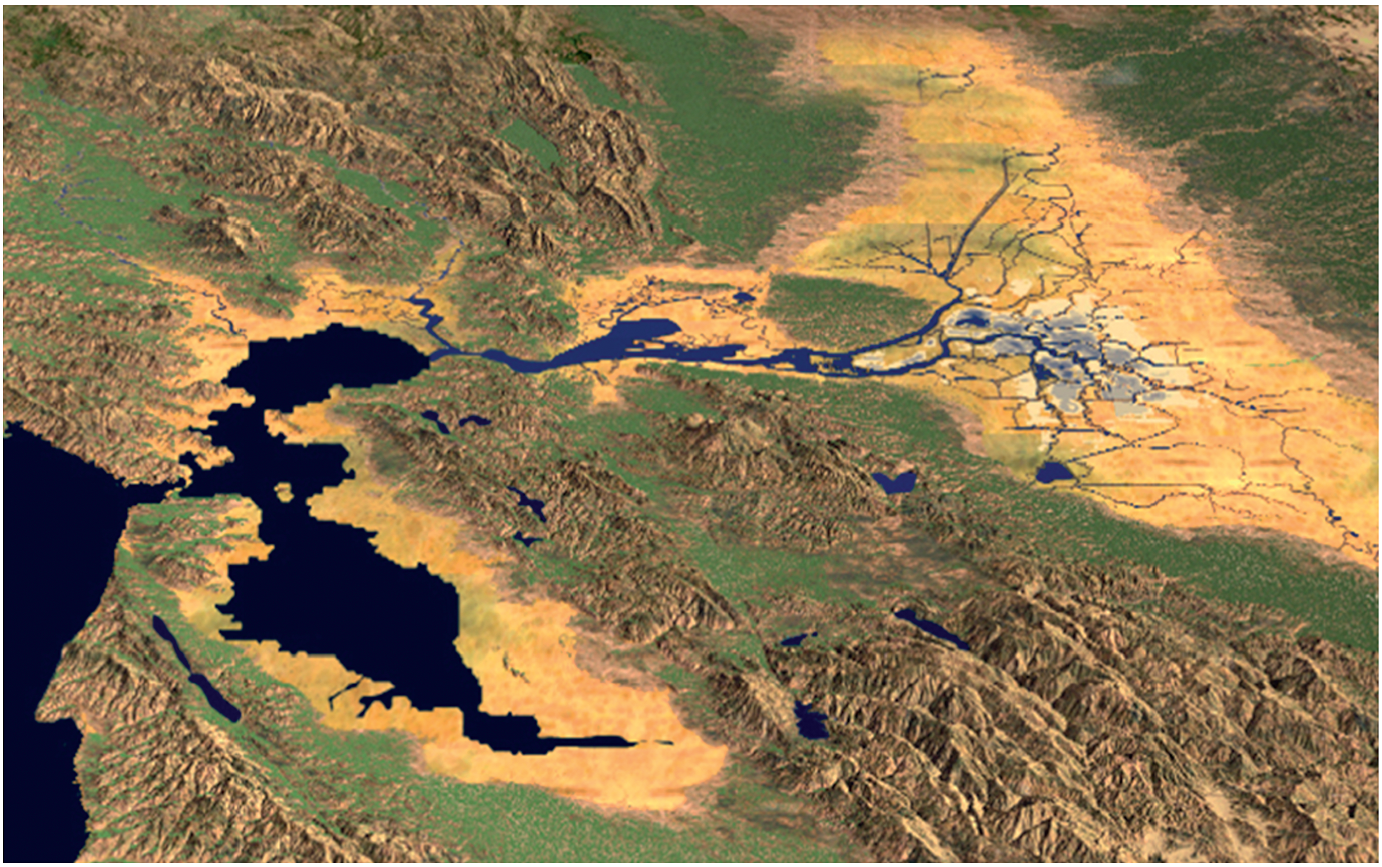

San Francisco Bay Estuary and its Delta. It is the complex system of waterways at the head of the estuary, formed by the confluence of the Sacramento and San Joaquin rivers that drain California's Central Valley (~40% of the state's watershed). [GIS figure developed for the CalFed program, and provided by the San Francisco Regional Water Quality Control Board.]

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Introduction

Sources, transport, fate, and toxicity of pollutants in the San Francisco Bay estuary

1. Introduction

This special issue of *Environmental Research* is designed to provide a synopsis of temporal and spatial variations of pollutants and their toxicities in the San Francisco Bay estuary that have been systematically investigated over the past few decades. As recently reported (Sañudo-Wilhelmy et al., 2004), "the Bay" is the only estuary in the US (and perhaps the world) where concentrations of potentially toxic metals in water have been regularly measured in a deliberate and methodical manner, employing trace metal clean techniques, for an extended period beginning in 1989 (Flegal et al., 1991). We believe the same is true for organic pollutants, for which measurements in water were begun at the same time in what now is referred to as the Regional Monitoring Program (RMP) for water quality in the San Francisco Estuary.

Numerous other water quality monitoring programs in San Francisco Bay and its delta have complemented the RMP over the years. Notable among these are the state and national Mussel Watch programs, which were initiated in the 1970s. Around the same time, long-term studies of nutrients, primary productivity, and contaminants in Bay waters, sediments, and biota were initiated by the United States Geological Survey (USGS), and many of their studies have since been coordinated with those of the RMP.

2. Objectives of this issue

The principal objectives of this special issue are to (1) synthesize the very large amount of data that has been generated on some of the principal contaminants of concern in the Bay, and (2) demonstrate the impact that those systematic measurements have had on environmental regulation and remediation efforts. Additionally, by publishing these peer-reviewed reports in a single volume, they are made readily accessible to a large audience of scientists and engineers, regulators, industry, environmental groups, and other interested individuals and organizations.

3. Why San Francisco Bay?

The reports in this special issue provide extensively documented case studies of the effects of the Clean Water Act of 1972 and subsequent efforts to improve the health of a major aquatic ecosystem. The impact of those efforts are especially important for the Bay, which went from a relatively pristine system prior to the California Gold Rush of 1849 to the "Urban Estuary" within a century (Nichols et al., 1986), and is now surrounded by a megalopolis of >7 million people (US Census Bureau, 2007). The Bay is also the largest estuarine system (1200 km^2) on the west coast of North America, and has a drainage basin (177,700 km^2) that covers 40% of the state of California, including the agriculturally-rich Central Valley.

As a consequence of the industrial and agricultural growth in the region, the Bay has received relatively large inputs of contaminants with sources ranging from historic mining operations to on-going agricultural, industrial, and urban activities. At the same time, the Bay's natural flushing capacity has been systematically reduced ($\sim$30%) by freshwater diversions and is now threatened with further reductions from climate change (Kimmerer, 2004; IPCC, 2007). In addition, $\sim$95% of its tidal wetlands have been lost (Nichols et al., 1986), and it has become the home of more invasive species than any other estuarine system in the US (Monroe et al., 1999).

Fortunately, Herculean efforts are being made not only to preserve but also to partly restore the Bay. It is now the site of the largest tidal wetland restoration project on the west coast of the US (www.southbayrestoration.org). As the following reports demonstrate, that physical and biological restoration coincides with quantifiable reductions in many chemical pollutant concentrations over the past two decades, resulting in both a larger and healthier ecosystem.

4. Articles in this issue

The multiple authorship of several articles in this issue evidence extensive collaborations. The authors include

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affiliates of both the San Francisco Estuary Institute, which manages the RMP and the USGS. Also included are scientists from other state (San Francisco Regional Water Quality Control Board) and federal (US Fish and Wildlife Service) agencies, universities (University of California, Davis; University of California, Santa Cruz; University of Maryland), and consulting companies (Applied Marine Science, CH2M Hill, Tetra Tech).

Perhaps, most unique among the collaborations are those with staff of the San Francisco Regional Water Quality Control Board. It is the state agency responsible for regulating water quality in the Bay, and—as the following articles demonstrate—many of the data generated from the monitoring programs have been utilized to develop better regulatory policies for the Bay. This direct connection between science and policy is relatively unique to the Bay, and is a principal justification for continuing with stable funding of the $3 million/year RMP.

In addition to connecting science and policy, another justification for continuing with the RMP is that it has scientifically demonstrated which metals and organics are now posing a threat to the health of the Bay and which ones are not. Notably, copper was considered to be a major environmental problem in the Bay when some of the first accurate measurements of total dissolved ($<0.45\,\mu m$) copper in the Bay were found to exceed both state and federal water quality criteria (Flegal et al., 1991). Subsequent studies of copper speciation in the Bay determined that organic ligands typically bind $>99.9\%$ of that copper in a form that is not readily available to the biota (Buck et al., this issue). To address this apparent disconnect, new site-specific water quality criteria for copper are being developed for the Bay. Water quality criteria for nickel in the Bay are also being reconsidered for similar reasons (Yee et al., this issue). As a result, point source dischargers have been able to refocus their wastewater treatment processes from further reducing increasingly small amounts of those two metals in their effluents to more effectively reducing inputs and mitigating adverse impacts of other pollutants that are negatively affecting the health of the Bay.

As noted by Flegal et al. (this issue), San Francisco may have a *Golden Gate*, but in the three previous decades it merited the title as the *Silver Estuary*, with the highest measured silver concentrations in its sediments and biota measured in any estuarine system. The silver pollution was traced to one industrial source—waste water discharges from a film processing plant—which was then shut in the 1970s (Squire et al., 2002). Although concentrations of silver in water, sediments, and biota in the Bay have markedly declined since then, studies by the USGS indicate it was still adversely impacting the biota in the 1990s and remains a concern today.

Another pollutant of concern in the Bay is mercury (Conaway et al., this issue). Recent studies have indicated health risks to humans from consumption of fish with elevated levels of mercury. In contrast to the industrial source for silver, most of the mercury contamination in the Bay is derived from historic inputs from large mercury mining districts and widespread gold mining in the watershed. As previously indicated, that began one and one-half centuries ago with the California Gold Rush, and mercury from that period continues to flow into and cycle within the Bay as a legacy pollutant. Efforts to control mercury contamination have largely focused on inputs of total mercury to the Bay. Because the form of mercury that is biomagnified in food webs and is most toxic to humans is methylmercury, the RMP has expanded its program from simply measuring total mercury concentrations to also measuring methylmercury compounds in water and sediments. Also, because many biogeochemical processes influence the link between methylmercury and total mercury, regulating mercury in the Bay has proved to be a great challenge.

In addition to the legacy metal contaminants mentioned above, there are also many legacy organic pollutants in the Bay. Notable among them are some organochlorine compounds (including PCBs, DDTs, chlordanes, and dieldrin), which have not been available commercially for use in the Bay's watershed for decades but are still found in some of its biota at surprisingly high levels–levels high enough to contribute to advisories against the consumption of some fish in the Bay (Davis et al., this issue; Connor et al., this issue). Concentrations of polycyclic aromatic hydrocarbons (Oros et al., this issue) are also high enough in the Bay that they may be adversely affecting its biota. Fortunately, concentrations of most of these organic contaminants have been declining over the past two decades, although the projected persistence of the legacy organic pollutants in the Bay is not completely resolved: There are yet some knowns and some unknowns.

What is known is that the biogeochemical cycles of many of organic pollutants, as well as those of many inorganic pollutants, in the Bay are regulated by their affinity to sediments. Consequently, the movement of sediments in the Bay is being monitored by the USGS in concert with the RMP to further resolve the geochemical cycling of particle-reactive contaminants in the Bay and to provide a relatively inexpensive proxy to monitor and model those cycles (Schoellhamer et al., this issue).

What remains to be known are the potential adverse effects of almost all of the over seven million organic and inorganic compounds that are commercially available in the US (CAS, 2007). Although these have not been systematically monitored in the Bay, the RMP is in the process of adapting to address the challenge of monitoring emerging pollutants in the Bay (Hoenicke et al., this issue).

Finally, difficulties in measuring concentrations of legacy, contemporary, and emerging pollutants in the Bay pale in comparison with resolving their individual, synergistic, and antagonistic toxicities to biota in the Bay

(Anderson, this issue; Thompson et al., this issue). Because many pollutants have a strong affinity for sediments, there are a number of sediment toxic hotspots in the Bay, often near its margins. Additionally, there are temporal variations of toxicity within the Bay that change both with levels of contamination and other environmental parameters (e.g., freshwater inflow and sediment type). No single contaminant has been consistently related to toxicity throughout the Bay; and no general pattern in space and time has emerged for toxicity to the Bay's plankton, benthos, fish, birds, and mammals. Consequently—and in spite of the extensive amount of information provided in reports in this issue—further research is still needed to document the sources, transport, fate, and toxicity of pollutants in the San Francisco Estuary.

5. Articles missing from this issue

Reports of several pollutants are noticeably missing from this issue, for a variety of reasons. These include reports on several inorganic contaminants (e.g., lead, chromium, and selenium), radioisotopes, nutrients, harmful algal blooms, invasive species, and pathogens. Also missing are reports on the adverse impacts of development and fresh water diversion (e.g., increased salinity, declining sediment budgets, and increased water temperature). Moreover, many of those adverse impacts are being exacerbated by climate change, which is projected to further increase sea level within the Bay by as much as ~1 m within this century. Fortunately, reports on many of these environmental concerns are published elsewhere.

Acknowledgments

There are simply too many individuals and organizations that have been involved in studies of the health of the Bay to rightfully acknowledge all of them, but some of the individuals whose pioneering efforts led to the establishment and maintenance of studies cited in this issue must be cited. These include Dave McCulloch, John Conomos, Dave Peterson, Fred Nichols, Sam Luoma, Jim Cloern, and others, who initiated many of USGS studies in the 1970s that remain in place today; Mike Carlin, Tom Mumley, Karen Taberski, and Steve Ritchie of the San Francisco Regional Water Quality Control Board (SFRWQCB), who created the predecessor of the RMP; and Bob Spies, Andy Gunther, Dane Hardin, and others at Applied Marine Sciences, who initially managed the program. Today, that program is managed by a dedicated staff at the San Francisco Estuary Institute, many of whom have contributed to the articles in this report.

The RMP is largely funded by agencies, municipalities, and industries that manage discharges of wastewater into the Bay. Representatives of those institutions, most notably David Tucker, have been actively involved in guiding the program from its inception, as well as adapting many of the methodologies developed for the RMP in additional studies to increase the number of complementary measurements of pollutants in the Bay and adjacent watersheds. RMP findings are reported annually in *Pulse of the Estuary*. That report and other RMP information products (raw data, technical reports, meeting materials) are available on the web at 〈http://www.sfei.org/rmp〉.

Finally, we are especially appreciative of the protracted efforts of Janine Burch and her associates at Elsevier to guide us to the completion of this special issue of *Environmental Research*.

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