and provide a linkage between mercury in the ecosystem and sources.

Sources and Allocations

Key sources of mercury, current annual loading of mercury from each source, and proposed load allocations are illustrated in Table 1 and Figure 3.

Mercury TMDL Adaptive Implementation Plan

The numeric targets and allocations are the TMDL tuning knobs that reflect our state of knowledge to define the problem quantitatively and to direct its solution. The actual solution is reflected in a plan of action within the context of adaptive implementation. We certainly realize the shortcomings of a mercury TMDL based solely on management of total mercury. Consequently, the implementation strategy calls for both short term and long term actions to improve our understanding and management of methylmercury. We are also constrained by limited understanding of sediment transport and its significant role in the transport and fate of mercury and other sediment-bound pollutants.

The proposed Mercury TMDL implementation plan has four principal objectives:

1. to reduce existing and future controllable discharges of mercury to San Francisco Bay;
2. to reduce the amount of mercury transformed to methylmercury;
3. to improve our technical understanding of mercury in San Francisco Bay and source control effectiveness, and then use this information to guide future decisions; and
4. water quality programs are most efficient when they address more than one pollutant, therefore, to the extent possible, the plan seeks to encourage implementation actions that reduce loads of multiple pollutants and not mercury alone.

Table 1 . Mercury Sources, Current Load, and Proposed Load Allocation. This table and the accompanying chart details the current sources of mercury to the Estuary, and how loads must be reduced (the allocation) in order to restore water quality.

SOURCE	2003 Mercury Load (kg/yr)	Allocation (kg/yr)
Bed Erosion	460	220
Central Valley Watershed	440	330
Urban Storm Water Runoff	160	82
Guadalupe River Watershed (mining legacy)[1]	92	2
Atmospheric Deposition	27	27
Non-Urban Storm Water Runoff	25	25
Wastewater (municipal and industrial)	19	19
Dredging and Disposal[2]		≤ ambient concentration
TOTAL	1,223	705

1 This load does not account for mercury captured in sediment removal programs conducted in the watershed.
2 Sediment dredging and disposal often moves mercury-containing sediment from one part of the bay to another. The dredged sediment mercury concentration generally reflects ambient conditions in San Francisco Bay sediment. This allocation is concentration-based. The mercury concentration of dredged material disposed in the bay must be at or below the baywide ambient mercury concentration. This allocation will ensure that this source category continues to represent a net loss of mercury.

Clearly, attainment of these objectives and ultimately water quality standards requires a comprehensive plan of action and significant time and resources. Therein lies the need for adaptive implementation and the power and benefit of application of the scientific method towards advancing knowledge and resulting management decisions. The proposed adaptive implementation plan for the San Francisco Bay Mercury TMDL has the following features.

1. **Immediate actions** commensurate with available data and information. These are summarized in Table 2. Relative to Figure 1, these actions will be implemented via regulatory actions (Step A) specific to each source, and appropriate tracking and evaluation mechanisms (type B monitoring) will be established for each source.

2. **Monitoring** to assess effectiveness of immediate actions and progress toward TMDL targets. Here again we are fortunate to have the RMP and its ongoing water, sediment, and fish tissue monitoring.

*“We are faced with not only physical and biological science challenges, but also **social** science challenges associated with decision-making.”*

Relative to Figure 1, fish tissue and bird egg monitoring are examples of type D (beneficial use). Water and sediment monitoring are examples of type C (response chemistry).

3. Statement of **management questions,** associated scientific hypotheses, and a framework and schedule for addressing the management questions. Relevant management questions are listed in Table 3. The Clean Estuary Partnership is currently developing a short and long term plan to seek answers to these questions. Implementation mechanisms include RMP special studies, Prop 13 and 50 grant projects, the California Bay-Delta Authority, and discharger studies.

4. A **process for reviewing and incorporating information** obtained through the studies and monitoring into the TMDL. The process will involve two scales of adaptation. The first involves modification of the adaptive implementation plan resulting in expanding, adding to, and/or eliminating immediate actions and modifications to the monitoring and special studies plan. This corresponds to step E in Figure 1. The second involves changes to the TMDL numeric targets and/or allocations and possibly the water quality standards.

A closer look at the urban stormwater runoff allocation and implementation actions further illustrates the adaptive implementation approach. First, we realize that there is considerable uncertainty in our estimates of current loading due to technical and economic constraints. However, we do know that levels of mercury in sediments discharged via urban runoff are greater than the sediment targets, and the uncertainty in magnitude of the elevated levels is not critical at this time. The allocation is based on attainment of the sediment target in all urban runoff discharges, and is driven by the regulatory driver that allocations must be set at levels that will result in attainment of numeric targets and ultimately water quality standards. We acknowledge that management of methylmercury is key to the protection of human and wildlife consumers, and allocations designed to just control total mercury will not solve the problem without commensurate management of methylation processes. Nevertheless, refinements of the allocation are not critical at this time if we apply adaptive implementation.

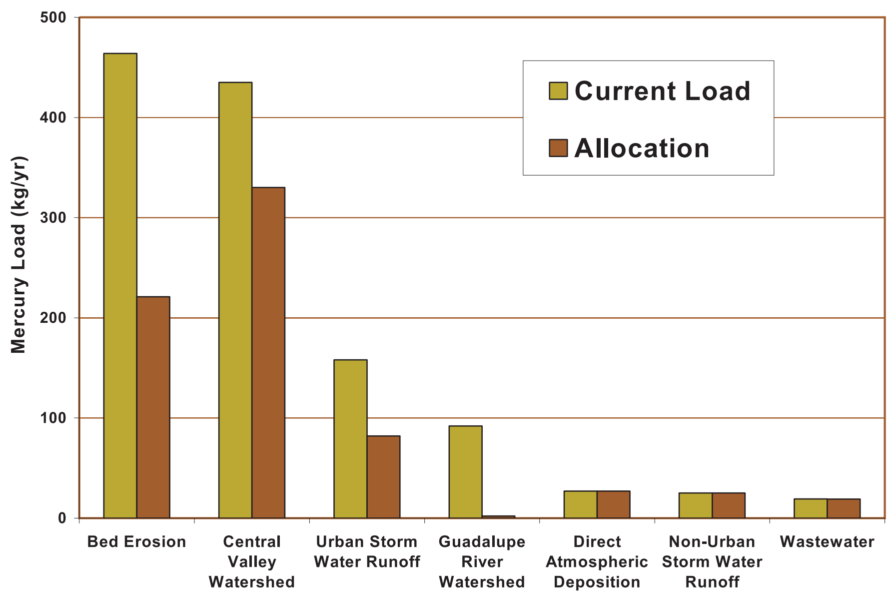
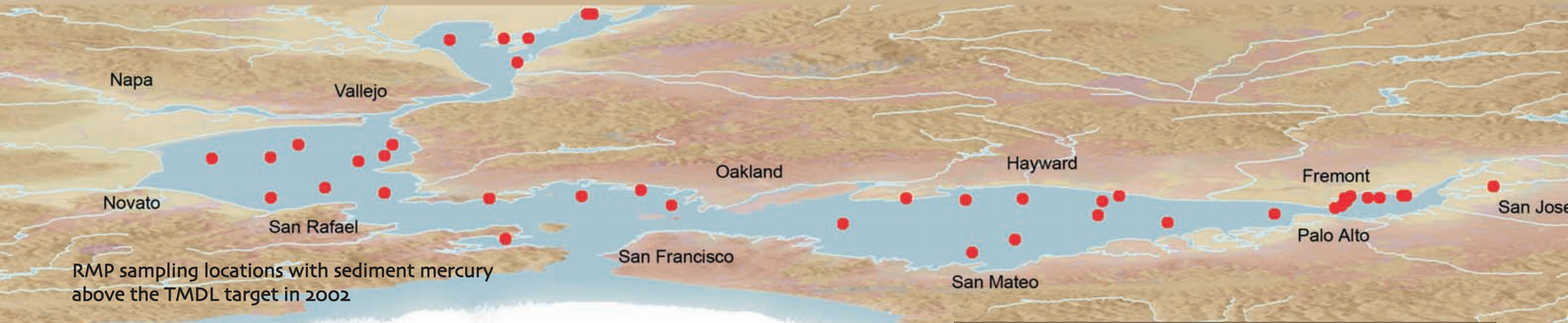


Figure 3. Current Loads and Proposed Load Allocations

The adaptive implementation scheme for urban runoff involves implementing the allocation in phases using an interim ten-year mercury-loading milestone for this source category of 120 kg/yr, which is halfway between the current load and the allocation. Rather than requiring demonstration of load reduction, the plan will recognize load avoided by implementing pollution prevention and control programs as credit toward attaining the TMDL allocation.

Many communities have already made a lot of progress in minimizing the use of mercury-containing products, replacing mercury thermometers, and recycling fluorescent light ballast. Also, other urban runoff management practices prevent erosion and runoff of mercury-laden soils or intercept or remove sediments and associated mercury in urban runoff.

Immediate implementation actions will involve identification and evaluation of these current actions and quantification of their benefit in terms of loads avoided and associated costs. This in turn would lead to benchmarking successful programs and expanding, adding to, and/or eliminating current practices and actions. Meanwhile we seek improved understanding of the methylation process and will apply such knowledge to the evaluation of actions. Ultimately we can expect to reach a point of diminishing returns associated with technical



RMP sampling locations with sediment mercury above the TMDL target in 2002

and economic constraints. At this point we will have realized implementation of actions to control mercury in urban runoff and methylmercury to the maximum extent practicable. At this time, we cannot forecast whether this maximum extent practicable load avoidance/reduction will attain the allocation. Obviously, if it doesn't, we can't require the impossible, and we will have to reconsider the allocations and possibly the other TMDL elements. This is why adaptive implementation is the way to proceed.

Timeframe and Other Considerations

Implementation of the TMDL will take time and resources. Furthermore, the adaptive implementation approach calls for an iterative process of taking actions, evaluating their benefit while improving our understanding of the system, revising decisions, and ultimately solving the problem. As such, we envision ten-year milestones with five-year checkpoints to review progress and to evaluate findings from early implementation actions, monitoring, special studies, and relevant scientific literature. Five years correspond to NPDES permit terms, and thus, provides opportunity to revise permit requirements to reflect adaptive implementation progress.

The five-year reviews will be coordinated through the Water Board's Basin Planning Program, and any modifications to the TMDL elements will be incorporated into the Basin Plan. At a minimum, the following focusing questions will be used to conduct the reviews. Additional focusing questions will be developed in collaboration with stakeholders prior to each review.

1. Is the Bay progressing toward TMDL targets as expected? If it is unclear whether there is progress, how should monitoring efforts be modified to improve our ability to detect trends? If there has not been adequate progress, how might the implementation actions or allocations be modified?
2. What are the loads for the various source categories, how have these loads changed over time, and how might source control measures be modified to improve load reduction?
3. Is there new, reliable, and widely accepted scientific information that suggests modifications to targets, load allocations, or implementation actions are appropriate? If so, how should the TMDL elements be modified?

Source	Immediate Actions	Potential Long Term Actions
Central Valley	Identify sources and implement actions via development and implementation of Delta and Central Valley Tributary mercury TMDLs	Implement Delta and Central Valley Tributary mercury TMDLs; implement methylmercury management actions
Urban Stormwater Runoff	Implement pollution prevention and control programs and determine loads avoided with interim load reduction of 40 kg/yr within ten years; evaluate mercury bioavailability of discharge and feasibility of minimizing mercury uptake into the food web	Expand implementation of effective immediate actions and/or implement additional actions to further reduce loads iteratively leading to attainment of allocation; demonstrate control of mercury in discharges to the maximum extent practicable; implement methylmercury management actions
Guadalupe River Watershed (Mining Legacy)	Identify sources and implement actions via development and implementation of TMDL for Mercury in the Guadalupe River Watershed	Implement Guadalupe River Watershed mercury TMDL; implement methylmercury management actions
Atmospheric Deposition	Support and track national efforts	Support and track national efforts and implement appropriate local actions
Municipal Wastewater	Implement pollution prevention programs to assure no net increase in load; evaluate mercury bioavailability of discharge and feasibility of minimizing mercury uptake into the food web	Expand pollution prevention actions; expand reclamation and reuse; implement mass offset actions; implement methylmercury management actions
Industrial Wastewater	Implement pollution prevention programs to assure no net increase in load, evaluate mercury bioavailability of discharge and feasibility of minimizing mercury uptake into the food web, evaluate air emissions	Expand pollution prevention actions; expand reclamation and reuse; implement mass offset actions; implement methylmercury management actions
Dredging and Disposal	Implement Long Term Management Strategy for the Disposal of Dredged Material (LTMS) and investigate effect of dredging activities on mercury uptake into bay food web	Implement LTMS; implement methylmercury management actions
Other	Identify and quantify sources, implement mercury and methylmercury control measures as appropriate	Identify and quantify sources, implement mercury and methylmercury control measures as appropriate

Table 2. Immediate and Potential Long-Term Implementation Actions. A TMDL recognizes the need for action, and identifies both immediate actions based on current knowledge, and potential long-term action based on advances in understanding.

We are fortunate to have the Regional Monitoring Program and the resulting benefits of continuing improvement of our understanding of the complex San Francisco Bay-Delta Estuary and tracking of progress. We are also fortunate to have the Clean Estuary Partnership that provides a forum for collaboration and joint fact-finding. Together these forums will play a critical role in the adaptive implementation and review process.

Meanwhile, efforts are underway. We have been successful in obtaining Prop 13 grant funding for two key projects. One funded at $1.3 million is designed to evaluate the effectiveness and the pollutant avoidance/removal benefit of urban runoff management practices. Another project funded at $1.2 million is designed to evaluate mercury methylation in wetlands and options for managing wetlands so as to minimize methylation. We have begun development of a TMDL for mercury in the Guadalupe River watershed, and the Central Valley Regional Water Quality Control Board is in the process of developing TMDLs for the Sacramento River and key tributaries. The California Bay-Delta Authority is funding several mercury related studies. We will coordinate our San Francisco Bay mercury TMDL adaptive implementation actions and studies with these efforts.

The mercury problem in San Francisco Bay may take decades to control to the point where beneficial uses are restored. The current regulatory strategy relies on simplifications of a complex environmental system. There is much yet to learn about mercury and how the Bay will respond to control efforts. Much research is underway, and more is planned for the future to shed light on the remaining questions. We have an obligation to adapt the regulatory program in the future as relevant information becomes available, and we intend to do so. We also have an obligation to protect water quality by taking actions now based on the information currently available. Adaptive implementation provides the way to fulfill these two obligations.

Table 3. Management Questions. These questions define what must be known if we are to achieve an understanding of mercury in the Estuary sufficient to plot a successful course to ending the problem.

San Francisco Bay System Processes and Effects
Where is methylation occurring in the system and what are the controlling factors?
Will erosion of mercury-laden sediment from certain regions of the bay affect water quality?
Are there local methylation or bioaccumulation effects at the point of discharge?
What is the mercury and sediment flux out the Golden Gate?
What is the timeframe for recovery of the system and attainment of targets?
Are the assumptions used in the simple box model valid? • The Bay system is composed of two compartments - bay waters and the active sediment layer. • The depth of the active sediment layer is 0.15 meters. • Mercury below the active sediment layer is not considered in the bay system, but can enter the system when overlying sediment erodes. • The active sediment layer is completely well mixed. • The mass of sediment leaving the bay balances the mass of sediment entering the bay either naturally or via dredged material disposal out of the Bay.
Source Loads and Implementation of Control Strategies
How much of the direct and indirect atmospheric deposition to San Francisco Bay is from California sources and Bay Area sources?
What is the relative bioavailability of mercury from different sources to San Francisco Bay?
What is the mercury load from the Central Valley rivers?
How much mercury is in storage in the Bay-Delta tributaries?
What is the relationship between mercury concentrations in sediment and mercury concentrations in the food web?
TMDL Targets
Are the fish tissue, bird egg, and sediment targets appropriate?

Using Conceptual Models to Address High Priority Pollutants

Mike Connor (mikec@sfei.org), San Francisco Estuary Institute, and Chris Werme

Key Points

- *Conceptual models are very effective tools for organizing and communicating existing knowledge about priority contaminants*
- *The Clean Estuary Partnership is developing conceptual models for many priority contaminants: mercury, PCBs, legacy pesticides, dioxins, selenium, and diazinon*
- *These models describe the expected benefits of different management options and key uncertainties and information needs*

What Are Conceptual Models

In our junior high school days, no tests were dreaded more than those with "word problems" that described complex situations from which we needed to develop key equations to calculate solutions. Our teachers would advise: "Draw a picture of the problem—that will help you understand it." Little did we know that this same process that we used in eighth grade would be the basis for how scientists and managers attack complicated water quality problems in the Bay.

Conceptual models provide a framework for organizing our knowledge in order to help us understand how systems function (Nichols et al., 1998). In fact, all environmental managers and scientists work with a conceptual model, whether or not they refer to it as such, and whether or not it is formally documented. This article, however, uses "conceptual model" to mean formally documented models. Water quality conceptual models generally include a written description and visual characterization of the essential features that link an ecological endpoint to the stressors that may affect it (after EPA, 2004), but they can take different forms depending on the modeler and purpose. Good conceptual models are dynamic and evolve with increased understanding because they help to uncover key uncertainties.

In the last year, the San Francisco Regional Water Quality Control Board and the Clean Estuary Partnership have developed conceptual models for mercury (Johnson and Looker, 2003), PCBs (Hetzel, 2004), legacy pesticides (DDTs, chlordanes, and dieldrin) (Connor et al., 2004b), dioxins and furans (Connor et al., 2004a), selenium (Abu-Saba, 2003), and diazinon (Ogle, 2003). In creating these conceptual models, local scientists have relied upon the extensive RMP database. But, as Nichols et al. have noted, the process of creating and debating these conceptual models by the CEP partners may be more important than the models themselves in developing a consensus of our current understanding of these contaminants, key data gaps and uncertainty, and priorities for gathering additional information. Through the CEP, diverse organizations plan to work together to design and conduct the technical studies needed to address the uncertainties highlighted by the conceptual models. The results of these studies will be used to revise the conceptual models and subsequently the strategies for attaining water quality standards based upon these models. This is the process of adaptive management.

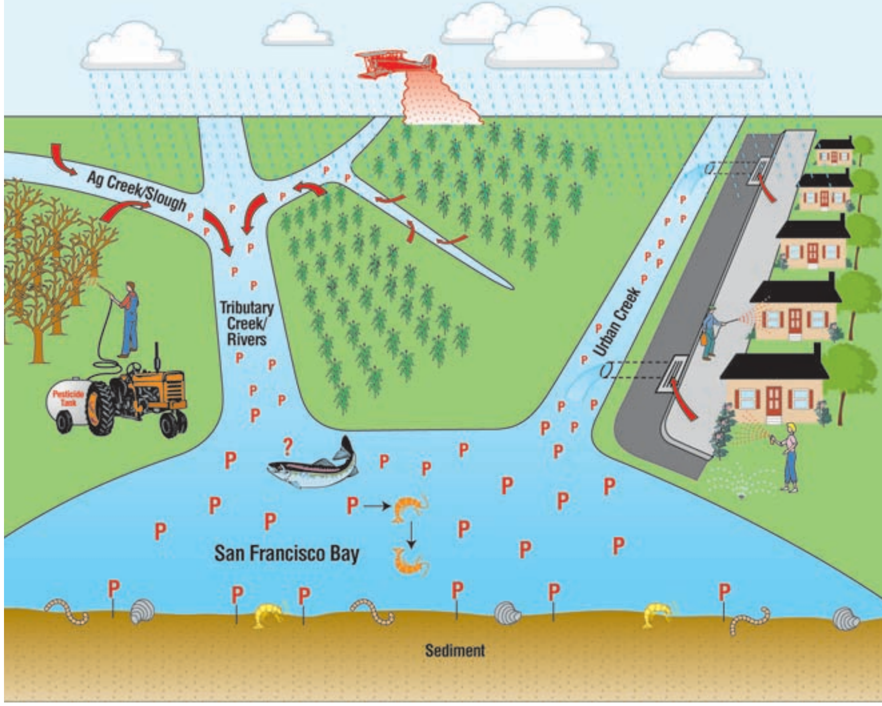


Figure 1. A "conceptual model" for a contaminant describes our understanding of how the contaminant enters the ecosystem, reaches sensitive species, and causes toxic effects. Every environmental manager works with a stated or unstated conceptual model. This is a graphical representation of the CEP's conceptual model for diazinon in San Francisco Bay. The pesticide (P) enters tributary creeks and rivers in agricultural and urban runoff, primarily driven by rainstorms. Sensitive species in the Bay include small invertebrates in the water column and the sediment, and possibly fish.

Each of the conceptual model reports describes the linkage of contaminant sources to beneficial use impairments. They identify and prioritize the major sources of contaminants, describe the ecological processes that influence the fates of the contaminants in the Bay, and determine the major ways in which these contaminants impair beneficial uses. Figure 1 illustrates a graphical representation of one of these conceptual models (Ogle, 2004).

What Have We Learned from Conceptual Models So Far

Now that six conceptual models have been completed, it is possible to compare what insights the process gives us in the possible control strategies for these contaminants

- Sources. What are the most important ways that contaminants are released to the Bay?
- Fate and Transport. What are the most important processes that affect the distribution and loads of the contaminants?
- Effects. What parts of the Bay's ecosystems are the most sensitive receptors for the contaminants?

Sources

The most important thing to understand about all these priority contaminants is that they have been the subject of management plans for 20-30 years (except for diazinon, which has been studied for less than a decade). PCBs and legacy pesticides have been totally banned, diazinon has had some of its major uses phased out, and all of the contaminants have been regulated through strict discharge limits. As a result, the current discharges are dwarfed by the historical amount of these chemicals that already exists in the Bay's water and sediments. Figure 2 presents a "legacy ratio," which shows the relative importance of historic compared to existing discharges. For instance, the amount of PCBs present in the active sediment surface layer accumulated from historic discharges is more than 30 times greater than the amount of PCBs entering the Bay each year. The "legacy ratio" shows that the historical reservoirs of PCBs, dioxins, and mercury can overwhelm any effect of our efforts to control new sources of these contaminants to the Bay. For some of the legacy pesticides, the historic reservoirs are dwindling, and we are near to meeting our water quality goals. For diazinon, the relative importance of the reservoir is small, and management controls have the potential to quickly allow compliance with water quality goals.

Because of the dominant role that the sediment reservoir assumes for these contaminants, this is a critical intersection of key management and science issues. How deeply must materials be buried in the sediments before they are below the region of biological activity? How

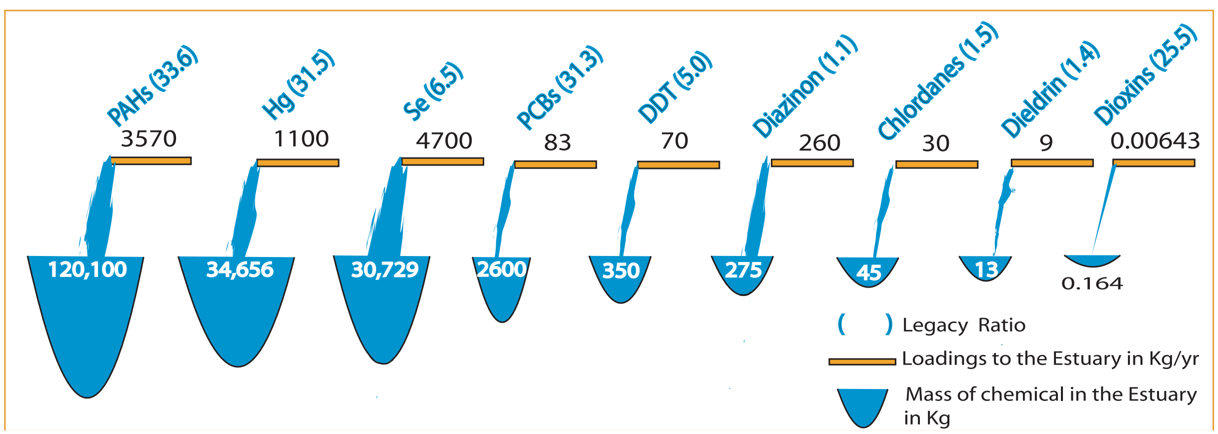


Figure 2. Many contaminants have been managed for decades, and as a result current inputs are dwarfed by the amount already accumulated in Estuary water and sediment. The ratio of the amount of contaminant in the Bay's water and surface (top 15 cm) sediments compared to its annual input (the "legacy ratio") indicates the importance of historical sources of contamination. The higher the legacy ratio, the larger the significance of legacy sources of contamination.

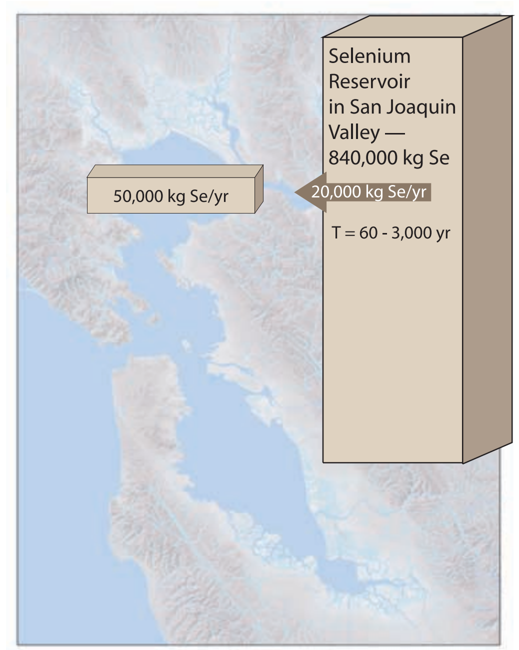


Figure 3. A major limitation of all the conceptual models has been inadequate knowledge of the quantity of contaminant in the soil of Bay watersheds, and the potential for this material to reach the Bay. This Figure depicts the soil reservoir of selenium compared to its loading and reservoirs in the Bay (modified from Abu-Saba, 2004). For many priority contaminants, the amount of material stored in watersheds with the potential to wash off into the Bay presents the biggest challenge to the continued recovery of the ecosystem. In general, the size of the soil reservoir and its potential to reach the Bay are very poorly understood.

should we address sediment erosion and dredging? How can we use our sediment management policies to meet our goals of restoring tidal wetlands, minimizing the impacts of levee catastrophic failures, providing navigation, and meeting beneficial use goals for water quality?

A major limitation of all the conceptual models has been the ability to estimate the relative magnitude of the reservoir of the contaminants that reside in the soils of the watersheds draining into the Bay. Abu-Saba (2004) estimates that the size of the soil reservoir of selenium that could wash into the Bay far exceeds the reservoir in the Bay itself. (Figure 3; Abu- Saba, 2004)

But, because of the size of the soil reservoir and the progress made in managing these contaminants in the last 20-30 years, industrial and municipal wastewater are generally not significant sources for any of these contaminants compared to urban and agricultural runoff. Figure 4 shows the relative importance of industrial and wastewater sources compared to non-point sources that originate from Central Valley (agriculture and mining) or local (stormwater runoff) tributaries to the Bay. Due to the studies of Lester McKee, our appreciation of the importance of local runoff sources is rising (see article on page 46).

Fate and Transport

Three characteristics are critical in determining the behavior of these contaminants:

1) Solubility: Are they more likely to be found dissolved in the water column or attached to particles and associated with sediments?

2) Volatility: How easily do they volatilize from the water and leave the airshed?

3) Degradability: How easily are they degraded in the water and sediments?

Figure 5 provides a summary of the characteristics of the conceptual model contaminants. For most of the organic contaminants, the figure displays the results of a simple mathematical model of the Bay, which predicts the fates of the contaminants after 10 years if all the sources were perfectly controlled. The model estimates the proportion of material that

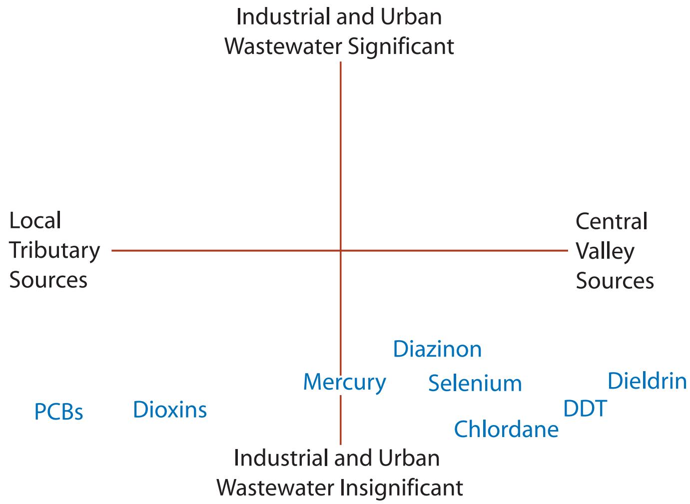


Figure 4. Due to major investments in wastewater treatment over the past 30 years, industrial and municipal wastewater are generally not significant sources for any of the contaminants discussed here, compared to urban and agricultural runoff. The relative significance of industrial and municipal wastewater sources compared to runoff from local tributaries and the Central Valley is shown. Agricultural runoff is a dominant source for pesticides (dieldrin, DDT, chlordane, and diazinon) and selenium. Urban runoff is a dominant source for PCBs and dioxins. Historic mercury and gold mining activities in the watershed have created major sources in both local tributaries and the Central Valley.

would be retained in the Bay's water and sediments, lost by export through the Golden Gate or volatilization, or degraded in the water and sediments. For diazinon, mercury, and selenium, the diagram presents rough estimates of fates.

Many legacy contaminants, especially mercury, PCBs, and dioxins, have low degradation rates, low volatility, and low solubility. As a result, mercury, dioxins, and PCBs can persist in the Bay for decades, even if there is absolutely no new discharge of these materials, because the sediments in the Bay have a half life of more than 100

Clean Estuary Partnership

The San Francisco Bay Regional Water Quality Control Board, the Bay Area Clean Water Agencies, and the Bay Area Stormwater Management Agencies Association have signed a Memorandum of Understanding reflecting their belief that a collaborative approach for developing TMDLs will be the most effective method for achieving sustainable water quality benefits for the Bay. The Clean Estuary Partnership (CEP) formed to implement the intent of this Memorandum of Understanding. The mission of the Clean Estuary Partnership is to use sound science, adaptive management, and public collaboration to develop and implement technically valid and cost-effective strategies including TMDLs that result in identifiable, sustainable water quality improvements for San Francisco Bay. Please visit <www.cleanestuary.org> for more information about the CEP, to obtain copies of CEP reports, and to find out how you can become more involved in this program.

	Aquatic Toxicity	Sediment Toxicity	Fish and Wildlife Consumption	Bird Eggs
Mercury	Medium	Uncertain	High	High
PCBs	Low	Low	High	Medium
Dioxins	Low	Uncertain	High	Uncertain
DDTs	Low	Medium	Medium	Low
Chlordanes	Low	Medium	Low	Low
Dieldrin	Low	Low	Medium	Low
Diazinon	Medium	Uncertain	Uncertain	Uncertain
Selenium	Low	Low	Medium	Uncertain

Table 1. Most priority contaminants threaten beneficial uses of the Bay by accumulating in the food chain, resulting in risk to humans consuming fish or wildlife from the Bay. The table summarizes risks posed by the different priority contaminants. Mercury poses the greatest overall threat across these four categories of impact.

years. More soluble chemicals, such as diazinon and selenium, should be much more responsive to management actions, because the waters of the Bay are exchanged with the coastal ocean in days or months, depending on season and location. In fact, selenium concentrations in the water have already declined with stricter management controls (Abu-Saba, 2004). Diazinon is also quite soluble, with higher degradation and volatilization rates, and diazinon-based toxicity has declined significantly in the last decade (Ogle, 2004).

Effects

The chemical characteristics that cause many of these legacy contaminants to persist for a long time in the Bay's sediments also cause them to bioaccumulate up the food chain where they pose a risk to subsistence fish-eaters or higher trophic level wildlife. (The behavior of mercury and selenium is a bit more complicated, but it is their organo-metallic form that causes them to bioconcentrate.) Mercury, PCBs, selenium, dioxins, and legacy pesticides contamination in fish have triggered health advisories in the Bay. Diazinon, which is not as persistent nor as associated with sediments, does not present health concerns to fish eaters, but fails to meet aquatic toxicity guidelines (Table 1).

Hatching success of bird eggs is often correlated with health concerns to humans, particular pregnant and nursing mothers. The Regional Board has determined that if mercury concentrations in fish meet standards for human consumption, there should be no significant risk to bird populations. Selenium first came to our attention because of its effects on bird development; there is also an advisory to protect duck hunters from eating the birds they harvest. Historically, DDTs first came to our attention for their impact on egg shell thinning, but DDT health advisories now also exist for Bay fish.

While the comparison of contaminant levels in fish and wildlife to public health standards would seem to be fairly straightforward, in fact, there is a significant amount of variation used in the assumptions about the consumption of Bay fish and the size of the populations at risk. The guidance that most of the advisories are based upon has often remained as draft documents, and the levels of concern for some contaminants, such as mercury and potentially dioxins, are changing. The conceptual models point to a need for the relevant agencies and scientists to develop a consensus on the level of consumption of Bay fish and on "acceptable" risk levels.

Toward Better Conceptual Models

The current conceptual models are the first step in the development of mathematical models that will be used to predict the response of the Bay to management actions. The RMP has been using a simple Excel spreadsheet model of equilibrium partitioning and transformation processes in the Bay to calculate the time course of contaminant clean-up strategies for the Bay. This simple model considers the Bay to consist of one giant box of water adjacent to a box of sediments and air. This simple simulation does not allow us to distinguish among the varied geography of inputs or areas of high concentrations of waters and especially sediments at the margins of the Bay.

Since the RMP redesign has segmented the Bay into five major subareas, it will be easiest to interpret future monitoring data with a contaminant model that has the same subdivisions. Dave Schoellhamer, from the USGS, has developed a more detailed model of sediment movement in the Bay, subdividing the area into several dozen boxes. Another very-detailed model of contaminant movement in the Bay was prepared by URS as part of the evaluation of a new runway for San Francisco Airport. The URS model consists of small (~1 km^2) boxes that very accurately represents the movement of water and sediments in the Bay with a similar characterization of chemical partitioning to that used in the spreadsheet models. The sophistication in the URS model must be balanced against the time and expense necessary to run the model compared to the spreadsheet models described above.

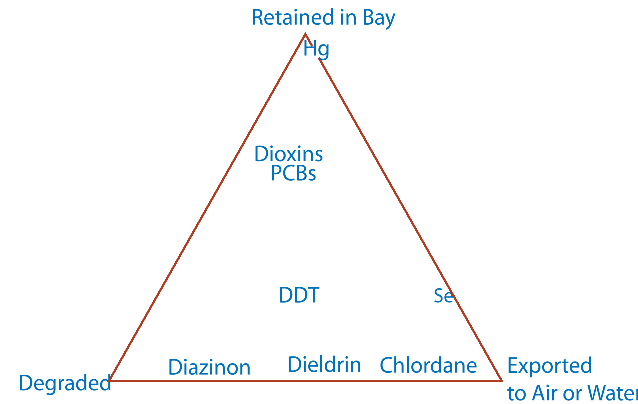


Figure 5. Knowing what happens to a contaminant after it enters the Bay (contaminant "fate") is a critical aspect of understanding the linkage between sources and adverse impacts on Bay organisms. This diagram shows the extent to which the fate of the different contaminants is dominated by transport out of the Bay, degradation in the Bay, or retention in the Bay. The closer the position to the triangle apex, the more that process dominates. For instance, mercury is primarily retained in the Bay after ten years, while DDTs are about equally divided between all three processes. The data for the organic contaminants (except diazinon) are based on calculated fate after ten years, assuming no new inputs. The data for diazinon, mercury and selenium are estimates.

Besides improving the geographic coverage of the models, the RMP is also improving the extrapolation from water and sediment contaminants to contaminant concentrations higher up the food chain to fish birds, and mammals. Frank Gobas of Simon Fraser University in British Columbia has completed a fish food chain model for PCBs and is extending that approach to birds and mammals that feed on fish in the Bay.

Conceptual models will serve as our scorecard for the improvement of our understanding of the Bay. Better models will allow us to develop more effective management strategies that adapt to our improved understanding of the Bay.

A Regional Board Perspective on the RMP:

Ten Years of Benefits, and Challenges for the Future

Karen Taberski (KMT@rb2.swrcb.ca.gov), San Francisco Bay Regional Water Quality Control Board

Key Points

• Information from the RMP has been of great value in supporting many of the Regional Board's programs to manage water quality in the Bay

• The RMP has provided the information needed to determine what is and what is not a problem, and thus focus limited resources where they are most needed

• Future challenges include reducing key technical uncertainties and achieving institutional efficiencies in times of extremely tight budgets

This article is excerpted from a RMP technical report: "The Regional Monitoring Program - Science in Support of Managing Water Quality in San Francisco Bay." *The report includes sections describing the perspectives of the regulators, the regulated, and scientists on benefits of the RMP and challenges facing the Program. This article presents the regulator perspective. For a copy of the full report, contact Jay Davis <jay@sfei.org>.*

The San Francisco Bay Regional Water Quality Control Board (Regional Board) has primary responsibility for regulating water quality in the Bay. The Regional Monitoring Program (RMP) was created in the early 1990s through the vision and initiative of the Regional Board in order to provide the information needed for effective water quality management. The Regional Board, in collaboration with other RMP participants, has been intimately involved with the direction of the Program from the beginning. Information gained from the RMP has been of great value in supporting many of the Regional Board's programs to manage water quality in the Bay. However, the RMP will have to continue to evolve to meet the management and scientific challenges surrounding implementation of Total Maximum Daily Loads (TMDLs) and other management initiatives.

Benefits of the RMP to Regulators

Regional Board activities to manage water quality in the Estuary can be divided into two broad categories. One is impairment assessment, which is performed to determine whether any contaminant is impairing a beneficial use. The second broad category is the development of water quality attainment strategies. TMDL development is one type of water quality attainment strategy. Other types of water quality attainment strategies include public outreach and pollution prevention. RMP information is contributing significantly to both impairment assessment and water quality attainment strategy development by the Regional Board.

Impairment Assessment and 303(d) Listing

The RMP has provided the Regional Board with information to determine what is and what is **not** a problem, and thus focus limited resources where they are most needed. An early example of the focus that the RMP provided was apparent in the 1998 303(d) "impaired waterbodies" listing process. Prior to 1998, the San Francisco Estuary was listed as impaired by "metals". In the 1998 303(d) list, the Regional Board staff determined that there was sufficient evidence to show that only copper and nickel exceeded water quality objectives to a level that required listing, and all other metals, except mercury and selenium, which cause bioaccumulation problems, were removed from the list. This allowed for a focused effort to take place, which included the efforts of the regulated industries and municipalities, environmental groups, scientists, and the Regional Board to concentrate on this specific problem. Out of that process came site-specific water quality objectives for copper and nickel in South San Francisco Bay, south of the Dumbarton Bridge, that are fully protective of aquatic beneficial uses; a Water Quality Attainment Strategy featuring pollution prevention, source control and monitoring activities; and the removal of copper from the 303(d) list.

In another example of the improved focus provided by the RMP, in 1994, the Regional Board, through the Bay Protection and Toxic Cleanup Program (BPTCP), conducted a study to measure contaminant concentrations in fish that people consume from San Francisco Bay. This study resulted in a health advisory for consuming San Francisco Bay fish. The fish advisory was primarily based on high levels of mercury and PCBs. The fish advisory caused the Regional Board to list San Francisco Bay as "impaired" by mercury and PCBs on the 303(d) list. Currently, the Regional Board is developing Total Maximum Daily Loads (TMDLs) (see page 16) for both of these chemicals in the Estuary. Following up on the 1994 study, in 1997 the RMP started to measure contaminants in Bay fish every three years to determine temporal trends of contaminants in fish that people consume. The continued monitoring of contaminants in fish will allow the Regional Board to determine

The "Regional Board"

The San Francisco Bay Regional Water Quality Control Board (Regional Board) is the implementing agency of the federal Clean Water Act and the State of California's Porter Cologne Water Quality Control Act (California Water Code) in the San Francisco Estuary. Under the California Water Code the Regional Board is required to protect beneficial uses in the Estuary. Beneficial uses are primarily designed to protect aquatic life, wildlife and human health. In order to protect beneficial uses the Regional Board has adopted water quality objectives in their Water Quality Control Plan (Basin Plan). Water quality objectives include numerical water quality objectives for individual contaminants and narrative objectives that prohibit toxicity due to contaminants, as well as any detrimental increase of bioaccumulative contaminants.

Visit "Our Water, Our World," a San Francisco Bay Area regional campaign to reduce pesticide use in the home and garden at <http://sfwater.org>.

the effectiveness of TMDLs, whether legacy contaminants such as chlorinated pesticides remain a concern, and whether contaminants that are only recently being measured, such as the flame retardant compounds polybrominated diphenyl ethers (PBDEs), have become a significant problem.

In 1999 the RMP made a decision to proactively identify emerging contaminants of concern before they reach concentrations at which beneficial uses are impacted and TMDLs are necessary. In 2000 and 2001 the RMP conducted a special study to determine if contaminants that have recently become a concern have been detected in RMP samples. A list of chemicals came out of this study that have been tentatively included in the annual monitoring conducted by the RMP. The Regional Board considers that surveillance monitoring for emerging contaminants is necessary as a means of identifying potential impairments in their early stages before they become a threat to beneficial uses and the legacy contaminants of the future.

One group of chemicals that has emerged as chemicals of concern from this process are the flame retardant polybrominated diphenyl ethers (PBDEs). These chemicals have been banned in Europe, and a 2003 state law banned the use of two types of PBDEs in California by 2008. PBDEs are currently in the environment and used in furniture foam, computers, and other business equipment. This information led the Regional Board to list PBDEs on the 2002 303(d) "watch" list to encourage increased monitoring and studies to determine how PBDEs are getting into the aquatic food chain. Determining pathways could help to identify management actions that would decrease the input of these and similar chemicals to the Estuary. These chemicals seem to have increased exponentially in the tissues of estuarine organisms, such as harbor seals (see page 13), over the past ten years. Tracking the trends in these chemicals is extremely important to determine if management actions are necessary and what effect the ban will have on concentrations in the future.

The 1997 Program Review resulted in a redesign of the RMP water and sediment monitoring element. The new design will develop data that will be statistically representative of the Estuary as a whole and by individual segments and enable the Regional Board to better evaluate whether water or sediment quality is impaired. This design will allow the Regional Board to better evaluate: 1) spatial patterns of contamination; 2) whether the Estuary or segments of the Estuary exceed water quality objectives; and 3) the proportion of the Estuary that is contaminated and/or toxic.

The RMP is currently developing a program to directly measure impairment associated with contaminants in the Estuary food web. The RMP has set up a workgroup to develop an Exposure and Effects Pilot Study to: 1) measure contaminants in target species (i.e., bird eggs) that would be a better indicator of long- term trends in contaminants in the Estuary and 2) directly measure effects associated with contaminants. This connection between cause and effect is necessary in order to take effective regulatory/management actions that will result in measurable improvements in water quality.

Total Maximum Daily Loads (TMDLs)

A Total Maximum Daily Load (TMDL) is required for waterbodies on the 303(d) list. A Total Maximum Daily Load is the pollutant load level necessary to attain the applicable water quality standard. The 1997 Program Review provided the impetus for a redesign of the program. As a result of the redesign, the RMP was poised to provide the data synthesis, model development, studies to validate mass budget models, and information on target species (fish contamination for human health and effects on bird reproduction) that is providing valuable information for the development of TMDLs. Since that time, the Clean Estuary Partnership (CEP) was set up among wastewater agencies, stormwater agencies, industrial dischargers, and the Regional Board to provide additional information needed in order to complete TMDLs.

Data integration, synthesis, and analysis conducted through the RMP are proving to be instrumental in the development of the TMDLs for mercury and PCBs in the Estuary. Sediment concentrations have been mapped to determine sources and hot spots of contaminants. A mass balance model was developed for

Mercury TMDL targets would protect fish consumers

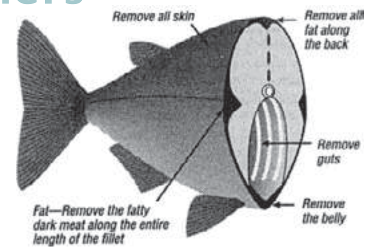
Fish Consumption Advisory

The following text is taken from the interim fish consumption advisory for San Francisco Bay. The full text is available at http://www.oehha.org/fish/nor_cal/int-ha.html.

Adults should limit their consumption of San Francisco Bay sport fish to, at most, two meals per month.

Adults should not eat any striped bass over 35 inches.

Women who are pregnant or who may become pregnant, or who are breast-feeding, and children under 6, should not eat more than one meal per month and, in addition, should not eat any meals of large shark (over 24 inches) or large striped bass (over 27 inches). This advisory does not apply to salmon, anchovies, herring, and smelt caught in the bay; other ocean sport fish; or commercial fish.



PCBs that allowed the Regional Board to: 1) identify the relative significance of sources; 2) determine the approximate time it would take to meet targets based on various input scenarios; and 3) to identify data gaps. A food web model is also being developed to help determine how far concentrations of PCBs need to decline in the sediment to bring fish concentrations down to levels that are protective of human and wildlife health.

RMP measurements of mercury on suspended solids, in bedded sediment, and in fish were used to develop a mercury sediment target in the mercury TMDL. These targets are intended to be protective of human health (through fish consumption) and wildlife (by protecting the most sensitive receptor, bird reproduction). A special study to measure air deposition of mercury and PCBs funded by the RMP and the City of San Jose helped Regional Board staff determine the relative contribution from that pathway. A study currently being funded by the RMP and CEP to measure contaminant loadings from small tributaries (see "In Pursuit of Urban Runoff in the Urbanized Estuary," page 46) will enhance understanding of transport of sediment bound pollutants, improve load estimates, and assist with development of feasible and effective implementation plans. Continued monitoring of mercury and PCBs by the RMP in water, sediment, and tissue will allow the Regional Board to evaluate the success of TMDL implementation plans and to make adjustments if necessary.

Implementing Water Quality Attainment Strategies

Water quality attainment strategies are development and implementation actions associated with attaining water quality standards. These strategies include TMDLs, public education, pollution prevention, scientifically valid water quality guidelines/objectives, appropriate permit limits, sediment cleanups, and better scientific methods for evaluating whether water quality standards are being attained. The RMP has made a significant contribution to the Regional Board's ability to develop TMDLs and generate scientifically valid sediment guidelines and permit limits. The RMP has also provided the impetus and information necessary to foster public education programs that are being carried out by other agencies and has provided information that is being used in monitoring estuaries and developing standards statewide.

The fish consumption advisory that was issued as a result of the 1994 studies led the RMP to fund a study of fish consumption in the Bay that was conducted, and co-funded, by the California Department of Health Services (DHS). Using results from this study, DHS has developed an appropriate outreach and education program to inform the public about the health advisory and about ways to prepare fish that minimize exposure to contaminants. This effort, which has included state, county and city agencies and environmental and community groups, has resulted in the posting of signs in six different languages describing the advisory, as well as outreach presentations to communities that are most at risk. In an ecosystem where recovery from contamination will take decades, educating the public is the best way of providing short-term reductions in exposure to the contaminants found in Bay fish.

Another outreach and education program that grew out of information provided by the RMP, as well as many others, is "Our Water Our World," a regional campaign to reduce pesticide use in the home and garden. Due to the increased awareness of the impact of pesticide usage on aquatic organisms, stormwater and wastewater agencies have developed outreach and education efforts to minimize the use of pesticides and encourage integrated pesticide management. This pollution prevention program develops information targeted at the general public to prevent future pesticide toxicity.

RMP data have been and continue to be used by Regional Board staff to develop regulatory guidelines for the Estuary and to support permit conditions; a few examples are mentioned here. The results of the RMP consumption study enabled the Regional Board to calculate target values for mercury in Bay fish in the mercury TMDL that would protect 95 percent of all Bay fish consumers. In 1998 the Regional Board developed ambient sediment guidelines, using RMP and BPTCP data, to determine "background" concentrations of contaminants in the Estuary. The calculation of Estuary-specific background concentrations allows the Regional Board to determine when concentrations of contaminants at a particular site are "high" due to a possible contaminant source. The RMP also provides data that are used in writing NPDES permits for discharges to the San Francisco Estuary. RMP data are used to determine background concentrations that are used in determining effluent limits. Recently, the RMP has conducted a special study to determine, based on ambient data, whether the 126 contaminants listed in the California Toxics Rule (CTR), promulgated in 2000, should be listed in permits.

On a statewide basis, the RMP has given the State Water Resources Control Board and the other Regional Boards methods to better understand their bays and estuaries. RMP data are currently being used to develop statewide sediment quality objectives. RMP efforts in measuring sediment chemistry, conducting toxicity tests, identifying toxic agents, and performing a pilot study on benthic invertebrates to understand the relationship between benthic communities and contaminants, are an important component of this statewide process.

A Regulator Perspective on Challenges Facing the RMP

There are many complex technical issues concerning contaminants in the Estuary that are not currently being adequately addressed. Studies that would provide a better understanding of food web transfer are needed to determine how best to regulate concentrations of contaminants in sediment and water to protect humans, aquatic organisms, and wildlife. Studies in wetlands that are crucial to the understanding of processes linking contaminant concentrations in sediment to concentrations in wildlife need to be conducted. Especially during this time, when extensive wetland restoration is planned, it is extremely important to understand the mechanisms by which contaminants, particularly mercury, become bioavailable in order to minimize the potential for creating wetlands that increase methylmercury accumulation in the food chain.

In this time of severe financial resource limitations it is crucial to reconsider how programs could better cooperate and coordinate to develop this needed information. Therefore, some of the biggest challenges in the future will be institutional.

Although studies from the RMP have been very helpful in the development of TMDLs, the dischargers and the Regional Board have recognized that additional studies and assistance are needed in order to complete scientifically sound TMDLs. Because of this, the Clean Estuary Partnership (CEP) was initiated. The mission of the CEP is to use sound science, adaptive management, and public collaboration to develop and implement scientifically valid and cost-effective strategies, including TMDLs, that result in identifiable, sustainable water quality improvements for the Bay. From an institutional perspective and for the purposes of consistency, efficiency, and cost-effectiveness it may be advantageous to merge the RMP and CEP in some way.

Another institutional challenge is the coordination and synthesis of large-scale environmental programs that monitor and assess the San Francisco Estuary. CALFED, as well as the Interagency Ecological Program (IEP), are two large programs that are also involved in monitoring and special studies in the Estuary. These programs might be better coordinated with RMP studies to understand how contaminants interact with food web dynamics. Better coordination, cooperation, and synthesis of data are needed to develop a more comprehensive view of the Estuary and to provide an improved understanding of the underlying processes that create impairment so that sound management decisions can be made.

An example of successful coordination of the RMP and another large program is the partnership between the U.S. Geological Survey (USGS) and the RMP. Since the inception of the RMP, USGS has been an integral partner. As part of larger programs to characterize the Estuary, the USGS has provided important information on basic water quality parameters such as dissolved oxygen and nutrients, as well as explaining the relationship between the fluctuation of suspended solids and concentrations of contaminants. These USGS studies have provided an essential context to understanding contaminants in the Estuary.

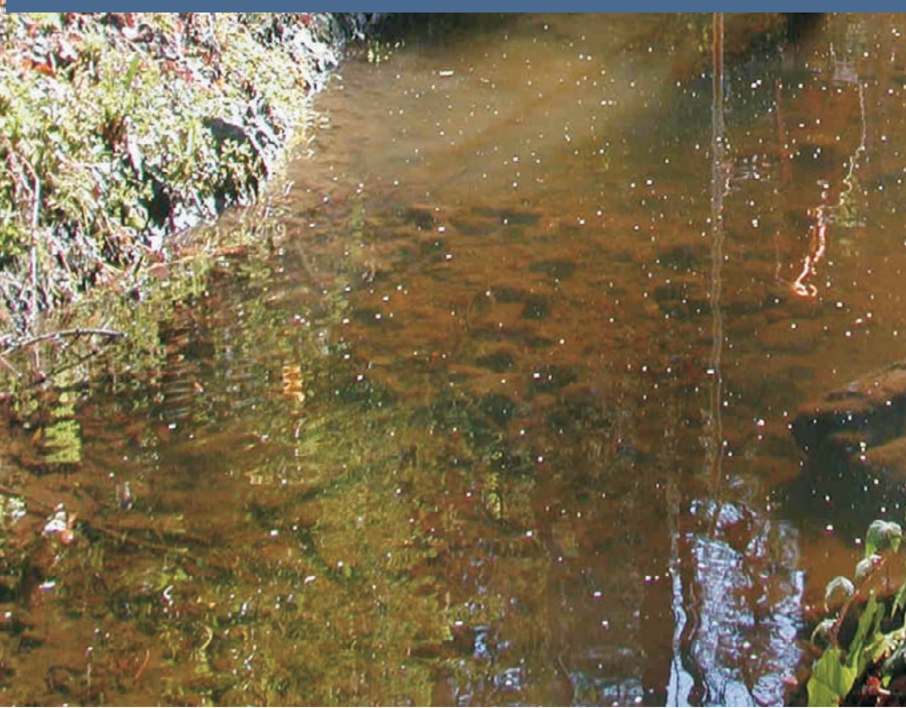
Better coordination could be accomplished through shared funding of programs, coordinating grant funding, creating a forum for data synthesis such as the *Pulse* and an environmental report card for the Bay (see page 54), and having more participation by other agencies and programs on RMP committees. This type of collaboration would enable the RMP to put data in a broader context, to better understand the processes that work in the Estuary, and to ultimately assist the Regional Board in better assessing impairments and protecting beneficial uses.

A Model Monitoring Program

The Regional Monitoring Program is a testament to the importance of maintaining the institutional and monetary commitment to measuring meaningful indicators of water quality, and linking them to programs of action. In only ten years, the credibility of the Regional Board and local implementing agencies in preventing pollution to the Bay has dramatically increased and become reliant on the scientific information consistently provided by the RMP. We now have answers to water quality attainment questions. We can advise the public on how to consume fish from the Bay and remain healthy. We have seen the decline in toxicity in tributaries to the Bay, associated with a change in pesticide use patterns. We have started educational programs on alternatives to pesticide usage. We have raised local scrutiny of the use of copper, nickel, and mercury in industrial processes. With diverse participation, a foundation in scientific principles, and a continual commitment to improvement over time, the RMP has become a model for water quality monitoring programs around the world.

the big picture of water quality in the Estuary

feature articles



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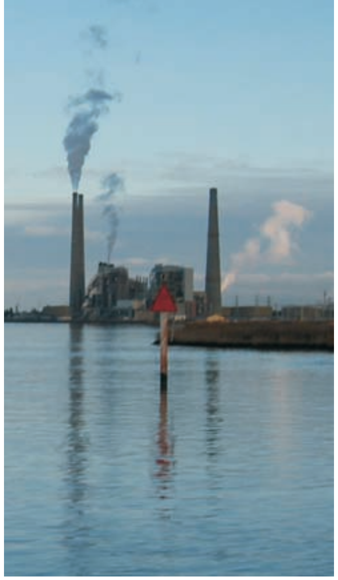

Long-Term Trends in Metal Contamination in San Francisco Bay Water and Sediment

A. Russel Flegal (flegal@etox.ucsc.edu),[1] Christopher H. Conaway[1] and Sergio A. Sañudo-Wilhelmy[2]

[1]University of California at Santa Cruz, [2]Marine Sciences Research Center, Stony Brook University

Key Points

- ***The RMP has been essential in gauging the effectiveness of investments in wastewater treatment and other control efforts***
- ***The Bay now has one of the best datasets on metal contamination for any estuary in the world***
- ***The gradual erosion of dispersed watershed contaminants like lead slows improvements in Bay water quality***
- ***Silver concentrations in the South Bay have declined in response to load reductions from wastewater treatment plants***

Billions of dollars have been spent over the past five decades to improve the water quality of San Francisco Bay (Figure 1), where concentrations of some trace elements have approached or exceeded state and federal water quality criteria (Flegal et al., 1991; 1996; Thompson et al., 2000; Hoenicke et al., 2003; Sañudo-Wilhelmy et al., 2004). Until recently, it has not been possible to quantify the benefits of most of those remediation efforts because of the absence of sufficient, valid water quality data for toxic metals. These data are required to accurately evaluate the changes in concentrations that occur seasonally, annually, and over decades and centuries. With the availability of robust water quality data obtained through comparatively small investments in the RMP over the past ten years, however, these evaluations have been made for lead and silver, and are now being made for mercury.

The Dark Ages for metals

There are limited data on trace element concentrations in San Francisco Bay waters prior to the 1990s, and even those few measurements are perhaps inaccurate. As noted over a decade ago (Flegal et al., 1991), there were relatively few published reports of dissolved trace element concentrations in the Bay at that time, and almost all of those measurements were limited to a few areas within the Bay. In addition, most of the values that had been reported in either peer-reviewed scientific journals or non-peer-reviewed "gray" literature are suspect, because they i) did not utilize currently

accepted trace metal clean techniques that include rigorous precautions to prevent sample contamination, ii) were not corroborated by independent calibrations, and iii) were inconsistent with more recent values obtained with reliable techniques.

Consequently, comparable data on trace element concentrations in the Bay are, with some exceptions, limited to those in reports published since 1990. This was well after efforts to reduce contaminant loadings to the Bay in the 1950s–1960s, and also after the passage of the U.S. Clean Water Act in 1972, which accelerated source control programs and the installation of secondary and advanced treatment facilities at publicly owned treatment works (POTWs) to reduce total metal loadings to the Bay (California Regional Water Quality Control Board, 1995). Although the impact of those efforts are evidenced in subsequent decreases in contaminant concentrations in sediment cores (e.g., Hornberger et al., 1999; Conaway et al., 2004), there is not—and can never be—a direct measure of changes in contaminant concentrations in Bay waters during that earlier period.

The Bay's complex hydrology

In addition to limited historic data, the effect of seasonal and annual variations of freshwater inflow to San Francisco Bay presents a further obstacle to analysis of long-term trends. The hydrology of the Bay is complex, with pronounced variation over time and among different locations (Conomos, 1979; Kimmerer, 2002; Monismith et al., 2002). The Bay receives runoff from 40% of California's land area, with over 90% of that discharge from the Sacramento and San Joaquin rivers, which both flow into the northern reach of the Bay. Conversely, less than 10% of the natural freshwater flow is into the southern reach of the Bay. Freshwater flows into the system are characterized by their seasonality and interannual (year-to-year) variability. There are relatively large discharges during the winter and spring periods, and relatively small discharges during the summer and fall periods. Long-term trends in flow are further complicated by interannual differences in freshwater discharges associated with El Niño Southern Oscillation (ENSO) cycles.

Figure 2 illustrates the difficulties of sampling Bay waters during those different hydrologic regimes. It shows our sampling periods over the past decade superimposed upon freshwater discharges into the northern reach of the Estuary. Because of disconnects between the collection periods and freshwater discharges, the water quality data obtained from the cruises were often neither representative of average nor of extreme conditions.

Human impacts

The large spatial variations in contaminant metal concentrations in San Francisco Bay are also partially due to historic and contemporary industrial inputs of those metals to the system (Flegal et al., 1996). The Bay was heavily impacted by mercury and gold mining operations beginning in the 1850s, and the legacy of those activities continues to account for much of the elevated mercury concentrations in the Bay (Conaway et al., 2004). Additionally, human activities began contributing to the inputs of other contaminant metals, notably lead, to the Bay, in the 1800s (Hornberger et al., 1999; Ritson et al., 1999).

The complexity and diversity of human impacts have increased over the past two centuries with the settling and industrial development of the Bay, which is now referred to as the "urban estuary" (Nichols et al., 1986). Today, the Bay is surrounded by a megalopolis of approximately 7 million people; and the Bay and Delta, which comprise 6% of California's area are projected to contain 25% (10 million people) of the state's burgeoning population within two decades. At the same time, freshwater discharges to the Bay are increasingly being diverted to provide drinking water to two thirds of the state's population (22 million people) and to irrigate 4.5 million acres of farmland outside of its drainage basin (Knowles, 2002).

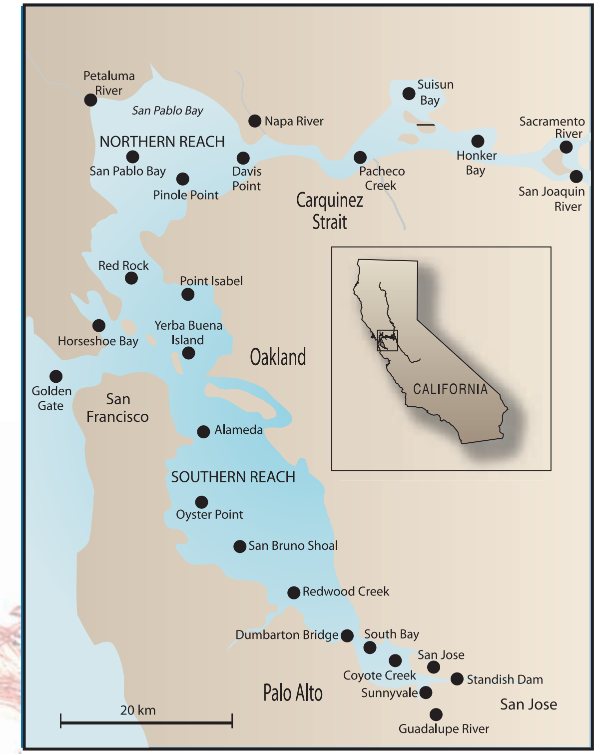

Figure 1. Billions of dollars have been spent over the past five decades to improve the water quality of San Francisco Bay. The RMP is a primary tool for gauging the effectiveness of this investment. Below is a map of the San Francisco Bay and tributaries showing the fixed stations where water and sediment samples were collected for the first nine years of the RMP. This article is based on data from these fixed stations. A new RMP sampling design with randomly distributed stations was adopted in 2002 (see page 14).

Some of the complexity resulting from this urbanization is illustrated in Figure 3. It shows the location of some of the more than 200 sewage plant and industrial discharges directly into the Bay. It also shows the disparity in natural freshwater flows into the northern (~90%) and southern (~10%) reaches of the Estuary. Conversely, 76% of the total POTW effluent released into the Estuary enters the shallow waters (typically < 2m deep) of the southern reach and only 20% enters the waters of the northern reach (Squire et al., 2002).

Lead concentrations steady in spite of load reductions

Despite limited data from previous years, variations in hydrology, and human perturbations to the system, long-term trends of some trace elements have now been characterized by studies using rigorous quality control methods. Long-term changes (hundreds of years) in lead contamination in San Francisco Bay were chronicled in sediment cores, using analyses of both lead concentration (Hornberger et al., 1999) and analyses of the different isotopes of lead in different sources (^{204}Pb, ^{206}Pb, ^{207}Pb, ^{208}Pb) analyses (Ritson et al., 1999). The analyses show human influences dating back to the California Gold Rush of 1849, when the source of sediments deposited in the Bay was altered by hydraulic mining, and when fossil fuel combustion increased within the Bay's drainage basin. Industrial lead inputs were then compounded by the operation of the Selby lead smelter (near Rodeo), which went into operation in the latter half of the 19th century, continued until 1970, and altered lead isotopic compositions and markedly elevated lead concentrations in the Bay and its watershed (Rabinowitz and Wetherill, 1972; Ritson et al., 1999; Steding et al., 2000). Other inputs of industrial lead, notably leaded gasoline, further changed lead isotopic compositions and increased contaminant lead concentrations until the 1980s, when controls were placed on those emissions and the phase out of leaded gasoline was initiated (Steding et al., 2000). Notwithstanding these controls and the passing of time, isotopic compositions of those diverse lead inputs are still evident in Bay sediments and surface waters (Rivera-Duarte and Flegal, 1994; Ritson et al., 1999; Dunlap et al., 2000; Steding et al., 2000).

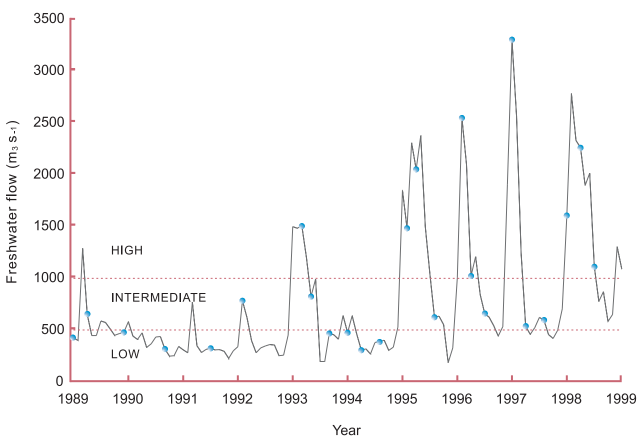

Figure 2. The Bay's freshwater inflow can have a large effect on measured contaminant concentrations. Because sample collection has taken place during varying freshwater inflow, the water quality data obtained from the cruises are often neither representative of average nor of extreme conditions. Sampling dates in San Francisco Bay from 1989–1999, under the RMP and its precursor, plotted along with freshwater discharges ($m^3 s^{-1}$) to the system during that period.

The lead isotope data were used to estimate decadal changes in industrial lead inputs to San Francisco Bay waters (Steding et al., 2000). The isotope data were used because there was no apparent decline in total lead concentrations in Bay waters, even after atmospheric emissions of industrial lead were decreased one hundred-fold with the elimination of leaded gasoline, and also after lead loadings to the Estuary from POTW effluents were reduced 20-fold over the past three decades (Squire et al., 2002). That consistency in lead concentrations in the Bay was supported by the isotope data, which also indicated that lead was retained in the Bay and that there had been no measurable decrease in inputs of historic lead to the Bay over the past decade.

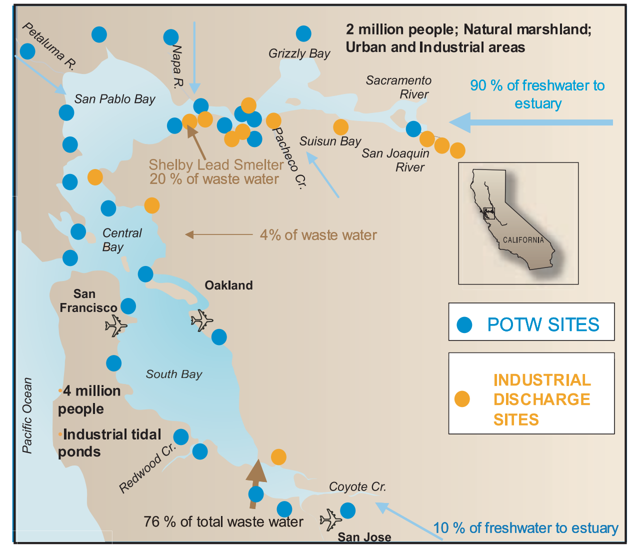

Figure 3. The complexity resulting from numerous contaminant inputs makes it difficult to assess the factors controlling long-term trends in contaminant concentrations. This map shows locations of major publicly operated treatment works (POTW) and industrial outfalls. Also shown are the relative amounts of wastewater discharged to the northern reach (20%), Central Bay (4%), and southern reach (76%); the natural freshwater discharges to the northern (90%) and southern (10%); and the location of the Selby lead smelter, which was a principal source of industrial lead for nearly a century.

The persistence of historic levels of contaminant lead in San Francisco Bay was further corroborated by statistical analysis of lead concentrations in San Francisco Bay waters (Squire et al., 2002), which confirmed that lead concentrations in the northern reach remained essentially constant over the past decade (1989–1999). The analysis also showed dissolved lead concentrations in the southern reach also remained essentially constant over that period, in spite of a concurrent 40% decline in total lead concentrations in that region. The persistence of lead concentrations in Bay waters over the past decade was attributed to i) the ongoing input from previous atmospheric deposition and industrial lead to its drainage basin that are slowly being eroded into the Estuary and ii) the internal recycling of lead between the sediments and the water column within the Bay.

Silver concentrations fall in response to load reductions

In contrast to lead, comparable analyses showed marked declines in dissolved silver concentrations in some parts of San Francisco Bay (Squire et al., 2002). Although there were (similar to lead) no quantifiable decreases in either dissolved or total silver concentrations in the northern reach over the past decade, there were marked decreases in both dissolved (70%) and total silver (40%) concentrations in the southern reach during that time. These temporal declines were attributed to the concurrent two-fold decrease in silver loadings from POTWs and a comparable decline in the silver concentration of surface sediments within that region.

Mercury concentrations remain problematic

Analyses of long-term trends in mercury concentrations in San Francisco Bay waters have yet to be conducted. However, mercury, like lead and silver, has a legacy of large inputs to the Bay spanning the past two centuries; those historic inputs are chronicled in sediment cores and surface sediment distributions; and

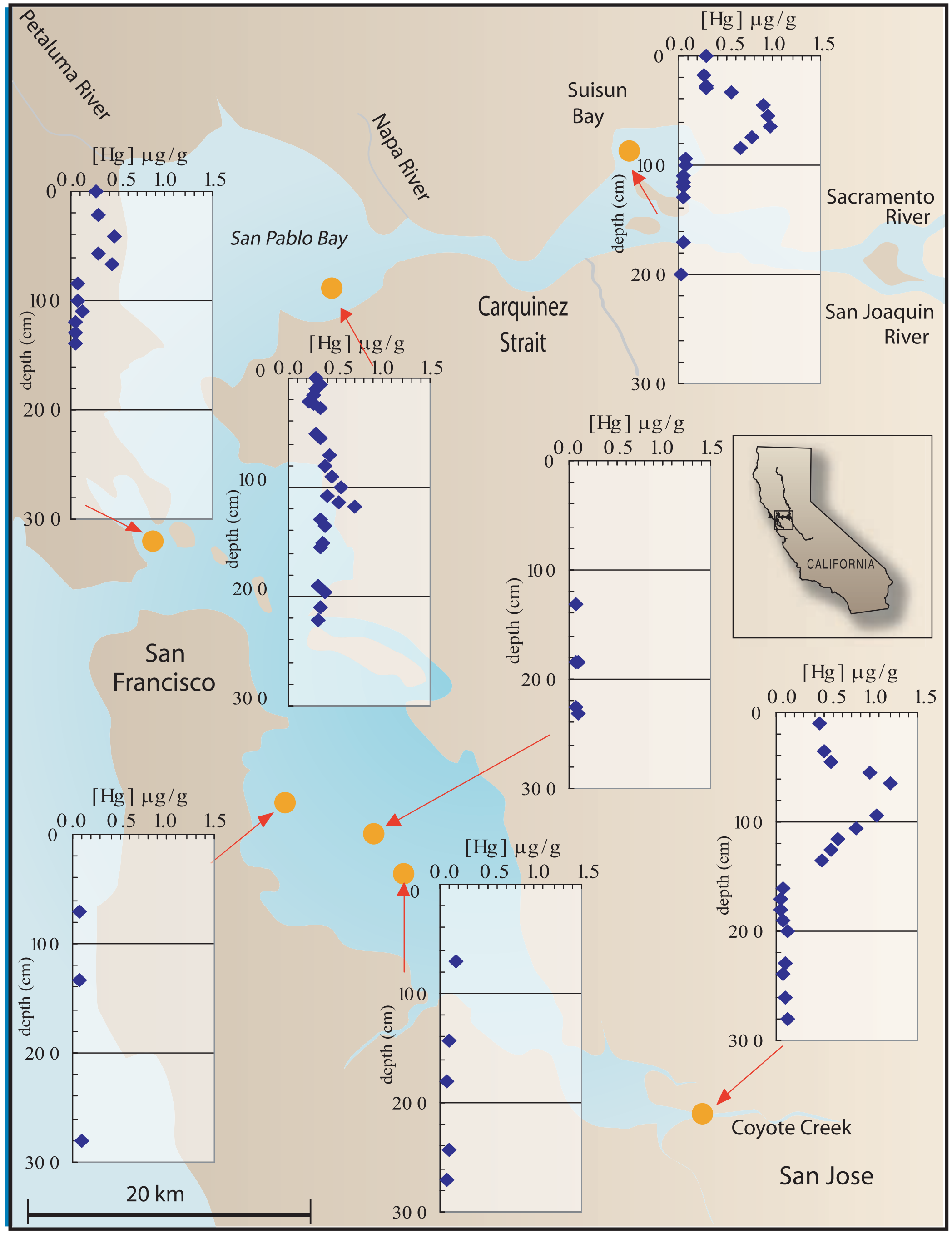

Figure 4. Mercury has a history of large inputs to the Bay spanning the last two centuries, a legacy chronicled in the Bay's sediments. These charts depict mercury concentration versus depth in sediment cores from locations in San Francisco Bay. Contemporary surface sediment concentrations in the Bay are still elevated relative to baseline conditions in most of the Bay, especially in the extreme southern reach (7-fold higher than baseline).

Solving riddles using isotopes

Our knowledge of and ability to measure chemical isotopes provides an enormously powerful set of tools, allowing us to gain new information and solve riddles in a wide variety of concerns—from past Earth climates, to fish diets, to likely sources of San Francisco Estuary lead contamination.

All atoms of a given element—for example, lead—are not identical. Some are a little heavier than others. The different "weights" of an element are called isotopes. All else being equal, heavier isotopes of a given element move more slowly than their lighter counterparts—this difference causes the isotopes to participate at different rates in chemical reactions and processes such as evaporation.

The unique history of a given portion of lead lends it a potentially unique composition of lead isotopes. Each particular pathway of lead to the Estuary environment—operation of the Selby lead smelter; combustion of leaded gasoline; erosion of lead from the Earth's crust—may be associated with a particular isotopic "signature." If we can measure the isotopic composition of lead found in Estuary water or sediment, the possibility arises of distinguishing the relative contributions of these different lead pathways.

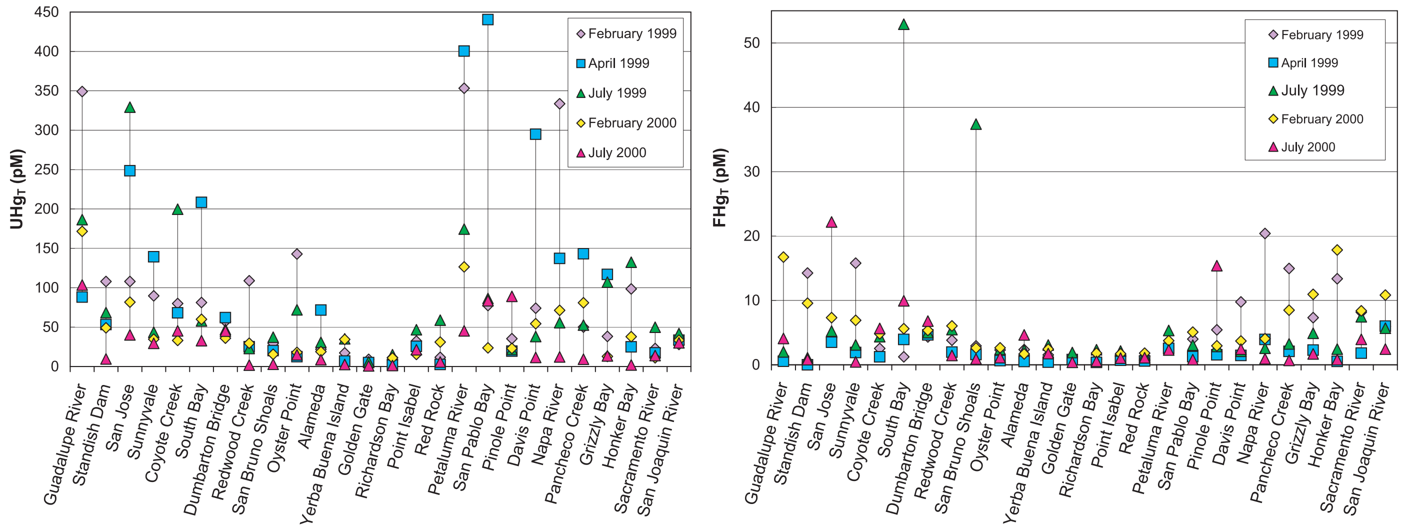

Figure 5. The distribution of mercury in sediments is mirrored in the distribution of mercury in waters of San Francisco Bay. These charts indicate surface water total mercury concentrations in unfiltered (UHg$_T$) and filtered (FHg$_T$) waters from San Francisco Bay sites in 1999–2000. Drop lines illustrate the differences in maximum and minimum values across seasons for each sampling location. Locations of sampling sites are shown in Figure 1. The UHg$_T$ concentrations generally reflect the resuspension of contaminated sediment, while the FHg$_T$ are controlled by water chemistry such as salinity and dissolved organic carbon.

those sediment distributions are reflected in surface water distributions (Conaway et al., 2003; Choe and Gill, 2003; Choe et al., 2003). In addition, current atmospheric inputs of industrial mercury to the system appear to be relatively substantial (Steding and Flegal, 2002; Conaway et al., 2003).

Historic inputs of industrial mercury to the Bay have been chronicled in sediment cores from its northern (Hornberger et al., 1999) and southern (Conaway et al., 2004) reaches (Figure 4). Both sets of cores showed baseline concentrations which were consistent with concentrations in sediments from other relatively uncontaminated estuaries. Values increased in the southern (20-fold higher than baseline) and northern (15-fold higher than baseline) reaches from inputs from mercury mining and the use of mercury in gold mining, respectively, that were initiated about 150 years ago and continued well into the 1900s. As a consequence of ongoing inputs from those historic activities and the reworking of Bay sediments—along with contemporary inputs from other industrial activities—surface sediment concentrations in the Bay are still elevated relative to baseline conditions in most of the Bay, especially in the extreme southern reach (7-fold higher than baseline).

The distribution of mercury in surface sediments is reflected in the distribution of mercury in surface waters of San Francisco Bay (Conaway et al., 2003, Choe and Gill, 2003; Choe et al. 2003) (Figure 5). Concentrations of dissolved mercury are relatively high in the northern reach, relatively low in the Central Bay, and relatively high in the southern reach. Again, that distribution is, in part, comparable to those of lead and silver because of their similar biogeochemical cycles and historic industrial loadings in the Bay.

In addition to the contribution of sediments on water concentrations, there appears to be an increasing atmospheric flux of mercury to San Francisco Bay and its drainage basin from industrial activities (Steding and Flegal, 2002). That atmospheric input is attributed to local, regional, and global emissions of industrial mercury from the combustion of fossil fuels with relatively high mercury concentrations. This is based on preliminary measurements of mercury concentrations in precipitation along the California central coast, which on average were only half as high as those measured near the Bay. That doubling in average mercury concentrations is ascribed to local and regional emissions of industrial mercury and/or other chemicals that enhance the deposition of mercury from the atmosphere within the Bay region.

Ten-fold variations in mercury concentrations in both coastal and Bay precipitation is hypothesized to be due to differences in trans-Pacific fluxes of contaminants (Steding and Flegal, 2002). These include industrial mercury, oxidants, halogens, and particulates from fossil fuel combustion in Asia (e.g., industrial mercury emissions from China are estimated to be 2-fold greater than US industrial emissions). Atmospheric inputs directly to the Bay surface and to the watershed surface (tens to hundreds of kg/year) represent an important fraction of the total mercury input (hundreds to thousands of kg/year) to the Bay (Domagalski, 2001; Conaway et al., 2003). Consequently, after presumed reductions in mercury concentrations in Bay waters associated with reductions in mining activities, those concentrations may now be staying the same or even increasing due to new industrial inputs from both local and global sources

Projections of future concentrations

Both the seasonal and decadal variations in inputs from creeks and rivers attest to the potential importance of hydraulic flushing on metal levels in the Bay (Flegal et al., 1991). Mass balance calculations, which indicate that only a small fraction (5–10%) of the leaded gasoline fallout from the late 1980s has been washed out of the San Francisco Bay's watershed (Steding et al., 2000), and the inefficient removal of that lead from watershed soils and the persistence of prior (1960–1980) gasoline lead in sediments of the Sacramento and San Joaquin rivers indicate that historic gasoline lead deposits may be retained in the watershed for decades before they are flushed into the Bay. That projected persistence is in contradiction to recent reports of rapid (annual) decreases in lead contamination in other types of ecosystems (rivers, coastal waters, and oceanic surface waters) that have been positively correlated with reductions in emissions of industrial lead to the atmosphere. The persistence is, however, consistent with previous reports on the protracted biogeochemical cycling of lead in other estuarine ecosystems.

The acquisition of a decade of data for San Francisco Bay also enables projections of the impacts of current (Chen et al., 1996) and future (Bessinger et al., unpublished ms) processes on contaminant concentrations. Figure 6 shows predicted changes in copper concentrations in Bay waters after the proposed 1–3 km expansion of San Francisco Airport runways into the Bay. Copper has been a concern in the Bay, because its concentrations have exceeded state and federal water quality criteria. However, the prediction indicated that the perturbation of the copper cycle by the proposed construction would have been negligible.

An extensively studied estuary

In addition to the RMP work, many other studies have substantially improved our understanding of the cycling and bioavailability of trace elements in Bay waters. These include other short-term and more spatially restricted studies. Consequently, San Francisco Bay is now one of the most extensively studied estuaries, if not the most extensively studied estuary, in the world for trace metals. Although there are limitations in the long-term trend analyses, they are still more rigorous than those that could be made in any other estuary. That rather disturbing observation is based on our recent review of the status of research on toxic metals in U.S. estuaries (Sañudo-Wilhelmy et al., 2004). In the review, we found that no articles have been published on contaminant metal concentrations in about half of the estuaries in the U.S.

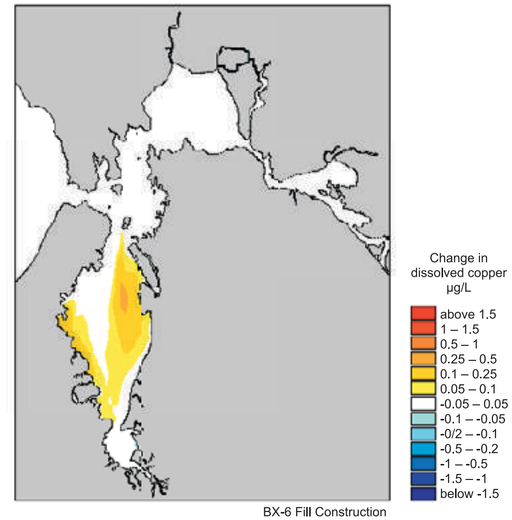

Figure 6. With a decade of reliable water quality data available, models can be developed to predict future contaminant concentrations. This map shows predicted changes in total dissolved copper concentrations in San Francisco Bay from the proposed expansion of the San Francisco airport into the southern reach of the Bay. The perturbation of the copper cycle by the proposed construction was predicted to be negligible.

In contrast, trace metal work in the Bay has included studies of biogeochemical cycles and speciation of metals within the water column and sediments, which have been briefly noted in this article, and a comparably large set of studies on trace metals in the Bay's biota, which is beyond the scope of this article. Still, our understanding of the biogeochemical cycling and toxicity of metals in the Bay is far from complete, and additional research is needed to accurately assess the health of the Bay and quantify the success of efforts to improve that status.

Lessons Learned About Metals in the Estuary:

The Importance of Long-term Clam Accumulation Data

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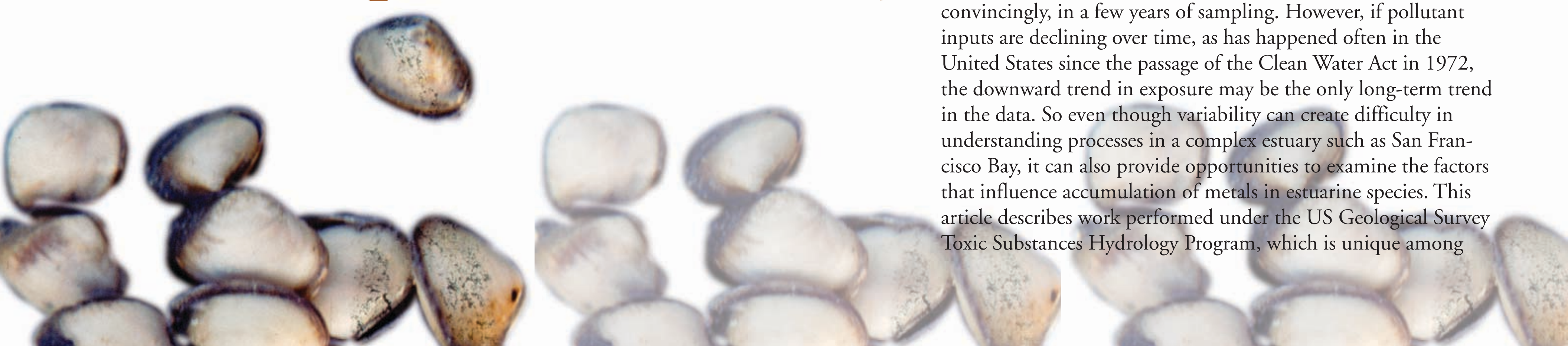
Key Points

- *Natural variability can create difficulty in understanding processes in a complex estuary such as San Francisco Bay, it can also provide opportunities to examine the factors that regulate accumulation of metals in estuarine species*
- *Freshwater inflow is a primary influence on accumulation of some metals*
- *Silver concentrations have declined significantly in the South Bay, with the greatest declines occurring in the 1980s, before the RMP began its sampling*
- *Evidence strongly points to silver (perhaps in combination with copper) as a potential disrupter of clam reproduction at concentrations well below those typically used in toxicity tests*

Introduction

Trace metals can be an influential factor in ecosystem processes, affecting the well-being of organisms, populations, and communities (Luoma 1996). Metal bioaccumulation in tissues of clams and other bottom dwelling organisms is an indicator of metal exposures that can either degrade the health of the organism, or be transferred up the food web to potentially harm higher organisms. It is critical to understand the interaction between ecosystem processes and the bioaccumulation of metals to begin to evaluate the metals' importance in the ecosystem.

Ecosystems are complex and variable. Environmental factors such as hydrology, water chemistry, sediment characteristics, and food availability fluctuate widely from year-to-year in estuaries and affect interpretation of pollutant influences. Yet on the time scale of a decade or more, consistent increases or decreases over time in the environmental factors are rare. If effects of pollutant exposure are imposed on this system, they cannot be separated, convincingly, in a few years of sampling. However, if pollutant inputs are declining over time, as has happened often in the United States since the passage of the Clean Water Act in 1972, the downward trend in exposure may be the only long-term trend in the data. So even though variability can create difficulty in understanding processes in a complex estuary such as San Francisco Bay, it can also provide opportunities to examine the factors that influence accumulation of metals in estuarine species. This article describes work performed under the US Geological Survey Toxic Substances Hydrology Program, which is unique among



estuarine studies in its long-term approach to quantitatively defining the processes that affect contaminant transport and distribution in major urbanized estuaries (Kuwabara et al. 1999).

Background of work

Bioaccumulation in the clams *Potamocorbula amurensis* and *Macoma balthica* has been used to assess both the fate and effects of trace metals in San Francisco Bay (Brown and Luoma 1995, Brown et al. 2003, Linville et al. 2002). By comparing this high-intensity, long-term data set with other long-term environmental data sets (e.g., river inflow, amount of suspended sediments in the water column, salinity, and reproduction in the clams), various processes affecting the availability of metals to the biota in the ecosystem have been examined. Four challenges to understanding trace metal bioavailability and effects illustrated by the data are discussed here:

1) do river inflows affect the bioavailability of different metals?

2) what is the influence of water chemistry (salinity)?

3) can metal effects be separated from other influences in an environment this complex? and

4) how does history affect interpretations of long-term data sets?

Freshwater inflow is a primary influence on metal accumulation

The northern portion of San Francisco Bay is influenced by large seasonal and year-to-year fluctuations in freshwater inflow from the Sacramento and San Joaquin rivers, which combine to provide 90% of the freshwater inflow into the Bay (Conomos et al. 1985). Each year is characterized by a distinct high and low inflow period driven by the Mediterranean climate of the region, snowmelt runoff, and controlled releases from the reservoirs. River inflow is highest in the winter/spring and lowest in the summer/fall. The magnitudes of these fluctuations differ among years. A major challenge in ascertaining the fate and effects of metals is understanding the influences of this highly variable flow regime.

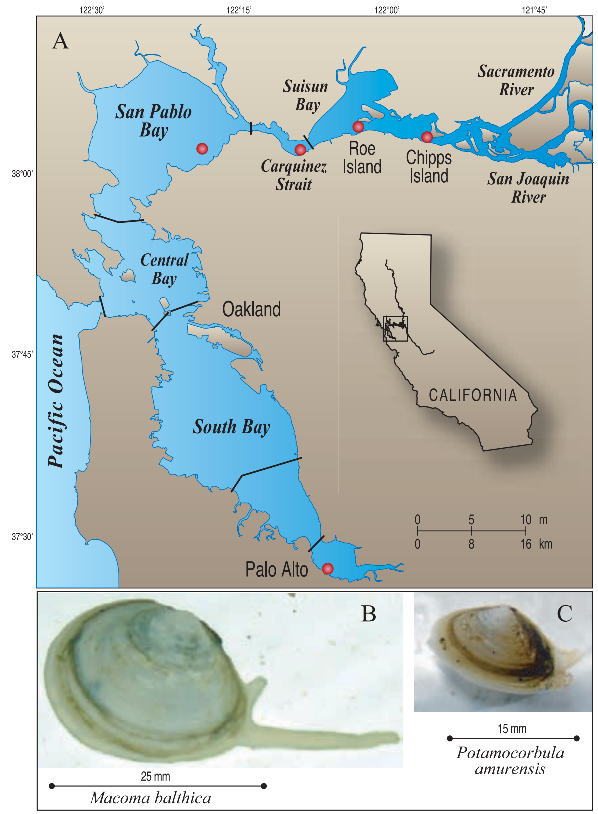


Figure 1. San Francisco Bay is a complex and variable ecosystem. A) Map of San Francisco Bay with four sites in the northern reach of the Bay (Chipps Island, Roe Island, Carquinez Strait, and San Pablo Bay) and one site (Palo Alto) in the southern portion. B) *Macoma balthica*, the deposit feeding clam collected in the mudflat at the Palo Alto site. C) *Potamocorbula amurensis*, the suspension feeding clam collected in the channel at the northern reach sites.

Our sampling occurred over a period of extreme year-to-year differences in weather and inflow. Drought conditions occurred in 1989 through 1992, and 1994, when the annual mean inflow of freshwater from the rivers was 152 - 252 cubic meters per second ($m^3\ s^{-1}$). The wet season of 1993 marked the end of a seven-year drought with annual mean inflow of 760 $m^3\ s^{-1}$. Annual mean inflow increased to a range of 1094 - 1823 $m^3\ s^{-1}$ in 1995-1999 (Interagency Ecological Program [IEP] 2002). The seasonal and yearly variability in freshwater flow exposed the species living in this segment of San Francisco Bay to changes in salinity, river-borne contaminant inputs, carbon load, and distribution of sediments and contaminants. Although inflows were highly variable from year-to-year, there was no overall trend in the variability over the 10-year study period.

The two time scales of change in inflows are examples of predictable and unpredictable variability. The extreme year-to-year differences are not predictable in advance. But, the seasonal pattern in variability of river inflow, and the environmental factors related to river inflow, is somewhat predictable. A relatively predictable spatial (landward-to-seaward) gradient in salinity also reflects the seasonal influences. In sampling over a long time period, the differences between years can be viewed as "natural experiments" that provide insights into seasonal processes. But interpreting the outcome of those experiments requires a sampling strategy that captures seasonal variability, so differences among years can be separated from variability within years. Understanding the patterns in both year-to-year and seasonal variability is critical to understanding the differences between natural and anthropogenic effects on the ecosystem.

Metal Abbreviations

- **Ag** (silver)
- **Cd** (cadmium)
- **Cr** (chromium)
- **Cu** (copper)
- **Hg** (mercury)
- **Ni** (nickel)
- **Pb** (lead)
- **V** (vanadium)
- **Zn** (zinc)

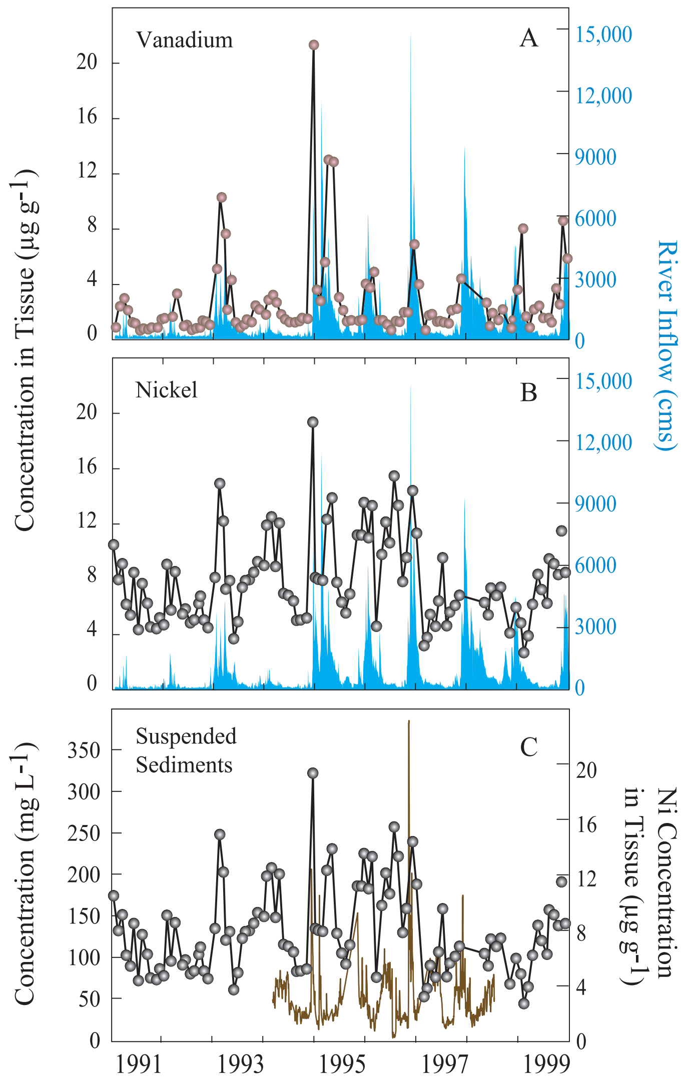


Figure 2. The seasonal patterns of vanadium and nickel in clam tissue suggest both are brought into the Bay by inflow from the Sacramento/San Joaquin rivers. In contrast, nickel also has sources within the Estuary. A) Monthly mean tissue concentrations of V in *Potamocorbula amurensis* at Carquinez Strait over the length of the study (1991-1999) compared with river inflow. Vanadium tissue concentration increased in clams only when river inflow was high during wet winter months. These data indicate that the primary source of V to the Estuary is from the rivers. B) Monthly mean tissue concentrations of Ni ($\mu g\ g^{-1}$) in *Potamocorbula* at Carquinez Strait over the length of the study (1991-1999) compared with river inflow. Nickel tissue concentrations increased in clams when river inflow was high in the wet winter months, but also increased again in the dry windy summer months. C) Monthly mean tissue concentrations of Ni ($\mu g\ g^{-1}$) in *Potamocorbula* at Carquinez Strait over the length of the study (1991-1999) compared with near-bottom suspended-solid concentration data showed evidence of Ni sources within the Bay, in particular wind/wave resuspension of bottom sediments, causing an increase in the accumulation of Ni.

Within the tissues of *Potamocorbula*, river inflow variability is the primary influence on the accumulation of the metals chromium (Cr), nickel (Ni), and vanadium (V). These metals are important because they are common in the Estuary and are environmental contaminants. They are enriched in certain rocks that are common throughout the watershed and thus are naturally high in the sediments in the Bay. Vertical cores of sediments indicate that the high concentrations of Cr, Ni, and V extend back to before the Gold Rush and the acceleration of human activities in the area (Hornberger et al. 1999). Each also has industrial sources in the northern reach of San Francisco Bay such as oil refining, chemical manufacturing, mining activities, and steel refining. Specific forms of V, Cr, and Ni that commonly occur in aquatic environments are known to be toxic, but little is known about their bioavailability in estuaries, especially regarding V.

The seasonal pattern of Cr, Ni, and V concentrations in the tissues of the clams suggests that freshwater flow into the Bay from the Delta affects their bioaccumulation. Vanadium has the strongest relationship with river inflow (Figure 2a). Vanadium concentrations increase during pulses of high inflows and are low in the tissues at all stations during low flow periods. Tissue concentrations at the most landward site, near Chipps Island, are often as low as tissue concentrations at

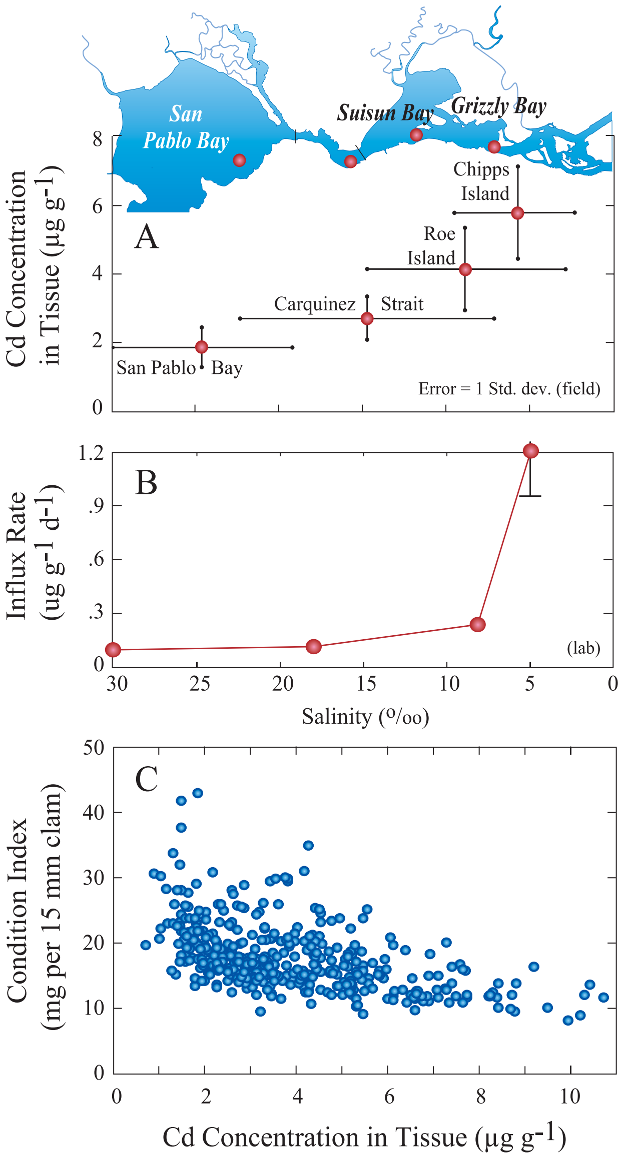


Figure 3. Salinity can also influence the bioaccumulation of contaminants. Cadmium in the tissues of *Potamocorbula amurensis* and its relationship to the salinity gradient in the northern reach of San Francisco Bay shows the influence of salinity on bioaccumulation.
A) Cadmium (µg g^{-1}) in the tissues of *Potamocorbula* at each station over the entire period of the study compared with salinity at each station. Cadmium was more readily accumulated by the clams at lower salinities.
B) Laboratory experiments confirmed that Cd at low salinities was more readily accumulated by the clam. Uptake of Cd by the clam increased as salinity decreased. This information reinforced field observations. C) Cadmium may have affected the health of the clam, as seen in this comparison with the condition index. The range of condition is greatest in clams with low Cd tissue concentrations. As Cd concentrations in the clam increased, the clams were less able to gain weight and lose weight in their normal life cycle.

the most seaward site, San Pablo Bay, during low flows. However, when river inflows increase, concentrations of V are higher in clams at Chipps Island than in clams in San Pablo Bay.

Nickel (Figure 2b) and Cr (not shown) tissue concentrations behave similarly to V during high flows. But during low flow periods, tissue concentrations of Ni (and Cr) do not decrease to the lowest levels seen in San Pablo Bay, and the land-to-sea gradient is sustained (Figure 2b). Potential input of Ni from internal industrial or sedimentary sources could explain an apparent Ni source within the Estuary that appears to add to the Ni from the watershed; the influence of these internal sources is most evident when freshwater inflows decrease (less Ni input from the watershed) (Topping and Kuwabara, 2003). Measurement of near-bottom suspended solids concentrations (SSC, the amount of sediment suspended in the water column) was used to evaluate whether resuspension of Ni and Cr trapped in the bottom sediments, during the windy summer months, might prevent summer concentrations in the clams from dropping to low values (Buchanan and Ruhl, 2001, Figure 2c). Annually, the pattern of SSC followed a pattern similar to river inflow, with highest concentrations of SSC coinciding with highest river inflow within each year. The first annual increase in SSC coincided with river inflow and peaked to the highest concentrations of the year (200-400 mg L^{-1}). These peaks were fairly short in duration (2-3 months), and then SSC decreased to concentrations representing the lowest of the year (10-20 mg L^{-1}). However, following the first peak and drop in SSC, a second rise in SSC occurred during the dry summer months (low flow period). It was not as high as the first peak of the year (75-100 mg L^{-1}), and was of longer duration (4-5 months). This second rise in SSC was similar from year-to-year in magnitude and duration and occurred when wind velocity was the greatest and resuspension of bottom sediments was dominant throughout the Bay. As mentioned above regarding river inflow, V tissue concentrations dropped to annual lows (and Bay-wide lows) at each station during the low flow periods. Vanadium tissue concentrations never increased during the second SSC rise that occurred each year during the dry summer months. In contrast to V, the seasonal pattern of Ni tissue concentrations more closely followed that of the SSC seasonal pattern. Ni concentrations peaked during the high river inflow peak, dropped to lowest annual concentrations (at each station) following that peak, and then increased again coincident with the second, longer SSC peak. This pattern was observed at every station.

The trends for Cr, Ni, and V in the tissues of *Potamocorbula* show how physical processes and natural sources within an ecosystem interact with anthropogenic inputs to affect metal bioaccumulation. Bioaccumulation of these three metals appears to be primarily controlled by the interaction of the hydrodynamics and natural sources in the watershed, with secondary influences by anthropogenic (industrial discharge) and natural processes (sediment resuspension) within the northern reach of San Francisco Bay.

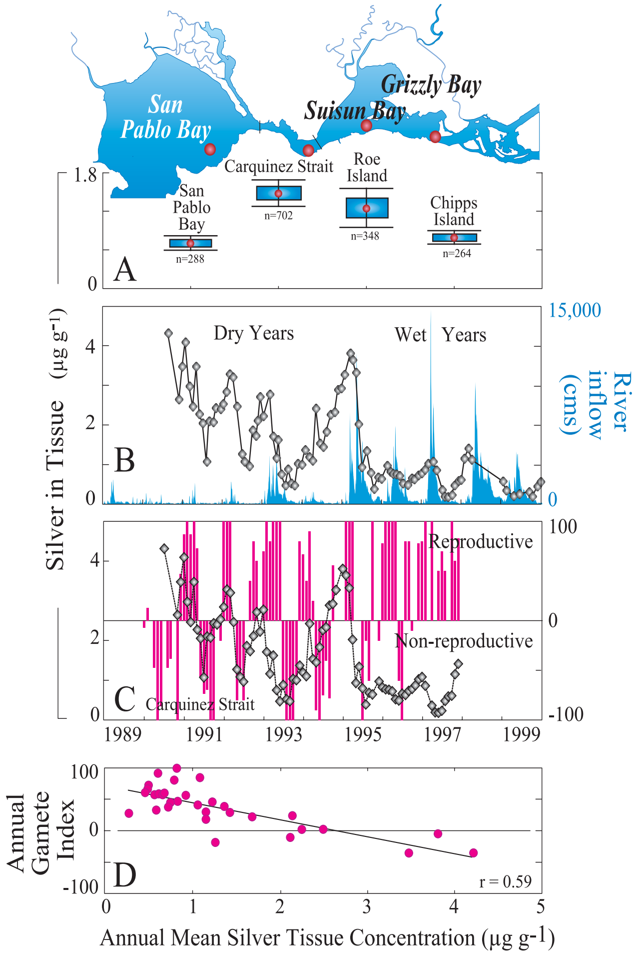


Figure 4. Long term monitoring in clams provided evidence of a detrimental effect of silver on clam reproduction.
A) Grand mean silver tissue concentrations in *Potamocorbula* at each site in the northern portion of San Francisco Bay. The points represent the grand means of all data from 1990-1999 in µg g^{-1} dry weight, with number of samples (n) per mean shown at the bottom of each box plot. The boxes represent 1 standard error and the whiskers represent 1.96 standard error. Silver concentrations in *Potamocorbula* were highest at the two mid-estuary sites (Roe Island and Carquinez Strait) and lowest at the two end-estuary sites (San Pablo Bay and Chipps Island) suggesting a mid-estuary source. B) Monthly mean silver concentrations (µg g^{-1} dry weight, left axis) in the tissues of *Potamocorbula* at Carquinez Strait plotted with the river hydrograph (m^3 s^{-1}, right axis). The bioaccumulation of silver by *Potamocorbula* was linked to the timing and length of high inflow periods of freshwater from the Sacramento and San Joaquin rivers into the northern portion of San Francisco Bay. C) Monthly mean silver concentrations (µg g^{-1} dry weight, right axis) in the tissues of *Potamocorbula* at Carquinez Strait plotted with the central tendency of the reproductively active and non-reproductively active *Potamocorbula* (left axis) at each site. Central tendency of the reproduction data is the proportion of clams that were reproductively active (% active + % ripe + % spawned) minus the proportion of clams that were non-reproductively active (% inactive + % spent) collected each month. The timing of the increase in proportion of reproductively active clams coincided with the timing of the decrease of silver in the tissues of *Potamocorbula*. D) Correlation between the annual proportions (%) of reproductive clams (*Potamocorbula*) with the annual mean silver concentrations (µg g^{-1} dry weight) at the four sites. Y-axis represents the central tendency of the reproduction data. Net reproductively active populations are positive (plot above the zero line) and net non-reproductively active populations are negative (plot below the zero line). Populations with high silver in their tissues have a significantly lower proportion of reproductive clams.

Water chemistry (salinity) affects cadmium bioaccumulation

A second challenge to understanding bioaccumulation of trace metals in San Francisco Bay is variable water chemistry (salinity). A good example is cadmium (Cd) concentrations in *Potamocorbula amurensis* (Figure 3). There is not the distinct flow-related seasonal trend in the Cd tissue concentrations that is seen in Cr, Ni, and V. However, there is a seasonally consistent spatial pattern (Figure 3a). Cadmium concentrations are highest in clams near Chipps Island and lowest in clams in San Pablo Bay. This pattern is consistent among all the years of the study. Potential sources of cadmium include oceanic upwelling, urban and industrial effluents, and mining. It is not clear which source is dominant for the clams, because both geochemical processes and anthropogenic inputs could contribute. Dissolved cadmium concentrations in the Sacramento and San Joaquin Rivers are lower than dissolved concentrations in the Pacific Ocean (SFEI 2003). However, Cd is more available to the biota from fresh water. Cadmium dissolved in river water is mostly in a form highly accessible to clams (the free ion). When the river water mixes with the ocean water, Cd forms chloro-complexes that are less available to the clams than the free ion. The spatial gradient of Cd in the clams is correlated to the salinity gradient, consistent with this switch in chemical form. Cadmium in the clams nearest the rivers (Chipps Island, lower salinity) is consistently higher than Cd in the clams closer to the ocean (San Pablo Bay, higher salinity).

The effect of salinity on Cd uptake was studied with *P. amurensis* in the laboratory. This work confirms that Cd at low salinities is more available to the clam. There was an increase in Cd uptake by the clam as salinity decreased (Figure 3b). The critical salinity where uptake greatly increased was less than 6 PSU. These results reinforced what was observed with the field data.

Long-term data sets allow for the integration of environmental data with trace metal data to further the understanding of processes in this complicated ecosystem

An indicator of the overall fitness of *Potamocorbula* measured coincident with the metal data showed significant correlations with the cadmium tissue concentrations (Figure 3c). Condition index values followed a pattern that was the inverse of the Cd tissue concentrations. Clams have their lowest condition index near Chipps Island where Cd tissue concentrations are highest and their highest condition index in San Pablo Bay where Cd tissue concentrations are lowest. The details of this relationship between Cd and condition index are not clear and have not been fully examined.

Detecting metal impacts in a complex estuary

A third challenge in understanding processes that influence bioaccumulation of trace metals in San Francisco Bay is detecting the effects of sources within the Bay in such a complex environment. The example is silver (Ag) and *Potamocorbula* (Figure 4; Brown et al. 2003). Silver is an element of importance in aquatic systems because it is highly toxic and readily accumulated through the combination of its reactivity with chlorides in seawater and the ease with which it becomes bound by suspended sediment particles (in contrast to Cd, the chloride complexation of silver in estuaries makes it available to organisms; Luoma et al. 1995). Silver occurs in such low concentrations naturally that its presence in moderate to high concentrations is almost always indicative of an anthropogenic source.

The spatial distribution of Ag in *Potamocorbula* indicated that a site-specific source occurred in the middle region of the study area (Figure 4a). On all time scales (monthly, annual means, or means for the decade), the highest Ag tissue concentrations in *Potamocorbula* occurred at the two mid-estuary sites, Roe Island and Carquinez Strait. When data from all 10 years were aggregated, concentrations at Roe Island and Carquinez Strait were significantly higher (two-fold) than the two end-estuary sites at Chipps Island and San Pablo Bay. The central estuarine peak made detection of impacts easier, because there is not a co-variance with factors like salinity or carbon/organic matter input from river flows.

Changes through time in Ag accumulation were partly driven by the hydrology of the Estuary. The variability of silver concentrations was related to the pattern of freshwater inflow from the Sacramento and San Joaquin rivers (Figure 4b); most noticeably at the site of highest silver concentrations (Carquinez Strait). However, the influence of river inflow on Ag accumulation was opposite from what was observed with Cr, Ni, and V. For example, in most years, Ag concentrations in the clams at Carquinez Strait decreased as high (winter) river inflow began. During the period of low river inflow, concentrations in the tissues steadily increased until the next episode of high river inflow began. Deviations from this pattern occurred at Carquinez Strait only in very low flow years. For example, in 1993, tissue Ag concentrations declined after the winter rains, but steadily increased through 1994 (a critically dry year), to levels as high as those seen in 1990. After 1995, there were no periods of low flow that extended beyond the typical seasonal pattern, and Ag in the tissues did not accumulate as high as they had prior to 1995. This suggested that the longer the period of low flow, the greater the accumulation of Ag.

Silver in the tissues of the clam showed a similar negative relationship with condition index as seen with cadmium. In addition, differences in silver accumulation in the tissues also correlated with changes in the reproductive activity of the clam (Figure 4c). This was not observed for Cd. Clams were collected for reproduction analysis concurrently with the clams collected for metal analyses. Gender and developmental stage of the gonads were characterized in at least 10 specimens at each time and place. Five qualitative stages of gonad development were described: inactive, active, ripe, spawning, and spent. Clams in the active, ripe and spawning stages were defined, for simplicity, as reproductively active. Clams in the inactive and spent stages were considered non-reproductive. Data for reproduction were available through 1997 (Parchaso and Thompson 2002).

Reproductive activity decreased whenever tissue concentrations of silver increased above 1 - 2μg/g Ag in the clam tissues (Figure 4c). Monthly sampling was essential for identifying the reproductive status of the different populations because of the complex annual pattern of the maturation of gonadal tissues. Each population of clams from the four sites showed a different reproductive pattern over the length of the study. At Carquinez Strait (Figure 4c), a majority of clams were reproductive in 61% of the months sampled through 1997. During the period of highest Ag contamination (Figure 4b), up until 1995 at Carquinez Strait, many months occurred when most clams were non-reproductive (Figure 4c). When Ag concentrations in the tissues were highest (annual mean > 1 µg g^{-1}), the clams were reproductively active only 20†– 60% of the year. Prior to 1995, the pattern of reproductive activity at this mid-Estuary site was different than landward at Chipps Island or seaward at the San Pablo Bay site (low Ag tissue concentrations). The proportion of reproductively mature clams at these sites averaged 80 – 100% through all years. As Ag concentrations declined, the proportion of months the clams were reproductively mature at Carquinez Strait increased to values similar to those at the Chipps Island and San Pablo Bay sites (after 1995), and remained at 80-100% for the duration of the study. Across all times and places (Figure 4d), when Ag concentrations in the tissues of the clams were at an annual mean < 1µg g^{-1}, the clams were reproductively active 80-100% of the year. A significant negative correlation between annual mean Ag tissue concentrations and reproductive activity was observed (Figure 4d).

Absent any additional data, the relationship between Ag in *Potamocorbula* tissues and reduced reproductive activity alone would not be sufficient to indicate causality. But the intense spatial and temporal sampling allowed demonstration of: 1) coincidental changes in both time and space; 2) lack of co-variance with aspects of the estuarine gradient that could cause stress (salinity) or affect food availability (freshwater input); 3) a rigorous representation of the entire reproductive cycle, so correlations were not happenstance. Brown et al (2003) discussed the necessary criteria to draw a strong association between exposure and effects in a field study and concluded that the Ag and reproductive effects in *P. amurensis* met those criteria.

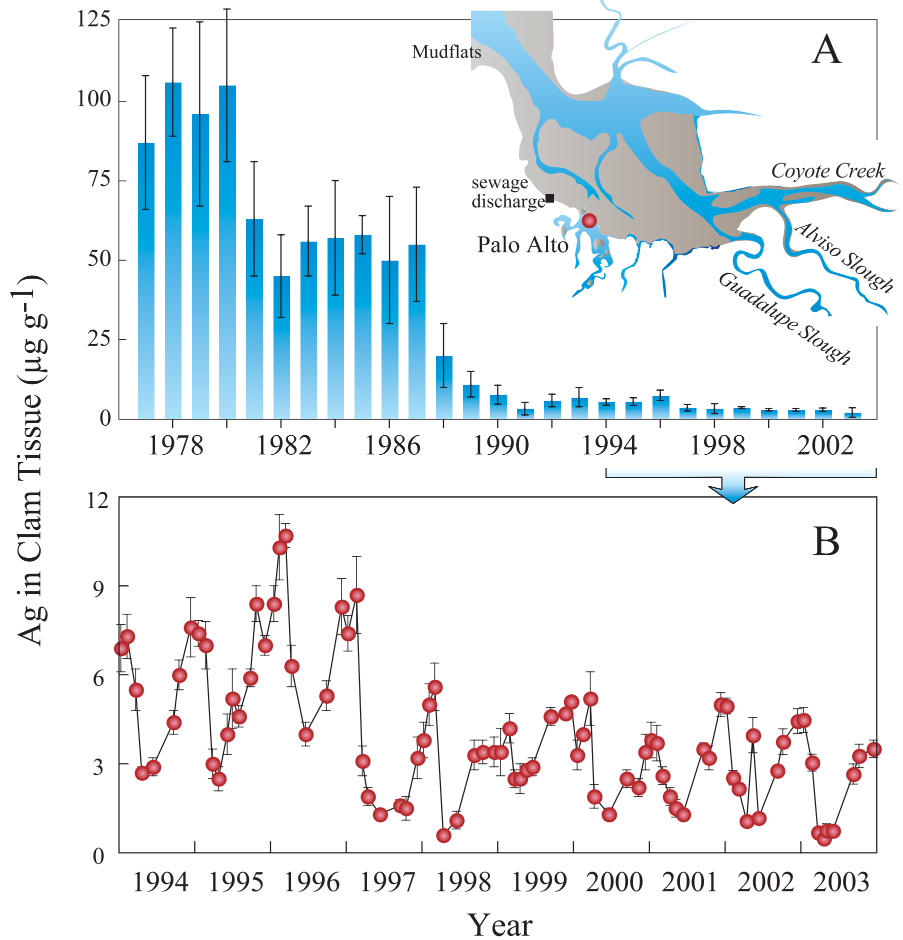


Figure 5. Annual trends of silver in *Macoma balthica* from the Palo Alto site in the southern reach of San Francisco Bay show the importance of a long term perspective when assessing progress in Estuary clean-up. A) Annual average trend of declining Ag tissue concentrations (µg g^{-1}) between 1977 and 2003. The decline in silver was unambiguous until 1990. B) After 1990, silver in the clams fluctuated in concentration from year-to-year, with some additional decline in recent years.

The importance of a long term perspective

The association observed in northern San Francisco Bay between Ag exposure as indicated by tissue concentration and changes in reproductive activity in *Potamocorbula* was also observed at a site in the southern portion of San Francisco Bay (Hornberger et al. 2000) (Figure 1a). The South Bay study generated another long time-series (1977-1999), but using a different clam species, *Macoma balthica* (Figure 1b) as a bioindicator. Metals were determined in *Macoma* and sediments at an intertidal mudflat, one kilometer south of the Palo Alto Water Quality Control Plant. Before 1990 only Cu, Ag and Zn were determined. After 1990, the data include a larger suite of metals and metalloids (Luoma et al., 1998). Like the North Bay situation, this facility had reported high concentrations of silver in their effluent.

Trends in metal concentrations in sediments varied. Concentrations of Cd, Cr, Hg, Pb, Se, and V in the 1970s and 1980s were similar to concentrations typical of the Bay region in the 1990s (Hornberger et al. 1999). In contrast, Cu and Ag concentrations declined between 1975 and 1998. Average silver concentrations in surface sediments decreased by 87% from 1.6 µg g^{-1} in 1977 to 0.2 µg g^{-1} in 1991 (the year of lowest concentration). Average concentrations of

Cu in surface sediment decreased by 50% from 86 μg g^{-1} in 1979 to 43 μg g^{-1} in the year of lowest concentration, 1993.

Concentrations of both Ag and Cu in *Macoma* were extremely high in the late 1970s, compared to those typically found worldwide in this type of bioindicator (e.g. Luoma and Phillips 1980). Because the seasonality in Cu and Ag concentrations was characterized by the near monthly sampling, unbiased comparisons of annual mean concentrations were possible. The annual average trend of declining Ag (and Cu, not shown) concentrations between 1977 and 1990 was unambiguous (Figure 5a). Studies elsewhere in South Bay support the possibility that a Bay-wide decline in Ag concentrations has occurred in that region since the 1970s (Stephenson and Leonard 1994). After 1990, both metals fluctuated in concentration from year-to-year, with some additional decline in Ag concentrations in recent years (Figure 5b).

During the course of the study, general environmental conditions varied widely, but did not progressively change. A variety of wet and dry years occurred, including El Niño events and periods of drought. Monthly salinity varied from 5 to 33 over the >20 year study period and followed seasonal and year-to-year rainfall patterns. Sediment characteristics, like particle size and total organic carbon, varied seasonally and year-to-year, but did not change progressively (Thompson-Becker and Luoma 1985). Phytoplankton productivity may influence food availability for clams in South San Francisco Bay (Nichols and Thompson 1985); but like other variables, the magnitude and frequency of phytoplankton blooms varied from year-to-year and showed no progressive trends. Thus, factors that might influence metal bioaccumulation or clam reproduction, such as food availability, redox, particle size, salinity, temperature, isolation, or hydrodynamics were not related to the progressive change in metal exposures of the clams, nor were any of the factors progressively different for the period for which reproductive data were available. The decline in concentrations of Cu in *Macoma* between 1977 and 1988 was strongly correlated to declining metal concentrations and loads from the Palo Alto treatment plant.

Hornberger et al. (2000) showed the improvement in reproductive capabilities in *Macoma* after Ag and Cu concentrations declined. Mature gonadal tissues were not observed, during any month of the year, in more than 50% of individual clams when the concentrations of Ag and Cu were elevated. The evidence indicated *Macoma* was probably not reproducing successfully at Palo Alto in most years before 1989. After contamination receded in 1989, mature gonadal tissues returned. These observations suggest chemical disruption of reproduction by Ag and/or Cu. Other environmental factors show no such association and thus are unlikely causes. Other signs of stress in *Macoma* during the period of high metal exposure supported the suggestion of chemical disruption.

One unique aspect of the Palo Alto data set is that it began before widespread monitoring was common in the Bay. The greatest declines in contamination occurred in the 1980s, before the RMP began its sampling. From RMP data alone, one might conclude that efforts to improve waste treatment in the South Bay have had little impact. But when a more robust history of South Bay is considered, it is clear that great changes happened before 1990 in response to investments in waste treatment facilities. Since the 1990s, regional processes (perhaps recycling of contamination from sediments; or inputs from urban runoff) have been more important factors in controlling contamination than improvements in any single waste treatment facility.

The remarkable consistency in biological response in two independent and separate episodes (seen in *Potamocorbula* in the North Bay and *Macoma* in the South Bay) also strongly points to Ag (perhaps in combination with Cu) as potential disrupters of reproduction in clams at concentrations well below those typically used in toxicity tests. Most natural confounding factors (food, salinity, temperature) were eliminated as possible causative agents of the reproductive effects in both cases. A lack of information on organic contaminants prevents them from being discounted as possible stressors, but patterns of the effects in space and time were not consistent with what is known about these contaminants.

Conclusions

The data presented here show that bioaccumulation and the impacts of one contaminant do not necessarily explain the patterns of bioaccumulation of other contaminants. Environmental processes affect the availability of metals in different ways. Each of the metals discussed showed different accumulation patterns, which in turn facilitated the determination of the different processes involved in creating these patterns. As compellingly shown with Ag, inputs of trace metals can cause adverse biological effects that are detected in the Estuary. Changes in flow conditions may be very important for the availability of metals to the system. For example, if flow is limited, silver is more bioavailable, so hydrology may indirectly cause impairment of reproductive processes.

Only such a long-term data set allows for the integration of hydrodynamics, sediment dynamics, reproduction, and biogeochemistry data along with the trace metal data to further the understanding of processes in this complicated ecosystem. Decadal-scale data empowers a growing understanding of the processes that influence metals in the ecosystem, of what to expect when certain conditions occur (high flows, low flows, high winds), and of the ability to apply this understanding to other organisms in the Bay, particularly the fish and bird predators of the clams.

In Pursuit of Urban Runoff in the Urbanized Estuary

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Key Points

- ***Urbanized portions of Bay Area watersheds are significant sources of most priority contaminants, including PCBs, mercury, copper, organochlorine pesticides, dioxins, diazinon, PAHs, and PBDEs***
- ***The mercury and PCB TMDLs propose large reductions in urban runoff loads***
- ***Sound science, including loads monitoring and research on urban best management practice (BMP) performance, will be essential ingredients to adaptive management of urban runoff***

The big rainstorms usually happen in the middle of the night, on a weekend. Holidays are also a strong possibility, so it was no surprise that most of the stormwater runoff activity last wet season in the Guadalupe River watershed happened in late December. "First flush effects" and "flashy" Bay Area watersheds mean that most of the contaminant transport from urban runoff to San Francisco Bay happens during the first hours of the big rainstorms of the year. In order to measure this transport, scientists must maintain a vigilant watch of unfolding weather patterns and be prepared to rapidly drop everything or jump out of bed, gather their equipment, and rush to the sampling station at any time of day or night. In water year 2004 (October 2003 to September 2004) the biggest storm started at 2 A.M. on December 16, 2003. With other storms occurring on December 14, December 19, December 28, and December 31, Christmas was narrowly averted but New Year's Eve was not.

For the past two years Dr. Lester McKee and a highly dedicated team of SFEI scientists have been committed to collecting samples to characterize contaminant transport by stormwater runoff in the Guadalupe River watershed (the "Guadalupe River Study"). How do these scientists explain to their partners why they must spend the night standing in the wind and rain on a bridge near the San Jose airport instead of asleep in bed with visions of sugarplums dancing in their heads? Put simply, the answer is that continuing inputs of persistent contaminants to the Bay from urban runoff are predicted to delay by decades the elimination of the Bay's water quality problems. Urban runoff transports significant amounts of many priority contaminants to the Bay, such as PCBs, mercury, and legacy pesticides, and seems to be where regulators are looking for potential load reductions that would accelerate recovery of the Bay from contamination by these chemicals. For these reasons, the Draft PCB Total Maximum Daily Load (TMDL) Project Report (SFBRWQCB 2004) and the Mercury TMDL Project Report (SFBRWQCB 2003) both emphasize load reductions from urban runoff as a means of improving water quality in the Bay.

This article summarizes the findings of a recent literature review (McKee et al. 2003) that established many important concepts regarding contaminant transport by urban runoff in the Bay Area. Recent fieldwork on the Guadalupe River has demonstrated some of the concepts described in the literature review and has also led to some interesting new discoveries. The article will briefly describe why urban runoff is such an important pathway for contaminant input to San Francisco Bay, where the contaminants are coming from, how transport occurs, and what management options are being considered to reduce loads.

The Urbanized Estuary

One of the most important scientific publications about San Francisco Bay, published in 1979, was titled: San Francisco Bay: The Urbanized Estuary (Conomos 1979). That label becomes more appropriate with each passing year. A natural color, satellite image of the Bay Area taken in 1999 illustrates this well (Figure 1), with a gray fringe of urbanized land surrounding the Bay, especially the Central and South Bay regions. This urban fringe developed mostly over the past 100 years, spreading from early urban centers in San Francisco, Oakland, and San Jose (Figure 2), and is where most of the 7 million Bay Area residents live and work today. This is also where many of the industrial and commercial activities that are sources of contamination to the Bay have occurred in the past or are occurring today. As the Bay Area population continues to grow, with another one million people expected by 2020 (Figure 3), the urban fringe will continue to expand and exert a large influence on water quality in San Francisco Bay.

Bay Area watersheds generally consist of a non-urban upper watershed that begins in the Coast Range hills surrounding the Bay and a lower watershed that includes the urban fringe (Figure 4). Important features of the landscape in the upper watershed from a contaminant loading perspective include historic mercury mines and associated piles of tailings and contaminated streambeds, reservoirs that modulate water flow and trap mercury-contaminated sediment particles, large areas of open space with natural deposits of heavy metals and that provide a large surface for deposition of contaminants from the atmosphere, and, at lower elevations, agricultural lands that are sites of historic and present pesticide application. The non-urban upper watersheds in the Bay Area can be significant sources of mercury and agricultural pesticides, and minor sources of PCBs and other priority contaminants.

The lower parts of the watersheds are predominantly urban and characterized by heavy use of motor vehicles (and the associated vehicle emissions and paved surfaces), industrial activity, and urban and suburban use of chemicals for pest control and other applications (Figure 4). Urbanized lower watersheds in the Bay Area are significant sources of most priority contaminants, including PCBs, mercury, copper, organochlorine pesticides, dioxins, diazinon, PAHs, and PBDEs.

For example, surveys of sediments in creeks and storm drains of the Bay Area give us a glimpse of the distribution of PCB contamination in urban areas (Figure 5). PCBs are ubiquitous at low concentrations, due to their tendency to volatilize into the atmosphere and then redeposit in watersheds. For this reason, PCBs are measurable throughout the watershed, including the non-urban upper watershed. Since environmental PCB contamination is primarily associated with industrial sites where PCBs were used in capacitors and transformers, as hydraulic fluids, and in other applications, sediments with higher concentrations have been almost exclusively found in the urbanized lower watershed.

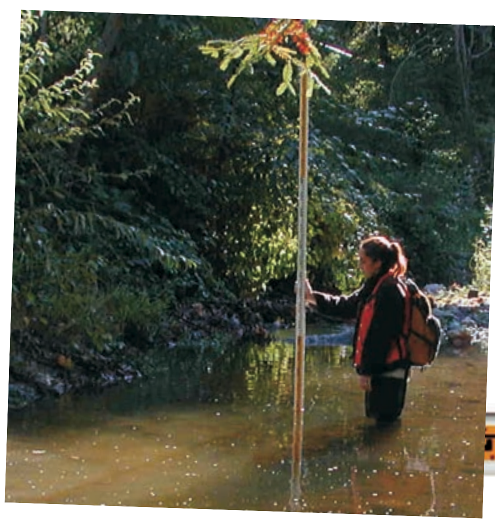

Figure 1. A natural color satellite image of the Bay Area taken in 1999 clearly illustrates the grey urban fringe surrounding the Bay, especially the Central and South Bay regions. This urban fringe is where most of the 7 million Bay Area residents live and work. This is also where many of the industrial and commercial activities that are sources of contamination to the Bay have occurred in the past or are occurring today. As the Bay Area population continues to grow, the urban fringe will continue to expand and to exert a large influence on water quality in San Francisco Bay. (Photo taken by LANDSAT, July 7, 1999. Image obtained by Jeff Kapellas, San Francisco Bay Regional Water Quality Control Board.)

For PCBs and mercury, urban runoff from these lower watershed regions appears to be the second largest pathway for contaminant transport into the Bay – only loads from the Central Valley carried by the Sacramento and San Joaquin rivers are larger. The urban fringe therefore has a large influence on water quality of the Bay.

Several characteristics of urban lands in the Bay Area make it challenging to measure loads from urban runoff. Urban areas have a high proportion of paved surfaces, which leads to more runoff and more rapid runoff during storms than would occur from unpaved surfaces. Urban areas are also dominated by storm drains and flood control channels rather than natural creeks, and this also leads to more rapid water flow and higher peak flows. Rainstorms over urban areas therefore lead to the rapid flow of large volumes of water and associated contaminants toward the Bay. Since urban zones are in close proximity to the Bay, urban stormwater enters the Bay within a matter of a few hours after the rain first begins to fall. This is what is meant by the term “flashy.” Directly measuring contaminant concentrations in this rapidly flowing water requires that scientists respond very quickly when the rain begins to fall, requires special equipment, and a mindfulness of safety.

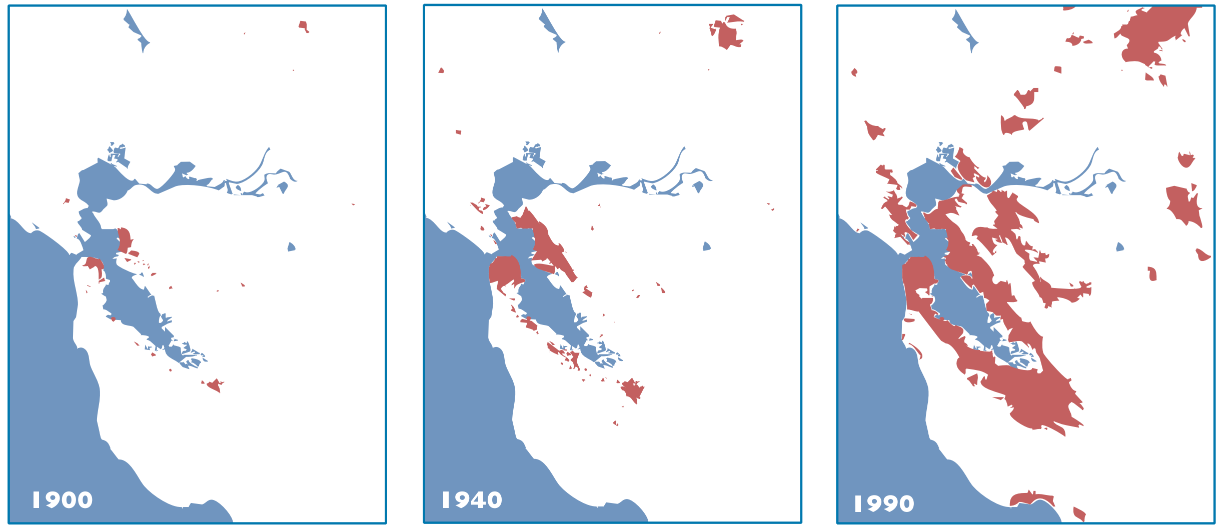

Figure 2. The urban fringe surrounding the Bay developed mostly over the past 100 years, spreading from early urban centers in San Francisco, Oakland, and San Jose. Graphic from: Beach, D. 2002. Coastal Sprawl: The Effects of Urban Design on Aquatic Ecosystems in the United States. Pew Oceans Commission, Arlington, Virginia. <www.pewoceans.org>

An Elusive Subject

The Clean Water Act is over 30 years old, and urban runoff has long been known to be a major pathway for contaminant transport to the Bay (e.g., Gunther et al. 1987). Why are we only now starting to obtain good estimates of loads from urban runoff? The answer is that urban runoff in the Bay Area is very difficult to measure due to extremely high variability on time scales ranging widely from hour-to-hour to year-to-year. The Guadalupe River Study, jointly funded by the Clean Estuary Partnership and the RMP, is a determined effort to tackle this difficult subject. Monitoring at the downstream end of the Guadalupe River is providing detailed information that is illustrating important concepts regarding transport of contaminants by urban runoff.

Rainfall is the driving force behind urban runoff, and rainfall is highly variable over several different timescales in the Bay Area's Mediterranean climate. Storm flows and contaminant loads both vary greatly over the course of a storm (Figure 6A). Flows and concentrations rise rapidly in response to rainfall. For example, in the largest storm of the year on December 16, 2003, flows in the Guadalupe rose from 200 cubic feet per second (cfs) to 4500 cfs in a matter of about 6 hours. Peak flows typically last for about two or three hours, then rapidly decline. Concentrations of some contaminants, such as PCBs, increase in response to increased flow, leading to very large loads in short

The ***non-urban upper watersheds*** *in the Bay Area can be significant sources of mercury and agricultural pesticides, and minor sources of PCBs and other priority contaminants...*

*...****Urbanized lower watersheds*** *in the Bay Area are significant sources of most priority contaminants, including PCBs, mercury, copper, organochlorine pesticides, dioxins, diazinon, PAHs, and PBDEs.*

periods of time. Measuring these peak flows and concentrations is critical to accurately estimating urban runoff loads.

Flows and loads also vary considerably between storms (Figure 6B). In general, the largest storms of the year carry the largest contaminant loads, due not only to the high volumes but also higher concentrations of sediment and many contaminants. During high flows, the water in creeks and storm drains becomes murky with suspended sediment because the higher velocity waters are more effective at suspending and transporting contaminated soil and sediment particles downstream. In addition to variation in flow, another phenomenon causing variation between storms is the "first flush" effect, in which the first storms of the wet season exhibit higher concentrations than storms later in the rainy season. During the dry season, dust, oils, and chemical contaminants accumulate on the surface of the watershed. The first storms of the rainy season wash this accumulated material off of the watershed surface and transport it down to the Bay. The largest storms of the rainy season account for the majority of contaminant loading. In the Guadalupe River Study water year 2003 (October 2002 to September 2003), 53% of the total annual PCB load occurred during the storms in the second half of December. Sampling these storms at the right hour was critical to accurately measuring loads.

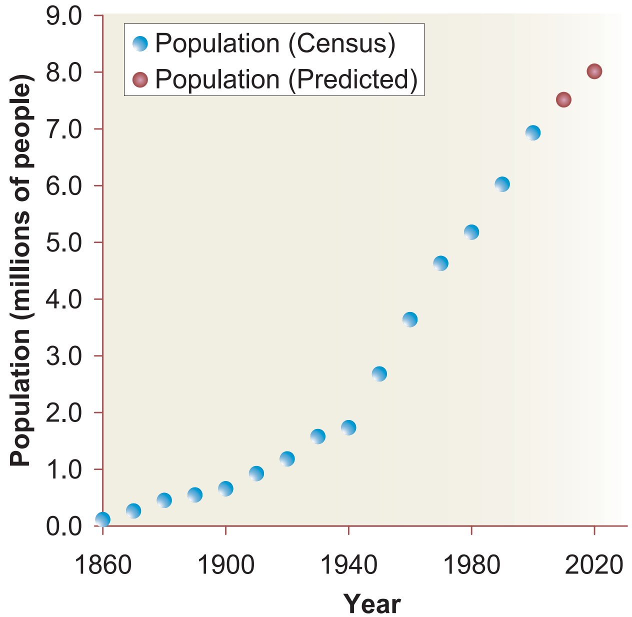

Figure 3. As the Bay Area population continues to grow, with another 1 million people expected by 2020, the urban fringe will continue to expand and to exert a large influence on water quality in San Francisco Bay.

Flows and loads can also vary significantly from year to year ("interannual variation"). Annual rainfall in the Bay Area varies greatly (Figure 6C). For example, in dry years total annual rainfall at San Francisco can be as little as 8 inches, while in wet years it can be as high as 47 inches. Contaminant loads are correspondingly larger in the years with higher rainfall.

This wide variation at multiple time scales means that in order to accurately measure contaminant loads from urban runoff, it is necessary to sample the largest storms of the year at precisely the right hour. This is why scientists endeavoring to measure these loads must be willing to jump into action as soon as the storm clouds start to roll in. The high degree of interannual variation means that monitoring programs intending to measure urban runoff must include long-term, multi-year commitments in order to characterize the spectrum of variation in annual rainfall. It is especially crucial to capture the high rainfall years, when much of the transport from a long-term perspective occurs.

The Guadalupe River watershed is the first Bay Area watershed where careful load estimation techniques are being applied. Another challenge in measuring urban runoff that has yet to be tackled is the spatial variation from watershed to watershed. Bay Area watersheds probably behave similarly in a general sense, but there is likely to be some degree of variation among watersheds. Some contaminants, like PCBs and mercury, are spread unevenly throughout the landscape, and will likely be more variable among watersheds than other contaminants such as household pesticides or automobile emissions and wear debris (e.g., brake pad dust and crankcase oil drippings). The strategy being employed to deal with this spatial variation, with a reasonable budget and

amount of effort, is to carefully select watersheds for study that are representative of the range of watershed types in the region.

Urban Runoff Carries Significant Loads of Contaminants to the Bay

The Guadalupe River Study has confirmed that urban runoff carries significant quantities of contaminants to the Bay. This conclusion is primarily based on measured PCB loads, which predominantly originate from the urbanized lower watershed. The Guadalupe also carries significant loads of mercury, including mercury from urban runoff, but the urban runoff mercury measured at the River mouth is smaller than and hard to distinguish from the large loads from the historic mercury-mining district in the upper watershed. PCB loads are discussed here as an index of urban runoff loads from the Guadalupe River watershed.

PCB loads from the Guadalupe River watershed in water year 2003 totaled about 2 kg. The Guadalupe River watershed is the fifth largest watershed in the Bay Area, 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), loads from other Bay Area watersheds can be estimated by assuming that they 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 is about 25 kg per year. Since the Guadalupe River had average streamflow in water year 2003, this might be a reasonable estimate of the average annual loading. This estimate is not far off from the estimate of 34 kg per year used in the draft PCB TMDL Project Report (SFBRWQCB 2003) (developed using a different approach based on PCB concentrations in sediments combined with estimates of sediment transport to the Bay). More than 99% of the load calculated for the TMDL Report was attributed to urban, rather than non-urban, runoff.

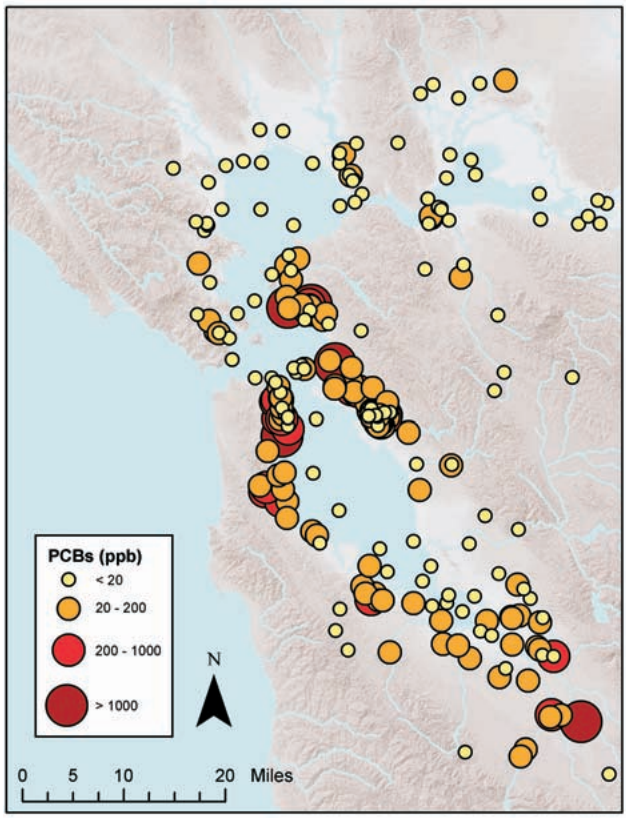

Figure 5. Sediments with higher PCB concentrations have been almost exclusively found in the urbanized lower watershed. Surveys of sediments in creeks and storm drains of the Bay Area give us a glimpse of the distribution of PCB contamination in urban areas. PCBs are measurable throughout the watershed, including the non-urban upper watershed, due to their tendency to volatilize into the atmosphere and then redeposit in watersheds. Environmental PCB contamination is primarily associated with industrial sites where PCBs were used in capacitors and transformers, as hydraulic fluids, and in other applications; these sites are primarily located in the urbanized lower watershed.

Figure 4 (facing page). Conceptual diagram of contaminant transport from urban watersheds of the Bay Area. Bay Area watersheds generally consist of a non-urban upper watershed that begins in the hills surrounding the Bay and a lower watershed that includes the urban fringe. The non-urban upper watersheds in the Bay Area can be significant sources of mercury and agricultural pesticides, and minor sources of PCBs and other priority contaminants. The lower parts of the watersheds are predominantly urban and characterized by heavy use of motor vehicles (and the associated vehicle emissions and paved surfaces), industrial activity, and urban and suburban use of chemicals for pest control and other applications. Urbanized lower watersheds in the Bay Area are significant sources of most priority contaminants, including PCBs, mercury, copper, organochlorine pesticides, dioxins, diazinon, PAHs, and PBDEs.

An annual PCB load of 34 kg from urban runoff is a significant input. The only other pathway with a greater estimated annual load in the TMDL Project Report is Delta outflow (42 kg). The Delta outflow load in the TMDL Report is a preliminary estimate based on data that were not ideally suited for load estimation. A study similar to the Guadalupe River Study is currently underway in the RMP to accurately measure PCB loads from Delta outflow. Preliminary estimates based on these data are lower than the 42 kg listed in the TMDL Report, and suggest that loads from the Delta and from urban runoff are approximately equal. The total annual PCB load estimated in the TMDL Report is 83 kg – this estimate is also subject to revision, but indicates that urban runoff accounts for a large fraction of the overall annual load to the Bay. The urban runoff load is therefore significant relative to both other inputs and the overall estimated input. The urban runoff load is also significant relative to the 10 to 20 kg annual inputs predicted by a mass budget model (Davis 2004) to delay recovery of the Bay from PCB contamination over the next several decades.

For several reasons, it is also possible that inputs of PCBs and other contaminants from urban runoff are more likely to contribute to accumulation in Bay food webs (and water quality impairment) than loads from Delta outflow. First, contaminant loads from the Delta enter the Estuary at a single point in the North Bay, a part of the Estuary that undergoes more rapid flushing than the South Bay. Second, Delta loads are based on transport of sediment particles with relatively low concentrations of contaminants carried by a very large volume of water. Third, during very high flows, some of this water and sediment load is carried all the way through the Estuary and out through the Golden Gate. In contrast, several characteristics of urban runoff inputs are likely to lead to more effective trapping of these materials in the Bay. 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. In addition, the sediment particles carried by urban runoff have relatively high contaminant concentrations. Finally, 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.

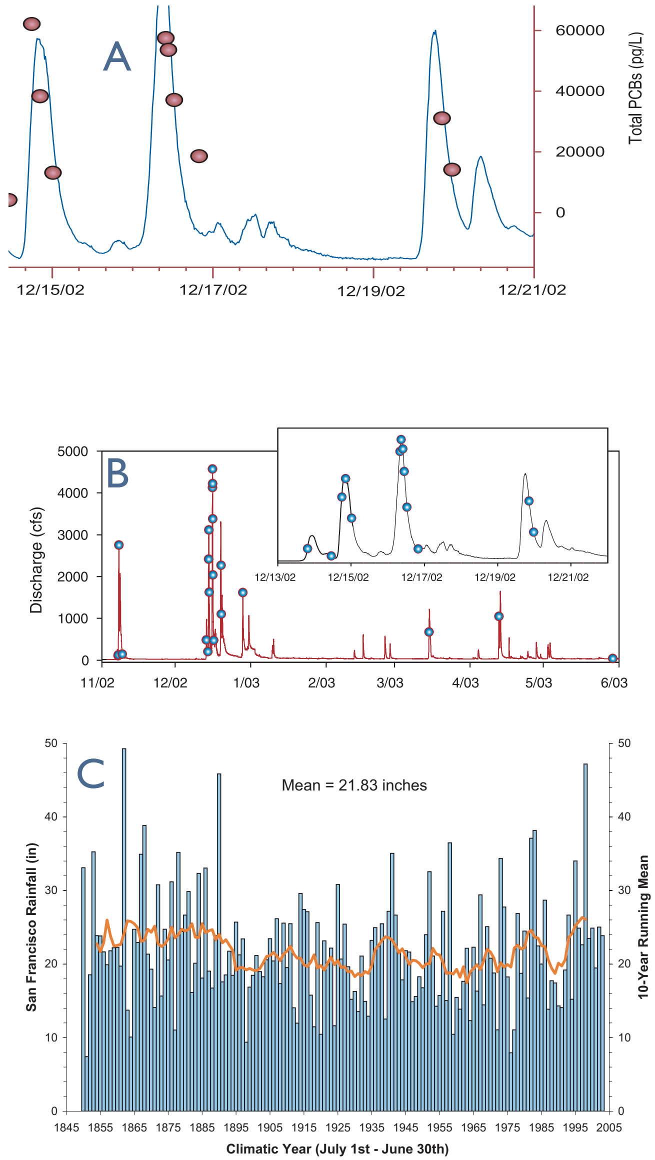

Figure 6. Contaminant inputs to the Bay from urban runoff are very difficult to measure because conditions can change dramatically hour-to-hour and year-to-year. Storm flows and contaminant loads both vary greatly over the course of a storm (Figure 6A). Capturing these peak flows and concentrations is critical to accurately estimating urban runoff loads, which means that sampling must be performed at precisely the right hour. Flows and loads also vary considerably between storms (Figure 6B). In general, the largest storms of the year carry the largest contaminant loads, due not only to the high volumes but also higher concentrations of sediment and many contaminants. Flows and loads can also vary significantly from year to year ("interannual variation"). Annual rainfall in the Bay Area varies greatly (Figure 6C). For example, in dry years total annual rainfall at San Francisco can be as little as 8 inches, while in wet years it can be as high as 47 inches. Contaminant loads are correspondingly larger in the years with higher rainfall. This wide variation at multiple time scales means that in order to accurately measure contaminant loads from urban runoff, it is necessary to sample the largest storms of the year at precisely the right hour. The high degree of interannual variation means that monitoring programs intending to measure urban runoff must include long-term, multi-year commitments in order to characterize the spectrum of variation in annual rainfall.

(Rainfall figure: Jan Null, Golden Gate Weather Services)

A Management Challenge

While the diffuse and fleeting nature of urban runoff makes it difficult to measure, it is even more difficult to manage. If control of urban runoff were easier, much more progress would have been made since the passage of the Clean Water Act in 1972. Nevertheless, the Mercury and PCB TMDL reports indicate that further reductions in overall contaminant loads to the Bay will depend heavily on reductions in urban runoff. The Mercury TMDL calls for a reduction of urban runoff loads from 160 kg per year to 82 kg per year, with other large load reductions targeted for Delta outflow and runoff from the historic mining district in the Guadalupe River watershed. The draft PCB TMDL Report calls for a 32 kg per year reduction in urban runoff inputs, from 34 kg per year to 2 kg per year. This is the largest load reduction targeted for PCBs. The feasibility of achieving this proposed load reduction will be a focus of discussion as the PCB TMDL moves forward.

The Mercury and PCB TMDL reports identify several possible measures to control contaminant loading from urban runoff. For mercury, source control and pollution prevention activities are discussed, including fluorescent light bulb and thermometer collection and disposal programs, and other household hazardous waste collection programs. Proposed control measures specific to PCBs include cleanup of "hotspots" on land, in storm drains, and in the vicinity of storm drain outfalls. Loads of mercury, 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 that cover larger, more diffuse areas in the urban landscape. Although it is known that these measures do make an impact on contaminant loads, there is limited scientific information available presently that can be used to estimate the magnitude and therefore the likelihood of success towards achieving the TMDL loading targets.

Addressing Information Needs

Given a subject as challenging to measure and manage as urban runoff, an adaptive management approach is essential. "Adaptive Implementation of TMDLs – the Mercury Example" on page 16 provides a detailed discussion of this topic.

Sound science, including loads monitoring and research on urban best management practice (BMP) performance, will be essential ingredients to adaptive management of urban runoff. The RMP plans to continue providing partial funding for the Guadalupe River Study in 2005, and with a bit of luck may have the opportunity to measure urban runoff loads during a year with above average rainfall and flow. Some of the local agencies are presently conducting feasibility studies to determine how their in-place programs for wastewater and stormwater management are already reducing loads of priority contaminants such as PCBs.

Over the next three years, SFEI will be leading another major effort to evaluate the effectiveness of urban runoff BMPs with funding provided by Proposition 13. The project titled "Regional Stormwater Monitoring and Urban BMP Evaluation: A Stakeholder-Driven Partnership to Reduce Contaminant Loadings" is a collaboration between SFEI, BASMAA, and the San Francisco Bay Regional Water Quality Control Board (SFBRWQCB). In this project, we will conduct detailed reviews of the effectiveness for urban BMPs for reducing trace contaminant loads in other parts of the United States and in other countries. We will use this information to make rough estimates of the effectiveness of stormwater management programs in the Bay Area, to develop conceptual models of contaminant processes, and to finalize design of field studies to monitor BMPs more closely. In addition, some of the project money will be used to develop a model for characterizing landscape features in our watersheds and associated suspended sediment loads entering the Bay. This is an important first step for modeling the contaminants that are carried on sediment particles such as mercury and PCBs. Some of the project money is also assigned to improving our knowledge on how storm drains transmit stormwater to the Bay.

Overall, by 2007, consistent with adaptive implementation of the TMDLs, we will be in a much better position to accurately estimate total annual loadings of contaminants to the Bay, reduce these loadings through sensible management actions in our urban watersheds, and measure the success of our efforts.

Recent studies document the magnitude of diffuse sources of pollutants attached to soil and sediment particles in watersheds draining into the Estuary and their role in delaying recovery of water quality. Seasonal and episodic pulses of sediment-associated pollutants into streams, rivers, and ultimately the Bay represent a difficult management challenge.

The San Francisco Bay Water Quality Index: A Tool to Communicate Progress Toward Reaching Environmental Standards

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Key Points

• The Water Quality Index is one of eight Scorecard indexes providing a broad overview of San Francisco Bay ecosystem health

• The water quality grade for the Bay for 2001 is a C

• Efforts are underway to refine the Index for continued use

Assessing and monitoring water quality in a large and complex ecosystem such as San Francisco Bay is challenging. San Francisco Bay is a dynamic estuary, connected to large rivers and small ephemeral streams, urban and agricultural watersheds, and the Pacific Ocean. The Bay is one of the most urbanized estuaries in the United States, and receives polluted runoff from urban, industrial, and agricultural areas along its shores and from its vast watershed. Transport of many contaminants into the Bay coincides with periods of high freshwater inflow, episodic and often short-duration weather events in California's Mediterranean climate. Dispersal of contaminants within the Bay is driven by multiple tributary inflows, strong tidal influences, and the complicated topography of the Bay. The list of contaminants detected in Bay waters continues to grow: new chemicals replace those found to be too harmful while legacy chemicals, discharged into the Bay or its tributaries years ago, still seep into Bay waters. It is essential to monitor and report the status of these pollutants to understand the overall condition of the Bay, discover where problems exist, and detect new problems as they arise.

A water quality index can help facilitate these goals and summarize water quality problems to galvanize public involvement and support for clean-up efforts. The Bay Institute has developed an Ecological Scorecard for San Francisco Bay comprised of eight condition indices, including a Water Quality Index (Figure 1). The Water Quality Index measures the levels of contamination of San Francisco Bay waters for several classes of toxic compounds that are harmful to aquatic life and impair ecosystem function. The Index aggregates the results of five "indicators" or contaminant categories: pesticides, trace elements, PCBs, PAHs, and dissolved oxygen.

An Index Facilitates Communication

Pollution can harm the plants, animals, and people that live in and around the Bay, reduce the productivity and health of the ecosystem, and contaminate fish, birds, and shellfish to the point at which they are not safe to eat. Decision-makers and the general public are frequently unaware of these problems and do not know where to obtain consistent and reliable information on water quality in the Bay region. The San Francisco Estuary Regional Monitoring Program for Trace Substances (RMP)[1] and the U. S. Geological Survey Ecology and Contaminants Project are examples of projects that have begun to bridge this gap by providing consistent yearly reports for managers and the informed public. However, there is still a need for information that can be readily communicated to the public and decision-makers who want concise information about the state of the Bay. "Is water quality good? Is it getting better or worse?" These are basic questions for which the average person wants straightforward answers. An index can provide a summa-

Ecological Scorecard

SAN FRANCISCO BAY INDEX

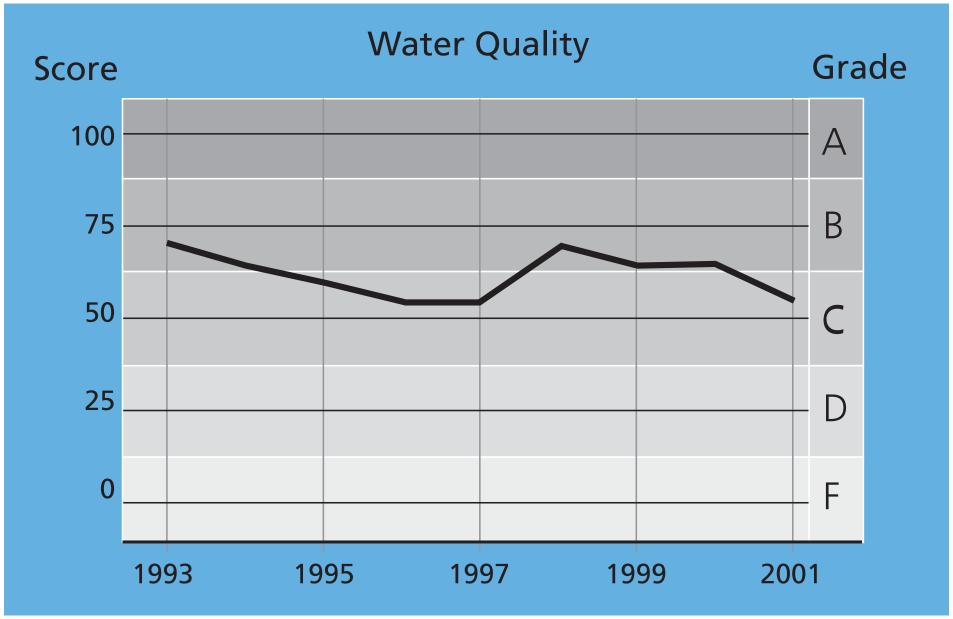


Figure 1. The Water Quality Index is one of eight Scorecard indexes providing a broad overview of San Francisco Bay ecosystem health. The index aggregates the scores of five indicators (contaminant groups) calculated from RMP data: pesticides, trace elements, PCBs, PAHs, and dissolved oxygen. The score for 2001 is 55 and the grade is a C. The water quality index has fluctuated from a B to a C indicating good to fair conditions during the recent time period and the trend is relatively stable. Limited historic data indicate that for some contaminants, conditions have improved, hence the upward arrow for the long-term trend.

Grade	Indicator	Long-term	Short-term
D+ Score = 32	**Habitat** Bay habitat loss is slowly being reversed, but it could take nearly 200 years to reach the tidal marsh restoration goal.	↓	↑
D Score = 29	**Freshwater Inflow** Reduced inflows are still degrading the Bay ecosystem, and recent gains from wetter years and new standards are being eroded	↓	↓
C Score = 55	**Water Quality** Open waters are cleaner, but standards are not met in parts of the Bay. Toxic sediments and storm runoff are a major problem.	↑	↔
F Score = 10	**Food Web** Plankton levels in the upper Bay have crashed, reducing food sources for fish and birds. Alien species are locally dominant.	↓	↔
B- Score = 63	**Shellfish** Crab and shrimp numbers are increasing, but commercial harvest is still down from previous high levels.	↓	↑
C- Score = 39	**Fish** After a long decline, fish populations are stable at low levels, but some species are still endangered.	↓	↔
D+ Score = 31	**Fishable-Swimmable-Drinkable** Fish are harder to catch, and unsafe to eat. Beach closures are up, drinking water violations are down.	↓	↔
C- Score = 43	**Stewardship** Water conservation, pollution limits, monitoring, and restoration efforts are finally underway, but progress is slow.	↓	↔

rized interpretation of water quality that is not possible with multiple data streams. While an index cannot replace a detailed analysis of environmental monitoring data, it can provide a broad overview of environmental performance that can be easily communicated. Furthermore, an index can be created using a tiered information system providing levels suitable for multiple audiences.

There have been a variety of attempts worldwide to create a water quality index (e.g., the EPA Index of Watershed Indicators). The most successful attempt to date appears to be the index developed by the Canadian Council of Ministers of the Environment (Zandbergen 1998, Rocchini and Swain 1995, CCME 2002). The CCME developed a water quality index for use by a number of Canadian provinces. This index is unique in that it not only allows a quantification of the frequency of water quality exceedances but it includes measures of the scope of contamination (the number of contaminants which exceed standards) and the magnitude of the exceedances. The CCME index approach was therefore employed in the San Francisco Bay Water Quality Index.

Scorecard Grades for the Bay

The Water Quality Index is one of eight indexes developed for the Bay region of the San Francisco Estuary and its watershed as part of The Bay Institute's Bay-Delta Ecological Scorecard Project (Figure 1). The "Bay Index" (www.bay.org) was released in October of 2003 and received wide media coverage throughout the Bay Area. This is the first version of the Scorecard Bay Index intended to improve our understanding of how the entire Bay watershed is doing and to identify future directions for management, monitoring, and research. The Bay Index uses science-based indicators to grade the condition of the Bay region: how well its ecological resources are faring, how much human activities are harming or helping the Bay, and how human uses of the Bay's resources are affected by the Bay's health. The Index was developed by staff scientists at the Bay Institute (Scorecard team) with input from an independent review panel of nationally recognized experts in estuarine science and indicator development. The grading system (described below for the Water Quality Index) compares current conditions in the Bay and its watershed to historical conditions, environmental and public health standards, and restoration targets. For the water quality index, we compared 2001 RMP measurements for over 50 constituents (chemicals) to water quality standards established for the protection of aquatic life and human health, and evaluated trends based on the nine-year RMP dataset.

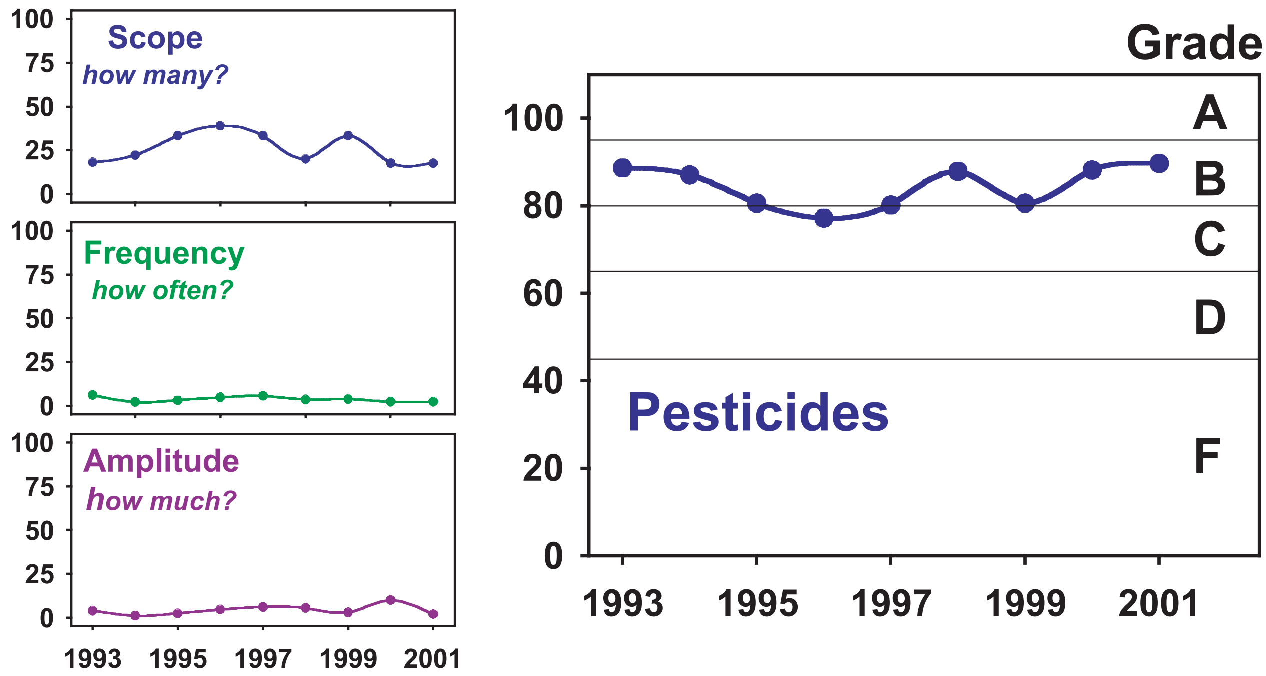


Figure 2. The Pesticide indicator received a B in 2001 and the overall trend is neither increasing or decreasing during the past five to nine years. This figure illustrates how each contaminant category indicator is calculated from three measurements and converted to a score using a 100 point scale. *Scope* measures the number of contaminants measured in the bay for which concentrations were above the standards. *Frequency* measures the proportion of water samples in which standards were not met. *Amplitude* measures the magnitude of each exceedance, the amount by which the measured concentration for a contaminant exceeded the standard.

Using Tried and True Techniques

The Scorecard team developed a list of criteria for the water quality index to summarize aspects of water quality impairment consistent with public supported goals and policies. These criteria include the ability to:

a) Summarize the scope, magnitude, and frequency of the water quality problem,

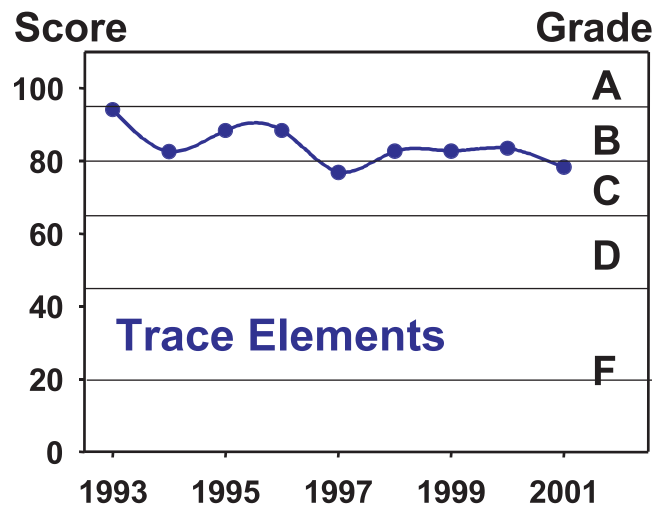
b) Summarize the results for key classes of compounds that impair ecosystem health,

c) Compare water quality using existing standards,

d) Facilitate comparison with studies in different regions, and

e) Score water quality on a 0-100 scale with 100 being the best and 0 the worst condition consistent with the grading system used for other Scorecard indexes.

Several alternative methods were discussed (simple graphic techniques for key variables, EPA's Index of Watersheds, and others); however, the CCME Index was the only methodology that came close to fulfilling the criteria. The CCME method allows water quality data to be compiled and reported in a consistent manner by designated regions. Its straightforward calculation is well documented in a user's manual and technical documents using three facets of water quality that matched the criteria developed for the Bay region. In addition, the technique happened to use a 100-point scale and could be easily adapted to summarize specific classes of compounds (Table 1).



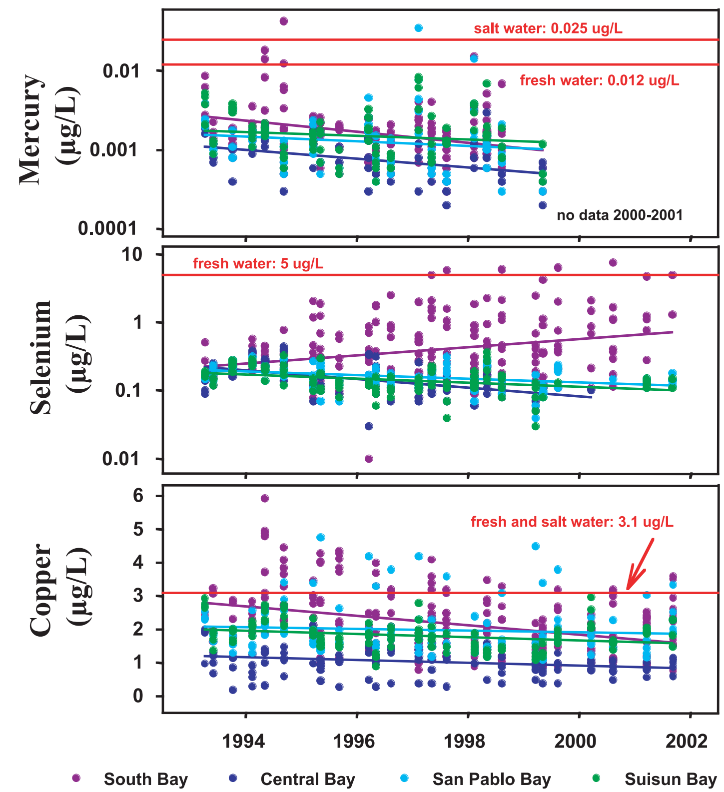


Figure 3. The Trace Elements Indicator received a C in 2001 and the overall trend is declining, with standards exceeded exclusively in the South and San Pablo Bays. Four trace element standards were consistently exceeded: mercury, copper, selenium, and nickel. From 1993-2001, an average of 10% (range: 2-18%) of all water samples exceeded the standard for one or more trace elements. The graph on the right depicts the concentrations of three "problem" trace elements: mercury, selenium, and copper in the four subregions of the San Francisco Bay from 1993-2001. Each point is the contaminant concentration measured at a single location during a survey. Each line is the linear regression of the contaminant concentrations over time from a subregion. From 1993-2001, an average of 10% (range: 2-18%) of all water samples exceeded the standard for one or more trace elements. Note that the mercury and selenium graphs use a log scale.

Finding the Best Data: the Regional Monitoring Program and USGS Studies

The San Francisco Estuary Regional Monitoring Program for Trace Substances (RMP) is the only long-term and consistent data set that extends across the entire Bay region that covers a wide range of water quality parameters, so it was chosen for index development. The five Water Quality Indicators were calculated for each year using data from the RMP, which has conducted two or three surveys per year since 1993, sampling 26 stations distributed throughout the Bay. In the first iteration of the index, the Expert Panel and the San Francisco Estuary Institute suggested we add information

Table 1. Indicator calculations use the CCME Water Quality Index 1.0 Method

Each indicator was calculated using methods developed by the British Columbia Ministry of the Environment, Lands and Parks and adopted by the Canadian Council of Ministers of the Environment. Using this method, calculation of each indicator incorporated three different measurements:

1. the number of variables whose objectives are not met (Scope),
2. the frequency with which the objectives are not met (Frequency), and
3. the amount by which the objectives are not met, (Amplitude).

The results for each indicator are combined to produce a single value (between 0 and 100) that describes water quality. A score of 100 is the best and 0 the worst condition. For more in-depth information on these calculations, see the Scorecard Water Quality Technical Report at <www.bay.org>.

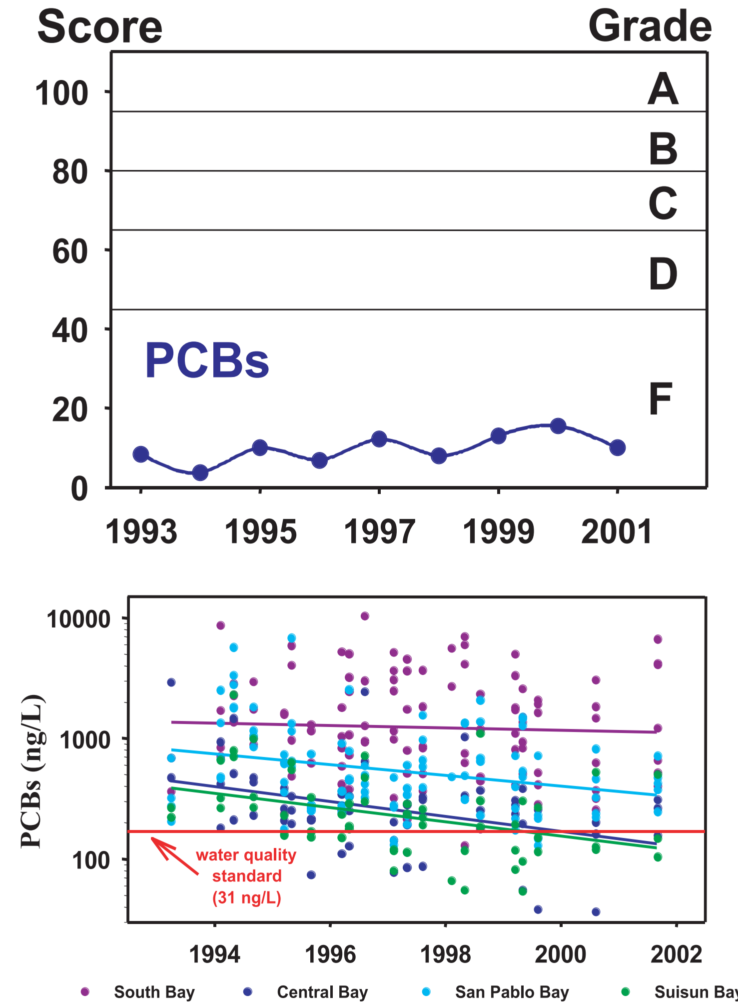
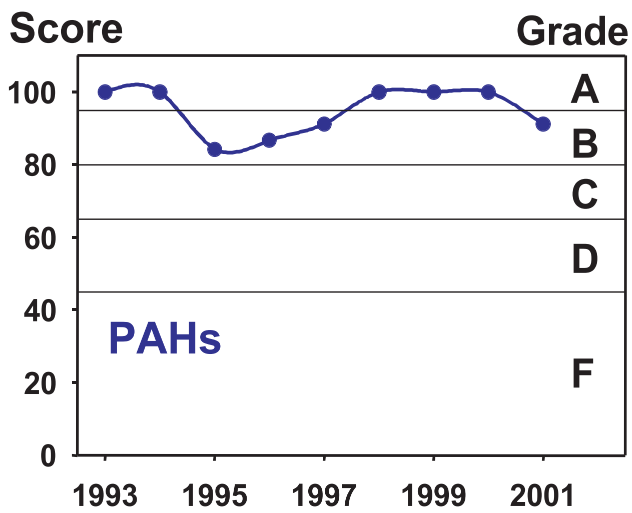


Figure 4. The PCB indicator received an F in 2001 and the overall trend is not declining. PCB concentrations in San Francisco Bay exceeded water quality standards in every year, in every part of the Bay, and at nearly every sampling location. The problem is particularly severe in the South Bay, where there is no sign of decline despite the ban. The figure on the right shows the PCB concentrations in the four subregions of San Francisco Bay from 1993-2001. Each point is the PCB concentration measured at a single location during a survey. Each line is the linear regression of the contaminant concentrations over time from a subregion. Note the log scale and the high values for locations in the South and San Pablo Bays.

on dissolved oxygen. Additional data for dissolved oxygen concentrations and for the general evaluation of long-term trends in Bay water quality were obtained from the U. S. Geological Survey's Ecology and Contaminants Project.[2] For more detailed information on the methods used to calculate the index, see <www.bay.org>.

Pollution Category Indicators

The CCME method can be used to group all classes of compounds into a single index; however, in order to more clearly connect problem pollutant sources with human uses and management responses, we believed that we needed to develop a hierarchical presentation that could be easily aggregated into a single index and disaggregated into pollutant categories. For example, agriculture and urban landscaping applications are common sources of insecticides, herbicides, and fungicides, so it was deemed important to calculate an indicator that grouped these pollutants, which we termed "pesticides." These categories also match traditional contaminant groups found in the water quality pollution literature. In all, five categories of contaminants (indicators) were evaluated and aggregated into the overall San Francisco Bay Water Quality Index. The categories included trace elements (heavy metals and other trace elements), pesticides, PCBs (polychlorinated biphenyls), PAHs (polycyclic aromatic hydrocarbons), and dissolved oxygen. Individual contaminants included in each of the indicators are shown in Table 2.



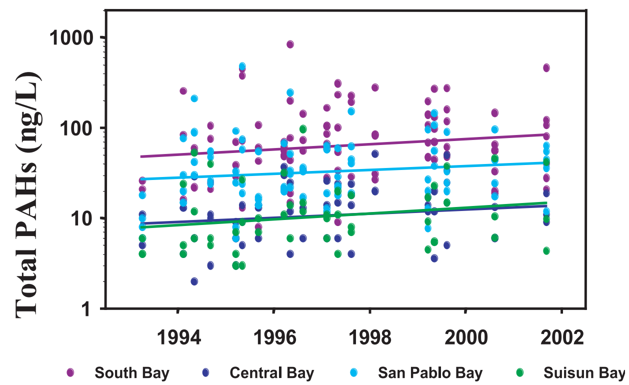


Figure 5. The PAH indicator measures the concentration of polycyclic aromatic hydrocarbons and received a B in 2001. The overall trend neither increased or decreased during the past decade. PAH concentrations exceeded water quality standards in four of nine years during the RMP survey. Total PAH concentrations were highest in South Bay, intermediate in San Pablo Bay, and lowest in Central and Suisun Bays. The figure on the left depicts the PAH concentrations in four subregions of San Francisco Bay from 1993-2001. Each point is the total PAH concentration measured at a single location during a survey. Each line is the linear regression of the contaminant concentrations over time from a subregion. Note that the Y axis uses a log scale.

Evaluating the Results and Grading the Index

For each indicator, the grading scale followed the "ranking" scale recommended by the CCME (2001). That scale also used five categories or levels that corresponded to specific levels of water quality impairment (Table 2). The Water Quality Index was calculated as the "grade point average" of the component indicators, and was reported as a Grade (i.e., A-F) and a Score. A grade of "A" represents the virtual absence of threat or impairment and conditions very close to natural or pristine levels, which is based on the CCME scoring system. An "F" grade represents very poor water quality with widespread exceedances of environmental standards. Trends over time for the Water Quality Index are represented as arrows pointing up (improving), down (declining), or horizontally (stable conditions or no trend). Information is included regarding both long-term (usually 25 years or more) and short-term (usually five years) trends. The overall grade, and score of 0 to 100, for the Index is derived from the grade point average of all five indicators, based on the data from the 2001 RMP survey.

Findings:

Overall trends show no improvement in the last decade

The Bay's open waters are cleaner than they were thirty years ago, but the Water Quality Index indicates that, during the past decade, pollution levels have not changed (Figure 1). Between 1993 and 2001, water quality in the open waters of the Bay was fair (Grade = C) to good (Grade = B) and in 2003 the overall score was a C. Although the Water Quality Index has fluctuated slightly from year to year, it has not significantly increased or decreased during the nine-year period for which contaminant data were available (Figure 1).

Pesticides exceeded standards in nearly one third of RMP samples and are not declining

Insecticides, herbicides, and fungicides used throughout the San Francisco Bay Area and its upstream watersheds enter Bay waters in runoff, and their concentrations in Bay waters often peak following rainfall events. These compounds, which are intended to control terrestrial pests, can be equally harmful or lethal to aquatic organisms. The RMP monitors 29 pesticides or pesticide breakdown products in the Bay, but water quality standards have been established for only 17 of these contaminants.

The Pesticide indicator received a B in 2001 and the overall trend for the aggregated group has neither increased nor decreased during the past five years (Figure 2). From 1993-2001, an average of 31% of all water samples exceeded the standard for one or more pesticides. In 2001, only 17% of samples had pesticide concentrations greater than the water quality standard; however, this lower percentage is probably due to a shift to dry season sampling in that year. Concentrations of diazinon, dieldrin, heptachlor epoxide, and DDT compounds exceeded water quality standards in most years. Furthermore, the concentrations of these pesticides have not declined during the past decade. For most pesticides, the highest contaminant concentrations occurred in South and Suisun Bays.

Table 2. Indicators (contaminant categories) and associated contaminants included in the San Francisco Bay Water Quality Index

1. Trace elements: Ag (silver), As (arsenic), Cd (cadmium), Cr VI (chromium VI), Cu (copper), Hg (mercury), Ni (nickel), Pb (lead), Se (selenium), Zn (zinc)
2. Pesticides: Alpha-HCH, Beta-HCH, Chlorpyrifos, Diazinon, Dieldrin, Endosulfan I, Endosulfan II, Endosulfan sulfate, Endrin, Gamma-HCH, Heptachlor, Heptachlor oxide, Hexachlorobenzene, Mirex, p,p'-DDD, p,p'-DDE, p,p'-DDT
3. PAHs: Acenaphthene, Anthracene, Benz(a)athracene, Benzo(a)pyrene, Benzo(b)fluoranthene, Benzo(k)fluoranthene, Chrysene, Dibenz(a,h)anthracene, Fluorathene, Fluorene, Indeno(1,2,3-cd)pyrene, Pyrene
4. PCBs (total)
5. Dissolved oxygen

Trace element concentrations are generally declining, with standards exceeded in the South and San Pablo Bays

Trace elements, including arsenic, mercury, copper, and selenium, are contained in industrial and wastewater discharges, enter Bay waters in runoff, and are reintroduced into the water column during high flow events when Bay sediments are re-suspended. For many aquatic organisms, exposure to even slightly elevated levels of dissolved metals or other trace elements can be lethal or affect reproduction or early development. Some trace elements, such as mercury and selenium, bioaccumulate in aquatic organisms in the Bay's food web and contaminate Bay fish and shellfish. The RMP measures 14 trace elements in open waters, but only ten for which standards exist were included in the indicator calculation.

The trace elements indicator received a C in 2001, and the overall trend is declining (Figure 3). From 1993-2001, an average of 10% (range: 2-18%) of all water samples exceeded the standard for one or more trace elements. Four trace elements standards were consistently exceeded: mercury, copper, selenium, and nickel in the South and San Pablo Bays (Figure 3). Water quality standards for copper were exceeded in all years: however, recent changes in the application of these standards, particularly for the South Bay, may reduce the number of exceedances. Mercury concentrations (measured for only 1993-1999) exceeded standards in 1994, 1997, and 1998 and were most severe in the Central and South Bays; however, there is some discussion over the current mercury standard. Selenium standards were exceeded in each of the last five years of the survey. Nickel (not graphed) standards were exceeded at least once in most years. Trace element concentrations are declining in most parts of the Bay's open waters; however, they still exceed water quality standards in most years and in many locations. It is interesting to note that selenium levels have increased significantly in the South Bay (Figure 3).

Legacy PCB contamination is widespread and significantly exceeds standards

Polychlorinated biphenyls (PCBs) are highly toxic and persistent man-made chemicals that were used extensively in a variety of applications for more than 50 years. The manufacture of PCBs was banned in 1979, but runoff from PCB contaminated streams and urban areas continues to deliver these pollutants to the Bay. In addition to their toxic effects on animals, PCBs bioaccumulate in the food web, contaminating Bay fish and shellfish.

The PCB indicator received an F in 2001 and the overall trend is neither increasing nor decreasing during the past decade (Figure 4). PCB concentrations in San Francisco Bay exceeded water quality standards in every year, in every part of the Bay, and at nearly every sampling station. The problem is particularly severe in the South Bay, where there is no sign of decline despite the ban. San Pablo Bay levels are also high but depicted a significant decline, as did the levels in Central and Suisun Bays.

PAHs exceeded water quality standards in four of nine years and did not decline

Polycyclic aromatic hydrocarbons (PAHs) are a group of chemicals that occur naturally in coal, crude oil, gasoline, and in smoke from the combustion of organic matter. Most PAHs enter the environment from incomplete burning of oil, wood, garbage, or coal, and can persist for months or years. Identified health effects of PAH exposure include cancer and adverse reproductive and developmental effects. The RMP has identified 25 different polycyclic aromatic hydrocarbons in San Francisco Bay waters; however, standards have only been established for 12 compounds so only these were used in the PAH indicator calculation.

The PAH indicator received a B in 2001 and the overall trend neither increased or decreased during the past five years (Figure 5). PAH concentrations exceeded water quality standards in four of nine years during the RMP

Ecology and Contaminants Project, dissolved oxygen conditions in the South Bay have improved during the past thirty years.

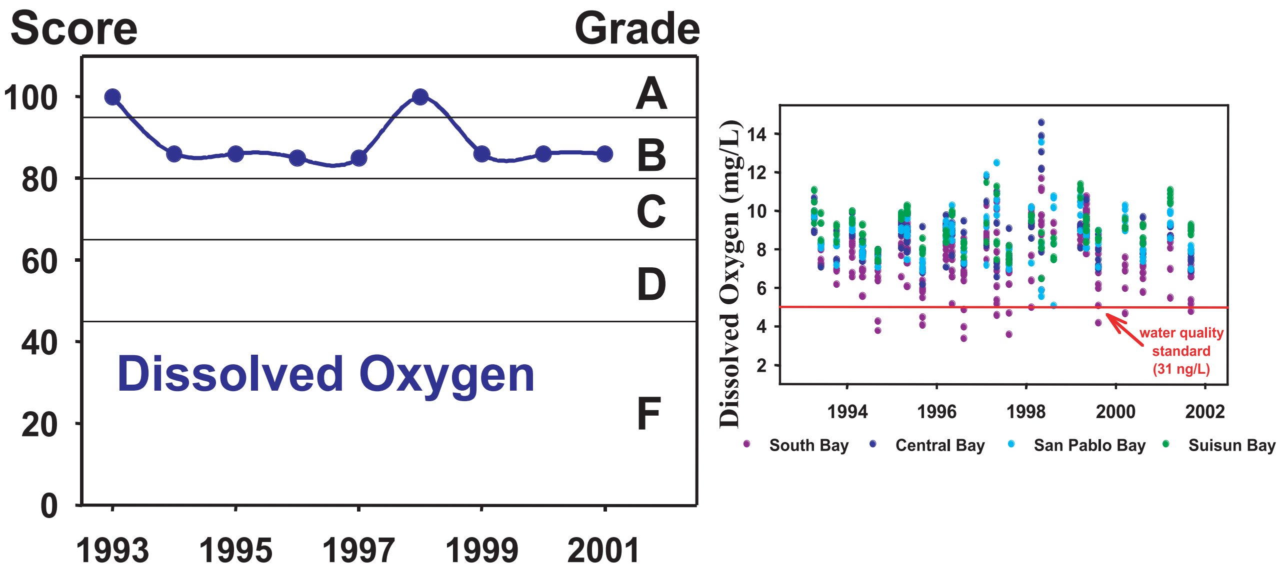


Figure 6. The dissolved oxygen (DO) indicator received a B in 2001; the trend varied but neither increased or decreased during the RMP study. Low dissolved oxygen levels cause impairment of aquatic life, so in this case low DO levels indicate an unhealthy condition. The graph on the right depicts the dissolved oxygen concentration measured in four subregions of San Francisco Bay from 1993-2001. DO concentrations were above the minimum standard in all areas of the Bay except the South Bay where they fall below the standards in nearly all years. Historic USGS data indicate improvement in DO conditions in the South Bay during the past thirty years (see 2003 *Pulse of the Estuary*).

survey. Total PAH concentrations were highest in South Bay, intermediate in San Pablo Bay, and lowest in Central and Suisun Bays.

Dissolved oxygen trends remain stable, are lowest in the South Bay but have improved since the early 1970s

Low dissolved oxygen concentrations can kill fish and invertebrates and exclude many aquatic animals from large areas of habitat. Oxygen depletion usually results from high rates of microbial and/or algal respiration that exceed the capacity of the water body to replenish oxygen through phytoplankton photosynthesis and diffusion from the air. Excessive inputs of organic material and nutrients, from poorly treated sewage discharges or surface runoff, can accelerate respiration rates and trigger localized and regional oxygen depletion.

The dissolved oxygen indicator received a B in 2001, and the trend varied but neither increased or decreased during the past five years (Figure 6). Dissolved oxygen concentrations were above the minimum standard in all areas of the Bay except the South Bay. South Bay oxygen concentrations were consistently and significantly lower than those measured in all other bay subregions; however, based on the longer-term data record from the USGS

Conclusions and Future Directions

Although the role of contaminants in affecting ecosystem productivity and aquatic population levels is not fully understood, current levels of several contaminants exceed those considered potential health threats to fish and wildlife species and humans. The first version of the San Francisco Bay Water Quality Index measures concentrations of contaminants in open waters, not in sediments or stormwater runoff, and does not reflect uptake of contaminants by plants and animals. (Biological uptake is addressed in other Scorecard indexes for the Bay, however). In addition, in providing an overview, it does not tell the story of small bay watersheds, though one could use the same techniques using finer scale localized water quality data. Though the index only tells part of the Bay's story, the results are informative and important to the public. The media coverage of the Bay Index in October 2003 is an indication of the public's interest in comprehensive but concise information on water quality. The index's layered approach and presentation aggregates component indicators to provide an overview that is easily communicated to the public and can also be disaggregated to provide more detailed information for managers and decision-makers who require a more in-depth understanding of water quality issues. It provides an example that can be used for the development of indexes in other Bay Delta regions and smaller tributary watersheds.

Contrary to other Scorecard indexes in which the ecosystem in the upper portion of the Bay depicted the highest sign of impairment, the Water Quality

Expert Guidance for the Index

Staff scientists at the Bay Institute involved an expert scientific review panel whose members included renowned scientists from academia, government, and the private sector: Bruce Herbold, U.S. Environmental Protection Agency; James Karr, University of Washington; Matt Kondolf, University of California, Berkeley; Peter Moyle, University of California at Davis; Fred Nichols, United State Geological Survey (retired); and Phil Williams, Philip Williams and Associates.

In addition to the scientific review panel, more than sixty individuals provided Bay Institute staff with data, editorial advice, and other assistance in the preparation of the Score Card.

Index subcomponents and RMP dataset clearly show the South Bay as the most contaminated subregion, especially in the southern reaches of South Bay. San Pablo Bay is the second most contaminated subregion, partially explained by sediment dynamics in this embayment (see Schoellhamer article in last year's Pulse). Future calculations of the water quality index should attempt to segregate the shallow water sites from deep water open bay stations and calculate overall index values for each subregion to further investigate these patterns. In addition, variability in freshwater flows during water quality monitoring contributes to variability in the data and possibly the index calculation. Though the RMP sampling program was designed to cover a range of flow patterns (Also see Flegal, Figure 2), the effect of hydrologic variability should be evaluated in future calculations of the Water Quality Index. The infrequency of RMP sample collections each year, may pose a problem that could be addressed through more frequent sampling or in-depth investigations.

The analysis shows the persistence and widespread distribution of pollutants whose uses have been discontinued (legacy pollutants such as PCB) or are being phased out. For example, though diazinon, an organophosphate pesticide, was banned for urban use and has declined by 75% (See Scorecard Stewardship Index www.bay.org), it does not show a significant decline in the RMP dataset. The PCB problem is widespread and severe (Figure 4); however, in most regions we are seeing slight improvements as predicted by previous RMP PCB pollution budgets (Davis, 2004). In addition, the PCB indicator analysis segregates PCBs from other contaminants in its own category, so it may somewhat overstate this contaminant's importance relative to other contaminants. However, as Figure 4 emphasizes, the PCB values are extremely high relative to standards across nearly all of the Bay's subregions.

The calculation of the index and identification of existing standards also pointed to the need to evaluate additional constituents in future versions of the index and to reevaluate the categories chosen. For most of the categories, such as pesticides, trace elements, and PCBs, no applicable standards were available for certain RMP measured compounds resulting in their exclusion from the current index calculation. Clearly we need to evaluate the extent and magnitude of the pollution due to these pollutants if they are important enough to measure. In addition, there is debate over which standards should be applied in some instances; particularly for certain trace metals. Finally, there are categories and/or constituents that may be added if additional data sources become available. For example dissolved oxygen is in a category alone, but we had originally hoped to have a larger array of traditional conventional pollutants represented such as nitrogen and phosphorus compounds.

There is more to do to enhance the San Francisco Bay Water Quality Index, to link it to finer level analyses, and to educate the public about their role in reducing contaminant effects. A key to the index's utility as a communication tool is to influence local stewardship of the bay, and that requires significant outreach efforts. The Bay Institute, the San Francisco Estuary Institute, and the Center for Ecosystem Management and Restoration have joined forces to assist the San Francisco Estuary Project in refining and developing Indicators of Estuary Condition this year. One of the first tasks is to assemble a work group to review and refine the San Francisco Bay Water Quality Index.

The Bay Institute

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Adaptive Implementation of TMDLs –The Mercury Example

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Long-Term Trends in Metal Contamination in San Francisco Bay Water and Sediment

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(Footnotes)

[1] More information on the RMP can be obtained at www.sfei.org and at www.sfei.org/rmp/index/html. RMP water quality data can be downloaded at www.sfei.org/rmp/data/rmpwater.htm.

[2] More information on the USGS Ecology and Contaminants Project can be obtained at http://wwwrcamnl.wr.usgs.gov/tracel/. Water quality data from this program are available for download at http://sfbay.wr.usgs.gov/access/wqdata.

Notes on water quality objectives and other contaminant guidelines used in this edition of the Pulse.

Total mercury in water: The water quality objective of 0.025 µg/L was used, except for the Lower South Bay region (south of the Dumbarton Bridge), which used 0.051 µg/L per the California Toxics Rule.

Dissolved copper in water: Copper water quality objectives for estuarine regions of the Bay are the lower of either the saltwater or freshwater objectives. Freshwater objectives were calculated based on the hardness of the water where a sample was collected. None of the calculated freshwater objectives were less than the saltwater objective so the saltwater objective of 3.1 µg/L was used for samples collected in most of the Bay. The new site-specific objective of 6.9 µg/L was used to evaluate samples from the Lower South Bay (south of the Dumbarton Bridge).

Total PCBs in water: The water quality objective of 170 pg/L was used.

Total mercury in sediment: The guideline used was the TMDL mercury target, 0.2 mg/kg.

Total PAHs in sediment: The guideline used was the Effects Range Low, 4022 mg/kg.

Progress graphic, page 7: The guidelines used for sediment were the Effects Range Low.

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City of Saint Helena

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City of San Mateo

City of South San Francisco/ San Bruno

City of Sunnyvale

Delta Diablo Sanitation District

East Bay Dischargers Authority

East Bay Municipal Utility District

Fairfield-Suisun Sewer District

Las Gallinas Valley Sanitation District

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Millbrae Waste Water Treatment Plant

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Napa Sanitation District

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San Francisco International Airport

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Sewerage Agency of Southern Marin

Sonoma County Water Agency

South Bayside System Authority

Town of Yountville

Union Sanitary District

Vallejo Sanitation and Flood Control District

West County Agency

Industrial Dischargers

C & H Sugar Company

Chevron Products Company

Dow Chemical Company

General Chemical Corporation

TOSCO – Rodeo Refinery

Rhodia, Inc.

Shell – Martinez Refining Company

Ultramar Inc - Avon Refinery

USS – POSCO Industries

Valero Refining Company

Cooling Water

Mirant of California

Stormwater

Alameda Countywide Clean Water Program

Caltrans

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Fairfield-Suisun Urban Runoff Management Program

Marin County Stormwater Pollution Prevention Program

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The Pulse of the Estuary

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Attaining "Beneficial Uses"–The Goal of Water Quality Management

Beneficial uses form the foundation of water quality protection mandates and statutes under which the State Water Resources Control Board and its Regional Boards operate. Beneficial use protection and restoration is the ultimate goal of all water-quality-related regulatory and grant-making activities.

Beneficial uses are those services and qualities of aquatic systems that we value and want to protect. Examples of beneficial uses include: agricultural, municipal, and industrial water supply; water recreation; preservation of rare and endangered species; and provision of healthy aquatic habitats. Each California water body has its own set of identified beneficial uses, listed in the Basin Plans of the nine Regional Water Quality Control Boards (see <http://www.swrcb.ca.gov/rwqcb2/Basin%20Plan/chap_1_bp.pdf>).

One of the many questions the "uninitiated" frequently ask about the Clean Water Act and its corresponding sections in the California Water Code is: "What is the difference between 'Designated Uses' (federal Clean Water Act language) and 'Beneficial Uses' (California's Porter-Cologne Act language)?" The answer is that they are essentially the same.

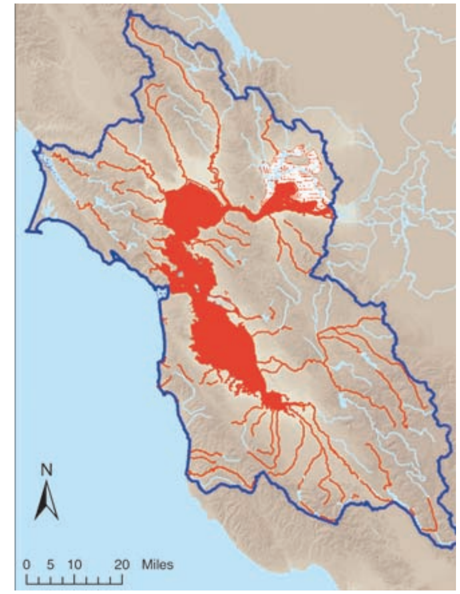
Water quality objectives

Chemical, physical, biological, and radiological *water quality objectives* are established for each water body that seek to protect its specific beneficial uses. These water quality objectives can be expressed in numeric or in narrative form. The latter is particularly important, since only a small proportion of potential pollutants have numeric water quality objectives associated with them (the list of so-called Priority Pollutants with specific numeric water quality objectives has not been updated since the 1970s, while thousands of new synthetic compounds have been approved for manufacture and use each year).

Often, it is not a single pollutant, but "pollution" in general, that might impair beneficial uses. A *pollutant* is defined in Section 502(6) as "dredged spoil, solid waste, incinerator residue, sewage, garbage, sewage sludge, munitions, chemical wastes, biological materials, radioactive materials, heat, wrecked or discarded equipment, rock, sand, cellar dirt and industrial, municipal, and agricultural waste discharged into water." The term "*pollution*" means the "man-made or man-induced alteration of the chemical, physical, biological, and radiological integrity of water (Section 502(19))." The difference between the two terms has some far-reaching implications, since *pollution* reduction often requires different approaches than control of a particular *pollutant.* The Total Maximum Daily Load (TMDL) process is one current approach when a specific pollutant is implicated. Some impairments are not directly attributable to a particular pollutant, but to modifications such as water diversions (a man-induced alteration of the physical integrity of water)—in these cases, strategies other than TMDLs are required to restore *beneficial uses*.

All of these intricacies speak toward a comprehensive watershed approach, which the Regional Board, the regulated community, land use planners, and other environmental stakeholders are beginning to pursue jointly.

New Developments in the "Impaired Waters," or 303(d) List



Section 303(d) of the Clean Water Act requires that the SWRCB compile, and periodically revise, a list of waters throughout the state that do not attain water quality standards. The law also requires that a calculation of the maximum allowable pollution be developed for any water on this list. These calculations are called Total Maximum Daily Loads or TMDLs. They can be specified in any number of ways to allow for appropriate definition of the problem. A means of implementing the TMDL must also be developed and followed through to ensure that implementation is taking place as needed. The Regional Board has prepared a number of project reports outlining how water quality standards could be attained.

In most cases, undertaking implementation steps will bring waters into conformity with water quality standards. However, in some cases, the uncertainty surrounding the initial assessments of impairment and other factors could lead to actions that do not in fact result in desired water quality attainment. Therefore, all TMDLs should undergo regular evaluation and be revised when necessary. The Regional Board's strategy for attaining water quality standards in impaired waters encompasses all of these features. In the San Francisco Bay Region, the data generated primarily by the RMP and the Clean Estuary Partnership, but also by monitoring and special studies funded by USGS, various state bond measures, and other agencies are an integral part in the evaluation and revision to both the 303(d) list and water quality attainment strategies. The Regional Board is currently engaged in developing over 30 TMDLs to address more than 160 listings for water bodies, including various segments of the Estuary.

On July 25, 2003 USEPA gave final approval to California's 2002 Section 303(d) List of Water Quality Limited Segments. The Regional Board segmented the Estuary along very similar lines as indicated by the sampling regime the RMP is following: the Delta, Suisun Bay, Carquinez Straight, San Pablo Bay, Central Bay, Lower Bay, and South Bay. In addition, several sub-segments, such as Richardson Bay, Oakland Inner Harbor, San Francisco Central Basin, San Leandro Bay, and the tidal portions of several tributaries, are listed as impaired. The Estuary itself comprises only a portion of the more than 160 listings, with PCBs, mercury, exotic species, selenium, diazinon, organochlorine pesticides, dioxins, furans, and PAHs in sediment being the main pollutants listed at various level of priority for TMDL development. Nickel is listed only for the tidal portion of the Petaluma River.

Update on Regional Board TMDL schedule. <http://www.swrcb.ca.gov/rwqcb2/TMDL/tmdl_projects/sfbrwqcb_current_tmdl_proj_sch.pdf>

Future TMDLs: http://www.swrcb.ca.gov/rwqcb2/TMDL/tmdl_projects/sfbrwqcb_future_tmdl_proj_sch.pdf

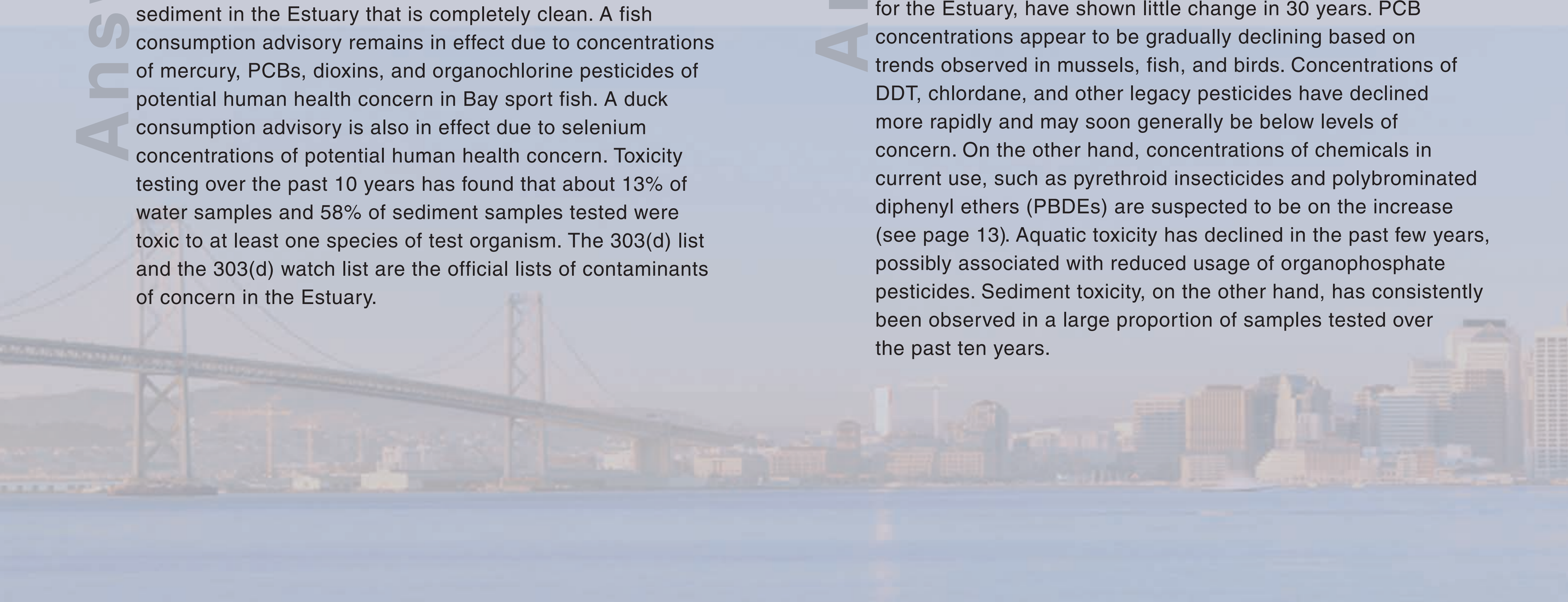
A Primer on Bay Contamination

Q: How contaminated is the Estuary?

A: Water and sediment of the Estuary meet cleanliness guidelines for most contaminants. In 2002, 87% of chemical concentrations measured in water were below their guideline, and 61% of chemical concentrations measured in sediment were below their guideline. However, a few problem contaminants are widespread in the Estuary, making it rare to find water or sediment in the Estuary that is completely clean. A fish consumption advisory remains in effect due to concentrations of mercury, PCBs, dioxins, and organochlorine pesticides of potential human health concern in Bay sport fish. A duck consumption advisory is also in effect due to selenium concentrations of potential human health concern. Toxicity testing over the past 10 years has found that about 13% of water samples and 58% of sediment samples tested were toxic to at least one species of test organism. The 303(d) list and the 303(d) watch list are the official lists of contaminants of concern in the Estuary.

Q: Is the contamination getting better or worse?

A: Over the long term, the Estuary has shown significant improvements in basic water quality conditions, such as the oxygen content of Estuary water, due to investments in wastewater treatment. Contamination due to toxic chemicals has also generally declined since the 1950s and 1960s. Distinct declines in silver concentrations have been documented in the South Bay (see pages 32 and 38). More recently, however, the answer to this question varies from contaminant to contaminant. Mercury concentrations in striped bass, a key mercury indicator species for the Estuary, have shown little change in 30 years. PCB concentrations appear to be gradually declining based on trends observed in mussels, fish, and birds. Concentrations of DDT, chlordane, and other legacy pesticides have declined more rapidly and may soon generally be below levels of concern. On the other hand, concentrations of chemicals in current use, such as pyrethroid insecticides and polybrominated diphenyl ethers (PBDEs) are suspected to be on the increase (see page 13). Aquatic toxicity has declined in the past few years, possibly associated with reduced usage of organophosphate pesticides. Sediment toxicity, on the other hand, has consistently been observed in a large proportion of samples tested over the past ten years.



Q: Are contaminants harming populations of organisms in the Estuary?

A: This critical question remains largely unanswered. There are indications that the current level of contamination is harming the health of the ecosystem, such as the frequent occurrence of contaminants above water and sediment guidelines, and the toxicity of water and sediment samples to lab organisms. Mercury concentrations appear to be high enough to cause embryo mortality in clapper rails, an endangered species found in Bay tidal marshes (page 12). PCB concentrations may be high enough to also cause low rates of embryo mortality in Bay birds (page 12) and to affect immune response in harbor seals (page 13). Assessments of benthic communities in the marine and estuarine regions of the Bay indicate that some areas may be impacted by contaminants. The RMP began a focused investigation of contaminant effects in 2002; results will begin to be available by the next Pulse.

Q: Do we know how to clean up the Estuary?

A: There are three general approaches to Estuary clean-up.

1. Reducing the entry of additional contaminants is essential. The Estuary acts as a long term trap for persistent contaminants; once contaminants enter the Estuary it takes a very long time for them to exit. Preventing contaminants from entering the Estuary is therefore imperative. Preventing a contaminant from entering the Estuary requires knowledge of its source or an interceptable part of its path to the Estuary. We are developing detailed descriptions of the sources, pathways, and repositories of contamination for several contaminants of concern. Much of this effort is in response to the Clean Water Act's requirement to develop contaminant clean-up plans known as Total Maximum Daily Loads (TMDLs, see page 18). While known contaminant problems are being addressed by TMDLs, surveillance monitoring is conducted in the RMP in an effort to provide an early warning for contaminants of emerging concern and allow for management actions to nip potential problems in the bud.
2. Removing some masses of contaminants from the Estuary is possible. Contaminated sediment can be dredged from the Estuary, placed on land and sealed with a layer of asphalt or similar material. Such dredging has been attempted in a few cases with mixed results.
3. Allowing contaminants to degrade and disperse naturally is necessary. Time will always be a large part of the remedy, naturally reducing the large quantity of contaminants now in the sediments through degradation, and transport to the ocean and atmosphere. Burial in deep sediment is normally a removal process in estuaries, but due to a reduced supply of sediment to the Estuary burial is not occurring (see page 8). For persistent contaminants found in large amounts in the sediments of the Estuary, such as mercury and PCBs, the time required to see change will be decades.