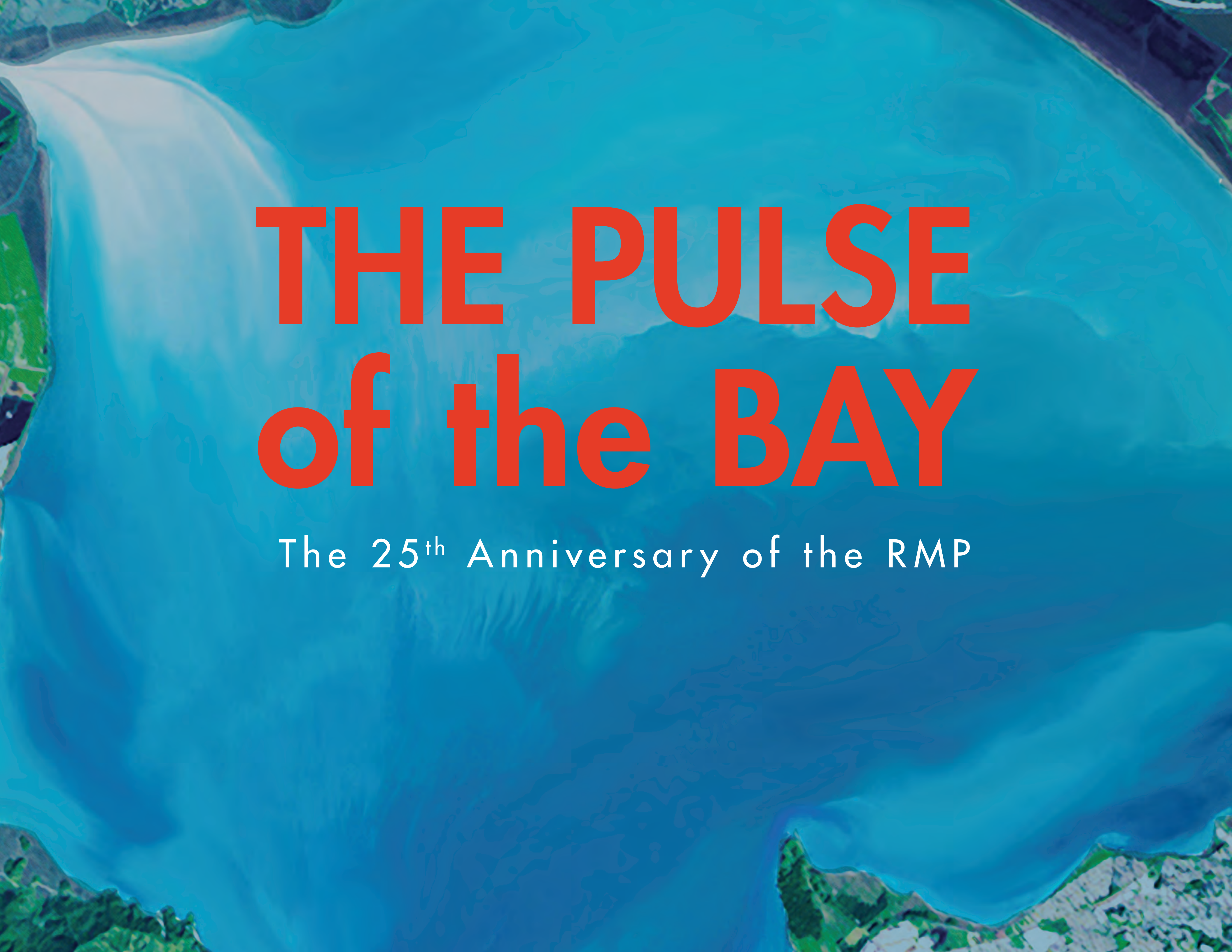

THE PULSE of the BAY

The 25th Anniversary of the RMP

COVER IMAGE:
Landsat-8 satellite source image captured on March 5, 2015.
Obtained from https://www.scientificcomputing.com/news/2015/06/satellite-view-san-francisco-bay-area
Website for Landsat-8 imagery: https://landsat.usgs.gov/landsat-8

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2017

THE PULSE of the BAY

The 25th Anniversary of the RMP

A REPORT OF
THE REGIONAL MONITORING PROGRAM
FOR WATER QUALITY IN SAN FRANCISCO BAY

OVERVIEW

San Francisco Bay is the defining feature of our region and a world-class ecosystem. The Bay Area is also known world-wide as a cradle of innovation, excellence, and success, especially in the technology sector. Less well known is the fact that over the past 25 years the Bay Area has been a world leader in water quality monitoring, supporting a pioneering program for the Bay that demonstrates how regional collaboration can provide the science needed to protect and improve water quality in a treasured ecosystem. The Regional Monitoring Program for Water Quality in San Francisco Bay (RMP) was established in 1993 and, with sustained local funding and continuous improvement, is going stronger than ever a quarter century later.

This 25th anniversary edition of the Pulse includes a review of some of the major milestones in the formation and development of the RMP (page 8). The review highlights the characteristics of the Program that have allowed it to continue to flourish over this long span.

These key ingredients to successful long-term monitoring include:

- **sustained financial support**;
- **sound science** supported by rigorous peer review of both study plans and reporting products;
- **active participation**, **collaboration**, and **partnership** on the part of regulators, dischargers, scientists, and other stakeholders;
- thoughtful and forward-looking **planning**;
- **effective communication** of the information generated; and
- **adaptation** in response to changes in the ecosystem, the regulatory framework, and advances in understanding of pollutants and the ecosystem.

The other three articles in this edition exemplify how adaptation is essential to the continued relevance and success of a long-term monitoring program. Major increases in the attention given to nutrients (page 22), emerging contaminants (page 34), and the Bay margins (page 44) have occurred in the last few years.

< The Golden Gate Bridge. Photograph by Shira Bezalel.

With regard to **nutrients**, long-term monitoring detected a steady increase in algae in the Bay from 1995 to 2005 (page 73), suggesting that the resistance of this ecosystem to high nutrient inputs could be waning, and the potential need for investment of billions of dollars to upgrade municipal wastewater treatment plants to improve nutrient removal. In response to these observations, the amount of work being done to understand nutrient dynamics in the Bay has increased tremendously. A separate, major collaborative regional monitoring effort - the Nutrient Management Strategy (NMS) - spun off of the RMP in 2012 to address this topic. The NMS is designing and beginning implementation of a comprehensive, collaborative long-term nutrient monitoring program for the Bay.

In 2017 RMP funding for **contaminants of emerging concern (CECs)** monitoring surged significantly, thanks to a redirection of wastewater monitoring funds that had previously been used for lower priority monitoring. A multi-year RMP CEC strategic plan was updated in 2017 to provide a framework for continued examination of a range of chemicals of known concern and surveillance to identify new potential threats. The ability to quickly gather information on newly identified contaminants or toxicity concerns as they arise is a recognized strength of RMP CEC monitoring. A small pilot study in 2014 to assess microplastic (page 41) in the Bay is a prime example: this study placed the Bay at the forefront of this emerging contamination issue, ultimately informed state and federal pollution prevention regulations, catalyzed formation of a RMP Microplastic Workgroup, and led to substantial foundation funding for a more thorough assessment in 2017 and 2018.

Another shift is underway in how the RMP monitors **legacy contamination**. The Program is paying increased attention to the margins of the Bay, as these areas are critical for evaluating the effectiveness of actions to reduce pollutant inputs from stormwater via green infrastructure and other load reduction measures. Understanding the margins is also becoming increasingly important as they are a focal point for nutrient impacts, habitat restoration (including dredged material re-use and use of treated wastewater), and adaptation to sea level rise.

Another highlight of this edition of the Pulse are the early indications of the effects of five years of epic drought followed by a similarly historic wet season in 2016/2017. These events underscored the importance of sustained monitoring in understanding long-term trends. Varying rainfall (page 58) had a tremendous effect on flows to the Bay, not only from rivers and streams (page 66), but also from municipal wastewater due to water conservation (page 58). The far-reaching impacts of the high flows are still unfolding, but the current water year (October 1, 2016 to September 30, 2017) will go down as one of exceptional pollutant inputs (page 66) and Bay water quality.

The success of the RMP is largely based on the active participation and contribution of time, energy, and talent by scores of people over the past 25 years. Some of these contributors are mentioned in the RMP timeline (pages 8-21), but the full group is too numerous to list in its entirety. In turn, the people directly participating in the RMP represent hundreds of other professionals working for the organizations that support the Program and have dedicated their careers to protecting Bay water quality.

Over the past 25 years, the population of the Bay Area has increased by 25% (an additional 1.5 million people). In spite of this, thanks to the vigilance of water quality managers and the careful tracking provided by the RMP, Bay water quality has gradually improved. The RMP has documented successful management of some pollutants, such as PBDE flame retardants (page 77), which fell quickly in response to bans and use reductions. Hopefully, RMP data will also show that new actions, such as the ban on plastic microbeads that goes into effect in 2018, are similarly effective.

Information from the RMP has also helped managers realize that some pollutants, such as copper (page 83), are of lower concern than they were initially thought to be, so that greater attention could be directed toward bigger problems. For the more significant and persistent problems such as mercury and PCBs, RMP information is focusing attention on the locations of greatest concern to support development of effective management strategies, and protecting public health by providing the data needed to update the Bay's fish consumption advisory. The RMP is also helping managers through an increasing emphasis on early detection and prevention of new pollutants. In addition, the RMP is helping water quality specialists throughout the nation and the world through both the rich information base available for the Bay and the development of new monitoring technologies and methods.

RMP monitoring will be crucial to ensuring that we continue to make progress in addressing existing Bay water quality problems and preventing new ones. The local organizations that fund the RMP have seen the benefits of decision-making that is based on solid information, and remain committed to providing the funds and the participation that is needed to sustain the Program. With this continued commitment, and building on lessons learned over the past 25 years, the RMP is well-poised for the future and the major changes in store for the Bay, driven by population growth; climate change; changes in water management; habitat restoration; and changes in chemical use in our homes, businesses, and across the landscape. The RMP can be expected to continue to be a model of shared regional responsibility, and an important way in which the Bay Area serves as a world leader in environmental protection. ●

Comments or questions regarding *The Pulse* can be addressed to Dr. Jay Davis, RMP Lead Scientist, (510) 746-7368, jay@sfei.org.
For PDF versions of all Pulses, go to: www.sfei.org/programs/pulse-bay

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FEATURE ARTICLES

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Website for Landsat-8 imagery: https://landsat.usgs.gov/landsat-8

The 25th Anniversary of the RMP

by Jay Davis (jay@sfei.org),
San Fancisco Estuary Institute

HIGHLIGHTS

- Stewardship of San Francisco Bay is supported by the Regional Monitoring Program, one of the best water quality monitoring programs in the world, now in its 25th year
- This article provides a chronology of major milestones in the history of the RMP that highlights the features that have allowed the Program to continue to flourish after a quarter century
- The key ingredients of a successful long-term water quality monitoring program include: sustained funding; sound science supported by thorough peer review; collaboration and partnership; thoughtful planning; effective communication of information; and adaptation in response to changes in the ecosystem, the regulatory framework, and scientific understanding
- The participants have seen the benefits of decision-making that is based on solid information, and remain committed to providing the funds to sustain the Program
- The RMP is well-poised for the future and the major changes in store for the Bay that will be driven by population growth, climate change, changes in water management, habitat restoration, and continuing efforts of water quality managers to protect this treasured ecosystem

A RMP workgroup meeting. Photograph by Jay Davis.

San Francisco Bay is the defining feature of our region, a big part of what makes the Bay Area a wonderful place to live and a world-renowned tourist destination. The Bay is also known as a world-class ecosystem. As the largest estuary on the west coast of the Americas, it provides habitat for vibrant populations of fish and wildlife that make their home in the midst of an urban area supporting seven million people. One indication of its global ecological significance is its recognition as a Site of Hemispheric Importance for migratory shorebirds.

Less well-known is the fact that stewardship of San Francisco Bay is supported by one of the best water quality monitoring programs in the world. The Regional Monitoring Program for Water Quality in San Francisco Bay (RMP) originated from an innovative idea, conceived in the mid-1980s, that reached fruition in 1993 with the inception of a systematic and multi-faceted monitoring program. In 2017, the RMP is now in its 25th year of monitoring and is stronger than ever.

This article provides a chronological account of the most momentous milestones in the history of the RMP. The stories behind these milestones highlight the features that have made the Program successful and allow it to continue to flourish after a quarter of a century.

RMP MILESTONES 1986-2017

The RMP has been made possible by the contributions of scores of people over the years. This timeline highlights people mentioned in the text and those who are still active in the Program and have been active for 10 years or more, with photos indicating each person's first year of RMP activity.

1986 — Water Board adopts Basin Plan with toxic pollutant standards

1988 — Steve Ritchie becomes Executive Officer of the Water Board

1989 — Mike Carlin and Tom Mumley oversee pilot metals monitoring

Monitoring methods development by Russ Flegal at UC Santa Cruz begins with funding from the Water Board

1986: Conception

In 1985, Roger James, the Executive Officer at the San Francisco Bay Regional Water Quality Control Board (Water Board), told his staff member Steve Ritchie that they would be adding toxic pollutant standards for metals in water to the Basin Plan. In early 1986, Ritchie and his colleagues realized that there were some unpublished data by Dr. Jim Kuwabara of the US Geological Survey (USGS) on toxic metals in Bay water, and that was about the extent of available data. The idea of establishing a toxics monitoring program for the Bay was born. Adopting the standards proved to be a contentious endeavor due to the lack of information on Bay water quality and whether it was getting better or worse after substantial investments (over $3 billion) had been made in wastewater treatment systems. Nevertheless, Basin Plan standards for toxic pollutants were indeed adopted in late 1986.

In 1988 Steve Ritchie became the Executive Officer. Addressing the lack of information on Bay water quality was one of his top priorities. He considered using the Water Board's authority to immediately require the discharge permit holders to monitor toxic pollutants in the open Bay, but he and his staff decided to wait due to a lack of established methods.

RMP Historical Documents

A collection of documents on the history of the RMP are available on a special archives page of the RMP website:
sfei.org/rmp/rmp-history

The collection includes an excellent overview written for the 20th anniversary of the Program, an article from the RMP newsletter with Steve Ritchie's remarks on the 10th anniversary, and other historical and foundational documents.

Decision to have SFEI (then the Aquatic Habitat Institute) administer the program

Pilot RMP (1991-1992) initiated

Resolution 92-043 of the Regional Board initiates the RMP

1990

Karen Taberski is hired to lead the Pilot RMP, beginning a 27 year period of leadership in the Program

Water Board begins meeting with dischargers

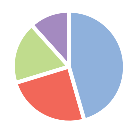
1991

Brian Anderson

1992

RMP Manager: Bruce Thompson

TRC Chair: Jim Salerno



Program participants agree on cost allocation and fund the program

1989: Laying a Solid Foundation

It is essential to the success of a monitoring program that all stakeholders with an interest in the ecosystem accept the data and information generated as unbiased, high quality science. An important way in which the RMP has maintained a high standard of scientific quality is through inclusion of leading scientists as RMP investigators. Many RMP investigators are recognized nationally or internationally as leaders in their fields.

In 1989, the Water Board took an important first step down the path toward high quality science when it set up a contract with Dr. Russ Flegal at UC Santa Cruz to monitor metals in the Bay using state-of-the-art ultra-clean techniques (Flegal et al. 1991). Funding for this initial work in 1989 and 1990 was provided by the Water Board. At that time Dr. Flegal was already established as one of the pioneers in measuring miniscule concentrations of metals in ocean waters, and he successfully adapted those techniques for monitoring the Bay.

The methods developed for the Bay by Dr. Flegal ultimately informed the development of US Environmental Protection Agency methods at the national level for sampling ambient water for trace metals at levels low enough to allow comparison to water quality criteria. Funding from the Bay Protection and Toxic Cleanup Program (BPTCP), which was established by the state in 1989 as a rider on a state bill to bail out the state Superfund program, made it possible to conduct further metals monitoring, along with monitoring of trace organic contaminants and toxicity, in 1991 and 1992 in the precursor of the RMP - the Pilot RMP (Taberski et al. 1992). The BPTCP funding also made it possible for the Water Board to bring Karen Taberski on staff to lead the Pilot RMP. Karen Taberski continued to play a major role in the RMP until her retirement in 2016. In addition to water monitoring, the Pilot RMP included monitoring of sediment (metals, organics, and toxicity) and bioaccumulation in mussels (metals and organics).

Investigators like Dr. Flegal have made the Bay a laboratory for advancing understanding of water quality in coastal ecosystems. Thanks to the work of Dr. Flegal and his students and post-docs at this early stage of the RMP, and over the first decade of the Program, we obtained a reliable and complete dataset of metals concentrations throughout the Bay to compare to water quality objectives. With the inception of the RMP, San Francisco Bay quickly became one of the best-monitored estuaries in the world.

Applied Marine Sciences, with a team led by Andy Gunther, is awarded the contract for conducting initial RMP monitoring

1992

Progress Report on the Pilot RMP (Taberski et al.)

The Aquatic Habitat Institute is transformed into the San Francisco Estuary Institute for the express purpose of administering the RMP

1993

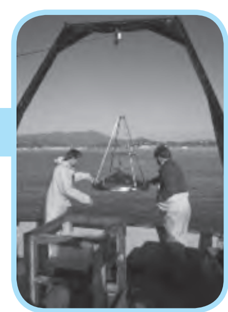
Jim Cloern

Dave Schoellhamer

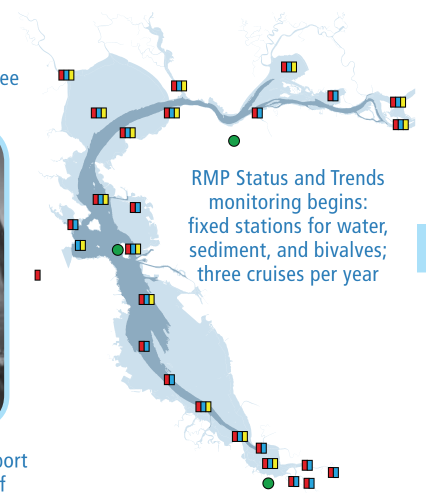
Bridgette DeShields

Bryn Phillips

Steering Committee and Technical Review Committee begin regular meetings



RMP begins long-term support of monitoring by USGS of 1) hydrography and phytoplankton and 2) suspended sediment



RMP Status and Trends monitoring begins: fixed stations for water, sediment, and bivalves; three cruises per year

1992: A Key Ingredient - Funding

While the Pilot RMP was demonstrating the feasibility of toxics monitoring in the Bay, the Water Board enacted Resolution 92-043 endorsing the Regional Monitoring Program, authorizing the Executive Officer to select dischargers to participate, requiring annual reports on the program, and stating the intention to include requirements for RMP participation in NPDES permits. Representatives of 48 publicly owned treatment works (POTWs), industries, local stormwater management agencies, the US Army Corps of Engineers, and Pacific Gas and Electric met with Steve Ritchie at the offices of SFEI (known as the Aquatic Habitat Institute at that time). The group collectively agreed to carry out the program in a collaborative fashion by asking SFEI to act as a coordinator and fiscal agent. Between July and December of 1992, Program participants agreed upon a cost allocation scheme and funded the Program, and SFEI, working with the Water Board and technical staff of participants, designed the Program and selected a prime contractor (Applied Marine Sciences [AMS]) to implement the monitoring. Dr. Andy Gunther of AMS led a team that included Dr. Flegal, Dr. Bob Risebrough (a pioneer in trace analysis of organic contaminants), and many others to conduct the sampling and analysis for the initial years of the Program.

A key ingredient of successful monitoring - sufficient and stable funding - was now in place. The cost allocation scheme and these institutional arrangements have stood the test of time and remain in place today. Funding for the Program has been steady and gradually increased over the years, from $1.2 million in 1993 to $3.5 million in 2017. Over the past 20 years, however, RMP funding has not quite kept up with inflation. In 2016, new funding streams - from permit violation penalties and modifications of effluent monitoring requirements - began to substantially augment the core budget. The participants have seen the benefits of decision-making that is based on solid information and long-term planning, and remain committed to providing the funds to sustain the Program.

First Annual Meeting

Fish monitoring initiated with BPTCP funding

First Annual Report

1994

Steering Committee Chair: Chuck Weir

Fish consumption advisory for the Bay

Jay Davis

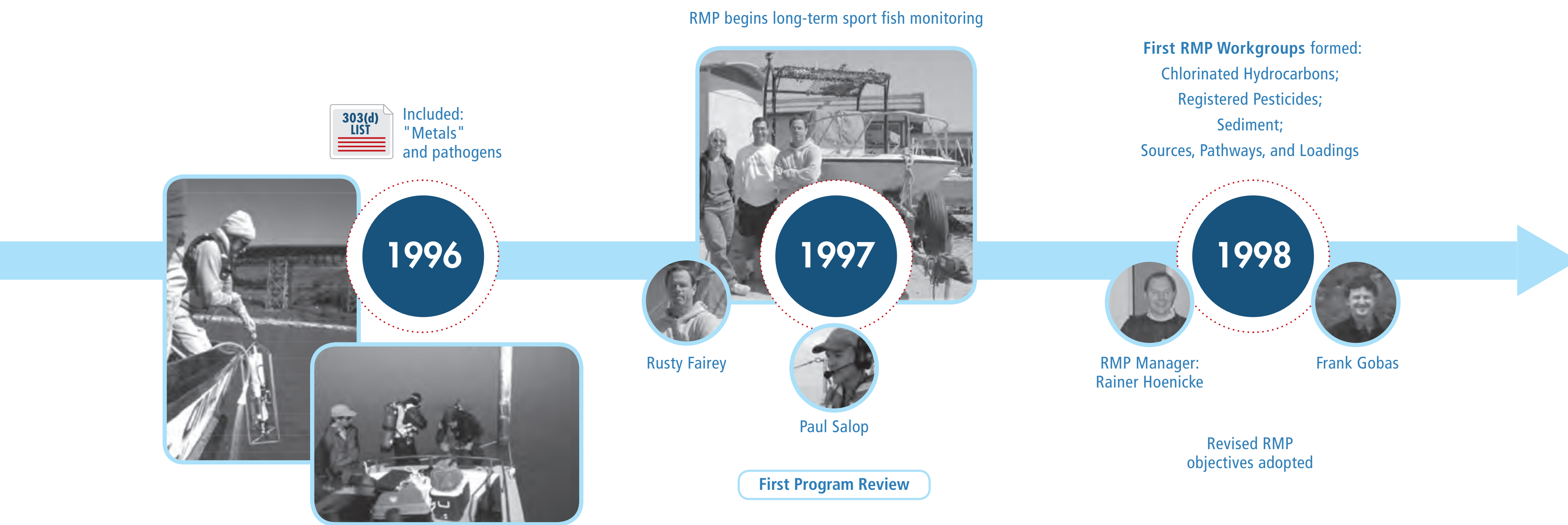
1995

TRC Chair: Ray Arnold

1993: The Era of Joint Fact-finding Begins

At the 2003 Annual Meeting celebrating the 10th anniversary of the RMP, Steve Ritchie noted the importance of collaboration and partnership to the success of the Program: "We have to force scientists and managers to meet at the table and stay at the table together and work at getting relevant information and using relevant information. That is the real key to the RMP and will continue to be the key over time." In 1993, the basic governance structure of the RMP was established, with a Steering Committee and a Technical Review Committee (TRC) that have each been meeting on a quarterly basis ever since. The Steering Committee consists of management representatives from the Water Board and each of five categories of discharger (wastewater, industrial, stormwater, dredger, and cooling water). The Steering Committee determines the overall budget and allocation of funds, tracks progress, and provides direction from a manager's perspective. The first chair of the Steering Committee was Chuck Weir. The TRC consists of technical representatives from the Water Board, discharger groups, USEPA (Region IX) staff, and a non-governmental organization, and provides oversight of the technical content and quality of the RMP. The first TRC chair was Jim Salerno.

These committees, along with later additions to the governance structure, have provided a forum for an innovative and highly valued collaboration among regulators, the regulated, scientists, and other interested stakeholders. The strong spirit of cooperation and joint fact-finding that emanates from the RMP has contributed greatly to a lack of combat science and legal battles over Bay water quality. The success of the collaboration in the RMP has led to other major cooperative efforts in the region: the process for developing site-specific objectives for copper and nickel, the Clean Estuary Partnership (2001-2006), and the Nutrient Management Strategy (2014-present) (pages 22-33). The governance structure of the RMP is also serving as a model for regional monitoring programs in the Delta, the Russian River, and other places.



1993: Let the Time Series Begin

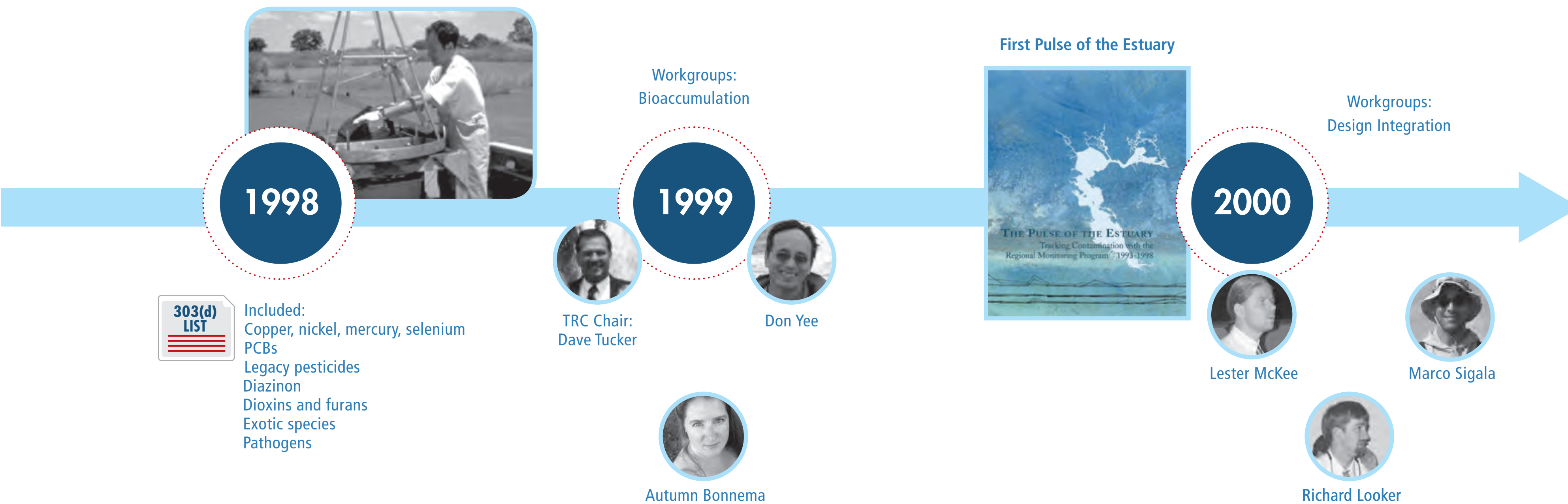
With the groundwork laid, the Program officially began in 1993 under the leadership of the first RMP manager: Dr. Bruce Thompson. From the beginning the Program included two categories of monitoring: 1) status and trends (S&T) monitoring; and 2) pilot and special studies. S&T monitoring in 1993 included sampling of water, sediment, and bivalves at fixed stations along the main channel of the Bay.

Two important pilot studies that were initiated in 1993 were later incorporated into S&T: monitoring of chlorophyll and other basic water quality parameters by Dr. Jim Cloern of USGS; and monitoring of suspended sediment by Dr. Dave Schoellhamer of USGS. These datasets provide excellent examples of the value of sustained long-term monitoring. Both datasets have been valuable in many ways, but detections of unexpected changes have been of particular interest. For suspended sediment, a sudden decrease of 36% was observed in 1999, leading to a new conceptual model for this important parameter. Possibly influenced by the decrease in suspended sediment, phytoplankton abundance (as indicated by chlorophyll concentrations) also began a period of change in the late 1990s. In particular, late summer chlorophyll in the South Bay increased from roughly 1995 to 2005, but then leveled off. This increase triggered concern that the Bay's historic resistance to its high nutrient loads might be weakening - a concern that has led to increased monitoring of nutrients under the Nutrient Management Strategy.

1994: First Annual Report and First Annual Meeting

The goal of the RMP is to "collect data and communicate information about water quality in San Francisco Bay in support of management decisions." Communication is central to the mission of the Program. Two communication platforms - the annual report and the Annual Meeting - that were established in 1994 have served the Program well over the past quarter century.

The format of the annual report has evolved considerably. The first annual reports provided thorough documentation of the monitoring methods and data, and were aimed at a technical audience. By the late 1990s the desire for a more accessible report led to a shift toward publication of an annual summary with a focus on



conveying information (interpretations of data to answer management questions): "The Pulse of the Estuary." The Pulse itself then began a process of evolution, with progressive improvements in the use of visual communication elements and the focus on a theme of current importance. At present, the Pulse is published every other year, and in the alternate years the RMP Update provides a concise overview to RMP stakeholders of recent activities and findings, and a look ahead to significant products anticipated in the next two years.

Annual Meetings have been held each year since 1994, and continue to be a communication forum that is highly valued by stakeholders. The nearly 200 attendees appreciate a day full of presentations and discussions on the latest developments in Bay water quality science and management.

1994: A Turning Point in Water Quality Regulation

After completing the Pilot RMP, Karen Taberski led the first Bay-wide survey of contaminant accumulation in fish, also using BPTCP funds. The sampling was conducted in 1994, and the release of the resulting report led the California Office of Environmental Health Hazard Assessment to issue a fish consumption advisory for the Bay at the end of that year. The advisory was intended to protect the public from exposure to harmful concentrations of mercury, PCBs, chlorinated pesticides and dioxins. The fish data ultimately led to the inclusion of these contaminants on the 303(d) List, and the development of TMDL control plans for mercury and PCBs. The water quality objectives established in these TMDLs were not for concentrations of these contaminants in water, as had been the case for Bay contaminants up to that point, but for concentrations in fish tissue, marking a major shift in the regulation of water quality.

The development and adoption of the TMDLs had a far-reaching and enduring impact on the activities of the RMP. Long-term monitoring of contaminants in sport fish was added to the Program in 1997 (the latest report on the fish monitoring was just released in June 2017). Monitoring of mercury, PCBs, and other contaminants that accumulate in fish tissue has been a major emphasis in both the Status and Trends and special studies elements of the Program. Sport fish-related work even included a major special study, conducted in collaboration with the California Department of Public Health, to determine consumption rates for different ethnic groups (SFEI 2000). The RMP fish monitoring effort has served as a model for similar efforts that were later conducted in the Delta region and throughout the state.

1998: Sharpening the Focus

Careful articulation of a monitoring program's objectives and the questions it is intended to answer is essential to obtaining the information needed to support decision-making. The original objectives of the RMP were somewhat imprecise and were not adequately articulated. A review of the Program in 1997 by a team of high caliber scientists, led by Dr. Brock Bernstein and Dr. Joe O'Connor, recommended that the objectives be re-evaluated and supported by a framework of management questions to provide a more precise focus for the Program. Revised objectives were established in 1998.

The 1998 objectives broadened the scope of the Program to include subject areas that had not been part of the original design: sources, pathways and loadings; effects; and synthesis. The RMP is presently guided by a framework of management questions developed after the 1997 Review, revised in 2004, and revised again in 2008. Management questions to be answered and decisions to be informed are carefully considered for each element included in the RMP.

1998: The Best Form of Peer Review

Changes to the activities of the RMP stemmed from the new objectives adopted in 1998. Subcommittees ("workgroups") were formed to develop study plans for several priority topics identified in the Review process: Chlorinated Hydrocarbons; Registered Pesticides; Sediment; and Sources, Pathways, and Loadings. The Sources, Pathways, and Loadings Workgroup remains active to this day.

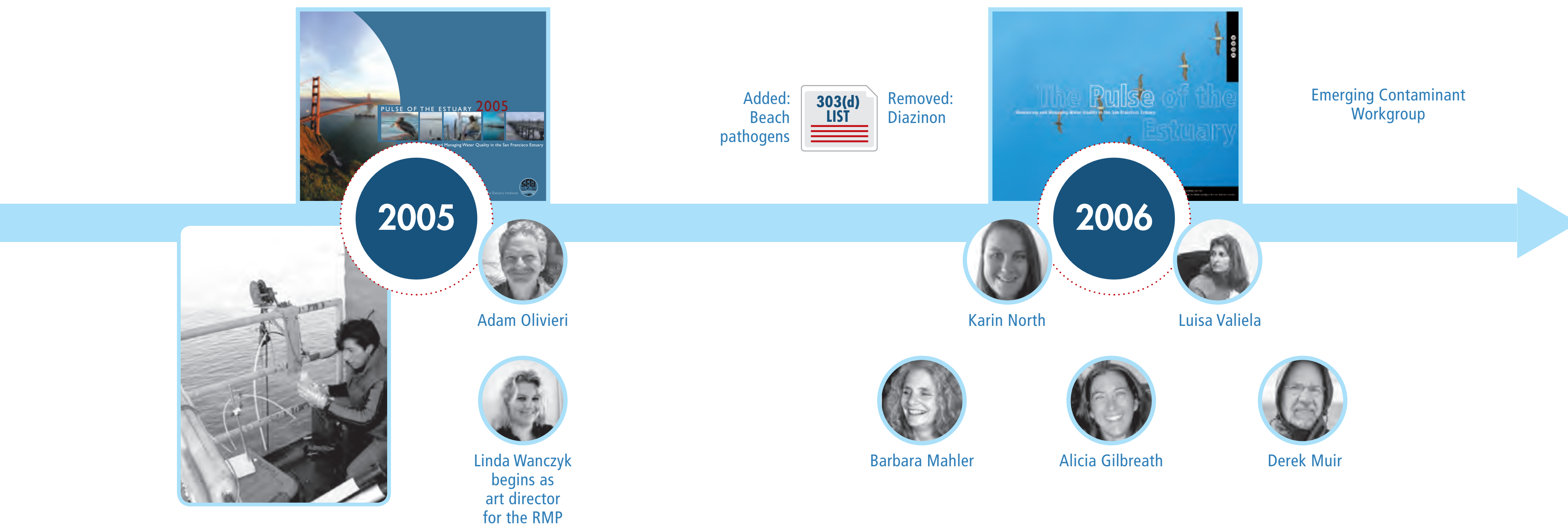
The Chlorinated Hydrocarbon Workgroup established a novel formula for developing the data needed for the PCB TMDL. This formula has served the Program extremely well. For this workgroup, two of the world's experts on chlorinated hydrocarbon fate and transport (Dr. Frank Gobas and Dr. Steve Eisenreich) were invited to join RMP stakeholders and local scientists and to advise the entire process of planning, implementing, and reporting on chlorinated hydrocarbon studies. With their guidance, a simple PCB mass budget was developed that ultimately served as the foundation for the PCBs Total Maximum Daily Load (TMDL).

This experience demonstrated that the best time to receive guidance from experts is in the planning stages of studies, to make sure the work sets off on a productive path to begin with. Peer review more commonly occurs in the reporting phase of a project, when it is too late to do anything about a potentially flawed study plan.

The RMP now has six workgroups that follow this formula, and many eminent scientists have served as science advisors. Dr. Gobas continues to advise the Program to this day as a member of the PCB and Dioxin workgroups. Having leading external scientists, scientists with local knowledge of the Bay, and stakeholders together at the table has proven to be a powerful approach to achieving the goal of the RMP: asking the right questions and efficiently answering them.

2000: A Shift to Forward-Looking Monitoring

RMP monitoring in the 1990s was highly focused on addressing the serious information gaps on legacy contaminants such as mercury, PCBs, and organochlorine pesticides, or on contaminants like copper that had long been recognized as a concern. The 1995 Annual Report included a chapter by Dr. Bob Risebrough, one of the global pioneers in measuring PCBs and DDT in the environment, titled "Polychlorinated Biphenyls in the San Francisco Bay Ecosystem: A Preliminary Report on Changes Over Three Decades." The chapter provided an entertaining summary of PCB data spanning from Dr. Risebrough's first measurements of shiner surfperch from the Bay in 1965 to the latest RMP data from 1994.



The chapter concluded with a section titled "Are There 'New PCBs' Out There?" Dr. Risebrough pointed out that there were hundreds of peaks in the chromatograms of RMP samples that were not identified, and that the concept of surveillance monitoring was being ignored. He wrote: "… the list of reported contaminants is a very imperfect description of the real world. A survey of potentially beneficial plants in a rainforest using a guidebook that identifies only bananas, the coconut palm, and five species of orchids would be equally incomplete."

In 2000, Dr. Daniel Oros began a RMP-funded study to identify some of those unidentified peaks in Dr. Risebrough's chromatograms. This study was a first foray into what has become one of the biggest focus areas of the RMP: monitoring for contaminants of emerging concern (CECs) (pages 34-43). The RMP is now a world-leader in monitoring for CECs, with the goal of early detection of problematic chemicals to support management intervention before they become "new PCBs."

2002: A Major Remodel for Status and Trends

Core elements of a monitoring program must remain constant in order to effectively track long-term trends in contamination. However, a purely static monitoring program would become less and less relevant over time as management priorities shift, as understanding increases, as technology advances, and as the ecosystem changes. The RMP strives to become more and more relevant and cost-effective, and has established several mechanisms that make adaptation a hallmark of the Program, most notably 1) continual review by stakeholders and science advisors, and 2) exploration of new approaches through pilot and special studies.

A prime example of this adaptation is the evolution of the Status and Trends (S&T) element. As mentioned above, S&T monitoring began in 1993 with sampling of water, sediment, and bivalves at fixed stations primarily along the main channel of the Bay, with three cruises per year for water and two cruises for sediment and bivalves.

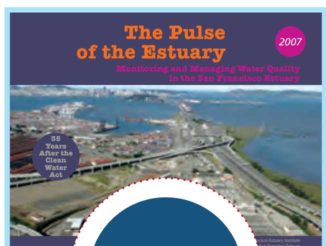
2007

Special Issue of Environmental Research on San Francisco Bay based on RMP studies

First RMP Strategy and 5 Year Workplan developed for Mercury

Steering Committee: Tom Mumley

First Themed Pulse: 35 Years After the Clean Water Act




Kelly Moran

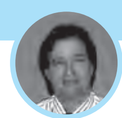

Mike Stenstrom


Lee Ferguson

2008

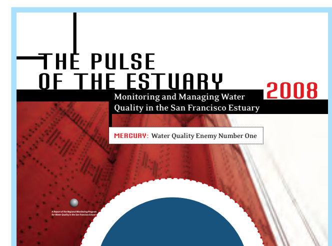
RMP Lead Scientist: Jay Davis

RMP Manager: Meg Sedlak


Rod Miller

TRC Chair: Bridgette DeShields

Mercury: Water Quality Enemy Number One




Eric Dunlavey

Dioxin Workgroup

Mercury TMDL approved

In 2002, in response to the 1997 Program Review, a pivotal revision to S&T was implemented after a significant amount of committee work led by Dr. Rainer Hoenicke, the RMP Manager at the time, and Dr. Bruce Thompson. A spatially randomized (or "probabilistic") sampling design was developed under the guidance of Dr. Don Stevens (one of the nation's leading experts on this topic), with the goal of generating data that are representative of the entire Bay and that allow the Water Board to better evaluate whether water and sediment quality in the Estuary is impaired.

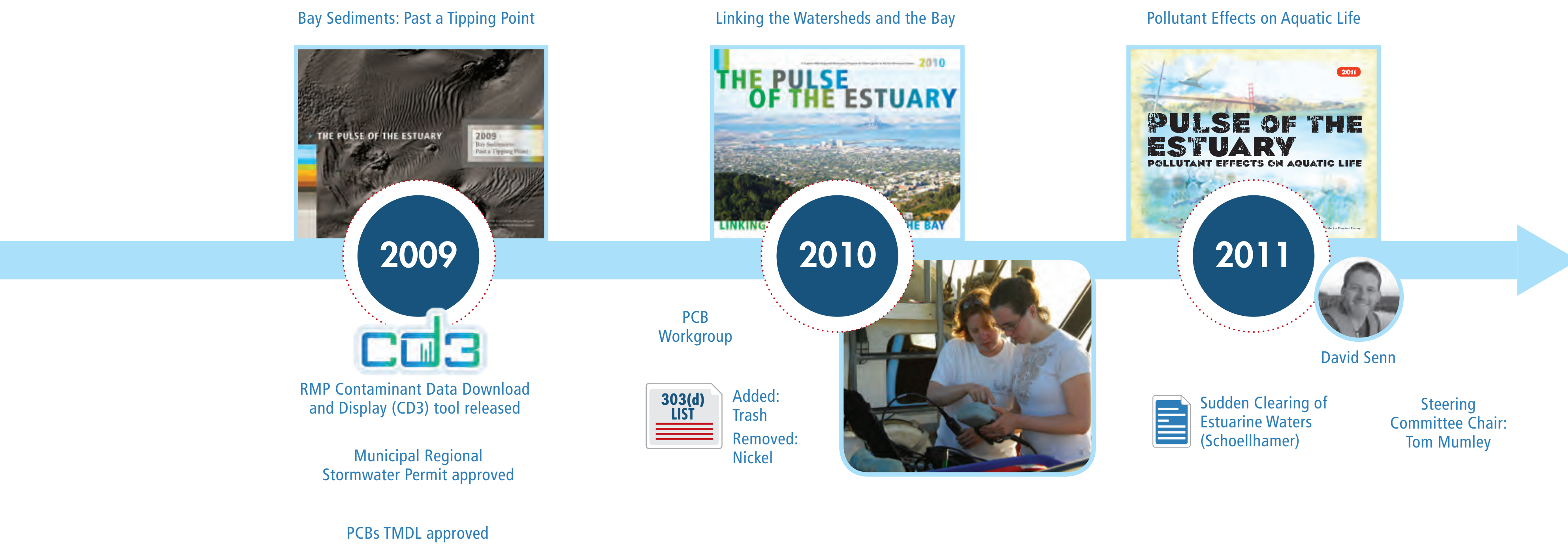
In order to afford this more spatially intensive sampling design within a fixed budget, the number of sampling events was reduced to one per year, during the dry season, since this is the least variable time period. Some of the original fixed stations were also retained to allow continued tracking of long-term trends. This design is still in place, but the frequencies of sampling have been further reduced, with water sampling occurring once every two years, and sediment sampling occurring once every four years. Reductions in S&T monitoring have allowed a larger proportion of the annual budget to go to a diverse array of special studies addressing higher priority information needs.

2007: A Shift to Forward-Looking Planning

In 2007, mercury was a hot topic in the Bay. The TMDL control plan had been developed by the Water Board and was on its way to approval by USEPA. The TMDL development process had identified some technical information gaps. Meanwhile, the Estuary (the Bay and Delta) had become a national focal point for mercury science due primarily to millions of dollars in funding from the Cal-Fed Program. The RMP was also fielding many proposals for mercury studies.

Dr. Tom Mumley of the Water Board, a Steering Committee member and future Committee chair, had the idea of taking a more proactive approach to the planning process for RMP mercury studies. He requested the development of a specific multi-year strategy for mercury studies to ensure that the RMP would provide the information most urgently needed to manage this top priority pollutant.

The RMP approach to tackling such tasks is to organize a collaborative team effort. Consequently, a Mercury Strategy Team comprised of several RMP



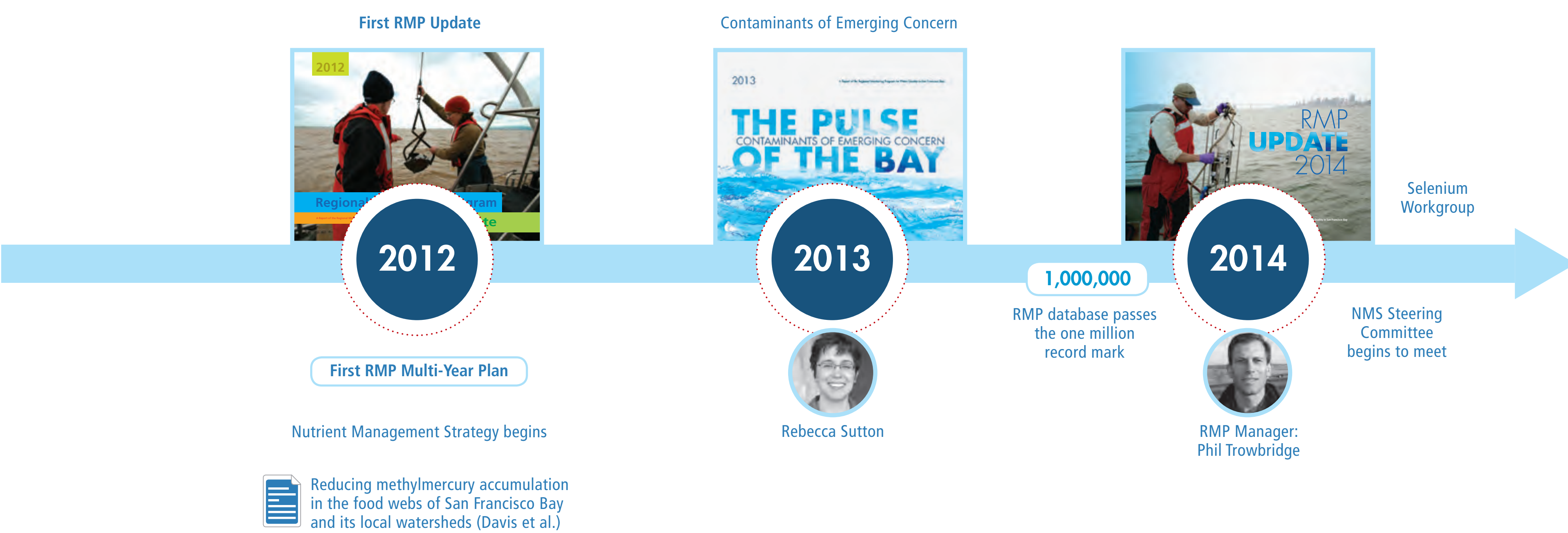
stakeholders was formed in the summer of 2007. The Team formulated a series of management questions to attempt to identify actions that would reduce mercury uptake in the Bay food web in a relatively short timeframe. The management questions and a five-year funding plan were articulated in the form of a RMP Mercury Strategy. The Strategy formed the basis of a request for proposals that was issued at the end of 2007. Over the next four years, the RMP invested $900,000 in mercury special studies to implement the Strategy, culminating in a synthesis paper in 2012 that largely answered the management questions.

Inspired by the Mercury Strategy, other RMP Workgroups also began developing five-year plans, identifying the highest priority management questions for their topics and planning series of studies to answer them. Beginning in 2012, all of these plans were bundled, along with other key Program information, into a Multi-Year Plan for the RMP as a whole. The forward-looking planning that has now become a hallmark of the RMP traces back to that turning point in 2007.

2014: The Rise and Fall of PBDEs - RMP Documents a Success Story

Thanks to all of the strong work on governance highlighted above, the RMP has monitored the Bay long enough to document significant changes in Bay water quality. Monitoring for polybrominated diphenyl ethers (PBDEs) provides an example of the Program documenting the full arc of a water quality management success story. PBDEs are a class of bromine-containing flame retardants that was widely used starting in the 1970s, but rarely studied until the 1990s. In response to observations in the 1990s of rapidly increasing concentrations in humans and wildlife, including Bay studies that reported some of the highest values in the world, the California Legislature banned two types of PBDE mixtures in 2006; the last mixture ("deca") was phased out in 2013.

A decade of PBDE monitoring by the RMP resulted in a dataset covering periods during and after PBDE use, and consisting of hundreds of measurements of water, sediment, and aquatic organisms. By 2014, PBDE levels in bird eggs



and bivalves declined by 74-95%, and levels in Bay sport fish (shiner surfperch) declined by nearly half. In sediment, concentrations of penta component BDE-47 also dropped, but the dominant sediment-bound PBDE compound, deca component BDE-209, has shown no sign of decline yet.

In 2017, due to the declines and resolved uncertainties about risks to humans and wildlife, PBDEs were reclassified by the RMP from a moderate concern to a low concern for the Bay. RMP data were critical to demonstrating the success of these management actions. This well-documented success story was published in *Environmental Science and Technology*, a leading environmental science journal (Sutton et al. 2015).

Looking Forward

With sustained commitment and funding over the past 25 years, the RMP has matured into a Program that is well-poised for the future. The RMP has proven that it can readily adapt to maintain its sharp focus on providing the science that is most urgently needed to protect Bay water quality. Continued financial support and a capacity for adaptation will be crucial to continued success in the next 25 years, with major changes in store for this ecosystem - driven by population growth, climate change, changes in water management, habitat restoration, and other forces - that will add to the challenge of tracking progress in managing the wide array of threats to Bay water quality.

> "We have a tremendous resource in the Bay, and I don't think we appreciate it as much as we should. We owe it to ourselves and to society, to understand it, manage it, and nourish it. That is a collective responsibility of all of us as managers and scientists: to make the Bay the best that it can be, and the RMP is a critical component of that."
> — STEVE RITCHIE

Microplastic Workgroup

The State of Bay Water Quality: 2015 and 2065

2015

The Regional Monitoring Program for Water Quality in San Francisco Bay: Science in support of managing water quality (Trowbridge et al.)

Declines in Polybrominated Diphenyl Ether Contamination of San Francisco Bay following Production Phase-Outs and Bans (Sutton et al.)

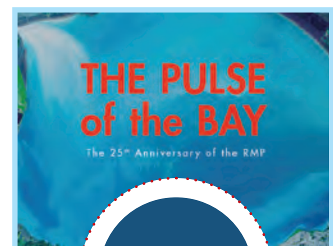
Municipal Regional Stormwater Permit re-issued

Sediment sampling in the Central Bay margins

2016

Selenium: North Bay TMDL approved

The 25th Anniversary of the RMP



2017

Microplastic Strategy

Beaches Bacteria TMDL approved

Unraveling the Mysteries of Nutrients in San Francisco Bay: Tackling a Complicated Puzzle, Piece by Piece

by Dave Senn (davids@sfei.org), Phil Trowbridge, Lissa MacVean, Morgaine McKibben, Rusty Holleman, and Anthony Malkassian,
San Francisco Estuary Institute

HIGHLIGHTS

- The Nutrient Management Strategy (NMS), a major collaborative regional science program that works in close collaboration with the RMP, has developed a 10-year Science Plan for addressing monitoring and research needs for the complicated issue of nutrients in the Bay
- The key focus areas of the NMS are the effects of nutrients on dissolved oxygen for fish habitat, algae growth and the toxins produced by certain species of algae, and computer models of how nutrients move and react within the Bay
- High-frequency sensors are providing new data for identifying the mechanisms that drive dissolved oxygen concentrations in the Bay, such as algae blooms, tidal currents, suspended sediment, and stratification of the water column that limits transfer of oxygen to the bottom waters
- Studies conducted to date indicate that algae growth is most often limited by factors other than nutrients, such as high turbidity and strong tidal mixing, but the role of nutrients in fueling algae blooms at certain times and locations still needs to be resolved
- Algae that produce potent toxins have been detected in the Bay and these toxins are regularly detected in water and shellfish at levels that justify continued investigation
- Major progress on numerical models has been made in first two years of the program; ongoing efforts are adding algae growth calculations and expanding the range of the models into the Delta and the sloughs of Lower South Bay

A Special Estuary

San Francisco Bay is special in many regards, and its response to nutrients follows suit. Decades of observations (e.g., Cloern et al. 2007, 2010) indicate that the Bay is less sensitive to excess nitrogen (N) and phosphorus (P) inputs than many other estuaries.

Those same data, along with observations from recent studies, reveal important gaps in our understanding, and point to the need for thorough exploration of complex nutrient-related questions in the Bay.

- The dynamics of nutrient cycling and ecosystem response in the Bay are extremely complex, and the "dose-response" relationships for important water quality indicators, like chlorophyll-a concentration ("Chl-a", a measure of phytoplankton bloom magnitude), vary dramatically between subembayments and seasonally.

- Even after taking into account those spatial and seasonal differences, water quality responses vary considerably year-to-year.

- In addition, the Bay's dose-response relationship transitioned to a more sensitive state in some regions and seasons, as evidenced by a doubling of Chl-a concentrations in late summer and fall in South Bay (Cloern et al. 2007).

- Other nutrient-related water quality indicators, like dissolved oxygen (DO) levels in shallow margin habitats and toxins produced by harmful algae, only began receiving attention in the past few years. Early results from that work indicate low DO in sloughs and algal toxins are important.

< Deploying a CTD profiler and a Niskin water sampler near Angel Island. Photograph by Morgaine McKibben.

Determining whether nutrients are adversely impacting ecological health in the Bay and identifying protective nutrient loads is a large and complex undertaking. The solution to tackling large complex problems is to break them down into smaller pieces. Therefore, the Nutrient Management Strategy (**Sidebar**) recently completed a Science Plan that charts a 10-year path to methodically tackling major monitoring and research needs (SFEI 2016). A team of collaborating scientists worked with SFEI to develop the plan based on their knowledge of nutrient issues in the Bay and other estuaries. With a topic area as wide and deep as nutrients, choosing a few key focus areas is critical if progress is to be made. One of the important elements of the Science Plan is clear priorities for the limited resources available, and guideposts for the types of investigations needed to target those priorities. Work over the past two years has been moving forward on several fronts through a combination of continued and expanded monitoring, special studies, and numerical modeling, with several examples presented below.

Dissolved Oxygen – A Critical Measure of Fish Habitat

Dissolved oxygen (DO) is a key indicator of water quality in the Bay. DO's importance derives from the fact that fish and sediment-dwelling organisms need sufficient DO to survive and prosper. DO is also a useful indicator of net ecosystem metabolism, which is the balance between the production of living organisms and the decay of organic material.

While DO levels in open Bay deep subtidal habitats meet, in general, the 5 mg/L Basin Plan standard, early NMS work suggested that levels could be much lower in shallow margin habitats of Lower South Bay. The NMS Science Program installed a 7-station network of moored sensors in Lower South Bay and its sloughs starting in 2014-2015 (**Figure 1a**), and has been collecting data and studying the drivers and variability in DO over the past 2 years (**Figure 1b**). Time-series plots of DO, Chl-a, and water depth illustrate great variability in Chl-a and DO over tidal and annual timescales, and between sites. The high-frequency data are helping us unravel mechanisms that drive DO levels in the Bay. For example, at the Dumbarton Bridge, DO generally remains above 5 mg/L and tidal fluctuations dominate the signal. The low-DO events that occur are observed at the lowest water depths. The data suggest that DO

What is the Nutrient Management Strategy (NMS) and what does it have to do with the RMP?

The Nutrient Management Strategy's mission is to develop the scientific foundation to support nutrient management decisions. The NMS Steering Committee, first convened in 2014 and representing 13 stakeholder groups (regulators, dischargers, water purveyors, non-governmental organizations, and resource agencies), oversees NMS implementation, including financial oversight and high-level input on programmatic priorities. The San Francisco Estuary Institute (SFEI) directs the day-to-day operation of the NMS Science Program. SFEI staff work closely with regional collaborators to carry out NMS-sponsored field investigations, monitoring, and data interpretation. The RMP played an important role in helping to launch the NMS through convening early meetings and funding foundational work that shaped the NMS science direction (e.g., SFEI 2014). On-going funding for NMS projects comes from several sources, including fees required under a Bay-wide nutrient permit for wastewater agencies (50%), special study funding from the RMP (25%), and project-specific grant funding from multiple sources (25%; e.g., State Water Resources Control Board, Delta Science Program, individual dischargers). The highest priority NMS topics being pursued are: 1) dissolved oxygen; 2) phytoplankton blooms, community composition, and harmful algal species; and 3) nutrient loads and cycling.

Figure 1a. Map of Lower South Bay moored instrument stations.

is consumed in the margins, and then the low-DO water is flushed into the Bay on ebb tides. Along the way, turbulence and waves mix the slough and Bay water and help entrain new oxygen from the atmosphere, so that the Dumbarton sensor does not see the lowest DO levels.

In some of the fringing sloughs (Alviso and Guadalupe), DO varies over a much wider range of concentrations than at the Dumbarton Bridge, reaching far higher and far lower oxygen levels. At other locations (Coyote, Newark, and Mowry), the DO signals are intermediate between the Dumbarton and lower-DO sloughs. Chl-a measurements offer clues to a factor contributing to the spatial differences: organic matter loads, in the form of live or decaying algae, from managed ponds, or former salt ponds, that exchange with sloughs on each tide. Algae grows more rapidly in these ponds' warmer, quiescent waters, and enters the adjacent sloughs on ebb tides. Sloughs that receive algae from managed ponds show greater oxygen consumption as that organic matter accumulates in the sediments and is respired by microbes. The DO and Chl-a measurements during the summer 2015 period (**Figure 1b**) illustrate how higher DO variability tended to occur where Chl-a levels were higher.

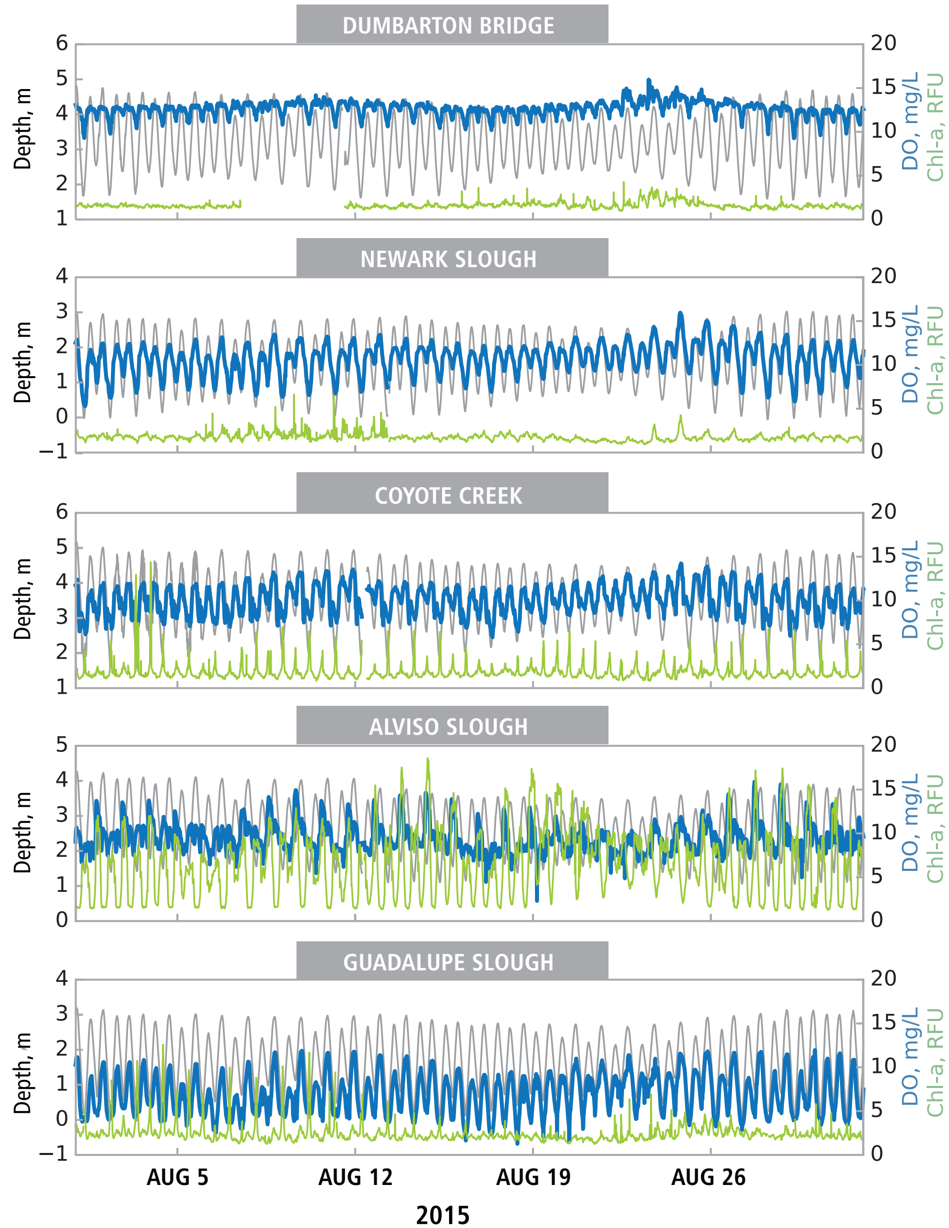
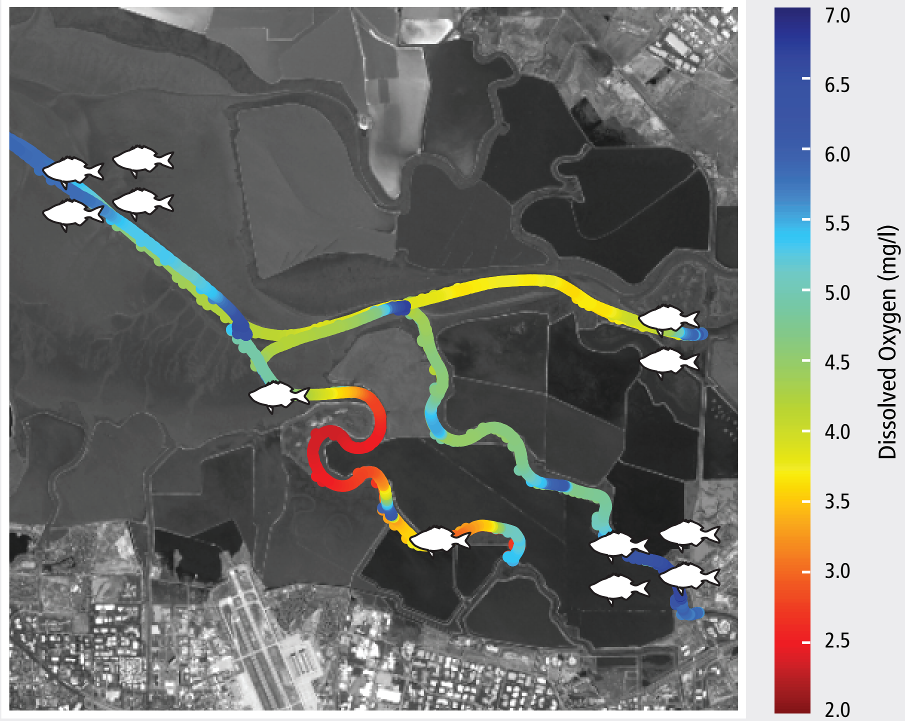


Figure 1b. Time-series of DO (blue, right axis), chlorophyll (green, right axis), and water depth (grey, left axis) from five stations in August 2015.

Understanding Fish Habitat Quality in Lower South Bay

In April 2017 the NMS team convened a workshop on DO in estuarine environments, gathering a group of local and international experts to develop the scientific foundation for understanding habitat quality in Lower South Bay (LSB). The workshop targeted several topics:

- Defining habitat - what species live where - in the highly-dynamic LSB, where large, strong tides empty and refill a large percentage of slough volume each day, and fast tidal velocities carry small fish several kilometers with each tidal cycle.
- Quantifying habitat quality, considering both the organisms that use (or should use) different habitats and the sometimes rapidly-fluctuating DO levels in those habitats.
- Identifying major uncertainties and studies needed to address those uncertainties.



Surface DO measured on an ebb tide in September 2015. These environmental data will be merged with surveys of fish and benthos to determine the water quality condition preferred by Lower South Bay biota.

Based on workshop discussions with experts and stakeholders, we developed a plan to merge DO observations with the needs of fish and other wildlife that live in the LSB to develop guidance for assessing habitat quality (**Figure**). Next steps include working with fish ecology collaborators at UC Davis to analyze their extensive fish trawl and invertebrate survey data to characterize habitat usage or habitat suitability (e.g., considering space, time, salinity, temperature) and exploring DO preferences for different functional groups of fish. The longer-term plan includes continued and potentially expanded DO monitoring and biota surveys, and working toward assembling a multi-stressor characterization of habitat condition.

DO drawdown may be enhanced in sloughs where physical mechanisms interact with biological processes. Two sets of processes may have particularly important effects. First, strong tidal currents keep fine suspended sediment particles afloat in the water column, reducing light penetration into the water and slowing algae growth and oxygen production, so much so that DO levels do not exhibit the classic "diel" (daily) oxygen cycle of increasing DO concentrations around mid-day; but respiration does continue, drawing down DO. Second, stratification in the water column (heavier, salty water flowing beneath lighter, freshwater) literally puts a cap on the mixing of oxygen from the atmosphere to bottom waters, causing DO to drop more quickly due to DO consumption near the bed. Field measurements will help us determine what conditions lead to stratification, and its strength and persistence.

What Algae Grow in the Bay and Why?

Phytoplankton (also referred to as "algae") are a vital food resource at the base of the food web, and thus play a linchpin role in ecosystem health. Like any healthy diet, both the amount and type of food are important. Some minimum phytoplankton production is needed to support the Bay food web. However, excessive phytoplankton production can negatively impact the Bay by causing low DO levels. In addition, nutritional quality varies considerably among phytoplankton species due to factors such as the essential fatty acids they contain. Beyond nutritional quality, some harmful algae produce potent toxins that can harm estuarine biota and humans.

Elevated N and P levels in estuaries and coastal zones are considered one of the most impactful and widespread water quality problems worldwide (National Research Council 2000). Elevated nutrient loads promote phytoplankton blooms that in turn lead to low DO. Under some circumstances, the frequency and severity of harmful algal blooms (HABs) have also been linked to elevated N and P concentrations (Anderson et al. 2002). In addition, the relative concentration and form of available N and P can influence the mix of phytoplankton groups growing in the water column (Heisler et al. 2008).

Multiple factors influence phytoplankton growth rates, overall phytoplankton biomass, and the relative abundance of phytoplankton species, including: light levels, salinity, temperature, transport and mixing, and nutrient concentrations (e.g., Phillipart et al. 2000; Rabalais et al. 2009). From the standpoint of phytoplankton growth, studies conducted to date indicate that San Francisco Bay is generally a light-limited and "nutrient-replete" system (e.g., Cloern and Dufford 2005; Kimmerer and Thompson 2014): i.e., phytoplankton growth rates are primarily limited by low light levels, caused by high turbidity and strong tidal mixing, and N and P concentrations are high enough that they seldom limit growth rates. However, major uncertainties remain about the factors that control how the phytoplankton community varies spatially and seasonally (including HAB-forming species), and year-to-year variability in bloom size and occurrence. In order to understand the role nutrients play, we need to disentangle the effects of all the major factors.

< Deploying the CTD profiler in Central Bay. Photograph by Charles Martin.

One way to understand the phytoplankton community better is through careful analysis of datasets. A recent analysis is shown in **Figure 2**, which depicts phytoplankton community composition and abundance across five subembayments during 2014-2016. Compositions are depicted as the relative proportion of major classes of phytoplankton, with Chl-a concentrations providing an indication of the total phytoplankton biomass. The phytoplankton community is generally dominated by Diatoms (accounting frequently for over 50% of biovolume in the samples, including during several periods of maximum Chl-a concentrations and a rare major bloom in Suisun Bay). On a number of dates, though, Cryptophytes and Dinoflagellates contributed substantially, including periods when Chl-a was moderately elevated, such as a modest Dinoflagellate bloom in Lower South Bay (20 g/L Chl-a), a modest Cryptophyte bloom in San Pablo Bay (10 g/L Chl-a), and a modest mixed-assemblage bloom in Central Bay (10 g/L Chl-a). Diatoms, Dinoflagellates and Cryptophytes are considered as a high food quality (i.e., allowing a more efficient transfer of energy through the food web) (Cloern et al. 2014). Going forward, we will continue working with collaborators at the U.S. Geological Survey (USGS) and the University of California Santa Cruz (UCSC) to analyze recent data alongside long-term phytoplankton data from the past 20 years to gain more insights into phytoplankton blooms in the Bay.

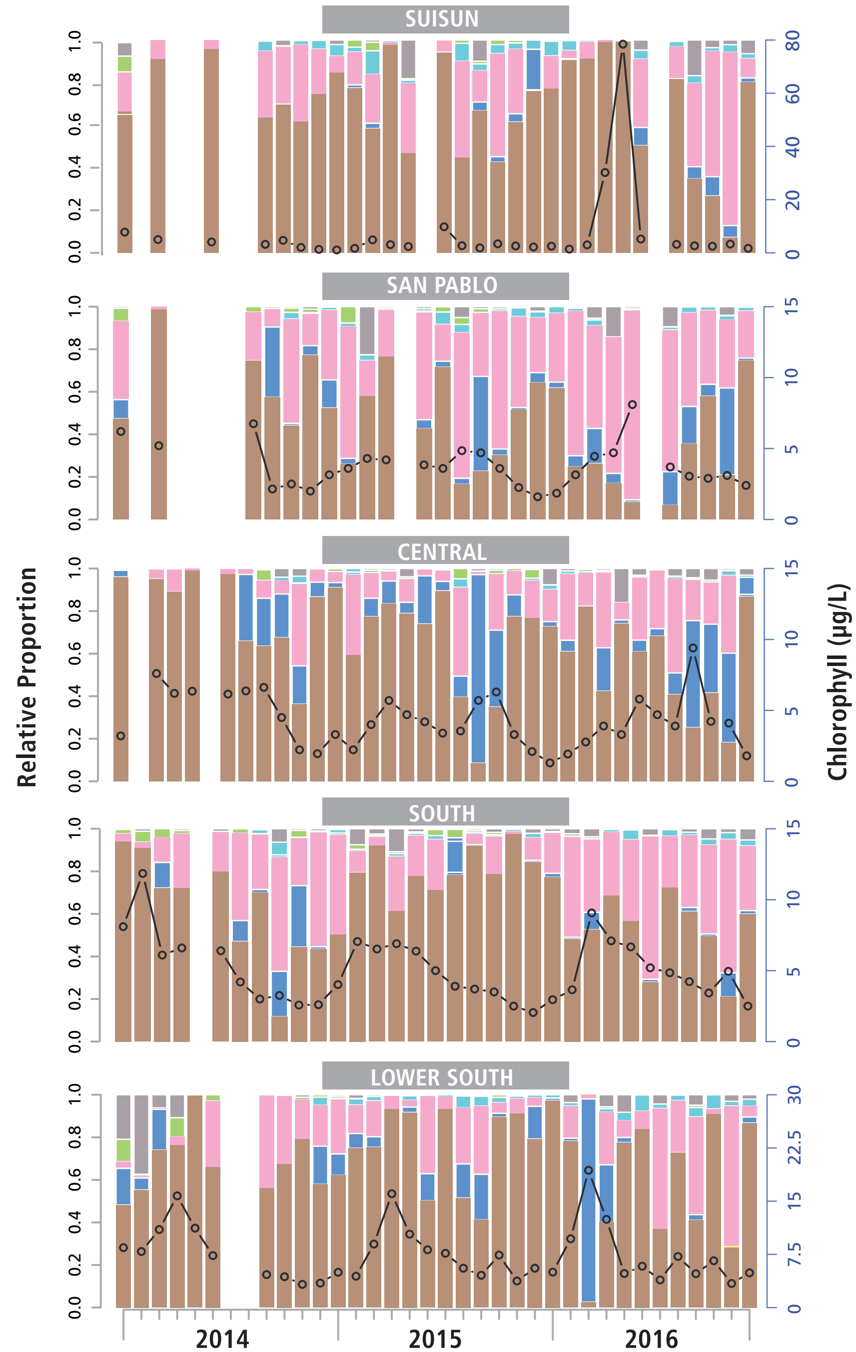


Figure 2. Monthly evolution of the phytoplankton community composition in the Bay from January 2014 to December 2016. The bar plots represent the relative proportion of total biovolume for the main 6 phytoplankton functional types (diatom, dinoflagellate, cryptophyte, cyanobacteria, green, and other) derived from taxonomy data for each sub-embayment. The black line shows the associated chlorophyll a concentrations.

Algal Toxins

Some species of algae produce potent toxins that can pose a threat to the health of humans and wildlife. Prior to 2013 few data existed on the occurrence of algal toxins in San Francisco Bay. Through collaborations with USGS and UCSC, NMS studies are finding that multiple distinct toxins are commonly detected Bay-wide and year-round in water and biota (Peacock et al. 2017 submitted; Novick et al. 2016).

∧ Mussels collected for toxin analysis. Photograph by Zephyr Sylvester.

A 2015 NMS study with collaborators at UCSC found that domoic acid, microcystin, and saxitoxin were all consistently detected, at low to moderate levels, in mussels deployed throughout the Bay (Peacock et al. in prep). Motivated by these results, a pilot mussel monitoring program was launched in September 2015 involving biweekly sampling of naturally-occurring mussels from Central and South Bays to explore several important questions: What toxin concentrations are entering the food web, and how do they vary seasonally and spatially? Where, and under what conditions, do toxin-producing blooms develop? Can naturally-occurring mussels serve as reliable time-integrated bioindicators of toxin levels?

Domoic acid and microcystin were detected with high frequency in Central and South Bay mussels. Results from roughly 150 mussel samples spanning September 2015 - September 2016 show that a majority (over 60%) of samples test positive for the presence of domoic acid or microcystin. Domoic concentrations were far below a threshold for human consumption of shellfish (20 ppm). The range in microcystin concentrations, however, was closer to the recommended human consumption threshold of 10 ppb with a few surpassing the threshold and about 60% of all samples ranging from 1-10 ppb. This initial dataset spans one year, just enough to begin detecting potential seasonal patterns in mussel toxin levels. Analysis of a second year of data is underway.

The NMS is also investigating these HAB-related topics through collaborative efforts such as:

- working with USGS and UCSC to use long-term (USGS 25-year phytoplankton taxonomy) and newly collected data (dissolved and particulate toxins measured over the past several years; Peacock et al. in prep.) to identify spatial and temporal patterns in the occurrence of HAB-forming organisms and toxins, and potential causal factors, and
- a HAB expert workshop (May 2017) focused on gathering input and recommendations on 1) the implications of the HAB and algal toxin data available to date in terms of ecosystem health; and 2) priority research and monitoring to address key uncertainties.

Modeling - Understanding the Mechanisms that Drive Nutrient Concentrations

In an ecosystem as complex and varied as San Francisco Bay, timely answers to management questions require drawing on a wide range of tools. Direct observations of present day condition are invaluable. However, as the number of sources, sinks, and processes compound, numerical models enable the synthesis of those observations into a working and testable understanding of the ecosystem.

Numerical models, after sufficient calibration and validation, enable many new analyses either not possible or prohibitively difficult from observations alone. As daily consumers of weather forecasts, derived from weather models, we are keenly aware of the forecasting capabilities of numerical models, but forecasting is just one way in which numerical models can be utilized. In the context of nutrient management decisions for the Bay, we need to develop not just forecasts of nutrient concentrations, but also a mechanistic understanding of nutrient sources, pathways, and sinks. Beyond diagnosing the drivers of current condition, models also allow for testing potential responses to changes in condition, in anticipation of shifts in environmental factors and in investigating potential management alternatives.

The NMS nutrient modeling program has made significant progress in its first two years in both hydrodynamic and water quality modeling. Building on the efforts of previous work, we have a solid hydrodynamic model serving as the foundation for transport and nutrient studies. The hydrodynamic model shows how water moves in the Bay in response to tides, river flows, wind, and salinity gradients. This model has been successfully validated against tides, currents, and salinity distributions throughout much of the Bay (**Figure 3**). While there is always room for improvement when it comes to calibrating numerical models, the validation process has shown that the model captures transport and mixing in the Bay quite well.

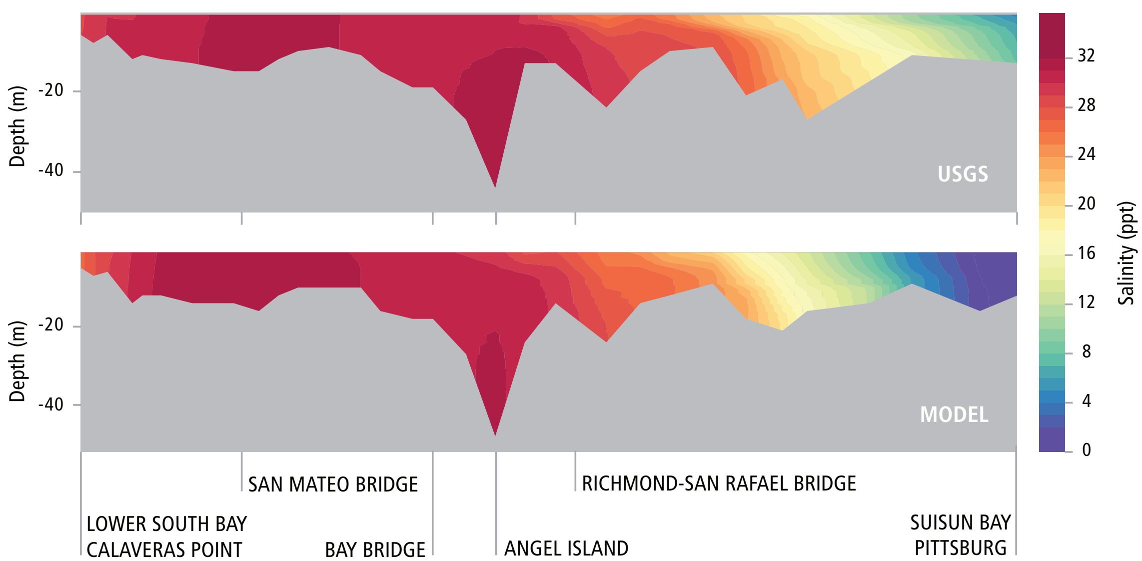
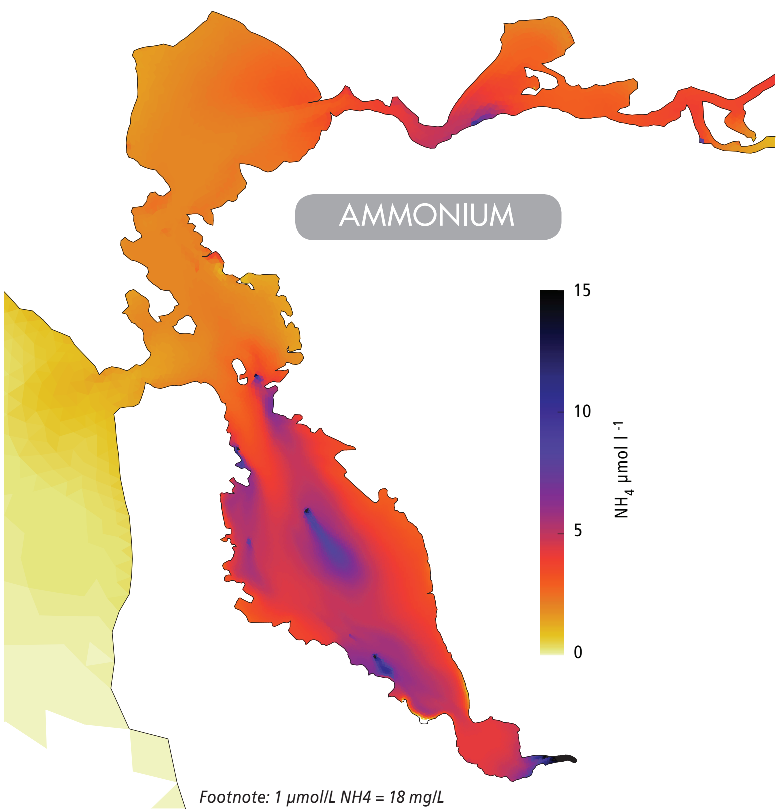


Figure 3: Observations from USGS cruises along the spine of the bay from south to north are used for assessing the model's skill in predicting conditions in the Bay. A comparison between the observed salinity field in November 2012 (upper panel) and the modeled salinity (lower panel) shows encouraging performance in much of the Bay.

Progress has also been made on adding the water quality component to predict nutrient concentrations. The water quality model is tightly linked with the hydrodynamic model, where the tidal currents and mixing predicted by the hydrodynamic model are used to transport and disperse nutrients and other water quality constituents. Two key steps in the development of the water quality model are the addition of nutrient sources and the characterization of nutrient transformations. Wastewater treatment plants are the dominant source of nitrogen in the Bay (Novick and Senn 2014), and the water quality model currently includes estimated loads from 37 wastewater treatment plants as well as loads entering from the Delta and five refineries. Even without the inclusion of nutrient transformations, the water quality model was useful in tracing out the regions of the Bay influenced by specific discharges, an early step in framing discussions of nutrient trading and the effects of nutrient discharge reduction.

Beyond nutrient inputs and transport, the model can also capture a wide array of nutrient transformations - the conversion of various forms of N and P into other forms. Modeling to date has focused on the nitrogen forms common in wastewater effluent such as ammonium and nitrate, as well as two major transformations affecting these nutrients: nitrification and denitrification. Nitrification is a process carried out by microbes that metabolize ammonium (prevalent in wastewater effluent) into nitrate. Over the course of days to weeks, this process converts ammonium-rich effluent to the nitrate-rich waters in the Bay. Denitrification is another microbial process in which nitrate is converted to nitrogen gas, which leaves the Bay and enters the atmosphere. In this simplified version of nutrient cycling, all discharged nitrogen faces one of two fates: transport out of the Bay via the Golden Gate or conversion to nitrogen gas. Snapshots of the resulting spatial distributions of ammonium and nitrate are shown in **Figure 4**. With these two basic processes layered on the transport and mixing information supplied by the hydrodynamic model, we can already explain much of the observed variation in nutrient concentrations.



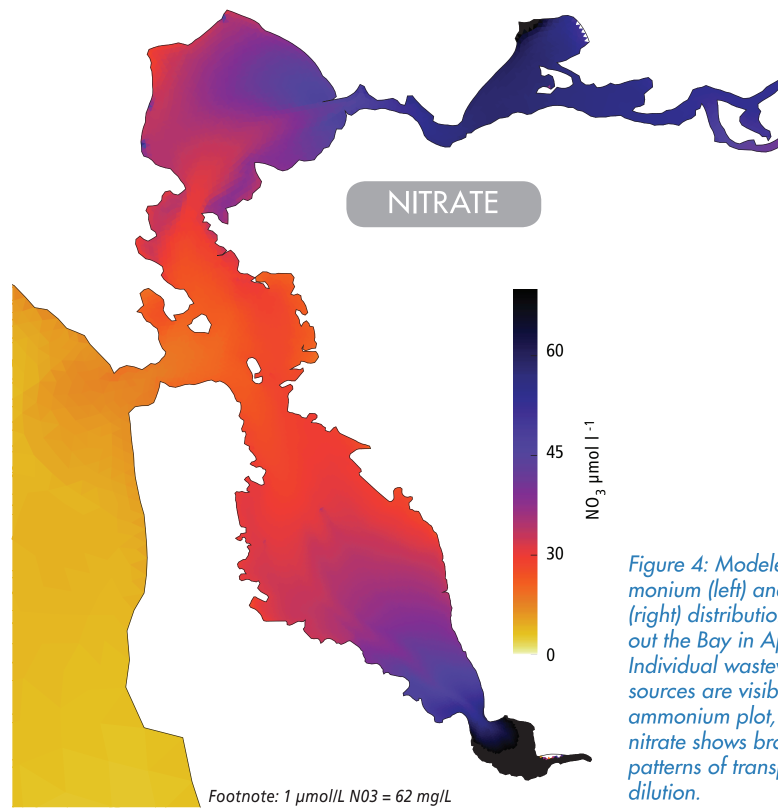


Figure 4: Modeled ammonium (left) and nitrate (right) distributions throughout the Bay in April 2013. Individual wastewater sources are visible in the ammonium plot, while nitrate shows broader patterns of transport and dilution.

The next major step is to include phytoplankton in the water quality model. The data needs for accurately modeling phytoplankton are significant, including estimating the amount of light in the water column available for photosynthesis, and rates of grazing by clams and other organisms. The potential complexity in modeling estuarine water quality is almost limitless, but past research suggests that these processes are the next most important drivers.

We are also working on expanding the geographic reach of the model. These projects have been made possible with additional external funding from sources such as Water Board penalty monies for Supplemental Environmental Projects and direct support from some wastewater agencies. In the north, this has allowed a better representation of Suisun Bay and extension of the model into the Delta. Towards the south end of the Bay, we are developing a highly-refined Lower South Bay model. These extensions to the model have also opened up new opportunities for a greater range of collaborations between SFEI and other groups pursuing mechanistic models in the Bay, an avenue sure to pay dividends in the future.

Thinking Ahead - A Monitoring Program for the Future

While the NMS is drilling down on a few key topics, it is also looking ahead to design a comprehensive long-term observation program for nutrients in the Bay. No matter how well we understand the system now, we can be certain that conditions will change in the future. Therefore, scientists and managers will need a comprehensive observation program for adaptive management and answering new questions.

The observation program is expected to have three major components. The first component is ship-based water column sampling. The current program of biweekly to monthly cruises along the Bay's deep channel is critical, needs to be sustained, and will likely need to incorporate additional measurements. In addition, monitoring needs to target shallow shoal areas, including through high-frequency water quality "mapping", to provide a more complete picture of conditions throughout the Bay. The second component is a moored sensor network, building upon the current NMS program, using high-frequency sensors for near-continuous measurements of water quality parameters that fluctuate with tidal cycles. The third component will be biological sampling, including using bivalves as biomonitors of toxins entering the food web, and, in the future, assessments of populations of fish and sediment-dwelling organisms, coupled with DO measurements in key locations. That core program will be augmented by pilot studies as needed, to test the measurement of new parameters as the program expands, and mechanistic studies aimed at understanding the underlying factors driving DO, phytoplankton abundance, and HABs.

Building this new program is not just a science question but a resource question. Therefore, partnerships and leveraging of other monitoring programs will be a big part of the future observation program. The USGS, which has been monitoring water quality in the Bay since the 1970s, will be a key partner. Partnerships with the Interagency Ecological Program, the National Oceanic and Atmospheric Administration, ocean observing systems, and the Delta Regional Monitoring Program will also be developed, and the partnership with the Bay RMP will continue. Substantial effort will need to be invested toward inter-program coordination and communication, proactively maintaining partnerships, and data sharing. Protocols for data quality assurance will need to be developed to ensure that consistent field and lab methods are used across programs. In FY2018, there are plans for a first step in this direction with a project about intercalibration of fluorometers for Chl-a. The Delta RMP has committed funds to this project already and the NMS is likely to join forces.

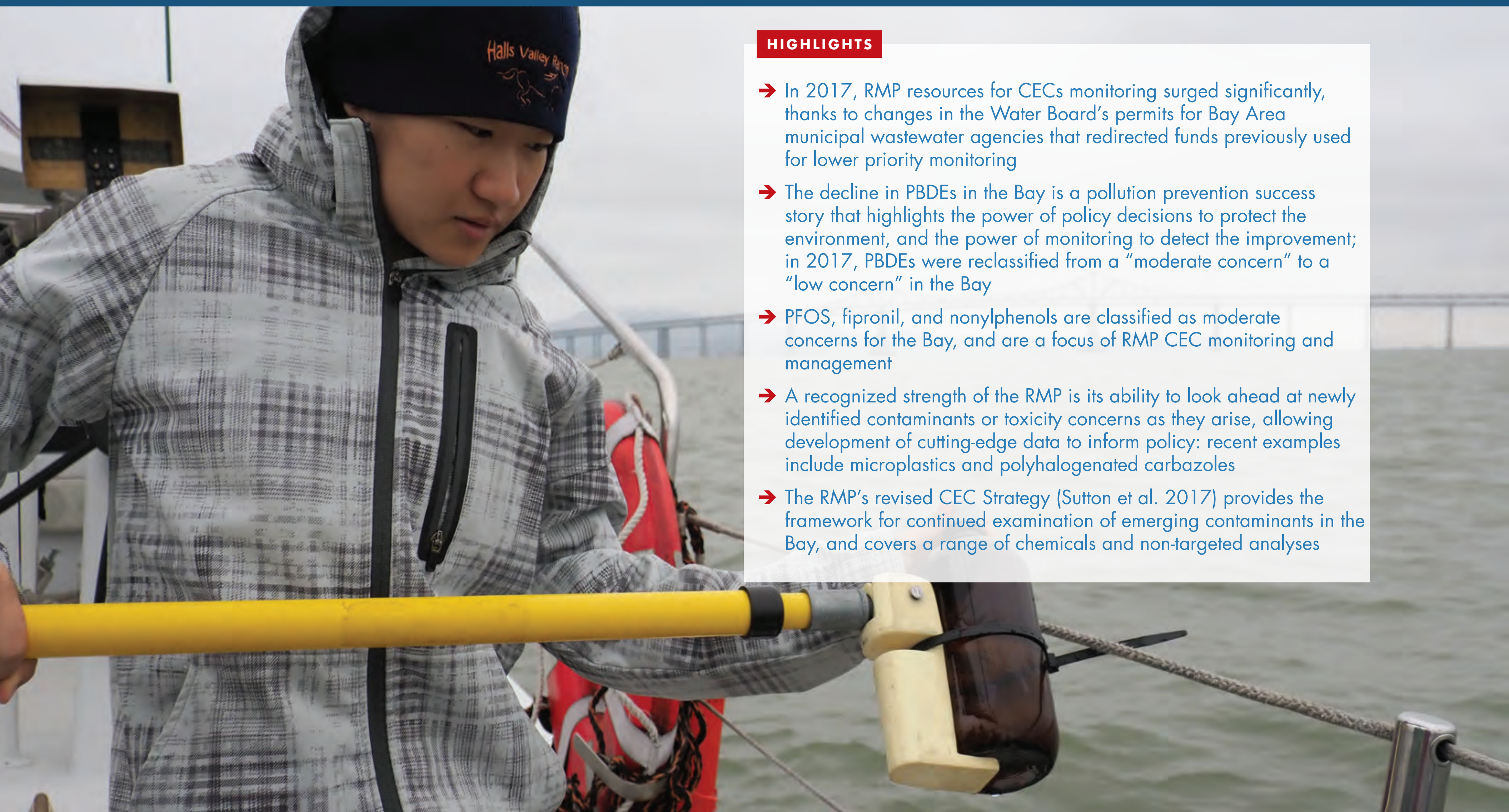
Unravelling the mysteries of nutrients in San Francisco Bay is an enormous challenge. The NMS Science Program is working with collaborators from the region to attack the problem on multiple fronts, and proceeding with careful planning, input from outside experts, and guidance from stakeholders. Long-range planning for a comprehensive observation program is also underway so that the NMS is ready for the next set of challenges and questions. ●

Deploying a CTD profiler and a Niskin water sampler in Central Bay. Photograph by Morgaine McKibben. >


USGS
POLARIS

A Surge in Support for Emerging Contaminant Monitoring

Rebecca Sutton (rebeccas@sfei.org), Meg Sedlak, and Diana Lin, San Francisco Estuary Institute



HIGHLIGHTS

- In 2017, RMP resources for CECs monitoring surged significantly, thanks to changes in the Water Board's permits for Bay Area municipal wastewater agencies that redirected funds previously used for lower priority monitoring
- The decline in PBDEs in the Bay is a pollution prevention success story that highlights the power of policy decisions to protect the environment, and the power of monitoring to detect the improvement; in 2017, PBDEs were reclassified from a "moderate concern" to a "low concern" in the Bay
- PFOS, fipronil, and nonylphenols are classified as moderate concerns for the Bay, and are a focus of RMP CEC monitoring and management
- A recognized strength of the RMP is its ability to look ahead at newly identified contaminants or toxicity concerns as they arise, allowing development of cutting-edge data to inform policy: recent examples include microplastics and polyhalogenated carbazoles
- The RMP's revised CEC Strategy (Sutton et al. 2017) provides the framework for continued examination of emerging contaminants in the Bay, and covers a range of chemicals and non-targeted analyses

In the late 1990s, a convergence of advances in analytical chemistry and molecular biology illuminated a new and wide-ranging set of contaminants with the potential to impact ecosystems worldwide. Major improvements in analytical instruments allowed chemists to identify compounds at parts per billion or trillion levels, providing an unprecedented ability to detect unregulated and previously unknown chemicals in natural systems. Meanwhile, biologists and toxicologists discovered that extremely minute exposures to certain contaminants could trigger outsized impacts to the health of organisms, through critical mechanisms such as disruption of the endocrine system.

These breakthroughs led to an upwelling of investigations into contaminants of emerging concern (CECs), a term that encompasses synthetic or natural compounds that are not regulated or monitored and that have the potential to enter the environment and harm people or wildlife. One of the first major studies of CECs in US surface waters examined 139 rivers and streams across 30 states, and detected contaminants in 80% of sites (Kolpin et al. 2002). Some of these chemicals were easily recognizable to the public, such as caffeine, DEET, and cholesterol; others were less well known, such as triclosan (an antibacterial agent), 4-nonylphenol (a surfactant), and tris(2-chloroethyl) phosphate (a flame retardant). These findings triggered public concern that pharmaceuticals, steroids, hormones, and personal care product ingredients could be found in rivers and streams used for recreational activities, fishing, and drinking water.

At the same time, biologists had begun to identify so-called “intersex fish,” male fish with female characteristics, in natural systems (e.g., Jobling et al. 1998). There was growing concern that trace levels of unregulated contaminants in the environment might be perturbing the endocrine systems that control reproduction, growth, metabolism, and development in a wide variety of species.

< Sampling Bay water for microplastic. Photograph by Shira Bezalel.

It was against this backdrop that RMP stakeholders David Tucker and Karin North led the effort to create the RMP's Emerging Contaminants Workgroup in 2006. According to Tucker, "the goal of this workgroup was to help us develop an early warning system to prevent a contaminant from becoming a pollution challenge in the future." Thanks to this forward-looking leadership, the RMP has conducted monitoring and special studies on CECs for over a decade.

The RMP continues to refine its early warning system, scanning the chemical horizon and providing information needed to protect water quality in San Francisco Bay. In 2017, a major revision to the foundational strategy document that guides the RMP's emerging contaminants focus area was completed (Sutton et al. 2017). The 2017 strategy document reaffirmed the power of the RMP's risk-based approach for CEC evaluation and prioritization. It also underscored the value of examining broad classes of chemicals, as a proactive means of building data on under-studied chemicals that may see future increases in use, with the potential for corresponding increases in environmental contamination.

In 2017 RMP resources for CECs monitoring surged significantly, thanks to changes in the Water Board's permits for Bay Area municipal wastewater agencies. After many years of monitoring for contaminants that were not detected in wastewater effluent, dischargers may now redirect the funds formerly used for this monitoring toward CEC studies. Thanks to this new arrangement, RMP resources for CECs have tripled. The scope and impact of the RMP's CECs science and information will expand significantly in future years.

PBDEs – A Continuing Success Story for San Francisco Bay

The RMP's early monitoring of polybrominated diphenyl ethers, or PBDEs, in San Francisco Bay was part of an extensive body of science that informed multiple regulatory and business decisions designed to ban or phase-out the use of these toxic flame retardants in California and the US. The RMP was able to track the impact of these decisions on the Bay through long-term monitoring, documenting statistically significant declines in these contaminants across multiple matrices (page 77) (Sutton et al. 2015). The decline in PBDEs in San Francisco Bay has been celebrated as a pollution prevention success that highlights the power that such policies have to protect the environment.

This year, 2017, represents a new chapter in the story, when the RMP reduced PBDEs from a "moderate concern" to a "low concern" within the tiered risk framework for CECs in San Francisco Bay **(Figure 1)**. The most recent RMP data on PBDEs relative to available toxicity thresholds now indicates that the contaminants likely no longer pose risks to Bay wildlife. Levels in sediment, fish, and bird eggs now appear to be well below levels of concern; levels in harbor seals are declining, though ecotoxicity information for this species is lacking.

While the declines are auspicious, strategic monitoring of these contaminants must continue. The latest measurements of PBDEs in bivalves indicate a small increase, primarily at sites located at the mouths of the Sacramento and San Joaquin rivers, and possibly driven by drought and related water conservation measures. These and other recent measurements suggest the most dramatic declines in PBDE levels in wildlife may have already occurred. Sediment monitoring will be an essential means of evaluating whether one particular PBDE congener, BDE-209, declines as expected. BDE-209 is primarily found in sediment and is the principal component of the DecaBDE commercial mixture that was phased out of US production in 2013, long after bans and phase-outs of other PBDE mixtures.

Emerging Contaminants of Moderate Concern in San Francisco Bay

Although PBDEs are no longer considered a moderate concern, three other contaminants remain at this level within the RMP's tiered risk framework for CECs, as they are present at concentrations that have the potential to trigger low level impacts to wildlife. Despite diligent surveillance, the RMP has yet to identify an emerging contaminant of high concern, capable of producing higher level impacts.

	TIER ASSIGNMENTS	MANAGEMENT	MONITORING
HIGH CONCERN	No CECs currently in this tier	303(d) listing TMDL or alternative management plan Aggressive control actions for all controllable sources	Studies to support TMDL or an alternative management plan
MODERATE CONCERN	PFOS Fipronil Nonylphenol and nonylphenol ethoxylates	Action plan or strategy Aggressive pollution prevention Low-cost control actions	Consider including in Status and Trends monitoring Special studies of fate, effects, sources, pathways, and loadings
LOW CONCERN	PBDEs HBCD Pyrethroids * Pharmaceuticals and personal care products PBDDs and PBDFs	Low-cost source identification and control Low-level pollution prevention Track product use and market trends	Conduct periodic screening in water, sediment, or biota, or discontinue monitoring Periodic screening in wastewater or urban runoff to track trends
UNCERTAINTY POSSIBLE CONCERN	Alternative flame retardants Microplastic Pesticides PFASs and PHCZs Plastic additives Many, many others	Identify and prioritize contaminants of potential concern, track international efforts Develop targeted and non-targeted analytical methods	Screening in water, sediment, biota, wastewater, urban runoff

* *Pyrethroids are of low concern in the Bay, but high concern in Bay Area urban creeks*

Figure 1. Tiered CEC management and monitoring framework for San Francisco Bay.

PFOS

Perfluorooctane sulfonate (PFOS) is a fully fluorinated, eight carbon chain molecule that is part of a much larger class of compounds referred to as the poly- and perfluoroalkyl substances (PFASs). PFASs including PFOS were widely used for decades due to their chemical stability, useful surfactant properties, and unique oil and water repellency. Notable uses included the popular stain and water repellant Scotchgard, as well as aqueous fire-fighting foams found at airports and military bases. Concern for the toxicity of PFASs has gradually increased. In mammals, PFOS exposure has been associated with compromised immune systems, reproductive and developmental defects, neurotoxicity, and cancer. Recent detection of PFOS and PFASs in grease-proof paper products used by fast food retailers and bakeries (Schaider et al. 2017) have led states including California and Washington to consider bans of fluorinated chemicals in these products.

The carbon-fluorine bond is one of the strongest in nature, making PFOS extremely persistent in the environment. It is also bioaccumulative, and toxic to people and wildlife. In early 2000, PFOS was widely detected in biota and people; as a result, by 2002, US manufacturers voluntarily phased out the manufacture of PFOS and some related PFASs, though exemptions exist for specific uses (e.g., aviation hydraulic fluids) and for imported products. In California, PFOS is being considered for listing as a reproductive toxicant under Proposition 65.

Over the last decade, the RMP has detected PFOS in Bay sediment, water, bivalves, sport fish, bird eggs, and seals (page 76). Concentrations in sediment, water, and bivalves are low compared to other locations in the US. Concentrations of PFOS in sport fish are below PFOS fish consumption guidelines set by Minnesota Department of Health, but occasionally higher than those set by the state of Michigan for high-fish diets (Sun et al. 2017a).

In contrast, elevated concentrations that exceed thresholds of concern have been observed in South Bay bird eggs, driving the classification of PFOS as a moderate concern for the Bay (Sedlak and Greig 2012; Sedlak et al. 2017a). In birds, PFOS has been associated with reduced hatchling success (Newsted et al. 2005). The concentrations of PFOS observed in bird eggs from the South Bay (approximately 500 ng/g ww) have been associated with an approximately 50% decline in hatching success of Midwestern tree swallows (Custer et al. 2013). South Bay harbor seals also show unusually high levels of PFOS contamination, though ecotoxicity information specific to this species is not available.

Though the US production phase-out occurred 15 years ago, only the most recent monitoring data show early signs of a potential decline in PFOS contamination of Bay birds and seals (Sedlak et al. 2017a). Declines in wastewater were also suggested by recent data collected through a collaboration between the RMP and the California Department of Toxic Substances Control (DTSC; Houtz et al. 2016). While hydrology may drive the particular persistence of PFOS in wildlife in the poorly flushed South Bay, other factors unique to the PFAS family may be at play.

For example, some chemicals within the 3,000-member PFAS family can break down to form PFOS in the environment. So-called “PFOS precursors” have been identified in Bay Area wastewater, stormwater, and sediment (Higgins et al. 2005; Houtz and Sedlak 2012; Houtz et al. 2016; Sedlak et al. 2017a). Ongoing sources of PFOS to the Bay may therefore include remnants of past PFOS use leaching from point sources such as military facilities, airports, and landfills, as well as current uses of PFOS precursors.

This highlights a broader concern relating to “regrettable substitution,” whereby a well-established toxic compound is removed from commerce, only to be replaced by a relatively unknown compound of potentially equal or greater concern. While a number of regulatory restrictions have been put in place to limit the use of PFOS and other eight-carbon and longer perfluorinated compounds, replacement compounds from the PFAS family are suspected of having similar concerns relating to persistence and toxicity.

As industry moves to shorter-chained alternatives (four and six carbon chains) and to other members of the PFAS family including PFOS precursors, the RMP is pursuing new techniques such as non-targeted methods to identify and track them. The RMP will continue to monitor bird eggs to assess trends in PFASs, and plans to conduct special studies to track specific alternatives. More details on the RMP PFOS strategy can be found in the 2017 PFAS Synthesis and Strategy document that is currently under review (Sedlak et al. 2017b).

Fipronil

Fipronil is a phenylpyrazole pesticide that is widely used in urban environments to control ants, fleas, and ticks. As an alternative to pyrethroids, the use of fipronil has increased dramatically in the last decade. It is present in the environment as fipronil, as well as breakdown products, primarily fipronil sulfide, fipronil sulfone, and desulfinyl fipronil. Fipronil and its degradates have been detected in Bay watersheds at concentrations that exceed the USEPA aquatic life benchmark for chronic toxicity to freshwater invertebrates.

The RMP has routinely monitored fipronil and its breakdown products in Bay sediment since 2009. Levels have ranged as high as approximately 0.56 parts per billion (dry weight) for fipronil sulfone in a Lower South Bay sample in 2010, comparable to concentrations causing harm to freshwater invertebrates in laboratory experiments (Maul et al. 2008). The most recent RMP sediment monitoring data, from 2014, featured detections of this degradate at levels similar to this toxicity threshold.

To further examine the pathways by which this contaminant class reaches San Francisco Bay, in 2016 the RMP monitored wastewater influent and effluent from eight Bay municipal wastewater treatment plants for fipronil and its degradates (page 78) (Sadaria et al. 2017). The study revealed the ubiquity and persistence of fipronil and degradates during conventional wastewater treatment, with no clear differences among secondary versus advanced facilities. Scientists from the study team, which included the California Department of Pesticide Regulation (DPR), assessed the concentrations and concluded that a primary source of contamination is likely to be pet flea control products. Fipronil is undergoing reviews by DPR and USEPA aimed at reducing environmental contamination and the ecological impacts of the pesticide; the RMP study will inform these reviews.

Ongoing RMP work on this moderate concern contaminant will include monitoring ambient Bay sediment, as well as water and sediment in South and Lower South Bay margins. Findings may inform state and federal efforts to reduce the impacts of this pesticide on the environment.

Sampling municipal wastewater for microplastic. Photograph by Meg Sedlak. >

Nonylphenol

Nonylphenol ethoxylates (NPEs) are a broad class of surfactants used in a variety of industrial and consumer applications, including cleaners, paints, textiles, paper, and applications for oil and process industries. NPEs were once common in laundry detergents, but industry has largely phased out this particular use due to concerns about their toxicity. NPEs are produced and used in high volumes in the US, on the order of hundreds of million pounds, and are widely detected in the environment (USEPA 2010). NPEs degrade to form shorter chain NPEs and nonylphenol, an endocrine disruptor that is toxic to aquatic species and bioaccumulates.

A few key members of this class, specifically nonylphenol and nonylphenol mono- and diethoxylates, have been quantified in RMP samples, most recently in 2010. Concentrations in Bay sediment, bivalves, small fish, and bird eggs are high compared to other CECs. However, they appear to be below most available toxicity thresholds. Moderate concern for the Bay remains, due in part to the potential for synergistic impacts with other widely observed, estrogenic contaminants, such as pesticides. Preliminary results from a recent exploratory, qualitative broad scan of contaminants in water samples identified many other members of the NPE family as present in the Bay, with particularly high abundance at a Bay site influenced by stormwater discharges. The broad array of NPEs identified have not been quantified in Bay samples previously.

Since NPEs are used in so many different applications, the potential sources are broad and unknown. Wastewater treatment plant effluent was traditionally a dominant pollution pathway due to use in laundry detergents. Existing, wastewater-specific uses in textiles, cleaning products, or other household and industrial products likely continue to contribute to discharge via this pathway. However, recent non-targeted analysis suggests that Bay stormwater may be an important pathway for nonylphenol and NPEs to enter the Bay environment. European studies found that as NPEs were phased out of residential products, the relative NPE contribution of stormwater runoff has increased, with sources possibly dominated by car products and concrete (Kjolhølt et al. 2007; Björklund 2010).

The European Union and Canada prohibit or restrict the use of NP and NPEs due to concerns for harmful environmental effects. While nonylphenol and NPEs are not currently regulated in the US or California, both USEPA and DTSC are gathering information on these compounds with the ultimate goal of reducing environmental contamination. The RMP does not regularly monitor the Bay for members of this contaminant class, but in 2017 collected and archived sediment samples from the South Bay and Lower South Bay margins for later analysis, if this is warranted. Data from such an effort may inform state and federal pollution prevention activities.

Scanning the Scientific Horizon for Emerging Issues

A recognized strength of the RMP is its ability to look ahead at newly identified contaminants or toxicity concerns as they arise, allowing development of cutting-edge data to inform policy. For example, a small RMP screening study on microbeads and microplastic placed the Bay at the forefront of this emerging contamination issue (**Sidebar** page 41). RMP findings ultimately informed state and federal pollution prevention regulations, and catalyzed formation of an independent RMP workgroup.

Another recent example arose from a pro bono collaboration with Dr. Da Chen, an academic partner at Southern Illinois University. Chen and collaborators recently discovered a class of environmental contaminants, polyhalogenated carbazoles (PHCZs), in sediment samples from the Great Lakes. PHCZs have chemical properties similar to PBDEs and PCBs, including the potential to be persistent, bioaccumulative, and toxic. Analysis of RMP samples indicates this class of newly discovered contaminants is ubiquitous in Bay sediment and biota including bivalves, sport fish, cormorants, and harbor seals (page 79) (Wu et al. 2017). While the true impact of levels of PHCZs on Bay wildlife cannot be evaluated due to the lack of established toxicity thresholds, studies such as this one are expected to motivate the scientific community to fill this major data gap. Information concerning potential sources of PHCZs is also lacking. Studies indicate that PHCZs can be derived from both natural sources (such as marine fungus) and anthropogenic sources, the latter including halogenated indigo dyes and polymer production for electronics (Fang et al. 2016; Wu et al. 2017). For now, the RMP considers PHCZs a possible concern for the Bay, and will pursue further pro bono study opportunities.

A recognized strength of the RMP is its ability to look ahead at newly identified contaminants or toxicity concerns as they arise, allowing development of cutting-edge data to inform policy

Microplastic

by Meg Sedlak

Plastic has become a cornerstone of modern life. Cheap, versatile, and durable, it is estimated that one third of manufactured plastic is used for packaging, another third for building materials, and the remaining third for miscellaneous applications such as automobile parts, furniture, and the ubiquitous plastic toy (Andrady and Neal 2009). In the last 50 years, plastic production has grown exponentially, from 15 million tons in the 1960s to 311 million tons in 2014 (World Economic Forum 2016).

An unfortunate consequence of the widespread use of plastic is that approximately eight million tons of discarded plastic ends up in the ocean every year (Jambeck et al. 2015). While many are familiar with the Great Pacific garbage patch of floating plastic debris in the Pacific Ocean, only recently has a less visible form of plastic, microplastic, been widely recognized as a potentially significant issue for marine life. Microplastic can be a physical hazard, as ingestion can lead to lacerations or obstructions. It may also be a vector for contaminants that are adsorbed to the plastic, such as PCBs or PBDEs, or embedded in the plastic, such as flame retardants, plasticizers, or dyes.

A microplastic sampling jar. Photograph by Shira Bezalel. ∧

Defined as plastic particles that are less than 5 mm in size, microplastic is a chemically and physically diverse contaminant class comprised of a myriad of plastic types including polyethylene, polypropylene, polystyrene, polyester and polystyrene. The morphology of microplastic particles provides clues as to their origins. Microfibers may be shed from clothing, textiles, or fishing lines; rounded, bead-like pellets may be derived from pre-production plastic "nurdles" or washoff microbeads from facial cleansers, toothpaste, or other personal care products; and films and foam bits may derive from weathered and fragmented packing materials.

In 2014, the RMP embarked on a small study to assess whether microplastic was present in San Francisco Bay surface water and Bay Area effluent. The results indicated surprisingly high concentrations in water and effluent. RMP findings received considerable media coverage and informed state and federal legislation to ban microbeads in personal care products. In response, the RMP convened a workshop with RMP stakeholders, regional scientists, and national experts to articulate priority management questions for this new contaminant. Based on the management questions, RMP staff, in consultation with experts and BACWA, developed a Microplastic Strategy (Sutton and Sedlak 2017) to monitor Bay sediment, surface water, and small fish; potential pathways such as wastewater effluent and stormwater runoff; and surface water in the sanctuaries just outside of the Golden Gate.

The first two years of the Strategy are largely being funded by a generous grant from the Gordon and Betty Moore Foundation, and will be conducted in partnership with the 5 Gyres Institute. Results from the study will be used to develop a fate and transport model of microplastic migration in the Bay and Pacific Ocean, as well as policy recommendations, educational outreach materials, and scientific papers. We will convene a symposium in early 2019 to share the findings – stayed tuned for details!

The RMP also supports development of non-targeted monitoring tools, to provide a measure of assurance that unexpected yet potentially harmful contaminants do not escape notice simply because of failures to predict their occurrence. Two alternative tools are used: broadscan screening (also known as non-targeted analysis) and bioanalytical assays.

Investigations using non-targeted analysis to screen for CECs are useful for creating an inventory of compounds that accumulate in tissues, or that are present in water or sediment. Findings from these investigations can be used to inform targeted chemical monitoring or toxicity studies. Preliminary findings from the most recent broadscan study, focused on identifying polar or water-soluble compounds in Bay water and treated wastewater samples, suggest the presence of a number of contaminants that have not yet been the subject of RMP study. Tentatively identified chemicals include an array of nonylphenol ethoxylates, as noted above, as well as a wide range of polyethoxylated surfactants; the largest number and most intense contaminant signals were associated with samples from a site in San Leandro Bay heavily influenced by stormwater, suggesting this pollution pathway may merit examination in the future. Of course, the mere presence of a contaminant does not connote risk. Once the study is completed, by the end of 2017, a thorough examination of the literature for ecotoxicity data will allow the RMP to select appropriate targets for future, quantitative monitoring.

Bioanalytical tools screen for the cumulative impacts of classes of chemicals that share a common mode of toxic action in the aquatic species. Existing bioanalytical tools, which indicate whether tested matrices have the potential to elicit biological responses in cells, show promise as a complementary monitoring technique. In 2013, the RMP sponsored a project to link estrogenic effects on cells to effects in whole organisms. Researchers at University of Florida and the Southern California Coastal Water Research Project used the inland silverside, a species present in the Bay, to evaluate the estrogenicity of compounds including estrone, 17 β-estradiol, and nonylphenol. The results established quantitative linkages between the screening levels in the *in vitro* cell-based assays and higher order *in vivo* responses in fish that are influenced by estrogen, such as growth and gonadal sex differentiation (Denslow et al. 2017). As expected, the *in vitro* responses occurred at far lower levels than *in vivo* responses, meaning the bioassays can be used as a screening tool for estrogenic impacts that provides a margin of safety. The RMP has provided additional funds for the research team to refine the estrogenicity bioanalytical tool and then screen Bay water and sediment samples from South Bay with the bioassay.

< Sampling stormwater for microplastic. Photograph by Meg Sedlak.

Looking Forward

The RMP's revised CEC Strategy (Sutton et al. 2017) provides the framework for continued examination of emerging contaminants in San Francisco Bay. The RMP first published a formal CEC Strategy in 2013, as part of a continuous effort to refine approaches for supporting the management of CECs in the Bay. The revised Strategy lays out an expanded set of management questions to guide design of special studies, and formalizes an annual cycle of program activities.

It also describes three major strategy elements. Two of these elements, the tiered risk framework and non-targeted monitoring, have been described above. The third element of the RMP CEC Strategy involves review of the scientific literature and other CEC monitoring programs as a means of identifying new CECs for which no Bay occurrence data yet exist. Initial monitoring to establish the presence of these newly identified CECs in the Bay is needed to evaluate the risks they may pose.

The RMP's multi-faceted approach to addressing the challenge of CECs is designed to be flexible and adaptive to new data from both the RMP and other sources. The multi-year plan outlining monitoring and science priorities suggests a series of special studies for PFASs including the moderate concern PFOS, and a more limited range of studies for fipronil and nonylphenols and NPEs. Targeted special studies are also recommended for alternative flame retardants, pharmaceuticals, plastic additives, personal care and cleaning product ingredients, and current use pesticides. Exploration of Bay sediment via non-targeted analysis is proposed. Finally, modifications to the CECs analyses included in routine RMP Status and Trends monitoring are also suggested.

The additional resources available for CECs monitoring in 2017 have been channeled into a number of studies. Neonicotinoid pesticides like imidacloprid, phosphate-based flame retardants, and bisphenol-based plastic additives will all be measured in water samples collected in conjunction with the RMP's Status and Trends water cruise. Triclosan and methyl triclosan will be evaluated in fish collected in the Lower South Bay, leveraging existing, external collection activities.

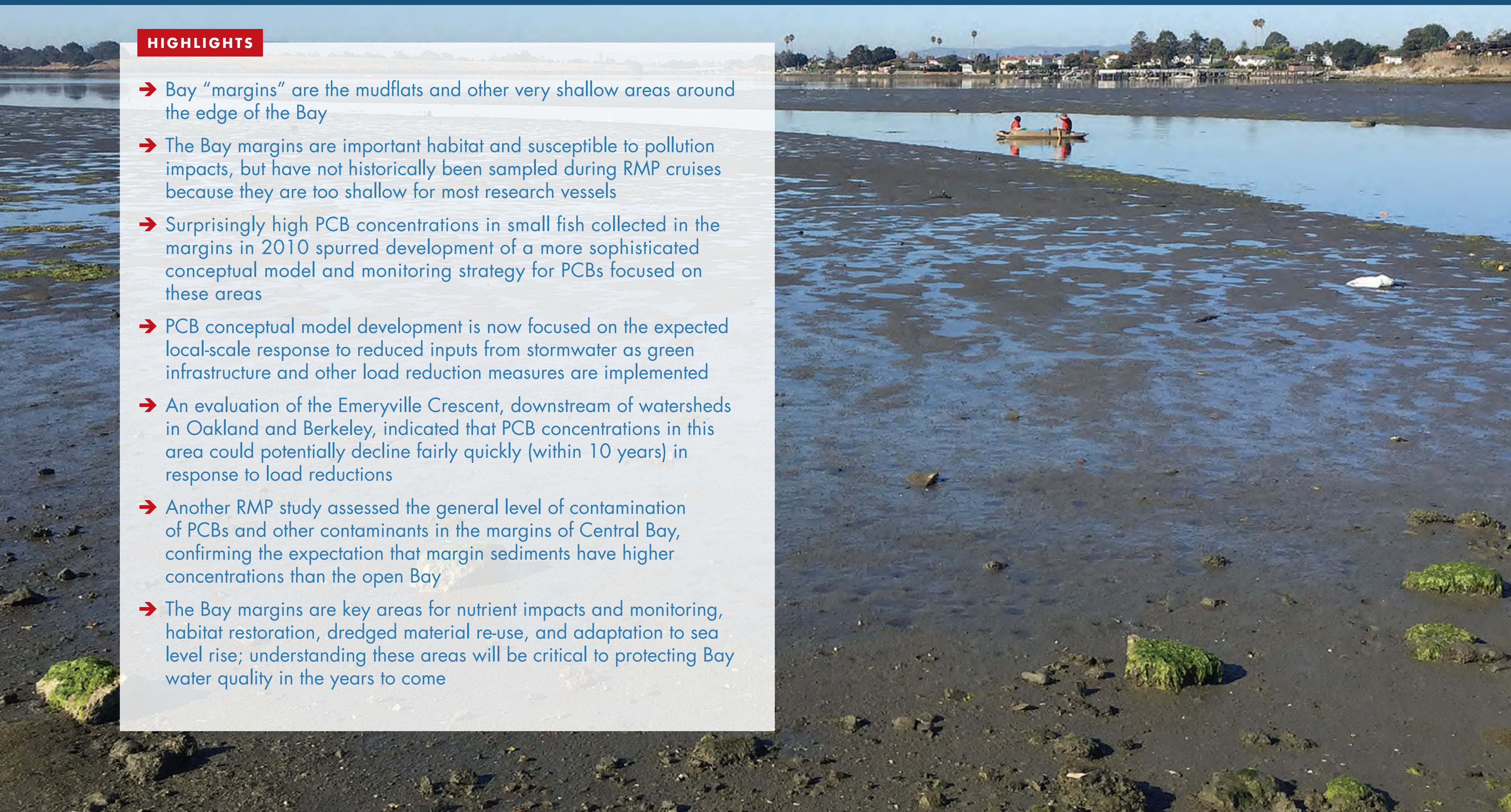
Key studies funded with the 2018 budget leverage the RMP's South and Lower South Bay margin sediment monitoring activities in the summer of 2017, providing considerable information on levels of CECs in a portion of the Bay that is important habitat for wildlife, and located near stormwater and wastewater discharges burdened by urban pollution. Another 2018 Special Study provides quality assurance review to data on pharmaceuticals in wastewater, an independent analysis funded by participating wastewater agencies in the Bay Area; modeling will be used to determine whether any pharmaceuticals detected in treated effluent merit examination in the Bay. By leveraging RMP and external monitoring activities, the additional RMP CECs funding is channeled directly to analysis of emerging contaminants prioritized as part of the CEC strategy, with little to no resources expended on administration or operations.

The overarching goal of the RMP's CEC activities is to develop cost-effective strategies to identify and monitor these contaminants to support management actions that minimize impacts to the Bay. The RMP has generated one of the world's most comprehensive datasets for CECs in an estuary. When possible and appropriate, data are made publicly available via CEDEN.

Despite the considerable challenges posed by the study and management of emerging contaminants, the RMP has established a proven track record in providing high-impact data and information to help craft meaningful pollution prevention approaches and informing management decision-making at the local level and beyond. Newly expanded funding will allow the RMP to enhance its efforts to screen for CECs and, where potential risks are identified, conduct more refined studies that better inform policy. Future work in this field will build on RMP successes and help to better protect San Francisco Bay.

The Critical Edge: Insights into Water Quality in the Bay Margins After 15 Years

by Phil Trowbridge (philt@sfei.org),
San Fancisco Estuary Institute



HIGHLIGHTS

- Bay "margins" are the mudflats and other very shallow areas around the edge of the Bay
- The Bay margins are important habitat and susceptible to pollution impacts, but have not historically been sampled during RMP cruises because they are too shallow for most research vessels
- Surprisingly high PCB concentrations in small fish collected in the margins in 2010 spurred development of a more sophisticated conceptual model and monitoring strategy for PCBs focused on these areas
- PCB conceptual model development is now focused on the expected local-scale response to reduced inputs from stormwater as green infrastructure and other load reduction measures are implemented
- An evaluation of the Emeryville Crescent, downstream of watersheds in Oakland and Berkeley, indicated that PCB concentrations in this area could potentially decline fairly quickly (within 10 years) in response to load reductions
- Another RMP study assessed the general level of contamination of PCBs and other contaminants in the margins of Central Bay, confirming the expectation that margin sediments have higher concentrations than the open Bay
- The Bay margins are key areas for nutrient impacts and monitoring, habitat restoration, dredged material re-use, and adaptation to sea level rise; understanding these areas will be critical to protecting Bay water quality in the years to come

If you have ever stood on the shore of the Bay and looked out over the mudflats and shallow waters, you know something about the margins of the Bay. In fact, between the Bay Trail, public beaches, regional shorelines, and the Embarcadero, the margins are the most commonly seen areas of the Bay. It is therefore surprising that, while swimmers, fishers, and windsurfers have a firsthand knowledge of these areas, RMP scientists are just starting to understand the importance of the Bay margins to water quality. There are limited data for this part of the Bay and getting new data is challenging. The margins have not been sampled during the routine RMP cruises because they are too shallow for the research vessel, and the long stretches of sticky mudflats make them difficult to access from land.

While small in area compared to the rest of the Bay, the margins are long in length, shallow in depth and ecologically very important. For perspective, they only account for 15% of the area of the Bay (**Figure 1**). Yet, the margins provide nursery habitat for many fish and other wildlife. A diverse mixture of wildlife uses this area, which changes from water to exposed mudflat twice per day with the tides.

< Sample collection in the margins of San Leandro Bay. Photograph by Don Yee.

What are the Bay margins?

Bay "margins" are the mudflats and very shallow areas around the edge of the Bay. The figure on this page shows the approximate area covered by margins using the RMP's relatively narrow definition of unvegetated areas between the high tide line and one foot below mean lower low water. The extent of margin areas around the Bay could be larger if a different definition were used. Functionally, wetland, margin, and Bay ecosystems overlap and are interconnected, so definitions or delineations of "margin" boundaries are flexible and context dependent.

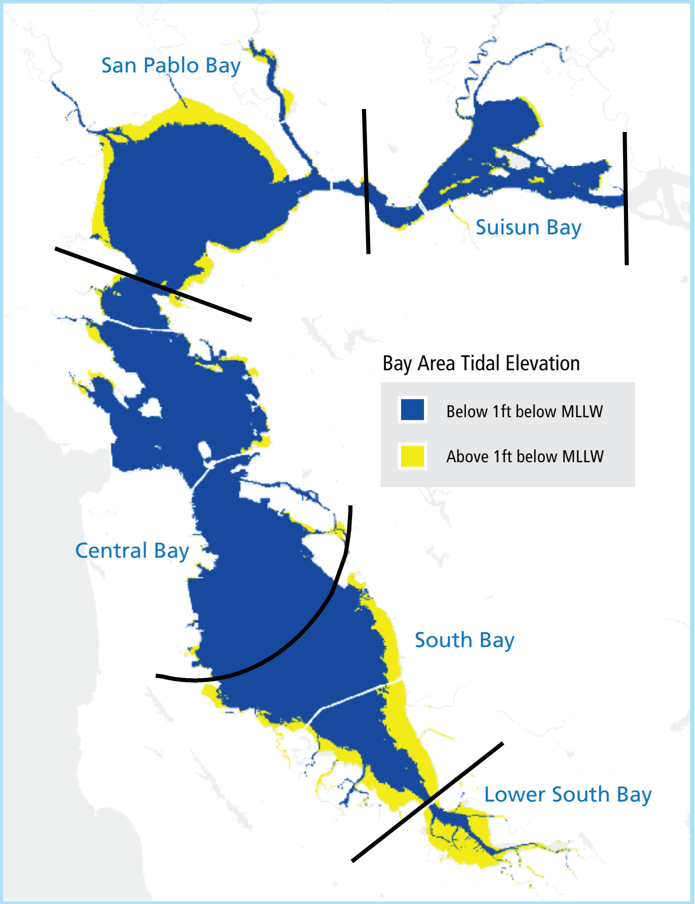


Figure 1: Margin areas in San Francisco Bay

Aside from their importance as habitats, the margins play important roles in Bay water quality. They serve as a link between the open Bay and pollution sources on the land. Contaminants from land are discharged to and settle in the margins, then bioaccumulate in birds, fishes, and other creatures feeding there. Because margins trap contaminants near their entry points to the Bay, they may be good locations to measure progress on reducing pollutant loads. The margins may respond faster to pollution control than the waters and sediments of the deeper Bay. Margins are also ground zero for changes due to sea level rise and a focal point for restoration activity. For all these reasons, margins are the critical edge of the Bay. We need to understand the nature of the Bay margins to answer basic questions about the Bay as a whole.

What Have We Learned So Far?

Studying the margins may seem like a new focus for the RMP, but actually the first steps to understanding these shoreline regions occurred in 2002. The RMP's quest to understand water quality in the margins and how it affects the rest of the Bay is outlined in the following sections.

2002: Branching Out from the "Spine of the Bay"

In 2002, the RMP took its first major step toward monitoring the Bay margins by switching from collecting samples primarily along the "spine of the Bay" (the deep channel that runs the length of the Bay) to collecting samples throughout the Bay. The new spatially randomized design greatly expanded the area monitored by the RMP, including the shallower shoal areas near the shore. Whereas the RMP sites previously fell on a single line (**Figure 2**), the newer sites were more widely distributed, almost to the edges of the Bay in many areas (**Figure 3**). The Water Board and others had collected some data in the margins near sources, but it was not known how widespread or severe contamination was within the broader context of the whole Bay. While the new RMP monitoring design did not extend into what we now call the "Bay margins" (see definition on page 45), the expansion of the RMP design to the shallow shoal areas was a major step toward acknowledging the importance of the margins.

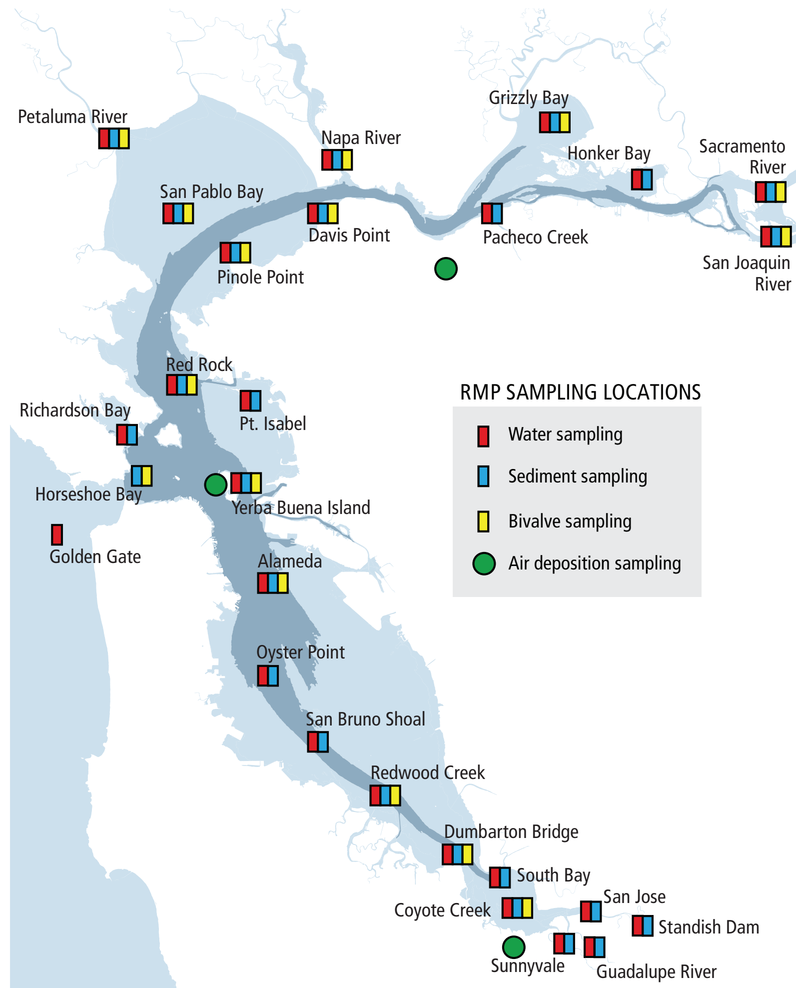


Figure 2: Pre-2002 RMP Monitoring Design

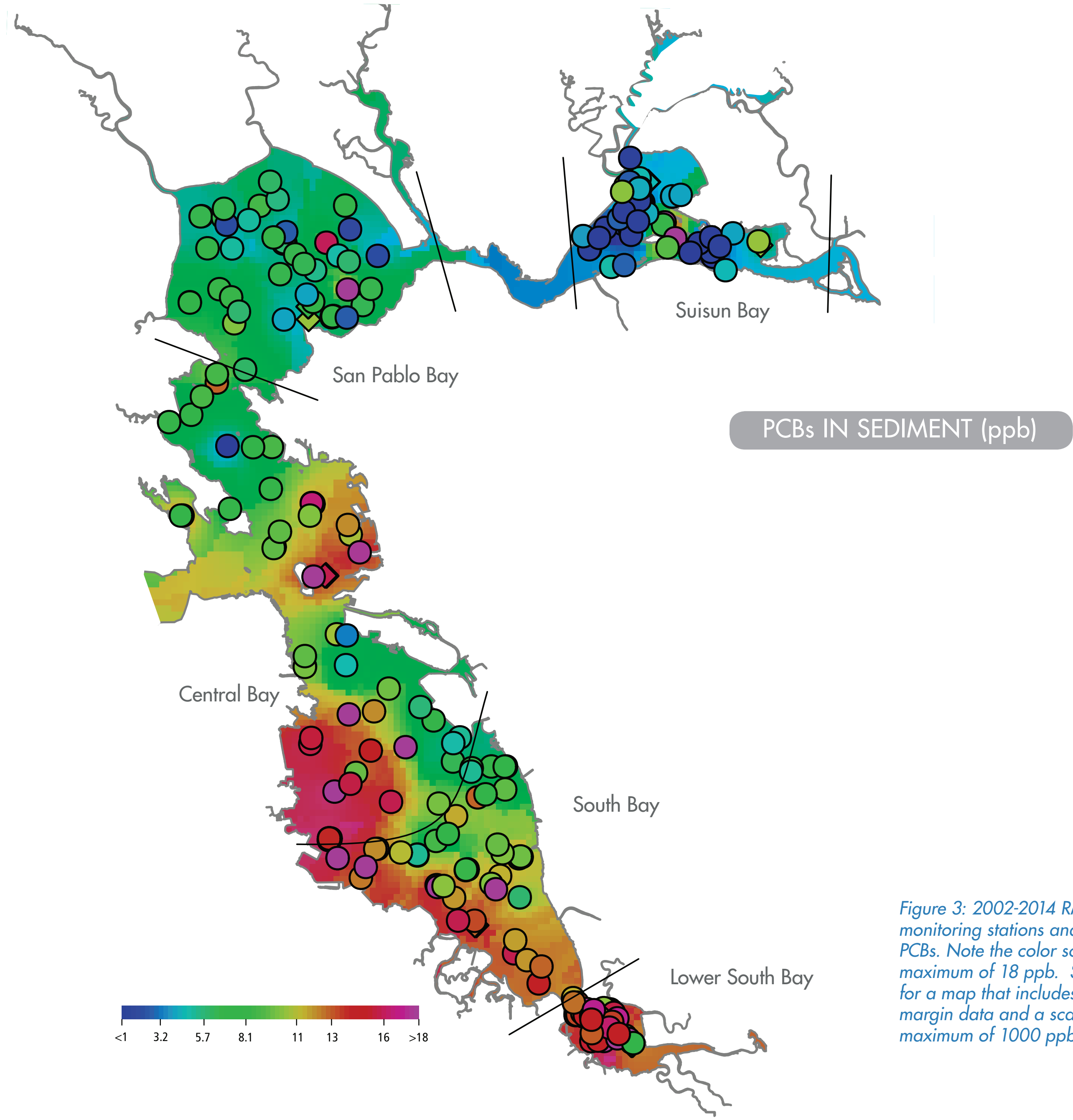


Figure 3: 2002-2014 RMP sediment monitoring stations and results for PCBs. Note the color scale has a maximum of 18 ppb. See page 71 for a map that includes the 2015 margin data and a scale that has a maximum of 1000 ppb.

2010: Small Fish Drive a Shift in Attention to the Margins

Data collected using the new monitoring design showed that some areas near the margins had higher levels of contamination (**Figure 3**). This observation was one of the factors that led the RMP to conduct a study in 2010 of small forage fish that live in the margins of the Bay. The study measured PCB concentrations in the tissue of two forage fish species (also called "prey fish"). Fish were collected from 12 sites near historically polluted locations and from 17 spatially randomized sites meant to be representative of ambient conditions (Greenfield and Allen 2013). One goal of the study was to test for differences in the contaminant concentrations in the fish near the polluted sites and ambient sites.

These small fish accumulated surprisingly high concentrations of PCBs in many locations, frequently exceeding the highest concentrations measured in Bay sport fish that are higher in the food chain. The highest PCB concentrations were observed in samples from margin sites with well-documented historic contamination (Hunters Point, Stege Marsh, and Oakland Harbor) (**Figure 4**). The high PCB concentrations observed in prey fish in spite of their low position in the food chain, along with the correlation of concentrations in fish with gradients in sediment contamination, suggested that bioaccumulation from contaminated margin sites was an important factor in the persistent exposure observed in some Bay fish and wildlife.

A more detailed conceptual model for PCBs in the Bay was needed to explain the results of the Forage Fish Study. The Study greatly enhanced our understanding of PCB contamination of the Bay food web and pathways of exposure for sensitive wildlife species such as birds and seals through their use of Bay margins.

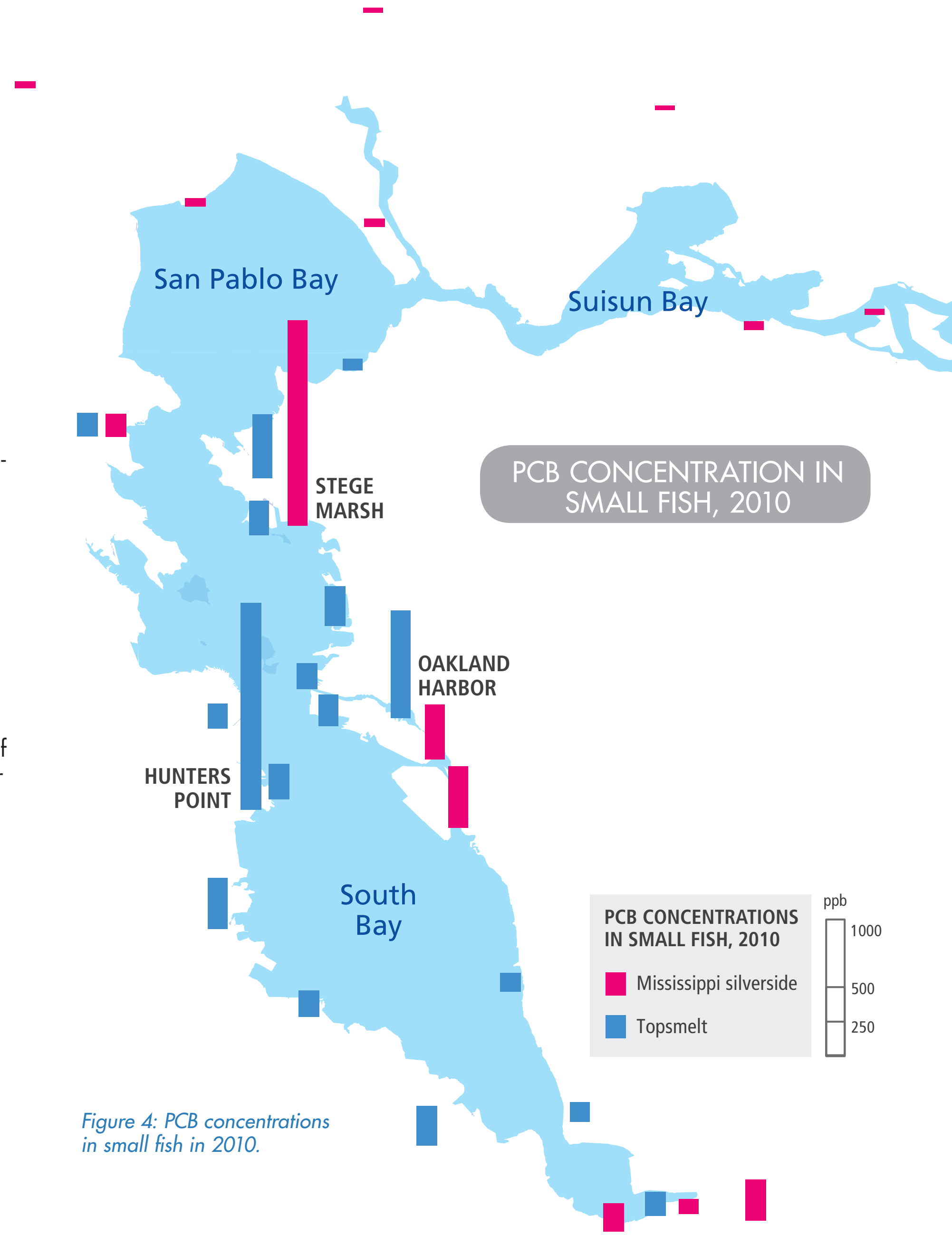


Figure 4: PCB concentrations in small fish in 2010.

2012-2014: Back to the Conceptual Drawing Board

As a result of the Forage Fish Study, the RMP reconsidered the conceptual models for fate and transport of pollutants in the Bay. First, in 2012, the RMP developed a conceptual model for processes in margin areas (Jones et al. 2012). The report highlighted the importance of local sources and loads on conditions in different margin areas, as illustrated by sediment loads. Although no individual local watershed delivers anywhere near the total quantity of sediment coming from the Delta, local tributaries are often a dominant influence on nearby Bay margins, and the combined sediment load from all local watersheds is comparable to that from the Delta (McKee et al. 2013). Also, based on the results of the Forage Fish Study, it was hypothesized that bioaccumulation of contaminants by forage fish in the margins could be a major factor contributing to elevated fish tissue concentrations throughout the Bay.

The 2014 PCB Synthesis (Davis et al. 2014) further developed the new conceptual model for margin areas. For the PCB TMDL, a single box model was used to represent PCB fate processes in the whole Bay (SFBRWQCB 2008). The PCB Synthesis concluded that this model over-simplified patterns of PCB distribution and recovery in the Bay. The data indicated that there are two broad habitat categories with food webs that only partially overlap or exchange: the margins and the open Bay. Therefore, a multi-box model (**Figure 5**) with multiple margin areas and the open Bay would be more accurate. The new model hypothesized that margin areas could deliver PCBs to the open Bay, not just through the movement of contaminated water and sediment, but also through bioaccumulation of PCBs into fish living in the margins. In addition, reduced contamination in the open Bay or nearby margin areas would show limited direct benefit to other margin units. Local-scale actions within a margin area, or in upstream watersheds, would be needed to reduce exposure within each area.

The RMP's PCB Strategy was updated in 2014 in response to the PCB Synthesis (Davis et al. 2014). The Strategy called for a multi-year effort based on the new conceptual model. The approach included developing site-specific conceptual models and performing detailed studies of PCBs in priority margin areas downstream of watersheds where pollution loads are thought to be higher and where management actions were likely to have greater impact or are being planned. The RMP began implementing this plan in 2015, starting with the Emeryville Crescent (Davis et al. 2017).

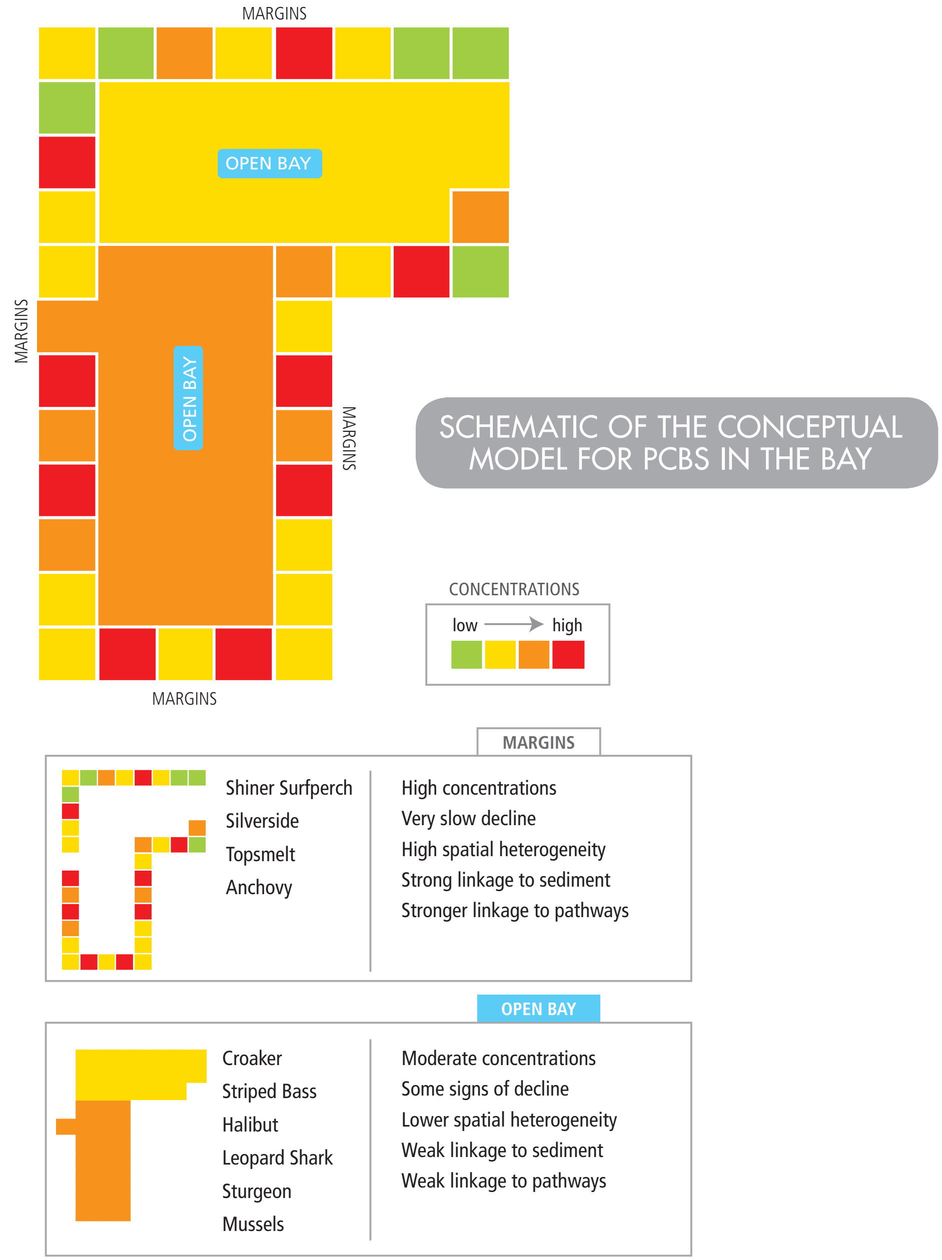


Figure 5: Revised conceptual model for PCBs in the Bay.

2016-2017: The Emeryville Crescent Test Case Hints at Fast Response

An assessment of Emeryville Crescent established a conceptual model as a foundation for monitoring response to load reductions and for planning management actions. The study evaluated whether the following key management questions could be answered.

- Can we expect a decline in any compartment of the margin unit in response to projected load reductions in the margin area's watersheds?
- How should tributary loads be managed to maximize margin area recovery?
- How should the margin area be monitored to detect the expected reduction?

Information on inputs of water, sediment, and PCBs from the urban watersheds was combined with simple models of transport and processes in the margin areas to estimate mass balances in the Crescent. In addition, the expected food web in the margin area was evaluated to determine the best indicator species for monitoring trends (**Figure 6**).

The key finding was that PCB concentrations in sediment and the food web could potentially decline fairly quickly (within 10 years) in response to load reductions from the watershed. This conclusion suggests that it would be possible to "move the needle" for PCB contamination in at least some of the margin areas that are contributing to the regional PCB problem. The report also used detailed information on PCB loads to identify areas of the surrounding watersheds wherein early actions would achieve the greatest load reductions to the margin area. For example, the following management actions could be implemented in the watershed to reduce PCB loads to the margin area: cleanup and abatement of contaminated properties, annual cleanouts of wet wells, pre-treatment of runoff, bioretention tree well filters, and media filters in pump stations. For monitoring the effects of load reductions, the authors recommended annual monitoring of PCB concentrations in forage fish and periodic monitoring of shiner surfperch. The food web conceptual model indicated that these species would be the best indicators of bioaccumulation in the margin area, harkening back to the design of the Forage Fish Study. Monitoring for trends in PCB loads from the watershed and concentrations near inputs with sediment traps to assess effectiveness of actions was also recommended especially in relation to documentation of management efforts.

Aerial view of the Emeryville Crescent and location on the eastern side of San Francisco Bay (inset).

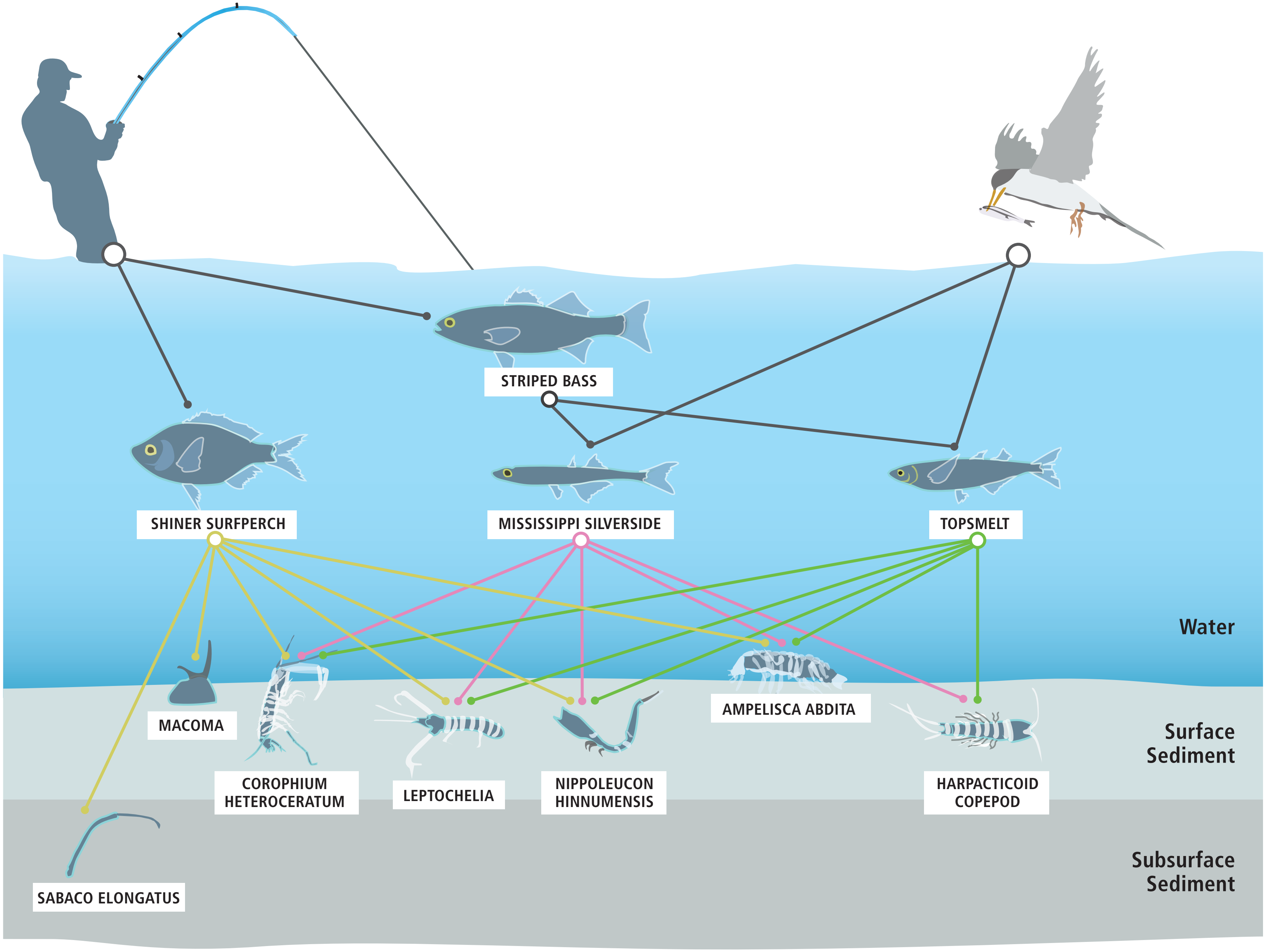


Figure 6: Schematic of the Emeryville Crescent food web for species of interest.

2015-2017: Starting to Determine "Background"

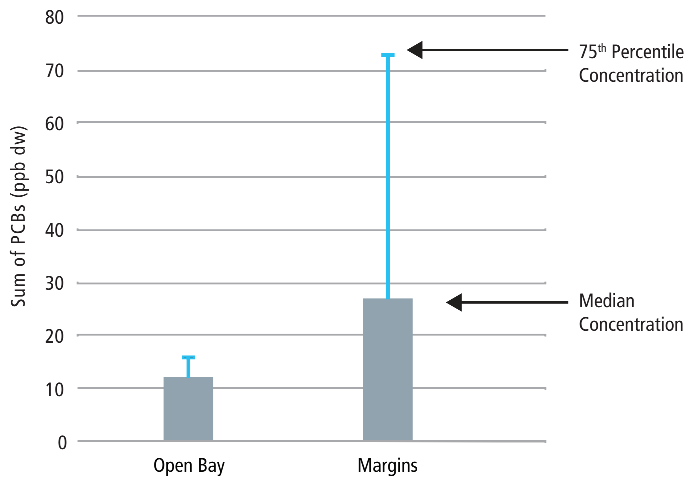
Knowledge about typical ambient conditions is a crucial piece of information for understanding margin contamination. This type of assessment has been conducted along the spine of the Bay for 25 years and since 2002 for the open Bay, but most of the margins have not been assessed. Most of the available data for the margins were collected during targeted investigations, particularly at contaminant hotspots. Without a measure of ambient concentrations in the margins, comparative assessments of exposure and risks would have to rely on data from the open Bay or contaminated hotspots, both of which would be misleading. Therefore, in 2015, the RMP conducted a study to provide an unbiased, spatially distributed characterization of sediment contamination in Central Bay margin areas.

The results of the study generally confirmed the conceptual model expectation that the margin sediments are more contaminated than those in the subtidal open Bay. PCB concentrations in sediment showed the largest differences between margins and open Bay (4-5 times higher on average, **Figure 7**) (Yee et al. 2017). These differences between Central Bay margins and open water areas are likely the largest to be found in San Francisco Bay, as margins in other Bay segments generally account for more of the total area, and the adjacent land use is less heavily industrial.

The ambient concentrations were also used to improve estimates of contaminant inventories in margins. For example, based on data from this study, contamination in the margin areas accounted for 20% of PCBs in Central Bay, which is disproportionately high compared to the margin area (5% of Central Bay). This calculation demonstrates the relatively high impact that margins can have on localized water quality.

The ambient margin data will provide a useful baseline against which the severity of contamination at specific sites can be compared. The baseline data will also be useful in setting targets and tracking improvements in watershed loads, evaluating contaminant concentrations in the margins, and potentially for setting contaminated sediment cleanup goals in the margins.

Figure 7: Distribution of PCB concentrations in the open Bay and the margin areas of Central Bay, not including Marin County. Units: Sum of 40 PCBs (ppb dry weight)



Sample collection in the margins of San Leandro Bay. Photograph by Don Yee.

2002-2017: What Have We Learned in 15 Years?

These RMP studies confirmed our expectations and improved our understanding of fate and transport of contaminants in the margins and how these processes affect the rest of the Bay. It is clear that the whole Bay system cannot be adequately modeled as a single homogeneous box. Margin areas receive and sometimes retain loads of contaminants from the watersheds. Also, margins serve as locations where pollutants enter the food web through bioaccumulation into small fish and other creatures. Finally, contamination in the margins spans a wide range of concentrations, driven by local and regional sources and transport processes. Therefore, a mixture of ambient concentration surveys and site-specific assessments are needed to characterize conditions in the margins.

Management actions to reduce pollutant loads could improve conditions in some margin areas relatively quickly. PCB concentrations in the Emeryville Crescent could show measurable response to reduced loads in approximately 10 years, which is fast compared to the estimated 100-year timeline for exposure reductions in the open Bay (SFBRWQCB 2008). And, to the extent that contamination in the margins affects the food web and exposure of fish to contaminants, targeted management at hotspots in the margins could be the most effective strategy for achieving regional improvements.

The path taken to monitor and understand the Bay margins is a good model for future investigations. The approach relied heavily on developing conceptual models and then testing them with carefully designed studies. As a result, the limited studies were focused, productive, and economical: a modest investment of $550,000 over the past 7 years (3% of total RMP budget for this period) has greatly improved our understanding of these important areas of the Bay. The combination of regional and focused studies proved particularly useful. Regional assessments, such as the 2010 Forage Fish Study and the 2015 Central Bay Margins Sediment Study, established spatial patterns and ambient conditions. Focused studies, such as the Emeryville Crescent Study, provided insight into the dominant sources and processes at work in specific locations. Having information at both the local and regional scales was essential for developing more realistic models of contaminant processes in the Bay.

Increasing Interest in the Margins

In the coming years, the RMP will continue to monitor processes in the margins for contaminants and nutrients to answer current management questions and to prepare for new management challenges on the horizon.

In 2017, ambient concentrations in the large margin areas of South and Lower South Bay will be monitored for PCBs, mercury, and trace metals. The RMP's Emerging Contaminants program will take advantage of the boat access to collect a number of samples for their projects at the same time. After this study, the RMP will have information on ambient concentrations in the margins everywhere south of the Richmond-San Rafael Bridge.

A major field study and conceptual model report for PCBs in the San Leandro Bay margin area will be completed in 2017. Samples of water, sediment, and fish were collected and tested for PCBs to validate and refine a site conceptual model. Most of the funding for the study came from Water Board penalty monies that were directed to the RMP for a Supplemental Environmental Project. Conceptual model reports are also planned for the Steinberger Slough and Richmond Harbor margin areas.

Margin areas are also important for understanding the effects of nutrients on water quality. These shallow areas can have the highest densities of algae and the lowest dissolved oxygen concentrations. Productivity and transformation rates are typically greater in these areas compared to the open Bay. Therefore, the Science Program of the Nutrient Management Strategy has a number of activities planned for the margins areas in 2017 and beyond. For example, a dense network of water quality sensors was installed in the sloughs of Lower South Bay starting in 2013 (page 25). The sensors measure dissolved oxygen and other water quality parameters. A forthcoming analysis of the data will provide insights into the availability of habitat for fish and overall ecosystem productivity in Lower South Bay.

At a larger scale, measurements of nutrients and indicators of phytoplankton will be made in the shallow shoal areas of South Bay. Shoals refer to the semi-shallow areas between the deep channels along the spine of the Bay and the margins. Similar to the early contaminant monitoring by the RMP, most nutrient samples traditionally have been collected along the spine of the Bay. Therefore, getting information from the shoals is crucial for understanding the cycling of nutrients in the system. The shoal measurements in 2017 will be especially important because of the large amount of rainfall this year. The stratification caused by high rainfall events, when the large amount of less dense fresh water runoff into the Bay can form a sustained layer on top of the denser Bay water, creates a situation that may result in algae blooms.

While the RMP's interest in the margins has been about water quality impairment and improvement, the margins are also important for habitat restoration and adaptation to sea level rise. The pace of wetland restoration is poised to accelerate in coming years. The Bayland Goals Update report (Goals Project 2015) reaffirmed a target of 100,000 acres of tidal marsh restored and maintained around the Bay. While progress has been made toward this goal, there is still a long way to go. Achieving the goal is further complicated by sea level rise, which threatens to submerge existing marshes, and the potential for future reductions in sediment supply from the Delta and local rivers which helps maintain the elevation of the marshes. In 2016, Bay Area voters approved Measure AA, which will provide $500 million over 20 years for habitat restoration. With an increasing demand for sediment due to sea level rise and increasing marsh area, beneficially using all suitable dredged sediments (and upland soils where possible) and reconnecting our watersheds to better deliver sediment to the Baylands become important strategies for restoration and adaptation. Also, in support of restoration efforts, treated wastewater may be needed to re-establish salinity gradients in marshes through horizontal levee systems such as the experiments undertaken in the Oro Loma Pilot Study or may be routed through constructed wetlands to remove nutrients.

Consistent with observations to date in the margins, any contamination that is introduced to the margin areas through sediment or wastewater reuse will have the potential to increase exposure of sensitive aquatic species. Moreover, nearly 40% of old industrial land use lies within 1 km of the Bay shoreline. Release of contaminants as these properties are inundated, or if wetlands are eroded by rising seas, may be another potential source of pollution into the margins. Therefore, in a few years or a decade, wetland restoration and sea level rise could become major drivers for water quality management of the Bay. Managers will need mass balance calculations and assessments of cumulative impacts and contaminant exposure in order to make decisions about beneficial reuse of dredged sediments, reconnecting watersheds, use of treated wastewater, and identifying high priority areas for additional contaminant remediation.

Bay margins are important areas for recreation, support unique biological productivity, and form a critical buffer between pollution sources on land and the open Bay. They are long and narrow and diverse in style and therefore challenging to study. Yet, understanding these areas is critical if we are to improve water quality in the Bay going forward. The RMP, with 25 years of experience supporting Bay science and 15 years of experience in studies focused in the Bay margins, is already leading the way to study the margins and is poised to address the next generation of management questions about these important areas. ●

Sample collection in the margins of San Leandro Bay. Photograph by Don Yee. >

WATER QUALITY UPDATES

< Landsat-8 satellite source image captured on March 5, 2015.
Obtained from https://www.scientificcomputing.com/news/2015/06/satellite-view-san-francisco-bay-area
Website for Landsat-8 imagery: https://landsat.usgs.gov/landsat-8

NOTEWORTHY TRENDS

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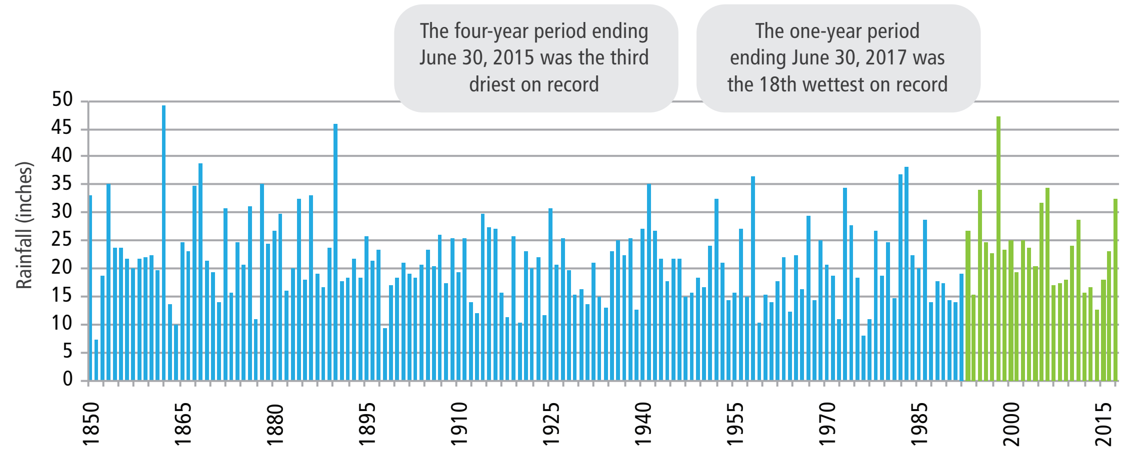
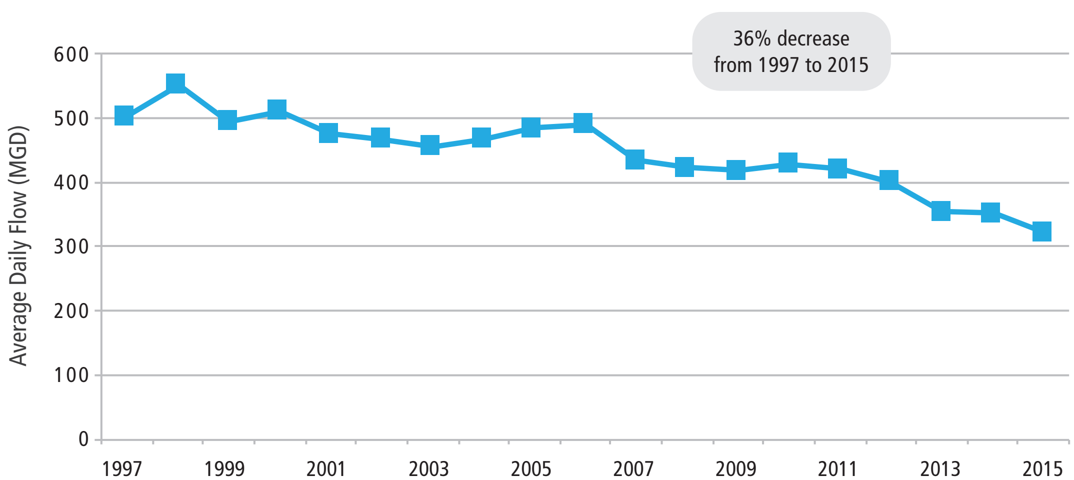
Rainfall in the Bay Area

The wet season of 2016/2017 brought an end to a five-year period of drought from 2012-2016. The total rainfall for the climate year (July 1-June 30) in San Francisco was 32.4 inches, the 18th wettest year recorded since 1850 at this location. The 4-year period ending in June 2015 was the third driest on record for this location. The average annual rainfall since 1850 is 21.9 inches.



Footnote: Annual rainfall measured at downtown San Francisco shown as index for Bay Area rainfall.

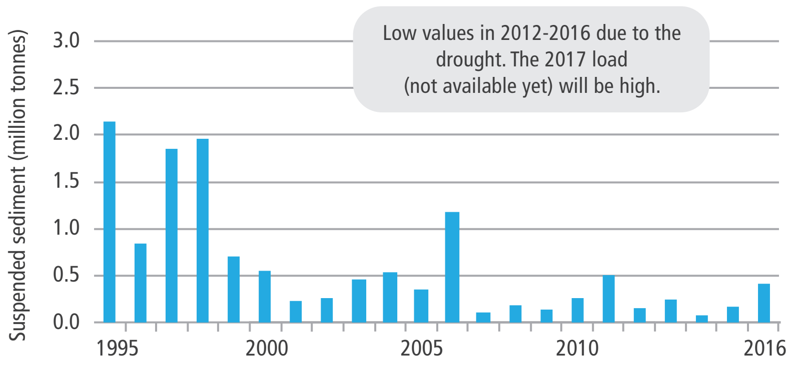


Flows to the Bay from the Ten Largest Municipal Wastewater Treatment Plants

Treated municipal effluent is one of the major pathways for pollutant input to the Bay. In spite of population growth, these flows are on the decline. The average daily flow for 2015 was 322 million gallons, the lowest for the 19-year period of record. The 2012-2016 drought and water conservation led to the significant drop in flows over the last few years.

NOTEWORTHY TRENDS

GRAPH DETAILS ON PAGE 90



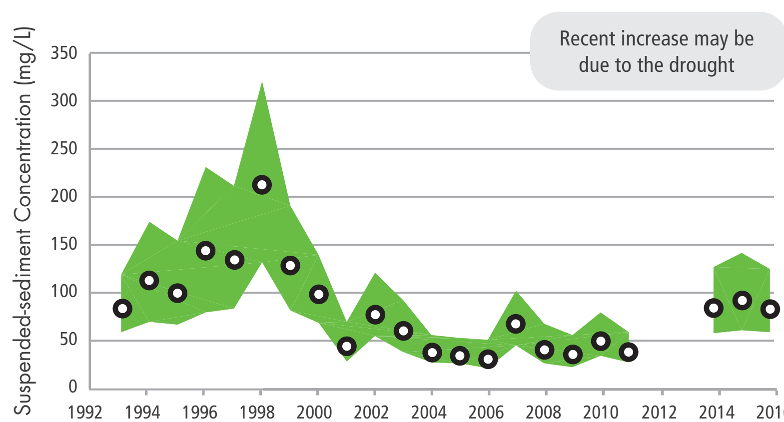
Footnote: Total sediment loads for each water year.

Delta Sediment Load

Flows from the Delta provide a large proportion of the Bay's sediment supply. Delta sediment loads are highly variable from year to year due to fluctuation in precipitation. Delta sediment loads have been relatively low in the past few years due to the 2012-2016 drought. Record rainfall in the watershed in the wet season of 2016/2017 will lead to a high value for water year 2017 when those data are available.

Suspended Sediment

Suspended sediment particles in the Bay are a source of sediment for wetland restoration, affect sunlight penetration and algae growth, and are a vehicle for transport of pollutants. A sudden Bay-wide shift in suspended sediment occurred in the late 1990s, and concentrations remained low for the next 10 years, as indicated in this plot for a station at the Dumbarton Bridge. Levels were higher, however, at this location in 2014-2016, possibly reflecting an altered distribution of suspended sediment across the Bay due to the drought.

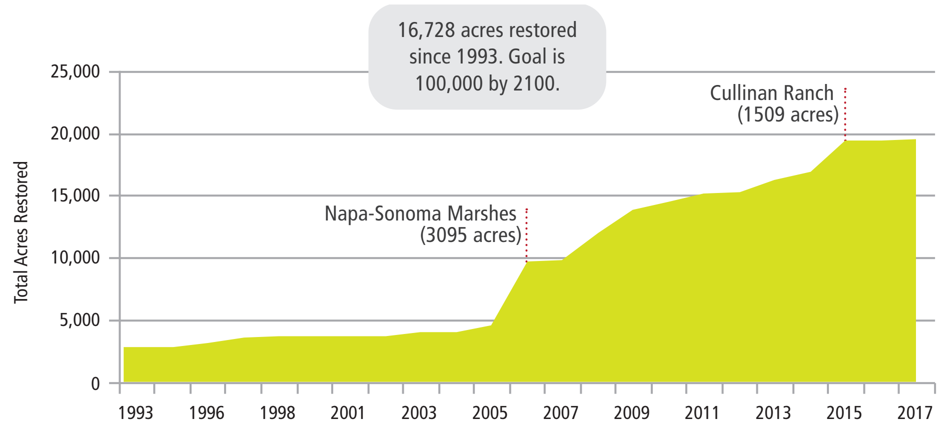


Footnote: Water year median (dots) and range between the 25th and 75th percentiles (green), Dumbarton Bridge. Data gap due to bridge construction.

NOTEWORTHY TRENDS

Restored Wetland Opened to Tidal Action

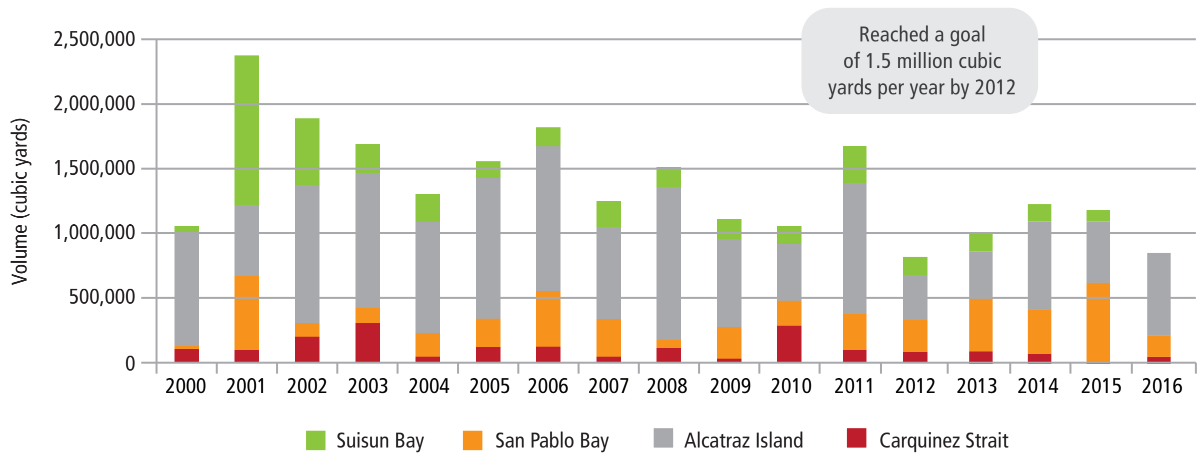
Tidal wetlands are part of the Bay. They are intimately connected to the open waters of the Bay through the exchange of water and sediment and the movement of aquatic species, and have a strong influence on Bay water quality. The ambitious plan to restore 100,000 acres by the year 2100 will add an area equivalent to one-third of the surface area of the Bay. Almost 17,000 acres have been restored in the past 25 years.



Footnote: Data summarized from Project Tracker (ptrack.ecoatlas.org).

In-Bay Disposal of Dredged Material

In 2000, state and federal agencies adopted a Long-Term Management Strategy to reduce in-Bay disposal of dredged material and to maximize the beneficial reuse of dredged material. Beneficial reuse includes constructing wetland restoration projects, levee repair, and use as construction fill. The LTMS Plan called for reduction of aquatic disposal in the Bay to approximately 1.25 million cubic yards per year by 2012. This goal has been met in each of the five years from 2012-2016. The in-Bay disposal in 2016 was 852,000 cubic yards.



Footnote: Data source: Dredged Material Management Office annual reports and records

The tide gauge at the Golden Gate Bridge. Photograph by Shira Bezalel. >

NOTEWORTHY TRENDS

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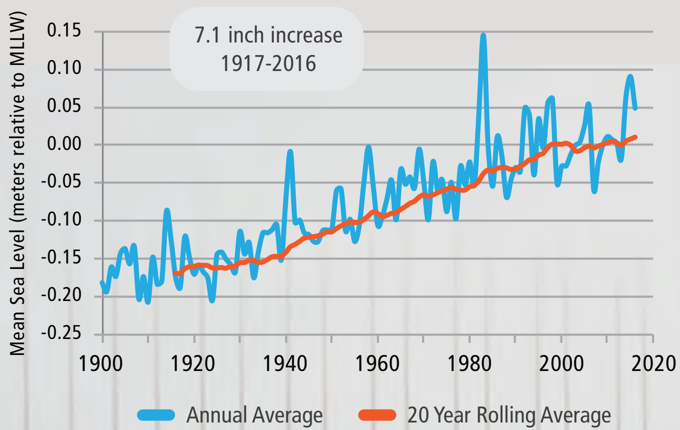


Sea Level at the Golden Gate

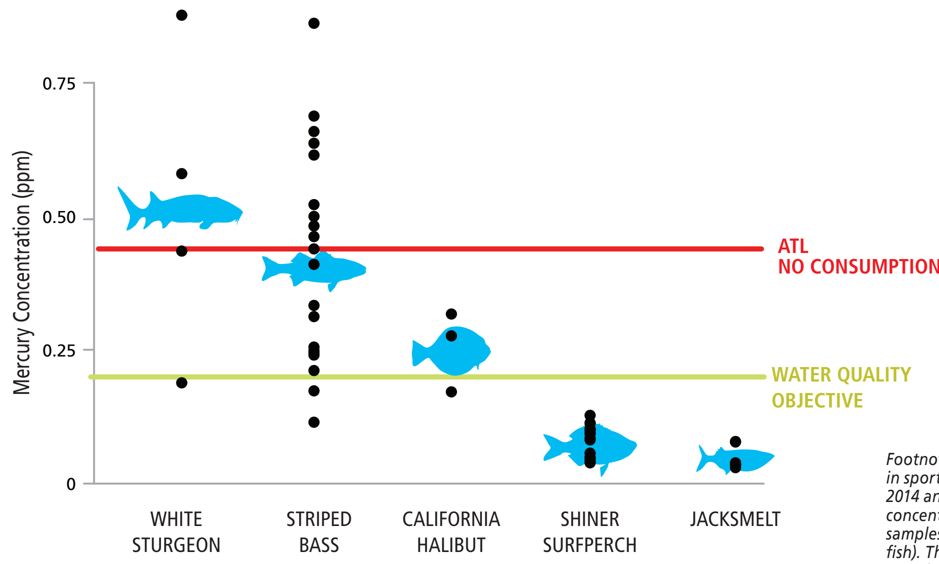
Rising sea level will affect Bay water quality in many ways, through its influence on the evolution of shoreline habitats and on pollutant fate in Bay waters. A tide gauge at the Golden Gate Bridge has been in operation since 1854, making it the nation's oldest continually operating tidal observation station and providing the longest continuous tide record in the Western Hemisphere. Based on a 20-year rolling average, sea level at the Golden Gate rose 7.1 inches over the past 100 years (from 1917-2016).

MERCURY

GRAPH DETAILS ON PAGE 90

Mercury in Sport Fish Species

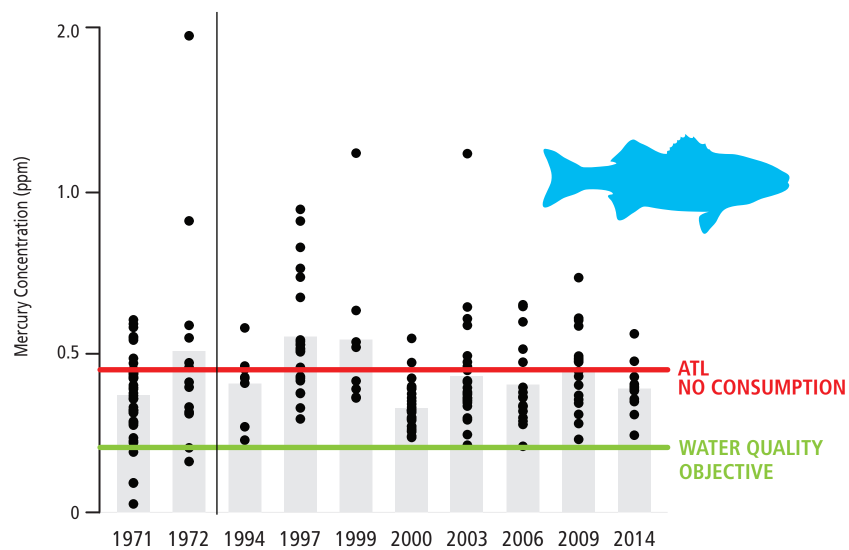
Mercury contamination is a high priority for Bay water quality managers due to concern for risks to humans and wildlife from consumption of Bay fish. Mercury is a primary driver of the fish consumption advisory for the Bay (https://oehha.ca.gov/advisories/san-francisco-bay). The RMP measures mercury and other pollutants in Bay sport fish once every five years. Results from the latest sampling (2014 and 2015) indicate that human exposure from fish consumption is a continuing concern, especially for long-lived predators like striped bass and white sturgeon.



Footnote: Mercury concentrations (ppm) in sport fish species in San Francisco Bay, 2014 and 2015. Fish icons indicate average concentrations. Points represent individual samples (either composites or individual fish). This graph includes striped bass data from Artesian Slough, a location not included in the long-term trend plot shown below. Data from the RMP.

No Long-term Mercury Trend in Striped Bass

Mercury in striped bass is the most important indicator of mercury contamination in the Bay and Delta from a human health perspective. This is due to a combination of the high mercury concentrations that tend to occur in their tissue and their popularity among anglers. A relatively extensive historical dataset exists for striped bass in the Bay, allowing evaluation of trends over 44 years from 1971-2014. Average concentrations in recent years are not significantly different from those measured in the early 1970s. The Bay-wide average concentration in 2014 (excluding the fish caught in Artesian Slough) was 0.3 ppm; the average including the Artesian Slough fish was 0.4 ppm.

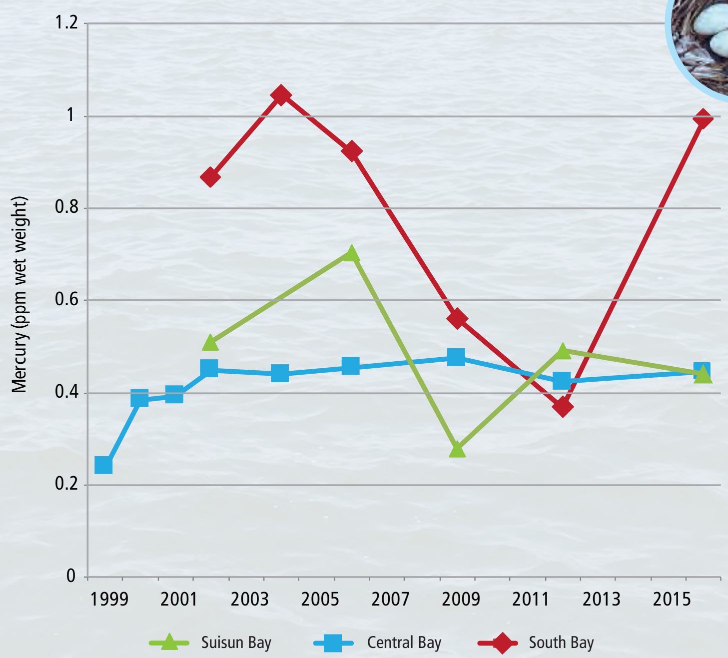


Footnote: Mercury concentrations (ppm) in striped bass from San Francisco Bay, 1971-2014. Bars indicate average concentrations. Points represent individual fish (and some composite fish samples in 2014). Data from the RMP (1994-2014) and an earlier study (1971-1972).

MERCURY

Mercury in Cormorant Eggs

The RMP tracks concentrations of mercury and other pollutants in cormorant eggs as another means of assessing trends in contamination of the food web over time. The period of record now spans 15 years or more at three locations in Suisun Bay (Wheeler Island), Central Bay (Richmond Bridge), and South Bay (Don Edwards National Wildlife Refuge). Mercury concentrations have been highest, and most variable, in the South Bay. No long-term trend is apparent in these data.



< Double-crested cormorants. Photograph by Meg Sedlak..

Footnote: Average mercury concentrations (ppm wet weight) in cormorant egg composites. Each point represents three composites, with 7 eggs in each composite. Data from Ross et al. (2016). Data available from cd3.sfei.org

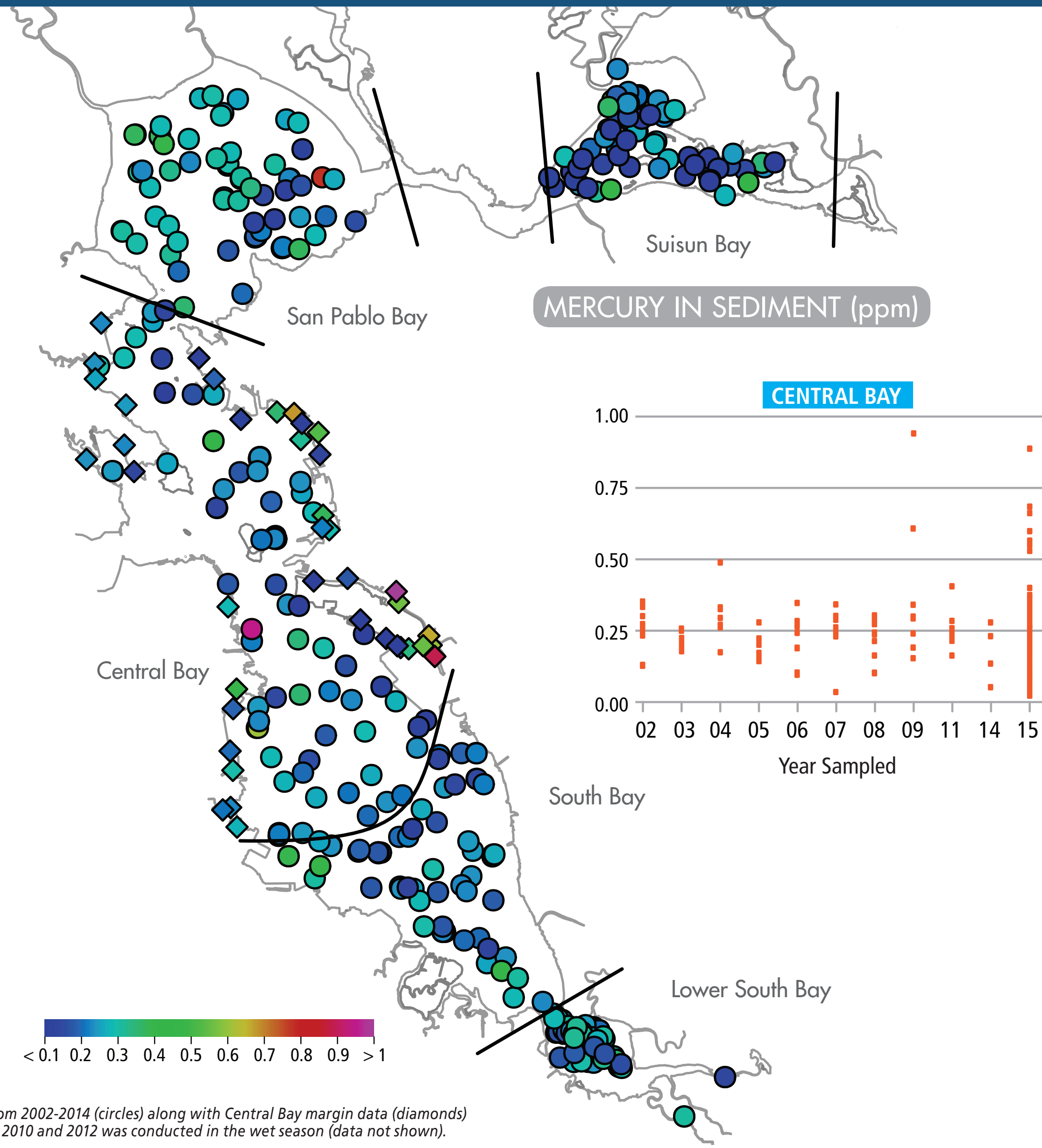
MERCURY

GRAPH DETAILS ON PAGE 90

Mercury in Sediment

Mercury binds to sediment particles, so mercury concentrations in the sediment deposits on the bottom of the Bay are an important index of contamination of the ecosystem. The RMP measures mercury and other pollutants in sediment across the entire Bay once every four years, most recently in 2014.

In 2015, the RMP performed a focused sampling of sediment in the margins of Central Bay - a shallow portion of the Bay that had previously not been monitored (page 52). Mercury concentrations in margin sediment were very similar to concentrations in the deeper waters of Central Bay (inset graph), in terms of both the median (0.23 ppm in the margins versus 0.24 ppm in the open Bay) and 75th percentile concentrations (0.31 ppm in the margins versus 0.28 ppm in the open Bay). However, a handful of sites with relatively high concentrations (above 0.5 ppm) were observed in the margins; most of these occurred in Oakland Harbor and San Leandro Bay.



Footnote: Points on the map show all available dry season RMP data from 2002-2014 (circles) along with Central Bay margin data (diamonds) from 2015. Trend plot shows the data points for each year. Sampling in 2010 and 2012 was conducted in the wet season (data not shown).

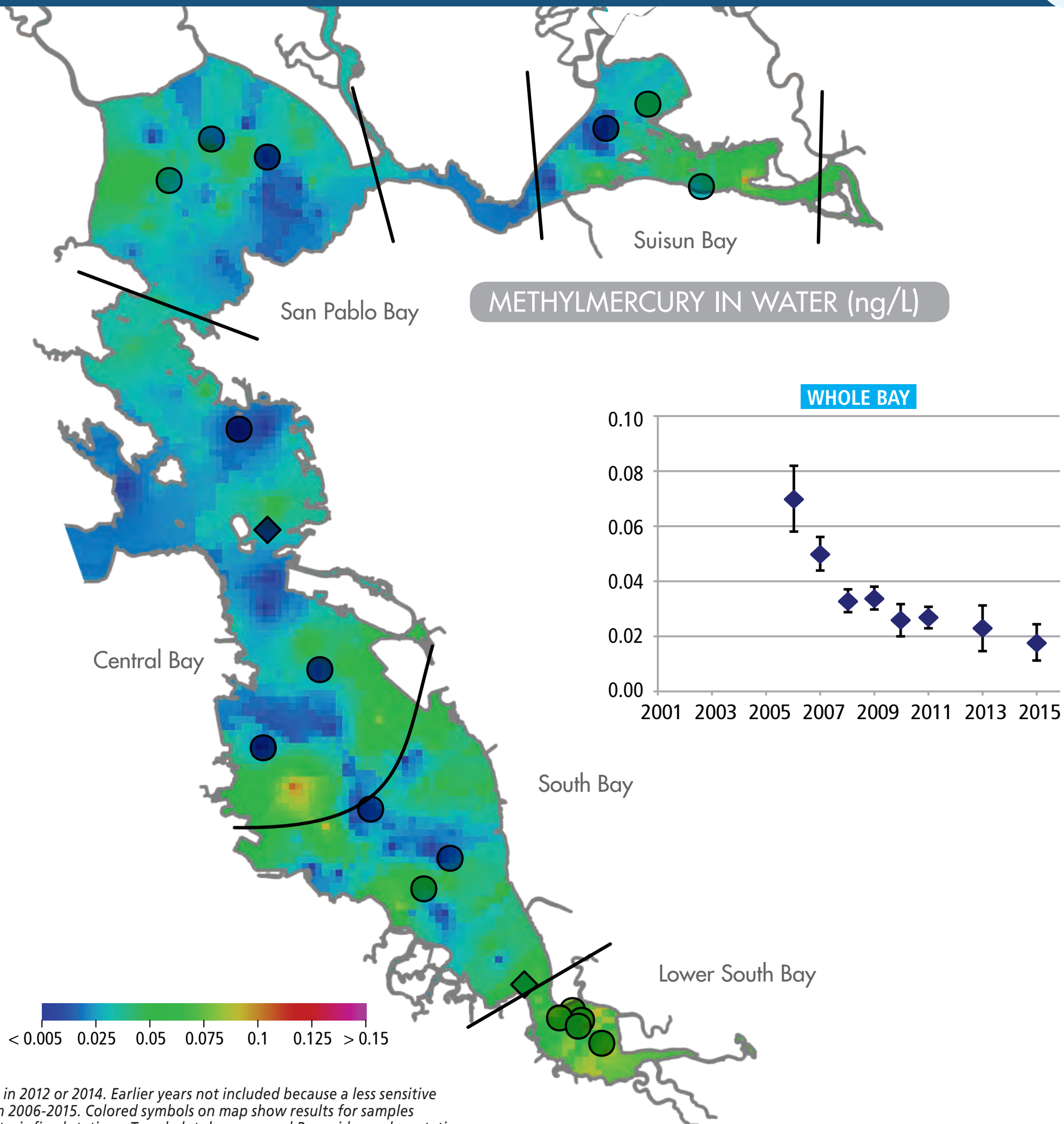
MERCURY

GRAPH DETAILS ON PAGE 90

Methylmercury in Water

Methylmercury in water is an index of the amount of mercury that can enter the food web. Methylmercury typically represents 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. No regulatory guideline exists for methylmercury in water.

Water from Lower South Bay had the highest average concentration of methylmercury by far (0.104 ng/L) of any segment from 2006 to 2015. South Bay had the next highest average (0.051 ng/L). The Bay-wide average in 2015 was 0.018 ng/L. The Bay-wide average for the ten-year period was 0.038 ng/L. The Bay-wide average concentration has been progressively declining over this ten-year period, most distinctly in Central Bay.



Footnote: Water is sampled only in the dry season, and was not sampled in 2012 or 2014. Earlier years not included because a less sensitive method was employed. Contour plot based on 221 RMP data points from 2006-2015. Colored symbols on map show results for samples collected in 2015: circles represent random sites; diamonds represent historic fixed stations. Trend plot shows annual Bay-wide random station means with error bars indicating the 95% confidence intervals of the means. The maximum concentration at a random station was 0.28 ng/L in Lower South Bay in 2011. Data are for total methylmercury.

MERCURY

Water Flow and Mercury Load from the Guadalupe River

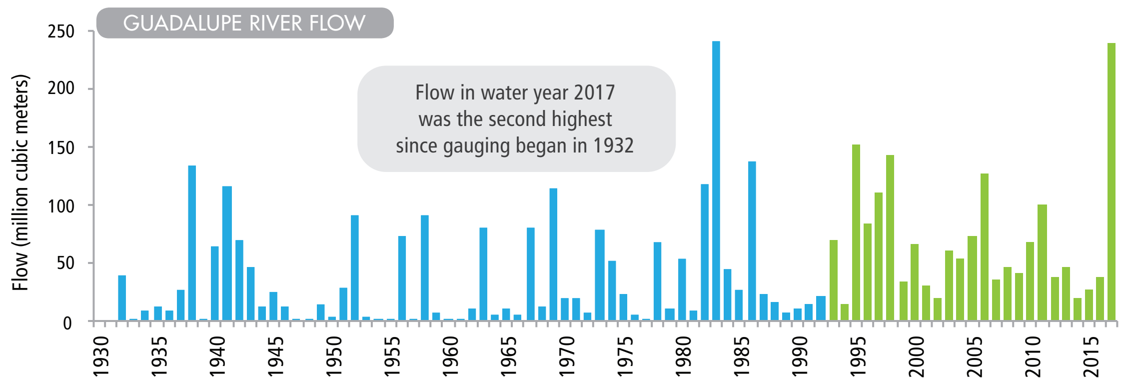
Efforts to reduce mercury loads to the Bay are primarily focusing on the Guadalupe River and urban stormwater. The Guadalupe River carries runoff from the New Almaden Mercury Mining District, historically the nation's largest mercury mining region and a continuing source of legacy contamination to the Lower South Bay. Load reduction activities in the Guadalupe watershed have been underway for over a decade and are planned to continue for at least another two decades.

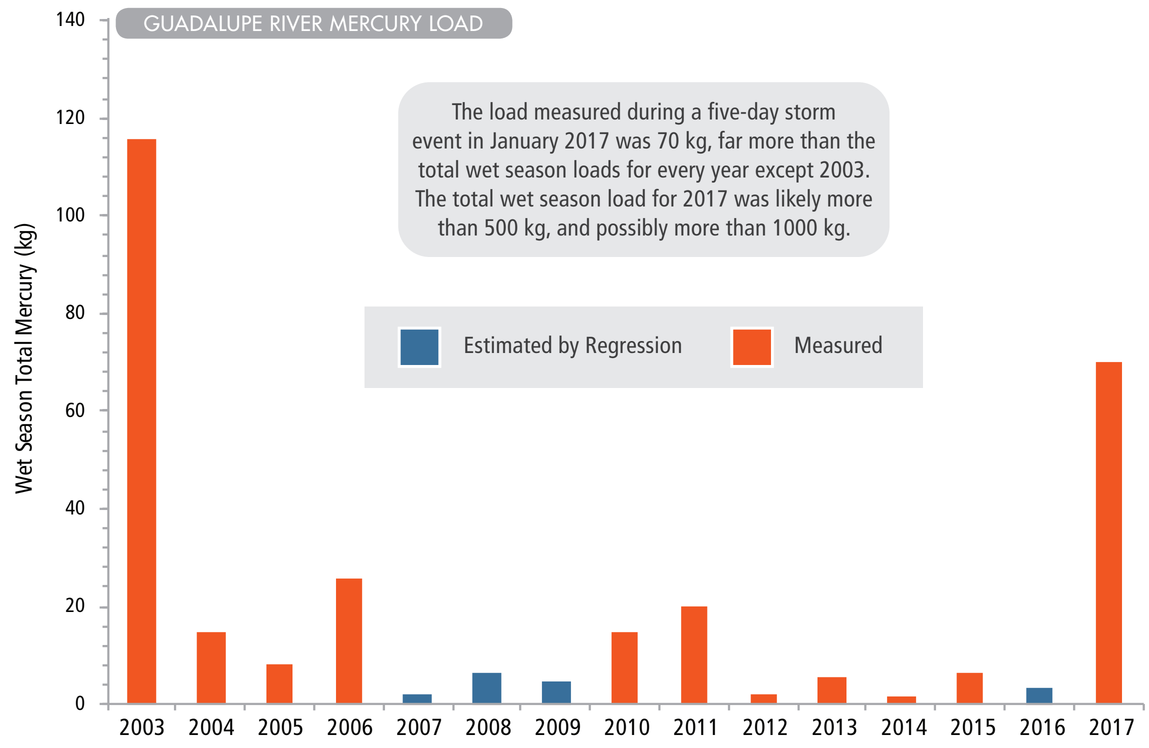
Guadalupe River flow has a major influence on mercury loading to the Bay, and the flow in the wet season of 2016/2017 was extremely high. A series of large storms yielded an estimated total flow for the water year of 239 million cubic meters, only slightly lower than the highest annual flow (241 million cubic meters in water year 1983) observed since gauging began in 1932.

The RMP mobilized a team to sample mercury in the Guadalupe during the high flows of January 2017, adding to an extensive long-term dataset for loading from this watershed. The load measured during a five-day storm event was 70 kg, far more than the total wet season loads for every year except 2003. Total flow for 2017 was four times higher than the total for 2003. The total wet season load for 2017 was likely more than 500 kg, and possibly more than 1000 kg, but is difficult to estimate without more than five days of measurements. These estimates highlight the highly episodic nature of mercury transport from the watershed, which poses challenges for both monitoring and management.

Footnotes: Upper graph: Data from the U.S. Geological Survey. Green bars indicate flows during the period of the RMP (1993-2017). Data for are for water years (Oct 1 to Sep 30).

Lower graph: Total loads for each water year (Oct 1 to Sep 30). Additional matching funds for this study provided by the CEP, USACE, SCVWD, and SCVURPPP. Data from McKee et al. (2017) and related publications.





MERCURY

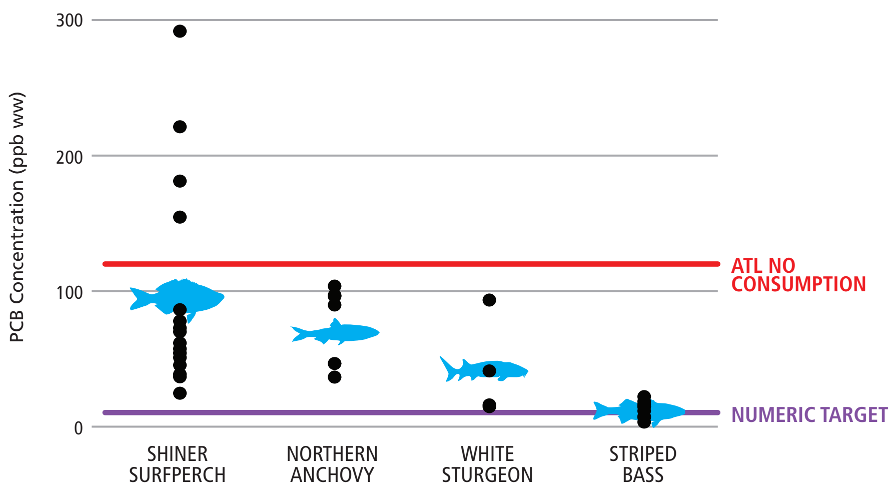
∧ Fishing at Point Pinole. Photograph by Shira Bezalel.

PCBs

GRAPH DETAILS ON PAGE 90

PCBs in Sport Fish Species

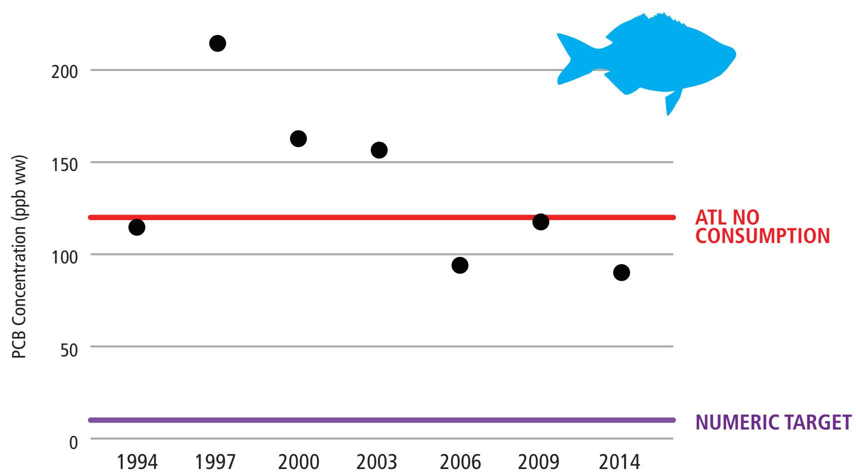
Concern for PCBs in the Bay is primarily due to concentrations in fish species that are consumed by humans. Shiner surfperch is the species with the highest concentrations - 9 times higher than the Regional Board's numeric target. Because of the high concentrations in shiner surfperch, the Office of Environmental Health Hazard Assessment (OEHHA) advises no consumption of any surfperch species in the Bay (https://oehha.ca.gov/advisories/san-francisco-bay). PCB concentrations in other species also are high enough to make them a factor in OEHHA's consumption advice. The RMP measures PCBs and other pollutants in Bay sport fish once every five years. Results from the latest sampling (2014) indicate that PCB concentrations in multiple species remain at levels of concern.



Footnote: PCB concentrations (ppb) in sport fish species in San Francisco Bay, 2014. Fish icons indicate average concentrations. Points represent values for each composite sample. Data from the RMP. ATL = Advisory tissue level.

Little Evidence of PCB Decline in Shiner Surfperch

PCB concentrations in shiner surfperch, a key sport fish indicator species, have shown little evidence of decline. During the past three rounds of sampling, the Bay-wide average wet weight PCB concentration in shiner surfperch has been below OEHHA's no consumption advisory tissue level of 120 ppb, while average concentrations were above this threshold between 1997 and 2003. The Bay-wide average in 2014 was the lowest measured over the 21-year period of record. Overall, the PCB data for shiner surfperch suggest that concentrations have not declined substantially Bay-wide between 1994 and 2014, but may be beginning to show evidence of declines in certain regions, specifically Berkeley and San Pablo Bay.

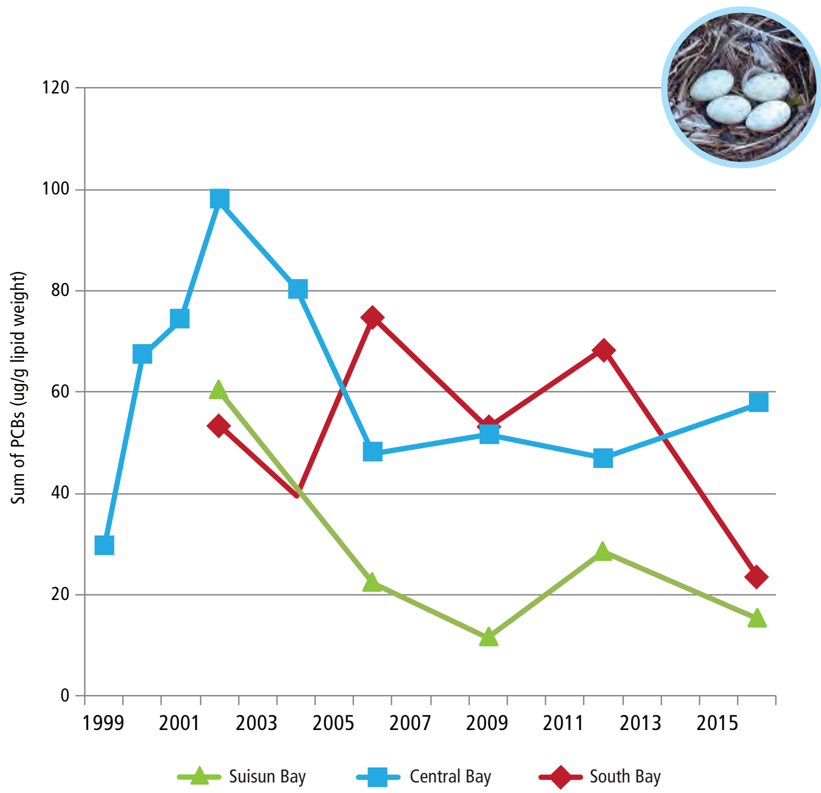


Footnote: Points show Bay-wide average for each year.

PCBs

PCBs in Cormorant Eggs

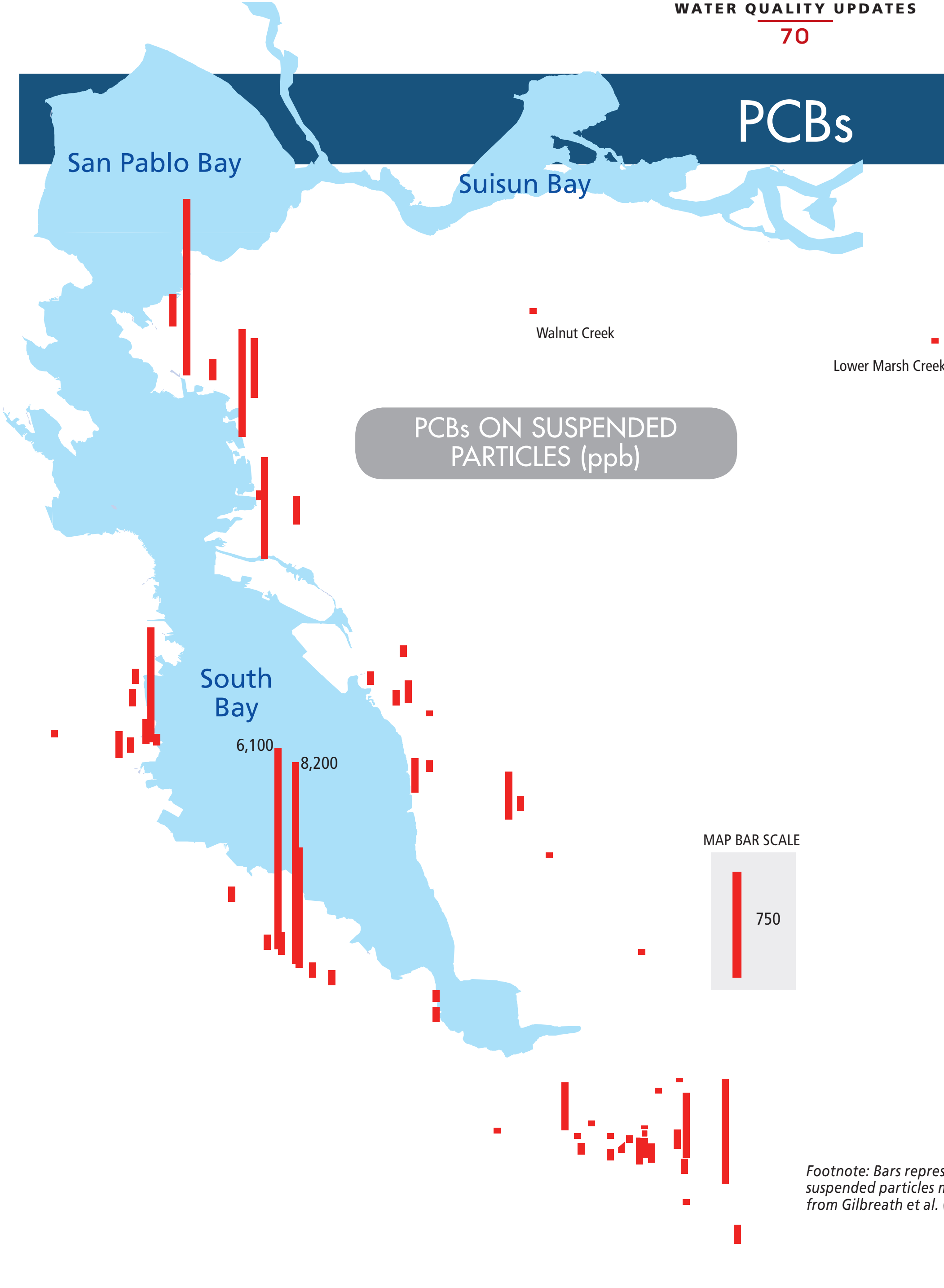
The RMP tracks concentrations of PCBs and other pollutants in cormorant eggs as another means of assessing trends in contamination of the food web over time. The period of record now spans 15 years or more at three locations in Suisun Bay (Wheeler Island), Central Bay (Richmond Bridge), and South Bay (Don Edwards National Wildlife Refuge). Average PCB concentrations have been higher in the South Bay and Central Bay than in Suisun Bay. The average concentration in the South Bay in 2016 was the lowest yet measured for that region. No distinct long-term trend is apparent in these data.



Footnote: Average PCB concentrations (sum of 40 PCBs, ppb lipid weight) in cormorant egg composites. Each point represents three composites, with 7 eggs in each composite. Data from Ross et al. (2016). Data available from cd3.sfei.org

^ Double-crested cormorant on the old Bay Bridge. Photograph by Mark Rauzon.

PCBs



Footnote: Bars represent the average PCB concentration on suspended particles measured during a storm at each location. Data from Gilbreath et al. (2017).

PCBs in Stormwater

Urban stormwater is the largest pathway of PCB loads to the Bay. As one major element of the RMP, concentrations of PCBs and mercury on suspended sediment particles from a wide range of watersheds are being measured as an index of the degree of watershed contamination and potential for effective management action. Stormwater samples from Pulgas Creek Pump Station North and South, Industrial Road Ditch, and Gull Drive Storm Drain in San Mateo County; Santa Fe Channel in Contra Costa County; Outfall at Gilman Street and Ettie Street Pump Station in Alameda County; and Outfall to Lower Silver Creek in Santa Clara County had the highest concentrations of PCBs on suspended sediment particles measured to date. These watersheds may present good opportunities for load reduction.

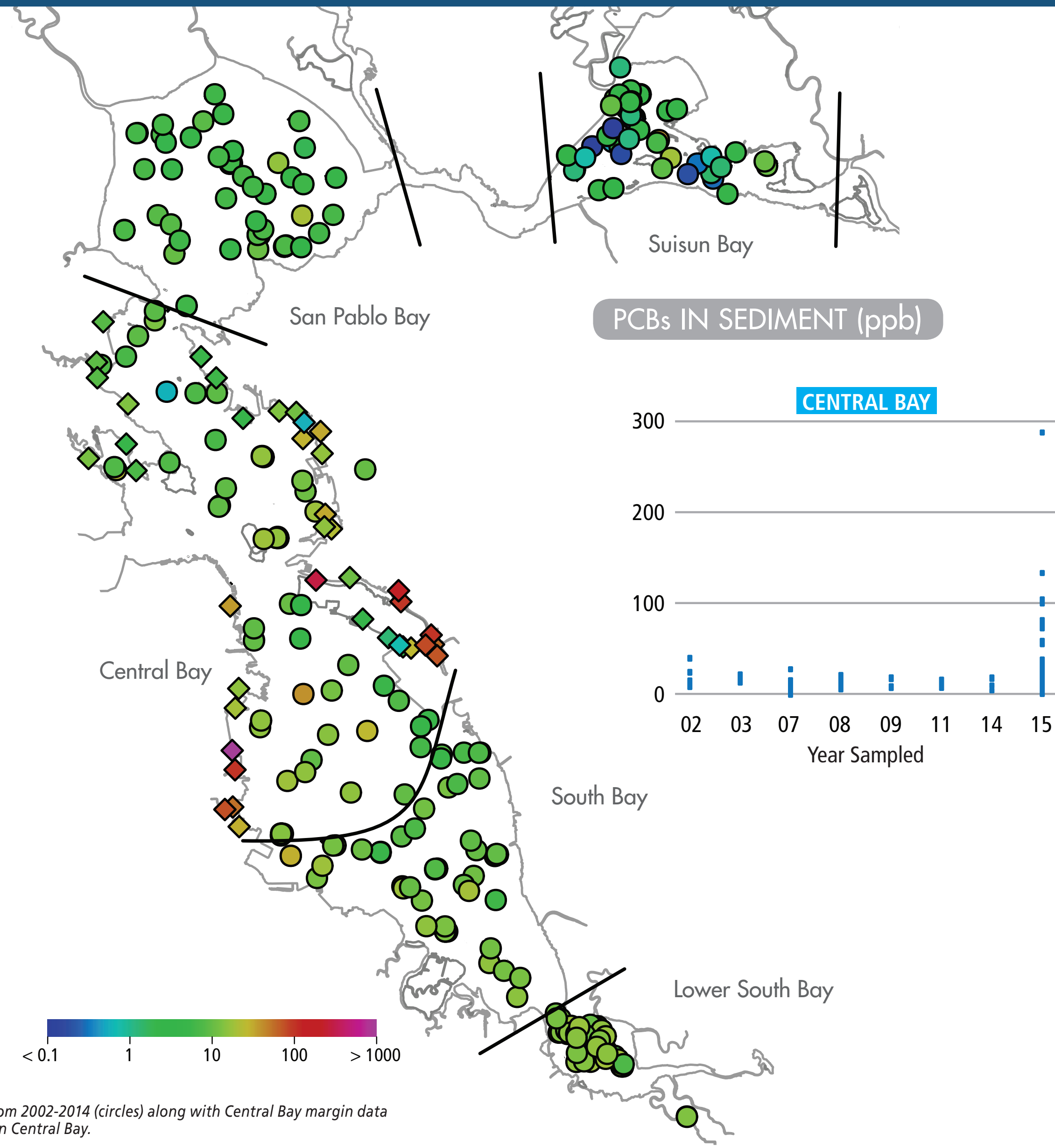
PCBs

GRAPH DETAILS ON PAGE 90

PCBs in Sediment

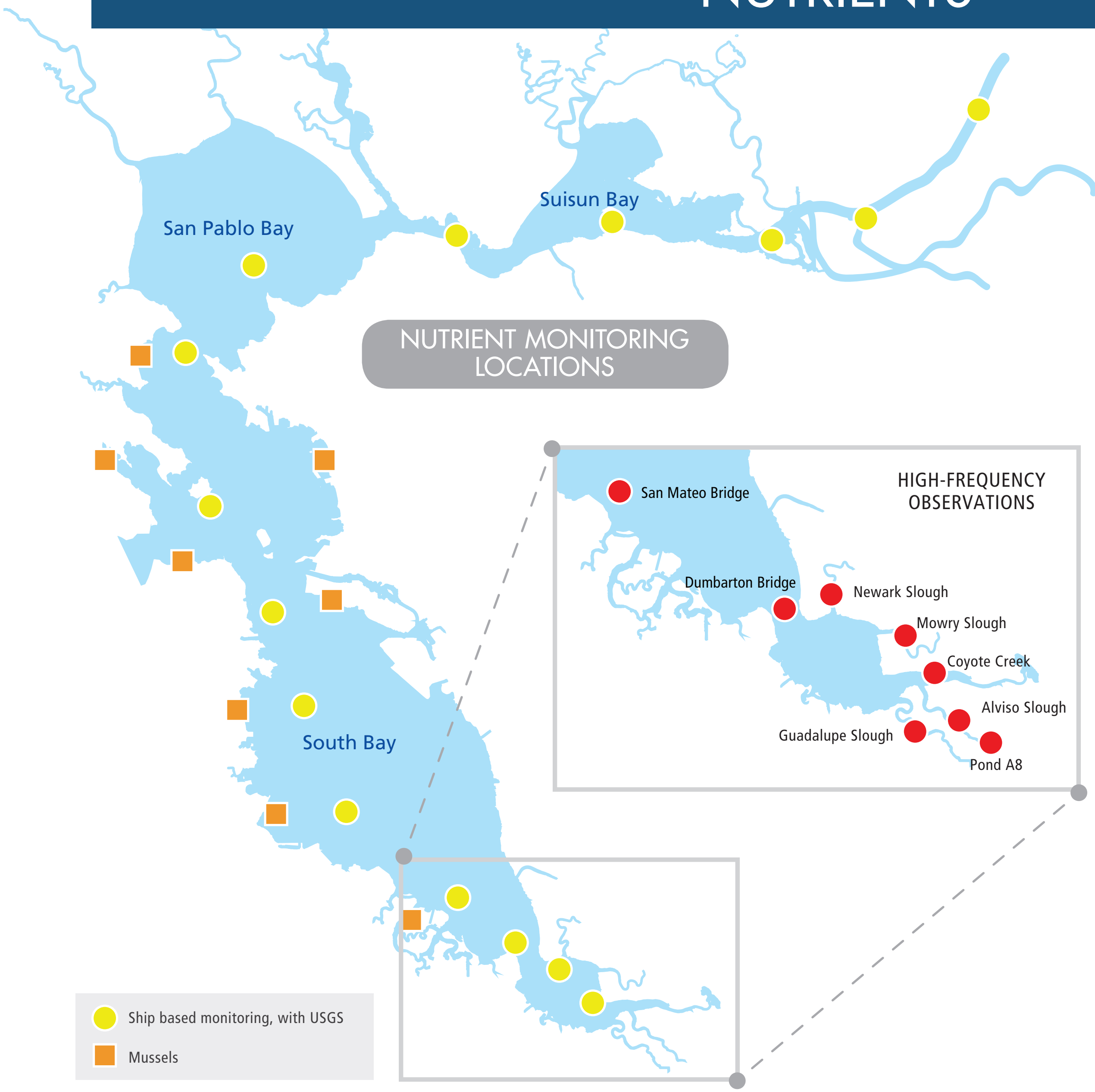
Like mercury, PCBs bind to sediment particles, so PCB concentrations in the sediment deposits on the bottom of the Bay are an important index of contamination of the ecosystem. The RMP measures PCBs and other pollutants in sediment across the entire Bay once every four years, most recently in 2014.

In 2015, the RMP performed a focused sampling of sediment in the margins of Central Bay - a shallow portion of the Bay that had previously not been monitored (page 52). PCB concentrations at many sites in the Central Bay margins were higher than the maximum concentration (40 ppb) observed at deeper water sites in Central Bay. Clusters of sites with relatively high concentrations were observed near Brisbane and South San Francisco on the west side of Central Bay, and in the Oakland Harbor/San Leandro Bay region on the east side of Central Bay. Although the median concentration of PCBs in the margins (13 ppb) was similar to the median for the open Bay (11 ppb), the 75th percentile for the margins (32 ppb) was twice as high as the 75th percentile for the open Bay (16 ppb). The difference between contamination in margin and open Bay areas is even more pronounced if one focuses on the urban shoreline in Central Bay (Figure 7, page 52).



Footnote: Points on the map show all available dry season RMP data from 2002-2014 (circles) along with Central Bay margin data (diamonds) from 2015. Trend plot shows the data points for each year in Central Bay.

NUTRIENTS



Nutrient Monitoring

The Nutrient Management Strategy Observation Program has three major components.

- Ship-based water column sampling: The Nutrient Management Strategy collaborates with the US Geological Survey (USGS) to conduct biweekly (South Bay and Central Bay) and monthly (full Bay) cruises to measure water quality along the spine of the Bay, continuing the long-term USGS program that has been in place since the early 1970s. Field measurements and samples collected during the cruises provide essential information on basic water quality (temperature, salinity, suspended particles), nutrient concentrations, phytoplankton, and algal toxins.
- Moored sensor network with high-frequency sensors: SFEI has installed a network of moored sensors in the South Bay that continuously measure dissolved oxygen, chlorophyll-a, and other water quality parameters. The sensors record data every 15 minutes. The high-frequency data are critical for understanding the dynamic processes affecting dissolved oxygen and nutrient cycling in this portion of the Bay.
- Biological sampling: Native mussels are collected every two weeks from docks around the edge of the Bay and tested for algal toxins. The mussels serve as time-integrated samplers of algal toxins in the Bay and indicators of algal toxins levels entering the food web.

NUTRIENTS

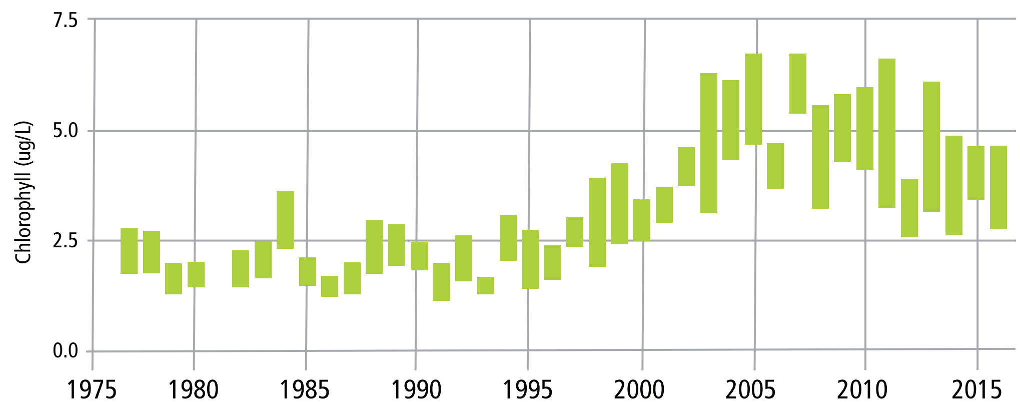
GRAPH DETAILS ON PAGE 90

South Bay Chlorophyll

Excessive increases in phytoplankton abundance in response to elevated nutrient concentrations are common in estuaries around the world. To date, the Bay has exhibited resistance to the large algal blooms and resulting low dissolved oxygen that have plagued other nutrient-enriched estuaries. Chlorophyll concentrations in water provide an index of the abundance of phytoplankton and a key means of tracking whether a problem may be developing.

Chlorophyll concentrations in South Bay and Lower South Bay have increased since the late 1990s. Cloern et al. (2007) first documented increasing fall chlorophyll concentrations in South Bay, with approximately a 2.5-fold increase between 1995 and 2005. The trend of increasing chlorophyll led to concerns that South Bay's resistance to nutrients was declining. At that point it was unclear whether phytoplankton biomass would continue increasing or stop. Data over the subsequent 10 years suggest that phytoplankton biomass has stopped increasing and reached a new plateau, but at a higher level than the concentrations that prevailed from 1980 to 1995.

LATE SUMMER CHLOROPHYLL IN THE SOUTH BAY



Footnote: The middle range (between the 25th and 75th percentiles) of annual chlorophyll concentrations in the South Bay in late summer. Historically, the South Bay had low chlorophyll production compared to other estuaries with comparable nutrient inputs. Data from USGS.

NUTRIENTS

Long-term Trends in Important Nutrient Parameters

The following graphs provide an overview of several parameters relevant to the Nutrient Management Strategy. The data illustrate the substantial variability in these parameters by season, year, and region in the Bay, and why capturing this variability requires a robust observational program (page 72).

Nitrogen (N) and phosphorus (P) are natural and vital components of healthy estuarine ecosystems. Sufficient nutrient levels are needed to support the growth of phytoplankton (microscopic floating algae) that in turn serves as the base of the food web. Too much N or P, however, can yield unhealthy levels of phytoplankton depending on other factors such as water clarity, temperature, and vertical mixing. The concentrations of N and P are typically highest in the South Bay, reflecting the large discharges of nutrients from wastewater treatment facilities and slow mixing in this portion of the Bay. During the recent drought years, the concentrations peaked because there was less water for dilution.

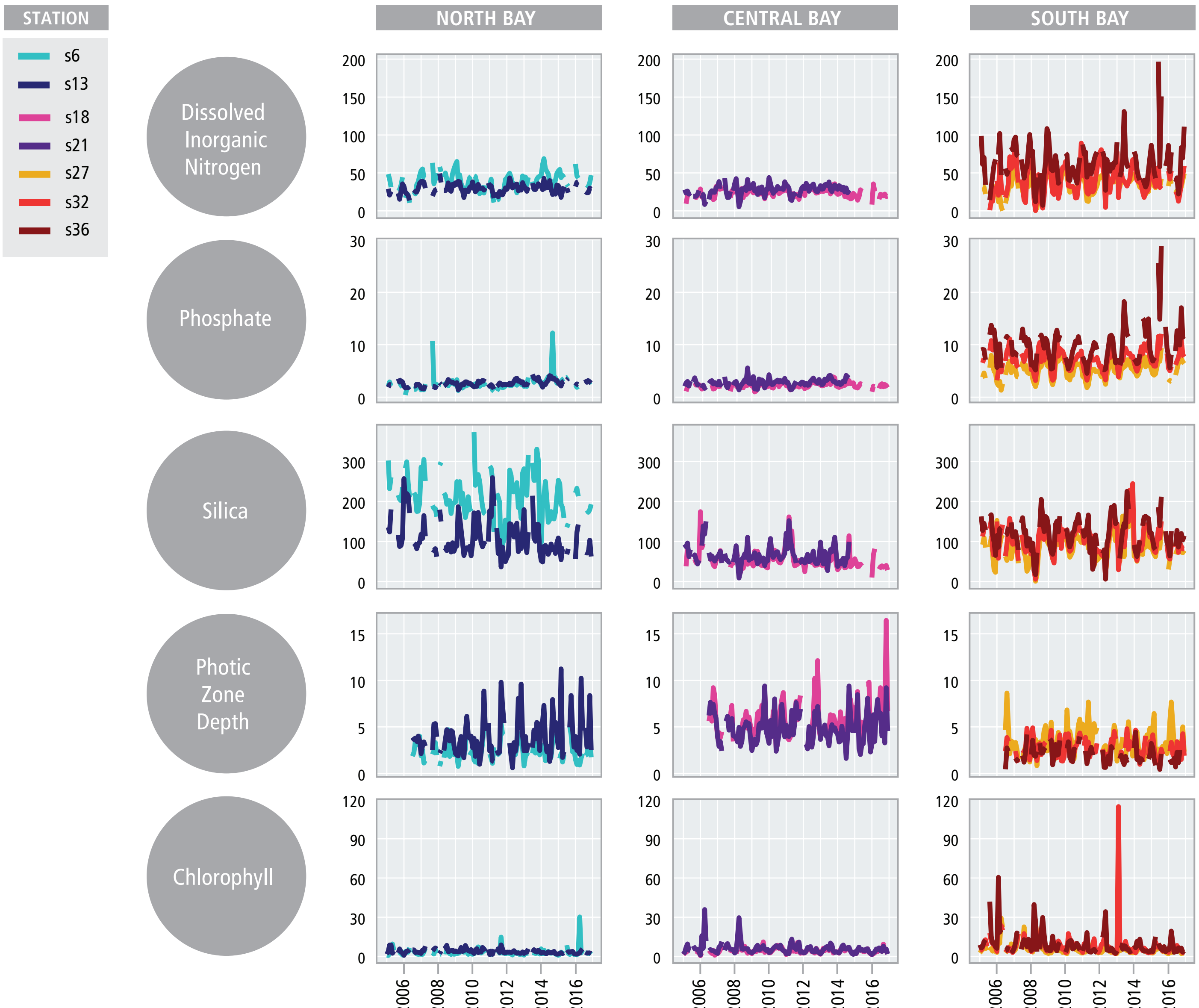
Silica is another nutrient that is important because certain phytoplankton (diatoms) need it to form their shells. In contrast to N and P, silica concentrations are highest in the North Bay, where the Sacramento and San Joaquin Rivers enter the Bay. These rivers originate in the Sierra Nevada where the geology is rich in silica.

Photic depth, a measure of water clarity, is the depth at which light levels are 1% of incident light. Higher values of photic depth indicate greater water clarity. The clearest waters in the Bay are in Central Bay, where a photic depth of 5 meters is common. In contrast, the waters of South Bay tend to be turbid with a photic depth of only 1-2 meters. The thin photic layer in South Bay is one of the factors that limit algae blooms in this area despite the high nutrient concentrations.

Chlorophyll-a is a measure of phytoplankton abundance. While South Bay has historically experienced sizable spring phytoplankton blooms (Cloern and Jassby 2012), major blooms have been notably and inexplicably absent over the past several years, except for a short-lived peak observed at South and Lower South Bay stations in February 2013. An increase in fall chlorophyll-a levels in South Bay, observed beginning in the late 1990s through 2005 (Cloern et al. 2007), was among the original motivations for the Water Board to establish the Nutrient Management Strategy. This indicator continues to be tracked (page 73), and observations through 2015 suggest that fall chlorophyll-a levels have leveled off. A discussion of hypothesized factors contributing to these changes can be found in Cloern et al. (2007) and Crauder et al. (2016).

NUTRIENTS

GRAPH DETAILS ON PAGE 90



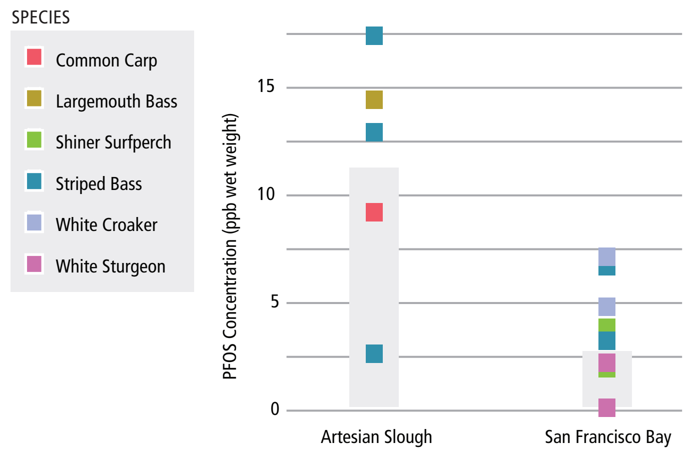
Footnote: Concentrations of dissolved inorganic nitrogen, phosphate, and silica are µmol/L in the dissolved phase. Photic depth is expressed as meters. The units for chlorophyll-a concentrations are µg/L.

CECs

PFOS in Sport Fish

PFOS is an emerging contaminant of moderate concern in the Bay (page 37). PFOS is a fluorine-rich surfactant that is toxic, extremely persistent in the environment, and accumulates in biota. PFOS and related fluorine-based chemicals were measured in the RMP sport fish monitoring conducted in 2014 and 2015. In addition to the usual collection of fish from popular fishing areas throughout the Bay, this sampling included fish from the Artesian Slough in the South Bay, just downstream of the outfall of the San Jose-Santa Clara Regional Wastewater Facility - the Bay's largest municipal wastewater outfall. PFOS concentrations were higher in fish from Artesian Slough than at other Bay locations, indicating that municipal wastewater is a pathway for PFOS input to Bay biota.

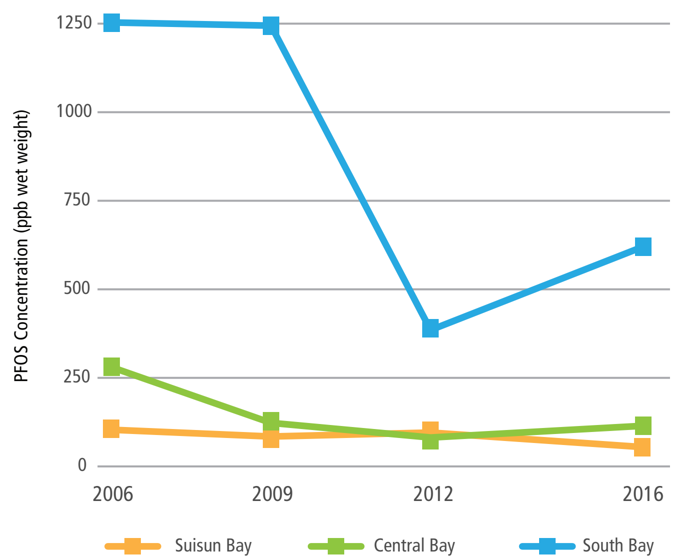
There are no California thresholds for evaluating risks to humans from PFOS concentrations in Bay sport fish. The highest concentrations observed at Artesian Slough approached a range (19-38 ppb) at which the State of Michigan advises limiting consumption to four servings per month.



Footnote: Artesian Slough samples were collected in 2015; other Bay samples were collected in 2014. Each point represents an individual fish (carp, striped bass from Suisun Bay) or composite fish (all other species, including striped bass composites from San Pablo Bay, Central Bay and Artesian Slough) samples. Data from Sun et al. (2017a). Data available from cd3.sfei.org

PFOS in Cormorant Eggs

Cormorant eggs are a valuable indicator of regional patterns in contamination of the open Bay food web, both for legacy contaminants like mercury and PCBs and emerging contaminants like PFOS. PFOS concentrations in cormorant eggs have been higher in the South Bay than in Central Bay (Richmond Bridge) or Suisun Bay (Wheeler Island). The South Bay concentrations have varied considerably, falling from over 1200 ppb in 2006 and 2009 to approximately 400 ppb in 2012, then rising to around 600 ppb in 2016. Concentrations at the other locations have been lower and fairly constant since 2009. PFOS concentrations in cormorant eggs in the South Bay may be of concern. Field studies have indicated an approximately 50% reduction in hatching success of tree swallows at a PFOS concentration of 500 ppb wet weight in eggs, a level similar to that observed in South Bay cormorant eggs (Custer et al. 2013).



Footnote: Average PFOS concentrations (ppb wet weight) in cormorant egg composites. Each point represents three composites, with 7 eggs in each composite. Data from Ross et al. (2016). Data available from cd3.sfei.org

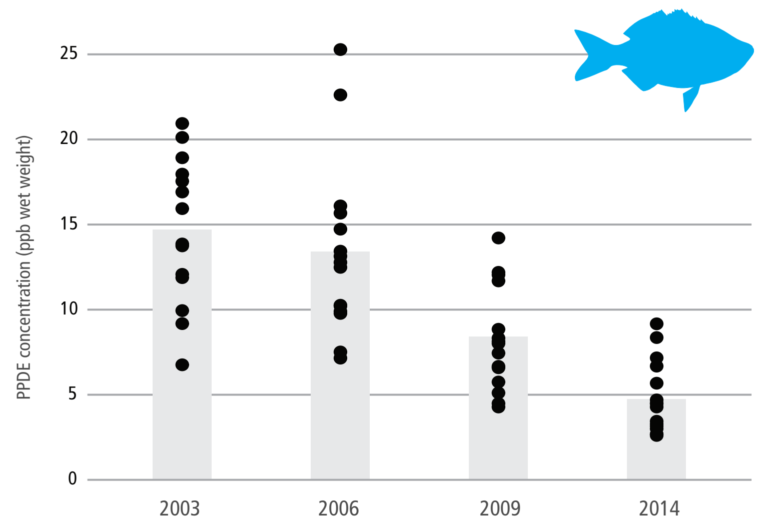
CECs

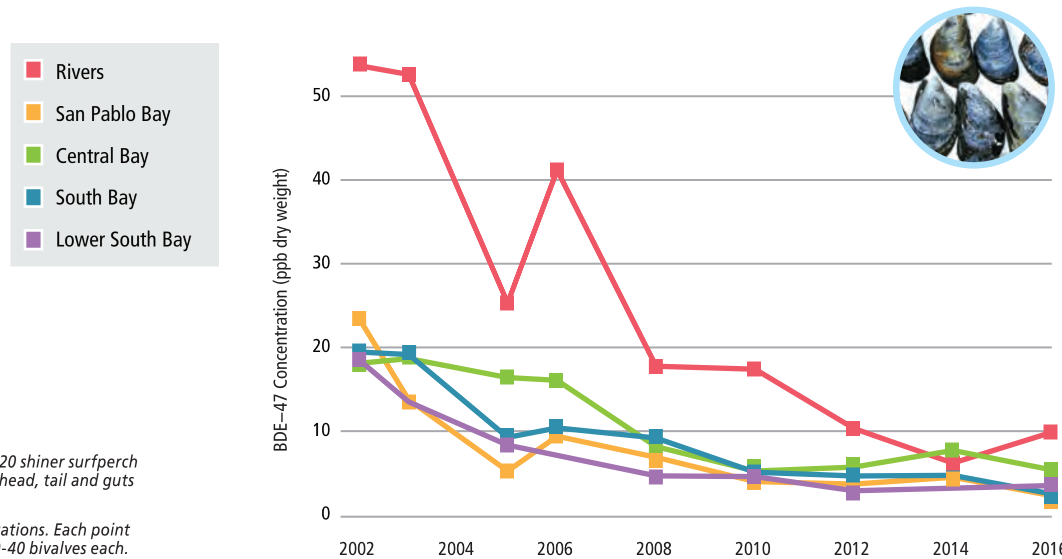
PBDE Declines in Sport Fish and Bivalves

PBDEs are a class of bromine-containing flame retardants that was widely used starting in the 1970s. In response to observations in the 1990s of rapidly increasing concentrations in humans and wildlife, the California Legislature banned two types of PBDE mixtures in 2006; the last mixture was phased out in 2013.

A decade of PBDE monitoring by the RMP has resulted in a dataset covering periods during and after PBDE use, and consisting of hundreds of measurements of water, sediment, and aquatic organisms. By 2016, PBDE levels in bivalves (mussels and clams) and in Bay sport fish (shiner surfperch) had declined significantly.

In 2017, due to the declines and resolved uncertainties about risks to humans and wildlife, PBDEs were reclassified by the RMP from a moderate concern to a low concern for the Bay (page 37).





Footnotes:

Upper graph: Each point represents a composite sample of approximately 20 shiner surfperch each. Samples were collected throughout the Bay and processed with the head, tail and guts removed.

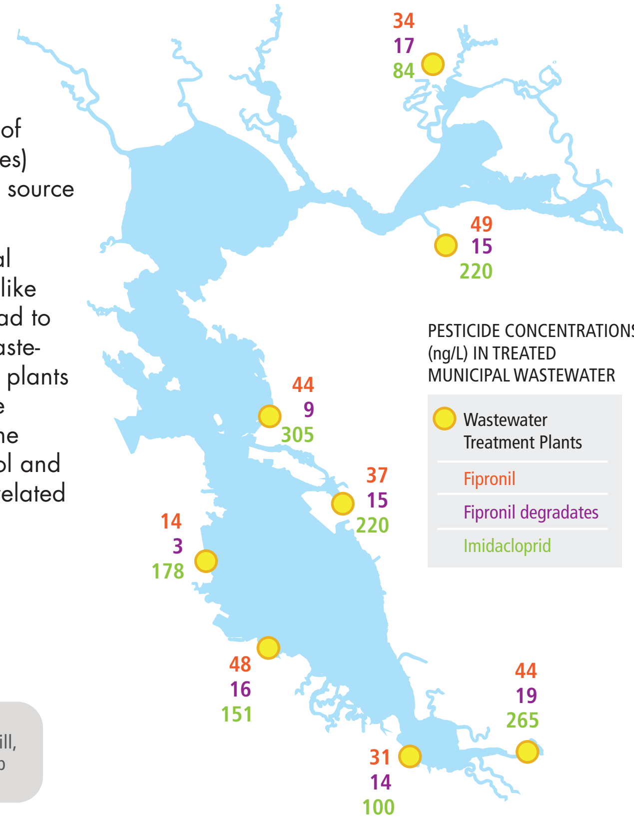
Lower graph: Clams were monitored at the Rivers; mussels at the other locations. Each point represents a mean concentration of 1 to 2 composites of approximately 30-40 bivalves each.

CECs

Flea Control Chemicals

Fipronil is an insecticide that is of moderate concern for the Bay because levels in sediment are in the range of toxicity thresholds for freshwater aquatic life (limited toxicity data are available for estuarine or marine species) (page 39). A recent RMP study on fipronil identified spot-on flea control products as likely to be an important source of this contaminant to the Bay, and one that has received very little study.

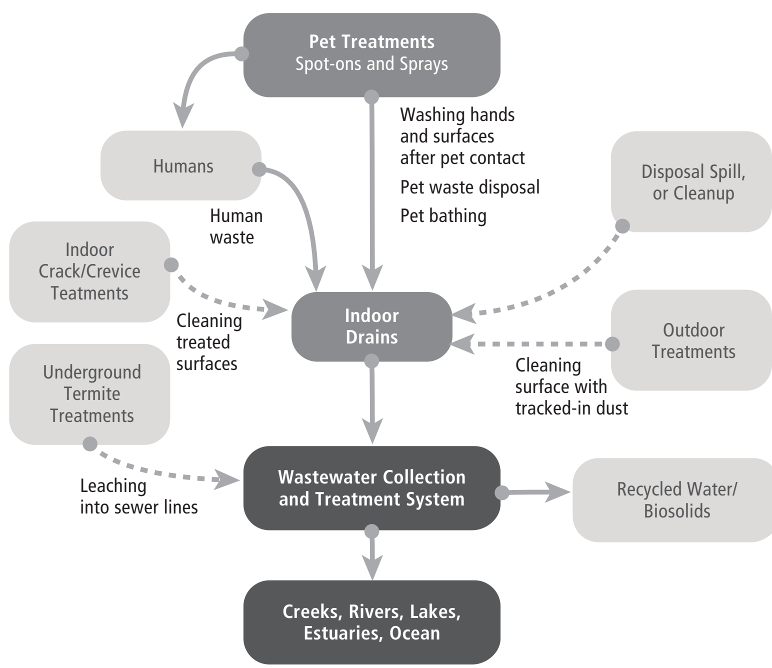
Fipronil is used for flea, ant, and termite control in California. Outdoor pesticide use can contaminate local creeks and urban runoff that enters San Francisco Bay. The RMP study was the first to suggest indoor uses like flea control may also be significant sources of fipronil to the Bay. Pet treatments and other activities can lead to inputs into indoor drains, which are then carried through the wastewater collection system to municipal wastewater treatment plants. The research team tested wastewater flowing in and out of eight sewage treatment plants around the Bay Area and detected fipronil at all of them. Even the most advanced facilities did not remove significant levels of fipronil and related compounds. This means the contaminants are also discharged to the Bay via treated wastewater. The RMP study also examined imidacloprid, another insecticide for flea control and other urban and agricultural uses. Detections in wastewater motivated a 2017 study of imidacloprid and related pesticides in San Francisco Bay water - the results will be available in 2018.



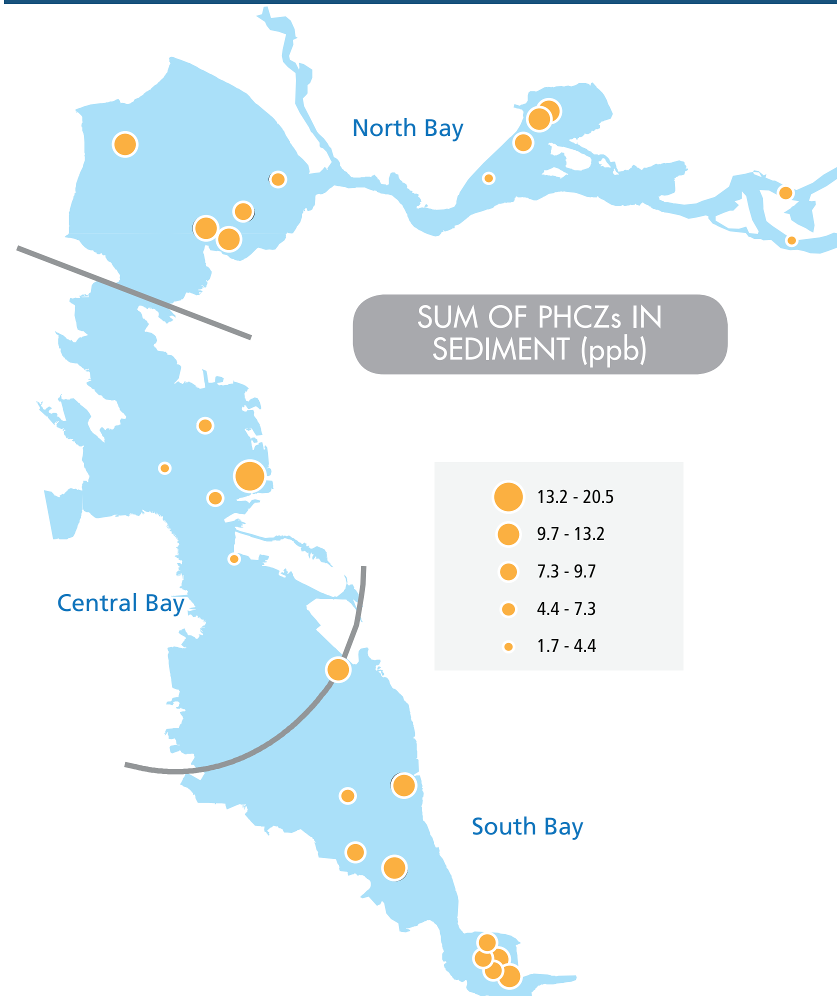
Footnote: Data from Sadaria et al. (2017).

Flea Control Chemicals Pathways to Bay

This conceptual model shows how fipronil and imidacloprid can contaminate municipal wastewater that is discharged to San Francisco Bay. The RMP study indicates flea control products are likely to be an important indoor source for this pollution. Light gray boxes and dashed lines denote sources and pathways believed to be relatively small.



CECs

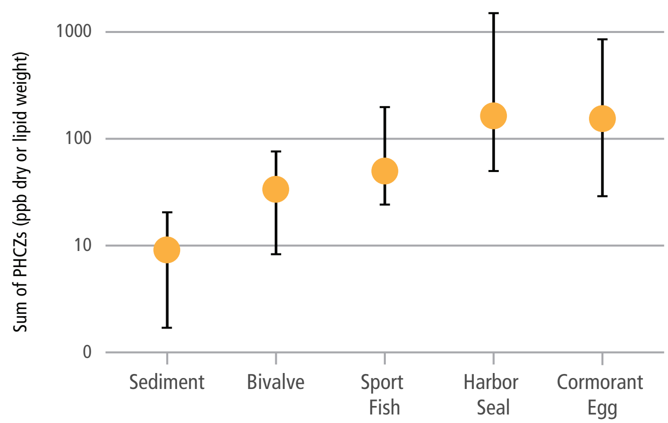


Footnote: Values shown based on single grab samples. After Wu et al. (2017).

Polyhalogenated Carbazoles: A New Class of Emerging Contaminant

Polyhalogenated carbazoles (PHCZs) are a class of chemicals recently discovered to be present in aquatic environments in several locations around the globe, including the Great Lakes, the North Sea, and China. Evidence is also emerging that these chemicals are of toxicological concern, producing dioxin-like effects. Sources are thought to include indigo dyes as well as natural metabolism by organisms such as marine fungi.

In 2017, Dr. Da Chen of Southern Illinois University and colleagues published a paper documenting the first comprehensive investigation of PHCZs in an aquatic ecosystem, based on analysis of Bay samples from the RMP sample archive (page 40) (Wu et al. 2017). PHCZs in sediment were found to be distributed relatively uniformly across the Bay regions. Biomagnification (increasing concentrations at higher levels in the food chain) was observed from fish to harbor seal and cormorant eggs. The toxicity of this new class of contaminants to Bay wildlife can be calculated relative to dioxin using dioxin equivalents. PHCZ dioxin equivalents in sport fish and cormorant eggs were approximately one-tenth of the dioxin equivalents attributed to dioxins and dibenzofurans measured in these species in other RMP monitoring (Ross et al. 2016, Sun et al. 2017a).



Footnote: Concentrations of Sum of PHCZs in sediment (ppb dry weight) and biological samples (ppb lipid weight) from the Bay. Points indicate medians; bars indicate the 5th and 95th percentiles. After Wu et al. (2017).

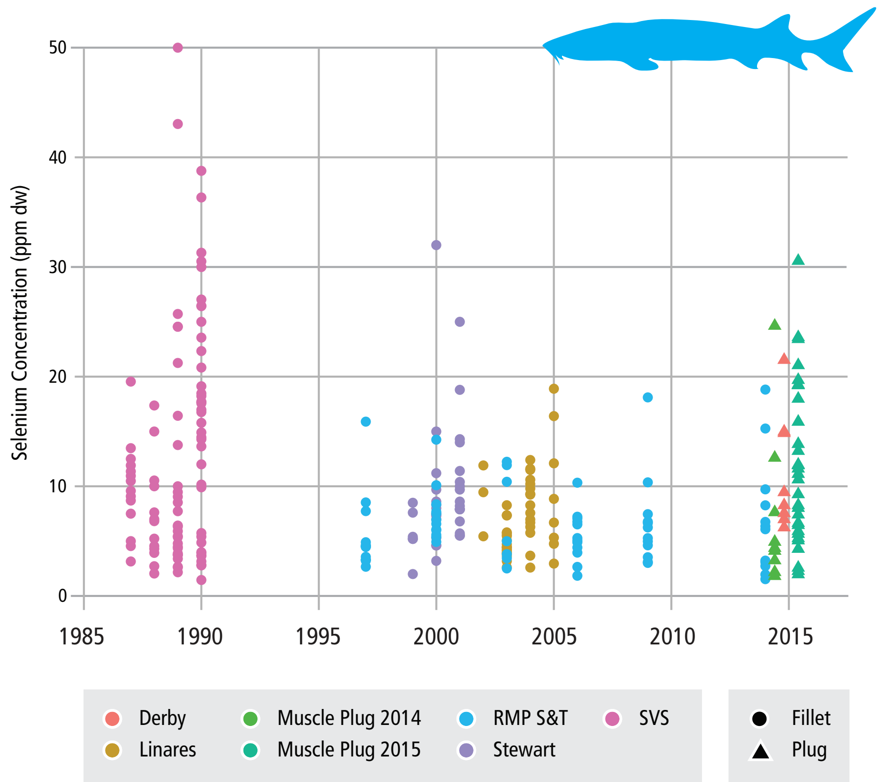
SELENIUM

Selenium in White Sturgeon

White sturgeon, a species that preys on clams and other bottom-dwelling invertebrates, is recognized as a key indicator of selenium impairment in the North Bay due to its susceptibility and sensitivity to selenium bioaccumulation.

In recent years, the RMP has focused on improving information on impairment through more extensive monitoring of white sturgeon. Non-lethal sampling of muscle plugs from sturgeon, in collaboration with the California Department of Fish and Wildlife, began in 2014 and is greatly expanding this critical dataset. The RMP has also analyzed muscle plugs and other tissues obtained through a collaboration with an annual fishing contest in Suisun Bay - the Original Sturgeon Derby - in 2015, 2016, and 2017.

The long-term dataset for selenium in sturgeon muscle generated by the RMP and other programs suggests that concentrations were relatively high in 1989 and 1990, and fairly constant in subsequent years up through 2014. A target of 11.3 ppm in white sturgeon muscle was established in the TMDL for selenium in the North Bay that was approved in 2016. Recent results up through 2014 indicate that average concentrations were below the target, but a few samples exceeded it. A relatively extensive dataset on muscle plugs obtained in 2015, however, had a median concentration of 10.9 ppm (just below the 11.3 ppm target), and 46% of the 30 samples were above the target. The overbite clam (*Potamocorbula amurensis*) is a primary prey item for white sturgeon in the North Bay, and tends to have higher selenium concentrations during dry years (page 81). The relatively high concentrations in the 2015 muscle plugs may therefore be related to the extended drought. Muscle plugs will be sampled again in the fall of 2017 with an expectation that concentrations will be lower in the wake of the high flows from the extremely wet winter of 2016/2017.



Footnote: All data in ppm dry weight. Points represent samples of individual white sturgeon. Data from the RMP and other sources as follows: Derby – Sun et al. (2017b); Linares-Casenave et al. (2015); Muscle Plug 2014 – Sun et al. (2016); Muscle Plug 2015 – Sun et al. in prep; RMP S&T (1997-2014); Stewart – Stewart et al. 2004

SELENIUM

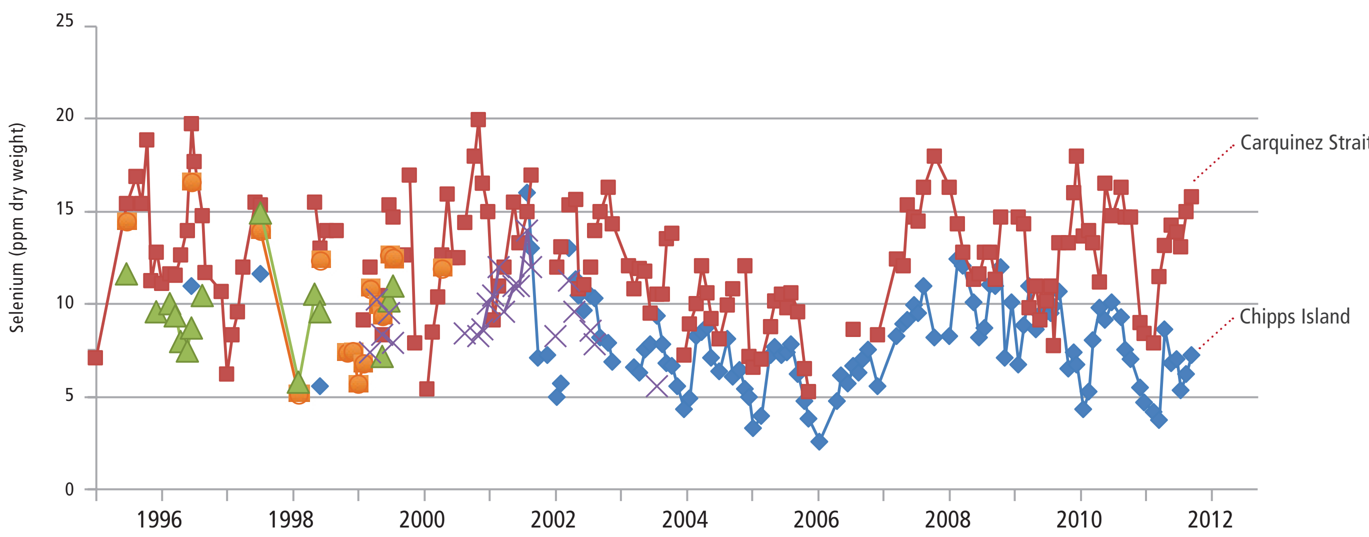
Selenium in North Bay Clams

The overbite clam (*Potamocorbula amurensis*) is a dominant invertebrate in North Bay sediment that accumulates selenium to an unusually high degree due to its slow depuration of this element. These clams are a primary prey item for white sturgeon, the key target species identified in the North Bay Selenium TMDL (page 80).

Since 1995, the U.S. Geological Survey has measured selenium concentrations in *Potamocorbula* on a monthly basis to track seasonal and interannual trends and to better understand factors influencing variability over time. For example, clam size was found to influence the uptake of selenium by individual clams and thus impact the apparent selenium burden of the population.

Anthropogenic sources of selenium, including agricultural inputs to the San Joaquin River and refinery discharges in the Bay, have been reduced since the 1980s. Refinery loads were reduced from approximately 2000 kg/yr in the late 1980s to 570 kg/yr from 2009-2012. After 1998, clam selenium concentrations (adjusted for differences in clam size) declined to levels 50% of pre-1998 concentrations, but in 2008-2012 they returned to the range of 1990s values.

The long-term dataset indicates that high freshwater flow from the Delta into the Bay has been correlated with lower selenium concentrations in North Bay clams. Clam concentrations were relatively high during the 2012-2016 drought (Robin Stewart, personal communication; data not shown). The extremely high freshwater flow during the wet season of 2016/2017 is expected to lead to lower concentrations in clams, which should also lead to lower concentrations in the white sturgeon tissue that will be collected in the fall of 2017.

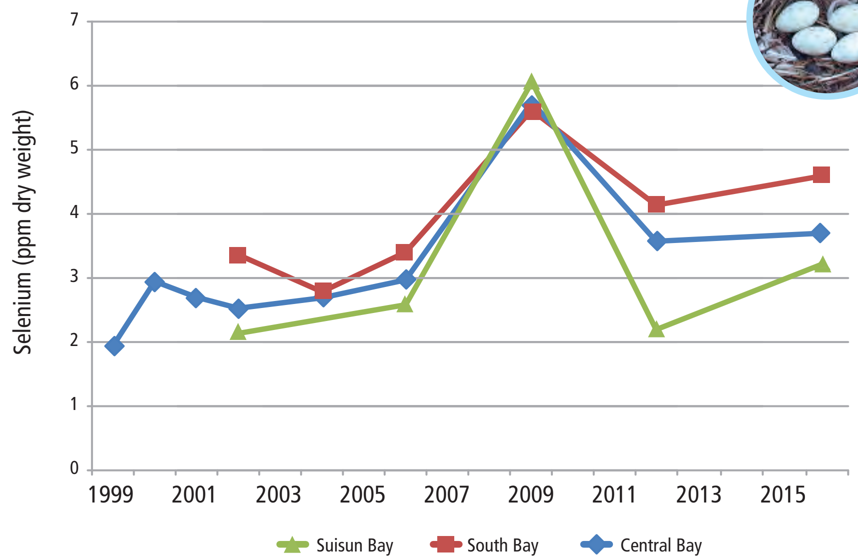


Footnote: From Stewart et al. (2013). Selenium concentration in Potamocorbula amurensis collected monthly at stations in northern San Francisco Bay. Points shown are means (n = 2 to 3 composites of 3 to 94 individuals each). Blue diamonds: Stn 4.1; orange circles: Stn 6.1; red squares: Stn 8.1; green triangles: Stn 12.5; purple crosses: Stn 415.1.

SELENIUM

Selenium in Cormorant Eggs

Avian predators of fish and aquatic invertebrates can also be at risk from selenium accumulation, and avian eggs are therefore another valuable indicator of potential impairment and trends. A selenium standard of 12.5 ppm in bird eggs was approved for Great Salt Lake in 2011. The RMP has tracked selenium concentrations in double-crested cormorant eggs at three locations for a span of 15 years. The highest concentration measured in a single composite sample was 8.7 ppm in 2009. Concentrations were unusually high in 2009, and relatively constant in the other years sampled. Average concentrations in 2015 were the second highest observed over the period of record.



Footnote: Average selenium concentrations (ppm dry weight) in cormorant egg composites. Each point represents the average of three composites, with 7 eggs in each composite. Data from Ross et al. (2016). Data available from cd3.sfei.org

RMP Selenium Studies

The RMP, under the guidance of the RMP Selenium Workgroup, is developing a monitoring plan for sturgeon, water, and clams to track trends, with a special emphasis on early detection of change. The Workgroup's goal is to have an integrated, long-term design for all three indicators based on a solid statistical framework that is explicitly linked to management decision-making. Funding from a North Bay Supplemental Environmental Project supported the data analysis and statistical evaluation conducted in 2017. Additional development of the design and framework in 2018 will take the form of a synthesis of information for North Bay selenium indicators that will support an integrated and strategic approach to monitoring in support of the TMDL.

COPPER

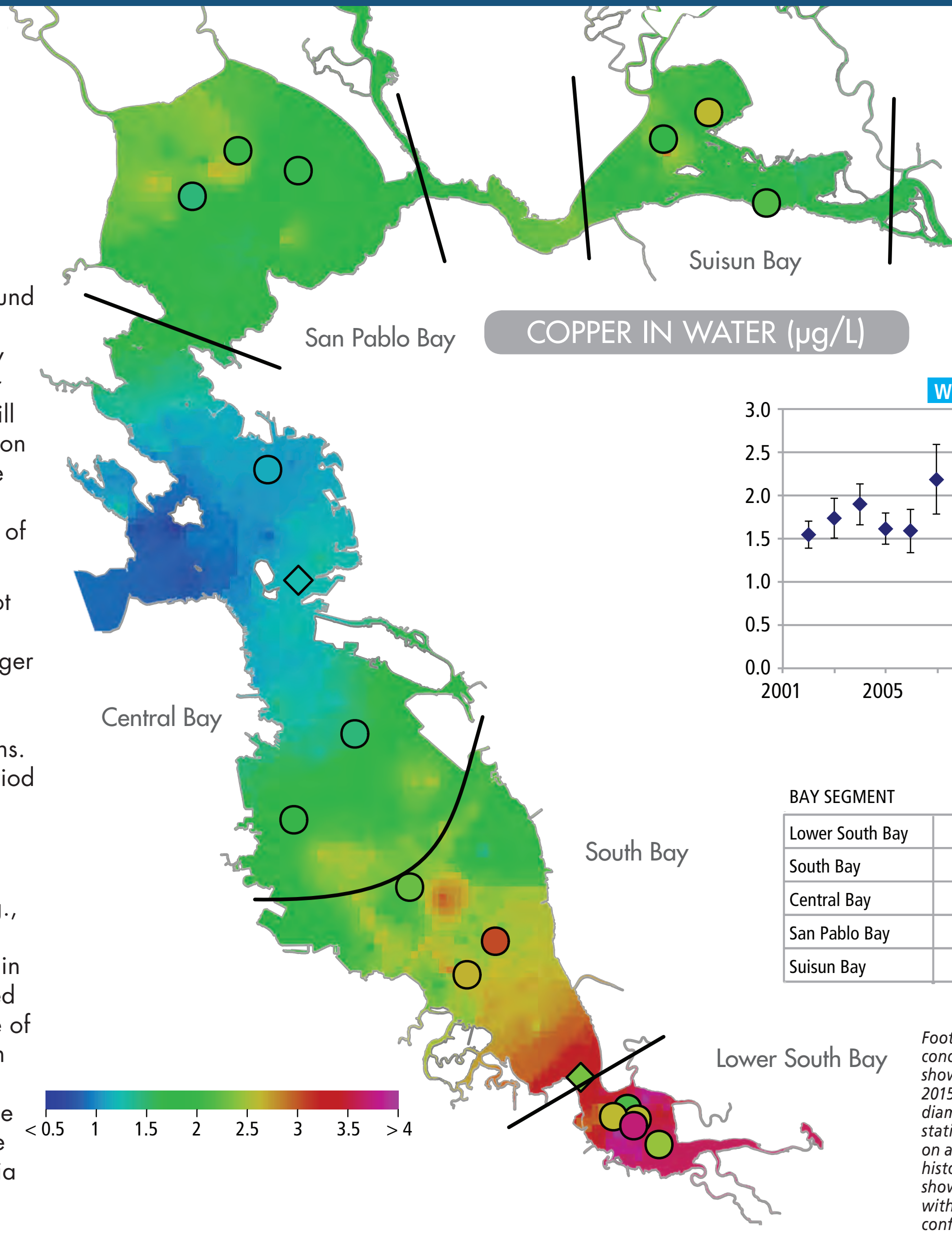
Copper Remains Below Trigger Levels

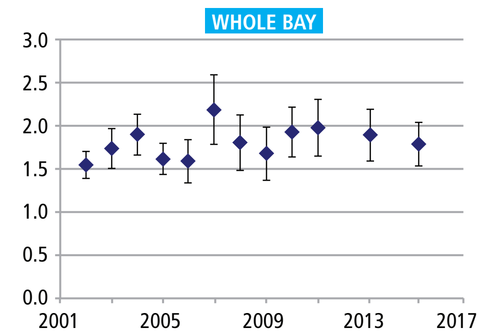
Copper in the Bay was a major concern in the 1990s. An evaluation of the issue by the Water Board and stakeholders, based on an extensive dataset provided by the RMP and other studies showing that most of the copper in the Bay is bound up in a harmless form, concluded that the existing water quality objectives were inappropriately low. These findings led to new Bay-specific water quality objectives for copper (less stringent but still considered fully protective of aquatic life), pollution prevention and monitoring activities to make sure concentrations remain below the objectives, and the 2002 removal of copper from the 303(d) List of pollutants of concern in the Bay.

In order to determine that concentrations have not increased, monitoring data collected by the RMP are compared to specific trigger levels. If the trigger concentration is exceeded in any Bay segment, the Water Board will investigate causes of the exceedance and consider potential control options. Concentrations in the most recent assessment period were below the triggers (lower right).

To maintain water quality in the Bay, municipalities are required to implement actions to control discharges to storm drains from architectural (e.g., roofs) and industrial (e.g., metal plating) uses of copper, as well as copper used as an algaecide in pools, spas, and fountains. They are also required to address vehicle brake pads, the largest source of copper to the Bay, which they have done through participation in the Brake Pad Partnership, a public-private collaboration whose work led to the passage of legislation (SB 346) requiring that the amount of copper in brake pads sold in California be reduced to no more than 0.5% by 2025.

COPPER IN WATER (µg/L)





BAY SEGMENT	TRIGGER (µg/L)	2011-2015 ROLLING AVERAGE (µg/L)
Lower South Bay	4.2	3.6
South Bay	3.6	2.8
Central Bay	2.2	1.5
San Pablo Bay	3.0	2.0
Suisun Bay	2.8	2.3

Footnote: Dissolved copper concentrations. Points on the map show results from samples collected in 2015. Circles represent random sites; diamonds represent historic fixed stations. Color contours are based on all available RMP data, excluding historic stations. Bay-wide trend plot shows annual random-station means with error bars indicating the 95% confidence intervals of the means. Data available from cd3.sfei.org

BEACH BACTERIA

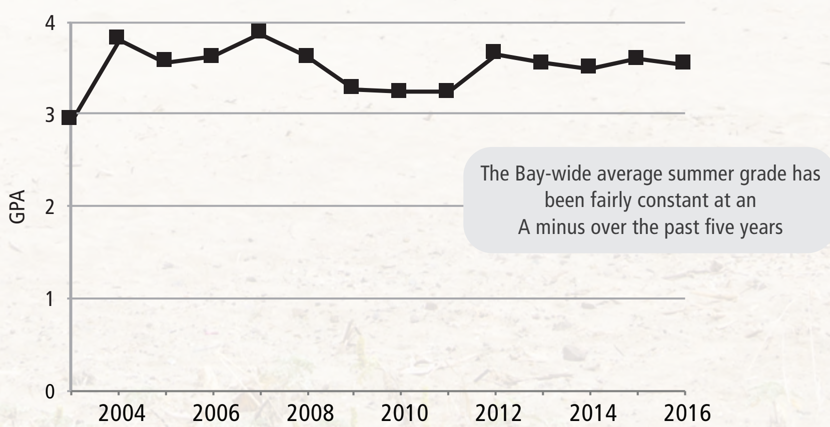
Beach Report Card Summary

Pathogenic organisms found in waste from humans and other warm-blooded animals can pose health risks to people who recreate in contaminated waters. Six Bay beaches are on the 303(d) List of impaired water bodies because fecal indicator bacteria exceed water quality standards, and a TMDL was approved in February 2017 to address this impairment.

County public health and other agencies routinely monitor fecal indicator bacteria (FIB) concentrations at 28 Bay beaches where water contact recreation is common and provide warnings to the public when concentrations exceed the standards.

Using these data, Heal the Bay, a Santa Monica-based non-profit, provides evaluations of over 400 California bathing beaches in Beach Report Cards as a guide to aid beach users' decisions concerning water contact recreation (Heal the Bay 2017). The Report Cards use a familiar A through F grading scale to summarize the results of the county monitoring. The risk of illness from pathogen exposure increases with lower grades.

The Bay-wide average summer grade for 2016 was an A minus (GPA of 3.54). The Bay-wide average summer grade has been fairly constant at this level over the past five years.



Footnote: Average of Bay Area summer beach season (April-October) grades from Heal the Bay's annual beach report card (Heal the Bay 2017).

∧ Crissy Field Beach. Photograph by Shira Bezalel.

BEACH BACTERIA

	2011	2012	2013	2014	2015	2016
SAN MATEO COUNTY						
Oyster Point	D	A	A	A	A	A
Coyote Point	A	A	A	A	A	A
Marina Lagoon Aquatic Park	F	F	F	F	C	B
Lakeshore Park	F	D	F	F	C	F
Kiteboard Beach		A	C		A	
ALAMEDA COUNTY						
Alameda Point North	A	A	A	A	A	
South	A	A	A	A	A	
Crown Beach Crab Cove			A	A	B	B
Bath House	A	A	A	A	A	A
Windsurf Corner	A	A	A	A	A	A
Sunset Road	A	A	A	A	A	A
Shoreline Drive	A	A	A	A	A	B
Bird Sanctuary	B	A	A	A	B	B
CONTRA COSTA COUNTY						
Keller Beach North	B	A	A	A	B	C
Mid-Beach	B					
South	B	A	A	A	B	C
SAN FRANCISCO COUNTY						
Crissy Field Beach West	A	A	A	A	A	A
East	A	A	A	A	A	A
Aquatic Park Beach 211 Station	B	A	A	B	A	A
Hyde Street Pier	A	A	A	A	A	A
Islais Channel						A
Candlestick Point Jackrabbit Beach	B	A	A	A	A	A
Windsurfer Circle	B	C	C	C	C	B
Sunnydale Cove	A	A	B	F	D	B
MARIN COUNTY						
Baker Beach Horseshoe Cove NE	B	A	A	A	A	A
NW	A	A	A	A	A	A
SW	A	A	A	A	A	A
Schoonmaker Beach	B	A	A	A	A	A
China Camp	A	A	A	A	A	A
McNears Beach			B	A	A	A

Footnote: Beach summer water quality grades for 2011-2016. Beach names listed in red are included in the Bay Beaches TMDL that was approved in February 2017. Data from Heal the Bay (2017).

Beach Report Card Details

Overall, the monitoring data and resulting Beach Report Card grades indicate that most Bay beaches are safe for summer swimming, but that bacterial contamination is a concern at a few beaches in the summer, and at a higher number of beaches in wet weather.

Data for the summer beach season in 2016 are available for 26 beaches. In 2016, 18 of the 26 monitored beaches received an A or A+ grade, reflecting minimal exceedance of standards. Three of these beaches received an A+: Coyote Point, Aquatic Park Beach Hyde Street Pier, and Crissy Field Beach West. Most Bay beaches, therefore, are quite safe for swimming in the summer. Eight of the 26 beaches monitored in the summer in 2016 had grades of B or lower, indicating varying degrees of exceedance of bacteria standards. Lakeshore Park in San Mateo County received an F. These low grades indicate an increased risk of illness or infection. Overall, the average grade for the 28 beaches monitored from April-October was an A-.

During wet weather, which mostly occurs in the winter, water contact recreation is less popular but is still enjoyed by a significant number of Bay Area residents. Bacteria concentrations are considerably higher in wet weather due to stormwater runoff and sewer overflows, making the Bay less safe for swimming. This pattern is very evident in the 2016/2017 report card grades for wet weather (not shown), due to the extremely high rainfall that occurred. In wet weather, 13 of 27 beaches with data (48%) had grades of D or F. The following eight beaches had grades of F: Aquatic Park, Lakeshore Park, and Kiteboard Beach in San Mateo County; Crown Beach Crab Cove and Crown Beach Bird Sanctuary in Alameda County; and Islais Landing, Candlestick Point Windsurfer Circle, and Candlestick Point Sunnydale Cove in San Francisco County. Only five of the beaches (22%) had grades of A or A+ in wet weather. The overall average GPA for these 27 beaches in wet weather was 1.85 (a "C").


TO PEDESTRIANS
allCREATURES
We cut the curbs to claim the rain!
Check out the curbs along the street. Notice anything different?
Dirt Does the Work
La Tierra Hace el Trabajo
LET'S DO THIS.

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 and develop action plans, called Total Maximum Daily Loads (TMDLs), to improve water quality.

The list of impaired water bodies is periodically updated. The RMP is one of many entities that provide data to the State Water Board to assess water quality and inform the 303(d) List. The process for developing the 303(d) List for the Bay includes the following steps:

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

The primary pollutants/stressors for the Bay and its major tributaries on the 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, Polycyclic Aromatic Hydrocarbons (PAHs), and Indicator Bacteria

STATUS OF POLLUTANTS OF CONCERN

POLLUTANT	STATUS
Copper	Site-specific objectives approved for entire Bay San Francisco Bay removed from 303(d) List in 2002
Dioxins / Furans	Updated assessment in 2017
Legacy Pesticides (Chlordane, Dieldrin, and DDT)	Monitoring recovery
Mercury	Bay TMDL and site-specific objectives approved in 2008 Guadalupe River Watershed TMDL approved in 2010
Bacteria	Richardson Bay TMDL adopted in 2008 Bay beaches (multiple listings); TMDL approved in 2017
PCBs	Bay TMDL approved in 2009
Selenium	North Bay TMDL approved in 2016
Trash	Municipalities required to implement trash load controls in 2009

< Sampling inflow and outflow from a rain garden. Photograph by Alicia Gilbreath.

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GRAPH DETAILS

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(TOP) Rainfall in the Bay Area: Data are for climatic years (July 1 to June 30 with the year corresponding to the end date). Source: Jan Null, Golden Gate Weather Services.

(BOTTOM) Flows to the Bay from the Ten Largest Municipal Wastewater Treatment Plants: Data for the ten largest municipal wastewater dischargers to the Bay: San Jose, East Bay Dischargers, East Bay MUD, San Francisco, Central Contra Costa, Palo Alto, Fairfield-Suisun, South Bayside System Authority, San Mateo, Vallejo, and Sunnyvale. In 2013-2015, Sunnnyvale replaced Vallejo in the "top 10" POTWs.

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(TOP) Delta Sediment Load: Loads based on continuous measurements taken at Mallard Island by USGS (http://sfbay.wr.usgs.gov/sediment/cont_monitoring/). Data are for water years (October 1 to September 30 with the year corresponding to the end date)

(BOTTOM) Suspended Sediment: Data for Dumbarton Bridge, 20 feet below mean lower low water. Based on 15-minute data collected by the U.S. Geological Survey (Buchanan et al. 2014). Data gap during WY2012 and 2013 due to construction for seismic retrofit of highway bridge.

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Sea Level at the Golden Gate: Data from National Oceanic and Atmospheric Administration. Data and more information available at:

https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=9414290

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(TOP) Mercury in Sport Fish Species: Bay-wide average mercury concentrations. Includes striped bass from Artesian Slough in 2015. The no consumption advisory tissue level for mercury is 0.44 ppm, and the water quality objective is 0.20 ppm. Data from Sun et al. (2017a). Data available from cd3.sfei.org

(BOTTOM) No Long-term Mercury Trend in Striped Bass: Excludes fish from Artesian Slough. Concentrations for individual fish normalized to 60 cm. The no consumption advisory tissue level for mercury is 0.44 ppm, and the water quality objective is 0.20 ppm. Data from Sun et al. (2017a). Data available from cd3.sfei.org

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Mercury in Sediment: All concentrations for total mercury on a dry weight basis. Sampling in 2010 and 2012 was conducted in the wet season (data not shown). Central Bay margins data from Yee et al. (2017). Data available from cd3.sfei.org

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Methylmercury in Water: Data are for total methylmercury (dissolved plus particulate). Data available from cd3.sfei.org

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(TOP) PCBs in Sport Fish Species: The no consumption advisory tissue level for PCBs is 120 ppb, and the Basin Plan numeric target is 10 ppb. Data from Sun et al. (2017a). Data available from cd3.sfei.org

(BOTTOM) Little Evidence of PCB Decline in Shiner Surfperch: The no consumption advisory tissue level for PCBs is 120 ppb, and the Basin Plan numeric target is 10 ppb. Data from Sun et al. (2017a) and Fairey et al. (1997). Data available from cd3.sfei.org

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PCBs in Sediment: Concentrations for sum of 40 PCBs (ppb) on a dry weight basis. Sampling in 2010 and 2012 was conducted in the wet season (data not shown). Central Bay margins data from Yee et al. (2017). Data available from cd3.sfei.org

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South Bay Chlorophyll: Chlorophyll a averaged over the top 2 meters during August-October at stations s21, s22, s24, s25, s27, s29, s30, and s32. Data collected monthly at fixed stations along the spine of the Bay. Data from USGS: sfbay.wr.usgs.gov/access/wqdata.

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Nutrient Graphs: Data from USGS cruises. Data are available through the USGS portal at: https://sfbay.wr.usgs.gov/access/wqdata

Sediment sample containers. Photograph by Jennifer Sun.

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City of Burlingame

City of Calistoga

City of Millbrae

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City of Petaluma

City of Pinole/Hercules

City of Saint Helena

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Las Gallinas Valley Sanitation District

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Napa Sanitation District

Novato Sanitation District

Rodeo Sanitary District

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Sausalito/Marin City Sanitation District

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Silicon Valley Clean Water

Sonoma County Water Agency

Town of Yountville

Union Sanitary District

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Vallejo Sanitation and Flood Control District

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Chevron Products Company

EcoServices Operations, LLC

Phillips 66

Crockett Cogeneration

Shell Martinez Refinery

Tesoro Martinez Refinery

USS – POSCO Industries

Valero Refining Company

COOLING WATER

NRG Energy

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

Santa Clara Valley Urban Runoff Pollution Prevention Program

San Mateo Countywide Water Pollution Prevention Program

Vallejo Sanitation and Flood Control District

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City of Benicia – Marina

City and County of San Francisco (SF Marina)

Chevron Richmond Long Wharf Terminal

Mooring Road Neighborhood Association

Napa Yacht Club Homeowners Association

Phillips 66 Rodeo Terminal

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∧ Harbor seal in Central Bay. Photograph by Shira Bezalel.

Golden Gate Bridge at sunset. Photograph by Shira Bezalel. >

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