

#### **COVER IMAGE**

Shaded relief image of sediment deposits on the floor of Central Bay, generated from bathymetric data. Courtesy of USGS. Additional information available at: http://terraweb.wr.usgs.gov/projects/SFBaySonar/centralbay.html

# > THE PULSE OF THE ESTUARY

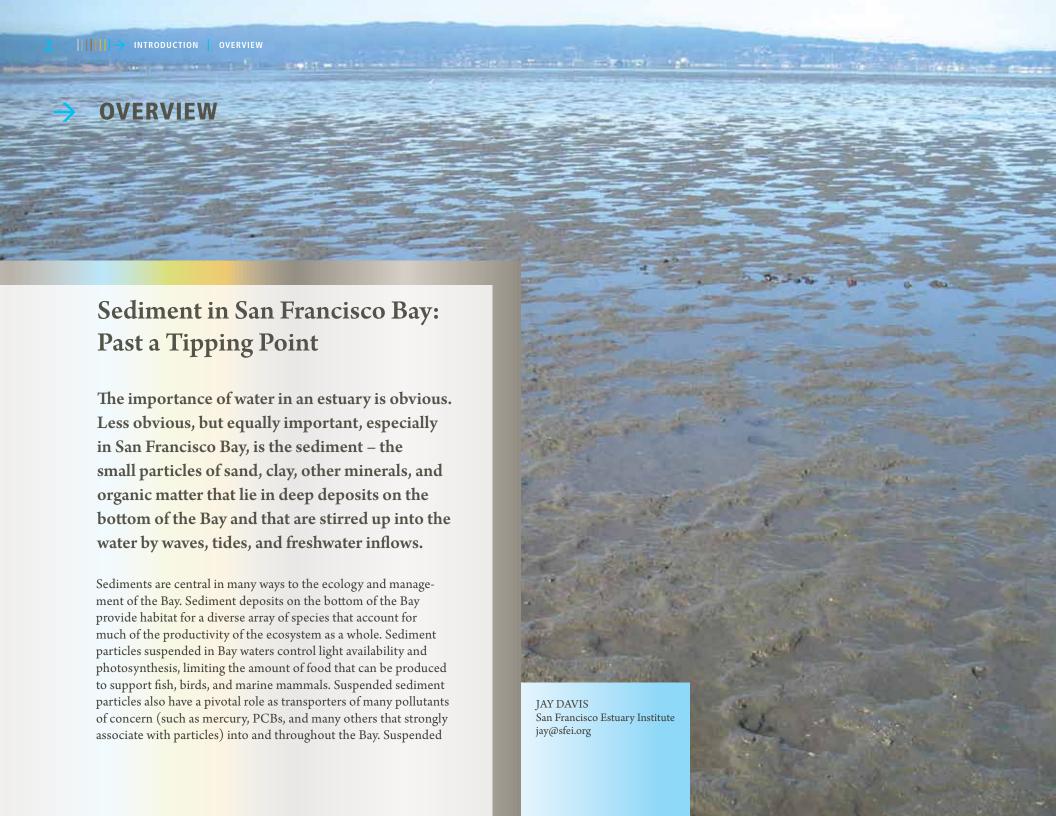
Monitoring and Managing Water Quality in the San Francisco Estuary

2009

Bay Sediments:
Past a Tipping Point

A Report of the Regional Monitoring Program for Water Quality in the San Francisco Estuary

September • 2009 Contribution #583



sediment particles are crucial in wetland restoration, as they are a primary source of the substrate that is needed for the establishment of wetland plants and the animal species that depend on them. On the other hand, suspended sediment particles also deposit in places where they interfere with beneficial uses of the Bay – specifically, in channels where they impede navigation and must periodically be dredged. Approximately four million cubic yards of sediment are dredged from Bay channels and moved to other locations each year, with millions of dollars spent to plan and conduct these activities.

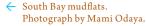
The shallow depth of the Bay further magnifies the importance of sediment in this ecosystem. At low tide, about half of the Bay is less than ten feet deep. Much of this shallow area consists of mudflats – one of the Bay's defining features. A good low tide exposes vast mudflats that cover about a sixth of the Bay's total area, with the largest expanses in the eastern and southern parts of the South Bay and the northern parts of San Pablo and Suisun Bays. These mudflats are vital habitat for the hundreds of thousands of shorebirds that pass through the region in spring and fall. The Bay's shallow depth also increases the capacity for waves and water flows to resuspend sediment into the water column, where it has such a large influence on water quality.

Past a Tipping Point

Given the central importance of sediment habitat and sediment dynamics, the Regional Monitoring Program for Water Quality in the San Francisco Estuary (RMP) invests substantial resources into monitoring and modeling sediment. Sediment transport into the Bay is measured in monitoring and modeling studies of the loading of mercury and other particle-associated pollutants from the Sacramento and San Joaquin rivers and small tributaries (page 50). The quality of the surface sediments, which provide habitat for most benthic (sediment-dwelling) species, is extensively monitored using a "triad" of chemical analysis of a host of contaminants, evaluation of toxicity, and assessment of benthic populations. A major effort in the last few years has been made to measure contaminant concentrations in cores of deeper sediments to evaluate the potential for these buried deposits to erode and prolong recovery of the Bay (page 76). A primary focus of the RMP over the next several years will be development of a model that describes the movement of sediment and sediment-associated contaminants, providing a tool that water quality managers can use to forecast recovery of the Bay at local and regional scales (page 75).

Intensive monitoring of concentrations of suspended sediment has also been a significant component of the RMP since the Program began in 1993. This work has been conducted by Dave Schoellhamer and his colleagues at the U.S. Geological Survey. Maintaining this dataset over this 16 year period has enabled us to detect a sudden and fundamental change that occurred between 1998 and 1999 (page 56). It appears that the Bay passed a tipping point at that time due to the depletion of a pool of easily erodible sediment that had been slowly moving through the watershed ever since the Gold Rush. In 1999 this pool seems to have been exhausted, and suspended sediment concentrations fell by 40%.

This shift to clearer waters is affecting the ecology and management of the Bay in many ways. Ecologically, the Bay shifted from a system where photosynthesis by phytoplankton was limited by a lack of light penetration in the murky waters, to one where phytoplankton abundance has been increasing (page 53) and represents a growing concern. Water quality managers now must pay closer attention to the potential for nutrient pollution to cause the problems associated with excessive algal production that are common in many other estuaries, such as Chesapeake Bay.





#### **OVERVIEW** continued

A great deal of effort goes into managing sediment itself in San Francisco Bay. The Bay is a major international shipping hub, with an estimated 4,000 commercial ocean-going vessels carrying approximately \$20 billion worth of cargo passing through every year. Navigational channels have been created, deepened, and maintained by dredging to enable these and other vessels to navigate safely into and out of ports, harbors, and marinas without running aground. Most of the four million cubic yards of sediment dredged each year is disposed of in the Bay at aquatic disposal sites (page 52) or used to raise sediment elevations in restoration of tidal wetlands. Many successful projects in the Bay Area have demonstrated the benefits of re-use of dredged sediment in wetland restoration (page 8). Lower concentrations of suspended sediment will likely result in a mix of positive and negative impacts, including a reduced need for maintenance dredging and increased capacity of the in-Bay aquatic disposal sites, but a diminished supply of the sediment that is naturally delivered to restoration sites by the tides. With a smaller natural supply of sediment, there will be an even greater demand for re-using dredged sediment in restoration projects. In light of all of these changes, the Long-Term Management Strategy for dredged material may need to be updated.

There have been major shifts in the sediment regime of the Bay before (page 66), and this has been the largest human influence on the morphology of the ecosystem. High suspended sediment concentrations resulting from hydraulic gold mining in the Sierra Nevada led to deposition of over 300 million cubic yards of sediment in the Bay in the middle and late 1800s. In the 1900s the sediment supply was largely cut off as reservoirs were constructed in the Central Valley, and the Bay entered an era of net erosion from the Bay floor. Patterns of erosion and deposition in the Bay are likely to continue to change due to changes in sediment supply, sea level rise, and intentional or unintentional restoration of tidal action to large areas in the Bay and Delta.

One concern related to erosion of Bay sediment deposits is that the relatively high concentrations in layers that formed in more contaminated eras could be time-bombs waiting to be uncovered, and could prolong recovery in spite of current efforts to reduce contaminant inputs. A new RMP study found that concentrations of trace metals in these deeper sediment layers were lower than expected, suggesting that this is less of a concern than previously thought (page 76). The data suggest that extensive mixing of more-contaminated older Bay sediments with less-contaminated sediments from recent years has resulted in substantial dilution.

#### Other Highlights of this Edition of the Pulse

An important shift in how contaminants are managed in the Bay is also underway. The "sediment quality triad" mentioned above (chemistry, toxicity, abundance) is providing a foundation for application of sediment quality objectives (SQOs) – a new tool that has been developed to better manage sediment contamination (page 16). California adopted SQOs in 2008, becoming one of the first states to implement such an approach. The SQO framework will provide a useful context for addressing the widespread sediment toxicity that has been consistently observed since the RMP began in 1993 (page 47).

As always, this Pulse also presents an overview of other noteworthy information that has been generated in the past year by the RMP and other programs. Year after year, the RMP continues to build high quality datasets on water quality parameters that are critical to the health of the Bay, and our understanding incrementally advances. The fundamental shift observed through sustained measurement of suspended sediment concentrations is a classic example of the tremendous value of long-term monitoring of critical parameters, especially in an ecosystem that is subject to as many formidable pressures as San Francisco Bay.









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

For PDF versions of the 2006, 2007 and 2008 Pulses, please go to www.sfei.org/rmp/pulse/ index.html.

# THE PULSE OF THE ESTUARY 2009

# > TABLE OF CONTENTS

#### 6 MANAGEMENT UPDATE

9

Dredged Sediment: From "Spoils" to Valued Resource

16

Sediment Quality Objectives: A New Tool for Protecting California's Bays and Estuaries

28

Sidebar: The Suisun Bay

**Reserve Fleet** 

**29** 

The 303(d) List and Regulatory Status of Pollutants of Concern STATUS AND TRENDS UPDATE

LATEST MONITORING RESULTS

WATER QUALITY
TRENDS AT A GLANCE

FEATURE ARTICLES

Suspended Sediment in the Bay:
Past a Tipping Point

How Humans and Nature
Have Shaped the San Francisco
Estuary Since the Gold Rush

76
Analysis of Sediment Cores:
Uncovering the Past

88 90 91
REFERENCES RMP COMMITTEE CREDITS MEMBERS AND PARTICIPANTS



LEFT Aerial view of Hamilton Army Airfield in 1970. Photograph courtesy of the U.S. Army Base Realignment and Closure Office.

# RIGHT Aerial view of the Hamilton Army Airfield restoration project in 2009. Photograph by Mark DeFeo (Aerialsondemand.com) courtesy of Manson/Dutra J.V., a Joint Venture.

# **→ MANAGEMENT UPDATE**

8

Dredged Sediment: From "Spoils" to Valued Resource

16

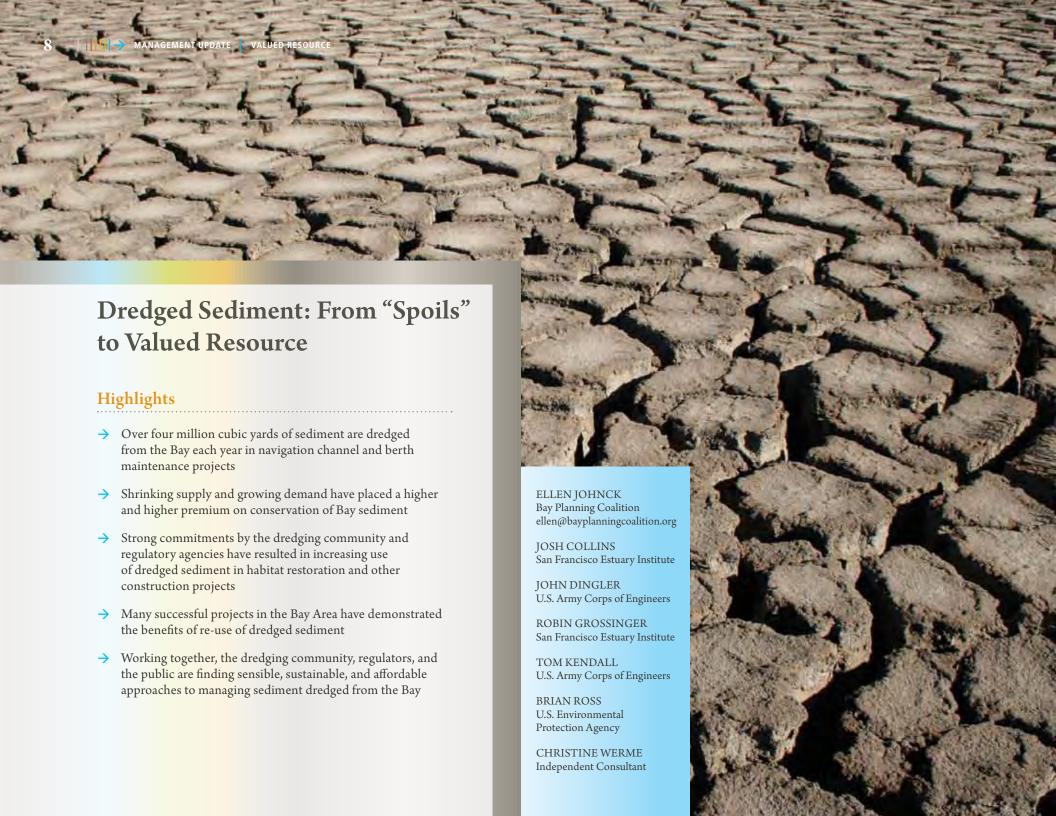
Sediment Quality Objectives: A New Tool for Protecting California's Bays and Estuaries

**28** 

Sidebar: The Suisun Bay Reserve Fleet

**29** 

The 303(d) List and Regulatory Status of Pollutants of Concern





# Maintaining a Busy Maritime Thoroughfare

We used to call them "dredge spoils." Then we went to a more neutral term, "dredged material." And increasingly, the most descriptive name for sediments that are excavated from our shipping channels and marinas is "valuable resource." How we view the material that we scrape, grab, and suction from San Francisco Bay to maintain our waters for safe and reliable shipping, travel, and transportation has changed a lot.

There are good reasons for this evolution in terminology. The shift reflects our increasing societal appreciation for sustainability and a "win-win-win" philosophy—wins for a strong economy, a healthy environment, and enhanced recreation opportunities. The shift also reflects the physical realities of sediment fate and transport in coastal management and wetland restoration. The shrinking supply of sediment to the Bay (page 56), coupled with a growing demand for sediment for habitat restoration, has placed a higher and higher premium on conservation of this increasingly valuable resource.

Dredging, whether in the open Bay or the most protected marina, is a necessary activity to maintain existing or create new navigation channels, which support a thriving maritime industry and recreational boating. Dredging has been a part of the busy commerce in San Francisco Bay since the Gold Rush, partly because hydraulic mining washed immense amounts of sediments from the Sierra Nevada foothills into streams, rivers, and San Francisco Bay. During the same period, changes in land uses in local watersheds, which supply much of the sediment entering the Bay, increased erosion of hillsides and streams. Concurrently, marshes

More and more, sediments are being used in beneficial habitat-improvement and flood risk damage reduction projects

in the Bay and the Delta, which would have trapped those eroded sediments, were being diked and leveed. Instead of being incorporated into marshes, the excess sediments filled natural shipping channels and made the already-shallow Bay even shallower.

Today the many dams and other control structures that dot the riverways of the Sierra foothills, the Central Valley, and the Coastal Range have diminished the excessive sediment loads of the Gold Rush era and altered the composition of the sediments that reach the Bay. Fine silts and clays mostly pass over the dams, but the coarse sands and gravels that could otherwise nourish beaches or provide habitat for salmon, are trapped. Trapping the coarse sediments also results in what is known as the "hungry water" effect, in which the capacity for the downstream water to move sediments is under-nourished, resulting in downstream erosion. This erosion is slowing, but hungry water has cut about seven feet into most of the streams around the Bay. Some streams have incisions as deep as 20 feet.

Over four million cubic yards of material are dredged from the Bay each year in federal navigation projects and other channel and berth maintenance projects (FIGURE 1). For many years, the sediments removed during those dredging operations have been disposed of on land, in the Bay, or in the ocean. But more and more those sediments are being used in beneficial habitat improvement and flood risk damage reduction projects (FIGURE 2).

# Regulatory Changes Encouraging Sediment Conservation

During the 1980s, disposal of dredged material became a controversial topic for Bay Area fishermen and environmental activists. The major site for disposing materials, near Alcatraz Island, had received so much sediment that a natural depression became a mounded navigation hazard. There were also worries that sediments dredged from urbanized areas contained toxic contaminants that would poison marine animals.

The Long-Term Management Strategy (LTMS) for Dredging and Dredged Material Disposal in the San Francisco Bay was developed in the early 1990s in response to these concerns and to improve the management of dredging and dredged material disposal. As a collaborative effort among state and federal regulatory and resource agencies and a host of other stakeholders, the LTMS has worked to reduce the volume of dredged material that is disposed of in the Bay. The LTMS has four main goals:

- maintaining the navigation channels in an economically sound manner,
- disposing of dredged material in the most environmentally sound manner,
- maximizing the use of dredged sediments as a resource material, and

creating a cooperative framework for permitting and managing dredging and disposal operations.

At first, the LTMS focused on getting sediments out of the Bay, and the major goal is still to minimize in-Bay disposal, but more recently the emphasis has been placed on promoting the use of the dredged sediments as a resource rather than a waste material. The 12-year-long process for developing the LTMS Management Plan resulted in goals that at least 40% of dredged material would be placed in uplands, 40% would be disposed of in the ocean, and no more than 20% would be disposed in the Bay. The 40% upland goal focused on the use of sediments for restoring and constructing wetlands in once-diked baylands, as cover for landfills or construction projects, for restoring levees, and in other beneficial projects. The LTMS recognized that restoration projects are expensive, but suggested that large projects could achieve an economy of scale. It also suggested that for some large restoration projects, it might be possible to use sediments that would be deemed too contaminated for in-Bay disposal sites, burying the harmful material deeply enough to render it harmless.

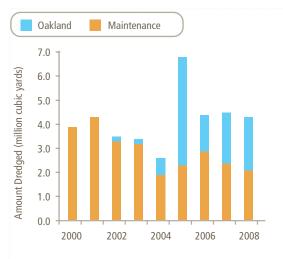
Today the LTMS agencies and the port and maritime industry community are working together to develop appropriate sediment re-use projects. Strong commitments on the parts of both the dredging community and the wide array of local, state, and federal agencies and organizations have allowed the LTMS regulatory agencies to promote increasing re-use of dredged sediment through cooperation rather than regulation.

#### Successful Partnerships and Projects

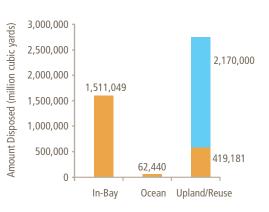
#### Sonoma Baylands

Successful projects depend on strong partnerships. The first successful dredged material re-use project in the Bay Area, the 320-acre marsh that is part of the Sonoma Baylands (FIGURE 3), resulted from such a partnership. Over the past 150 years, in general, San Francisco Bay's tidal marshes had been largely converted to salt-production ponds, agri-

cultural land, and urban uses. During the 1990s, the Sonoma Land Trust and the California State Coastal Conservancy jointly conceived a project to restore some of those wetlands in Sonoma County. Meanwhile, the Port of Oakland, the fourth largest container port in the U.S., was expanding its navigation channel capacity for imports and exports. Congress had authorized the Port to deepen channels to a depth of -42 feet, but that project lagged for a while under the difficulties in producing an



Footnote: Data from Shelah Sweatt, U.S. Army Corps of Engineers.



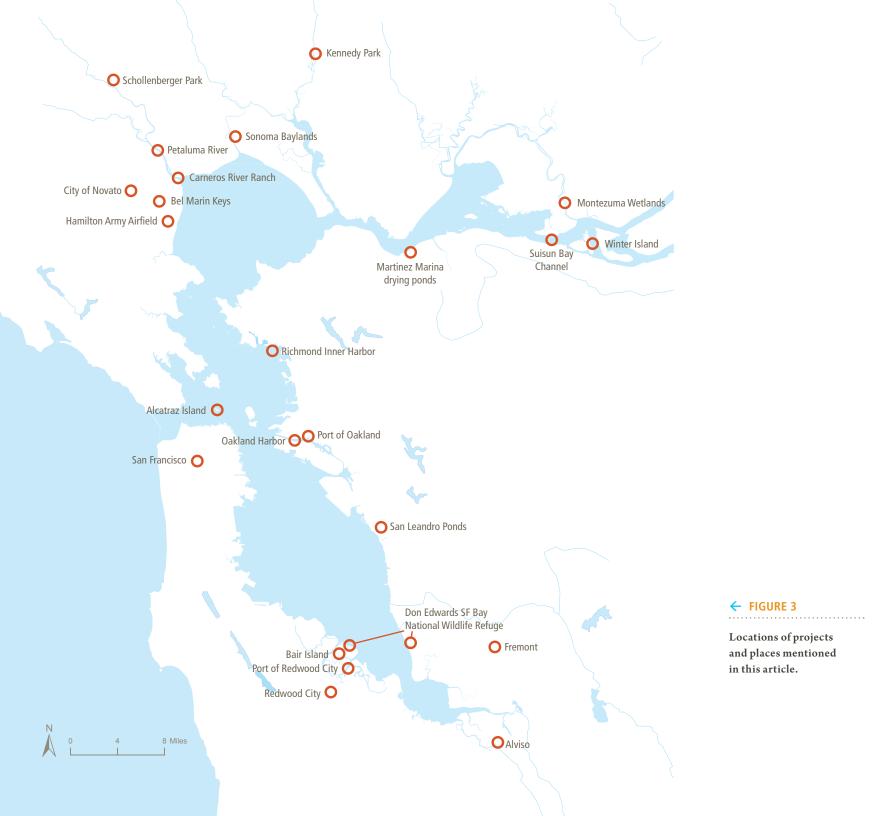
Footnote: Data from 2008 Dredged Material Management Office Annual Report. http://www.spn.usace.army.mil/conops/DMMO 2008 Annual Rep.doc

#### ↑ FIGURE 1

Over four million cubic yards of material are dredged from the Bay each year in federal navigation projects and other channel and berth maintenance projects. The annual amount dredged for maintenance has averaged 2.2 million cubic yards over the last five years. "New work" dredging to deepen the channel in Oakland Harbor has substantially increased the amount dredged in the last four years.

#### ↑ FIGURE 2

Dredged sediments are increasingly being used in habitat improvement and flood risk damage reduction projects. In 2008, 62% of the total amount dredged went to beneficial re-use. Much of this material (2.2 million cubic yards), however, was from the Oakland Harbor deepening project. Excluding that project, most material went to in-Bay aquatic disposal sites.





↑ Gladioli growing in dredged sediment at Carneros Ranch. Photograph by Brian Swedberg.

environmentally and economically feasible plan for the material that would be dredged from the Inner and Outer Oakland Harbor Channels. Federal and state authorities recognized that using the material to restore the Baylands marshes could benefit everyone. Now, after being supplied with almost two million cubic yards of material from the Port, the Sonoma Baylands supports a thriving tidal marsh, providing habitat for shorebirds, waterfowl, and other Bay flora and fauna.

#### Montezuma Wetlands

Similarly, the Montezuma Wetlands Restoration Project, an 1,800 acre site located in Solano County at the eastern edge of Suisun Marsh (FIGURE 3, benefitted from the vision of the site's private landowner, Jim Levine, and a partnership between

the Port of Oakland and a group of organizations similar to the one that supported the Sonoma Baylands project. The concept is to use dredged sediment to raise subsided former marshes to their natural tidal elevation faster than this would occur through natural sedimentation. Establishing elevations appropriate for intertidal marsh habitat will require about 20 million cubic yards of sediment. Montezuma Wetlands began to receive material in 2003 and about 3 million cubic yards of material have been placed at the site to date. The majority of the material has come from the Port of Oakland's recent 50 foot channel deepening project. For the -50 Foot Project, the U.S. Army Corps of Engineers (USACE) is widening and deepening the Oakland Harbor entrance, channels, and two turning basins to accommodate modern container ships, the culmination of several years of planning and coordination among federal, state, and local agencies and other interested parties the USACE, the State Coastal Conservancy, the Bay Conservation and Development Commission (BCDC), the City of Novato, the County of Marin, the San Francisco Bay Joint Venture, The Bay Institute, Ducks Unlimited, Save San Francisco Bay Association (Save the Bay), the National Audubon Society, Bay Planning Coalition, U.S. Fish and Wildlife Service, U.S. Geological Survey, the San Francisco Bay Regional Water Quality Control Board, and the residential and commercial communities who live and work near the site. The biggest problem faced by the Montezuma Project is that dredged material deliveries have been much slower than originally anticipated. The Montezuma Project is financially supported solely by dredged material re-use.

#### Hamilton Army Airfield

Hamilton Army Airfield, in Marin County (page 6, FIGURE 3) has the potential of becoming one of the largest regional beneficial re-use projects in the Bay, receiving sediment from multiple dredging operations. The first dredged material to be placed at Hamilton came from the Bel Marin Keys Community Services District in the spring of 2007 (190,257 cy). About 3 million cubic yards of sediments dredged from the Port of Oakland's -50 Foot Navigation Improvement Project are being used to carry out the first phase of wetland restoration at the Hamilton site. The first material from the Oakland Harbor deepening was delivered to Hamilton in December 2007.

The Hamilton site was originally mostly salt marsh. During the Gold Rush, sediments that washed from the Sierra Nevada foothills deposited in part of the area, and in the latter part of the 1800s, much of the area was diked for agriculture. In the 1930s, the Hamilton Army Airfield was built. The Airfield was a staging area for overseas activities during World War II and remained in operation until 1974. Since passage of the Defense Base Realignment and Closure Act in 1988, the USACE, the State Coastal Conservancy, and BCDC have been working to restore the wetland habitats and establish public access.

The Hamilton site includes not only a part of the former Airfield but also a small Navy site and lands that are currently under control of the State Lands Commission. Originally, the properties were all tidal. Now the site includes pickleweed marsh, seasonal wetlands, brackish marsh, and developed areas covered by concrete, asphalt, and buildings.

The endangered California clapper rail resides there, as do several other species of concern. As is typical for military sites, parts of the site were contaminated with low levels of petroleum hydrocarbons, PCBs, herbicides, pesticides, and heavy metals. However, all of the area within the tidal marsh restoration footprint underwent an extensive cleanup process under the Base Realignment and Closure Program prior to the start of restoration activities.

The Hamilton Restoration Plan calls for raising the elevation of land that has subsided within the diked area. The plan is to create a 1,000-acre natural area that gently grades from upland habitats to intertidal salt marshes, mudflats, and tidal channels. A perimeter levee will be constructed to support the wetland habitats. A hydraulic off-loader, anchored on a barge offshore from the site, allows for efficient transfer of the dredged sediments being used for fill and levee construction from ships to the site via a pipeline.

Hamilton Airfield, now owned by the State Coastal Conservancy, combined with another restoration project at Bel Marin Keys, has a capacity to take 20 million cubic yards of sediments. Eventually, sediments from other dredging projects, such as federal projects at Richmond Inner Harbor and Suisun Bay Channel and private harbor dredging projects, could also be used, fulfilling the goal of making the Hamilton restoration the largest re-use site in Central Bay.

#### Port of Redwood City/Bair Island

In launching another beneficial re-use project in December 2008, the Port of Redwood City became

a model that other partnerships and projects can emulate. This project has built a partnership that includes the USACE, the U. S. Fish and Wildlife Service, the City of Redwood City, the Port of Redwood City, the Bay Planning Coalition, Save the Bay, and South Bayside System Authority.

Located on the Peninsula, about 25 miles south of San Francisco (FIGURE 3), the Port of Redwood City is the only deep-water port in the South Bay. The Port opened in 1850, and maintenance dredging of the shipping channel has been conducted since 1886. Over the years, the channel has been deepened to allow for modern vessels at the federally authorized depth of -30 feet. Almost two million tons of bulk cargo, such as cement, gypsum, and aggregate sand and gravel, are brought into the Port each year for use in the Bay Area and throughout Northern California. The Port has established a special niche delivering building supplies in the South Bay while the other ports in the Bay and Delta have specialized in cargo. Maintaining channel depths is imperative for all the ports and marine terminals in the Bay to operate. There are times when ships with full loads have risked running aground, and have been either forced to come in with lighter loads or to wait for high tide before entering the Port.

Last year the Port of Redwood City's \$3.6 million maintenance dredging project had a goal of removing 200,000 cubic yards of sediment. In the past, those sediments would have been disposed of at the in-Bay disposal site near Alcatraz Island. For this project, however, the sediments were slated for re-use in the restoration of tidal wetlands on Bair Island, a part of the Don Edwards San Francisco

Bay National Wildlife Refuge. Located in Redwood City, Fremont, and Alviso, the 30,000-acre Refuge is a stopping point for millions of migrating shore-birds and waterfowl that follow the Pacific Flyway every year. The endangered California clapper rail and salt marsh harvest mouse are year-round residents. Hundreds of thousands of people from the Bay Area visit the Refuge each year to learn about its upland and intertidal habitats, and to hike, jog, bike, fish, or hunt.

The Bair Island site has been heavily used during California's history, first as a place to graze cattle and then as part of the massive salt-evaporation enterprise that dominated the South Bay and was a significant feature of the Bay Area economy. Salt production began in the late 1800s and required diking marshes and wetlands to transform them into evaporation ponds. Now, the U.S. Fish and Wildlife Service is returning approximately 15,000 acreas of those ponds to tidal and managed wetlands in the South Bay Salt Pond Restoration Project, including restoring about 1,400 acres of Bair Island (Inner, Middle, and Outer) to tidal wetlands. The Bair Island restoration includes raising the level of the Island so that when tidal action is re-established, the area will evolve from a salt-evaporation pond to a vegetated marsh. The Bair Island restoration will require more than one million cubic yards of fill.

Besides creating valuable new wetland habitat, the Bair Island restoration will decrease the need to dredge the adjacent slough. Restoring tidal wetlands also restores the tidal prism—the volume of water entering and exiting the marshlands with the tides—and the increased flow causes channels to deepen.

#### **Additional Sites**

Other sites within San Francisco Bay and the Delta are suitable for using dredged sediments to restore wetlands, repair and maintain levees, cover landfills, or provide materials for general construction. Several of these sites are or have the potential to be regional projects, receiving sediments from multiple sources.

- Winter Island, a private island located at the confluence of the Delta and Suisun Bay, has used dredged material to maintain its perimeter levees.
- Van Sickle Island, at the eastern edge of the Delta, uses dredged material for levee maintenance.
- The Carneros River Ranch, an area located near the mouth of the Petaluma River that was diked for farming in the late 1800s, has used dredged sediments to raise the elevation of its subsided lands.
- The Ocean Beach Demonstration Project is a USACE experimental beach nourishment project outside the Bay on the Pacific Coast.

• The South Bay Salt Pond Restoration Project has the potential for re-use of sediments to restore the vast tidal wetlands of the South Bay. The largest tidal wetland restoration effort on the West Coast, the projects plans to restore more than 15,000 acres of commercial salt ponds to a mix of tidal marshes, mudflats, and other natural habitats.

Other re-use projects are related to specific adjacent dredging operations, such as Kennedy Park in Napa, San Leandro Ponds, Schollenberger Park in Petaluma, Martinez Marina drying ponds, and Oakland Middle Harbor (FIGURE 3).

Dredged sediments are also frequently suitable for cover, capping, or lining material at landfills. Another option studied in the late 1990s was the establishment of regional dredged material "rehandling" facility. The idea was to place dredged material at a site along the Bay's shoreline and provide an opportunity for contractors who needed fill for construction projects to access the site. The study, funded by the California State Coastal Conservancy and conducted in collaboration with the Bay Planning Coalition, located several possible locations for a rehandling site but was unable to identify a willing operator.

#### Regional Sediment Management

With evolving thinking about the opportunities for beneficial re-use of dredged material and the first success stories has come a recognition of the needs for advances in sediment use planning and management. In conjunction with the USACE, the California Natural Resources Agency and regional commissions, including BCDC, are engaged in both a statewide and a regional sediment management program. Comprising members from these and other state, federal and local agencies and other organizations, the Coastal Sediment Management Workgroup (CSMW) is pursuing development of a Sediment Master Plan, a plan that seeks to identify sediment-management needs along the entire California coast. CSMW's overarching goals are to reduce shoreline erosion and coastal-storm damage, restore and protect beaches and other coastal environments by restoring natural sediment supplies from rivers, impoundments, and other sources to the coast and optimizing the use of sediment from ports, harbors, and other sources.

The Sediment Master Plan pursues these goals through increasing agency and project coordination, compiling existing information related to coastal sediment management, making spatial data available through web-based mapping and geographical information products, holding public meetings to identify needs and opportunities, and proposing more consistent regulations, legislation, and policies.

Recognizing the value that sediments have in construction and reclamation, the plan provides a framework for identifying regional sediment-related problems and for planning and prioritizing projects that can solve those problems.





- LEFT
   Brian Swedberg holds a pumpkin from this year's crop. Photograph by Linda Wanczyk.
- RIGHT
   Tomato plants growing in dredged sediment at Carneros Ranch. Photograph by Brian Swedberg.

The Sediment Master Plan is being implemented on a regional scale through several Coastal Regional Sediment Management (Coastal RSM) plans. These regionally focused plans are designed to foster a consensus-driven management structure that concentrates on solutions to issues of importance to that region. To date, Coastal RSM plans have been developed by three regional agencies—the Association of Monterey Bay Area Governments, the San Diego Association of Governments, and the Beach Erosion Authority for Clean Oceans and Nourishment. These plans serve as prototypes and guidance for additional Coastal RSM plans to be developed in other parts of coastal California. The CSMW provides guidance and minimum requirements to ensure statewide consistency among plans.

A new round of Coastal RSM plans is underway, covering Orange County, Northern Monterey Bay, Eureka Littoral Cell, and San Francisco Bay and coastline. BCDC, with other partners, is the sponsoring agency for the San Francisco Bay and coastline RSM plan. BCDC's updated strategic plan, adopted in October 2008, fits into the structure of the state-wide program in that it includes goals to complete a sediment management plan for San Francisco Bay, and, when funds are available, to provide a briefing on the lessons learned through restoration projects.

#### **Delta LTMS**

Similar to the LTMS for San Francisco Bay, the Delta Long-Term Management Strategy (Delta LTMS) is a cooperative effort to coordinate, plan, and implement beneficial re-use of sediments in the Sacramento and San Joaquin River Delta. The Delta LTMS is a joint effort of the state and federal agencies that have regulatory authority in the region.

The Delta comprises a one thousand square-mile network of marshes, sloughs, and diked-anddrained wetlands. Maintenance of the shipping channels within the Sacramento and San Joaquin rivers is crucial for maintaining access to the ports of West Sacramento and Stockton. Within the Delta, many of the more than one thousand miles of levees that protect the region are in critical need of maintenance or rehabilitation. One possible solution to rehabilitate those levees is to strengthen them using sediments dredged from the navigation channels.

The ultimate goal of the Delta LTMS is to adopt a comprehensive plan for sediment management. The plan's objectives are to maintain channels for navigation, water conveyance, and recreation and to stabilize levees, while protecting and enhancing water quality and wildlife habitat. Several technical work groups, including one focused on sediment placement and re-use, currently are developing the management alternatives that will make up the overall plan, which is scheduled for completion in 2010 depending on available funds.

The Delta LTMS has also developed a database on sediment chemistry, toxicity, and benthic (bottom-dwelling) communities – the three types of indices commonly used in assessing sediment quality (page 16). This database, which continues to grow, is intended to be a tool for characterizing sediments where dredging is planned and selecting appropriate uses for the dredged material, including repair of existing levees or creation of new wetlands.

#### Win-Win-Win

The Bay Area is not alone in its recognizing that sediments that were once considered a liability can be a valued resource. Communities along the Great Lakes, the Eastern seaboard, and the Gulf of Mexico are also turning to re-use rather than disposal. European, Asian, and Australian projects are also underway. While not all sediments are suited for re-use, the federal government, state and local authorities, private corporations, and the public now realize that re-use can result in a "win-win-win" for commerce, the environment, and the local community.

The path towards re-use of dredged material is not always smooth. Toxicity of sediments removed from urban harbors remains a concern. In San Francisco Bay, 96% of the sediments dredged in 2008 were deemed acceptable for re-use, but the RMP has continued to find that many Bay sediments are toxic to test organisms (page 47). Furthermore, the costs of beneficial re-use can exceed those of simple disposal.

As concerns about climate change and rapid sea-level rise are addressed, it will be increasingly important to examine the economic and ecological costs and benefits of sediment re-use. Sediment has become a commodity, and its value is increasing as a means to offset the rise in sea level. There are some big questions—Should we allow any sediment dredged from San Francisco Bay to be disposed of in the ocean or the Bay? What criteria can be set to prioritize our re-use projects? Working together, the dredging community, regulators, and the public are finding sensible, sustainable, and affordable approaches to managing the valuable sediment dredged from this busy and vital waterway.

### Sediment Quality Objectives: A New Tool for Protecting California's Bays and Estuaries

#### Highlights

- → A new statewide sediment quality objective (SQO) for protection of aquatic life in bays and estuaries was established in 2008; a revised SQO for protection of human health is scheduled for adoption in December 2010
- → SQOs will significantly affect monitoring and management of water quality in San Francisco Bay
- → Key elements of the new initiative include narrative objectives for the protection of aquatic life and human health; specific indicators to determine if the objectives are met; guidance for monitoring, stressor identification, and corrective action; and a standardized assessment framework
- → An assessment of recent data from San Francisco Bay found 39% of stations exceeded the aquatic life SQO
- → Most of these stations were only moderately impacted, making it difficult to identify the contaminants responsible for the impacts
- → The RMP is allocating considerable resources to generate the data needed for SQO assessments and to improve assessment tools



#### California Leads the Way

In the fall of 2008, California became one of the first states in the U.S. to establish sediment quality objectives (SQOs). These objectives, which became effective in August 2009 by approval from USEPA, represent a new approach in regulatory policy, using multiple lines of evidence to evaluate sediment quality. SQOs will significantly affect monitoring and protection of sediment quality in San Francisco Bay. This article describes the new sediment quality objectives and how the Regional Monitoring Program (RMP) is adapting in response to them.

Chemical contaminants enter San Francisco Bay and other water bodies from many sources, partition into the water column and sediments and may affect aquatic life, wildlife, and human health (FIG-**URE 1A**). Until recently, most state and federal laws regulating water quality have focused on the effects of specific contaminants within the water column.

Sediments represent a long-term repository for contaminants and often provide the major source of exposure for many organisms. Nevertheless, most states have not developed numeric standards to protect sediments from contamination. The main difficulty in developing SQOs has been the complexity of the interactions between sediment and contaminants (FIGURE 1B). The concentrations of chemicals in sediments are affected by many processes. River discharge, tides, storms, and currents move and mix contaminated sediments. Sediment-dwelling (or "benthic") organisms also rework sediments. Additional processes such as contaminant partitioning and transformations influence the biological effects of sediment contami-

nants. The details of many of these processes are not known, making it difficult for states to develop numeric objectives comparable to those available for the water column.

Monitoring programs such as the RMP have shown that sediment contamination in bays and estuaries can adversely impact aquatic life, wildlife, and human health. Consequently, regulatory agencies have listed numerous areas throughout the state as impaired under Section 303(d) of the Clean Water Act. The lack of SQOs has complicated listing decisions because there has been no consistent method for determining whether sediment contamination is causing impairment. California's SQOs, contained within the Water Quality Control Plan for Enclosed Bays and Estuaries - Part 1 Sediment Quality (Sediment Quality Plan), now provide a framework for consistent listing decisions and development of management actions to restore sediment quality.

#### **Sediment Quality Objectives for Enclosed Bays and Estuaries**

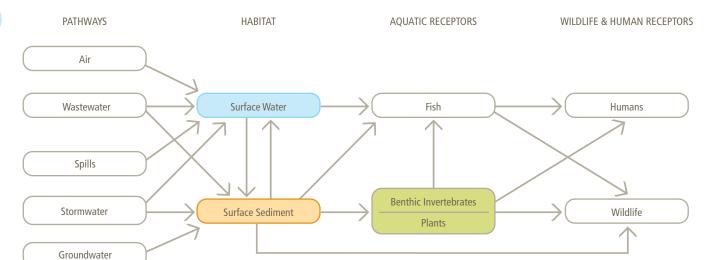
Though the State Water Resources Control Board (State Water Board) developed the SQOs and related policy within the past five years, the initial impetus occurred in 1989 through changes to the California Water Code (Sidebar, page 19). The Sediment Quality Plan is intended to protect the multiple beneficial uses likely to be affected by chemical contamination of sediments. These beneficial uses include the support of healthy marine and estuarine ecosystems and commercial or recreational fishing. SQOs are used in various regulatory programs, such as 303(d) listing and compliance monitoring of permitted discharges.

The key elements of the Sediment Quality Plan include:

- narrative SQOs for the protection of aquatic life and human health (Sidebar, page 21),
- specific indicators and tools to determine if the sediment quality at a sampling station meets the narrative objectives, and
- guidance for monitoring, stressor identification, and corrective action.

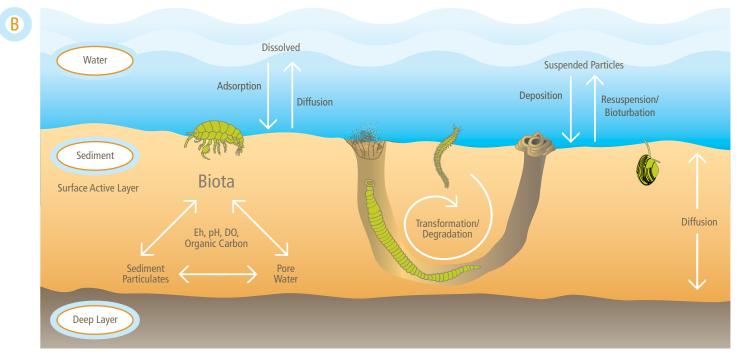
The program uses a standardized assessment framework to determine whether the SQOs are attained (Sidebar, page 22). This framework integrates data from multiple chemical and biological measures. The framework includes criteria for combining the individual lines of evidence in a consistent manner, ensuring that comparable results will be obtained throughout the state.

Development of the assessment framework and implementation guidance is occurring in two phases. In the first phase, completed in 2008, a framework and implementation language were developed for the SQO for the protection of aquatic life (benthic organisms) in marine bays and estuaries. Evaluation of compliance with the SQOs is based on a multiple lines of evidence (MLOE) approach. For aquatic life, the MLOE approach focuses on benthic organisms, using what is commonly known as the "sediment quality triad." The triad includes measurements of sediment chemistry, toxicity, and benthic organism abundance and diversity (FIGURE 2). The MLOE approach is needed because measurement of chemical concentrations alone is not a reliable indicator of effects on aquatic life. Complex interactions of the



#### ← FIGURE 1A

Principal pathways, fates, and effects of sediment contaminants in enclosed bays and estuaries. From the State Water Board Staff Report on sediment quality objectives (http://www.swrcb.ca.gov/water\_issues/programs/bptcp/sediment.shtml).



#### ← FIGURE 1B

Sediment processes affecting the distribution and form of contaminants. From the State Water Resources Control Board Staff Report on sediment quality objectives (http://www.swrcb.ca.gov/water\_issues/programs/bptcp/sediment.shtml).



#### Timeline for Development of the SQO Program

#### 1989

Legislature amended the California Water Code by mandating the State Water Board to develop SQOs. Amending the Water Code was part of the Bay Protection and Toxic Cleanup Program, a comprehensive program to protect beneficial uses in enclosed bays and estuaries.

#### 1991

State Water Board prepared a research plan to develop SQOs over seven years. However, due to limited resources and other competing mandates, SQOs were not developed.

#### 1999

A lawsuit was filed against the State Water Board for failing to adopt SQOs. The Court sided with the petitioners and ordered the State Water Board to immediately begin development of SQOs under a strict time schedule.

#### 2009

In August, USEPA approved the Sediment Quality Plan, resulting in formal state adoption. In adopting a SQO for protection of aquatic life, California became the first state in the U.S. to establish a SQO based on a multiple lines of evidence approach. To date, Washington is the only other state that has adopted sediment quality criteria into regulation, but these are applicable only within one water body (Puget Sound) and emphasize the use of pollutantspecific numeric standards that can be refuted only through biological testing.

#### 2010

Scheduled date of completion for Phase II of SQO development. Phase II will include technical tools for aquatic life assessment in the Delta and other moderate-salinity estuaries, and development of an SQO for indirect effects of sediments on human health.



↑ Anglers in San Francisco. Photograph by Linda Wanczyk.

contaminants with sediment particles can greatly alter the relationships between chemical concentrations and toxic effects. Over the last 15 years, the triad approach has become the standard practice for sediment quality assessments throughout the nation. It has been routinely used in regional monitoring programs in Chesapeake Bay, southern California, and San Francisco Bay, in the State Water Board's Bay Protection and Toxic Cleanup Program from 1993 to 1998, and in national programs such as USEPA's Environmental Monitoring and Assessment Program.

In the second phase, an assessment framework and guidance are being developed for the SQO for the protection of human health. The second phase also includes refinement of the aquatic life assessment tools for estuaries, with a particular emphasis on the San Francisco Bay-Delta. This second phase is currently underway, and is scheduled for completion in December 2010 (Sidebar, page 19). This effort benefits greatly from prior evaluations of bioaccumulative contaminants in San Francisco

### In the second phase, an assessment framework and guidance are being developed for the SQO for the protection of human health

Bay, especially evaluations performed for the Bay PCBs Total Maximum Daily Load (TMDL) plan, including evaluation and comparison of contaminant measurements in local sediments and fish and shellfish tissue (FIGURE 2), as separate lines of evidence. Seafood tissue and sediment data provide different information about potential human health risks due to sediment contamination. Seafood tissue measurements indicate how much risk there is to human consumers from eating local fish or shellfish. Sediment chemistry measurements indicate the extent to which sediments contribute to the observed tissue exposure. Data from bioaccumulation tests conducted in the laboratory can also be used as a line of evidence to help predict accumulation in the tissues of animals exposed to the sediments. Following the approach used for the PCB TMDL, these data are compared using a bioaccumulation model. The model estimates the contribution of local sediment-associated contaminants to bioaccumulation in fish and shellfish.

The SQO frameworks have been developed in coordination with other state and federal agencies and subjected to rigorous peer review. The assessment tools (toxicity tests, benthic indices, sediment quality guidelines, and bioaccumulation models) were developed by experts in California sediment quality assessment. Development and validation analyses have been conducted using a database of high quality California data representing over 1,200 samples from embayments. Emphasis was placed on independent validation to confirm the accuracy of the tools and assessment approach. Outcomes from application of the tools were also compared to the best professional judgment of experts to ensure that the results were consistent with current scientific practice. Finally, the program's technical approach, analyses, and recommendations were reviewed by a Scientific Steering Committee of national experts. Throughout the process of developing the framework there was frequent communication with stakeholders and regulatory agencies.

#### **SQO** Assessment in San Francisco Bay

In response to the implementation of SQOs, aquatic resource managers are asking two major questions:

- 1. How does my site compare to the objectives? and
- 2. What will this mean for future management of my site?

As the largest embayment in California, San Francisco Bay is an important case study for evaluating the real world consequences of applying of the SQO program. Thus, the RMP and the SQO program have teamed up to reevaluate current Bay conditions, and identify priority data collection and research needs.

# Narrative Objectives of the Program

#### **Aquatic Life**

This narrative objective addresses whether sediments are harmful to aquatic organisms. It answers the question: Are there chemical contaminants present in the sediments that cause toxicity to the organisms that naturally reside within the Bay? Because it focuses on direct exposure to the sediments via ingestion or physical contact, it is also referred to as the Direct Effects objective. Evaluations focus on potential effects to benthic organisms, which are sensitive indicators with high sediment exposure and well established procedures for toxicity testing and community assessment.

#### **Human Health**

This narrative objective will address to what extent sediments pose a risk to humans. It focuses specifically on the pathway of humans consuming seafood (fish or shellfish) that has accumulated contaminants from the sediments. It asks the question: To what extent are the sediments responsible for human exposure to seafood contamination? Because it focuses on contaminant bioaccumulation in seafood, rather than direct human exposure to sediments, it is also referred to as the Indirect Effects objective. Evaluations will focus on measuring seafood contaminant concentrations, and estimating how much sediments contribute to these concentrations.



#### ↑ FIGURE 2

Multiple lines of evidence are used in sediment quality objectives assessments. Effects on aquatic life are assessed through sediment chemistry, sediment toxicity tests, and evaluation of the benthic community. Effects on aquatic life are referred to as "direct effects" because they result from direct exposure to the sediments via ingestion or physical contact. Effects on human health are assessed through sediment chemistry and fish and shellfish tissue chemistry. Effects on human health are referred to as "indirect effects" because they result from consumption of seafood, rather than direct exposure to sediments.

#### The SQO for Aquatic Life: A Closer Look

The approach to evaluating sediment quality for protection of aquatic life is based on three levels of data integration.

In the first level, the results for individual measurements and indices are used to assign each line of evidence (LOE) into one of four response categories that range from no difference from background conditions to a large response indicative of extreme conditions.

In the second level of data integration, the individual lines of evidence are combined to address two key elements of risk assessment:

- Potential for chemically mediated effects: Is chemical exposure at the site high enough to potentially result in a biological response?
- Severity of effect: Is there biological degradation at the site?

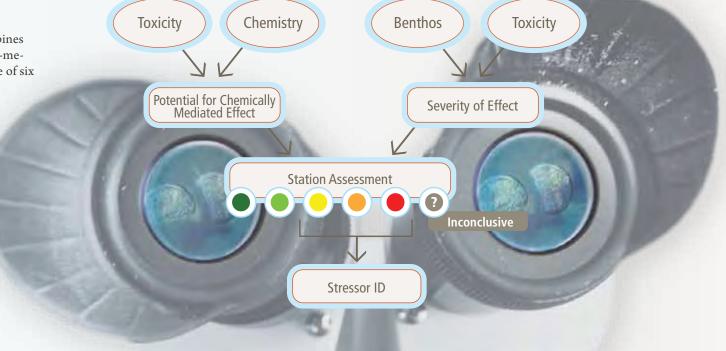
The third and final data integration level combines the severity of effect and potential for chemically-mediated effects information to assign a site into one of six impact categories.

- **Unimpacted.** Sediment contamination is clearly not causing significant adverse impacts to aquatic life at the site.
- Likely unimpacted. Sediment contamination at the site is not expected to cause adverse impacts to aquatic life, but some disagreement among the LOEs reduces certainty in classifying the site as unimpacted.

- Possibly impacted. Sediment contamination at the site may be causing adverse impacts to aquatic life, but these impacts are either small or uncertain because of disagreement among LOEs.
- Likely impacted. Evidence for a contaminant-related impact to aquatic life at the site is persuasive, even if there is some disagreement among LOEs.
- Clearly impacted. Sediment contamination at the site is causing clear and severe adverse impacts to aquatic life.
- Inconclusive. Disagreement among the LOEs suggests that either the data are suspect or that additional information is needed before a classification. can be made.

Examples of these site categorizations from San Francisco Bay and other California estuaries are shown on page 23.

Although the MLOE approach reduces uncertainty in sediment quality assessment, it is challenging to use in regulatory programs. Existing regulatory programs utilize a single LOE (sediment chemistry) to determine compliance, so additional guidance to reconcile program differences must be developed. Another challenge is identifying the cause of impairment for degraded sediments. To address this issue the State Water Board included stressor identification in the implementation policy. Stressor identification includes focused studies to determine what specific chemicals and conditions are impacting the benthic organisms at specific locations. Specific examples of preliminary stressor identification studies, already underway in San Francisco Bay, are described in the text.

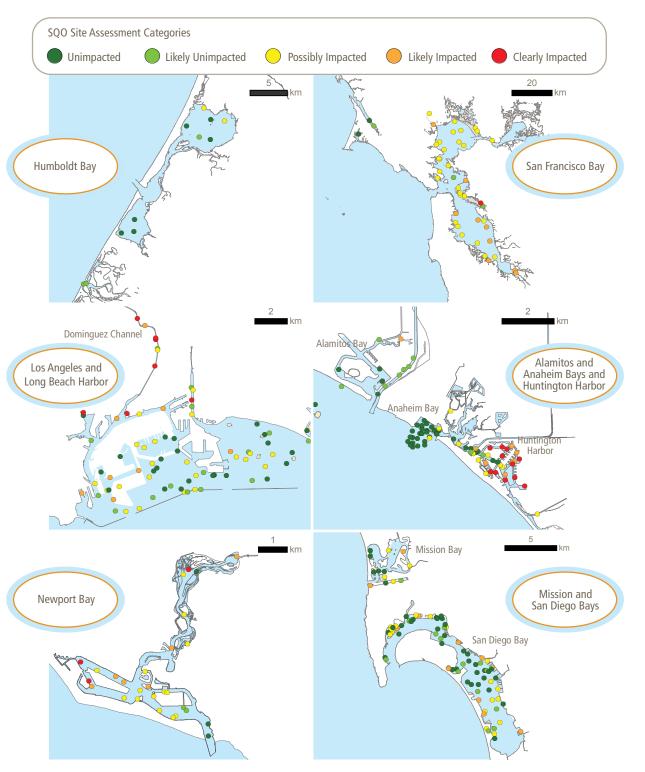


#### FIGURE 3 →

Assessments using the sediment quality objectives framework for impacts to aquatic life ("direct effects") have been performed for embayments throughout the state. San Francisco Bay stood out in this analysis as having an unusually high proportion of sites with impacts. No locations in the Bay fell into the "unimpacted" category, and only two locations (representing 4% of the total area of the Bay) were "likely unimpacted." Some degree of impact was considered possible in the remaining 96% of the Bay. Most of the Bay (73%) was classified as "possibly impacted." A primary driver of the results for San Francisco Bay was sediment toxicity, which has been documented by the RMP as a persistent and widespread problem (page 47). Future work on this issue in the RMP will refine the assessment tools to include evaluation of all regions of the Bay and will attempt to identify of the causes of sediment toxicity.

 $\leftarrow$ 

Integration of multiple lines of evidence for evaluating sediment quality objectives for aquatic life ("direct effects"). Three lines of evidence (toxicity, chemistry, and benthos) are used to assess the severity of effects and the potential that contaminants are responsible for the effects. These two pieces of information are then used to classify a site in one of six impact categories. Efforts to identify the contaminants causing effects ("stressor identification") are made at sites determined to have impacts.



# Anticipating the SQO program, the RMP and Water Board have proactively implemented stressor identification studies, monitoring design changes, and other efforts to improve sediment quality assessment tools

Assessments using the SQO framework for impacts to aquatic life ("direct effects") have been performed for embayments throughout the state (FIGURE 3). San Francisco Bay stood out in this analysis as having an unusually high proportion of sites (96%) with impacts. RMP scientists have carefully reevaluated recent San Francisco Bay multiple line of evidence data to assess the condition of the Bay using the SQO framework. In this reassessment 39% of Bay stations were classified as possibly impacted, likely impacted, or clearly impacted and therefore considered to exceed the SOOs. In most cases, each individual line of evidence fell within one of the intermediate categories, rather than a clearly unimpacted or a clearly impacted condition. These results are consistent with what RMP monitoring has indicated for decades: the Bay has widespread but moderate sediment contamination (page 47).

#### RMP Response to the SQOs

Anticipating implementation of the Sediment Quality Plan, the RMP and San Francisco Bay Regional Water Quality Control Board (Water Board) have proactively implemented stressor identification studies, monitoring design changes, and other efforts to improve sediment quality assessment tools. The Sediment Quality Plan

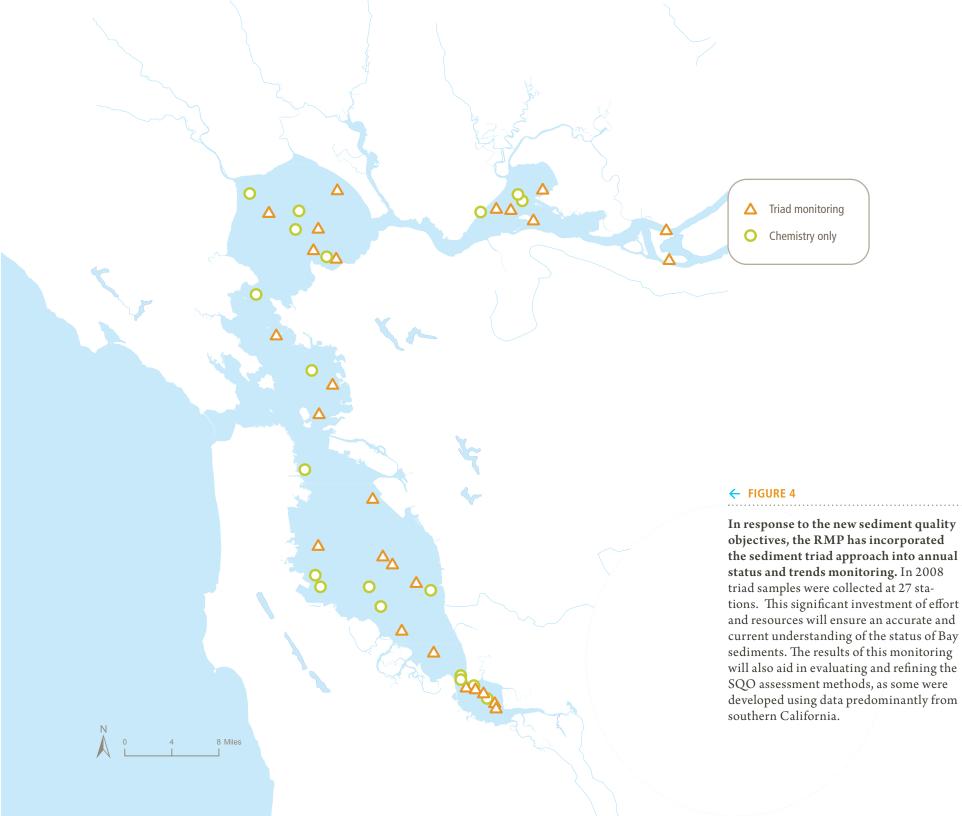
requires that stressor identification studies be performed on impacted locations. Stressor identification studies provide information on the specific pollutant classes that may cause the observed impacts. Stressor identification studies address the RMP goal to help environmental managers prioritize management actions.

In 2008, the RMP incorporated the sediment triad approach into annual status and trends monitoring at 27 stations (FIGURE 4). This significant investment of effort and resources will ensure an accurate and current understanding of the status of Bay sediments. The results of this monitoring will also aid in evaluating and refining the SQO assessment methods for application in the Bay, as the methods were developed using data predominantly from southern California.

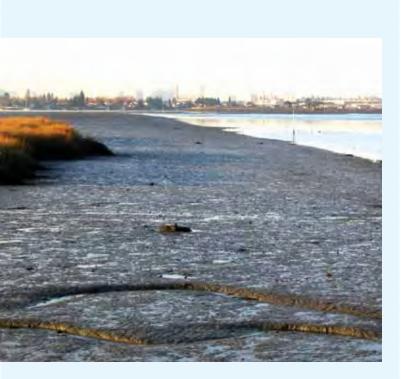
In 2009, RMP and Southern California Coastal Waters Research Project (SCCWRP) scientists are convening two collaborative state-wide workgroups to aid SQO development. One workgroup was established to develop and evaluate benthic assessment methods for several Estuary habitats (San Pablo Bay, Suisun Bay, and the Delta). Another workgroup will address causes of persistent moderate toxicity in the Bay. Identifying causes of moderate toxicity has

proven to be challenging using conventional toxicity assays and toxicity identification evaluations (TIEs) (Sidebar, page 27). Newer, more sensitive tools will be evaluated, including approaches from molecular biology, in which effects of contaminants and other stressors are identified by evaluating changes in gene and protein expression.

The RMP is also supporting the development of local assessment tools to support implementation of SQOs. A study of statistical associations between benthic indicators and contaminants showed that in many locations, sediment contamination and other environmental factors (including salinity and sediment type) affected benthic community composition. In locations such as Richmond Harbor, San Leandro Bay, and San Pablo Bay marshes, increased sediment contamination reduced the abundance and diversity of benthic organisms, and shifted the benthic community to more stress-tolerant organisms. In many cases, mixtures of several sediment contaminants were associated with these impacts. This kind of analysis is a preliminary step for stressor identification studies. The contaminant mixtures and thresholds identified become hypotheses to be tested further. Future management actions will be aided by understanding which contaminants, at what concentrations, cause benthic impacts.



The Water Board is planning to employ a case study approach to evaluate the application of the SQOs, as well as potential management options for contaminated sites



↑ San Leandro Bay. Photograph by Andreas Scheuller.

#### **Next Steps for the Bay**

The SQOs are expected to improve and streamline the evaluation of Bay sediments by the Water Board. The Water Board will use information generated by RMP Status and Trends monitoring and special studies to review and consider 303(d) listings for Bay and sub-embayment segments. Use of the SQO approach will likely result in listing of some new sites and delisting of others.

The Water Board will use the SQOs in its efforts to clean up contaminant hot spots in the Bay. To date, the Board has relied on the opportunistic cleanup of hot spots for which there is a proactive and engaged responsible party. Two examples of these clean up efforts are the Department of Defense remediation of sediment in Hunters Point and Chevron's cleanup of sediment in Castro Cove. The SQOs now provide the Water Board with a tool to assess other known or potential hot spots and to set priorities for appropriate cleanup and abatement actions.

The Water Board is planning to employ a case study approach to evaluate the application of the SQOs, as well as potential management options for contaminated sites. Currently, Water Board and SFEI staff are developing a collaborative proposal to evaluate San Leandro Bay. San Leandro Bay was selected because of the presence of legacy pollution, including 303(d) listing for multiple chemicals. Part of the case study effort will be collection of current multiple line of evidence data to compare with historic data. As with other contaminated sites, there is also interest in the role of San Leandro Bay as a potential contaminant source to nearby portions of San Francisco Bay. Therefore, the case study will also include contaminant fate and bioaccumulation modeling to evaluate inputs and outputs from San Leandro Bay. The ultimate goal of this case study will be to extend beyond the SQO assessment and stressor identification approach, towards evaluation of potential management alternatives. The study will help managers identify effective methods for restoring and maintaining a healthy Bay and potentially lead to further refinements of the Sediment Quality Plan.



#### **CSI San Francisco Bay**

The RMP has used Toxicity Identification Evaluations (TIEs) for many years. TIEs are well-established techniques for identifying contaminants responsible for toxicity in laboratory tests. In TIEs, a sediment sample is subjected to a series of treatments to increase or decrease the effects of specific contaminant classes. For example, charcoal can be added to a sample to bind organic contaminants and make them unavailable to the test organisms. Toxicity of the treated samples is then evaluated and compared to toxicity of untreated sediments. In the charcoal example, if charcoal treatment causes the toxicity to disappear, then it would indicate that organic contaminants are responsible for the toxicity. TIEs are forensic methods that can systematically rule out specific contaminant classes, and focus attention on other classes. However, sediments can be a challenging matrix, because of the difficulty of treating and extracting the bioavailable fraction.

The RMP recently performed TIEs on Mission Creek sediments. Mission Creek is a San Francisco waterway in an industrial watershed with relatively high contaminant concentrations and sediment toxicity. Its sediments were toxic to more than half of the amphipods in screening tests. Using the TIE approach, researchers determined that organic pollutants, rather than metals or ammonia, probably caused the toxicity in Mission Creek sediments. The TIE results, combined with sediment chemistry at the site, indicated that further evaluations or management actions at that site should focus on mixtures of organic chemicals, including PAHs and pesticides.





#### The Suisun Bay Reserve Fleet

Visible from your airplane window as you fly across the Delta or from your car as you drive along Highway 680 are imposing rows of stately gray ships, reminders of military exercises from years past. Approximately 72 decommissioned naval ships, sometimes referred to as the "mothball fleet," are currently moored in Suisun Bay just east of Benicia. The ships include commercial vessels such as tankers and cargo ships; US Naval vessels such as landing ships, amphibious assault ships, and tugs and barges; and US Coast Guard icebreakers and buoy tenders. Not all are permanently mothballed - select vessels from the Fleet are reactivated for national emergencies such as Hurricane Katrina.

The Bay Area is one of three sites across the county where the US Department of Transportation Maritime Administration stores obsolete fleets (the other two locations are James River, Virginia and Beaumont, Texas). The Navy began storing decommissioned vessels in Suisun Bay shortly after World War II.

Recent concern about the aging Fleet, specifically the potential for paint to flake off that may contain heavy metals or the leakage of oils and other materials from these vessels, triggered a request from the U.S. Congress for the National Oceanic and Atmospheric Administration (NOAA) Office of Response and Restoration to conduct a one year study of the sediments and bivalves around the Fleet to determine whether there was a potential for adverse impacts to Bay water quality.

In the summer of 2008, NOAA collected surface sediment samples, sediment cores to a depth of approximately four feet, and bivalve tissues from resident and transplanted clams for locations at various distances from the Fleet. The RMP assisted in providing background information to NOAA, sediment sampling expertise, and the loan of equipment for field sampling. The results of the study suggested that although concentrations of metals such as arsenic, copper, lead, and chromium at some individual stations were higher than other areas of San Francisco Bay, tissue and sediment samples on average were not significantly elevated compared to the reference sites (including RMP stations). The study therefore did not recommend sediment cleanup in the vicinity of the Fleet at this time.

Further information on this study can be found at: http://www.darrp.noaa.gov/southwest/suisunbay or by contacting Rob Ricker at Rob.Ricker@noaa.gov.



#### The 303(d) List

Section 303(d) of the 1972 Federal Clean Water Act requires that states develop a list of water bodies that do not meet water quality standards, establish priority rankings for waters on the list, and develop action plans, called Total Maximum Daily Loads (TMDLs), to improve water quality. The list of impaired water bodies is revised periodically (typically every two years). The RMP is one of several organizations that provide data to the State Water Board to compile the 303(d) List and to develop TMDLs.

The process for developing the 303(d) List for the Bay includes the following steps:

- development of a draft list by the San Francisco Bay Regional Water Board;
- adoption by the State Water Board; and
- approval by USEPA.

In February 2009, the San Francisco Bay Regional Water Board transmitted its recommended 2008 303(d) List to the State Board. The State Board will compile the information from all Regional Boards along with information from the public and interested parties and adopt the 303(d) List for California in early 2010. After State Board adoption, the 2008 List will be transmitted to USEPA for final approval.

The majority of new listings proposed for addition to the 2008 303(d) List by the San Francisco Bay Regional Water Board are for tributaries. There are new listings for trash in Central and South San Francisco Bay shorelines and a de-listing for nickel in the Sacramento-San Joaquin Delta, San Pablo Bay, and Suisun Bay.

The primary pollutants/stressors for the Estuary and its major tributaries on the proposed 2008 303(d) List include:

TRACE ELEMENTS: Mercury and Selenium

PESTICIDES: Dieldrin, Chlordane, and DDT

OTHER CHLORINATED COMPOUNDS: PCBs, Dioxin and Furan Compounds

**OTHERS:** Exotic Species, Trash, and Polycyclic Aromatic Hydrocarbons (PAHs)

# More information on the 303(d) List and TMDLs is available from the following websites.

#### 303(D) LIST FOR REGION 2 (WHICH INCLUDES THE ESTUARY):

www.waterboards.ca.gov/sanfranciscobay/water\_issues/ programs/ TMDLs/303dlist.shtml

#### TMDIS:

 $www.waterboards.ca.gov/sanfranciscobay/water\_issues/programs/TMDLs\\ www.epa.gov/region/water/tmdl/california.html$ 

# Regulatory Status of Pollutants of Concern

Pollutant	Status
Copper	Site-specific objectives adopted for entire Bay, approved for South Bay
	San Francisco Bay removed from 303(d) List in 2002
Cyanide	Site-specific objectives approved in 2008
Diazinon	TMDL approved in 2007
Dioxins / Furans	TMDL in early development stage
Legacy Pesticides (Chlordane, Dieldrin, and DDT)	TMDL in early development stage
Mercury	TMDL and site-specific objectives approved in 2008
Nickel	Site-specific objectives approved for South Bay and South Bay removed from 303(d) List in 2002
	Delisting of other Bay segments proposed for 2008
Pathogens	Richardson Bay TMDL adopted in 2008
	Bay Beaches (Aquatic Park, Candlestick Point, China Camp, and Crissy Field) added to 303(d) List
PCBs	TMDL adopted in 2008
Selenium	TMDL in development – completion projected for 2010
Trash	Central and South Bay shorelines proposed for addition to 2008 303(d) List

Adopted: San Francisco Bay Water Board adoption Approved: State Board and USEPA approval



RIGHT Rusty Fairey collecting a white sturgeon. Photograph by William Jakl.



# → STATUS AND TRENDS UPDATE

32
LATEST MONITORING RESULTS

WATER QUALITY TRENDS AT A GLANCE

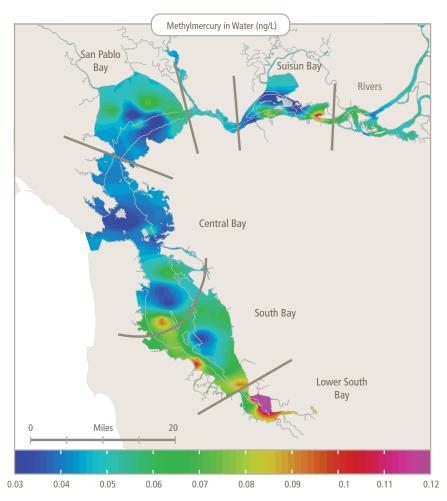
#### LATEST MONITORING RESULTS

#### Mercury

Mercury contamination is one of the top water quality concerns in the Estuary and mercury cleanup is a high priority of the Water Board. Mercury is a problem because it accumulates to high concentrations in some fish and wildlife species. The greatest health risks from mercury are generally faced by humans and wildlife that consume fish.



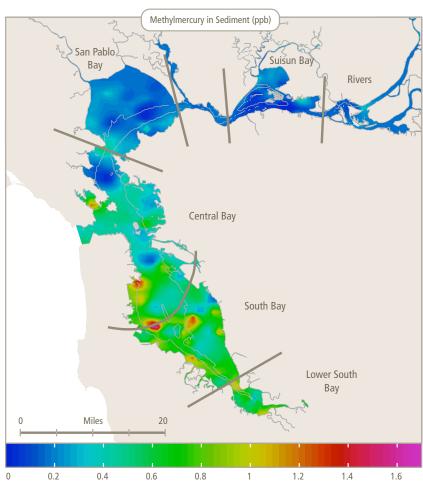
↑ May Nguyen of Brooks Rand Labs performing mercury analysis. Photograph by Mi Sun Um.



Footnote: Plot based on 75 RMP data points from 2006-2008. Earlier years not included because a less sensitive method was employed. The maximum concentration was 0.20 ng/L at a site in Lower South Bay in 2008. Data are for total methylmercury.

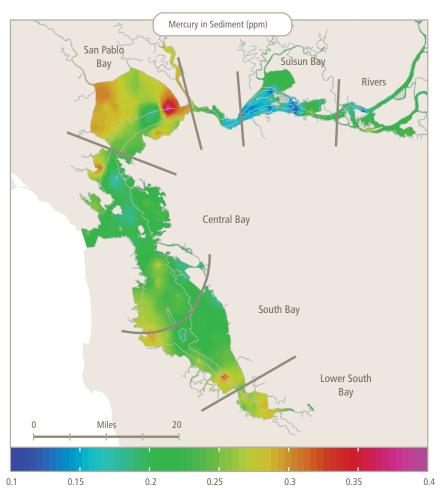
Water from Lower South Bay had the highest average concentration of methylmercury by far (0.12 ng/L) of any segment from 2006 to 2008. South Bay had the next highest average (0.05 ng/L). Methylmercury typically comprises only about 1% of the total of all forms of mercury in water or sediment, but it is the form that is readily accumulated in the food web and poses a toxicological threat to highly exposed species. Methylmercury has a complex cycle, influenced by many processes that vary in space and time. The RMP measures methylmercury in Bay water and sediment to better understand the sources of the methylmercury that are accumulated by fish and wildlife. The Bay-wide average for the three-year period was 0.05 ng/L. No regulatory guideline exists for methylmercury in water. The Bay-wide average in 2008 was 0.03 ng/L.





Footnote: Plot based on 331 RMP data points over a seven-year period from 2002–2008. The maximum concentration was 2.4 ppb at a site in Central Bay in 2002.

Concentrations of methylmercury in sediment south of the Bay Bridge have been consistently higher than those in the northern Estuary. Mercury is converted to methylmercury mainly by bacteria in sediment. Methylmercury production can vary tremendously over small distances and over short time periods, so the figure shown should be viewed as the result of several "snapshots" of Bay conditions. The Bay-wide average concentration in 2008 (0.39 ppb) was the same as in 2007, and well below the overall average for the seven-year period (0.53 ppb). Long-term average concentrations have been highest in South Bay (0.75 ppb) and Lower South Bay (0.74 ppb), and lowest in Suisun Bay (0.20 ppb) and San Pablo Bay (0.28 ppb). No regulatory guideline exists for methylmercury in sediment.



Footnote: Plot based on 331 RMP data points over a seven-year period from 2002–2008. The maximum concentration was 0.78 ppm near Mare Island in 2004.

In contrast to methylmercury, long-term average total mercury concentrations in sediment generally have been highest in San Pablo Bay and Lower South Bay (both averaging 0.27 ppm). Average concentrations have been slightly lower in the Central Bay (0.24 ppm) and South Bay (0.23 ppm), and lowest in Suisun Bay (0.16 ppm). Total mercury is the summation of all forms of mercury in a sample, and is a rough index of the amount of mercury available for conversion into methylmercury. The Bay-wide average for the seven-year period was 0.24 ppm. Also in contrast to methylmercury, Bay-wide average concentrations of total mercury in sediment have shown relatively little variability over this period.

#### Mercury continued

#### **Small Fish**

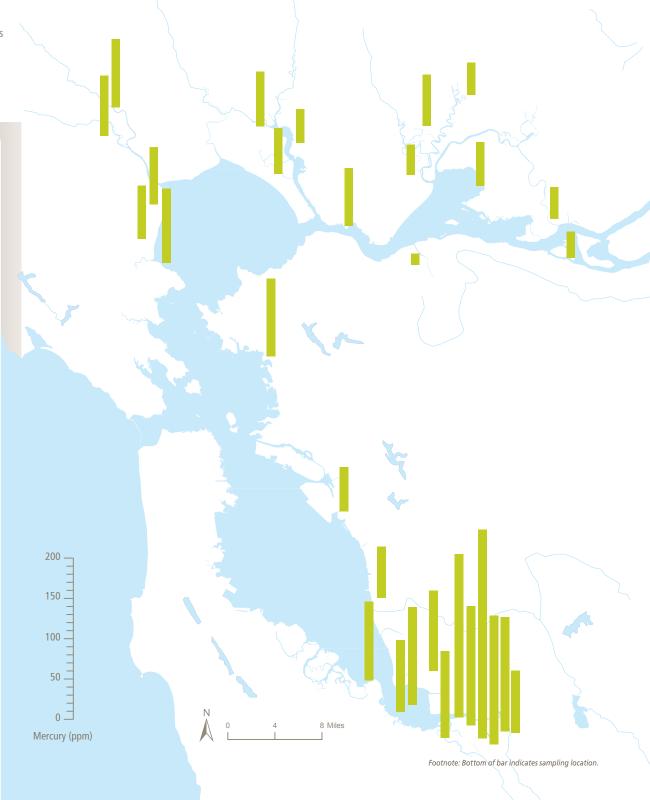
Contact:

Ben Greenfield, SFEI, ben@sfei.org

Extensive small fish monitoring by the RMP is revealing spatial patterns in food web uptake. The RMP recently formulated a Mercury Strategy to address large and important gaps that exist in our understanding of methylmercury impairment in the Bay. Gathering information on where and when methylmercury enters the food web has been identified as a top priority. Measuring mercury concentrations in small fish ("biosentinels") is a powerful means for obtaining this information. The young age and restricted ranges of small fish allow the timing and location of their mercury exposure to be pinpointed with a relatively high degree of precision.

In 2008, as part of the Mercury Strategy, the RMP began more extensive small fish monitoring in a concerted effort to determine patterns in food web uptake. Small fish biosentinel monitoring was expanded to an annual budget of \$150,000, allowing for sampling of approximately 50 sites per year. The plan is to sample at this level of effort for three years.

Results from the 2008 sampling are now available. Data for one of the biosentinel species (Mississippi silverside) are shown in this figure. As observed in previous years in the small fish pilot study, concentrations in the Lower South Bay were high compared to the rest of the Estuary. This observation is consistent with findings for methylmercury in water (page 32). Data from the 2008 sampling also suggest that food web uptake is relatively low near wastewater treatment plant outfalls, consistent with the conclusion of a study of the availability of mercury from different pathways for food web uptake (facing page).



# Mercury continued

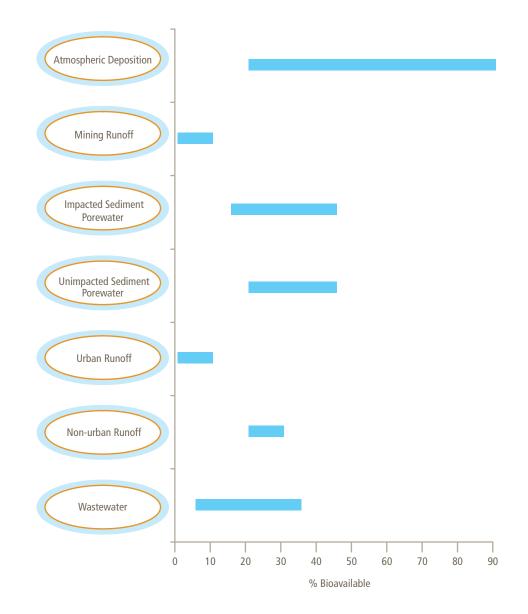
### **Wastewater Effluent**

### **Contact:**

Rob Mason, University of Connecticut, robert.mason@uconn.edu

A recent study of mercury in wastewater treatment plant effluent determined that bioavailable mercury (forms of mercury that are particularly susceptible to entry into the food web) levels are as low as or lower than those from other common sources such as atmospheric deposition and non-urban runoff. The project evaluated mercury bioavailability data captured from seven wastewater treatment plants, and found that average bioavailable mercury in the effluent of seven plants with advanced treatment was 21% of total mercury, lower than several other source categories (atmospheric deposition, sediment porewater, and nonurban runoff). The source categories with the lowest bioavailable mercury were urban runoff and mining runoff. Since wastewater treatment plants are known to be very effective in removing mercury, this study suggests that plants with advanced treatment may not contribute appreciably to local sediment mercury burdens. The findings in this study may explain the pattern observed in the preliminary finding in RMP small fish monitoring (facing page) of low mercury uptake near several wastewater treatment plant outfalls in the Bay.

The report on the study is available at: http://www.werf.org/AM/Template.cfm?Secti on=Home&CONTENTID=11429&TEMPLA TE=/CM/HTMLDisplay.cfm



# Mercury continued

### **Bay Area Lakes**

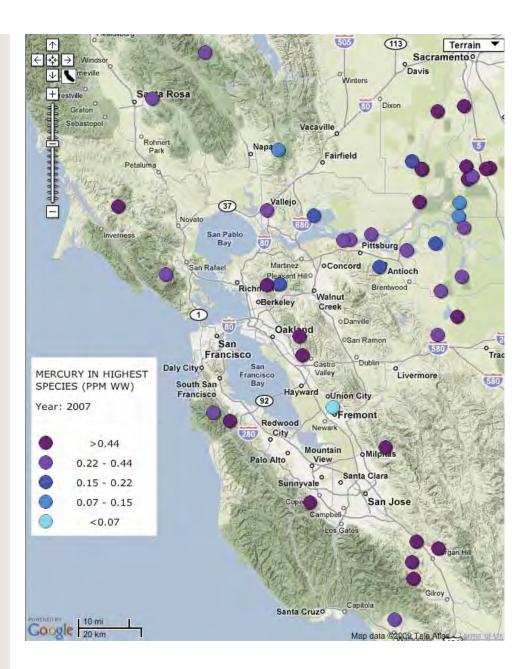
Contact:

Jay Davis, SFEI, jay@sfei.org

Recent monitoring has found high concentrations of mercury in sport fish from many Bay Area lakes. The State Water Resources Control Board's Surface Water Ambient Monitoring Program (SWAMP) has released the first findings from the largest survey ever conducted in California of contaminants in sport fish from lakes and reservoirs. The results are from the first year of the two year, statewide survey. Mercury was found to be a widespread problem, with 26% of the state's lakes having at least one fish species with an average mercury concentration above 0.44 ppm, a level at which the California Office of Environmental Health Hazard Assessment (OEHHA) considers advising no consumption by sensitive populations (women aged 18-45 years and children aged 1-17 years).

In general, indicator species from Bay Area lakes had relatively high mercury concentrations. The primary indicator species across the state was largemouth bass. Mercury concentrations in largemouth in eight of 12 Bay Area lakes were above the 0.44 ppm threshold. Several lakes had concentrations in the range of 1 ppm (Upper San Leandro Reservoir – 1.01 ppm; Anderson Lake – 0.98 ppm; Soulejule Lake – 0.94 ppm; and Lower Crystal Springs Reservoir – 0.85 ppm). The widespread distribution of lakes with high sport fish mercury suggests that atmospheric deposition may be a significant pathway. This hypothesis will be evaluated through analysis of the full two-year dataset from the lakes survey.

Data from the lakes survey are available on the web via a user-friendly interface developed by the California Water Quality Monitoring Council. The map shown is taken directly from a query made on the Council's "My Water Quality" website. This output also includes some river sites in the Delta. The website can be accessed at: http://www.swrcb.ca.gov/mywaterquality/index.shtml



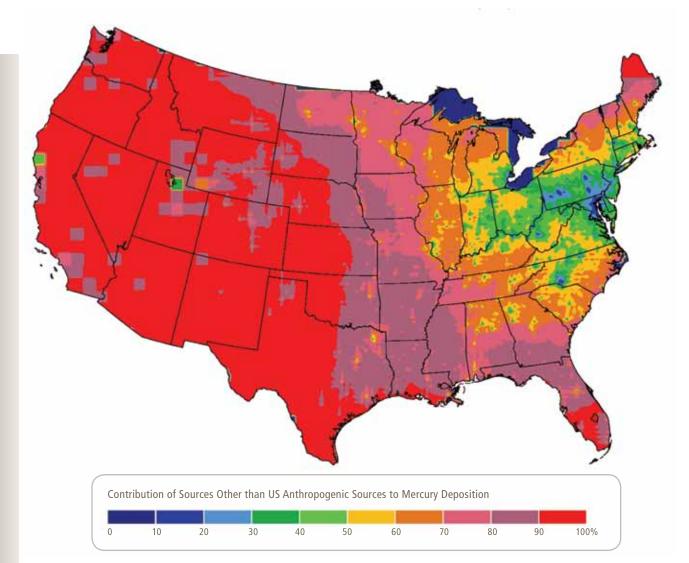
# Mercury continued

# **Atmospheric Deposition**

### Contact:

Krish Vijayaraghavan, AER, Inc., krish@aer.com

An estimated 70-90% of the atmospheric deposition of mercury in the Bay Area originates from outside of the U.S., especially from China. Atmospheric and Environmental Research (AER), Inc. and the Electric Power Research Institute have developed a global mercury chemistry and atmospheric transport model that they have used to estimate the contribution of various sources to mercury deposition across the U.S. The model estimates that of the 140-170 tons of mercury currently being deposited onto the United States mainland each year, 2/3 originates in other countries. Roughly half of the mercury from other countries originates on the Asian continent, mostly from China. The greater precipitation and larger number of sources in the eastern U.S. result in a higher fraction of mercury deposition being attributable to domestic sources.



### Footnotes:

More information available at: http://mydocs.epri.com/docs/public/0000000001018762.pdf

The results shown follow the methodology discussed by Vijayaraghavan et al. 2003 and Seigneur et al. 2004. The estimates are for total (wet plus dry) deposition of total mercury.

Seigneur, C., K. Vijayaraghavan, K. Lohman, P. Karamchandani and C. Scott, 2004. Global source attribution for mercury deposition in the United States, Environmental Science & Technology, 38, 555-569.

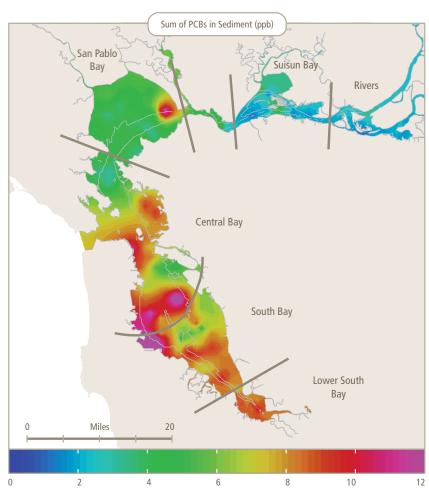
Vijayaraqhavan, K., C. Seigneur, K. Lohman, P. Karamchandani, L. Levin and J. Jansen. Simulation of mercury deposition over the eastern United States with a fine spatial resolution, Air Quality IV: Mercury, Trace Elements, and Particulate Matter Conference, 22-24 September 2003, Arlington, Virginia.

# **PCBs**

PCB contamination remains one of the greatest water quality concerns in the Estuary, and PCB cleanup is a primary focus of the Water Board. PCBs are a problem because they accumulate to high concentrations in some Bay fish and pose health risks to consumers of those fish.



↑ Vials containing extracts from sediment samples in line for injection into a gas chromatograph. Photograph by Saskia van Bergen.



Footnote: Plot based on 235 RMP data points from 2004–2008. Data from 2002 and 2003 are not available. The maximum concentration was 30 ppb in South Bay in 2008. This value was included in the figure, although the scale was not adjusted to it. Averages, except as noted, include this value. Excluding this value, the Bay-wide average for 2008 was 9.4 ppb – still the highest observed in the five-year period.

Average PCB concentrations in Bay sediment measured from 2004–2008 were highest in the southern reach of the Estuary: Lower South Bay (8.6 ppb), South Bay (7.9 ppb), and Central Bay (8.0 ppb). Average concentrations were lower in San Pablo Bay (4.4 ppb) and Suisun Bay (2.3 ppb). The Bay-wide average for 2008 was 10.0 ppb, the highest of the five-year period, and well above the overall long-term average of 6.6 ppb. The cause of this fluctuation is not known. Models suggest that sediment PCB concentrations must decline to about 1 ppb for concentrations in sport fish to fall below the threshold of concern for human health. Suisun Bay dipped below this value in 2006 (0.8 ppb), but averaged 3.6 ppb in 2008.

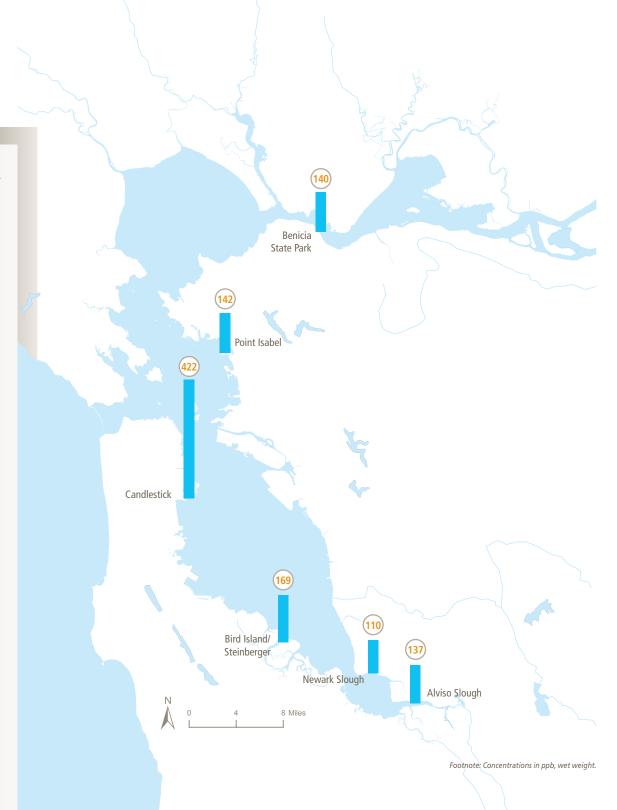
# → PCBs continued

### **Small Fish**

**Contact:** 

Ben Greenfield, SFEI, ben@sfei.org

A RMP pilot study in 2007 found surprisingly high concentrations of PCBs in small fish. These preliminary results indicate that, as for mercury, small biosentinel fish can be an effective indicator of the location and timing of PCB entry into the food web. This is useful because, also similar to mercury, our current understanding of precisely where and when PCBs enter the food web is very limited. In this study, a few of the samples collected for the mercury monitoring were also analyzed for PCBs. Unexpectedly, the topsmelt samples analyzed had concentrations that were almost as high as the highest sport fish species. (page 46) Since the small fish are important prey for piscivorous (fish-eating) species of fish and wildlife, this provides a fundamental insight into PCB movement through the food chain and accumulation in high trophic level predators. Supporting the concept that small fish can reveal spatial patterns in uptake, one of the six locations sampled (Candlestick Park) was found to have concentrations that were 2.5 times higher than those in the other locations. This site appears to be in an area with very high food web uptake. Concentrations at the other five locations sampled suggest a uniform and high degree of uptake broadly throughout nearshore areas of the Bay. Following up on these findings, and again piggybacking on the small fish mercury monitoring, expanded measurement of PCBs in small fish will be performed in 2010 to provide a clearer picture of how PCBs move from sediment and water into the food web and lead to the troublesome concentrations that are found higher in the food chain.

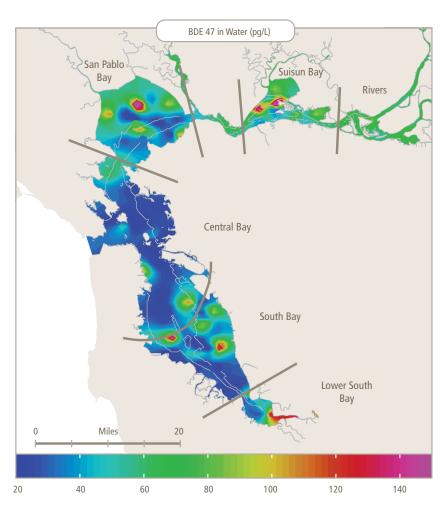


# **PBDEs**

PBDEs, a class of bromine-containing flame retardants that was practically unheard of in the early 1990s, increased rapidly in the Estuary through the 1990s and are now a pollutant of concern. The California Legislature has banned the use of two types of PBDE mixtures. Tracking the trends in these chemicals will be extremely important to determine what effect the ban will have and if further management actions are necessary. No regulatory guidelines currently exist for PBDEs.

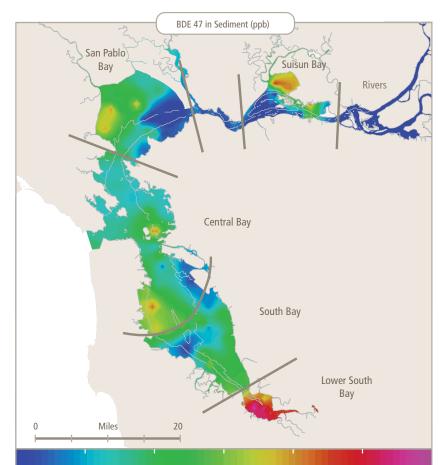


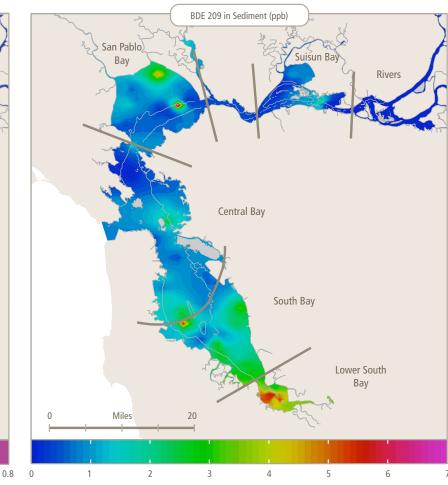
↑ Bob Jenkins performing analysis of organic contaminants in sediment. Photograph by Saskia van Bergen.



Footnote: Because BDE 47 is one of the most abundant PBDEs and was consistently detected by the lab, BDE 47 is presented as an index of total PBDEs. Plot based on 203 RMP data points from 2002–2008. The maximum concentration was 337 pg/L observed in Suisun Bay in 2004. Data are total (dissolved plus particulate) BDE 47 concentrations in water.

The highest average concentrations of PBDEs in water from 2002–2008 were found in Suisun Bay. The maximum concentrations of BDE 47 (one of the most abundant PBDEs and an index of PBDEs as a whole), two samples greater than 300 pg/L, were observed at locations in Suisun Bay and San Pablo Bay, both in 2004. The average concentration of BDE 47 for 2002-2008 was 76 pg/L. The high concentrations in Suisun Bay suggest the presence of PBDE inputs into the northern Estuary. The Bay-wide average concentration for the seven year period was 51 pg/L. The Bay-wide average for 2008 was the lowest recorded (23 pg/L). The highest Bay-wide average was 99 pg/L in 2004.





Footnote: BDE 47 is one of the most abundant PBDEs and was consistently detected by the lab. Plot based on 235 RMP data points from 2004–2008. Data from 2002 are available but were inconsistent with data for the other three years. The maximum concentration, by far, was 3.8 ppb in Lower South Bay in 2005.

0.5

0.7

0.6

0.3

0.4

0.2

Footnote: BDE 209 shown as an index of the "deca" PBDE mixture. Plot based on 235 RMP data points from 2004, 2006, 2007, and 2008. The maximum concentration by far was 52 ppb in San Pablo Bay in 2007 (the next highest concentration was 19 ppb in South Bay in 2006).

In contrast to the results obtained from water monitoring, long-term average concentrations of BDE 47 in sediment from 2004–2008 were highest in Lower South Bay (0.75 ppb). This spatial pattern in the longer-term data, however, may be waning - in 2008 Suisun Bay had the highest average of any segment (0.54 ppb). The Bay-wide average for 2008 (0.39 ppb) was close to the average for the seven year period (0.43 ppb). The Bay-wide average has shown little fluctuation over the seven years.

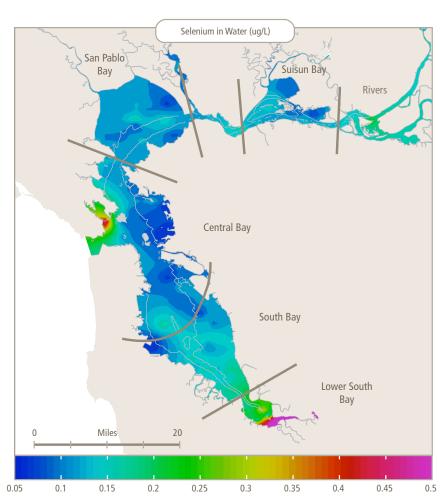
The Bay-wide average concentration of BDE 209 in sediment in 2008 was lower than in previous years (2004, 2006, and 2007). BDE 209 (also known as "decabromodiphenyl ether") is important because it represents the one remaining class of PBDEs that can still be used in California. Data from four years are available. Similar to BDE 47, average concentrations of BDE 209 in the three years were highest in Lower South Bay (5.1 ppb). Average concentrations in the other segments ranged from 2.9 ppb in San Pablo Bay to 1.0 ppb in Suisun Bay.

# Selenium

Selenium contamination is a continuing concern in the Estuary. Selenium accumulates in diving ducks in the Bay to concentrations that pose a potential health risk to human consumers. Selenium concentrations also pose a threat to wildlife in the Estuary. Recent studies suggest that selenium concentrations may be high enough to cause deformities, growth impairment, and mortality in early life-stages of Sacramento splittail and white sturgeon.



Meg Sedlak and Amy Franz collecting a RMP water sample. Photograph by Susan Klosterhaus.

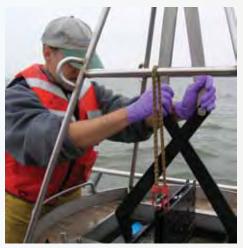


Footnote: Plot based on 203 RMP data points from 2002–2008. The maximum concentration was 1.2 µg/L at a historical station in the Southern Sloughs in 2002. Data are for total selenium.

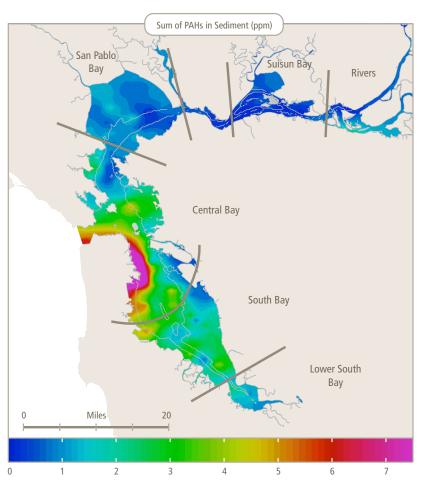
Selenium concentrations in water are well below the water quality objective established by the California Toxics Rule. However, concerns still exist for wildlife exposure as indicated by studies on early life-stages of fish. The highest concentration observed in water from 2002 to 2008 was 1.15  $\mu g/L$ , much lower than the CTR objective (5  $\mu g/L$ ). Lower South Bay had a higher average concentration over this period (0.25  $\mu g/L$ ) than the other Bay segments, which had strikingly consistent average concentrations (all other averages were between 0.12 and 0.13  $\mu g/L$ ). The Bay-wide average concentration in 2008 (0.14  $\mu g/L$ ) was just above the long-term Bay-wide average (0.13  $\mu g/L$ ).

# **PAHs**

PAHs (polycyclic aromatic hydrocarbons) are included on the 303(d) List for several Bay locations. Concentrations tend to be higher near the Bay margins, due to proximity to anthropogenic sources. In addition to historic industrial sources along the Bay margins, increasing population and motor vehicle use in the Bay Area are cause for concern that PAH concentrations could increase over the next 20 years, due to deposition of combustion products from the air directly into the Bay and from the air to roadway runoff and into the Bay via stormwater. On the other hand, PAH concentrations in Bay Area air have declined over the past ten years, and if PAH inputs to the Bay can be decreased, concentrations are expected to drop quickly.



 Paul Salop collecting a RMP sediment sample. Photograph by Nicole David.



Footnote: Plot based on 330 RMP data points from 2002–2008. The maximum concentration was 19 ppm in Central Bay in 2008. The four highest concentrations and nine of the top ten in the seven-year period were all measured in Central Bay.

PAH concentrations in sediment have been highest along the southwestern shoreline of Central Bay. Central Bay had the highest average concentration (3.6 ppm) of any Bay segment from 2002 to 2008. South Bay had the next highest average concentration (2.2 ppm), followed by Lower South Bay (1.7 ppm), San Pablo Bay (1.0 ppm), and Suisun Bay (0.5 ppm). The Bay-wide average in 2008 was 3.6 ppm, the highest for any year in the seven-year period. The next highest annual Bay-wide average was 2.5 ppm in 2006. Each segment also had its highest annual average concentration in 2008. Measured PAH concentrations have been quite variable from year to year, and do not suggest a trend. The Bay-wide average for the seven-year period was 2.3 ppm.

# **Current Use Pesticides**

Contact:

Inge Werner, U.C. Davis, iwerner@ucdavis.edu

Water toxicity in the north Bay and Delta that was attributable to pyrethroids raised concern for their impacts on aquatic life and their possible role in the "pelagic organism decline" (or "POD" – facing page). Inge Werner and her colleagues at U.C. Davis have conducted toxicity monitoring at many locations throughout the north Bay and Delta since 2005 as part of investigations of the causes of the POD. In these toxicity tests, the amphipod (shrimp-like crus-

tacean) Hyallela azteca, a species that is resident in the Estuary and sensitive to contaminants, was exposed to waters from the sampling locations. Data collected in 2006 and 2007 detected impacts on the survival of Hyalella in short-term exposures. In Bay samples, the rate of occurrence was relatively low, with a maximum of 8.5% of samples found to be toxic at a site near Benicia. However, the spatial distribution of the toxicity was broad. The testing indicated that

pyrethroids may have contributed to toxicity in some of the samples. In most cases, both pyrethroids and organophosphates were implicated. These were the first findings of water toxicity in open Bay waters in many years. The rate of occurrence of toxicity in the northern Delta was relatively high, especially on the Sacramento River at Hood.

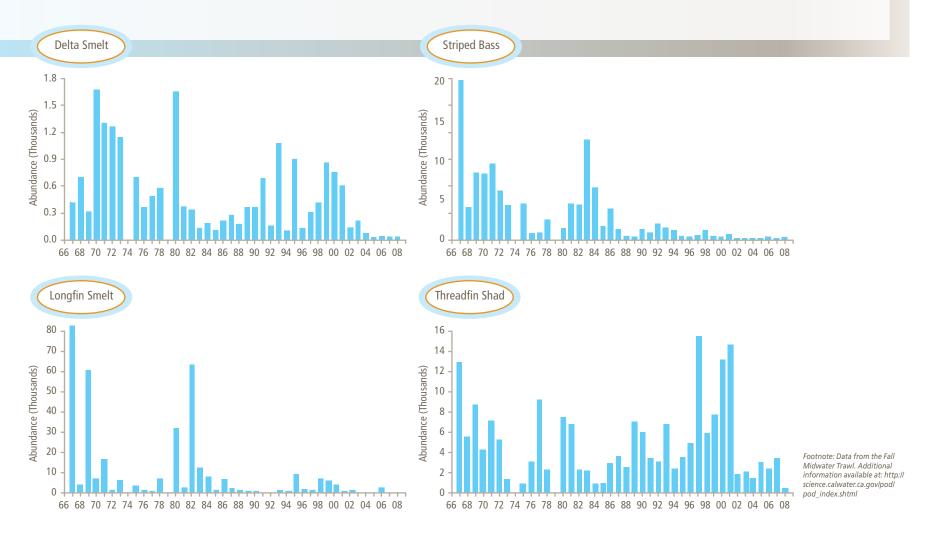
Following up on this study, the Central Valley Regional Water Quality Control Board provided funds to Don Weston of U.C. Berkeley to evaluate the relative contributions of pyrethroids from potential sources: wastewater treatment plants, urban runoff, and agricultural discharges from Delta islands. Preliminary results show that the highest magnitude toxicity occurs in urban runoff. Toxicity attributable to pyrethroid pesticides also was detected in every effluent sample from one of the three wastewater treatment plants sampled but at lower magnitude than in urban runoff samples.

2 of 50)

# **Fisheries**

Contact: Randy Baxter, California Department of Fish and Game, rbaxter@dfg.ca.gov

Serious declines of several important fish species in the Estuary (known collectively as the "pelagic organism decline") are continuing. Summer and fall abundance indices calculated by the Interagency Ecological Program (IEP) suggest recent marked declines in numerous pelagic fishes in the upper San Francisco Estuary (the Delta and Suisun Bay), known as the "pelagic organism decline (POD)". The fall indices have been collected for all but two of the last 30 years. The indices for the last two years continue to hover at record low levels for Delta smelt (listed as threatened under the Endangered Species Act), striped bass, longfin smelt, and threadfin shad.

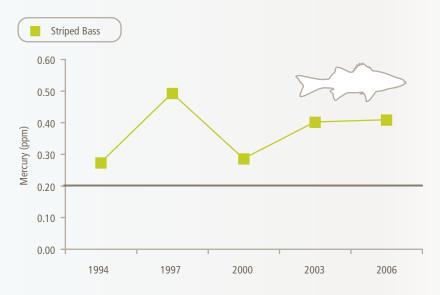


# WATER QUALITY TRENDS AT A GLANCE

# Mercury in Sport Fish

### **Contact:**

Jennifer Hunt, SFEI, jhunt@sfei.org



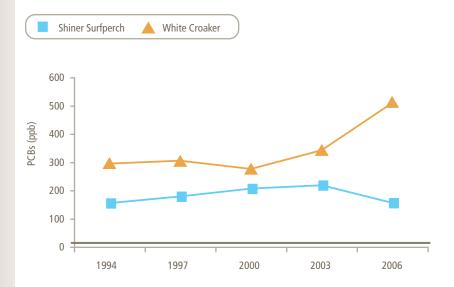
Footnote: Baywide medians. Striped bass: 45-59 cm. Black line indicates TMDL target for sport fish tissue (0.2 ppm). Data from the RMP and Fairey et al. (1997).

Mercury in Sport Fish. Striped bass accumulate relatively high concentrations of mercury and are popular with Bay anglers, making them important indicators of mercury impairment. Mercury concentrations have shown no clear long-term trend but have consistently been higher than the 0.2 ppm TMDL target for sport fish tissue. A more detailed study of contaminants in striped bass is in progress; data for 2006 will be available in late 2009. The latest round of sport fish samples was collected in summer of 2009; these data will be available in 2011.

# PCBs in Sport Fish

### Contact:

Jennifer Hunt, SFEI, jhunt@sfei.org



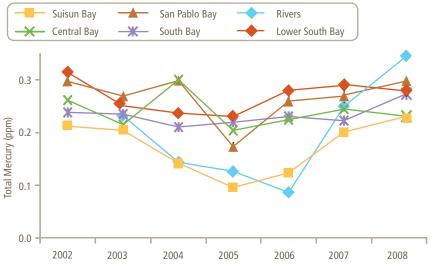
Footnote: Baywide medians. Black line indicates the TMDL target for white croaker (10 ppb). Data from the RMP and Fairey et al. (1997).

PCBs in Sport Fish. White croaker and shiner surfperch are sport fish species that accumulate high concentrations of PCBs and are consequently the key indicators of PCB impairment. Concentrations in white croaker in 2006 were the highest observed since monitoring began in 1994. In contrast, concentrations in shiner surfperch were among the lowest observed. The causes of these patterns are unknown. PCB concentrations in white croaker have consistently been much higher than the 10 ppb TMDL target for this species. The latest round of sport fish samples was collected in summer of 2009; these data will be available in 2011.

# **Total Mercury in Sediment**

### Contact:

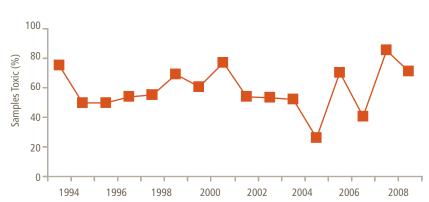
Don Yee, SFEI, donald@sfei.org



# **Sediment Toxicity**

### Contact:

John Ross, SFEI, john@sfei.org



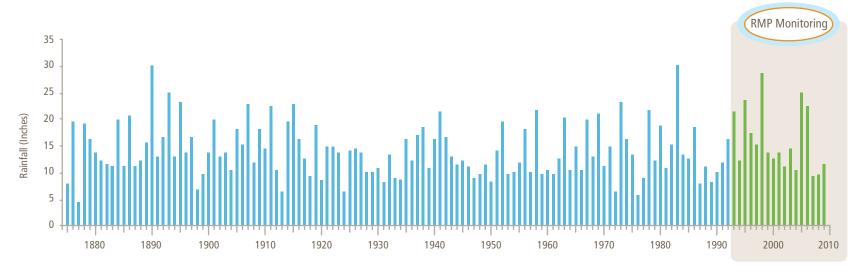
Footnote: Sediment samples are tested using amphipods and mussel larvae.

Annual Average Total Mercury in Sediment by Bay Segment. Concentrations of total mercury in sediments from each segment of the Bay were generally higher in 2008 than average concentrations measured since the RMP began to sample in a manner that yields representative average concentrations for each Bay segment in 2002 (page 33). The one exception to this general pattern was Central Bay. In contrast, methylmercury concentrations were relatively low in 2008 (page 33).

Percentage of RMP Sediment Samples Causing Toxicity in Lab Tests. The frequent occurrence of toxicity in sediment samples from the Estuary is a major concern. In every year since sampling began in 1993, 26% or more of sediment samples have been determined to be toxic to one or more test species. In 2008, 70% of the samples were found to be toxic to at least one of the two test species. No long-term trend is apparent in this time series.

# Annual Rainfall in the Bay Area

Contact: Lester McKee, SFEI, lester@sfei.org

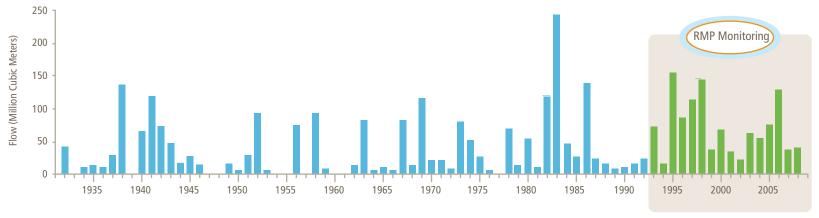


Footnote: Annual rainfall measured at San Jose shown as index for Bay Area rainfall. Green bars coincide with RMP monitoring. These data are for climatic years (July 1 to June 30 where the year corresponds to the end date). Source: Jan Null, Golden Gate Weather Services

Annual Rainfall in the Bay Area. Freshwater flow, as indicated by rainfall, fluctuates widely from year to year, making it more challenging to measure the trends in pollutant inputs and water quality, which are heavily influenced by flow. Records for San Jose date back to 1875. Rainfall at this location in 2008 (9.5 inches) was slightly higher than that in 2007 (9.3 inches – the lowest during the 16 years of RMP monitoring).

# Annual Flow from the Guadalupe River

Contact: Lester McKee, SFEI, lester@sfei.org



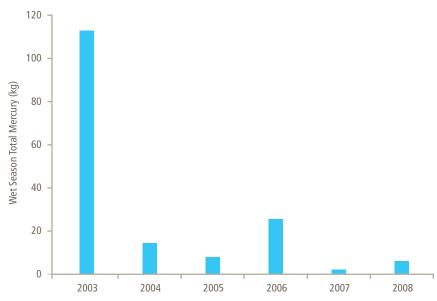
Footnote: Data from the U.S. Geological Survey. Green bars coincide with RMP monitoring. These data are for water years (October 1 to September 30 where the year corresponds to the end date). Source: U.S. Geological Survey.

Annual Flow from the Guadalupe River. Stormwater flows are a primary influence on pollutant loads from local Bay Area watersheds. Flows from the Guadalupe River, a major contributor of mercury to the Bay, were relatively low in 2007 and 2008 (36 and 41 million cubic meters, respectively). Year to year variation in flow from the Guadalupe watershed is a rough index of variation in flows from other local watersheds.

# Mercury from the Guadalupe River

### Contact:

Lester McKee, SFEI, lester@sfei.org



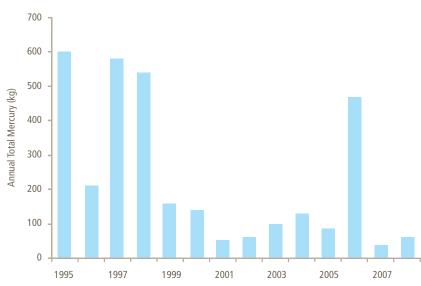
Footnote: Total loads for each water year (Oct 1–Sep 30). Additional matching funds for this RMP study were provided by the CEP, USACE. SCVWD, and SCVURPPP.

# Annual Loads of Mercury from the Guadalupe River. The Guadalupe River is a significant pathway for transport of mercury and other pollutants into the Bay, and the first small tributary to the Bay subjected to a rigorous evaluation of loads. Loads fluctuate from year to year due to variation in rainfall intensity, water flow, and other factors. For example, even though flow during 2006 was relatively high, it was a year of relatively low rainfall intensity; consequently there were many small-magnitude floods that did not transport a large amount of mercury. The load estimated for 2008 was 6 kg, the second lowest recorded since monitoring began in 2003. The year-to-year fluctuations are thought to be driven by climatic variation, and not indicative of a long-term trend.

# Mercury from the Delta

### Contact:

Nicole David, SFEI, nicoled@sfei.org

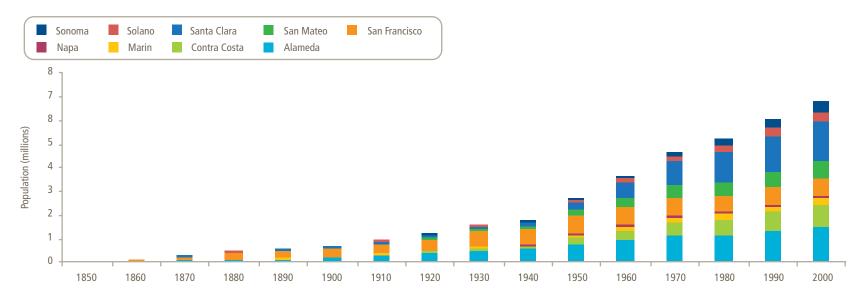


Footnote: Total loads for each water year (Oct 1–Sep 30). Loads from 2002–2007 are based on field data. Loads for earlier years are estimated from relationships observed between suspended sediment and mercury in 2002–2007.

Annual Loads of Mercury from the Delta. Delta outflow carries significant loads of mercury and other pollutants from the vast Central Valley watershed into the Bay. RMP studies allow estimation of loads from 1995 to the present. Loads of many pollutants are especially large in years with high flows. Sampling conducted during the high flows of January 2006 helped to refine the annual estimates, which had been significantly underestimated for large flood events previously due to a lack of information on concentrations during highflow events. The annual load in 2008 (59 kg) was the third lowest estimated for the 14-year period.

# **Bay Area Population**

Contact: Lester McKee, SFEI, lester@sfei.org

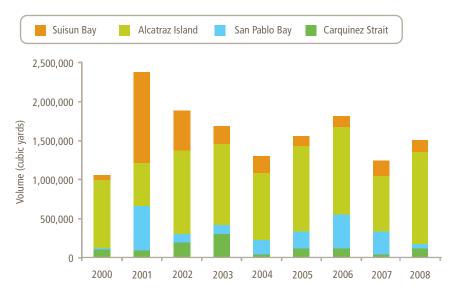


Footnote: Data from the Association of Bay Area Governments and U.S. Census Bureau. 2008 estimate from http://factfinder.census.gov/servlet/SAFFPopulation?\_submenuId=population\_0&\_sse=on.

Bay Area Population. The large and growing human population of the Bay Area places increasing pressure on Bay water quality through expanding urbanization, vehicle usage, and other mechanisms. The population of the Bay Area reached 6.8 million in 2000, is estimated to be 7.0 million in 2008, and is predicted to grow to 7.8 million by 2020.

# **Dredged Material Deposited**

# Contact: Michelle Lent, SFEI, michelle@sfei.org

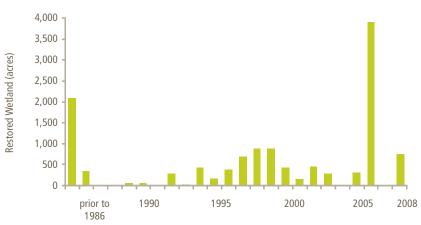


Footnote: Data from the U.S. Army Corps of Engineers.

Annual Volume of Dredged Material Deposited at In-Bay Aquatic Disposal Sites. Dredged material disposal is one of the pathways for pollutant redistribution within the Bay. In 2008, 1.5 million cubic yards of dredged material were deposited at the four disposal sites in the Bay. Most of this amount (79%) was disposed of at the Alcatraz site. Other dredged material was disposed of in the ocean (<0.1 million cubic yards) and used in upland restoration projects (2.6 million cubic yards) (page 10). Dredged material management agencies plan to limit in-Bay disposal to 1.5 million cubic yards per year by 2012.

# Acres Restored to Tidal Action

Contact:
Michelle Lent, SFEI, michelle@sfei.org

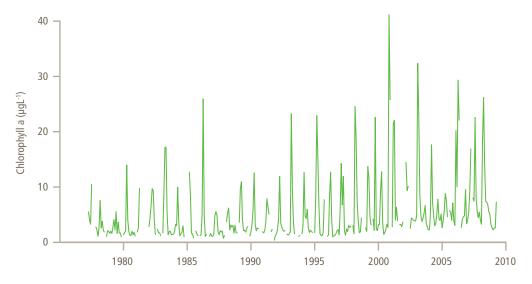


Footnote: 2008 data from Wetland Tracker (http://www.wetlandtracker.org/tracker/).

Acres of Salt Pond or Other Habitat Opened to Tidal Action. San Francisco Bay is home to the most ambitious tidal wetland restoration project ever attempted on the west coast of North America, the South Bay Salt Pond Restoration Project, which plans to restore 16,500 acres of San Francisco Bay salt ponds to tidal marsh. Several other major tidal wetland restoration projects are also underway (page 8). These projects could have a significant influence on Bay water quality, with the potential for increased mercury in the food web a particular concern. SFEI and others are conducting studies to assist restoration managers in developing methods to limit the production of methylmercury. In 2008, 737 acres were opened to tidal action.

# **Phytoplankton Biomass**

Contact: James Cloern, U.S. Geological Survey, jecloern@usgs.gov



Footnotes: Chlorophyll concentrations are an index of the abundance of phytoplankton in the Bay. Data for USGS Station 27. Median of all measurements shallower than 3 meters depth. Data from the U.S. Geological Survey (http://sfbay.wr.usgs.gov/access/wqdata/).

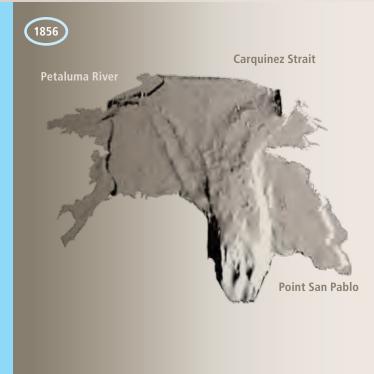
Graph prepared by Alan Jassby, U.C. Davis (adjassby@ucdavis.edu)

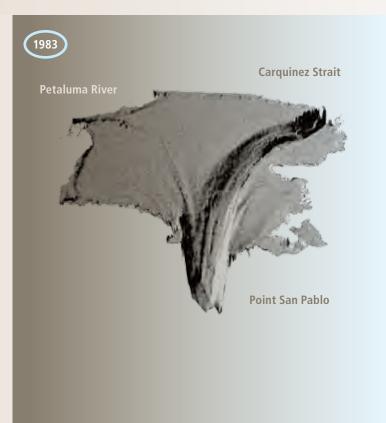
Reference: Cloern, J.E., A.D. Jassby, J.K. Thompson, and K.A. Hieb. 2007. A cold phase of the East Pacific triggers new phytoplankton blooms in San Francisco Bay. Proceedings of the National Academy of Sciences (104): 18561–18565.

Annual and Seasonal Trends in Phytoplankton Biomass. Since the late 1990s, significant changes in phytoplankton population dynamics in San Pablo, Central, and South bays have occurred; these include larger spring blooms, blooms during other seasons, and a progressive increase in the "baseline" or annual minimum chlorophyll. As an example, this series of monthly chlorophyll concentrations from one monitoring location shows the increase in baseline chlorophyll (the minimum value each year), and occurrences of autumn/winter blooms in the past decade. According to an article published in 2007 (Cloern et al. 2007), the increase in phytoplankton biomass and new blooms are thought to be caused by a cascade of effects driven by increased upwelling in the coastal ocean, leading to strong recruitment of flatfish and crustaceans into the Bay. These species are bivalve predators that appear to have reduced the populations of bivalves that consume phytoplankton. Increasing water clarity (page 56) may also be contributing to the increased phytoplankton biomass.



RIGHT San Pablo Bay bathymetry in 1983. Courtesy of Bruce Jaffe, USGS.





# → FEATURE ARTICLES

### 56

Suspended Sediment in the Bay: Past a Tipping Point

# 66

How Humans and Nature
Have Shaped the San Francisco
Estuary Since the Gold Rush

# **76**

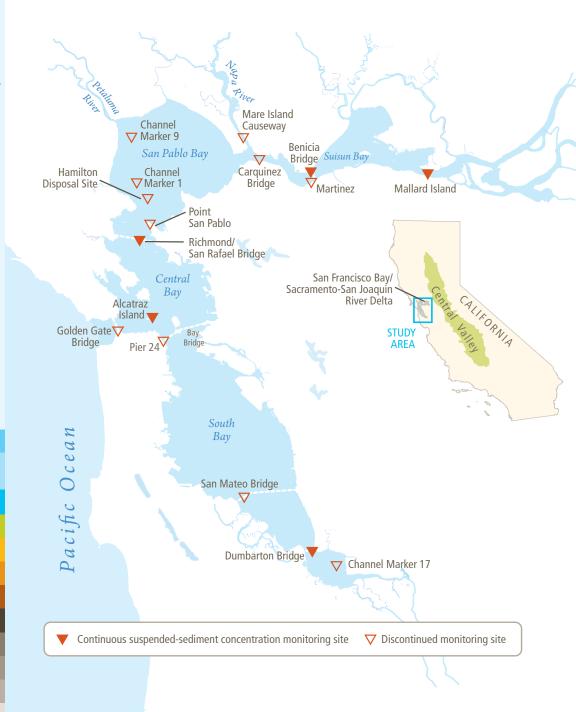
Analysis of Sediment Cores: Uncovering the Past

# Suspended Sediment in the Bay: Past a Tipping Point

### Highlights

- → Suspended sediment in Bay waters plays a critical role in wetland restoration, dredging, productivity of the ecosystem, and water quality
- → A sudden decrease in suspended sediment of approximately 40% occurred in 1999
- → The most plausible explanation for the decrease is the depletion of an erodible pool of sediment with origins dating back to the Gold Rush
- → The increase in Bay water clarity is likely to persist
- → Continuing to track suspended sediment will be essential to understanding and managing water quality and sediment movement in this dynamically changing ecosystem

DAVID H. SCHOELLHAMER U.S. Geological Survey dschoell@usgs.gov



# **Small But Important**

Tiny particles of solid material suspended in the water of San Francisco Bay have a large influence on conditions in this ecosystem. These "suspended sediments" transport associated contaminants, limit light availability and photosynthesis, settle on mudflats and tidal wetlands to create and sustain desirable habitats, and deposit in ports and shipping channels, creating the need for dredging. A significant decline in suspended sediment concentrations (SSC) in the Bay has occurred over the past 10 years. This article summarizes data describing the decline and presents a hypothesis explaining the mechanism behind it. If these lower SSC persist as expected, it could have major ramifications for dredged material management, wetland restoration, water quality, and the ecosystem.

As part of the Regional Monitoring Program for Water Quality in the San Francisco Estuary (RMP), the U.S. Geological Survey has measured suspended sediment concentrations at several stations since 1991 (FIGURE 1; Schoellhamer et al. 2007). In this article, I report on a sharp decrease in suspended sediment that began in 1999. Only recently have enough data accumulated through long-term monitoring to conclude confidently that the observed decrease represented a real long-term shift in this fundamental water quality parameter

### ← FIGURE 1

As part of the RMP, the U.S. Geological Survey has measured suspended sediment concentrations at several stations since 1991.

 Satellite image taken on January 9, 2006 showing a plume of sediment exiting the Bay during high flow conditions. Courtesy of NASA.

# Suspended Sediment Sensors in the Bay



↑ Paul Buchanan has led the collection of continuous time series of suspended sediment concentration, salinity, and temperature data in San Francisco Bay since 1993. Here he is cleaning sensor cables at the Dumbarton Bridge. Photograph by Greg Shellenbarger.

As part of the RMP, the U.S. Geological Survey has used automated optical sensors to measure suspended sediment at several stations since 1991 (FIGURE 1). Each sensor transmits a pulse of light that scatters off of suspended sediment particles and is measured by the sensor. Every 3 to 4 weeks the sensors are cleaned, calibrated, and the data are downloaded. In earlier years, about 50% of the data were invalid due to biofouling of the optical sensor, but the quantity of valid data is now approaching 75% because selfcleaning sensors have improved. The data have been used to explain the spatial and temporal variability of SSC and sediment-associated contaminants, estimate contaminant loads, develop sediment and contaminant budgets and numerical models, and plan wetland restoration projects (Schoellhamer et al. 2003). Even with losses due to biofouling, the frequency of these data can resolve variability at a tidal time scale, and tides are the factor with the largest effect on SSC (Schoellhamer 2002). Thus, these measurements can detect changes that less frequent data are unable to detect because semi-diurnal and diurnal tidal variation would appear as randomly sampled noise in the data. Other factors affecting SSC are fortnightly, monthly, and semiannual tidal cycles, seasonal wind, and river supply. All of this variability confounds the detection of trends in SSC, so time series of years to decades may be required to detect trends. This article describes a sharp decrease in SSC that began in 1999. Only recently have enough data accumulated to conclude confidently that the decrease is significant.

# 1999: The Year the Bay **Became Clearer**

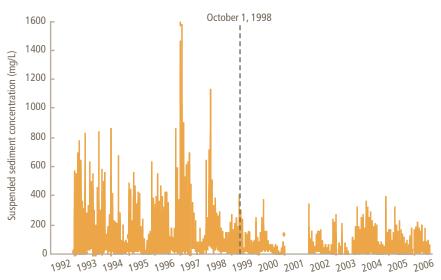
A sudden decrease in SSC in 1999 is evident in the time series of suspended sediment data from a representative station at Point San Pablo (FIGURE 2). This time series is shown because it is relatively lengthy and complete. The thickness of the band from top to bottom is an indication of the range of concentrations in a given season. The range is widest, with higher peak concentrations, in the spring and early summer when wind waves resuspend an ample supply of sediment deposited the previous winter wet season. The range is narrowest in autumn when wind decreases and before the wet season delivers new sediment from the watershed. Maximum values of SSC occurred during high flows in early 1997 and 1998. Most other Bay sites also showed a decrease in average SSC beginning in 1999 (FIGURE 3). SSC at most sites from the early 1990s through 1998 were about double those from 1999-2007 (FIGURE 4). The sharp decrease in average SSC that occurred from 1998 to 1999 was statistically significant at all sites except San Mateo Bridge.

Water samples collected to calibrate the sensors provide further confirmation of the decrease. For example, at Point San Pablo, 248 water samples were collected at mid-depth from 1993-2006 and the SSC showed a statistically significant step decrease from 1993-1998 to 1999-2006.

The monthly water quality sampling cruises by the USGS RV Polaris, another component of the RMP, also provide some confirmation of the decrease. On these cruises, USGS measures vertical

# **Water Years**

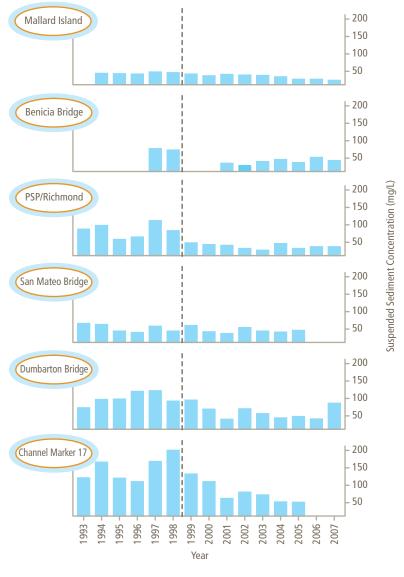
Unless otherwise noted,
the years referred to in this article are
"water years." California has two distinct
hydrologic seasons: a wet season from late
autumn to early spring, with the remainder of
the year being dry. Thus, the water year, which
begins on October 1 of one calendar year and
ends on September 30 of the next calendar
year, is a convenient period to average
water quality data such as SSC because
it begins in the dry season, includes
a full wet season, and ends in
the next dry season.



Footnote: Suspended sediment concentration, mid-depth, Point San Pablo. In 2001 the station was temporarily closed while the pier supporting the instruments was repaired.

### ↑ FIGURE 2

A sudden decrease in SSC in 1999 is evident in the time series of suspended sediment data from a representative station at Point San Pablo. This time series is shown because it is relatively lengthy and complete.



### ↑ FIGURE 3

Like Point San Pablo, most other Bay sites also showed a decrease in average SSC beginning in 1999.

of stations along the axis of the Bay from South Bay to the Delta (Cloern et al. 2003). In this dataset, SSC in Suisun Bay and San Pablo Bays showed a significant step decrease from 1975-1998 (median 34 mg/L) to 1999-2008 (median 23 mg/L). SSC in South Bay south of the Dumbarton Bridge also had a significant step decrease from a median of 36 to 27 mg/L. However, Central Bay and South Bay north of the Dumbarton Bridge did not have a significant decrease.

# Why The Sudden Change?

One possible explanation for the sudden decrease might be a comparable decrease in sediment supply from the Delta, but this does not appear to be the case. The RMP has estimated sediment supply to the Bay from the Delta (McKee et al. 2006). In general, most measured years before the decrease had large sediment loads and all but one year after the decrease had small sediment loads (FIGURE 5). The exceptions, however, indicate that sediment supply from the Delta is not the cause of decreased SSC in the Bay. Water year 2006 was wet (50,000 million m<sup>3</sup> of runoff from the Central Valley), with a large sediment supply, yet SSC remained low in the Bay. Water year 1994 was dry (7,400 million m<sup>3</sup>) and certainly had a small sediment supply before the decrease, but SSC remained high in the Bay. If river sediment supply in a given year is the only source of suspended sediment, then SSC would correspond closely with river sediment supply. The observations in water years 1994 and 2006 prove that river supply does not directly determine SSC.

profiles of basic water quality parameters at a series 
The most plausible explanation for the decrease is the depletion of an erodible pool of sediment with origins dating back to the Gold Rush. This erodible pool consisted of fine-grained sediment particles that were washed out of the ancient Sierran river beds that were exposed by the hydraulic mining water cannons.

> Evidence suggests that the pool of erodible sediment in the Bay and its watershed gradually diminished over the course of many decades, and became depleted in the late 1990s, causing the sudden decrease in 1999 (FIGURE 6). Until the decrease, Bay SSC had remained high, even in years with little sediment supply, because the erodible sediment pool continued to supply material to the water column. Sediment budgets prior to 1999 indicate that the Bay was eroding (Schoellhamer et al. 2005). During this period, the supply from the erodible pool exceeded the capacity of Bay waters to hold sediment in suspension. Because SSC remained high during low-supply years, the pool must have been larger than the average annual sediment supply. Water year 1998 was wet, with high flow persisting well into summer, probably flushing sediment from the Bay to the Pacific Ocean. Despite a large sediment supply from the Delta, sediment export from Suisun Bay in 1998 was over eight times greater than sediment supply (Ganju and Schoellhamer 2006). After the decrease in 1999, SSC have been lower, because they are now limited by the supply of bed sediment, not the capacity of Bay waters to hold sediment in suspension. Suspended and bed sediment continued to exchange through erosion and deposition, but a sizeable pool of erodible bed sediment was absent. Even years with a large sediment supply (such as

water year 2006) did not supply enough sediment to restore the pool, and SSC remained low.

The erodible sediment pool was probably formed by hydraulic gold mining debris in the late 1800s (Cappiella et al. 1999, Fergoso et al. 2008, Jaffe et al. 1998). Sediment mobilized by hydraulic mining washed down Central Valley rivers, depositing in them and in the Bay (Gilbert 1917). Mud dominates the bottom of the Bay so mud is the primary component of the erodible sediment pool. The thickness of the erodible sediment pool at any point in the Bay depends on how much hydraulic mining sediment deposited there. Sediment supply from the Sacramento River gradually decreased by half from 1957-2001 (Wright and Schoellhamer 2004) resulting in a long-term decrease in sediment supply to the Bay (FIGURE 7). In addition, dams built in the Central Valley watershed in the 1900s trap sediment (Wright and Schoellhamer 2004) and release clear water (FIGURE 8). For many years, the clear water eroded hydraulic mining deposits that had deposited in the downstream river channels, so the Bay continued to receive significant quantities of sediment. Over time, however, the eroding reaches of the river were depleted of erodible sediment, with the sites of erosion moving progressively further downstream. Eventually, the deposits of erodible sediment in the river channels were also depleted, and sediment supply to the Bay was reduced. Bank protection in Central Valley rivers to prevent erosion and deposition in Sacramento Valley flood bypasses also act to reduce downstream sediment supply (Florsheim et al. 2008, Singer et al. 2008). Decreasing sediment supply from the rivers increased the rate of loss of the erodible pool in the Bay, until the erodible



# WY 1995-1998 WY 1999-2007 3.00 2.50 2.00 Sediment supply, Mt 1.50 1.00 0.50 0.00 0 10,000 20,000 30,000 40,000 50,000 60,000 Delta outflow, Mm<sup>3</sup>

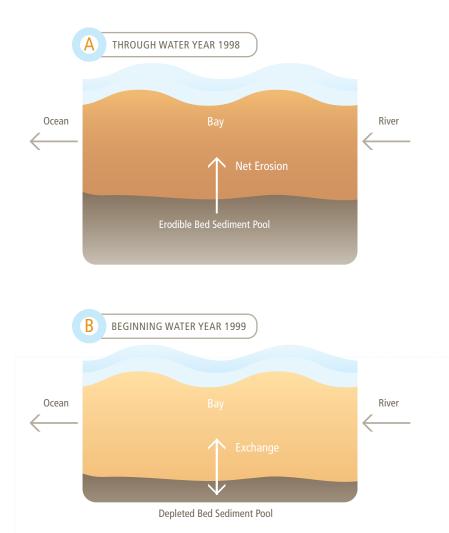
Footnote: From McKee et al. (2006).

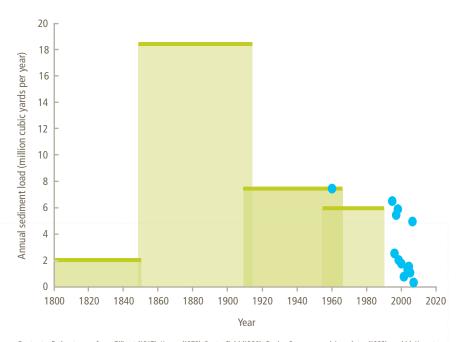
### ↑ FIGURE 4

SSC at most sites from the early 1990s through 1998 were about double those from 1999-2007. The sharp decrease in average SSC that occurred from 1998 to 1999 was statistically significant at all sites except San Mateo Bridge.

### ← FIGURE 5

One possible explanation for the sudden decrease might be a comparable decrease in sediment supply from the Delta, but this does not appear to be the case. Most years before the decrease had large sediment loads and all but one year after the decrease had small sediment loads. The exceptions, however, indicate that sediment supply from the Delta is not the cause of decreased SSC in the Bay. Water year 2006 was wet, with a large sediment supply, yet SSC remained low in the Bay. Water year 1994 was dry and certainly had a small sediment supply before the decrease, but SSC remained high in the Bay. The observations in these years prove that river supply does not directly determine SSC.





Footnote: Estimates are from Gilbert (1917), Krone (1979), Porterfield (1980), Ogden Beeman, and Associates (1992), and McKee et al. (2006). Bars indicate estimates over entire period and points indicate yearly estimates.

### ↑ FIGURE 6

Conceptual model of an erodible sediment pool. Prior to 1999 (top), the pool of erodible bed sediment was large enough to sustain high concentrations of suspended sediment in the water column. In 1999, the pool of erodible bed sediment reached a critically low point at which high concentrations of suspended sediment were no longer sustained, and Bay waters became significantly clearer.

### ↑ FIGURE 7

Estimated annual sediment supply from the Central Valley to San Francisco Bay. Hydraulic gold mining in the Sierra Nevada in the late 1800s greatly increased sediment loads over pre-1849 levels. Loads declined in the 1900s due to cessation of hydraulic mining, sediment trapping in reservoirs, deposition in flood bypasses, and protecting the banks of Central Valley rivers from erosion.

pool was exhausted in 1999. The hydraulic mining sediment pulse would have diminished and faded with time without dams, flood bypasses, and bank protection; these merely accelerated the decline.

# Ramifications of a Clearer Bay

The increase in Bay water clarity in recent years has significant ramifications for dredging, wetland restoration, water quality, and ecology.

The Long-Term Management Strategy (LTMS) for Dredging and Dredged Material Disposal in San Francisco Bay was developed in the early 1990s, before the 1999 decrease in suspended sediment. Lower SSC reduce deposition, which in turn reduces the amount of maintenance dredging that is needed. Lower SSC may also make the in-Bay dredged material disposal sites more dispersive and increase their capacity. Bay disposal sites may be able to accommodate more material, reducing the need for costly ocean disposal.

Wetland restoration typically involves opening a diked area to tidal action, allowing sediment to deposit until the bed elevation is high enough for wetland plants to germinate and grow. The rate of deposition is proportional to SSC. With lower SSC, more time is needed to accumulate the required amount of sediment. If SSC are so low that the rate of deposition is less than the rate of sea level rise, a vegetated wetland will never form. Decreased SSC therefore contributes to an increasing demand for the use of dredged sediment in wetland restoration (page 8).

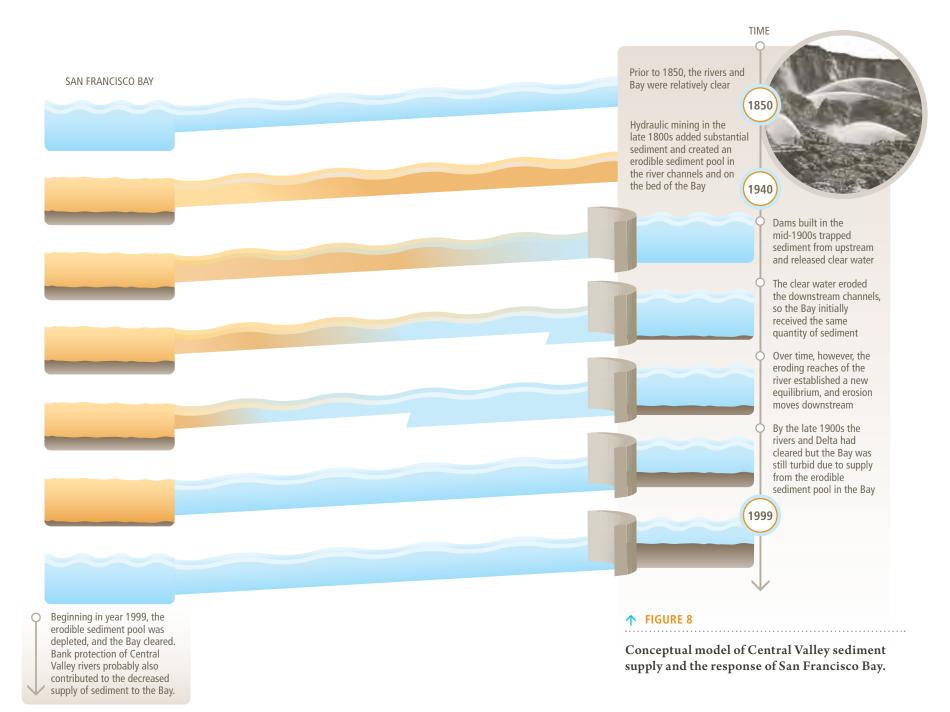
The abundance of phytoplankton in the Bay is of fundamental importance in supporting the food web and as a controlling influence on water quality. Beginning in the late 1990s, phytoplankton biomass in the Bay increased (Cloern et al. 2006). In addition, autumn phytoplankton blooms and larger spring blooms began occurring in 1999. The clearer waters following the decrease in 1999 may have contributed to this increase. Cloern et al. (2006) also suggest that a shift in currents in the Pacific Ocean, improved wastewater treatment, and introductions of new species may contribute to the chlorophyll increase. Together, the SSC and phytoplankton data indicate that the Bay crossed a threshold and fundamentally changed in the late 1990s. San Francisco Bay has been transformed from a low-productivity estuary to one more typical of temperate-latitude estuaries.

The shift toward increased clarity and higher phytoplankton production has resulted in increased concern about the possible impact of nutrient inputs to the Bay. In many other estuaries around the world, nutrient pollution is a major water quality concern, causing excessive phytoplankton growth which can lead to fish kills due to low levels of dissolved oxygen, excess turbidity, and can include nuisance algal species. In contrast to most estuaries, the relatively high SSC historically present in Bay waters limited phytoplankton growth and prevented these problems. With decreased SSC and increased clarity, controls on nutrient concentrations may become necessary to prevent excessive phytoplankton growth.

Reduced SSC will also affect concentrations and cycling of contaminants that are associated with sediment (Schoellhamer et al. 2007). Lower SSC decrease the water column concentrations of sediment-associated contaminants. Water quality standards written in terms of total (dissolved and sediment-associated) concentrations are more likely to be achieved, because SSC are smaller.



↑ Allan Mlodnosky has led the USGS sediment lab in Marina, California, and has analyzed the suspended sediment samples collected in San Francisco Bay since the first sample was collected in 1991. He has noticed a reduction in the quantity of material from Bay samples trapped on lab filters. Photograph by Kyle Stoner.



# With decreased SSC and increased clarity, controls on nutrient concentrations may become necessary to prevent excessive phytoplankton growth

Another ominous ecological change began around 2000 - the pelagic organism decline (or "POD") the collapse of populations of several fish species in the North Bay and the Delta (Sommer et al. 2007) (page 45). Reduced SSC may be one of several contributing factors. The decline has had the most serious consequences for Delta smelt, whose feeding sharply decreases when SSC are less than 24 mg/L (Baskerville-Bridges et al. 2004). Abundance of some fish species increases in more turbid waters (Nobriga et al. 2005, Feyrer et al. 2007), so water decisions on diversions from the Delta are partially determined by SSC, which are used as a surrogate for fish. The relation between decreased SSC and fish decline is not well established, however, the concurrence of lower SSC, more phytoplankton, and fewer fish merits additional study.

### A Clearer Future

If the depleted erodible pool hypothesis is correct, the decrease in suspended sediment is likely to persist. Sediment supply from the watershed has been declining and a severe disturbance to the watershed that would increase supply, such as hydraulic

mining, is unlikely. Wet years supply sediment to the Bay but they probably flush more sediment from the Bay through the Golden Gate (Ganju and Schoellhamer 2006), preventing reestablishment of an erodible sediment pool. High flow and sediment supply during water year 2006 demonstrated that a single wet year did not increase SSC. During dry years, sediment supply and sediment exported to the ocean are both small, maintaining low SSC and a depleted erodible pool.

USGS researchers are currently evaluating scenarios of how climate change may affect the Bay ecosystem as part of the Computational Assessments of Scenarios of Change for the Delta Ecosystem (CASCaDE) project (http://cascade.wr.usgs.gov/). As one part of this study, Ganju et al. (submitted) evaluated scenarios of sea level rise, altered freshwater inflow, and decreased sediment supply. Sea level rise will increase water depths, decrease wind-wave resuspension of bottom sediment, and decrease SSC. If sediment supply continues to decline then this will also contribute to lower SSC. Given these considerations, a physical scenario by which Bay SSC increases does not seem likely. With the Bay's susceptibility to invasive species, an invader that

disturbs the bed and thus increases the erodibility of the Bay bottom and thus SSC is possible and perhaps the most plausible mechanism that conceivably could reverse the trend of decreased SSC.

Whether the Bay and its watershed have achieved a new equilibrium or whether SSC will continue to decrease needs additional study. Continuing to track this critical parameter will be essential to understanding and managing water quality and sediment movement in this dynamically changing ecosystem.

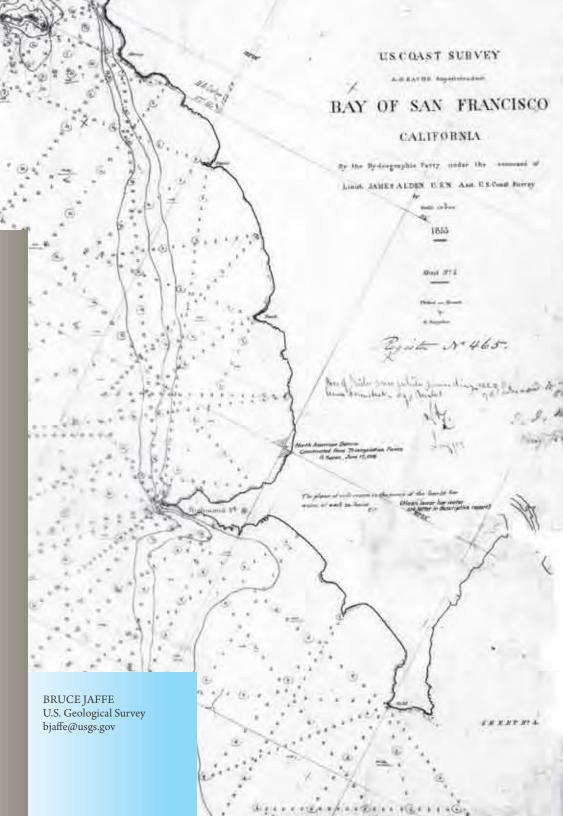
### Acknowledgements

I would like to thank those that have helped collect, process, and publish the continuous SSC data: Rick Adorador, Greg Brewster, Paul Buchanan, Laurie Campbell, Mike Farber, Amber Forest, Neil Ganju, Tom Hankins, Megan Lionberger, Allan Mlodnosky, Tara Morgan, Heather Ramil, Cathy Ruhl, Rob Sheipline, Brad Sullivan, and Jessica Wood. Jim Cloern and Jay Davis provided helpful comments on an early draft of this article. This work is supported by the U.S. Army Corps of Engineers, San Francisco District, as part of the Regional Monitoring Program.

# How Humans and Nature Have Shaped the San Francisco Estuary Since the Gold Rush

### Highlights

- → The distribution and extent of natural habitats in the San Francisco Estuary have changed markedly since the Gold Rush
- → The largest human influence on the morphology of the Estuary has been through increasing and reducing sediment inflow, promoting either deposition or erosion
- → Deposition of more than a quarter billion cubic meters of hydraulic gold mining debris reduced the average depth of the Estuary in the middle and late 1800s
- → The Estuary is now deepening as more sediment goes out the Golden Gate than enters from rivers and the ocean
- → Legacy contaminants are surfacing as erosion removes capping sediment
- → Sea level rise will tax an already taxed system as sediment demand outpaces sediment inflow





## A Changing Estuary

The San Francisco Estuary has undergone dramatic changes since the Gold Rush, as both natural forces and human activities have added and removed massive quantities of sediment, primarily sand and mud. A long-term perspective of sediment movement and patterns of sediment deposition and erosion is vital for effective management of wetlands, sediment contamination, dredging, mining, and other phenomena. Quantitative analysis of historical depth surveys and changes between surveys provides this perspective.

The historical chronicle of bathymetric change in the San Francisco Estuary is rich, with up to seven surveys having been completed since the Gold Rush. The U.S. Geological Survey (USGS) is in the final stages of a two-decade-long research program to analyze the changing bathymetry of the Bay (Cappiella et al. 1999, Foxgrover et al. 2004, Jaffe et al. 2007, Fregoso et al. 2008). A GIS program was used to explore the changes in depth resulting from natural and human-induced actions.

Although the magnitude and patterns of deposition and erosion are complex (FIGURES 1 and 2), there were two major behaviors:

- shoaling from deposition during the hydraulic gold mining period, and
- · deepening from erosion during the later half of the 20th century.

The volumes of sediment transported, deposited, and eroded have been huge. For example, during the hydraulic gold mining period, more than a

# During the hydraulic gold mining period, more than a quarter of a billion cubic meters of sediment were deposited in the Estuary, equivalent to about 60 Superdomes filled with sediment

quarter of a billion cubic meters of sediment were deposited in the Estuary, primarily in the north Bay (San Pablo and Suisun bays). This is equivalent to about 60 Superdomes filled with sediment. It would take trucks dumping 10 cubic yards of sediments every 10 seconds about a year to equal this amount of sediment.

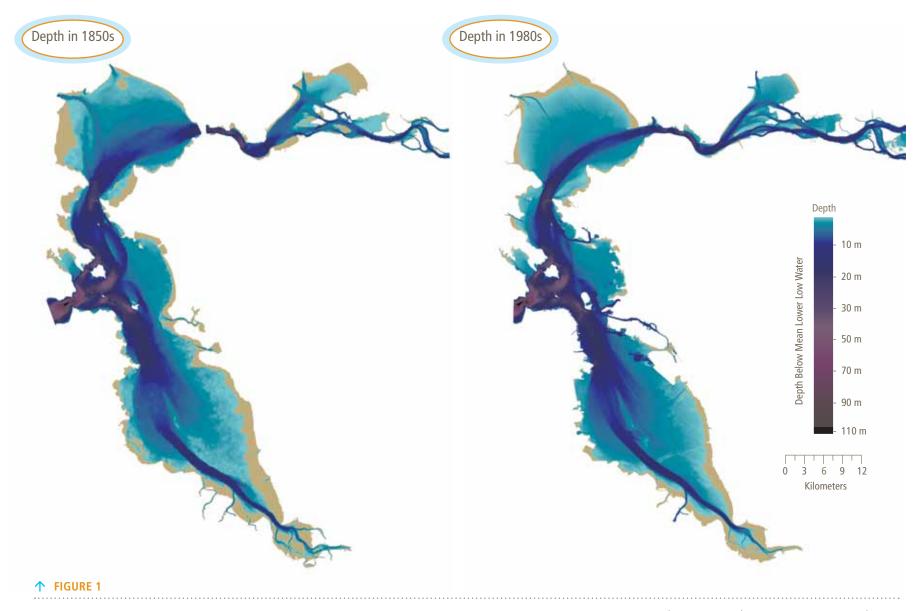
# **Human Activities that Changed** the Estuary

A myriad of activities have changed the morphology of the Estuary. The sharp, linear boundaries of areas where sediment was removed by dredging or mining catch the eye when looking at change maps from the 1950s to 1980s (FIGURE 2). These linear boundaries are especially apparent in the South and Central bays where the signatures of dredging, narrow straight-sided slots of deeper areas in channels, are easily detectable. Likewise, borrow areas, like the ones in South Bay, appear as straight-sided patches where deepening has occurred. The signature of sand mining is apparent in Central Bay.

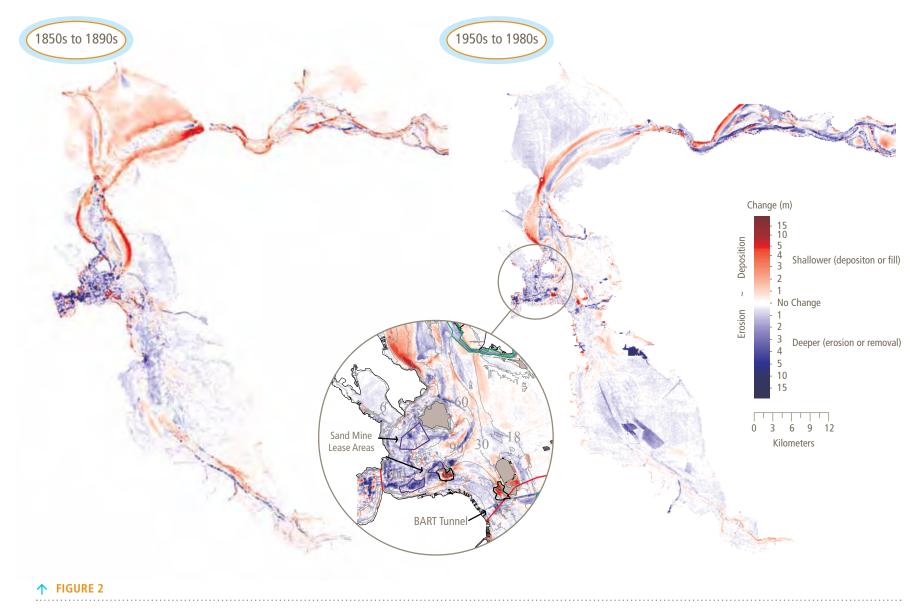
The volume of sediment removed from the Bay by human activity can be a significant portion of the total loss of sediment. In South Bay approximately 70 million cubic meters of sediment were lost from

1956 to 1983, with about 30 million cubic meters coming from borrow pits. Of the approximately 50 million cubic meters of loss in Central Bay from 1947 to 1980, about 30 million cubic meters was removed by borrow-pit excavation, dredging, and sand mining (Fregoso et al. 2008). Sand mining in Central Bay removes an amount of material that is on the same order of magnitude as the amount of sediment inflow from rivers to the Estuary (Schoellhamer et al. 2005). Considering that sand is only a fraction of the total sediment, mining may be significantly depleting the Estuary of sand.

A potentially far larger, and not as easily detectable, cause for change in the morphology of the Estuary is the increase or decrease of sediment inflow from rivers. The deposition during the hydraulic mining period was a response to the greatly increased sediment inflow associated with mining activities (Jaffe et al. 2007). The erosion of the Estuary in the middle to late 1900s may be linked to a decrease in sediment inflow. Wright and Schoellhamer (2004) found that delivery of suspended sediment from the Sacramento River, a major source of sediment to San Francisco Estuary, decreased by about half during the period 1957 to 2001. They attributed this reduction to multiple causes including trapping of sediment in reservoirs, riverbank protection, and alterations in land use (page 56).



Depths of the San Francisco Estuary fluctuated significantly between the 1850s and 1980s. Change in channels (darker colors) and loss of tidal flats (light brown) were the result of many influences, but were primarily caused by high sediment inflow during the hydraulic mining period and a subsequent reduction in sediment inflow in the 1900s from reservoir creation and altered land use in the watershed. Dredged areas, borrow pits, and mining sites appear as deeper regions with straight boundaries and sharp changes in depth (e.g., the trapezoidal shape in the middle of South Bay in the 1980s).



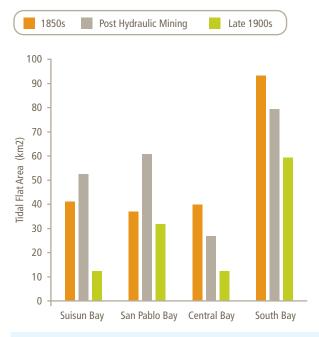
The Estuary changed from a regime of intense deposition during the hydraulic gold mining period to net erosion during the late 1900s. The North Bay was primarily depositional (red) during the hydraulic mining period (more than 300 million cubic meters of sediment were deposited). The change to an erosional (blue) regime from the 1950s to 1980s is apparent. Areas where sediment was removed by dredging, borrow pits, and mining are dark blue regions with straight boundaries (e.g., the borrow areas in the middle of South Bay). The signature of sand mining is apparent in Central Bay (inset).

### Changes in Habitat

As the morphology of the Estuary has changed, so have the types and extents of habitats. In the 1850s the channel systems were broad and tidal flats were extensive. Deposition during the hydraulic mining era filled and narrowed channels in the Estuary (FIGURES 1 and 2). Channels connected to diked marshes were particularly susceptible, as reduction in tidal exchange induced filling. Many channels migrated laterally as sediment was preferentially deposited on one side. Modeling has shown that flow through the altered channel system in San Pablo Bay was quite different from the flow pattern of the 1850s (van der Wegen et al. 2008).

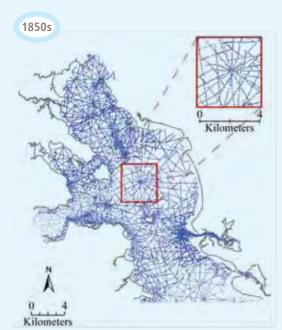
Habitats that are defined by depth have changed in the Estuary. For example, the total area made up of tidal flats (areas between mean lower low water and the shore) increased slightly, by about 3%, during the hydraulic mining period (FIGURE 3). However, this slight increase was short-lived and limited to the North Bay. As sediment inflow to the Estuary decreased after hydraulic mining, about half of the tidal flats were eroded. This erosion was greatest in the North Bay (i.e., Suisun and San Pablo bays) and in the 1900s.

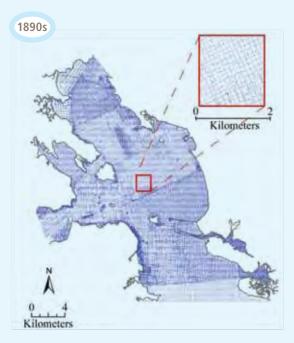
Bearman (2008) showed that the shapes as well as the extent of the tidal flats changed through time in the South Bay. The changes have been related to whether the shallows were depositional or erosional. The spatial distribution of sediment type (sand versus mud) in the Estuary has probably also changed.



### ← FIGURE 3

The distribution of habitats that are defined by depth has changed dramatically in the Estuary. For example, there was about a 50% overall reduction in tidal flat area from the 1850s to the late 1900s, although each sub-embayment behaved differently through time. In the North Bay (Suisun and San Pablo bays) deposition of hydraulic mining debris increased tidal flat area temporarily. The South and Central bays did not receive as much of the hydraulic mining debris as the North Bay and did not experience the temporary increase in tidal flats. South Bay had the most extensive tidal flats during all time periods.





### **Legacy Contaminants**

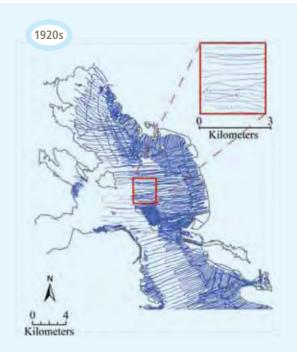
Legacy contaminants in bottom sediment deposits can either be isolated when covered by cleaner sediment or mobilized when exposed at the surface. As the morphology of the San Francisco Estuary has changed, so has the spatial distribution of legacy contaminants available for mobilization.

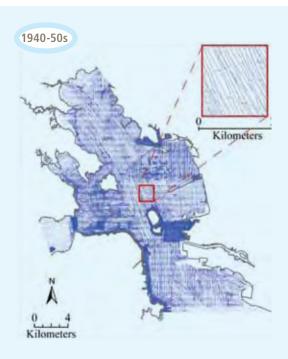
Using the historical series of depth surveys, it is possible to predict the age of near surface sediments (Higgins et al. 2005, 2007), and by association the distribution of legacy contaminants if the time periods when contaminants were deposited are known. An example of a reconstruction of the age of near surface sediments for San Pablo Bay

is shown in FIGURE 4. The sediments deposited between surveys made near the beginning (1856) and end (1887) of the hydraulic mining period have elevated mercury levels (Hornberger et al., 1999) from elemental mercury used to extract gold and lost from sluices at mines.

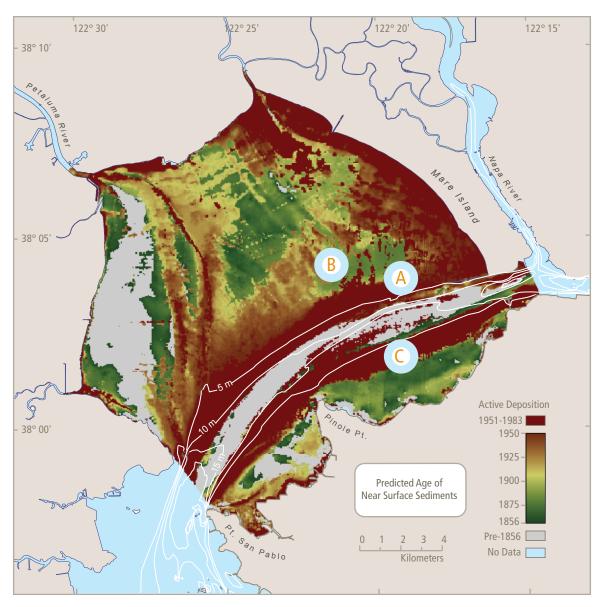
In addition to the age of the near surface sediments, a prediction can be made of the increase in age of sediments with depth for sediment deposited after the earliest survey (Higgins et al., 2005, 2007). This information is very useful in interpreting the results of contaminant concentrations in sediment cores. SFEI is using sediment-age reconstructions to aid in the interpretation of cores collected as part of the RMP-Clean Estuary Part-

nership Coring Study (page 76). FIGURE 5 shows reconstructions for three cores in San Pablo Bay. Core A was taken from an area where sediment was deposited between each survey after 1887. Similar locations are rare in San Pablo Bay; typically subsequent erosion has exposed older sediments. Such is the case for Core B, which was taken from an area where mercury-contaminated sediment from the hydraulic mining period was exposed. Often, there is a discontinuity in sediment age with depth because of alternating periods of deposition and erosion (e.g., Core C, FIGURE 5). When the history of contaminant loading is known, sediment age reconstructions and estimates of future morphology can be used to predict the vulnerability for legacy contaminants being exposed by erosion.





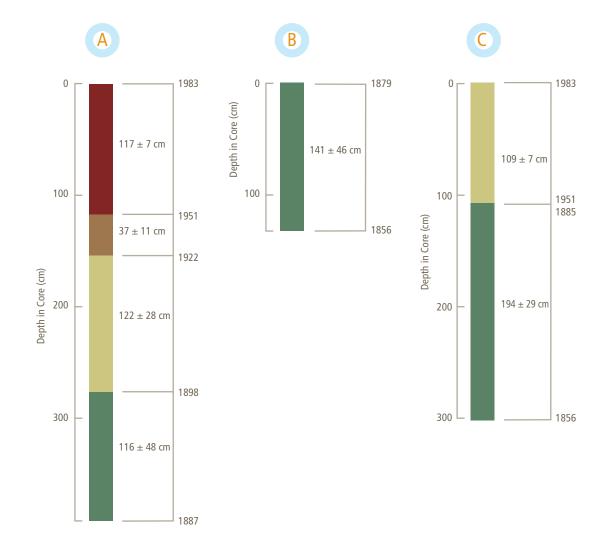
 Maps showing soundings from different time periods that were used for modeling bathymetry. From Fregoso et al. (2008).



#### ← FIGURE 4

Using the historical series of depth surveys, it is possible to predict the age of near surface sediments and, by association, the distribution of legacy contaminants. This map was produced using the six depth surveys made from 1856 to 1983. This technique is a powerful tool for determining the distribution of legacy contaminants if the time periods when contaminants were deposited are known. For example, the sediments deposited between surveys made near the beginning (1856) and end (1887) of the hydraulic mining period have elevated mercury levels (Hornberger et al. 1999) from elemental mercury used to extract gold and lost from sluices at mines. The letters (A, B, C) show locations of cores discussed in FIGURE 5.

Footnote: Figure from Higgins et al. (2007).



#### ← FIGURE 5

The historical series of depth surveys can also be used to predict the increase in age of sediments with depth at specific locations. This information is very useful in interpreting the results of contaminant concentrations in sediment cores (page 76). Predicted chronologies for three locations in San Pablo Bay are shown in this figure (see Figure 4 for locations of cores A, B, and C). Sediment was deposited between each survey after 1887 in Core A. In Core B, sediment was deposited from 1856 to later than 1879 and subsequently eroded to the 1879 level resulting in mercury-contaminated sediment from the hydraulic mining period being exposed. In Core C, there is a discontinuity in sediment age with depth because of alternating periods of deposition and erosion.

# The future morphology of the Estuary is uncertain, largely due to unknown effects of climate change and sea-level rise

### How Will the Estuary Continue to Change?

The future of the morphology of the Estuary is uncertain, in large part because of the unknowns brought by extreme climate change and sea level rise. The Computational Assessments of Scenarios of Change for the Delta Ecosystem (CASCaDE) project, a USGS project funded by CALFED and USGS, is addressing likely scenarios of change in morphology (Ganju et al. 2008; van der Wegen et al. 2008) and other components of the ecosystem (http://cascade.wr.usgs.gov/). The degree that humans will continue to alter sediment inflow, remove sediment, and create new demand for sediment is also unknown. However, enough is known about the sediment dynamics of the system that it is possible to formulate likely responses to scenarios of change.

Major restorations of salt ponds in the South Bay and of areas in the North Bay will increase sediment demand where restored areas (e.g., salt ponds in the far South Bay) are below the elevation of tidal marshes. It is unknown what portion of this sediment will be supplied from erosion of adjacent tidal flats. Increased tidal prisms associated with the formation of new tidal marshes will tend to deepen channels connected to the marsh, and, cumulatively, could deepen larger channels in the Estuary.

Sea level rise will also increase sediment demand. If the rate of sea level rise outpaces the deposition rate, the Estuary will deepen. This scenario is likely given the reduction in sediment inflow (page 56) and signs that the Estuary has entered an erosional regime. Even if there were enough sediment to raise the floor and rim of the Estuary at a rate equal to the rate of sea level rise, the morphology would still change. Contributing to this change are an altered tidal prism and upland areas that likely will be protected from flooding because of the presence of infrastructure and buildings. The effect of sea level rise on morphology, and by association habitat distribution and legacy contaminant vulnerability to erosion, is not currently predictable.

Climate change will further alter the morphology of the Estuary by altering sediment inflow as storms and winds change.

### Planning for the Future

The morphology of the Estuary will continue to change; that is a given. Our state of knowledge is at a point where gross trends in morphologic change in the Estuary can be forecast. These predictions have varied utility, depending on what morphologic feature is of interest. To decrease uncertainty in determining the likely future morphology of the Estuary, several steps should be taken.

Most importantly, development of an Estuary-wide numerical model or models linking hydrodynamics, sediment transport, and morphologic change will allow exploration of morphologic change. Development of such models has already begun (Ganju et al. 2009; van der Wegen et al. 2008) (Sidebar). These models will be used to assess effects of different scenarios of climate change, sea level rise, and human activities on the morphology of the Estuary.

Uncertainty will also be reduced as the properties of the sediment become better known. Without knowledge of the spatial (3D) pattern of sediment properties, primarily erodibility, it is not possible to make accurate predictions of when and where sediment will move and how morphology will change.

Lastly, a paradigm shift is needed from thinking about the sediment of the Estuary as just sediment to thinking about mud and sand separately because they behave so differently. The sediment system should be treated as a hybrid that requires attention to each of its components.





 Graphic courtesy of Rusty Holleman (UC Berkeley).

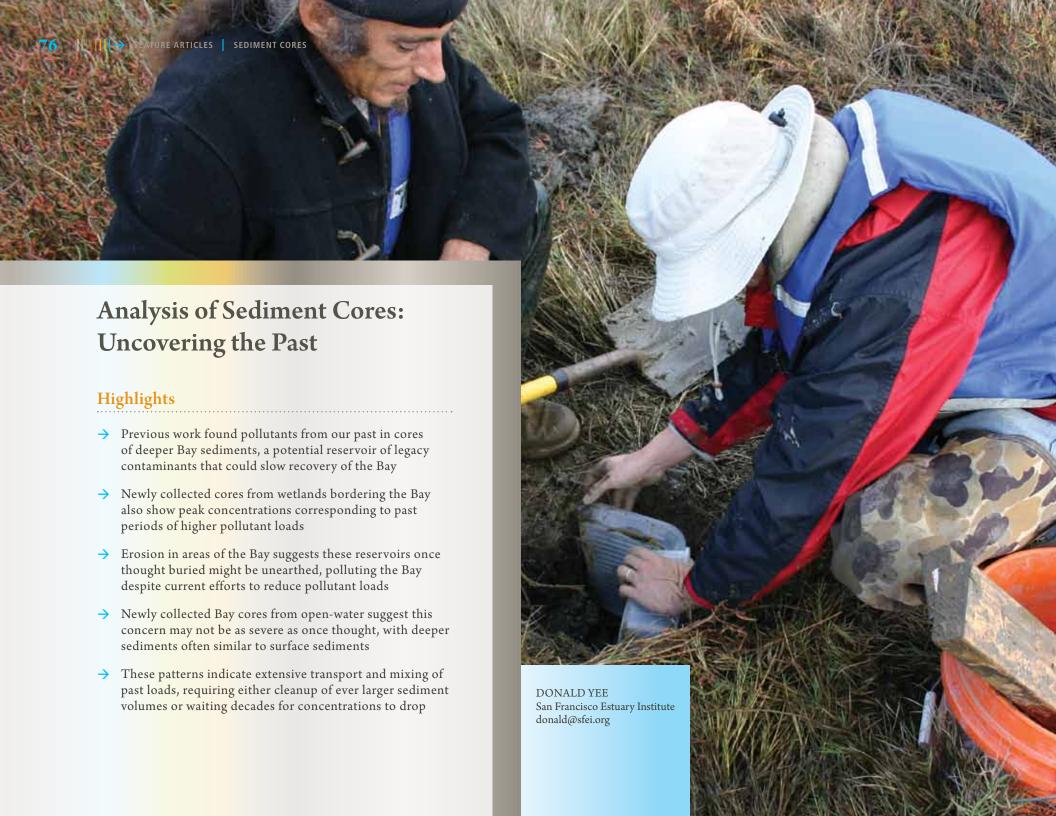
## **SUNTANS** for the Bay

Sediment dynamics are changing in San Francisco Bay. Predictive models are needed to understand the implications of these changes for the Bay and to help managers guide these changes. The RMP is planning to embark on a multi-year modeling effort in 2010 by working with U.C. Berkeley and independent consultants (Ed Gross) to develop and apply an existing model to answer RMP questions. The model to be used, known as "SUNTANS," is being developed by researchers at Stanford and U.C. Berkeley. The full name is the Stanford Unstructured Nonhydrostatic Terrain-following Adaptive Navier-Stokes Simulator model. The RMP selected the SUNTANS model because of its local ties (it is being co-developed by two local universities) and its open-source, community-driven approach to development and application. The model in its current form predicts the movement of water in the Bay on a grid composed of

6,266 triangles. The SUNTANS model takes as its inputs the river inflow from local tributaries and the Sacramento and San Joaquin rivers and the height of the water surface in the Pacific Ocean. These inputs influence the currents and height of the water throughout the Bay. In 2010, the RMP will begin developing specific applications of the SUNTANS model in South San Francisco Bay. Emphasis will be on understanding the exchange of material between small tributaries, near-shore Bay margins and the Bay as a whole. Subsequent efforts will extend these applications to other regions of the Bay. Ultimately the model will include sediment and contaminant transport capabilities.

Contact: John Oram, SFEI, joram@sfei.org

More information available at: http://suntans.stanford.edu/projects/sfbay.php





#### **Burying Our Dirty Past**

Pollutants have sometimes been handled with an "out of sight, out of mind" mentality, but unfortunately in some cases what you can't see, can hurt you. In landfills and dumps here and everywhere around the country, we have buried our discards - yesterday's papers, broken appliances, disposable diapers, hazardous wastes. For many years, the Bay was our watery dump, where we discarded our waste, hoping never to see it again. We're trying to live clean now, but watch nervously as the currents nibble away at the edge of the dump, threatening to exhume our dirty past. The story of buried contaminants in the Bay may not be as titillating as news stories or cable television dramas about mobsters and their buried bodies. However, unlike the latter, they are a concern that could potentially affect our personal health and other aspects of our quality of life.

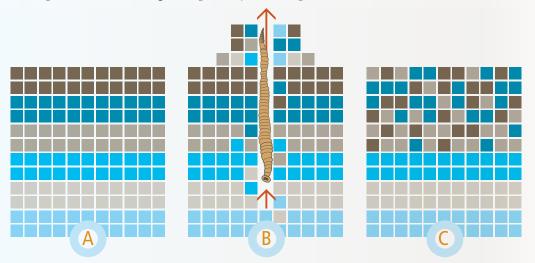
Even in the most poorly flushed areas, waters of the Bay are replaced by waters from surrounding watersheds and the ocean within a time frame of days to weeks. In contrast, it typically takes decades to centuries for new sediments from surrounding watersheds to replace the top few inches of sediment in the Bay. As a result, many contaminants that end up in Bay sediments also tend to linger for many decades. In deep water areas where the sediment can remain relatively unperturbed, sediments settling out of the water column quietly pile layers atop one another year after year, with only the burrowing and foraging activity of resident animals sporadically mixing the neatly deposited layers (Sidebar). Strong currents and waves can also mix sediments by repeatedly resuspending and redepositing sediment layers. Although bor-

dering shorelines are buffeted by wind and waves, wetlands are largely protected by their vegetation, which absorbs the brunt of the energy, allowing sediments to also accumulate relatively undisturbed in those areas. Eventually, later deposited sediments bury earlier layers so deeply that few currents, waves, or animals can disturb them, save for occasional humans with their dragged anchors, probes, samplers, and dredges.

Some older layers are from periods when less care was taken with pollutants and contain sediments more contaminated than those currently settling on the Bay surface. So long as they stay buried out of reach to most resident creatures, these sediments pose less of a risk than they would at the surface. However, things seldom are that simple; climatic shifts, rerouting of channels, watershed development, and other forces conspire to alter water and sediment flows, potentially eroding away the covering layers and exposing our dirty past.

# **Sediment Deposition and Mixing**

In the figures below, brown and blue boxes represent sediments from alternating years, with darker boxes representing more recent years. For an idealized case where only sediment deposition occurs, each layer of new sediment neatly stacks atop previous layers, with no mixing of sediments between years (FIGURE A). FIGURE B shows the influence of a burrowing worm feeding in a head downward orientation. Deeper (older) sediments are ingested by the worm and excreted upward, mixing older and newer sediments at the surface and along the walls of the worm tunnel. FIGURE C illustrates the effect of a large resuspension event mixing the top three years of deposited sediments.



Coring in Wildcat Marsh. Photograph by Bryan Bemis.

We can sample these layers of deposited sediment by collecting cores (Sidebar). Work done by the U.S. Geological Survey (USGS) in the early 1990s examined concentrations of pollutants found deeply buried in sediment cores from San Francisco Bay, finding layers with elevated concentrations of pollutants such as PCBs, mercury, and copper in locations from San Pablo Bay and Richardson Bay. Other work done at the USGS (page 66) by Bruce Jaffe's group suggested that many areas of the Bay have been eroding in recent decades, raising concerns that our legacy of pollution may be exhumed from its watery grave to haunt us, despite our best current efforts to stay clean.

Total Maximum Daily Load (TMDL) plans for mercury, copper, nickel, and PCBs acknowledged the persistence of contaminated sediments, with prognoses for recovery of the ecosystem projected to take decades, even with greatly reduced pollutant loading, in part due to the expectation of buried layers of highly contaminated sediments becoming re-exposed. Although the extent of these pockets of buried pollutants was poorly known, at the time, a few cores from the USGS studies were the best information available.

With the potential for erosion to expose these more contaminated deeper sediments, the need for informa-

tion to more thoroughly document the extent and degree of pollution in sediments became readily apparent. Subsequent to TMDL developments, recovery forecast models developed by the RMP also reinforced the need for better information, as the near- and mid-term trajectories for the Bay depended strongly on the initial sediment contaminant distributions.

### So Many Sites, So Little Time

Given the dearth of information on contaminant distributions in subsurface sediments, the RMP and the Clean Estuary Partnership jointly funded a new coring study to fill the gap. As the coring study was being developed in 2004, we considered the types of information that cores might be able to provide us, which would affect both where and how deep we would need to sample. Since our primary information need was a representative picture of the contaminant exposure that could be experienced by biota in the Bay, the majority of sampling sites were distributed widely and randomly, without seeking any special site characteristics. Two RMP sediment monitoring stations were chosen as the primary sites for each Bay segment. Because Central Bay represents a larger surface area than the other segments, an additional site was allocated to that segment. Bay sites (FIGURE 1) were sampled in May and July 2006.

A secondary information need for cores was to provide pollutant loading histories for various areas of the Bay. Because vegetation buffers the wetland surface sediments against mixing and resuspension by waves and tides, it was expected that the wetland sites would better maintain evidence of changing loads over time. One wetland site at the



# **Collecting a Sediment Core**

The corer, generally a hollow tube, is vertically driven into the sediment by mechanical force. The corer is then pulled, carrying with it the sediment forced inside the tube. Sediment is held within the corer by its inherent cohesion (e.g., for mud and clay), suction, and/or one way flaps/ valves. The corer contents can then be accessed by pushing out the contents, opening the tube, or cutting the tube laterally into disc-shaped sections. The sediment directly in contact with the corer wall is often discarded, as that sediment is often smeared by the cutting action of the corer and friction of the wall.

# Cores taken from wetlands all around the Bay reveal that newly deposited sediments are cleaner than those deposited around 30 years ago



↑ Collection of a wetland core in Wildcat Marsh. Photograph by Bryan Bemis.

edge of the Bay was chosen from each segment, with an eye towards selecting areas that were continuously wetlands, never isolated from the Bay by dams or levees. An additional wetland site was chosen along the banks of Alviso Slough in the Guadalupe River watershed, downstream of the New Almaden Mercury Mining District. Although the Alviso site was still within the tidal influence of the Bay and thus would include some mixed sediments from Lower South Bay, it was hoped that its closer proximity to historic mines would result in a mercury signal more directly linked to mining activities in the watershed. Wetland sites (FIGURE 1) were sampled in November and December 2006.

Given the large number of samples that would result if we were to analyze all sections in all the cores collected. in order to use project funds more cost-effectively we elected to examine a period of around 150 years (from the Gold Rush in the 1850s to the present), analyzing 10 sections per core to obtain approximately decadal resolution.

### Cleaning Up Our Act

Cores taken from wetlands all around the Bay reveal that newly deposited sediments are for the most part cleaner than those deposited around 30 years ago. FIGURE 2 shows copper concentrations in wetland cores taken around the Bay. The highest concentrations were generally found below the surface in wetland sediments, at depths between 10 to 40 cm, with exception of the core from Damon Slough (Central Bay), which had similarly high copper concentrations occurring right near the surface and at 20 cm depth.

For wetland sites in Suisun, San Pablo, and Central Bay, the sediments with the maximum copper concentrations generally corresponded to a period after the 1960s, based on cesium-137 and lead-210 radiodating (Sidebar, page 81). Point Edith (Suisun Bay) and Wildcat Marsh wetland (San Pablo Bay) showed maximum concentrations for copper in intervals corresponding to 1960 or slightly after. Although copper concentrations were highest near the surface for Damon Slough, concentrations remained nearly the same down to the 1960s layer.

South and Lower South Bay wetland cores showed similar general profiles, despite overall higher sediment accumulation rates due to land subsidence in the area. At Greco Island and Coyote Creek, the maximum copper concentration was found slightly above the 1960s layers, while at Alviso, there was no strong peak, but copper concentrations were above background to depths near the 1960s layer.

## How to Ask a Core Its Age

Beyond just capturing inventories of buried pollutants, cores can tell us approximately when their sediments were deposited. Along with the toxic pollutants of concern, various natural and anthropogenic substances find their way into the deposited sediment layers and serve as milestone markers of the past. For example, carbon-14 (\(^{14}\)C) is a radioactive tracer commonly used for determining the age of very old materials such as fossils. \(^{14}\)C is generated in the atmosphere, so its radioactivity is highest in newly formed material and decays over time with a half-life of 5,280 years. By comparing \(^{14}\)C radioactivity to the expected activity in new material, the age of a sample can be estimated. Given its long half life, the change in \(^{14}\)C radioactivity after 200 years is too small to measure accurately.

For radiodating on the time scale of a century, one of the most commonly used markers is lead-210 ( $^{210}$ Pb), a radioactive decay product of radon, a radioactive gas which itself comes from the radioactive decay of traces of uranium naturally present in many soils. Uranium has a half life of 4.6 billion years, so radon and  $^{210}$ Pb are generated within soils at a very slow but essentially constant rate.  $^{210}$ Pb has a half-life of 22.3 years, so within a century or so, its radioactivity in soil drops to near constant background levels, where the new  $^{210}$ Pb generated from uranium within the soil is exactly balanced by  $^{210}$ Pb losses via radioactive decay.

In enclosed areas such as poorly ventilated basements the amount of radon naturally generated from soils can build up and pose a health risk to residents, but in most areas much of the radon escapes from surface soils into the atmosphere and supplies <sup>210</sup>Pb to surface soils and sediments in "excess" of the background quantity generated from uranium within the soil; newly deposited sediment therefore has the highest excess <sup>210</sup>Pb. As the sediment gets buried deeper, it gets isolated from any new supply from the atmosphere; the excess <sup>210</sup>Pb originally from the atmosphere is lost through radio-

active decay, and <sup>210</sup>Pb returns to the constant background level continually maintained by uranium within the soil. By comparing the excess <sup>210</sup>Pb in any given sediment layer to the maximum amount at the surface and at background levels deep in the sediment, we can estimate how old the layer is. All other factors being equal, a 20 year old sediment layer will have half the excess <sup>210</sup>Pb of that found at the surface, as the other half will have been lost through radioactive decay.

Cesium-137 (137Cs) is another radioactive isotope frequently used in determining the age of sediments on decadal time scales. Unlike 210Pb, 137Cs is mostly not naturally formed, occurring only through nuclear fission reactions such as those in nuclear reactors and in atomic bombs. Releases peaked during the 1950s and early 1960s, coinciding with the period of maximum atmospheric tests of nuclear weapons. Atmospheric 137Cs releases have decreased greatly since the signing of the Partial Test Ban Treaty in 1963, although there have been some tests by non-signatory nations and releases in accidents such as Chernobyl. Since there were no significant fission releases prior to World War II, presence of 137Cs in a sediment layer indicates an origin around 1950 or later.

Other signals can also serve as historical markers. Natural or man-made catastrophes such as volcanic eruptions and large fires can release and leave ash particles as traces of their occurrence. Introduced invasive plant or animal species can also be used as markers; the presence of non-native pollens in sediments can be traced to the time of their first introduction by new settlers. Such markers can be especially useful for dating sediments too new to be accurately dated by <sup>14</sup>C, but older than 100 years, after which <sup>210</sup>Pb signals approach background levels and become difficult to measure reliably. Such techniques have not been used to date on cores collected for this study, although they have been used in studies from other locations in the Estuary.



Wetland cores from Wildcat Marsh. Photograph by Bryan Bemis.

These results, with the highest copper concentrations only a few decades ago, are in line with the Bay cores previously reported by USGS from two sites where sediments had been depositing, and are also consistent with long-term annual surface sediment and clam monitoring (FIGURES 3 and 4) conducted in the mudflats around the Palo Alto Water Pollution Control Plant (Hornberger et al. 1999). Concentrations of copper in surface sediment and clams residing in those sediments increased with population growth and urbanization of the Bay Area after World War II, reaching a maximum around 1980. Loads of metals such as copper entering the Bay via wastewater have dropped tremendously due to efforts to reduce sources as well as improveThe highest mercury concentrations generally were found at depths deposited around or slightly before 1960, suggesting a period of maximum mercury loading to all segments of the Bay after World War II

ments in treatment technology implemented in the 1970s and 1980s (FIGURE 5). The reduced copper concentrations with time in the USGS sampling at Palo Alto and near the surface in core profiles from most of our sampled wetland sites demonstrates the response and benefits to the ecosystem of management actions to reduce pollutant loads.

### Mercury: Not-So-Quicksilver?

Although Mercury was the speediest of the Roman gods, mercury in the environment may sometimes take its time to move. Mercury concentrations in wetland core sediments were especially high in surprisingly recent layers, arriving over a century after the widespread and poorly controlled use of mercury in the Sierra Nevada during the Gold Rush and the peak of mercury production in the mines of New Almaden and other mining districts in the Coast Range. Similar to the copper results, the highest mercury concentrations generally were found at depths deposited around or slightly before 1960, suggesting a period of maximum mercury loading to all segments of the Bay after World War II (FIGURE 6).

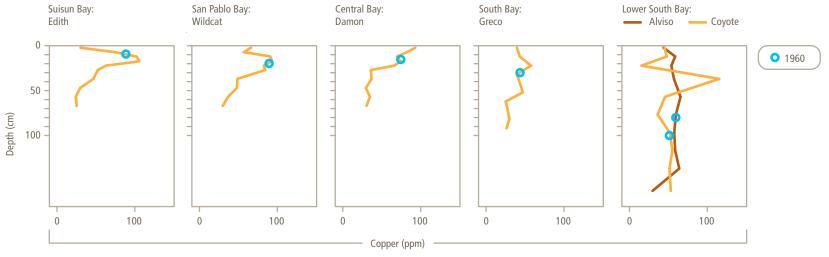
Although the Alviso Slough wetland site is in the Guadalupe River watershed, where the New Almaden Quicksilver Mine was located, maximum mercury concentrations in that core were lower than those from Damon Slough and Coyote Creek. For the Lower South Bay wetland sites, the earliest period of gold and mercury mining may not have been entirely captured in the cores. Extensive groundwater drawdown in Lower South Bay for agriculture and other uses during the 1900s caused the area around Coyote Creek and Alviso Slough





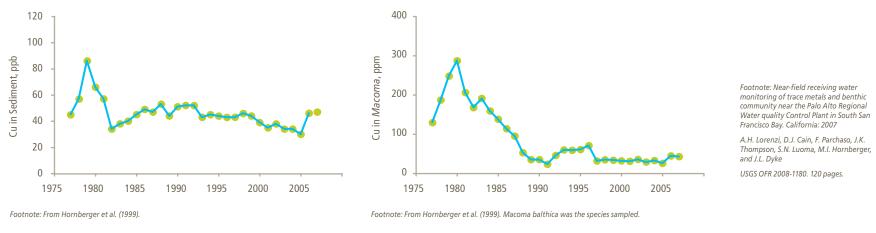


Collection of Bay sediment cores. Photographs by Bryan Bemis.



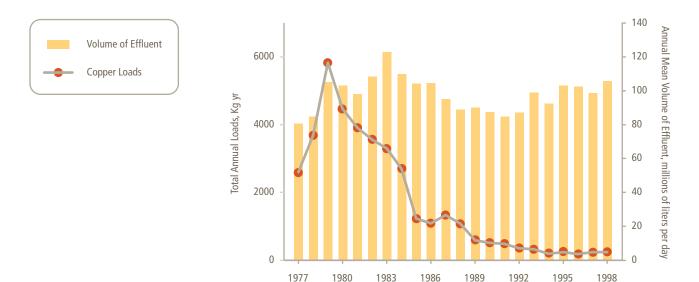
#### ↑ FIGURE 2

Cores taken from wetlands all around the Bay reveal that newly deposited sediments are for the most part cleaner than those deposited around 30 years ago. The highest copper concentrations were generally found below the surface in wetland sediments, at depths between 10 to 40 cm. For wetland sites in Suisun, San Pablo, and Central bays, the maximum copper concentrations generally corresponded to a period after the 1960s. South and Lower South Bay wetland cores showed similar general profiles, despite overall higher sediment accumulation rates due to land subsidence in the area.



#### ↑ FIGURE 3 and FIGURE 4

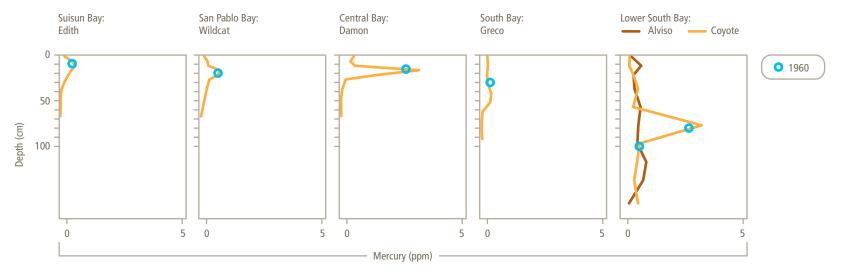
Long-term annual surface sediment (FIGURE 3) and clam (FIGURE 4) monitoring conducted in the mudflats near the Palo Alto Water Pollution Control Plant has shown that concentrations of copper in surface sediment and clams residing in those sediments increased with population growth and urbanization of the Bay Area after World War II, reaching a maximum around 1980. Loads of metals such as copper entering the Bay via wastewater dropped tremendously after 1980 due to efforts to reduce sources as well as improvements in treatment technology implemented in the 1970s and 1980s. The reduced copper concentrations documented by USGS and in RMP wetland coring demonstrate the benefits to the ecosystem of management actions to reduce pollutant loads.



#### ← FIGURE 5

Improved treatment technology and source reduction efforts by the City of Palo Alto resulted in sharp decreases in copper loads from their treatment plant, in spite of constant volumes of wastewater flow.

Footnote: From Hornberger et al. (1999). Annual average effluent volume (million Llday) from the Palo Alto Regional Water Quality Control Plant and total annual copper loads (kglyr). Treatment improvements were implemented as follows: a) trickle filters and nitrification processes – 1980; b) increased retention time and clarifiers – 1989; and c) specific source controls – 1990.



#### ↑ FIGURE 6

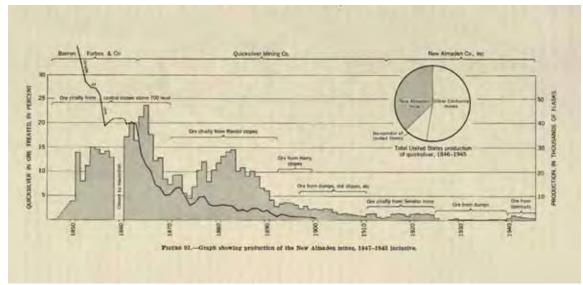
Mercury concentrations in wetland core sediments were especially high in surprisingly recent layers, arriving over a century after the widespread and poorly controlled use of mercury in the Sierra Nevada during the Gold Rush and the peak of mercury production in the mines of New Almaden and other mining districts in the Coast Range. Similar to the copper results, the highest mercury concentrations generally were found at depths deposited around or slightly before 1960, suggesting a period of maximum mercury loading to all segments of the Bay after World War II.

to subside, around one meter just in the period 1920-1960. Cores from both sites were collected and analyzed to a depth of just over 160 cm, so a large portion of the overall length for both cores is of recent origin. A core collected in 2000 from Triangle Marsh near the Coyote Creek site (Conaway et al. 2004) showed a maximum in mercury at a similar depth (65 cm), deposited between layers from World War II and 1983. In the Triangle Marsh core, mercury concentrations decreased back to background concentrations (around 0.1 ppm) in pre-Gold Rush era sediments at 160 cm depth, concentrations similar to those in the deepest sections from other locations in this study. Mercury concentrations above this regional background concentration in the deepest sections of the current Alviso and Coyote Creek cores suggest that they capture a period starting after the onset of mining in the New Almaden Mining District in the mid-1800s.

FIGURE 7 shows the production volumes of the New Almaden Mine from 1847-1945 (Bailey and Everhart 1964). Maximum production occurred in the late 1800s, long before the peak in sediment concentrations found in the wetland cores in the current and Conaway et al. (2004) studies. This may in part be due to a long lag time for transport of contaminated sediments from the upper watershed (where the mines were located) to the edge of the Bay. Previous work (Hornberger et al. 1999) has suggested that spatial trends in peak mercury concentrations and sediment inventories in these watersheds indicate historic sources (the mines). However, the highest mercury concentration for the Damon Slough site in Central Bay was similar to the highest concentration in Lower South Bay, despite being the location most distant from likely large sources from either mercury mining in the South Bay or gold mining in the Sierra Nevada. This would therefore suggest a local dominantly urban (Oakland) source for

mercury contamination in Central Bay, as there was little documented mercury mining in the watershed, yet maximum concentrations were similar to those for wetlands downstream of North America's largest mercury mines.

Based on high concentrations of mercury in areas of the Guadalupe River watershed, delayed transport of mercury from mining might still be the primary source of the peak in mercury found in wetland areas of Lower South Bay. However, with a large peak also seen in an Oakland location distant from mining, and given urbanization of much of the Bay area, local industrial urban sources may also explain a large portion of the post-World War II maximum in mercury loading, even for mercury-mining impacted areas in South and Lower South Bay. Given both plausible mining and urban sources, it may be difficult to resolve the relative contributions of various sources until specific markers for each source type



Footnote: Production of the New Almaden mines, 1847-1945 (Bailev and Everhart 1964).

#### FIGURE 7

Maximum production of the New Almaden mines occurred in the late 1800s, long before the peak in sediment concentrations found in the wetland cores in the current and Conaway et al. (2004) studies. This may in part be due to a long lag time for transport of contaminated sediments from the upper watershed (where the mines were located) to the edge of the Bay. However, with a large peak also seen in an Oakland location distant from mining, and given urbanization of much of the Bay area, local industrial urban sources may also explain a large portion of the post-World War II maximum in mercury loading, even for mercury-mining impacted areas in South and Lower South Bay.

# Stopping an ounce of pollutant release can save many pounds or even tons of sediment cleanup later

are developed. A study funded by the RMP is currently measuring mercury isotopes in an attempt to distinguish among various possible sources, information which may allow us to better identify effective management options.

# Where Have All the Time Bombs Gone?

One major impetus for this study was a concern that pollutants in subsurface sediments represented a major reservoir or "time bomb" of contamination that would threaten to thwart current cleanup efforts if areas of the Bay eroded. The wetland cores, many with mercury and copper concentration peaks in the post-World War II period, indicate that areas that have been primarily depositional in the past few decades would collect such sediments. However, when we examined sediment cores from open water areas of the Bay for similar highly contaminated layers, such peaks were absent or less prominent.

FIGURE 8 shows concentrations of copper in cores collected from various Bay segments. Concentrations throughout the core profiles were generally similar to average concentrations at the surface for each segment. Although peak copper concentrations in wetland cores were up to ten times higher than those at the surface, the maximum concentrations in most cores from Bay open waters were within about 30% of current surface concentrations. Mercury profiles (FIGURE 9) are similarly mixed through most of the

core, with fairly uniform concentrations similar to those currently at the surface and the deepest sections near pre-Gold Rush levels.

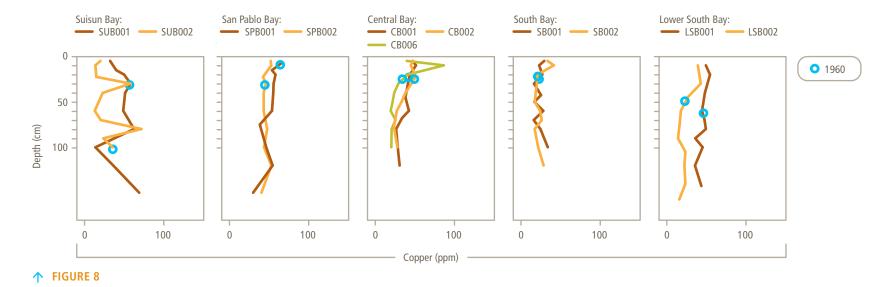
Bay cores are likely to show more uniform concentrations than those in wetlands due to a number of factors. There is a greater potential for resuspension and mixing of surface sediments in open waters. Sediments deposited during periods with higher concentrations mix with sediment layers from less contaminated periods deposited earlier and later. In contrast, although currents and waves can still move and mix wetland sediments, wetland plants retard sediment transport, much like sand dune plants reduce erosion on land. In addition to inhibiting the vertical mixing of sediments, wetland vegetation helps to reduce lateral transport of sediments over long distances, so pollutant loads from adjacent tributaries and point sources tend to remain nearby. In contrast, sediments deposited within the open Bay are more easily transported, dispersed further and wider with years of subsequent tides and waves. Some of these sediments are ultimately carried out to the ocean by currents.

Despite potential transport and mixing, there are still layers of highly contaminated sediments buried in some parts of the Bay. Studies of sediments around contaminated sites such as Hunter's Point, Lauritzen Canal in Richmond Harbor, and other locations demonstrate the persistence of contaminated sediments even without extensive vegetation retarding transport. Detailed data from two more cores per Bay segment,

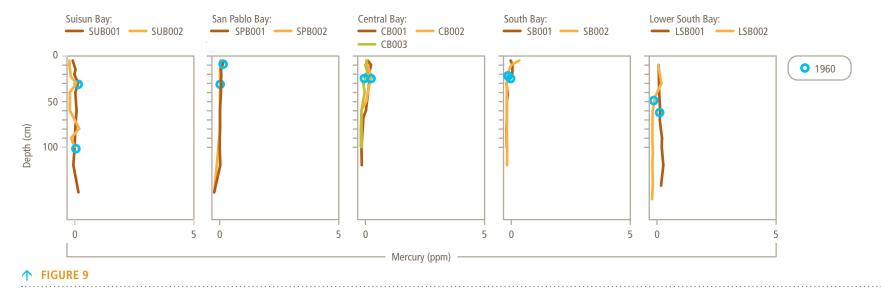
although a substantial improvement over the previous state of knowledge, still may not be fully representative of the Bay in general. From the limited additional data generated in this study, however, it appears that layers with highly elevated concentrations of metals are not found in the majority of locations, so for the most part, even if many areas of the Bay experience erosion in the coming decades, there are likely few nasty, concentrated reminders of our past to be unearthed.

#### Lessons for the Future

The history of contamination in San Francisco Bay, as told by cores, teaches us a few lessons. First, cleaner living does have its benefits. Contaminants in wetland surface sediments are generally much lower than those from just a few decades back, a reward for extensive and expensive efforts to improve wastewater treatment and reduce pollutant loads as a result of the Clean Water Act. The second is a case of good news and bad news: the good news is that there are relatively few hidden "time bombs" of contamination waiting to surprise us, but the bad news is that it appears to be because they have mostly already detonated and spread throughout the Bay. The latter reminds us of the last, but perhaps most important lesson; it is far better to stop the pollutant bombs of the future, intercepting them at or near their sources, rather than to trying clean them up after the fact, or having to wait decades until they disperse or degrade to levels that are no longer harmful. To repeat an old idiom that is near literally applicable: "an ounce of prevention is worth a pound of cure." Stopping an ounce of pollutant release can save many pounds or even tons of sediment cleanup later. Have we learned that lesson yet, or will we have to learn it all over again as we track the history of new contaminants in cores collected in the future?



Concentrations of copper throughout the profiles of cores from the open Bay were generally similar to average concentrations at the surface for each segment. Although peak copper concentrations in wetland cores were up to ten times higher than those at the surface, the maximum concentrations in most cores from Bay open waters were within about 30% of current surface concentrations. Compared to wetland sediments, there is a greater potential for resuspension and mixing of surface sediments in open waters.



Mercury profiles were similarly mixed through most of the core, with fairly uniform concentrations similar to those currently at the surface and with the deepest sections near pre-Gold Rush levels. From the limited new data generated in this study, it appears that layers with highly elevated concentrations of metals are not found in the majority of locations, so for the most part, even if many areas of the Bay experience erosion in the coming decades, there are likely few nasty, concentrated reminders of our past to be unearthed.

#### MANAGEMENT UPDATE

#### Bay

Arthur M. Barnett, Steven M. Bay, Kerry J. Ritter, Shelly L. Moore and Stephen B. Weisberg. 2008 Sediment Quality in California Bays and Estuaries. SCCWRP Technical Report # 522

Gobas FAPC, Arnot J. 2005. San Francisco Bay PCB food-web bioaccumulation model, Simon Fraser University, Vancouver, BC.

Melwani A and Thompson B. 2007. The Influence of Chemical and Physical Factors on Macrobenthos in the San Francisco Estuary

Phillips et al. 2008. RMP Sediment TIE Study 2007-2008: Using Toxicity Identification Evaluation (TIE) Methods to Investigate Causes of Sediment Toxicity to Amphipods. SFEI Contribution # 561

Thompson B and Lowe S. 2008. Sediment Quality Assessments in the San Francisco Estuary. SFEI Contribution # 574.

#### STATUS AND TRENDS **UPDATE**

#### **Water Quality Trends** at a Glance

Fairey, R., K. Taberski, S. Lamerdin, E. Johnson, R.P. Clark, J.W. Downing, J. Newman and M. Petreas. 1997. Organochlorines and other environmental contaminants in muscle tissues of sportfish collected from San Francisco Bay. Marine Pollution Bulletin 34(12): 1058-1071.

#### FEATURE ARTICLES

#### Schoellhamer

Baskerville-Bridges, B., Lindberg, J.C., and Doroshov, S.I., 2004, The effect of light intensity, alga concentration, and prey density on the feeding behavior of Delta Smelt larvae: American Fisheries Society Symposium, v. 39, p. 219-227.

Cappiella, K., Malzone, C., Smith, R., Jaffe, B., 1999, Sedimentation and bathymetry changes in Suisun Bay, 1867-1990: U.S. Geological Survey Open-File Report 99-563. http://pubs.er.usgs. gov/usgspubs/ofr/ofr99563

Cloern, J.E., 1987, Turbidity as a control on phytoplankton biomass and productivity in estuaries: Continental Shelf Research, v. 7, no. 11/12, p. 1367-1381.

Cloern, J.E., Jassby, A.D., Schraga, T.S., and Dallas, K.L., 2006, What is causing the phytoplankton increase in San Francisco Bay?: The Pulse of the Estuary: Monitoring and Managing Water Quality in the San Francisco Estuary, San Francisco Estuary Institute, Oakland, California, p. 62-70. http://www.sfei.org/rmp/ pulse/2006/index.html

Cloern, J.E., Schraga, T.S., Lopez, C.B., and Labiosa, R., 2003, Lessons from monitoring water quality in San Francisco Bay: The Pulse of the Estuary: Monitoring & Managing Contamiination in the San Francisco Estuary, San Francisco Estuary Institute, Oakland, California, p. 15-20. http://www.sfei.org/rmp/pulse/pulse2003.pdf Jaffe, B.E., Smith, R.E., Torresan, L.Z., 1998,

Feyrer, F., Nobriga, M.L., and Sommer, T.R., 2007, Multidecadal trends for three declining fish species: habitat patterns, and mechanisms in the San Francisco Estuary, California, USA: Canadian Journal of Fisheries and Aquatic Sciences, v. 64, p. 723-734.

Florsheim, J., Mount, J.F., and Chin, A., 2008, Bank erosion as a desirable attribute of rivers: Bioscience, v. 58, no. 6, p. 519-529.

Fregoso, T.A., Foxgrover, A.C., and Jaffe, B.E., 2008 Sediment deposition, erosion, and bathymetric change in central San Francisco Bay: 1855-1979: U.S. Geological Survey Open-File Report 2008-1312, 41 p. http://pubs.usgs.gov/of/2008/1312/ Ganju, N.K., and Schoellhamer, D.H., 2006, Annual sediment flux estimates in a tidal strait using surrogate measurements: Estuarine, Coastal and Shelf Science, v. 69, p. 165-178.

Ganju, N.K., Schoellhamer, D.H., and Jaffe, B.E., submitted, Simulation of decadal-timescale estuarine bathymetric change with a tidal-timescale model: application to historical change and future scenarios: Journal of Geophysical Research, Earth Surface.

Gilbert, G.K., 1917, Hydraulic mining debris in the Sierra Nevada: U.S.Geological Survey Professional Paper 105.

Sedimentation and bathymetric change in San Pablo Bay, 1856-1983: U.S. Geological Survey Open-File Report 98-759. http://pubs.er.usgs. gov/usgspubs/ofr/ofr98759

Krone, R.B., 1979, Sedimentation in the San Francisco Bay system: In T.J.Conomos (ed.), San Francisco Bay, The Urbanized Estuary, Pacific Division of the American Association for the Advancement of Science, San Francisco, California, pp. 347-385.

Krone, R.B., and Hu, G., 2001, Restoration of subsided sites and calculation of historic marsh elevations: Journal of Coastal Research, special issue 27, p. 162-169.

McKee, L.J., Ganju, N.K., Schoellhamer, D.H., 2006, Estimates of suspended sediment flux entering San Francisco Bay from the Sacramento and San Joaquin Delta, San Francisco Bay, California: Journal of Hydrology, v. 323, p. 335-352.

Nobriga, M.L., Feyer, F., Baxter, R.D., and Chotkowski, M., 2005, Fish community ecology in an altered river delta: Spatial patterns in species composition, life history strategies, and biomass: Estuaries, v. 28, no. 5, p. 776-785.

Ogden Beeman & Associates, Inc., 1992, Sediment budget study for San Francisco Bay: Report prepared for the San Francisco District, U.S. Army Corps of Engineers.

Petts, G.E., and Gurnell, A.M., 2005, Dams and geomorphology: Research progress and future directions: Geomorphology, v. 71, p. 27-47.

Porterfield, G., 1980, Sediment transport of streams tributary to San Francisco, San Pablo, and Suisun Bays, California, 1909-1966: U.S. Geological Survey Water-Resources Investigations Report 80-64, 91 p.

Schoellhamer, D.H., 2002, Variability of suspended sediment concentration at tidal to annual time scales in San Francisco Bay, USA: Continental Shelf Research, v. 22, p. 1857-1866.



Schoellhamer, D.H., Lionberger, M.A., Jaffe, B.E., Ganju, N.K., Wright, S.A., and Shelenbarger, G.G., 2005, Bay Sediment Budgets: Sediment Accounting 101: The Pulse of the Estuary: Monitoring and Managing Water Quality in the San Francisco Estuary, San Francisco Estuary Institute, Oakland, California, p. 58-63. URL http://www.sfei.org/rmp/pulse/2005/RMP05\_PulseoftheEstuary.pdf

Schoellhamer, D.H., Mumley, T.E., and Leatherbarrow, J.E., 2007, Suspended sediment and sediment-associated contaminants in San Francisco Bay: Environmental Research, v. 105, p. 119-131.

Schoellhamer, D.H., Shellenbarger, G.G., Ganju, N.K., Davis, J.A., and McKee, L.J., 2003, Sediment dynamics drive contaminant dynamics: The Pulse of the Estuary: Monitoring and Managing Contamination in the San Francisco Estuary, San Francisco Estuary Institute, Oakland, California, p. 21-26.

Singer, M.B., Aalto, R., and James, L.A., 2008, Status of the lower Sacramento Valley flood-control system within the context of its natural geomorphic setting: natural Hazards Review, v. 9, no. 3, p. 104-115.

Sommer, T. Armor, C., Baxter, R., Breuer, R., Brown, L., Chotkowski, M., Culberson, S., Feyrer, F., Gingras, M., Herbold, B., Kimmerer, W., Mueller-Solger, A., Nobriga, M., and Souza, K., 2007, The collapse of pelagic fishes in the upper San Francisco estuary: Fisheries, v. 32, no. 6, p. 270-277.

Wright, S.A., and Schoellhamer, D.H., 2004, Trends in the Sediment Yield of the Sacramento River, California, 1957 – 2001: San Francisco Estuary and Watershed Science. v. 2, no. 2, article 2. http://repositories.cdlib. org/jmie/sfews/vol2/iss2/art2

#### Jaffe

Bearman, J., 2008, Factors controlling tidal flat morphology in South San Francisco Bay between the 1890s and 2005, Masters Thesis, Virginia Institute of Marine Science, Gloucester, VA, 93 pp.

Cappiella, K, Malzone, C, Smith, R. E., and Jaffe, B.E., 1999, Sedimentation and bathymetry changes in Suisun Bay, 1867-1990: U.S. Geological Survey Open-File Report 99-563 [URL: http://geopubs.wr.usgs.gov/open-file/of99-563/].

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].

Fregoso, T.A., Foxgrover, A.C., and Jaffe, B.E., 2008, Sediment deposition, erosion, and bathymetric change in Central San Francisco Bay: 1855-1979: U.S. Geological Survey Open-File Report 2008-1312, 41 p. [URL: http://pubs.usgs.gov/of/2008/1312]

Ganju, N.K. and Schoellhamer, D.H., 2009, Calibration of an estuarine sediment transport model to sediment fluxes as an intermediate step for simulation of geomorphic evolution, Continental Shelf Research 29, 149-158.

Ganju, N.K., et al. 2008, CASCaDE hindcast of bathymetric change in Suisun Bay, 1867-1990: model uncertainty and parameter selection, CALFED Science Conference, p. 206.

Higgins, S.A., Jaffe, B.E., and Fuller, C.C., 2007, Reconstructing sediment age profiles from historical bathymetry changes in San Pablo Bay, California, Estuarine Coastal and Shelf Science, doi:10.1016/j.ecss.2006.12.018

Higgins, S.A., Jaffe, B.E., and Smith, R.E., 2005, Bathychronology: Reconstructing historical sedimentation from bathymetric data in a GIS, U.S. Geological Survey Open-File Report OFR-2005-1284, 19 p. plus appendix [URL: http://pubs.usgs.gov/of/2005/1273/].

Hornberger, M.I., Luoma, S.N., van Geen, A., Fuller, C., Anima, R., 1999, Historical tends of metals in sediments of San Francisco Bay, California, Marine Chemistry, 64 (1-2), 39-55. Jaffe, B.E., Smith, R.E., and Foxgrover, A.C., 2007, Anthropogenic influence on sedimentation and intertidal mudflat change in San Pablo Bay, California: 1856 to 1893. Estuarine, Coastal and Shelf Science 73 (1-2), 175-187, doi:10.1016/j.ecss.2007.02.17.

Schoellhamer, D.H., Lionberger, M.A., Jaffe, B.E., Ganju, N.K., Scott, S.A., and Shellenbarger, G.G., 2005, Bay Sediment Budget: Sediment Accounting 101, in San Francisco Estuary Institute (SFEI), 2005, The Pulse of the Estuary: Monitoring and Managing Water Quality in the San Francisco Estuary. SFEI Contribution 78. San Francisco Estuary Institute, Oakland, CA., p. 58-63.

van der Wegen, M., Roelvink, D., Jaffe, B.E., Ganju, N., Schoellhamer, D., 2008, CAS-CaDE research on hindcasting bathymetric change in San Pablo Bay, 1856-1983: A step towards assessing likely geomorphic change in response to climate change (abs.) Fifth Biennial CALFED Science Conference, p. 207.

Wright S.A., Schoellhamer D.H., 2004. Trends in the sediment yield of the Sacramento River, California, 1957-2001. San Francisco Estuary and Watershed Science [online serial]. Vol. 2, Issue 2 (May 2004), Article 2. http://repositories.cdlib.org/jmie/sfews/vol2/iss2/art2.

#### Yee

Bailey, E. H. and D. L. Everhart (1964). Geology and Quicksilver Deposits of the New Almaden District Santa Clara County California. Washington, D.C., U.S. Geological Survey, prepared in cooperation with the California Dept. of Natural Resources, Division of Mines: 206.

Conaway, C. H., E. B. Watson, et al. (2004). "Mercury deposition in a tidal marsh of south San Francisco Bay downstream of the historic New Almaden mining district, California." Marine Chemistry 90: 175-184.

Hornberger, M. I., S. N. Luoma, et al. (1999). "Historical trends of metals in the sediments of San Francisco Bay, California." Marine Chemistry 64(1): 39-55.

↑ South Bay mudflats. Photograph by Mami Odaya.

### $\rightarrow$

### RMP COMMITTEE MEMBERS AND PARTICIPANTS

# RMP COMMITTEE MEMBERS

#### **RMP Steering Committee**

Small POTWs, Ken Kaufman, South Bayside System Authority

Medium-sized POTWs, Daniel Tafolla, Vallejo Sanitation and Flood Control District

Large POTWs/BACWA, Dave Tucker, City of San Jose

#### Refineries, Kevin Buchan, Western States Petroleum Association

Industry, Dave Allen, USS-POSCO

Cooling Water, Steve Bauman, Mirant Delta LLC

Stormwater Agencies, Adam Olivieri, EOA, Inc.

Dredgers, Ellen Johnck, Bay Planning Coalition

San Francisco Bay Regional Water Quality Control Board, Tom Mumley

#### RMP Steering Committee Chair in bold print

# RMP Technical Review Committee

POTWs/BACWA, Francois Rodigari, East Bay Municipal Utility District; Rod Miller, San Francisco Public Utilities Commission

South Bay Dischargers, Tom Hall, EOA Inc.

### Refineries, Bridgette DeShields, ARCADIS BBL

Industry, Dave Allen, USS-POSCO

Stormwater Agencies, Chris Sommers, EOA, Inc.

Dredgers, John Prall, Port of Oakland

San Francisco Bay Regional Water Quality Control Board, Karen Taberski U.S. EPA, Luisa Valiela

City of San Jose, Eric Dunlavey

City/County of San Francisco, Michael Kellogg

U.S. Army Corps of Engineers, Robert Lawrence

RMP Technical Review Committee Chair in bold print

#### RMP SCIENCE ADVISORS

# Contaminant Fate Workgroup

Dr. Joel Baker, University of Washington - Tacoma

Dr. Frank Gobas, Simon Fraser University

Dr. Rob Mason, University of Connecticut

Dr. Keith Stolzenbach, University of California – Los Angeles

# **Emerging Contaminants Workgroup**

Dr. Lee Ferguson, Duke University

Dr. Jennifer Field, Oregon State University

Dr. Derek Muir, Environment Canada

Dr. David Sedlak, University of California - Berkeley

# **Exposure and Effects Workgroup**

Dr. Michael Fry, American Bird Conservancy

Dr. Harry Ohlendorf, CH2M Hill

Dr. Daniel Schlenk, University of California – Riverside

Dr. Steve Weisberg, Southern California Coastal Water Research Project Dr. Don Weston, University of California – Berkeley

# Sources Pathways and Loading Workgroup

Dr. Barbara Mahler, US Geologic Survey

Dr. Eric Stein, Southern California Coastal Water Research Project

Dr. Mike Stenstrom, University of California – Los Angeles

#### **RMP PARTICIPANTS**

#### **Municipal Dischargers**

Burlingame Waste Water Treatment Plant

Central Contra Costa Sanitary District

Central Marin Sanitation Agency

City of Benicia

City of Calistoga

City of Palo Alto

City of Petaluma

City of Pinole/Hercules

City of Saint Helena

City and County of San Francisco

City of San Jose/Santa Clara

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

Marin County Sanitary District #5, Tiburon Millbrae Waste Water Treatment Plant

Mountain View Sanitary District

Napa Sanitation District

Novato Sanitation District

Rodeo Sanitary District

San Francisco International Airport

Sausalito/Marin City Sanitation District

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

Conoco Phillips (Tosco-Rodeo)

Crockett Cogeneration

Dow Chemical Company

Rhodia, Inc.

Shell - Martinez Refining Company

Tesoro Golden Eagle Refinery

USS - POSCO Industries

Valero Refining Company

#### Cooling Water

Mirant of California Pittsburg Power Plant

Mirant of California Potrero Power Plant

#### Stormwater

Alameda Countywide Clean Water Program

Caltrans

City and County of San Francisco

Contra Costa Clean Water Program

Fairfield-Suisun Urban Runoff Management Program

Marin County Stormwater Pollution Prevention Program

San Mateo Countywide Stormwater Pollution Prevention Program

Santa Clara Valley Urban Runoff Pollution Prevention Program

Vallejo Sanitation and Flood Control District

#### **Dredgers**

Aeolian Yacht Club

**BAE Systems** 

Belvedere Cove

Chevron Richmond Long Wharf

City of Benicia

Clipper Yacht Harbor

Conoco Phillips (Tosco-Rodeo)

Larkspur Ferry

Marina Vista Homeowners

Association

Marin Rowing Association

Marin Yacht Club

Oyster Point Marina

Paradise Cay Yacht Club

Point San Pablo Yacht Harbor

Port of Oakland

Port of San Francisco

Richmond Yacht Club

San Rafael Yacht Harbor

Strawberry Channel

U.S. Army Corps of Engineers

Valero Refining Co.

### $\rightarrow$

### **CREDITS AND ACKNOWLEDGMENTS**

#### **Editors**

Jay Davis, Christine Werme, Meg Sedlak

#### Art Direction and Design Linda Wanczyk

#### **Contributing Authors**

Jay Davis, Meg Sedlak, John Oram, Richard Looker

#### **Information Compilation**

Katie Harrold, Jennifer Hunt, Lester McKee, John Ross, Michelle Lent

#### RMP Data Management

Sarah Lowe, Cristina Grosso, John Ross, Amy Franz, Parvaneh Abbaspour, Don Yee

#### **Mapping and Graphics**

John Oram, Michelle Lent, Mami Odaya, Shira Bezalel

#### **Information Graphics**

Linda Wanczyk, Joanne Cabling

#### **Printing**

Alonzo Printing www.alonzoprinting.com

#### The Paper

Reincarnation<sup>™</sup> is the most environmentally friendly matte coated paper stock available and is made from 100% recycled content, 50% Post-Consumer Waste, and processed entirely without chlorine.

#### The Ink

Soy-based ink is helpful in paper recycling because it can be removed more easily during the de-inking process, resulting in recycled paper with less damage to its paper fibers and a brighter appearance. The waste that is left from the de-inking process is not hazardous.

# Image and Information Gathering

Theresa Fregoso
Beth Christian
Ed Keller
Terry Hammerworld
Shelah Sweatt
Michelle Briscoe
Mike Connor
Aroon Melwani
Sarah Lowe
Karen Taberski
Bryn Phillips
Michele Jacobi

The following reviewers greatly improved this document by providing comments on draft versions:

#### Reviewers

Nicole David Karen Taberski Ben Greenfield Lisa Owens Viani Beth Christian Susan Klosterhaus Michelle Jacobi Tom Hall

RIGHT 
Sediment coring in Suisun Bay.
Courtesy of NOAA's Office
of Response and Restoration.

NEXT PAGE 
San Francisco Bay Bridge.
Photograph by Linda Wanczyk.





# **RMP**

Regional Monitoring Program for Water Quality in the San Francisco Estuary

A program of the San Francisco Estuary Institute 7770 Pardee Lane, 2nd Flr, Oakland, CA 94621 p: 510-746-SFEI (7334), f: 510-746-7300 www.sfei.org

For a PDF of the Pulse, please go to www.sfei.org/rmp/pulse



