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The Regional Monitoring Program for Water Quality in San Francisco Bay, California, USA: Science in support of managing water quality

P.R. Trowbridge[a,*], J.A. Davis[a], T. Mumley[b], K. Taberski[b], N. Feger[b], L. Valiela[c], J. Ervin[d], N. Arsem[e], A. Olivieri[f], P. Carroll[g], J. Coleman[h], P. Salop[i], R. Sutton[a], D. Yee[a], L.J. McKee[a], M. Sedlak[a], C. Grosso[a], J. Kelly[a]

[a] *San Francisco Estuary Institute, 4911 Central Avenue, Richmond, CA 94804, United States*
[b] *San Francisco Regional Water Quality Control Board, 1515 Clay Street, Oakland, CA 94612, United States*
[c] *U.S. Environmental Protection Agency, Region IX, 75 Hawthorne St, San Francisco, CA 94105, United States*
[d] *San Jose-Santa Clara Regional Wastewater Facility, 700 Los Esteros Road, San Jose, CA 95134, United States*
[e] *East Bay Municipal Utility District, P.O. Box 24055, Oakland, CA, United States*
[f] *EOA, Inc., 1410 Jackson Street, Oakland, CA 94612, United States*
[g] *Tesoro Golden Eagle Refinery, 150 Solano Way, Martinez, CA 94553, United States*
[h] *Bay Planning Coalition, 1970 Broadway, Oakland, CA 94612, United States*
[i] *Applied Marine Sciences, 4749 Bennett Drive, Livermore, CA 94551, United States*

HIGHLIGHTS

- The only long-term, systematic monitoring program for pollutants in the Bay.
- A collaborative partnership of scientists, regulators, and the regulated community.
- Led by an independent science team from the San Francisco Estuary Institute.
- A model for adaptive monitoring to answer evolving management questions.

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ABSTRACT

The Regional Monitoring Program for Water Quality in San Francisco Bay (RMP) is a novel partnership between regulatory agencies and the regulated community to provide the scientific foundation to manage water quality in the largest Pacific estuary in the Americas. The RMP monitors water quality, sediment quality and bioaccumulation of priority pollutants in fish, bivalves and birds. To improve monitoring measurements or the interpretation of data, the RMP also regularly funds special studies. The success of the RMP stems from collaborative governance, clear objectives, and long-term institutional and monetary commitments. Over the past 22 years, high quality data and special studies from the RMP have guided dozens of important decisions about Bay water quality management. Moreover, the governing structure and the collaborative nature of the RMP have created an environment that allowed it to stay relevant as new issues emerged. With diverse participation, a foundation in scientific principles and a continual commitment to adaptation, the RMP is a model water quality monitoring program. This paper describes the characteristics of the RMP that have allowed it to grow and adapt over two decades and some of the ways in which it has influenced water quality management decisions for this important ecosystem.

1. Introduction

The Regional Monitoring Program for Water Quality in the San Francisco Estuary (RMP) provides the scientific foundation for managing water quality in a treasured aquatic ecosystem. In the 22 years since its inception, the RMP has matured into a mul-

* Corresponding author. Tel.: +1 510 746 7345.
E-mail address: philt@sfei.org (P.R. Trowbridge).

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tifaceted, sophisticated, and efficient program that has demonstrated the capacity to adapt in response to changing management priorities and advances in scientific understanding. With shared financial support, direction, and participation by regulatory agencies and the regulated community, the RMP is a novel partnership. This paper describes the history, objectives, and approach of the RMP; the key characteristics that have sustained the program; and key examples of how the RMP has influenced management decisions for the Bay.

1.1. History and establishment of the RMP

The San Francisco Bay Regional Water Quality Control Board (Water Board) is the implementing agency of the federal Clean Water Act (33 U.S.C. Section 1251 et seq.) and the State of California's Porter-Cologne Water Quality Control Act (California Water Code 13 000 et seq.) in San Francisco Bay. Among other things, the Clean Water Act regulates discharges of pollutants to surface waters, requires states to develop surface water quality standards, and establishes the process for Total Maximum Daily Load (TMDL) studies for water bodies that do not meet standards. The Porter-Cologne Water Quality Control Act is the state law governing water quality in both surface waters and groundwater. The law also implements the federal requirements for permitting the discharge of pollutants to surface waters.

The RMP was formed to provide objective scientific information on San Francisco Bay to assist with the implementation of these laws. By 1986, the Water Board had adopted numerical water quality objectives, yet at that time there was no monitoring program to determine if these water quality objectives were being met or if beneficial uses were being protected as required by the Clean Water Act and the Porter-Cologne Act. Starting in 1989, the Water Board implemented a series of pilot studies to determine if water quality in the Bay was meeting standards. Studies were funded through US Environmental Protection Agency (USEPA) grants and the State's Bay Protection and Toxic Cleanup Program.

Around the same time, in 1987, the San Francisco Estuary Project, a State/Federal cooperative endeavor mandated by the National Estuary Program under the Clean Water Act, initiated the development of a Comprehensive Conservation and Management Plan (CCMP) for San Francisco Bay. The CCMP was developed with the assistance of over 100 stakeholders. One of the recommendations of the CCMP was the formation of an entity to be responsible for coordinating and integrating research and monitoring in the Estuary.

In 1992 the San Francisco Estuary Institute (SFEI) was formed, out of the former Aquatic Habitat Institute, to fill this role. The Water Board passed Resolution No. 92-043 directing the Executive Officer to send a letter to regulated dischargers requiring them to contribute to or implement a regional multi-media pollutant monitoring program in San Francisco Bay. The Water Board's regulatory authority to require such a program comes from California Water Code Sections 13 267, 13 383, 13 268 and 13 385. The Water Board offered to suspend some effluent and local receiving water monitoring requirements to provide cost savings to implement baseline portions of the RMP, although they recognized that additional resources would be necessary.

In 1993, with funding provided to SFEI from regulated dischargers, the RMP commenced monitoring. The original goal was to be a baseline program for the monitoring of toxic pollutants in the San Francisco Estuary in ambient water, sediment and tissue at 16 fixed stations. The RMP used the pilot studies conducted by the Water Board to form the basis of the early monitoring and assessment component of the RMP. Over time, the objectives and scope of the program have expanded (see Section 1.2).

More details about the history of the program are available in Thompson et al. (2000), Hoenicke et al. (2003), and Davis et al. (2006).

1.2. Goal and objectives of the program

The overarching goal of the RMP is to collect data and communicate information about water quality in San Francisco Bay to support management decisions. Maintaining relevance to management decisions is a key aspect of the goal. The intent of exchanging individual discharger monitoring requirements for contributions to the RMP was to obtain greater insight to inform management decisions through regional monitoring. Table 1 shows all of the management questions of the Program, which stem from this overarching goal.

To meet the communications aspects of the goal, the RMP produces technical reports and other products (see Section 2.2.5), presents information to committees of stakeholders, and holds an annual conference. The RMP also works closely with the San Francisco Estuary Partnership to provide technical information for their State of the Estuary reports (SFEP, 2011), State of the Estuary conferences (http://www.sfestuary.org/soe/), and outreach products, such as Estuary News (http://www.sfestuary.org/estuary-news/).

2. Methods

The methods of the RMP fall into two categories: what the Program does and how the Program operates. The Program's core elements (governance, status and trends monitoring, and special studies) are described in Section 2.1. Section 2.2 describes the six key attributes of how the RMP operates that have sustained this long-term monitoring program over the past 22 years.

2.1. Core elements of the program

2.1.1. Organization and governance

The RMP provides a forum for an innovative and highly valued collaboration among regulators, the regulated, and scientists. This forum is largely provided by an organizational structure with committees (Fig. 1) that meet quarterly to track progress and plan future work.

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), with administrative support from SFEI staff. The Steering Committee determines the overall budget and allocation of funds, tracks progress, and provides direction from a manager's perspective.

Oversight of the technical content and quality of the RMP is provided by the Technical Review Committee (TRC), which consists of technical representatives from the Water Board, discharger groups, USEPA (Region IX) staff, and non-governmental organizations.

There are six workgroups that report to the TRC and address the main technical subject areas covered by the RMP as shown in Table 2.

Workgroups consist of regional scientists and regulators and, importantly, external science advisors recognized as leaders in their field. Workgroups directly guide planning and implementation of special studies and Status and Trends monitoring. The external science advisers also provide objective peer-review of the study plans and final work products.

Nutrients is a focus area for the RMP but the technical oversight of these studies is handled by a separate Nutrient Management Strategy team formed by the Water Board. Nutrient research is not exclusively funded by the RMP. Therefore, a separate governance structure was created to oversee the use of the pooled funds. For more information about the Nutrient Management Strategy for San Francisco Bay, see http://sfbaynutrients.sfei.org/ and Section 3.5.2.

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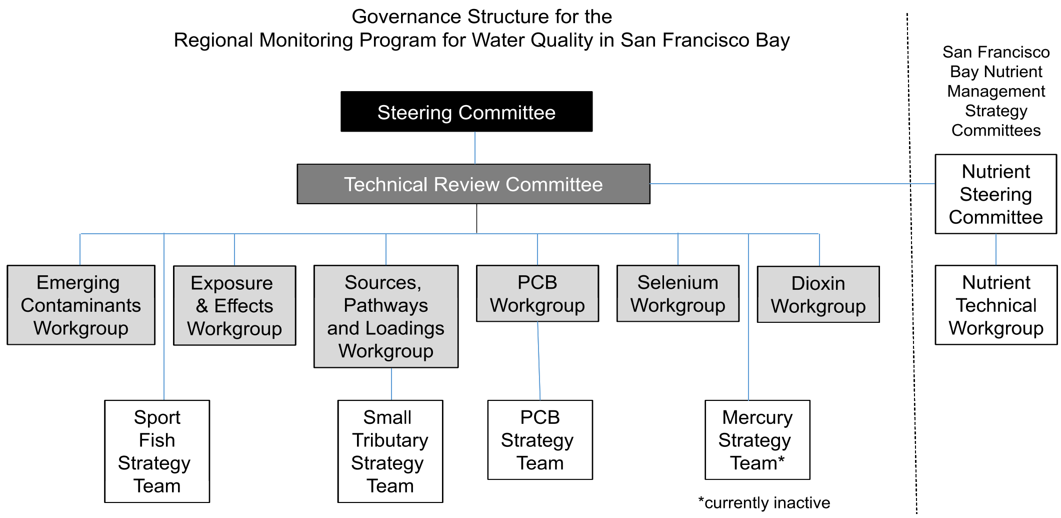

Fig. 1. RMP governance organization chart. The Steering Committee is responsible for executive functions. The Technical Review Committee provides technical oversight. Workgroups consist of interested stakeholders as well as external science advisers who provide peer-review for the program. Strategy teams are groups of interested stakeholders formed to meet frequently on topics of high interest.

Table 1
Goal and management questions guiding the Regional Monitoring Program for Water Quality in San Francisco Bay.

Goal	
To collect data and communicate information about water quality in the San Francisco Bay to support management decisions.	
Management questions	**Sub-questions**
1. Are chemical concentrations in the Bay at levels of potential concern and are associated impacts likely?	a. Which chemicals have the potential to impact humans and aquatic life and should be monitored? b. What potential for impacts on humans and aquatic life exists due to contaminants in the Bay ecosystem? c. What are appropriate guidelines for protection of beneficial uses? d. What contaminants are responsible for observed toxic responses?
2. What are the concentrations and masses of contaminants in the Bay and its segments?	a. Do spatial patterns and long-term trends indicate particular regions of concern?
3. What are the sources, pathways, loadings, and processes leading to contaminant-related impacts in the Bay?	a. Which sources, pathways, and processes contribute most to impacts? b. What are the best opportunities for management intervention for the most important contaminant sources, pathways, and processes? c. What are the effects of management actions on loads from the most important sources, pathways, and processes?
4. Have the concentrations, masses, and associated impacts of contaminants in the Bay increased or decreased?	a. What are the effects of management actions on the concentrations and mass of contaminants in the Bay? b. What are the effects of management actions on the potential for adverse impacts on humans and aquatic life due to Bay contamination?
5. What are the projected concentrations, masses, and associated impacts of contaminants in the Bay?	a. What patterns of exposure are forecast for major segments of the Bay under various management scenarios? b. Which contaminants are predicted to increase and potentially cause impacts in the Bay?

Table 2
Workgroups and their purpose for the six current focus areas of the Regional Monitoring Program for Water Quality in San Francisco Bay.

Focus area workgroup	Purpose
Emerging contaminants	Provide information on contaminants that are not currently regulated, yet may pose significant ecological or human health risks, with the goal of reducing harmful emerging contaminants in the Bay
Exposure and effects	Provide information on biological effects to help address beneficial use management questions
Sources, pathways and loadings	Produce recommendations for collection, interpretation, and synthesis of data on general sources and loading of trace contaminants to the Estuary
PCBs Selenium Dioxin	Provide the information most urgently needed by managers to address impairments in the Estuary due to priority contaminants

The final level of governance are strategy teams. Strategy teams are formed when there is a need for frequent feedback from stakeholders on an area of emerging importance. The major distinction between a strategy team and a workgroup is that workgroups always have external science advisors for peer review and strategy teams do not serve this function. The RMP currently has active strategy teams for sport fish monitoring, small tributary loadings, and PCBs.

RMP meetings also provide a forum for communication with other Bay stakeholders and scientists. All RMP committee and workgroup meetings are open to the public. Input from all parties is given consideration as consensus is sought on the issues at hand.

Table 3
Study design for status and trends monitoring in San Francisco Bay in 2014–2023. Additional parameters may be added for special studies.

Program	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Continuous: basic water quality (5 *targeted sites*)										
Water temperature, Salinity, SSC	X	X	X	X	X	X	X	X	X	X
Monthly: basic water quality in deep channel (38 *targeted sites*)										
CTD profiles, light attenuation, SSC, DO, Chl-a, Phytoplankton speciation, Nutrients (NO_2, NO_3, NH_4, PO_4, Si)	X	X	X	X	X	X	X	X	X	X
Every 2 *Years: priority pollutants in water* (5 *targeted sites and* 17 *random sites*)										
MeHg, Cu, Se, CN, Hardness, SSC, Chl-a, DOC, POC, Nutrients (NO_3, NO_2, PO_4, Si)		X		X		X		X		X
Aquatic toxicity (9 stations)		X		X		X		X		X
PCBs, PAHs, Pesticides										X
CTR parameters (10 samples at 3 targeted stations)		X								?
Every 2 *years: priority pollutants in bivalve tissue* (7 *targeted sites*)										
Se, PAHs, PBDEs	X		X		X		X		X	
PCBs	X								X	
Every 3 *years: priority pollutants in bird egg tissue*										
Cormorant eggs: Hg, Se, PCBs, PBDEs, PFCs (3 targeted sites)		X			X			X		
Tern eggs: Hg, Se, PBDEs (variable fixed sites)		X			X			X		
Every 4 *years: priority pollutants in sediment* (7 *targeted sites and* 20 *random sites*)										
Ag, Al, As, Cd, Cu, Fe, Hg, MeHg, Mn, Ni, Pb, Se, Zn, PAHs, PCBs, Pesticides, TOC, N, % Solids, Grain Size	X				X				X	
PBDEs	X				X					
Sediment toxicity					X				X	
Benthic macroinvertebrates					?				X	
Every 5 *years: priority pollutants in sport fish tissue* (7 *targeted sites*)										
Hg, Se, PCBs, PBDEs, PFCs, Dioxins	X					X				

Notes:
"X" = Planned sampling event. "?" = Event that is planned but must be approved by the RMP Steering Committee before implementation. Additional parameters can be added to sampling events to support RMP Special Studies.
Acronyms: SSC: Suspended Sediment Concentration, CTD: Conductivity, Temperature, and Depth, DO: Dissolved Oxygen, Chl-a: Chlorophyll-a, NO_2: Nitrite (dissolved), NO_3: Nitrate (dissolved), NH_4: Ammonia (dissolved), PO_4: Phosphate (dissolved), Si: Silica (dissolved), MeHg: Methylmercury, DOC: Dissolved Organic Carbon, POC: Particulate Organic Carbon, PCBs: Polychlorinated Biphenyls, PAHs: Polynuclear Aromatic Hydrocarbons, CTR: California Toxics Rule, see http://water.epa.gov/lawsregs/rulesregs/ctr/, PBDEs: Polybrominated Diphenyl Ethers, PFCs: Perfluorinated Compounds, TOC: Total Organic Carbon.

For more information on the RMP governance structure, see the Program's formal charter (SFEI, 2015).

2.1.2. Status and trends monitoring

The cornerstone of the RMP is status and trends monitoring. Since 1993, this element has measured priority pollutants in water, sediment, and bivalves. Measurements in bird eggs and sport fish were added later as indicators of bioaccumulation. The current study design for status and trends monitoring is shown on Table 3. The frequency of the monitoring varies depending on the parameter and media. For example, salinity and dissolved oxygen in water change hourly so the monitoring design for this aspect of the program uses in-situ sensors recording data at 15-min intervals. In contrast, the concentrations of contaminants in sport fish change very slowly, therefore this type of monitoring is conducted once every 5 years. The optimal sampling frequency and required parameters were developed by the TRC using information from power analyses (Lowe et al., 2005; Melwani et al., 2008). In 2015, the status and trends element amounted to 27% of the RMP budget ($966,000). The study area for status and trends monitoring and the RMP as a whole is shown in Fig. 2.

For ambient water and sediment monitoring, a stratified random sampling design was adopted after the 1997 Program Review (Bernstein and O'Connor, 1997), similar to USEPA's Environmental Monitoring and Assessment Program (see http://www.epa.gov/nheerl/arm/). This new design generated data that are more representative of the whole Bay and its segments to enable the Water Board to evaluate whether water or sediment quality in the Bay is impaired. This design improved evaluation of: (1) spatial patterns of contamination; (2) possible exceedance of water quality objectives in the Bay or segments of the Bay; and (3) the proportion of the Bay that is contaminated relative to guidelines or objectives. In contrast, the monitoring design for bioaccumulation in bivalves, sport fish, and birds continues to be based on targeted stations.

The Status and Trends Program benefits from long-term partnerships with government agencies, commercial laboratories, and universities. One important partnership is with the US Geological Survey (USGS) to monitor suspended sediments and conventional water quality in the Bay. The USGS has received reliable annual funding from the RMP since the beginning of the Program, which has been combined with funds from other sources to provide important information on water quality parameters such as nutrients on a monthly basis in the deep channel of the Bay, as well as intensive monitoring of suspended sediment concentrations at 15 min intervals at strategic moored sensor locations in the Bay (Schoellhamer et al., 2007). USGS programs have been conducted over a longer timeframe than the RMP (from 1969 for some parameters), with some measurements taken on finer temporal and spatial scales. These data have allowed the RMP to put trace contaminant data, collected once a year or once every few years, in a context with chemical, physical, and biological data collected on a much more intensive spatial and temporal scale, providing a better understanding of patterns and processes. Other important partnerships include the laboratories, both commercial and municipal, with which the RMP has developed methods and quality assurance procedures for analyzing samples from the Bay (Yee et al., 2015).

2.1.3. Special studies

In addition to the Status and Trends Program, the RMP also allocates funds for special studies every year. These studies have led to significant additions and refinements to status and trends

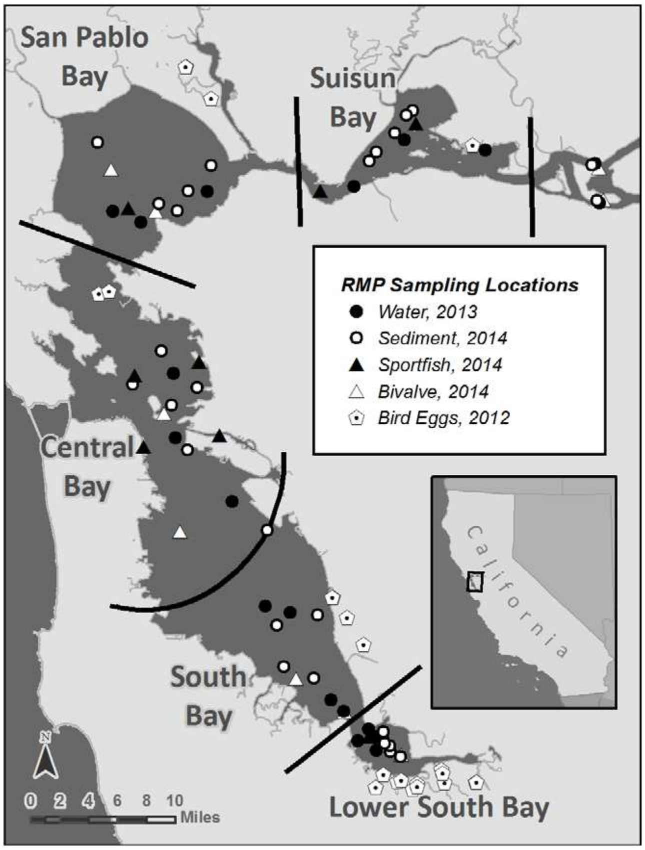

Fig. 2. Study area for the Regional Monitoring Program for Water Quality in San Francisco Bay. The Bay is divided into five segments for monitoring purposes. Monitoring stations for 2012–2014 Status and Trends Monitoring are shown.

monitoring. These studies sometimes include elements conducted on a trial basis in order to determine whether they are suitable for inclusion in the Status and Trends Program. Other special studies improve monitoring measurements or the interpretation of data, in particular by elucidating cause and effect relationships or by serving to meet RMP objectives through activities other than monitoring. Special studies accounted for 32% of the 2015 annual budget ($1,172,000). Section 3 summarizes many of the special studies that have influenced management decisions.

2.2. Key attributes of the program

Over the past 22 years, the RMP has been fortunate to have the following key ingredients to sustain a long-term water quality monitoring program.

2.2.1. A forum for collaboration

RMP committee meetings, workgroup meetings, workshops, and the Annual Meeting all provide opportunities for the managers of discharges to communicate with each other, with the Water Board, with environmental organizations, and with other stakeholders. The enhanced interaction occurs at multiple levels, including the leaders of these organizations and their technical staff. Shared interest in the success of the RMP has created an atmosphere of cooperation among these groups. The diverse groups of dischargers have developed a closer working relationship as a result of their participation in the RMP. The dischargers and the Water Board have also developed an effective collaborative relationship through their joint participation in the RMP. The collaborative atmosphere fostered by the RMP has allowed Bay stakeholders to largely avoid the expense and inefficiency of resolving disagreements through legal battles.

2.2.2. Clear objectives

Careful articulation of a monitoring program's objectives and the questions it is intended to answer are essential for effective design and execution of the program. The RMP is currently guided by an overarching goal: to collect data and communicate information about water quality in San Francisco Bay to support management decisions. The goal and its supporting management questions are shown in Table 1. These management questions guide the RMP and set the stage for adjusting the monitoring program, designing special studies capable of testing specific hypotheses prior to implementing management actions or revising policies, and communicating key messages to policy-makers and the public. In addition, subsets of the questions have been embedded into various Water Board discharge permits in order to guide the design, effectiveness, and collaboration of individual discharger and regional monitoring efforts.

The RMP has completed two Program Reviews by panels of prominent experts to ensure that its goals, objectives, and activities remain relevant. The first Program Review occurred in 1997 (Bernstein and O'Connor, 1997) and resulted in many fundamental changes to the Program. Through broader objectives, the scope of the Program was also expanded to include subject areas that were not part of the original design: pollutant sources, pathways and loadings; effects; and synthesis. The second Program Review, initiated in 2003, resulted in additional fine-tuning of the Program (Schubel et al., 2004). Following the second review, the Program has used an ongoing peer review process whereby external science advisors participate in the workgroups that propose special studies and monitoring.

2.2.3. Stable funding

Stable funding is essential for sustaining a long-term monitoring program. From its inception, the RMP has been funded by permitted dischargers by means of fees paid in lieu of individual monitoring requirements. As of 2015, the dischargers involved in the RMP include 35 wastewater dischargers, 9 industrial dischargers, 9 stormwater management agencies representing over 100 local municipal agencies, 12 dredgers (this number varies depending on what projects are active in a given year), and one once-through cooling water discharger. Each of these entities possesses a National Pollutant Discharge Elimination System permit or Clean Water Act Section 401 Water Quality Certification to discharge to the Bay. These include a provision for the permit-holder to participate in the RMP. Local funding of the RMP largely insulates the Program from waxing and waning cycles of state and federal budgets.

At the outset of the Program in 1993, the proportions that each sector would contribute were established based on the presumed relative impacts of the different types of discharges (Fig. 3). By mutual agreement among the groups, the proportions have remained fixed since 1993. Over time, monitoring needs change and potential contributing partners change. Adapting the RMP to include these changes while maintaining stable funding is an ongoing challenge.

In 1993, the RMP was a $1.2 million program focused on measuring spatial and temporal trends in contaminant concentrations and toxicity in the deep channels of the Bay. The budget steadily increased for the first five years and then grew more gradually to $3.4 million in 2015. The budget increase has corresponded to an expanding scope for the RMP, which now includes emerging contaminants, contaminant effects, contaminant loading, and broad-scale synthesis reports of information to answer management questions.

Stable funding provides many benefits to a long-term monitoring program. Maintaining the long-term time series of indicators of condition is the primary benefit. However, there are other benefits

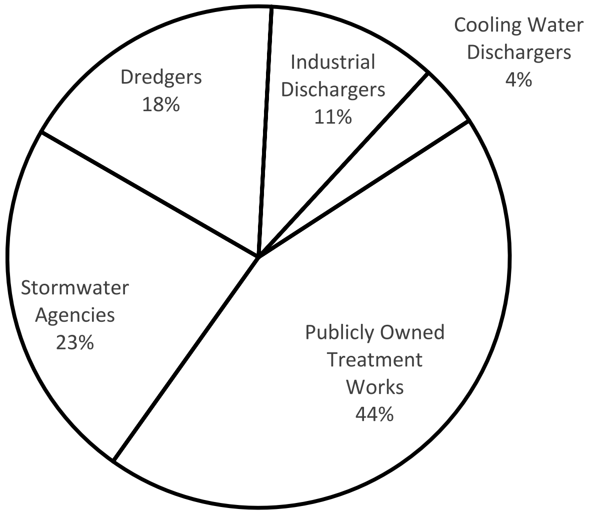

Fig. 3. RMP contributions by each category of discharger in 2015. By mutual agreement among the groups, the proportions have remained fixed since the beginning of the Program.

that are less obvious. Financial stability has allowed the RMP to develop an efficient organization and processes that enable the Program to adapt to changing management priorities and advances in scientific understanding (described further below in Section 2.2.6). Stable funding also allows the RMP to efficiently implement long-term plans. Another benefit of stable funding is continuity of the personnel involved. Staff turnover is inevitable, but the stability of the RMP allows staff at all participating institutions to develop professionally and maintain enough continuity and written documentation to provide the institutional memory that prevents the inefficiency of reinvention or repetition of mistakes of the past.

2.2.4. Sound science

It is essential that all stakeholders with an interest in monitoring the ecosystem accept the data and information generated by a monitoring program as unbiased, high quality, and incorporating the latest science. The RMP achieves this goal through several mechanisms.

Objectivity is assured at an institutional level by having the Program administered by an independent, non-profit scientific organization—the San Francisco Estuary Institute. SFEI is governed by a politically balanced Board of Directors comprised of Bay Area scientists, environmentalists, regulators, local governments, and industries. All of these sectors participate in review of RMP products through the various established committees and workgroups to ensure that the final science and synthesis presented is accurate and objective. Scientific objectivity and quality are also achieved through multiple levels of peer review, inclusion of leading scientists in the Program, and a rigorous and proactive quality assurance program (discussed below).

Peer review occurs at many levels in the Program. For specific projects, peer review is incorporated from planning stages through implementation and completion of final reports. Peer review at all of these stages is accomplished primarily by the RMP workgroups, which include science advisers from outside the RMP. The science advisers are preeminent in their field and ensure the quality of RMP science. Regional scientists also are members of the workgroups and contribute significantly to peer review. Technical experts on the TRC also provide general oversight on RMP studies from planning through completion. Finally, results from RMP studies are often published in peer-reviewed journals.

A quality assurance program ensures that monitoring data is high quality and reliable to answer relevant management questions. Data quality objectives were established in a Quality Assurance Program Plan (QAPP) (Yee et al., 2015). The QAPP covers all aspects of sampling and analysis in the many components of the RMP. Measures taken to evaluate quality of chemical data include both assessment of performance relative to data quality objectives for accuracy, precision, and completeness, and also comparison of the concentrations and patterns present in reported data with previously reported data. For example, for polychlorinated biphenyl (PCB) congener data, the reported concentrations can be compared to prior data both in terms of the magnitude of reported concentrations and the fingerprint (proportions) of congeners within each sample. The latter step screens out data that satisfy data quality objectives, but fail a reality-check against actual field data. Only data that are considered to have a high degree of reliability are included in the publicly-accessible database for unrestricted use. Careful and attentive screening of data and supporting quality assurance information is the key to a database of high quality data.

Another way in which the RMP maintains scientific quality is through inclusion of leading scientists as RMP lead or co-investigators. Many of the RMP contractors are recognized nationally or internationally as leaders in their fields. Collaboration with prominent laboratories to develop methods to measure emerging contaminants is one example. Other collaborators include regional scientists that also conduct high quality work. These investigators have made the Bay a laboratory for advancing understanding of water quality in a coastal ecosystem and actively publish their research in leading peer-reviewed scientific journals.

2.2.5. Communication

Effective communication at many levels is another key to the success of a monitoring program. Communication products generated by the RMP range from the ground level reporting of regular monitoring data and internally-focused communications for Program stakeholder committees and meetings, to detailed synthesis reports for external management and both technical and lay audiences. Most RMP communication products (aside from journal articles with distribution restrictions) are accessible through the website (www.sfei.org/rmp).

A vital foundation for the viability and credibility of a long term monitoring program is the transparency, reliability, and accessibility of the underlying data. Maintaining a high quality and reliable database that is standardized across all years requires considerable effort, particularly for a multi-faceted monitoring program that generates many different types of data. RMP status and trends monitoring and selected special study data are stored in an actively-maintained database that is comparable to state standards and accessible via the RMP website. RMP data can be visualized and downloaded via Contaminant Data Display and Download (CD3, cd3.sfei.org), a data access and visualization tool that enables users to perform spatial queries for water quality data from the San Francisco Estuary and Delta. In addition, RMP data are regularly exchanged with the California Environmental Data Exchange Network (CEDEN), which serves as a central repository for water quality information about the state's water bodies. RMP data are used by outside researchers (Rodenburg et al., 2014), water quality managers (see Section 3.1), and consultants.

Annual RMP reports serve as another means of communicating findings to a less technically-focused stakeholder audience. The *Pulse of the Bay* (SFEI, 2013) provides a concise, accessible, largely pictorial summary of RMP information that is targeted toward managers and engaged stakeholders. The *Pulse of the Bay* is produced and distributed every other year via hard copy and the web, with a circulation of several thousand copies. In 2014, the RMP published an *RMP Update* report (SFEI, 2014b) in eBook format

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providing additional engaging content including videos and interactive maps and charts (http://ebooks.sfei.org/update2014/). The *Annual Monitoring Summary* (SFEI, 2014a) includes brief narrative summaries and comprehensive data tables and charts of the most recent monitoring results, and is distributed via the SFEI web site.

The RMP Annual Meeting is an additional venue for providing information to water quality managers and engaged stakeholders. Speakers at the Annual Meeting address Bay water quality topics of current interest and summarize the latest RMP findings. The Annual Meeting also provides an opportunity for the diverse groups involved in the Program to interact. Presentations by RMP scientists at numerous other meetings and symposia throughout the year are another important channel for communicating information about the Bay to managers and engaged stakeholders.

2.2.6. Adaptation

Core elements of a monitoring program must remain constant over the long-term in order to track long-term trends in contamination. However, a purely static monitoring program would gradually become less relevant over time as management priorities change, as understanding increases, and as technology advances. In response to these forces, the RMP has undergone considerable evolution in its 22-year existence to-date and this will continue into the foreseeable future.

Adaptive management is achieved through several mechanisms in the RMP. One of these is the institutional structure with committees and workgroups that meet regularly to track progress and plan future work. Each year, committee deliberations culminate in a workplan for the coming year, which provides an overview of planned activities and documents the incremental evolution of the Program.

Program Review, where independent, prominent experts in environmental monitoring periodically evaluate the Program as a whole, is another mechanism by which Program adjustments are made (as discussed in Section 2.2.2).

Special studies are the third major mechanism by which the Program adapts. These studies constitute a mechanism for responding quickly to new information or concerns, assessing new technical approaches, investigating particular questions that have defined endpoints, and evaluating new directions for status and trends monitoring. RMP special studies have been key to both the refinement of status and trends monitoring and the success of the RMP in meeting its objectives related to effects, loading, and synthesis.

The annual monitoring cruises also allow the RMP to accommodate requests by stakeholders to collect additional information or include academic scientists who may be conducting research in an area of interest to the RMP. The base monitoring program sometimes adapts as a result of these ''add-on'' studies.

Collectively, these Program elements have allowed for adaptation in response to changes in the regulatory landscape, advances in understanding of the Bay, and a continual drive to adjust the RMP to better meet its objectives.

3. Results and discussion

The key attributes discussed in the previous section have sustained the RMP over 22 years, but the true value of the Program has been proven by its impact on water quality management decisions for San Francisco Bay. Through long-range planning, the RMP has maintained a clear focus on upcoming regulatory decisions and directed resources to resolve critical questions for decision-making. The result has been a long record of collaboration, monitoring, and special studies that support well-informed management decisions. Some of the specific examples of this impact are provided in the sections below.

3.1. Establishing scientific basis for TMDLs and other management decisions

Section 303 of the federal Clean Water Act calls for states to establish pollutant Total Maximum Daily Loads (TMDLs) for water bodies that are not meeting water quality standards. A TMDL is the pollutant load that would need to be met in order to attain the water quality standard for that pollutant in the water body. TMDLs have far-reaching impacts on the regulated dischargers to the Bay. Monitoring, special studies, and data analysis conducted through the RMP have been instrumental in the development and refinement of TMDLs for pollutants, such as PCBs and mercury, other permit requirements, and risk communication strategies.

3.1.1. TMDL for PCBs

A TMDL for PCBs in the Bay (SFBRWQCB, 2008), approved in 2009, relied heavily on RMP information. Gunther et al. (1999) demonstrated through bioaccumulation studies that PCBs remained a problem in the Bay, while other organo-chlorine chemicals did not. Sediment concentrations were mapped Bay-wide to identify internal sources and PCB hot spots. Loads from major pathways were measured for larger rivers and smaller tributaries, atmospheric deposition, and municipal wastewater (Yee et al., 2001; Tsai et al., 2002; Gilbreath and McKee, 2015; David et al., 2015). RMP scientists contributed to a mass balance model for PCBs that allowed the Water Board to: (1) identify the relative significance of sources; (2) determine the approximate time it would take to meet targets based on various input scenarios; and (3) to identify data gaps (Davis, 2004; Davis et al., 2007). A food web model was also developed to determine how far concentrations of PCBs need to decline in the sediment to bring fish concentrations down to levels that are protective of human health (Gobas and Arnot, 2010).

The RMP continued to assist TMDL implementation by developing a PCB Strategy in 2009. The Strategy has so far led to two additional studies to address priority management questions about PCBs. The first was a monitoring effort that revealed surprisingly high concentrations of PCBs in prey fish captured on the Bay margins (Greenfield and Allen, 2013). The second study was a synthesis and conceptual model update (Davis et al., 2014) that sharpened the focus on contaminated areas on the margins, based on the small fish data and observed spatial and temporal patterns in sediment contamination. These margin areas are important in terms of food web contamination and are where reductions in stormwater loading of PCBs from the watershed could lead to water quality improvements. Long-term monitoring of PCBs in sport fish by the RMP is another important implementation action.

The PCB Strategy, which was updated in 2014, now calls for a multi-year effort to: (1) identify margin areas that are high priorities for management and monitoring; (2) develop site-specific conceptual models and sediment mass balances for margin areas downstream of watersheds where management actions will occur; and (3) perform monitoring in these areas as a performance measure. RMP funding was allocated for studies in the margin areas, which will begin in 2015. These studies will inform adaptive implementation of the TMDL and the Water Board's consideration of revisions to the TMDL.

3.1.2. TMDL for mercury

RMP measurements of mercury in suspended solids, in bed sediment, and in fish along with loading studies (McKee et al., 2005; Tsai and Hoenicke, 2001; David et al., 2009; McKee and Gilbreath, 2015) were used to develop a mass balance model and numeric targets in the mercury TMDL (SFBRWQCB, 2006). These targets are intended to be protective of human health (through fish consumption) and wildlife (by protecting the most sensitive receptor, bird reproduction). A special study to measure air deposition of mercury and PCBs, funded by the RMP and the City of San Jose, helped Water Board staff determine the relative contribution from that source.

A RMP-funded study published in 2011 provided important evidence confirming the link between sources of mercury and accumulation in the food web. A key question that has been debated by scientists is whether the mercury present in mercury mining waste is recalcitrant or whether it can be subject to methylation and uptake into the food web. Gehrke et al. (2011) applied a novel technique of measuring mercury isotopes as tracers. Mercury is an element that occurs in several different isotopic forms. Mercury mining and other processes can lead to variation in the percentages of each form. Gehrke et al. (2011) measured mercury isotopes in prey fish and in Bay sediment, and compared the results to the isotopic signatures found in mining waste, soil, sediment, and other materials. In Lower South Bay, a clear association was found between the signatures found in sediment, prey fish, and mercury mining waste, pointing toward the historic New Almaden Mercury Mining District as the primary source in that area. This study confirmed the conceptual model that different sources of mercury were impacting biota in different parts of the Bay and that historical mining waste continues to impact Bay fish.

In 2014, the RMP produced a synthesis of information regarding methylmercury (MeHg) accumulation in the food web of San Francisco Bay (Davis et al., 2012). A previous RMP MeHg mass balance study had found that internal net production was the dominant source of MeHg that enters the food web (Yee et al., 2011). Therefore, in addition to source control of total mercury, controlling internal net production could be an important management tool, given its potential to reduce food web MeHg more effectively and within a much shorter time-frame than total mercury reduction alone. In particular, meaningful short-term reductions in MeHg exposure in Bay habitats may be possible for managed ponds, where wildlife exposure is high and where options for management appear to be most evident. The findings of this synthesis report and the ongoing RMP monitoring for mercury and MeHg in the Bay water, sediments, bird eggs, and fish will inform adaptive implementation of the TMDL and the Water Board's consideration of revisions to the TMDL.

3.1.3. TMDL for selenium

A selenium TMDL for the North Bay is in development by the Water Board. Development of a TMDL for the South Bay will be considered after the North Bay TMDL is completed. Initial loading estimates for selected watersheds were developed by the RMP (David et al., 2015; McKee et al., 2012) and an impairment assessment analysis was completed by the Water Board relying on RMP water quality data. In April 2014, the RMP formed a Selenium Strategy Team to evaluate information needs for the TMDL that can be addressed by the RMP in the next several years. The Team developed a list of priority questions for the next five years (SFEI, 2014b) and initiated expanded monitoring for selenium in the tissues of white sturgeon. These data will be directly relevant to the TMDL because the TMDL is expected to establish a target concentration in white sturgeon muscle tissue as the basis for evaluating impairment for all fish species. RMP water quality data will also be relevant to any numeric targets set for the water column.

3.1.4. Fish consumption advisories

In 1998 and 1999, the RMP partnered with the California Department of Public Health to fund a study of fish consumption in the Bay (SFEI, 2000). The study was designed to: (1) gather information on San Francisco Bay anglers and their fish consumption practices; (2) identify anglers who are at risk due to their fish consumption habits; and (3) gather information to aid development of effective educational messages about consumption of fish from the Bay. Over 1300 San Francisco Bay anglers participated in the study. Using the results of the study, Department of Public Health was able to develop an appropriate outreach and education program to inform the public about the health advisory and about ways to prepare fish that minimize exposure to contaminants. This effort, which included state, county and city agencies and environmental and community groups, resulted in the posting of signs in six different languages describing the advisory, as well as outreach presentations to communities that are most at risk.

A report on the 2009 RMP sport fish sampling was released in 2011 (Davis et al., 2011). At the same time, the California Office of Environmental Health Hazard Assessment released updated safe eating guidelines for the Bay. The guidelines replaced the earlier 1994 interim advisory, and drew on over a decade of more recent data, primarily from the RMP. They also incorporate nutrition science showing that fish provide dietary protein and essential nutrients, including omega-3 fatty acids that promote heart health and support neurological development.

3.2. Support permit conditions

In addition to supporting TMDLs, RMP data have been and continue to be used by Water Board staff to develop regulatory guidelines for the Bay and to support permit conditions.

3.2.1. Dredged material management support

In 1998 the Water Board conducted an assessment of data from the RMP and other sources to develop an understanding of ambient levels of contaminants in Bay sediment. RMP data continue to be collected and serve as the basis for the Dredged Materials Testing Thresholds for mercury, polycyclic aromatic hydrocarbons, and PCBs (http://www.sfei.org/content/dmmo-ambient-sediment-conditions). These thresholds determine when bioaccumulation testing will typically be required for dredged material proposed to be discharged at unconfined open water disposal sites in San Francisco Bay. The thresholds and process were established under an agreement to protect essential fish habitat between USEPA, the US Army Corps of Engineers, and the National Marine Fisheries Service (USACE and USEPA, 2011).

Management of sediment as a resource in the Bay requires understanding of the volumes, types, locations, and environmental drivers of sediment input in order to achieve informed decision-making. The RMP provides data to support development of permits to extract sand and aggregates from the Bay through extensive work describing suspended sediment concentrations in the Bay (Schoellhamer, 1996, 2002, 2011) along with monitoring at select tributary locations for computing estimates of suspended sediment loads (McKee et al., 2006, 2013). These data are being used to support estimates of the overall sediment budget of the Bay (Schoellhamer et al., 2005; Shellenbarger et al., 2013).

3.2.2. Small tributary loading strategy

A key aspect of the policies for PCBs and mercury management in the Bay has been the continued focus on finding specific highly-contaminated tributaries with disproportionately high loads or connections to sensitive Bay margins ("high-leverage" watersheds) (SFBRWQCB, 2008, 2006). This, in addition to the ongoing need to estimate regional-scale urban non-point source loads, trends in urban runoff concentrations and loads, and finding and managing contamination near its sources, led to the recognition for a need to develop a Small Tributaries Loading Strategy (STLS) (SFEI, 2009). The STLS outlined four key management questions about loadings and a general plan for studies consistent with management questions in the combined municipal regional stormwater NPDES Phase I permit (MRP) (SFRWQCB, 2011). During the first

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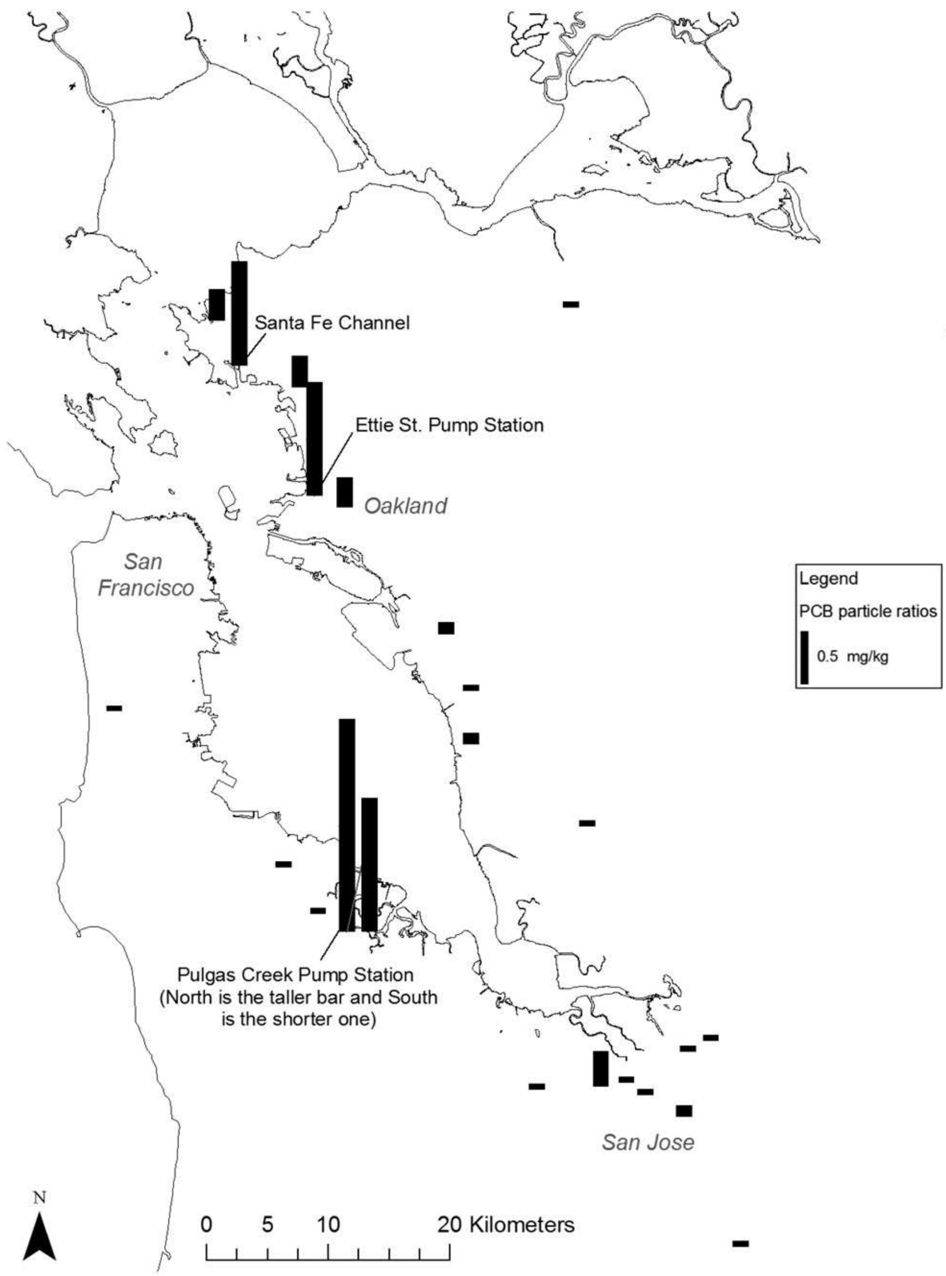

Fig. 4. Variation in PCB pollution in tributaries to San Francisco Bay as indicated by the median ratio of the sum of 40 PCB congeners to suspended sediment concentration measured in simultaneously collected whole water samples. For details on the list of congeners, please refer to Yee et al. (2015). Note, tributaries with particle ratios less than 0.05 mg/kg have a common minimum bar height.

term of the MRP (2009–14), the RMP supported refinement of pollutant loadings with additional emphasis on finding high-leverage watersheds and source areas within watersheds (Davis et al., 2014, 2012), consistent with the implementation plans outlined in the policy documents. The resulting data identified certain watersheds around the Bay with elevated PCB concentrations on suspended sediment particles (Fig. 4).

In support of refinements to provisions in the second MRP term, stakeholders have identified the need for an increasing focus on finding watersheds and land areas within watersheds at a scale paralleling management efforts (areas as small as polluted sub-watersheds, polluted "patches" of old industrial land use, or polluted source properties). The RMP has continued to support these needs through improvements to geographic information about PCB and mercury sources within the framework of a Regional Watershed Spreadsheet Model (McKee et al., 2014) and wet weather reconnaissance monitoring in watersheds and sub-watersheds downstream from older industrial areas and potential source properties.

3.2.3. Monitoring for reasonable potential analyses

The RMP also collects water column data that are used in writing wastewater discharge permits for the Bay. RMP data are used to determine background concentrations for reasonable potential analyses when setting effluent limits. For example, the RMP conducted a special study in 2002–2003 to determine, based on ambient data, whether the 126 contaminants listed in the California Toxics Rule (CTR), promulgated in 2000, should be listed in permits (Yee, 2003).

3.3. Ruling out non-issues to focus attention where it is needed most

Data provided by the RMP has helped managers to focus on water quality problems, and to determine what is **not** a problem. This enables managers to develop priorities so that resources can be used efficiently to address problems. Two examples of potential problems where monitoring and studies allowed for less intensive management actions are the site-specific objectives for copper and nickel, and special studies on the effects of copper on salmonids.

3.3.1. Site specific objectives for copper and nickel

An early example of the value of the monitoring database accumulated by the RMP was the 1998 303(d) "impaired waterbodies" listing process. Prior to 1998, the Bay was listed as impaired by "metals". In the 1998 303(d) list, Water Board staff determined that there was sufficient evidence to show that only copper and nickel exceeded water quality objectives to a level that required listing, and all other metals except mercury and selenium, which cause bioaccumulative problems, were removed from the list. This allowed for a focused effort to understand the toxicity of copper and nickel by an ad-hoc group including the regulated industries and municipalities, environmental groups, scientists, and the Water Board. Out of that process came site-specific water quality objectives for copper and nickel (Hoenicke et al., 2003; Tetra Tech, Inc., Ross & Assoc, and EOA, Inc., 2000; Olivieri et al., 2000). Attainment of these site-specific objectives continues to be assessed using RMP monitoring data.

3.3.2. Effects of copper on salmonids

Exposure to dissolved copper has been shown to cause olfactory impairment in salmon at lower concentrations in freshwater than the site-specific objectives that were set for the Bay. Therefore, there was a need for additional studies on the potential impacts of copper to the olfactory system of salmonids that migrate through the Bay and into the lower-salinity portions of the estuary. To address this information need, the RMP, in partnership with the Copper Development Association (a copper industry trade group), funded studies on the sensitivity of salmon olfaction to copper exposure in waters with the range of salinities found in estuarine waters. The studies measured the firing of neurons in response to exposure to odorant chemicals. The studies indicated that salmon in saline or moderately saline water are much less sensitive than salmon in freshwater, and that the potential effect of copper on salmon olfaction is not a concern for salmon migrating through the Bay (Baldwin, 2012, 2015).

3.4. Tracking the effectiveness of management actions and long-term trends

For an estuary as large as San Francisco Bay, it can take years before the effects of management actions are detectable. Therefore, the long-term nature of the RMP Status and Trends Program is critical to track the effectiveness of actions and other changes that are occurring in the Bay over long time periods, and for making adjustments as needed.

3.4.1. Phase out of PBDEs

Polybrominated diphenyl ethers (PBDEs), a class of bromine-containing flame retardants that was widely used but rarely studied in the early 1990s, increased rapidly in the Bay food web through the 1990s and became pollutants of concern (She et al., 2004). The California Legislature banned the use of two types of PBDE mixtures ("penta" and "octa") in 2006, triggering a nationwide production phase-out in 2004; the last mixture ("deca") was phased out in 2013.

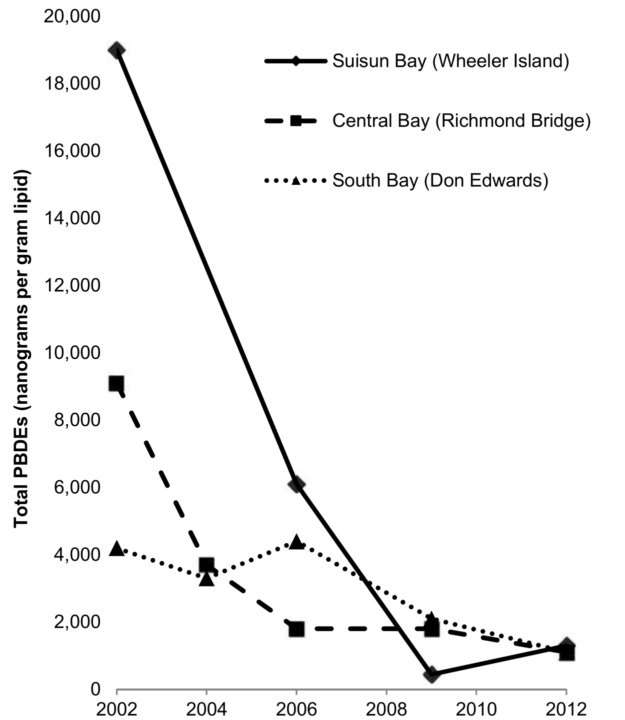

Fig. 5. Polybrominated diphenyl ether (PBDE) levels in cormorant eggs show general declines from 2002 to 2012, likely a result of the state ban and nationwide phase-out of two major PBDE commercial mixtures.
Source: Data originally published in Sutton et al. (2015).

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. As a first step, these data were used to develop a conceptual model and mass balance for PBDEs in San Francisco Bay (Oram et al., 2008). Over time PBDE levels in bird eggs and bivalves declined by 74%–95% (Fig. 5), 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 PBDE compound in sediment, deca component BDE-209, has shown no sign of decline. US production of deca ended in 2013; future monitoring may reveal declines of BDE-209 (Sutton et al., 2015).

Overall, RMP data were critical to demonstrating the success of these management actions. The data indicate that reduced PBDE production resulted in rapid declines in concentrations of these contaminants.

3.4.2. Mercury and PCBs in fish

Following up on a 1994 study by the Water Board, in 1997 the RMP started to measure contaminants in Bay fish every three years to determine temporal trends of contaminants in fish that people consume. Long-term monitoring of contaminants in fish is an essential means of measuring the effectiveness of management actions to reduce PCB and mercury loads to the Bay from TMDL implementation. Unfortunately, the latest data indicate no measurable change in mercury or PCB concentrations in Bay fish (Fig. 6) (Davis et al., 2011). The most recent report on sport fish sampling in 2009 included an unprecedented collaboration of the RMP, the California Surface Water Ambient Monitoring Program, and the Southern California Bight Regional Monitoring Program. Benefits of this collaboration for the RMP included more thorough sampling of Bay fish, elimination of reporting costs, and a valuable statewide context for interpreting Bay contamination. San Francisco Bay stood out among statewide coastal locations with relatively high concentrations of both methylmercury and PCBs.

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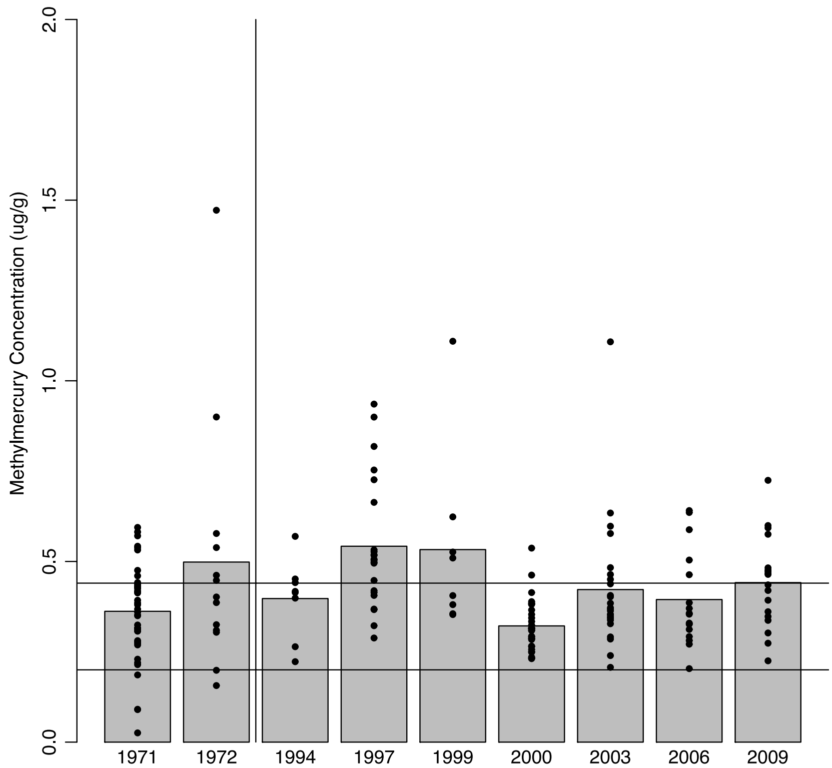

Fig. 6. Methylmercury concentrations (μg/g or ppm wet weight) in striped bass from San Francisco Bay, 1971–2009. Bars indicate average concentrations. Points represent individual fish. To correct for variation in fish length, all plotted data have been calculated for a 60-cm fish using the residuals of a length vs. log(Hg) relationship. Data from the RMP (1994–2009) and from California Department of Fish and Game historical records (1971–1972). The top horizontal line is the Office of Environmental Health Hazard Assessment advisory tissue level of 0.44 ppm calculated to protect women aged 18–45 years and children aged 1–17 years. The lower horizontal line is the water quality objective of 0.2 ppm.
Source: Data originally published in Davis et al. (2011).

For mercury, this highlights the importance of understanding the influence of Bay methylation processes in addition to the mining legacy in the Bay watershed. Fish tissue monitoring for mercury and PCBs was repeated in 2014 (data are still being quality assured) and will be continued every five years to gauge the success of management actions.

3.4.3. *Suspended-sediment concentrations in the Bay*

Long-term monitoring of suspended sediment concentrations has allowed an unanticipated decline in the Bay to be identified in spite of the extremely noisy signal that characterizes these data (Schoellhamer, 2011; McKee et al., 2013; Schoellhamer et al., 2013). Declining sediment loads to San Francisco Bay are a concern for both water quality and habitat restoration. Increased erosion of relatively contaminated buried sediment will likely delay improvements in water quality, and increased light in the water column has contributed to increased phytoplankton blooms. Suspended sediment in Bay waters is a primary source of sediment needed for tidal wetland restoration, although deposition patterns are variable around the Bay. While there are many questions still unanswered about how this trend in suspended sediment will affect the health of the Bay, managers would not know about the trends without the long-term monitoring programs of the RMP and the USGS.

3.5. *Preventing future problems*

The RMP stakeholders share a common understanding that preventing a problem is far less expensive than solving it after the fact. Therefore, a significant portion of the RMP resources are allocated toward understanding emerging issues that may require regulation in the future.

3.5.1. *Chemicals of emerging concern*

In 1999 the RMP made a decision to proactively identify chemicals of emerging concern (CECs) before they reach concentrations at which beneficial uses are impacted and regulatory action is necessary. RMP CEC work began in 2000. In 2013, the RMP published a summary of the state of knowledge on CECs in the Bay (Klosterhaus et al., 2013), followed by a strategy for investigations over the next several years (Sutton et al., 2013). Both documents are rich resources useful to scientists and managers working locally and statewide to protect water quality. The RMP CEC strategy consists of three major elements. First, for contaminants known to occur in the Bay, the RMP evaluates relative risk using a tiered framework. This risk-based framework guides future monitoring and management for each of these contaminants. Action plans are being developed by the Water Board for the highest priority CECs, supported by monitoring that is commensurate with the properties and risks of these chemicals. The second element of the strategy involves review of scientific literature and other aquatic monitoring programs to identify new contaminants of potential concern for which no Bay data yet exist. Initial monitoring to establish the presence of these chemicals in the Bay is conducted to evaluate the risks they may pose. The third element of the strategy consists of non-targeted monitoring. The RMP has launched two non-targeted monitoring projects: (a) broadscan analyses of Bay biota and water to detect previously unidentified contaminants; and (b) development of bioanalytical tools that detect endocrine disrupting chemicals.

3.5.2. Nutrient management strategy

Until recently, nutrients and phytoplankton growth were not considered an imminent threat to Bay water quality. Available information showed that nutrient loads to the Bay were as high or higher than in other US estuaries, but phytoplankton biomass has been low (Cloern and Jassby, 2012). The common belief was that high concentrations of suspended sediment (turbidity) caused a light-limited environment for phytoplankton production. Strong tidal mixing and grazing by clams were also considered factors in maintaining low phytoplankton biomass. However, data since the late 1990s have shown significant changes to conditions in the Bay, particularly in San Pablo Bay, Central Bay, and South Bay. These changes include less suspended sediment, larger spring blooms, increased incidence of fall blooms, increases in the annual biomass minimum, and declines in dissolved oxygen (Cloern and Jassby, 2012; Cloern et al., 2007).

Concerns about the high nutrient loads and changes in the system led a large group of regulators, dischargers, scientists, and stakeholders to collaboratively develop a Nutrient Management Strategy for the Bay (SFBRWQCB, 2012). The goal of this strategy is to inform important and potentially costly management decisions related to nutrient load reductions. The Nutrient Management Strategy effort was modeled based on experiences of the RMP (such as setting copper and nickel site specific objectives, see Section 3.3.1). In the early stages of implementing the strategy, the RMP has supported nutrient research through special studies funding. In particular, the RMP has funded deployment of in-situ sensors to provide near-continuous measurements of nitrate, chlorophyll-a and other nutrient-related parameters (Novick and Senn, 2014). The RMP is also supporting the development of conceptual models illustrating the current state of the science, defining the problem, and highlighting priority science needs.

4. Conclusion and future focus of the RMP

The goal of the RMP is to collect data and communicate information about water quality in San Francisco Bay to support management decisions. By all measures, the RMP is achieving this goal. The success of the RMP stems from collaborative governance, clear objectives, adaptability and long-term institutional and monetary commitments. Over the past 22 years, high quality data and special studies from the RMP have guided dozens of important decisions about Bay water quality. Moreover, the governing structure and the collaborative nature of the RMP have created an environment that allowed it to stay relevant.

Going forward, the goal of the RMP will remain the same but the specific management questions will continue to evolve over time. Each year, Program participants hold a workshop to anticipate upcoming management decisions and regulatory drivers and develop a multi-year monitoring plan (typically 3–5 years into the future) to inform those decisions. The current priorities are continued status and trends monitoring and special studies to inform permit decisions regarding nutrients and pollutant loadings to the Bay from stormwater. Emerging contaminants, PCBs, selenium, and exposure and effects are also active focus areas. Twenty years from now, the priorities for the RMP may be completely different but the end result will still be the same: high-quality information about water quality in San Francisco Bay to support management decisions.

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