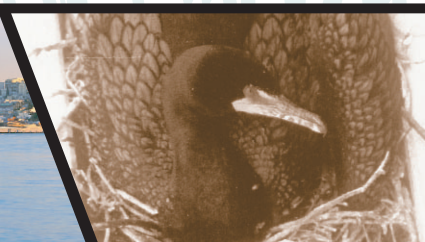
2003

# PULSE OF THE ESTUARY



monitoring & managing contamination in the san francisco estuary

## About This Report

This year marks the tenth anniversary of the San Francisco Estuary Regional Monitoring Program for Trace Substances (RMP). This milestone represents an appropriate time to examine how scientific understanding, regulation, and the degree of contamination in the San Francisco Estuary have changed over the course of a decade. The synthesis of findings from this first phase of the RMP is providing a general theme for the Program in 2003 and 2004. An integrated series of products and events are planned to accomplish an evaluation and long-term summary of the many components of the Program, including:

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

- the 2003 and 2004 issues of the *Pulse of the Estuary*,
- the 2003 and 2004 RMP Annual Meetings,
- a report summarizing the Program's successes and challenges for the future from a management perspective, and
- a Status and Trends Report that will summarize what has been learned from the RMP and other studies about contamination in the Estuary over the past 10 years.

This issue of the *Pulse* is the first of two consecutive issues dedicated to analysis of the initial 10 years of the RMP. In addition to the usual features of the *Pulse* summarizing the latest data on contamination in the Estuary, this issue contains feature articles focusing on specific components of the multifaceted Program. A particular highlight this year is an article by Jim Cloern and colleagues at USGS that provides an interesting overview of basic ecological lessons learned from 10 years of monitoring water quality in the Bay.

This issue of the *Pulse* has been designed to make information on water quality in the Estuary more accessible. More detailed figure captions have been written that convey 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 Update is now presented entirely as a graphical summary.

The *Pulse of the Estuary* is one of three RMP reporting products. The second product, the *Annual Monitoring Summary*, 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* collection. *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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## 2000

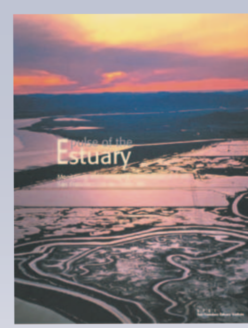
*Premier issue:*
- *Introduction to RMP Monitoring*

*Feature articles:*
- *Top Known Contamination Problems*
- *Contamination of Water, Sediment, and Fish*
- *Summary of Overall Condition*


## 2001

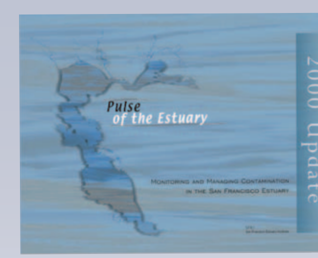
*Introduced Pulse feature:*
- *San Francisco Estuary Contamination Overview*

*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*



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# Feature Articles

Articles that examine the big picture of contamination in the Estuary, integrating information from the RMP and other sources into focused discussions on particular subjects

# Introduction

In this issue and the next issue of the *Pulse* this section will contain articles that synthesize information from the past ten years of water quality studies of the Estuary. In this issue the focus is on the intensive monitoring of basic water quality parameters and toxicity that have been components of the RMP from the inception of the Program. Next year's issue of the *Pulse* will focus on results from long term monitoring of chemical concentrations in the water, sediment, and food web of the Estuary.

The U.S. Geological Survey (USGS) has been a partner in the RMP from the beginning, combining funding from RMP with other sources to provide detailed insights into ecological processes in the Estuary. USGS monitoring of basic water quality parameters (page 15) has documented significant long term changes in the ecology of the Estuary in the past ten years, including improvements in the oxygen content of Bay waters related to improved sewage treatment and the extraordinary impact of the invasive Asian clam (*Potamocorbula amurensis*) on the food web. This article was designated a Pulse Highlight because it provides a readily understandable introduction to the basic ecology of the Estuary.

Detailed USGS investigations of sediment dynamics in the Estuary and sediment supply from the watershed (page 21) have yielded important insights regarding contaminant fluctuations over the short term and fate over the long term. Sediment is becoming a scarce resource in the Estuary. Reduced sediment supply and increased demand for sediment from the Airport extension, the Cargill salt pond restoration project, and other large scale restoration projects will lead to erosion of sediment from the bottom of the Bay and possibly degrade water quality.

Researchers from the Granite Canyon Marine Laboratory, Pacific EcoRisk, and SFEI present a summary of ten years of toxicity testing on page 27. The frequent occurrence of toxicity in water and sediment of the Estuary has been a major concern. A management highlight from the past ten years is the observation of an apparent reduction in toxicity in water, possibly associated with reduced use of organophosphate insecticides. A new concern has arisen, however, over the possible ecological impacts of the pyrethroid insecticides that are being used as replacements for the organophosphates. The evolution of the toxicity testing element during the past ten years provides an excellent example of how the RMP has adapted to in response to changes in our state of knowledge and conditions in the Estuary.

Adaptation of the RMP is also the theme of an article summarizing the diverse array of Pilot and Special Studies conducted by the Program in the past ten years (page 32). These studies have produced a significant body of knowledge and provided an important mechanism for the Program to continually increase its relevance to managing contamination in the Estuary.

# Lessons from Monitoring Water Quality in San Francisco Bay

James E. Cloern (jecloern@usgs.gov), Tara S. Schraga, Cary B. Lopez, and Rochelle Labiosa — U.S. Geological Survey, Menlo Park, CA


**Figure 1. Monitoring of basic water quality parameters.** The USGS, in cooperation with RMP, measures basic water quality indicators every month at 38 stations between the Sacramento River and South Bay with additional weekly sampling in the South Bay during spring. Submersible instruments measure salinity, temperature, suspended solids, light penetration, dissolved oxygen, and chlorophyll a from the water surface to the bottom. This basic information provides a foundation for understanding variability in the sources, transport, bioaccumulation, and ecosystem effects of contaminants in San Francisco Bay.

## INTRODUCTION

San Francisco Bay is the defining landscape feature of the place we call 'The Bay Area,' but most of us only experience the Bay as we view it from an airplane window or drive across one of its bridges. These views from afar suggest that the Bay is static and sterile, but this impression is deceptive. If you are one of the many thousands of students who have experienced the Bay through a school excursion with the Marine Science Institute or other educational programs, you observed its rich plankton soup under a microscope, sorted clams and worms and crustaceans from mud samples, and identified the gobies, sole, halibut, bat rays, sharks, sardines, and smelt caught with trawls. San Francisco Bay is much more than a landscape feature. It is a dynamic ecosystem, continually changing and teeming with life. The Bay once supported the most valuable fisheries on the west coast of the United States, but commercial fishing for shellfish, shrimp, sturgeon, shad, salmon, and striped bass ended many decades ago because of habitat loss, pollution, invasive species and over harvest.

Bay Area residents feel a sense of responsibility to protect San Francisco Bay and keep it healthy. Some even dream about the recovery of fish stocks so they can sustain commercial fishing once again inside the Bay. How is our Bay doing? Is it highly polluted or pretty clean? How does its health compare with other estuaries in the United States? Are things getting better or worse? Does costly wastewater treatment have benefits? What are the biggest threats to the Bay and how can we reduce or eliminate those threats? How will the Bay change in the future? These questions can only be answered with investments in study and monitoring, and they are the driving force behind the Regional Monitoring Program (RMP). We describe here some selected results from water quality surveillance conducted by the U.S. Geological Survey (USGS) as one component of the RMP. We present results as lessons about how the Bay works as a complex dynamic system, and we show how these lessons are relevant to the broad RMP objectives supporting Bay protection and management.

## The USGS-RMP Water Quality Monitoring Program

The RMP is one of several institutional investments to document and understand the changing condition of San Francisco Bay's living resources and water quality. The California Department of Fish and Game samples fish populations every month, and has maintained this invaluable Baywide monitoring since 1980 as a component of the Interagency Ecological Program <www.iep.water.ca.gov>. USGS scientists have studied physical, chemical, geological, and biological processes in San Francisco Bay since 1969, the longest continuing program of observation and study in a coastal ecosystem in the United States. The RMP filled a key gap when it became the first Baywide program to routinely monitor contaminants in water, sediments, and aquatic organisms, beginning in 1993. At its inception, the RMP established a partnership with USGS as a step toward the RMP objective of developing a complete picture of the sources, distribution, fate, and effects of contaminants in the Bay ecosystem.

The RMP is designed to detect trends of contaminant change over periods of years, but long-term trends can be difficult to identify or understand without knowledge of changes that occur over shorter time periods, within years. The function of USGS water quality monitoring within the RMP is to measure water quality indicators at weekly-to-monthly frequency to document changing Bay conditions over seasonal cycles and during events (floods, algal blooms, storms) that influence contaminant inputs, fate, and effects. This work builds a foundation of knowledge about Bay dynamics required to interpret trends measured in other RMP components. The USGS makes monthly measurements at 38 stations along the 145 km channel from the lower Sacramento River to the lower South Bay (Figure 1). Sampling is also done weekly in South Bay during spring when water quality is highly variable because of phytoplankton blooms. Measurements are made over the entire water depth with sensors for water temperature, salinity, suspended solids, chlorophyll a, and dissolved oxygen. Since 1993, the USGS has conducted 99 full-Bay and 175 South Bay sampling cruises, making over 61,000 measurements of each water quality parameter. Interested parties can download these data for their own analyses <http://sfbay.wr.usgs.gov/access/wqdata>. These data are used beyond the RMP: by marine-science teachers, students from elementary to graduate school, researchers around the world, consulting firms, and other government agencies. What have we learned about the Bay from this monitoring?

## Oxygen as an Essential Element

A common impairment of coastal water bodies, such as Chesapeake Bay and the northern Gulf of Mexico, is depletion of dissolved oxygen from bottom waters. Oxygen depletion can kill fish and shellfish and exclude biota from large areas of habitat. Oxygen depletion is caused by microbial communities in water

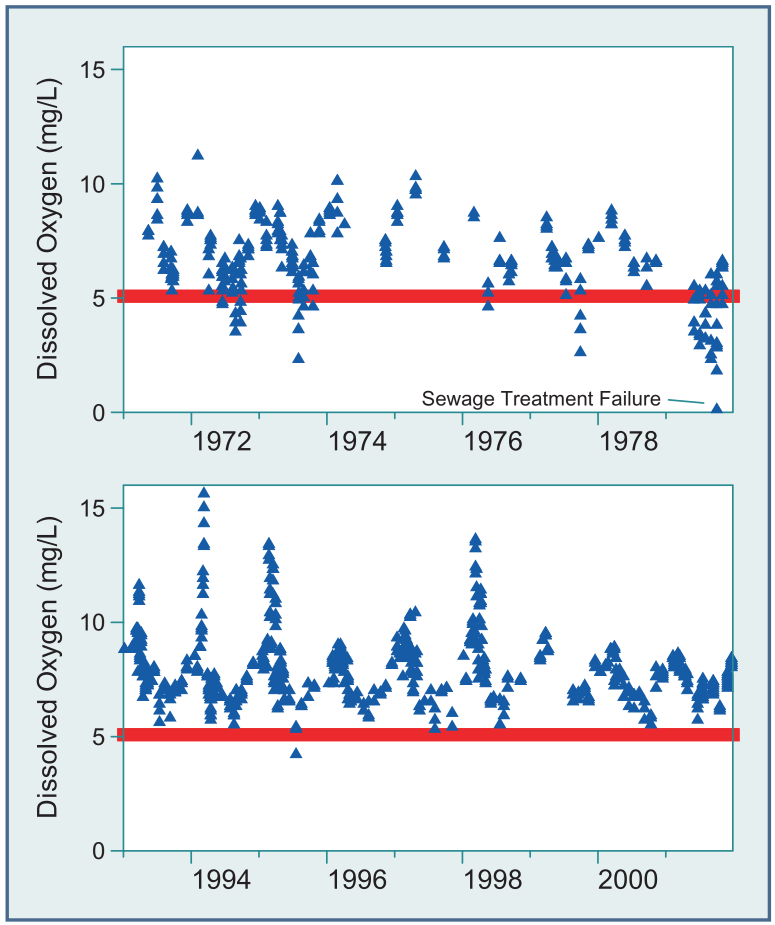


**Figure 2. Oxygen conditions in the Bay have improved due to investments in wastewater treatment.** Dissolved oxygen (DO) concentrations in San Francisco Bay nearly always exceed the 5 mg/L standard (red bar) protecting sensitive species of fish from oxygen depletion. The top panel shows bottom-water DO in lower South San Francisco Bay (USGS Stations 32-36) during the 1970s when summer DO episodically fell below the standard (note the disappearance of oxygen during the September 1979 disruption of sewage treatment). The bottom panel shows consistently high DO since 1993, reflecting improvements from advanced wastewater treatment that greatly reduced inputs of oxygen-consuming pollutants. San Francisco Bay is no longer impaired by low oxygen conditions.

and sediments as they respire to maintain their metabolism. Microbial metabolism depends on a supply of organic matter, and oxygen depletion occurs when the supply of organic matter exceeds the capacity of a water body to replenish oxygen. Organic matter comes either from direct inputs (e.g., of poorly-treated sewage) or from phytoplankton biomass produced from nutrients delivered by surface runoff or wastewater. Data collected by the USGS-RMP monitoring program since 1993 show that San Francisco Bay waters always have sufficient oxygen (> 5 mg/L) to sustain metabolism of the most sensitive fish species (Figure 2).

This was not always the case. In the 1950s and 1960s, before regulation of wastewater inputs by the 1972 Federal Clean Water Act, summer oxygen depletions were common, especially in the lower South Bay, which received large inputs of oxygen-demanding cannery waste and ammonia. Even in the 1970s, data collected by USGS showed episodic depletions of dissolved oxygen below 5 mg/L (Figure 2). The trend of steadily increasing dissolved oxygen and elimination of low-oxygen conditions is a compelling success story of water quality management, an

*Monitoring allows regulators to identify and focus on pollutants posing the greatest threats*

example of benefits derived from investments in advanced wastewater processes that reduce inputs of oxygen-consuming wastes.

The past decade of USGS-RMP data provides strong evidence supporting a regulatory decision to remove San Francisco Bay from the list of California water bodies impaired by low oxygen. This illustrates how monitoring provides a scientific basis for prioritizing management actions so that regulatory efforts can identify and focus on pollutants posing the greatest threats to water quality and human and ecosystem health. Continued vigilance through monitoring is essential, however, because events remind us that the oxygen content of water can still disappear rapidly following high organic inputs. In September 1979, the South Bay basin below the Dumbarton Bridge was oxygen-depleted and regions were devoid of fish and shrimp for several weeks (prompting the news headline *Sewage Leaves Bay a 'Dead Sea'*), following inputs of primary-treated sewage during a disruption of the San Jose-Santa Clara Waste Treatment Facility (Cloern and Oremland 1979).

## The Bay as an Open Ecosystem

San Francisco Bay is connected to large rivers, urban watersheds, and the coastal Pacific Ocean. The Bay is profoundly influenced by inputs from these three connections, each having its own chemical makeup and distinct variability. Salinity in the Bay is a simple indicator of river-runoff inputs, and salinity measurements before and after the 1997 New Year's Flood showed remarkable changes in the composition of Bay water (Figure 3). Average salinity dropped from 26.1 to 9.0 psu (the salinity of fresh water is 0 psu and the salinity of seawater is 35 psu), so the Bay as a whole changed from 79% seawater to only 27% seawater. Salt dilution of this magnitude shows that more than half the Bay's water volume was displaced by river inflow between November 1996 and January 1997. During these periods of high inflow, concentrations of runoff-derived contaminants (e.g., chromium, nickel) increase, and concentrations of locally-derived industrial contaminants (e.g., silver) decrease in clam tissues (Brown and Luoma 1999; Brown et al. 2003). The availability of some metals (e.g., cadmium) for uptake by aquatic organisms varies with salinity, so salinity monitoring provides essential information for understanding changes in organism contamination.

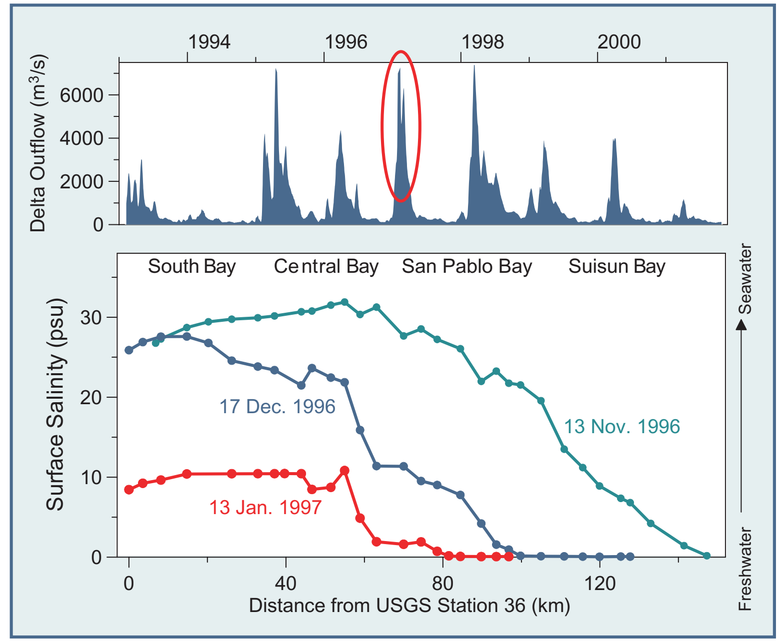


**Figure 3. The Bay is profoundly influenced by water inputs from the Delta.** Salinity measures the relative proportions of freshwater and seawater in an estuary, a key environmental factor for interpreting changes in the sources, concentrations and biological availability of toxic substances. Winter floods replace brackish Bay water with freshwater, diluting some contaminants (e.g., silver) and delivering others (e.g., mercury, PCBs). The bottom panel shows salinity along the Bay during three sequential USGS monitoring cruises to illustrate Baywide displacements of salt when Delta outflow increased in December 1996 and peaked during the 1997 New Year's flood. The top panel shows 1993-2001 Delta Outflow (California Department of Water Resources), highlighting this flood event. (Delta outflow is plotted as a 7-day average to smooth the large daily variability.)

The Pacific Ocean is another powerful force of change, and we can use other indicators to study the influence of oceanic processes on the living Bay system. In September 2002, patches of colored water were observed in Central Bay; microscopic analyses revealed that the 'red tide' was a bloom of *Heterosigma akashiwo.* This harmful alga has never been reported in the Bay before, and its presence is reason for concern because it is associated with fish kills in Puget Sound and other coastal ecosystems. Causes of the *Heterosigma* bloom in San Francisco Bay are a mystery, but satellite imagery suggests that it originated offshore and propagated into the Bay. A satellite image from SeaWifs (Figure 4) shows an abundance of phytoplankton (chlorophyll a) offshore on September 16, 2002, consistent with reports of red tides off Stinson Beach and Bodega Bay. This image clearly depicts the Bay's ocean connection and the lesson that water quality and living resources inside the Bay are influenced by events outside the Golden Gate, just as they are influenced by inputs from the rivers and urban watersheds. Lessons from monitoring teach that the Bay is an open system that responds to change at its boundaries.

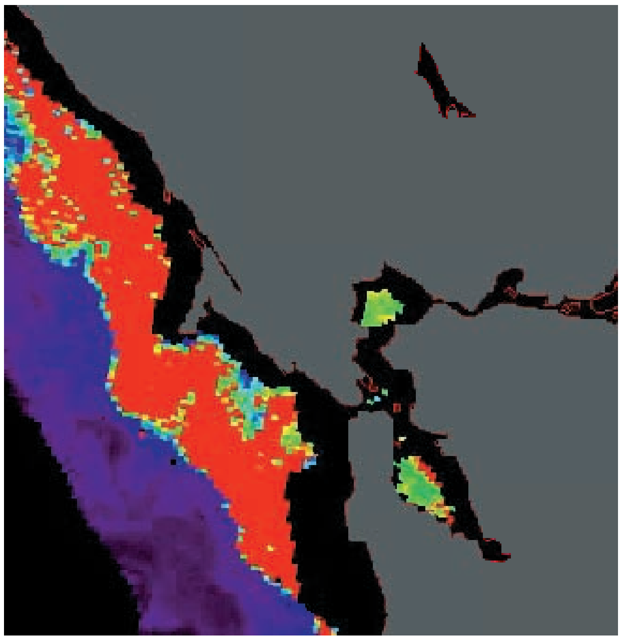

**Figure 4. Water quality and living resources inside San Francisco Bay are influenced by events outside the Golden Gate.** This satellite (SeaWiFS) image from September 16, 2002 shows high quantities of phytoplankton (microscopic algae) as red in the nearshore Pacific Ocean. At the same time, a red tide bloom of a toxin-producing species of phytoplankton was observed inside San Francisco Bay. [Black indicates no data, typically due to the presence of land or clouds. Color inside San Francisco Bay is not accurate because of interference by suspended sediments.]

## Phytoplankton as Food Resource and Contaminant Carrier

The largest living component of San Francisco Bay is invisible to the naked eye – the suspended microalgae, or phytoplankton. Phytoplankton photosynthesis is the most important energy supply to Bay-Delta foodwebs (Jassby et al. 1993; Sobczak et al. 2001), supporting clams, worms, shrimp, zooplankton, herring, sturgeon, striped bass, canvasback ducks, pelicans and, ultimately, harbor seals. Phytoplankton photosynthesis in the Bay produces about 120,000 tons of organic carbon each year, or the number of calories required to sustain over a million adult humans. This food supply is smaller than average for the world's estuaries (partly because the Bay is turbid), and as a result phytoplankton consumers such as zooplankton, mysid shrimp and clams are usually limited by the available supply of food. Food limitation disappears during phytoplankton blooms, when phytoplankton biomass becomes high enough to sustain maximum rates of growth and reproduction by these consumers (Cloern 1996).

Phytoplankton production also transforms dissolved chemicals (carbon dioxide, nitrate, phosphate, trace metals, organic molecules) into particulate forms (algal cells) that can be consumed by organisms at the next trophic level. This transformation is the entry point of contaminants into foodwebs, including priority pollutants such as selenium, mercury, and PCBs that increase to potentially toxic levels as they are transferred up the food chain. Because phytoplankton production and transformation of trace metals accelerate during blooms (Luoma et al. 1998; Beck et al. 2002), these events act as biological regulators of the toxicity and accumulation of contaminants in Bay foodwebs.

Phytoplankton monitoring at weekly-monthly frequencies reveals seasonal patterns such as the prominent spring bloom that occurs every year in South Bay (Figure 5), whereas continuous monitoring with moored instruments enables us to measure short-term variability between ship-based samplings. Sustained monitoring over decades shows that there has been a change in the annual pattern from a spring bloom cycle to a spring and autumn-winter bloom cycle in the South Bay (Figure 5). This recent departure from a 21-year pattern suggests that the South Bay has experienced a regime shift, for reasons not yet identified. Clues might come from a recent study showing multi-decade biological cycles around the Pacific Basin (Chavez et al. 2003). Could the recent appearance of autumn-winter blooms inside San Francisco Bay reflect a Pacific-scale regime shift? Records from a moored fluorometer (Figure 5) show that chlorophyll varies within a day, sometimes over a range comparable to that measured over seasons or decades. This record shows two peaks per day suggesting a tidal process such as oscillation of water masses containing patchy chlorophyll distributions (Jassby et al. 1997). Lessons from phytoplankton monitoring show that San Francisco Bay is a continually-changing and evolving biological system, over periods from hours to decades. An important challenge of monitoring design is to measure and understand variability at all time scales so that trends of long term change can be detected and interpreted with confidence.

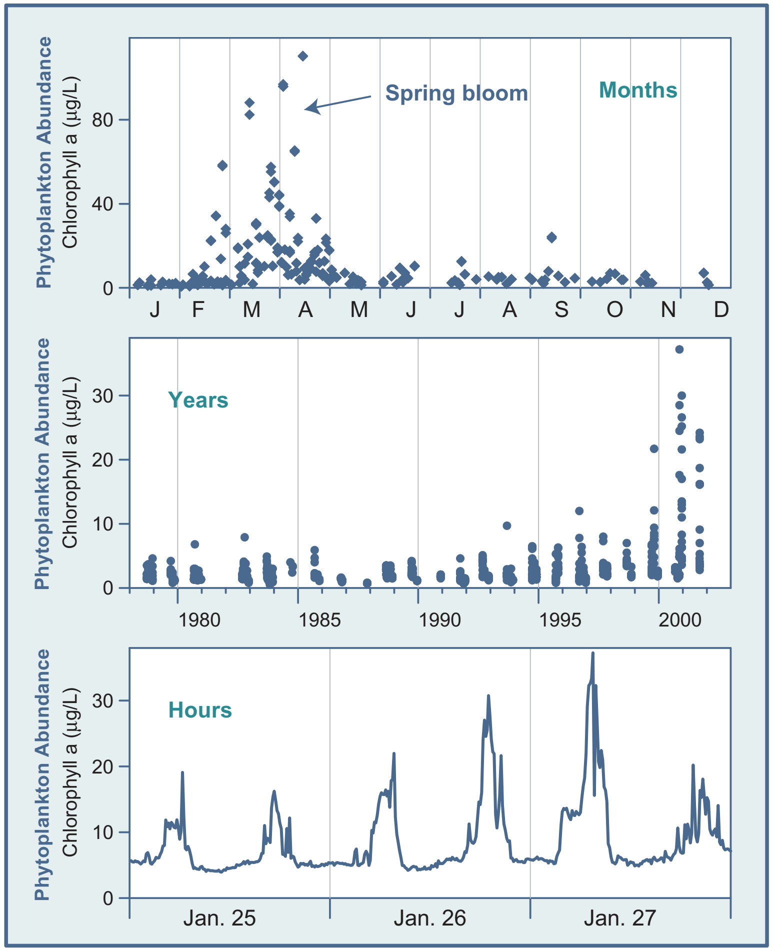


**Figure 5. Long-term monitoring has revealed fundamental shifts in seasonal cycles of the Estuary's food supply.** Phytoplankton (microscopic, suspended algae) is the largest living component of the San Francisco Bay ecosystem, and phytoplankton photosynthesis is the biological engine that fuels food webs, transforms contaminants, and moves contaminants such as selenium, mercury, and PCBs into food webs. These figures illustrate variability of phytoplankton abundance (as measured by chlorophyll a concentration) at three time scales: the top panel shows monthly variability near the Dumbarton Bridge from 1993-2001, highlighting the spring bloom that typically develops between mid February and mid April. The middle panel shows all measurements made in South San Francisco Bay during September-December from 1978-2002, suggesting a regime shift to autumn-winter blooms beginning in 1999. The bottom panel shows chlorophyll near the Dumbarton Bridge measured every ten minutes during 3 days of January 2003. Comprehensive monitoring documents variability at all these time scales, each of which may be important in understanding water quality in the Bay.

## Biological Pollution as Damaging as Chemical Pollution

San Francisco Bay's biological communities are a mix of native and alien species, and some habitats are dominated by aliens. Many species were introduced into the Bay long before monitoring began, so we have no knowledge of the Bay's biological community structure, water quality, or ecosystem functions prior to species introductions by humans. Monitoring in recent decades has provided direct measures of the disturbance caused by alien species. A compelling example is the suite of changes in northern San Francisco Bay that followed, almost immediately, invasion by the Asian clam *Potamocorbula amurensis*. Prior to this invasion in 1986, phytoplankton in Suisun Bay accumulated to high levels in summer (Figure 6). These summer blooms did not appear in 1987 and they have been absent since. *Potamocorbula* filter phytoplankton from water, and they are abundant enough to remove algal cells faster than phytoplankton can reproduce in Suisun Bay. As a result, *Potamocorbula* has reduced primary production five-fold (Alpine and Cloern 1992), creating an environment of chronic food limitation for consumers. Populations of the native shrimp, *Neomysis mercedis*, have nearly collapsed in Suisun Bay and one explanation is depletion of the phytoplankton food resource by *Potamocorbula* (Orsi and Mecum 1996). Similar changes occurred in the crustacean zooplankton communities, so the Interagency Ecological Program (IEP) and USGS monitoring have documented the disruption of communities and ecosystem functions caused by this alien species. Analysis by the Regional Water Quality Control Board concludes that "Exotic species are one of the greatest threats to the integrity of the San Francisco Estuary ecosystem, perhaps as great as any pollutant regulated under the Clean Water Act." Monitoring of biota and measurements of ecosystem functions provide a sound scientific basis for inclusion of exotic species on the 303(d) list of pollutants that impair San Francisco Bay (see Inside Back Cover).

## The Need for Comprehensive Monitoring

The lessons described here illustrate how monitoring contributes to resource management. For San Francisco Bay, monitoring data provide the basis for establishing water quality management priorities that have evolved over time and now focus on nonpoint sources of pollution, exotic species, and a prioritized set of toxic contaminants. Monitoring records changes in the chemical and biological condition of San Francisco Bay, providing an objective basis for measuring the benefits of advanced wastewater treatment and point-source reductions of toxic pollutants. It can similarly document responses to future actions such as steps to reduce pollutant loadings from nonpoint sources. Finally, monitoring data provide powerful clues revealing how San Francisco Bay functions as an ecosystem and how its functions respond to both natural forces and human activities.

The need for monitoring information is perpetual because San Francisco Bay will continue to change in ways we cannot predict. We can, however, identify forces of change that might reshape the Bay ecosystem, such as: conversion of salt ponds to new habitats; construction of airport runways; climate changes that alter the seasonal timing and quantity of river runoff; sea level rise; population growth adding over 1.4 million Bay area residents by 2020 <http://www.dof.ca.gov/>; unanticipated introductions of new species; and regulatory actions such as implementation of TMDLs. Although we know with certainty that San Francisco Bay will change in coming decades, there is no institutional framework to fully document, understand and support adaptive management to those changes. The USGS-RMP partnership illustrates how resources of two institutions can be combined to meet some specific monitoring needs, but the full suite of potential partnerships has not been melded into a Baywide comprehensive monitoring program.

Our ability to anticipate and document future change in the Bay is deficient in four areas. First, institutional commitments to biological monitoring do not support regular sampling of plankton, sediment-dwelling invertebrates, waterfowl, or mammals. Basic components of water quality such as nutrients, and ecosystem functions such as primary production, are also missing from the existing monitoring effort (IEP monitors nutrients and lower trophic level organisms, but not Baywide). Second, there is no mechanism for integrating and synthesizing information collected by agencies conducting specialized monitoring or research. Data are archived in disconnected databases, and cross-program data synthesis and integration are not supported institutionally. These deficiencies limit our progress toward an ecosystem-scale perspective of the Bay's systemic responses to changes in land use, habitats, waste loadings, climate, and invasive species. Third, existing programs do not fully exploit new technologies such as remote sensing and real-time data collection with moored instruments to measure changes at the spatial and temporal scales missed by ship-based sampling. Finally, institutional commitments have not been made to design, implement and permanently fund a comprehensive monitoring assessment and research program (CMARP), although the need is widely recognized and a general roadmap has been produced <http://www.iep.water.ca.gov/cmarp/>.

Given the value of monitoring to resource management and the certainty of forces that will change San Francisco Bay in uncertain ways, we wonder: How might the monitoring lessons described here be applied to stimulate implementation of a CMARP?

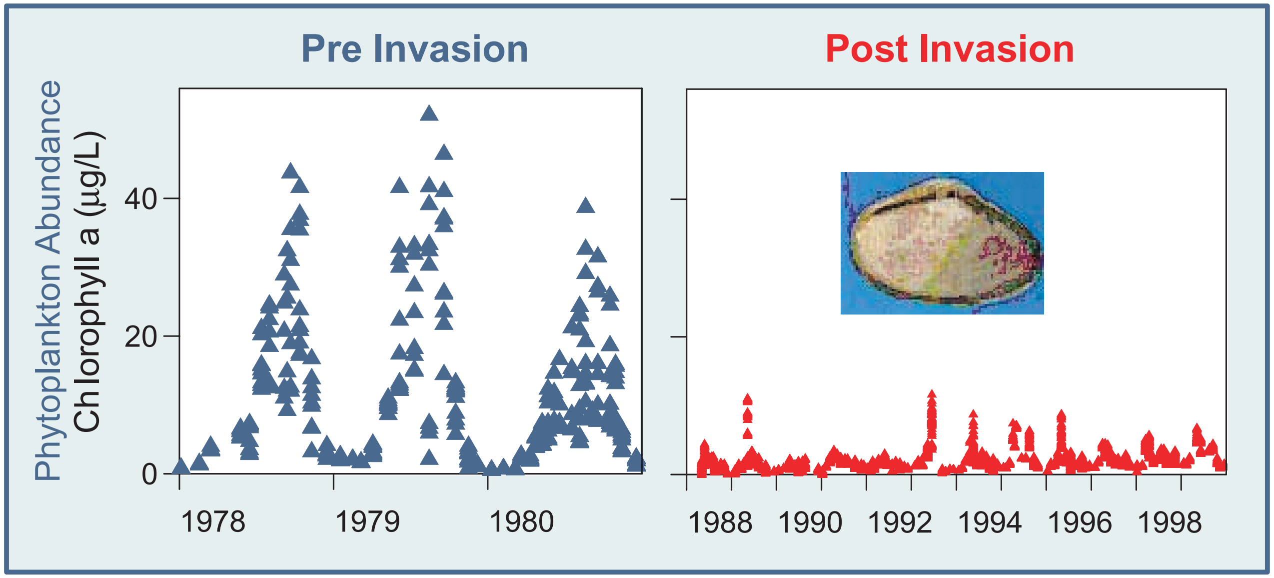


**Figure 6. Ecosystem disruption from biological pollution can be as powerful as disruption from chemical pollution.** The summer phytoplankton bloom disappeared and abundance and photosynthetic production decreased fivefold in Suisun Bay after invasion by the alien clam *Potamocorbula amurensis* in late 1986. This Figure compares annual cycles of phytoplankton abundance (chlorophyll a) in Suisun Bay for three years before (left panel) and 12 years after this invasion (right panel). The mean pre-invasion (1978-1980) chlorophyll concentration was 9.8 mg/L compared to the mean post-invasion concentration of 2.1 mg/L. Native invertebrates, including important forage species for fish, are now food-limited and populations of some species (the mysid shrimp *Neomysis mercedis*) have virtually collapsed since this invasion.