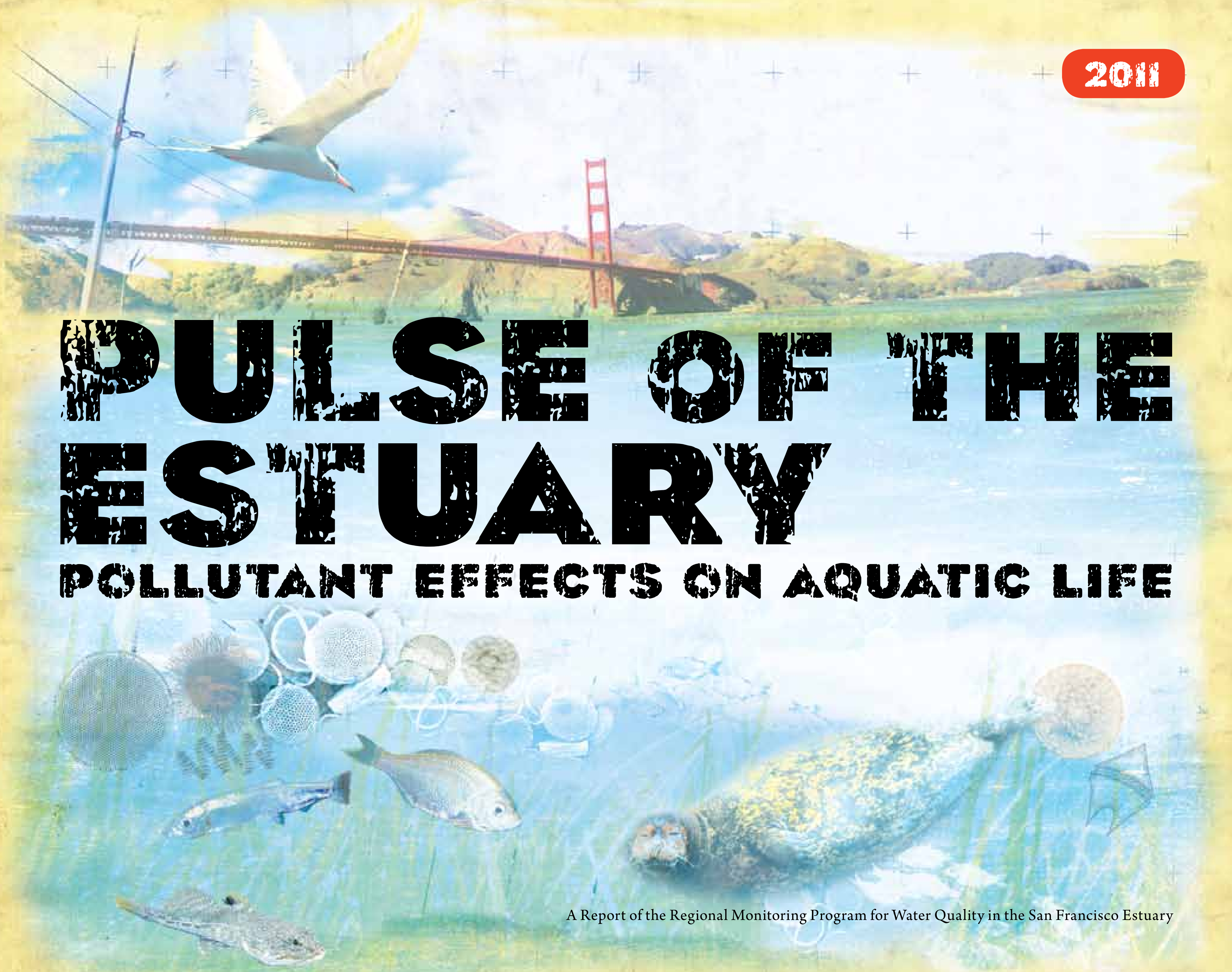
2011

PULSE OF THE ESTUARY

POLLUTANT EFFECTS ON AQUATIC LIFE



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

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PULSE OF THE ESTUARY

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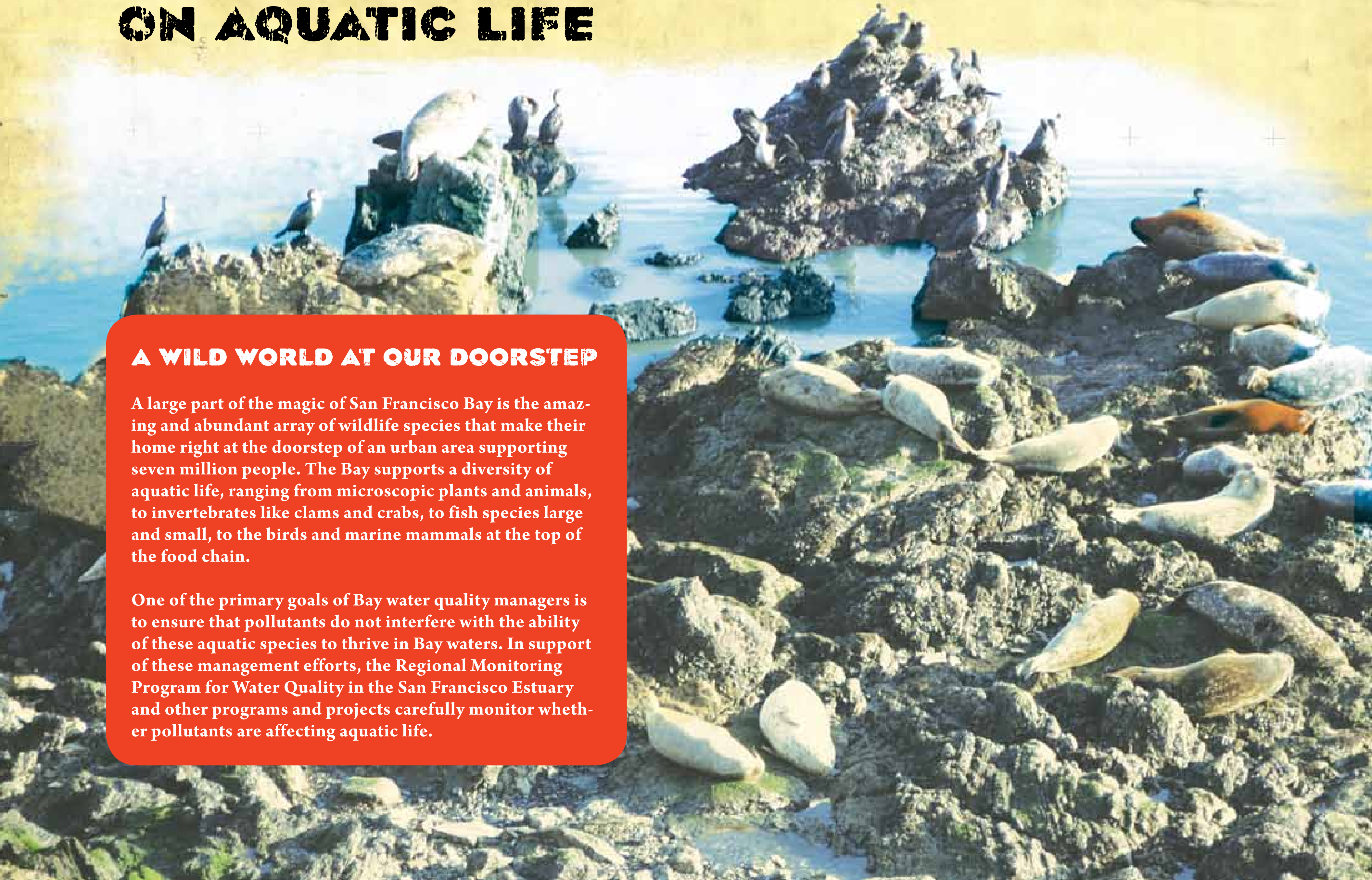
OVERVIEW: POLLUTANT EFFECTS ON AQUATIC LIFE



A WILD WORLD AT OUR DOORSTEP

A large part of the magic of San Francisco Bay is the amazing and abundant array of wildlife species that make their home right at the doorstep of an urban area supporting seven million people. The Bay supports a diversity of aquatic life, ranging from microscopic plants and animals, to invertebrates like clams and crabs, to fish species large and small, to the birds and marine mammals at the top of the food chain.

One of the primary goals of Bay water quality managers is to ensure that pollutants do not interfere with the ability of these aquatic species to thrive in Bay waters. In support of these management efforts, the Regional Monitoring Program for Water Quality in the San Francisco Estuary and other programs and projects carefully monitor whether pollutants are affecting aquatic life.

↓ Surf Scoters in pursuit of Pacific herring roe. Photograph by Joan Linn Bekins.

POTENTIAL IMPACTS OF CHEMICAL POLLUTION

Chemical pollutants can impact Bay aquatic life in many ways – some more severe, and some more subtle. Some forms of chemical pollution can cause immediate mortality of aquatic life. Oil spills are a vivid example, with their highly visible impacts on aquatic birds, along with the less visible impacts on fish (**PAGE 72**) and invertebrates beneath the Bay surface.

Discharge of organic waste from sewage into the Bay prior to the 1970s depleted the oxygen content of the water (**PAGE 51**) and made large fish die-offs a common occurrence. Investments in improved wastewater treatment greatly reduced organic input from this source and fish kills have become rare. Concern is growing, however, for a possible return of oxygen depletion due to trends of increasing abundance of algae in the Bay (**PAGE 48**). A combination of high concentrations of nutrients along with changes in other factors that affect algal populations appear to be driving the increase, and raising the question of whether additional control of nutrient loads may be needed.

Other pollutants can cause immediate mortality because of their toxicity to sensitive species. Insecticides, for example, are designed to kill insects and often have similar effects on their invertebrate aquatic relatives, and sometimes can be quite toxic to fish. Pyrethroid insecticides are currently in wide use, and pose significant threats to water quality in urban creeks and are also suspected of possibly playing a role in the decline of fish species in the Bay and Delta (**PAGE 72**).

Early life stages of many aquatic species, such as bird embryos, fish larvae, and seal pups are particularly vulnerable to the lethal effects of pollutants. Methylmercury and PCBs, for example, are found in eggs of some Bay birds at concentrations that are considered likely to cause an increased incidence of mortality in embryos as they develop (**PAGE 78**). Early life stages of fish are also thought to be especially vulnerable to pollutants such as pesticides, selenium, and PCBs. PCBs and other synthetic chemical pollutants also reach relatively high concentrations in seal pups and may pose higher risks during this life stage (**PAGE 91**).

Pollutants can also elicit more subtle, sublethal responses that can still significantly reduce the viability of populations of sensitive species, and several possible examples of these responses are suspected in the Bay. Many pollutants can act as endocrine disruptors, altering the sensitive systems regulated by hormone signals. A recent study of the endocrine status of Bay fish found disruptions of the thyroid and adrenal systems, suggesting an increased risk of impacts on metabolism, growth, immune function, and reproduction (**PAGE 74**). Perfluorooctane sulfonate (PFOS), a fluorine-containing chemical that accumulates in birds (**PAGE 81** and seals (**PAGE 96**), threatens to weaken the immune response of these species. Another type of sublethal effect is impairment of sensory abilities. Copper has been shown in laboratory studies to interfere with the sense of smell in salmon, which can limit their ability to find a mate, avoid predators, and to find their natal stream (**PAGE 75**). A study is currently underway to evaluate whether this type of inhibition may be occurring in the Bay. Pollutants can also have deleterious effects on behavior. One of the ways in which methylmercury appears to affect Forster's Terns in the Bay is by reducing the attentiveness of parents, which results in an increase in the rate of abandoned eggs (**PAGE 83**).

↖ Harbor seals and cormorants on Castro Rocks. Photograph by Suzanne Manugian.

Forster's Tern parent feeding a chick. Photograph by Robert Lewis.

OTHER IMPORTANT FORMS OF POLLUTION

Other forms of pollution also are considered among the most significant threats to Bay aquatic life. Based on past experience, exotic species are arguably the greatest threat. Introductions of exotic species have radically transformed the species composition of the Bay, displacing many native species, and have fundamentally altered the productivity of the ecosystem. Most of these invasions are essentially irreversible. Reducing the rate of introductions, however, appears readily achievable through implementation of state and federal ballast water discharge regulations.

Trash in the Bay is another form of pollution that poses a continuing threat to aquatic life. Plastic trash threatens aquatic life through ingestion and entanglement. Larger trash items degrade to tiny fragments that can have significant impacts on small aquatic life through ingestion and through exposure to pollutants that leach from the plastic particles. Aggressive new regulatory requirements adopted in 2010 are expected to significantly reduce the amount of trash entering the Bay in the next 30 years.

TRACKING PROGRESS IN MEETING CLEAN WATER GOALS

A new water quality report card (PAGE 8) provides an overview of how well we are doing in providing clean habitat to support aquatic life in the Bay. The report card also evaluates progress in making Bay fish safe to eat and in making Bay waters safe for swimming. Thanks to a considerable investment in infrastructure and the diligent efforts of water quality managers, the Bay is much safer for fishing, aquatic life, and swimming than it was in the 1960s. Substantial control efforts that began in the 1970s solved most of the obvious problems of the 1960s and set the Bay on a course for gradual recovery for many pollutants. However, challenges and uncertainties remain to respond to many pollutants. Complete and timely resolution of remaining and emerging water quality challenges will require significant investments of resources to replace and improve our aging water quality infrastructure.

THE NEXT PULSE: EMERGING CONTAMINANTS

In addition to the familiar pollutants that pose threats to aquatic life, there are thousands of other chemicals used by society, including pesticides, industrial chemicals, and chemicals in consumer products, and many of these make their way from our homes, businesses, and watersheds into the Bay. Due to inadequate screening of the hazards of these chemicals, some may pose a threat to Bay water quality. As understanding advances, some of these contaminants emerge as posing significant risks to the health of humans and wildlife. The next edition of the Pulse will focus on the status of these emerging contaminants in the Bay, and efforts to prevent them from being added to the toxic legacy that is passed on to future generations of humans and aquatic life that depend upon this productive ecosystem.

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COMMENTS OR QUESTIONS REGARDING THE PULSE OR THE REGIONAL MONITORING PROGRAM CAN BE ADDRESSED TO DR. JAY DAVIS, RMP LEAD SCIENTIST, (510) 746-7368, JAY@SFEI.ORG

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A WATER QUALITY REPORT CARD FOR SAN FRANCISCO BAY

HIGHLIGHTS

A new State of the Bay report summarizes progress in attaining management goals relating to habitat, water supply and quality, living resources, ecological processes, and stewardship

A water quality report card is a component of the Report that assesses whether the Bay is safe for aquatic life, whether Bay fish are safe to eat, and whether the Bay is safe for swimming

Many monitored pollutants are considered to pose very low risk to Bay aquatic life, but a few (especially methylmercury, exotic species, the toxicity of sediments, and trash) pose substantial threats

Fish from the Bay are not entirely safe to eat, due mainly to polychlorinated biphenyls (PCBs), methylmercury, and dioxins

Most Bay beaches are safe for swimming in the summer, but bacterial contamination is a concern at a few beaches in the summer, and at most beaches in wet weather

WHAT GETS TRACKED GETS DONE

An ongoing assessment of progress in improving the health of the Bay is essential. A concise assessment of Bay health can communicate the status of this highly valued resource, and present an accounting of progress in achieving the goal of protecting the integrity of the Bay. A periodic assessment of Bay health can also provide a summary of the current state of knowledge that can be used by scientists and managers as they consider new studies and findings.

The San Francisco Estuary Partnership, a coalition of resource agencies, non-profit organizations, citizens, and scientists, has sponsored production of a new State of the Bay Report (**www.sfestuary.org/StateofSFBay2011/**). The report summarizes progress in attaining established management goals relating to the following fundamental aspects of Bay health:

- habitat (baylands [tidal marsh and tidal flat], estuarine open water, watershed);
- water (freshwater inflow, water quality);
- living resources (fish, invertebrates, birds);
- ecological processes (aquatic food web, flood events); and
- stewardship (individual and community action, management action).

The Partnership plans to prepare State of the Bay reports on a periodic basis, and to refine and improve the report with each iteration.

The State of the Bay report is based on the latest and best available scientific information and is presented in a manner intended to be comprehensible to a broad audience. Providing all interested parties with an understanding of "how the Bay is doing" frames the discussion of whether we are doing enough of the right things to protect the Bay. The report is intended to encourage and inform thoughtful discussion about managing and protecting this tremendous resource, and to support continued efforts by citizens, professionals, and political leaders to protect and enhance the myriad benefits of a healthy and vibrant San Francisco Bay.

THE WATER QUALITY REPORT CARD

The water quality report card is an important element of the State of the Bay assessment. Clean water is essential to the health of the San Francisco Bay ecosystem and to many of the beneficial uses of the Bay that Bay Area residents enjoy and depend on. Billions of dollars have been invested in management of the wastewater and other pollutant sources that impact Bay water quality, and as a result the Bay is in much better condition than it was in the 1970s. Inputs of organic waste and nutrients have been greatly reduced and no longer cause fish kills or odor problems. Bacterial contamination has also been reduced. Inputs of many toxic pollutants to the Bay have also declined dramatically as a result of improved wastewater treatment and enforcement of the Clean Water Act. However, thousands of chemicals are carried into the Bay by society's waste streams, and significant and challenging water quality problems still remain.

The Bay Area is fortunate to have one of the best water quality monitoring programs in the world, the Regional Monitoring Program for Water Quality in the San Francisco Estuary (RMP), to track conditions in the Bay and to provide the information that water quality managers need to address the remaining problems. The report card on Bay water quality is based largely on information generated by the RMP. Other valuable sources of information are also available and were considered as well.

The water quality data summarized in the report card were evaluated using a scheme that takes into account both **1)** the distance from the relevant guideline in terms of the estimated length of time expected to reach the desired condition and **2)** the severity of the impairment of water quality.

The water quality report card addresses the three main beneficial uses of the Bay that are affected by water pollution and protected by the Clean Water Act, answering three key questions:

- Is the Bay safe for aquatic life?
- Are fish from the Bay safe to eat?
- Is the Bay safe for swimming?

Suites of indicators were identified to answer each of these questions (**FIGURE 1**).

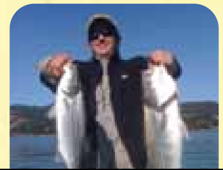
Fishing from Pier 42. Photograph by Jay Davis.

FIGURE 1

Summary of San Francisco Bay water quality, 2011. The star ratings are based on a combination of the severity of the problem and the anticipated time needed to attain water quality goals (see **FIGURE 2** and **5**). A five star rating indicates that regulatory goals have been met. Fewer stars indicate varying degrees of distance from regulatory goals.

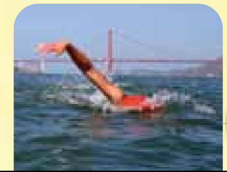
Safe for Aquatic Life

Methylmercury	★
Exotic Species	★★
Sediment Toxicity	★★★
Trash	★★★
Copper	★★★★
Dissolved Oxygen	★★★★★
Silver	★★★★★
Other Priority Pollutants	★★★★★
Selenium	?
PAHs	?
PBDEs	?
PFOS	?
Emerging Contaminants	?



Safe to Eat

PCBs	★
Methylmercury	★★
Dioxins	★★
Legacy Pesticides	★★★★★
Selenium	★★★★★
PBDEs	★★★★★
Other Priority Pollutants	★★★★★
Emerging Contaminants	?



Safe to Swim

Beach Bacteria (April-October)	★★★★
Beach Bacteria (Wet Weather)	★★★

poor	★
poor to fair	★★
fair	★★★
fair to good	★★★★
good	★★★★★
goals not established	?

IS THE BAY SAFE FOR AQUATIC LIFE?

The "Safe for Aquatic Life" water quality index quantitatively considers five key pollutants, and qualitatively considers many others. This index was compared to goals set by the State of California for concentrations of chemical pollutants in water, methylmercury concentrations in the food web, and the toxicity of Bay waters and sediments in laboratory tests. Exotic species and trash are included in this water quality assessment because they are considered pollutants subject to provisions of the Clean Water Act.

Enforcement of the Clean Water Act and other environmental laws over the past 39 years has resulted in tremendous improvements in overall Bay water quality, solving serious threats to aquatic life related to reduced dissolved oxygen and elevated concentrations of silver (**FIGURE 2**). Many other pollutants are also routinely monitored and found at concentrations below regulatory goals, and are considered to pose very low risk to Bay aquatic life. However, several pollutants still pose a substantial threat to the health of aquatic life in the Bay. Methylmercury, exotic species, the toxicity of sediments, and trash are the principal concerns.

Methylmercury continues to pose significant risks to Bay wildlife (**FIGURE 3**). This problem is mainly a legacy of historic mercury pollution that resulted from gold mining in the Sierra Nevada and mercury mining in the local Coast Range. Researchers have concluded that methylmercury poses a high risk for reducing the hatching and fledging success of some species of fish-eating birds (**PAGE 78**). Methylmercury concentrations in the Bay food web have not changed perceptibly over the past 40 years, and will probably decline very slowly in the next 30 years. It may be possible, however, to tackle at least some facets of this problem. For example, one of the species at greatest risk in the Bay, the Forster's Tern, forages primarily in salt ponds. Agencies that manage these habitats may be able to manipulate factors, such as water flow through the ponds, in ways that reduce the production and accumulation of methylmercury.

Exotic species pose the greatest threat to Bay aquatic life due to their displacement of native species, disruption of communities and the food chain, and their alteration of habitat. They also can pose a nuisance for people who swim in the Bay (**SIDEBAR, PAGE 25**). Scientists consider San Francisco Bay to be one of the most highly invaded estuaries in the world, and the ecological impacts of exotic species have been immense. Successful invasions by exotic species are essentially irreversible. Achievable goals are best focused on reducing the rate of introductions, which increased in the late 1900s. Progress on reducing the rate of introductions is achievable in the near-term. State and federal ballast discharge regulations could potentially have a very significant impact on one major vector for exotic species introductions.

Toxicity of Bay sediments in standard tests is another indication of possible impacts of pollution on aquatic life (**FIGURE 4**). In every year since routine sampling began in 1993, at least 26% of the sediment samples have been determined to be toxic. In 2009, 67% of the samples were found to be toxic. Neither the causes of this toxicity or the reasons that it is so variable are understood. These results suggest that pollutant concentrations in Bay sediments may be high enough to affect the development and survival of aquatic invertebrates. This problem will persist into the future until the chemicals (or mix of chemicals) causing this toxicity can be identified and remediated.

Trash in the Bay is also a continuing threat to aquatic life. Plastic trash persists for hundreds of years in the environment and threatens wildlife largely through ingestion and entanglement. Larger trash items degrade to fragments that can have significant impacts on small aquatic life through ingestion and through exposure to chemical constituents that leach from the plastic particles or accumulate on them. Aggressive new regulatory requirements adopted in 2010 should significantly reduce the amount of trash entering the Bay in the next 30 years.

There are several other pollutants that appear to pose risks to Bay aquatic life, but for which definitive regulatory goals for the Bay have not yet been developed. A few of the most prominent examples include selenium, PAHs, and perfluorooctanesulfonate (PFOS). Efforts to evaluate these pollutants and develop appropriate goals are in progress.

Overall, despite great progress in reducing threats to the health of the Bay's aquatic life, several key pollutants remain problematic. Although these pollutants present management challenges, significant progress appears attainable in several important areas, including reducing trash inputs to the Bay, stemming the influx of exotic species, and reducing methylmercury production in specific habitats.

FIGURE 2

Summary assessment related to the "safe for aquatic life" question. The two key dimensions of water quality problems are their severity (degree of concern) and how quickly the Bay is anticipated to respond to pollution prevention actions (whether rapid progress is likely or not). The assessment scores in **FIGURE 1** are based on a combination of these two factors.

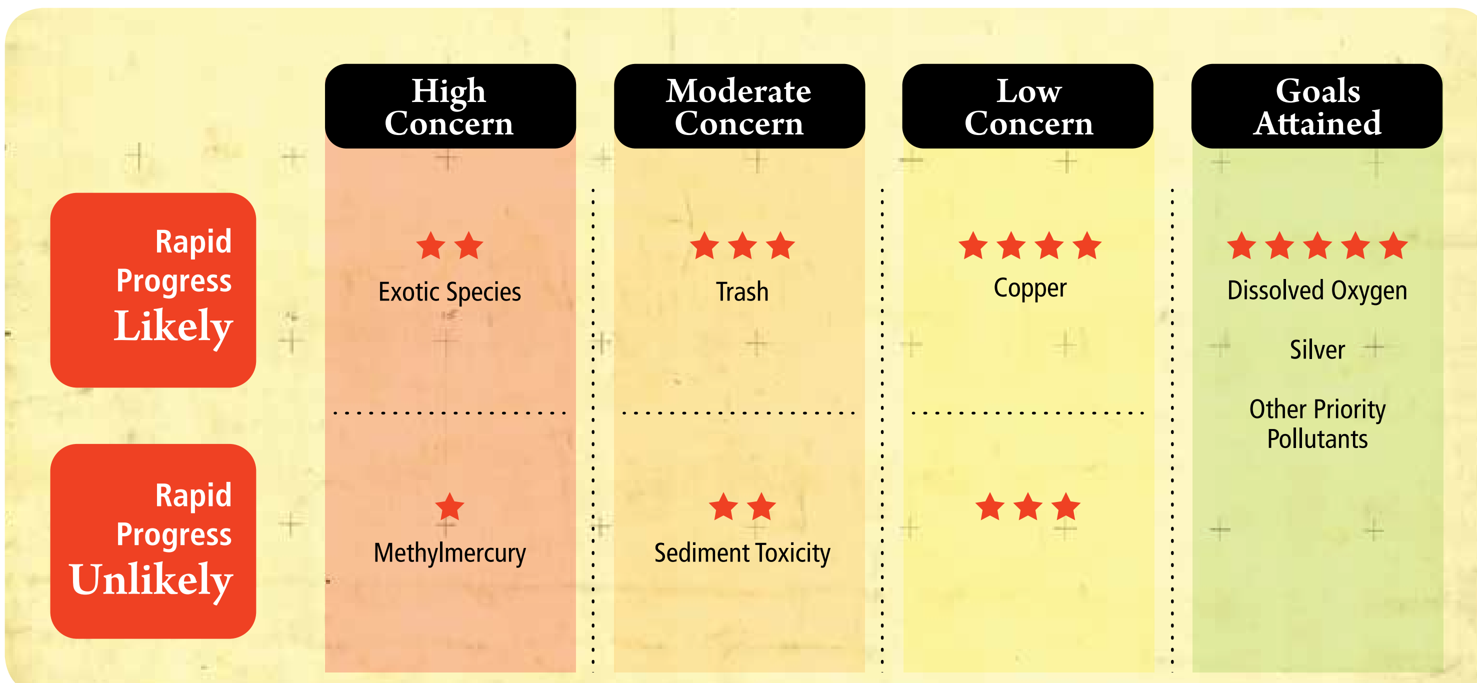
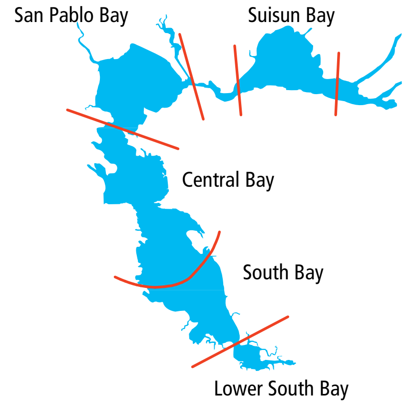
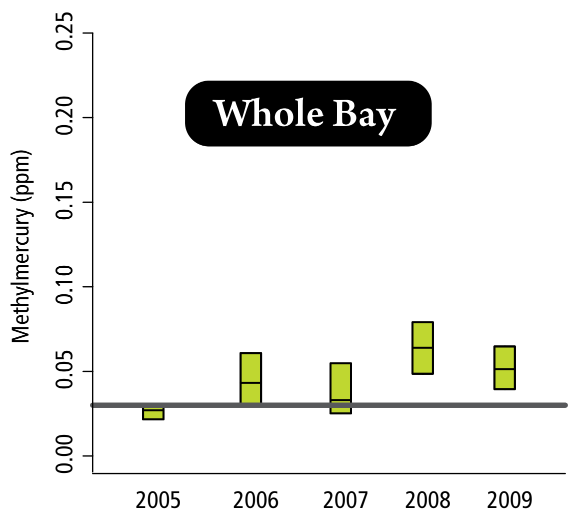
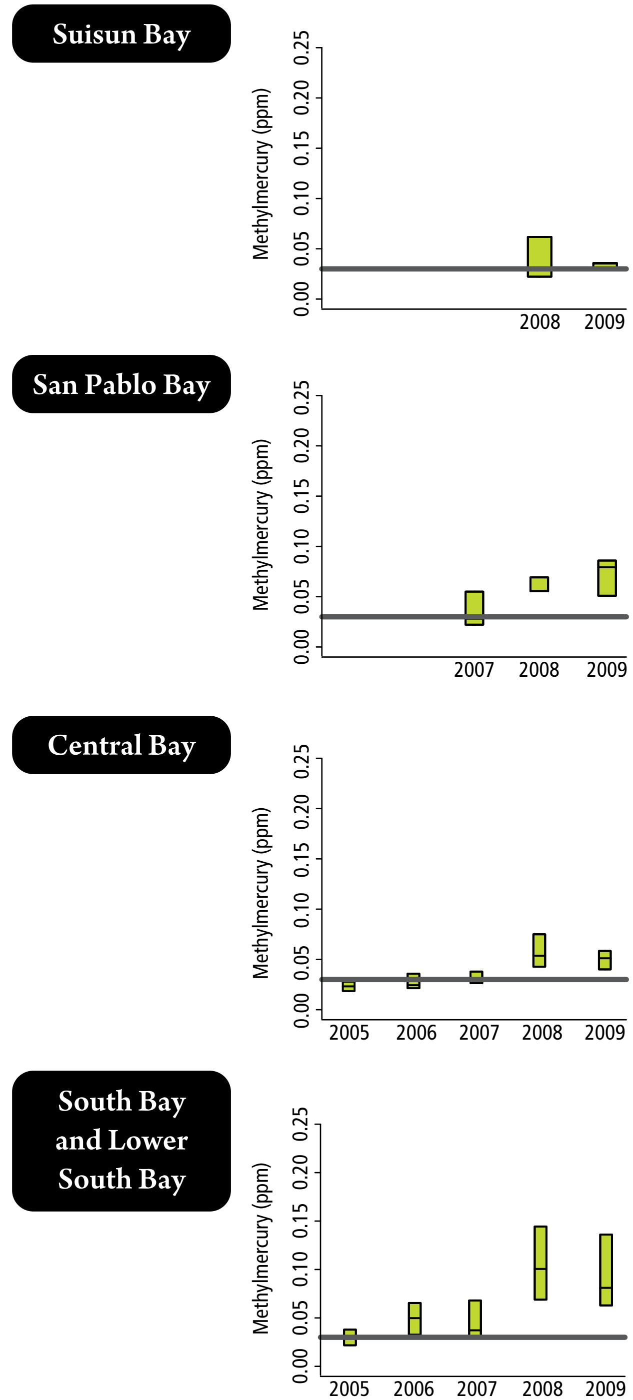


FIGURE 3

Methylmercury concentrations in small fish frequently exceed the 0.030 ppm target in the Mercury TMDL for protection of fish-eating birds. In the most recent sampling year, methylmercury concentrations in prey fish exceeded the 0.03 ppm target in approximately 95% of the samples collected. Similar results were obtained in 2008, the other year with a larger sample size. Results from a pilot study in 2005-2007 were lower, but the distributions for those years are based on a very small sample size. The Bay-wide median concentration in 2009 was 0.051 ppm.



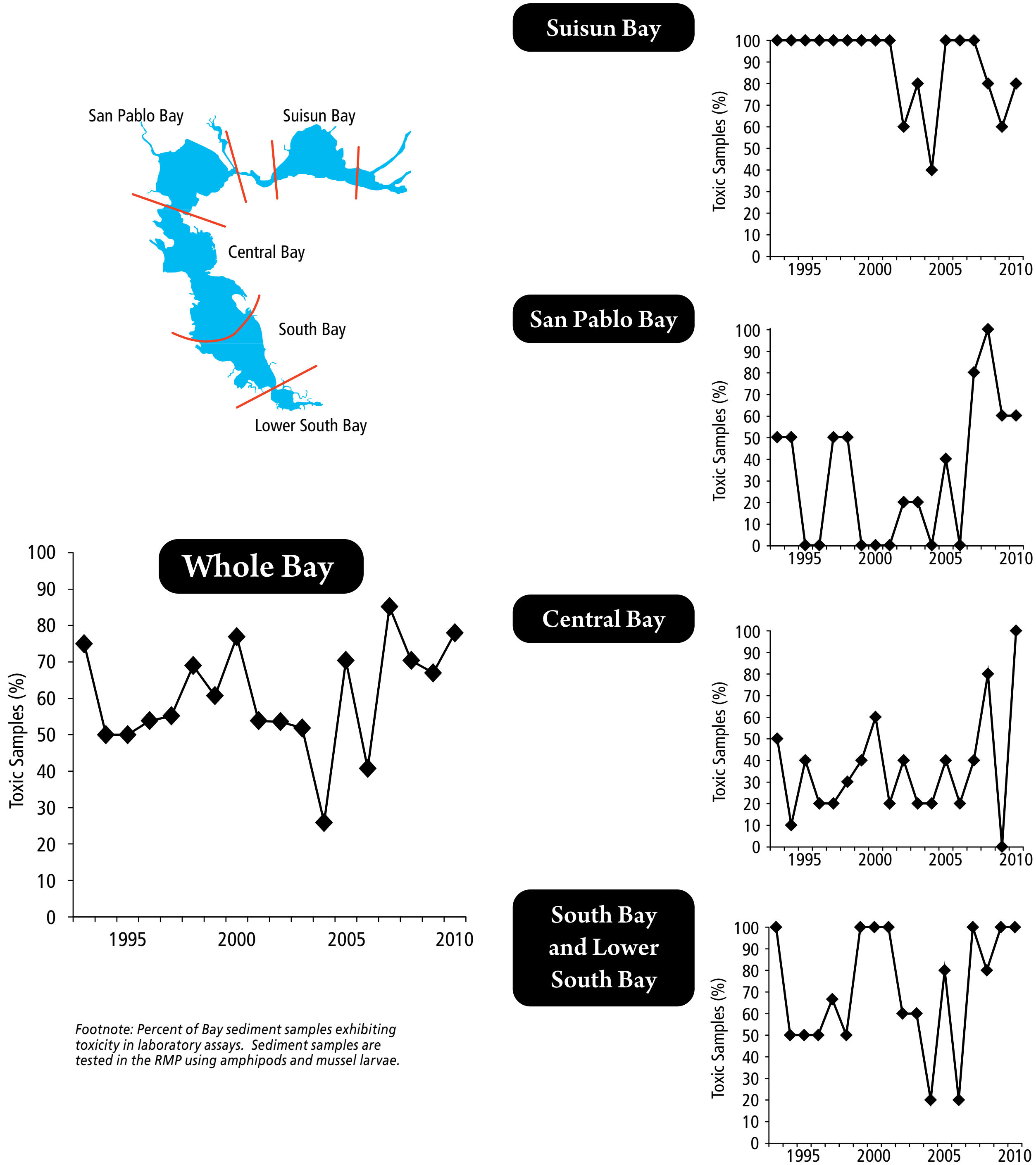




Footnote: Box plots indicate the 25th, 50th, and 75th percentiles. Data for Mississippi silversides and topsmelt in the 3-5 cm size range specified in the Mercury TMDL. The RMP did not specifically target this size range, therefore sample sizes for each year are limited. Reference line is the 0.030 ppm target from the Mercury TMDL.

FIGURE 4

The frequent and continuing toxicity of Bay sediments in standard tests is an important indicator of impacts of pollution on aquatic life. In every year since routine sampling began in 1993, at least 26% of each year's sediment samples have been determined to be toxic. In 2010, 78% of the samples were found to be toxic. The occurrence of toxic samples is greatest in Suisun Bay and South Bay. These results indicate that pollutant concentrations in Bay sediments are high enough to affect the development and survival of aquatic invertebrates. This problem will persist into the future until the chemicals (or mix of chemicals) causing this toxicity can be identified and remediated.



Footnote: Percent of Bay sediment samples exhibiting toxicity in laboratory assays. Sediment samples are tested in the RMP using amphipods and mussel larvae.

← Fishing on Fort Baker Pier. Photograph by Jay Davis.

ARE FISH FROM THE BAY SAFE TO EAT?

The "Safe to Eat" quantitatively considers eight key pollutants, and considers qualitatively the impact of many others. Pollutant concentrations in fish can be compared to goals established by the State of California to protect public health. It is important to note that the comparisons presented in this assessment are general indications of levels of concern, and are not intended to represent consumption advice. Consumers can exercise caution and reduce their exposure to these contaminants by following safe eating guidelines for the Bay developed by the Office of Environmental Health Hazard Assessment (OEHHA), which have just been updated this year (**SIDEBAR, PAGE 16**).

Pollutants in fish from the Bay pose a health concern (**FIGURE 5**) due mainly to polychlorinated biphenyls (PCBs) (**FIGURE 6**), methylmercury (**FIGURE 7**), and dioxins, which are generally found in Bay fish at moderate concentrations. Many other toxic pollutants (e.g., arsenic, cadmium, chlorpyrifos, diazinon, dieldrin, DDTs, polycyclic aromatic hydrocarbons, or "PAHs", polybrominated diphenyl ethers, or "PBDEs", and selenium) are found at concentrations too low to pose concerns.

Contamination in Bay fish varies by species. Striped bass, for example, have relatively high concentrations of methylmercury, while jacksmelt are relatively low in this contaminant. Shiner surfperch have relatively high concentrations of PCBs, and California halibut have relatively low concentrations. The safe eating guidelines for the Bay (**SIDEBAR, PAGE 16**) highlight the key differences among species to allow fish consumers to reduce their exposure. For example, the guidelines indicate that PCB concentrations in one group of species – surfperch – are high enough that OEHHA recommends no consumption.

While moderate contamination is generally found in fish throughout the Bay, PCBs in shiner surfperch are seen at levels that pose a greater concern in the Central Bay than in San Pablo Bay or South Bay (**FIGURE 6**). This exception to the pattern is due to the tendency of shiner surfperch to spend their lives in localized nearshore areas, which can result in greater accumulation when these areas are contaminated with PCBs. This finding suggests that identifying and cleaning up contaminated hotspots along the edges of the Bay could hasten the reduction of contamination at selected locations.

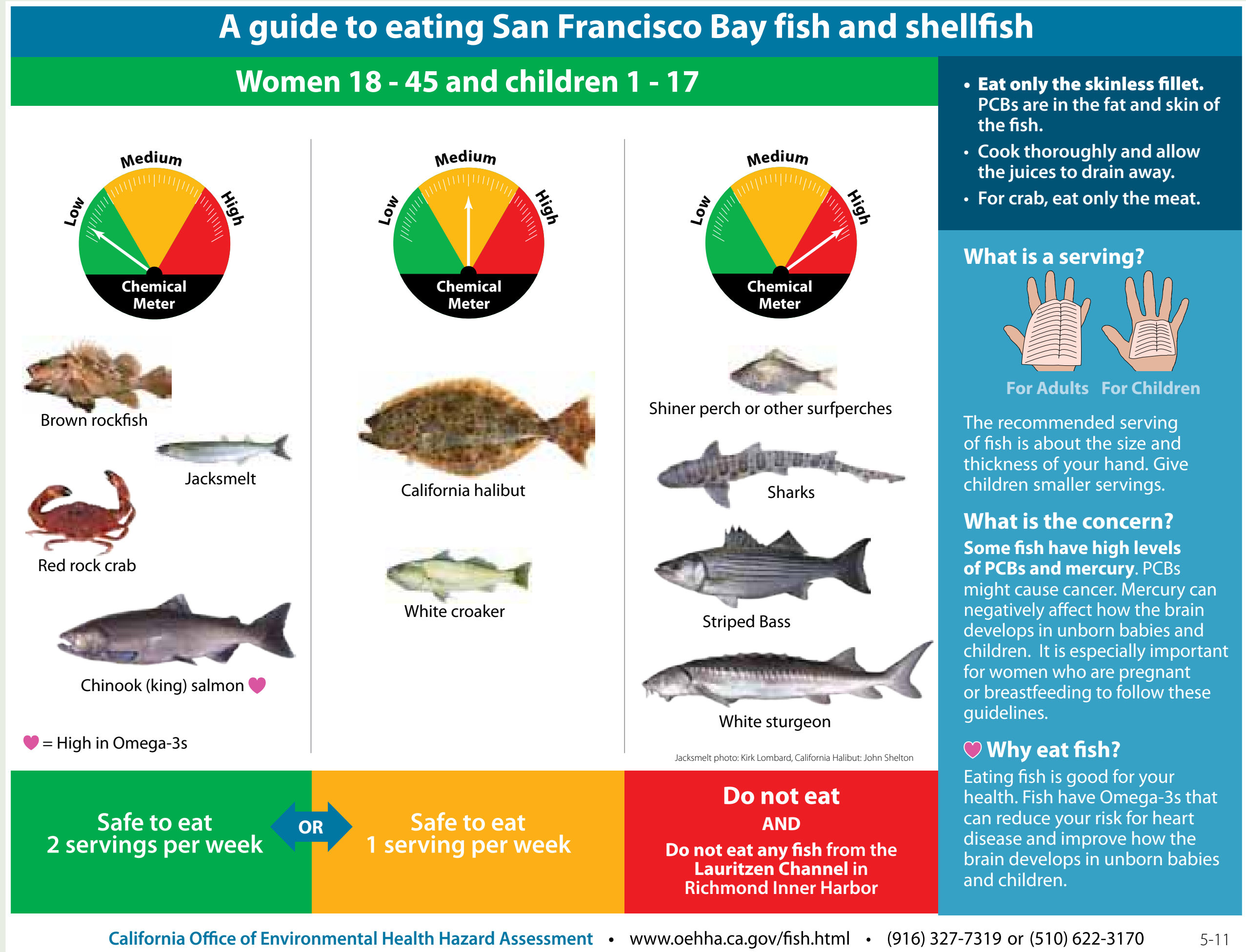
The risk we face today from consuming Bay fish is in large part a legacy of unregulated discharges of pollutants in the past. For example, even though a ban on the sale and production of PCBs went into effect in 1979, these persistent chemicals have become thoroughly spread across the Bay watershed and mixed throughout the Bay, creating a widespread pool of contamination that will dissipate very slowly. Monitoring of trends in fish contamination from 1994 to the present has found no indication of declines for PCBs, methylmercury, and dioxins. Attaining goals for these pollutants in sport fish will take many decades.

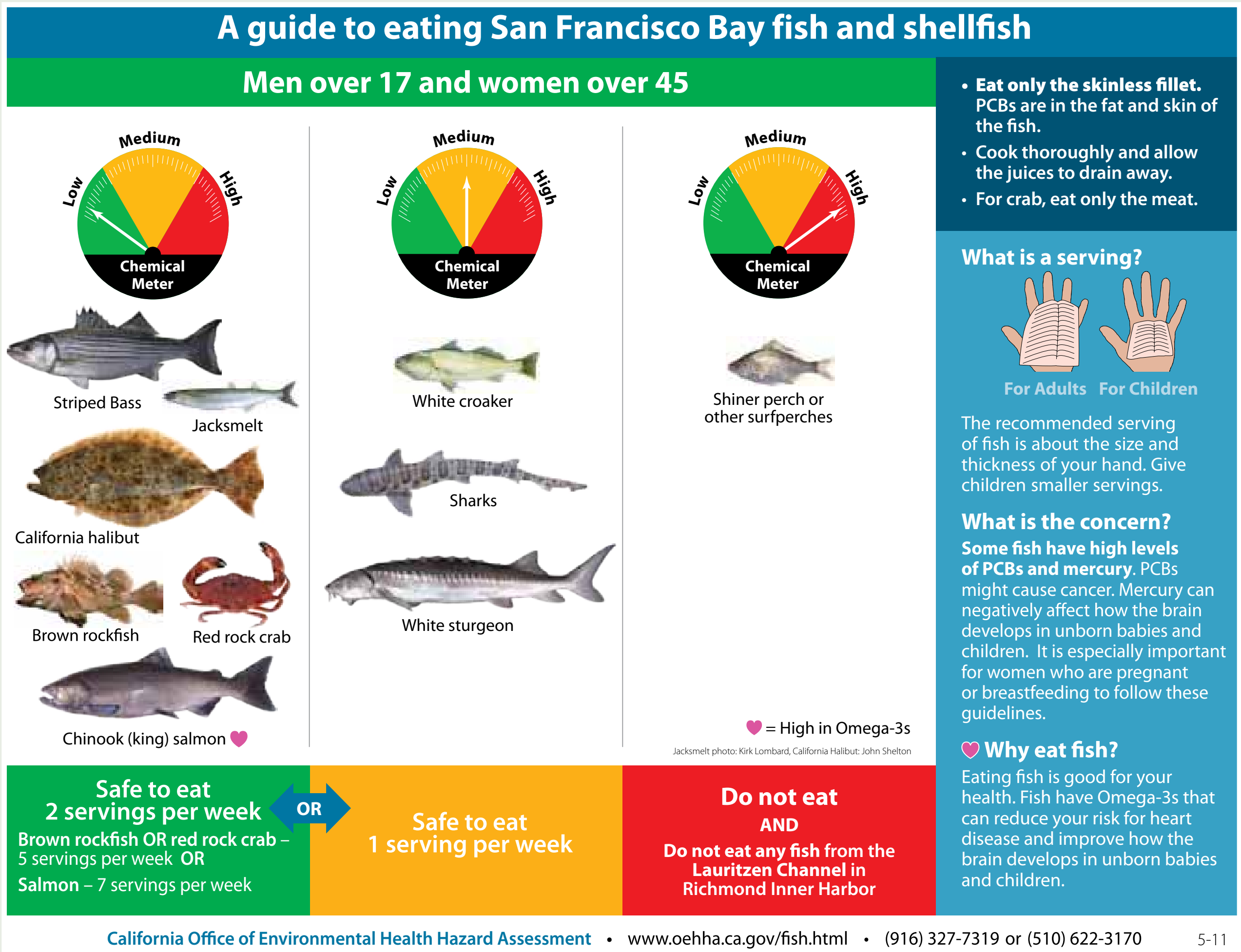
SIDEBAR

UPDATED FISH ADVISORY FOR SAN FRANCISCO BAY

In May 2011 the Office of Environmental Health Hazard Assessment (OEHHA) released an updated health advisory and safe eating guidelines for fish and shellfish caught from San Francisco Bay. The guidelines state that Bay Area anglers should eat a variety of different kinds of fish, avoid fish known to have high amounts of mercury and other contaminants, and properly prepare and cook fish. The advisory also provides special advice for women of childbearing age and children.

The advisory and guidelines replace an earlier 1994 advisory, and draw on over a decade of more recent data, primarily from the RMP, showing San Francisco Bay fish contain mercury and polychlorinated biphenyls (PCBs). 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.



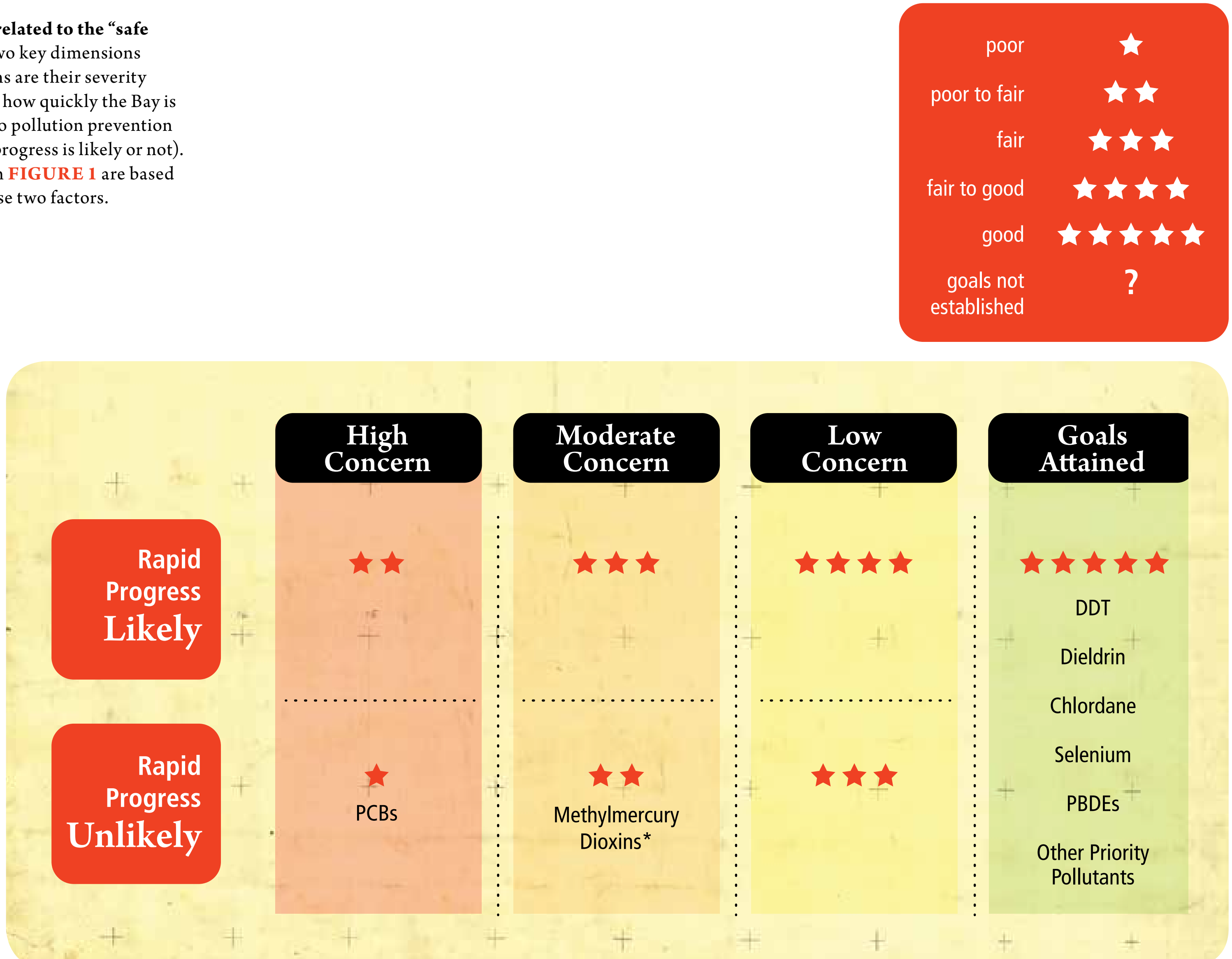


Some kinds of fish have more mercury and PCBs than others. Sharks have the highest levels of mercury, and shiner perch have the most PCBs. High exposures to methylmercury (the form of mercury prevalent in fish) can affect the nervous system and harm learning ability, language skills and memory. PCBs are common contaminants known to build up in fish. They have been found to cause cancer in animals and also cause health problems in young children and adults.

Complete information on the new advisory is available at: oehha.ca.gov/fish/general/sfbaydelta.html

FIGURE 5

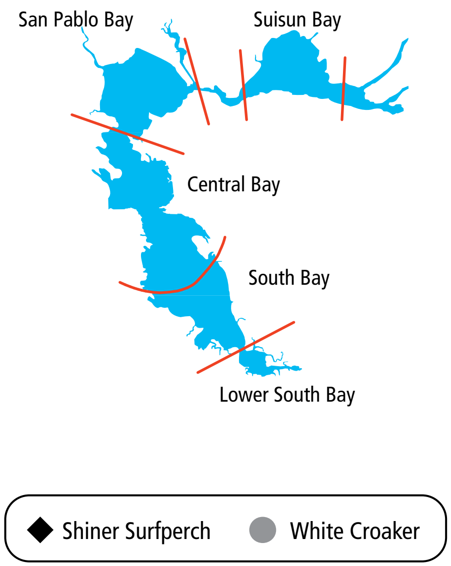
Summary assessment related to the "safe to eat" question. The two key dimensions of water quality problems are their severity (degree of concern) and how quickly the Bay is anticipated to respond to pollution prevention actions (whether rapid progress is likely or not). The assessment scores in **FIGURE 1** are based on a combination of these two factors.

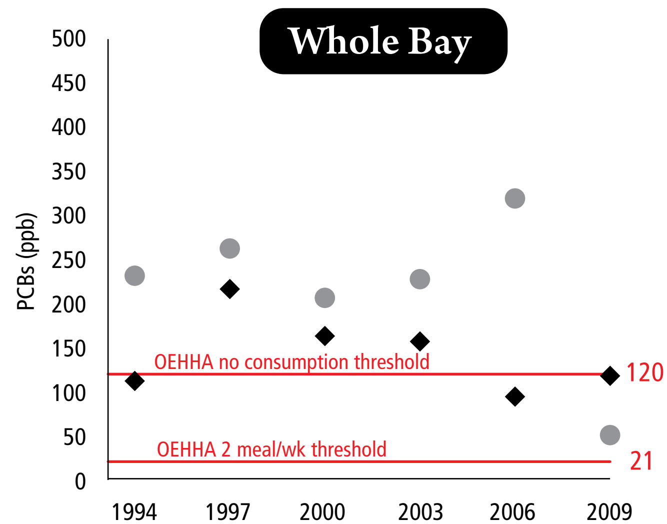


*Footnote: * Dioxins were assessed using a San Francisco Bay Regional Water Quality Control Board target, rather than the Office of Environmental Health Hazard Assessment thresholds used for the other pollutants.*

FIGURE 6

In the most recent sampling year (2009), both of the PCB indicator species (shiner surfperch and white croaker) had average concentrations between 21 ppb and 120 ppb. The Bay-wide average for shiner surfperch in 2009 (118 ppb) was just below OEHHA's 120 ppb no-consumption threshold. Based on this long-term dataset, the recently updated safe eating guidelines for San Francisco Bay recommend no consumption of shiner surfperch and other surfperch species. This corresponds to the "high concern" category in Figure 5. No clear pattern of long-term decline in PCB concentrations has been evident in these species. The summary rating for PCBs in Bay sport fish is therefore one star.





Footnote: Average PCB concentrations in sport fish indicator species. Sport fish are not routinely sampled in Suisun Bay. The no consumption advisory tissue level for PCBs is 120 ppb, and the two serving advisory tissue level is 21 ppb. White croaker were analyzed without skin in 2009, and with skin in previous years. Removing the skin reduced concentrations by 65% in 2009.

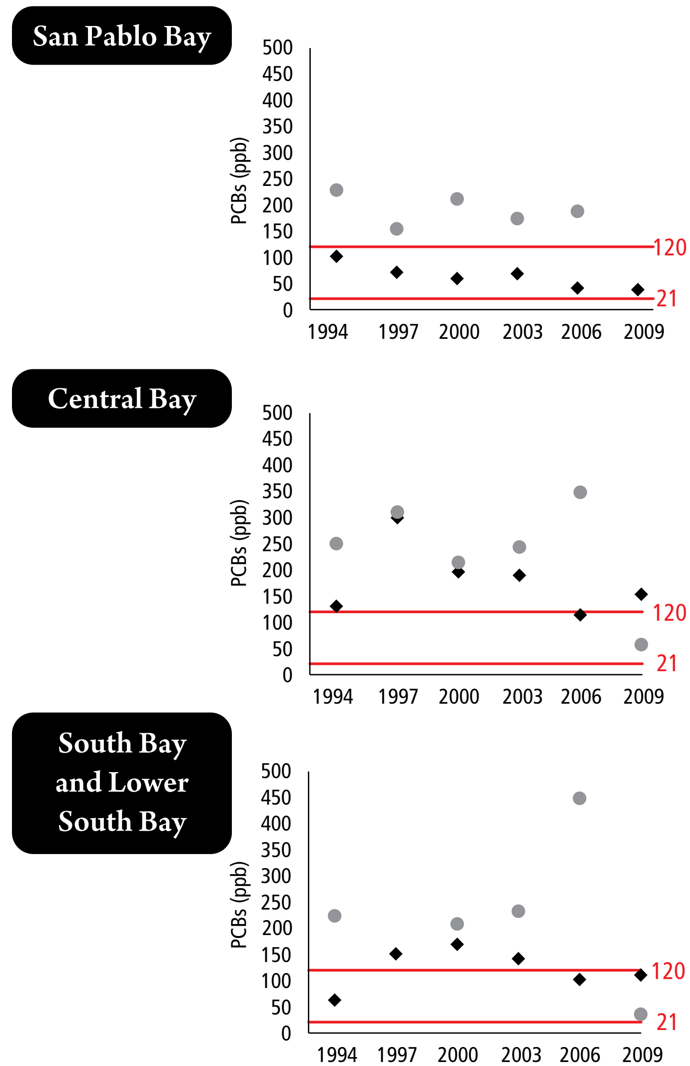
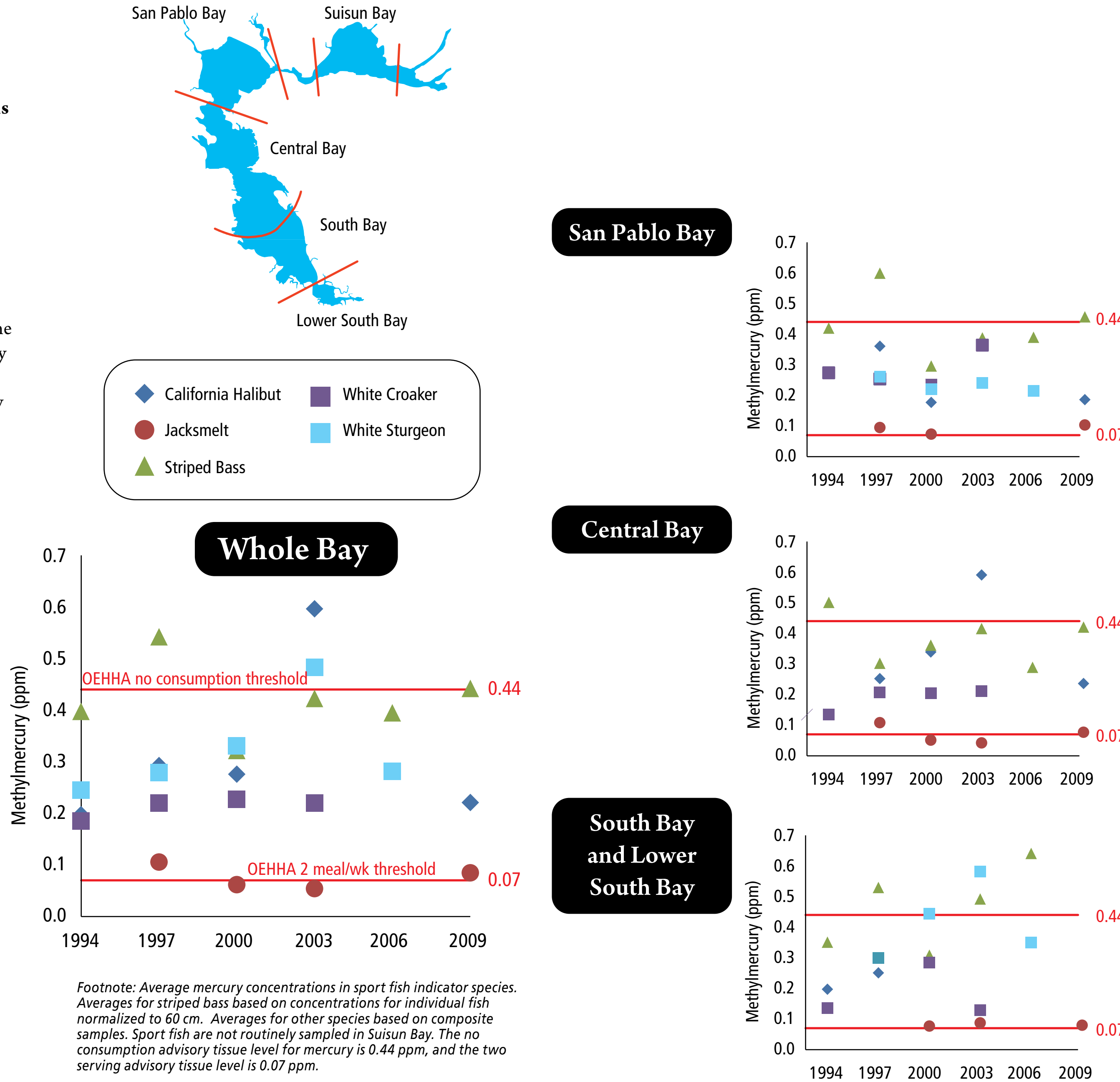


FIGURE 7

The methylmercury indicator species sampled in 2009 had average concentrations between 0.44 ppm (striped bass) and 0.08 ppm (jacksmelt). Concentrations in these species in recent years mostly fell between the no consumption advisory tissue level of 0.44 ppm and the two serving per week advisory tissue level of 0.07 ppm; this corresponds to the "moderate concern" category in **FIGURE 5**. Methylmercury concentrations in the Bay food web have not changed perceptibly over the past 40 years, and it is not anticipated that they will decline significantly in the next 30 years. The summary rating for methylmercury in Bay sport fish is therefore two stars.



Footnote: Average mercury concentrations in sport fish indicator species. Averages for striped bass based on concentrations for individual fish normalized to 60 cm. Averages for other species based on composite samples. Sport fish are not routinely sampled in Suisun Bay. The no consumption advisory tissue level for mercury is 0.44 ppm, and the two serving advisory tissue level is 0.07 ppm.

IS THE BAY SAFE FOR SWIMMING?

The "Safe to Swim" water quality index is based on measurements of bacteria in water at popular Bay beaches. To protect beach users from exposure to fecal contamination, California has adopted standards for high use beaches that apply from April through October at beaches that are adjacent to a storm drain that flows in the summer. Heal the Bay, a Santa Monica-based non-profit, provides comprehensive evaluations of over 400 California bathing beaches in both Annual and Summer Beach Report Cards as a guide to aid beach users' decisions concerning water contact recreation (**SIDEBAR, PAGE 22**). Overall, the latest beach report card covering the summer of 2010 indicates that most Bay beaches are safe for swimming in the summer, but that bacterial contamination is a concern at a few beaches in the summer, and at most beaches in wet weather.

The frequency of beach closures is another informative metric for evaluating how safe the Bay is for swimming (**FIGURE 8**). Based upon the number of days beaches were closed or posted by counties with advisories warning against water contact recreation, Bay beaches were open 80% to 100% of the time during the prime beach season of April through October from 2006 through 2010.

A variety of approaches can be taken to make the Bay safer for swimming. Sanitary surveys can be conducted to identify and mitigate contamination sources where possible. Low impact design installations may be possible at some sites to retain and treat stormwater before it reaches beaches. Diversion of storm water away from bathing beaches where possible may provide another solution. Repair and replacement of defective and aging sanitary sewer systems will be necessary in many instances before human fecal sources are considered controlled.

A STEP FORWARD

Thanks to considerable investment in infrastructure and the diligent efforts of water quality managers, the Bay is much safer for fishing, aquatic life, and swimming than it was in the 1960s. Substantial control efforts that began in the 1970s, in response to provisions of the 1972 Clean Water Act, solved most of the obvious problems of the 1960s and set the Bay on a course for gradual recovery for many pollutants. The general pace of water quality improvement, however, has slowed in the past three decades, due primarily to a lack of major new initiatives to control inputs to the Bay and the naturally decelerating trajectory of recovery dictated by the dynamics of sediment mixing in the ecosystem.

Preventing the entry of problematic pollutants into this vulnerable ecosystem is the ideal way to protect Bay water quality. We use thousands of chemicals in our homes and businesses, including pesticides, industrial chemicals, and chemicals in consumer products, and many of these enter the Bay. A lack of information on the chemicals present in commercial products, their movement in the environment, and their toxicity hinders efforts to track and manage the risk posed to people and aquatic life by these emerging contaminants. Numeric goals to assess our environmental measurements for emerging contaminants are not yet available, but should be part of future assessments of Bay health. The occurrence of emerging contaminants also underscores the importance of "green chemistry" efforts to prevent potentially problematic chemicals from entering the Bay in the first place so that they do not become additional legacies of health risk for future generations of Bay and Bay Area residents.

↑ Photograph courtesy of Swim Across America, raising money and awareness for cancer research, prevention and treatment: www.swimacrossamerica.org

This summary of Bay water quality highlights several pollutants that continue to pose substantial water quality concerns, and facets of these problems where progress seems attainable. Hopefully this summary will serve as a step forward in effective communication of progress in achieving water quality goals and a foundation for future improvements in reporting and management of Bay water quality.

SIDEBAR

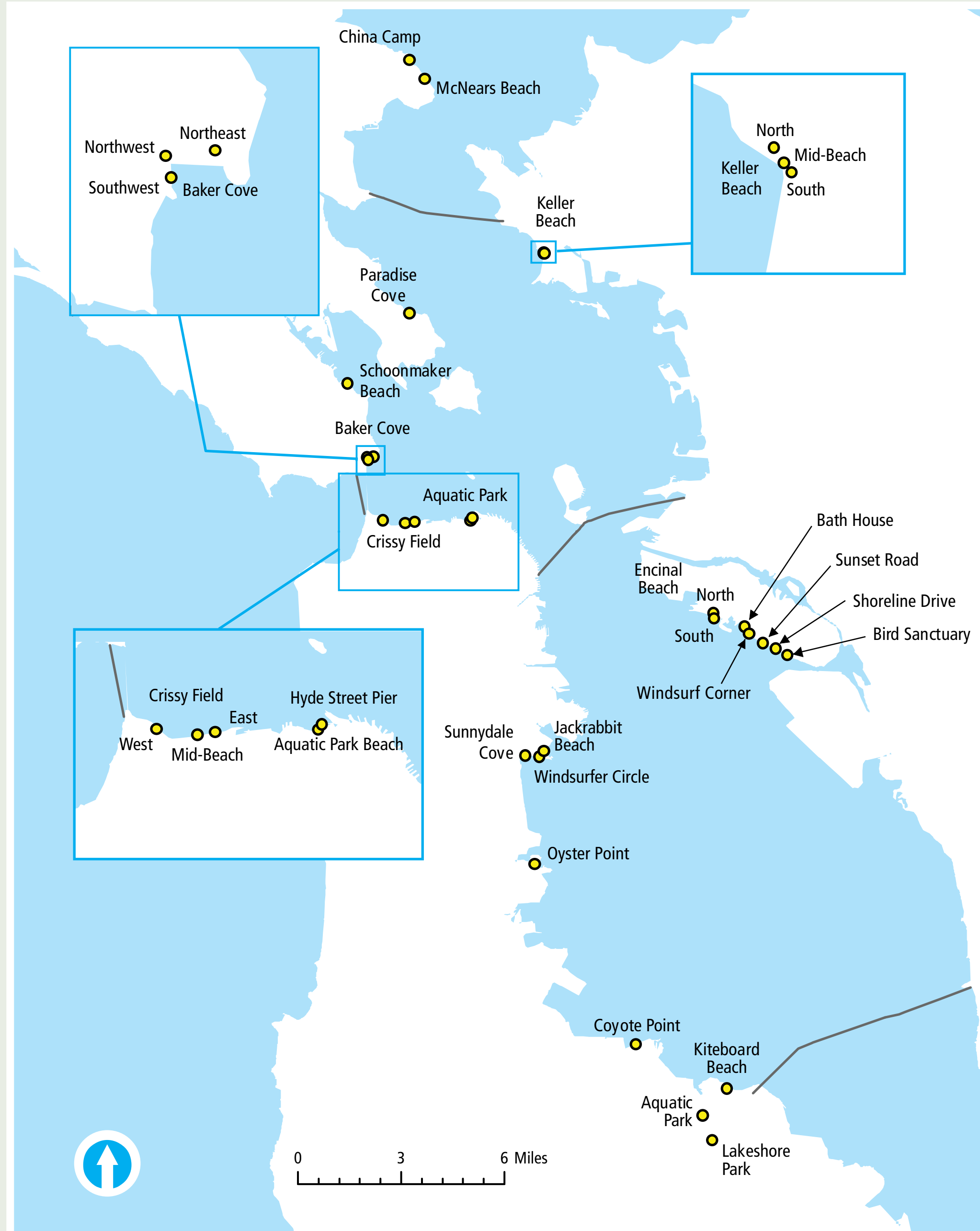
A BEACH REPORT CARD

Heal the Bay, a Santa Monica-based non-profit, provides comprehensive evaluations of over 400 California bathing beaches in both Annual and Summer Beach Report Cards as a guide to aid beach users' decisions concerning water contact recreation. Grades from these report cards, which use the familiar "A to F" letter grade scale, provide a valuable and easily accessible assessment of how safe Bay waters are for swimming.

Overall, the latest monitoring data from 2010 indicate that most Bay beaches are safe for swimming in the summer, but that bacterial contamination is a concern at a few beaches in the summer, and at most beaches in wet weather.

For the summer beach season in 2010, 19 of the 26 monitored beaches received an A or A+ grade, reflecting minimal exceedance of standards. Ten of these beaches received an A+: Coyote Point, Alameda Point South, Bath House, Windsurf Corner, Sunset Road, Shoreline Drive, Hyde Street Pier, Crissy Field East, Crissy Field West, and Schoonmaker Beach. Most Bay beaches, therefore, are quite safe for swimming in the summer. Seven of the 26 beaches monitored in the summer in 2010 had grades of B or lower, indicating varying degrees of exceedance of bacteria standards. Keller Beach North and Keller Beach Mid-Beach were the two beaches receiving an F. Five beaches received a D, including one in Contra Costa County, two in San Mateo County, and two in San Francisco County. These low grades indicate an increased risk of illness or infection. Overall, the average grade for the 26 beaches monitored from April-October was a B.

During wet weather, which mostly occurs from November-March, 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 making the Bay less safe for swimming. This pattern is evident in Heal the Bay report card grades for wet weather. In wet weather, only five of 22 beaches with data received an A. Six of these 22 beaches, on the other hand, received an F. The average grade for these beaches in wet weather was a C+.



HEAL THE BAY ANNUAL BEACH REPORT CARD GRADES

	APRIL - OCTOBER					DRY WEATHER, YEAR-ROUND					WET WEATHER, YEAR-ROUND				
	2006	2007	2008	2009	2010	2006 -07	2007 -08	2008 -09	2009 -10	2010 -11	2006 -07	2007 -08	2008 -09	2009 -10	2010 -11
SAN MATEO COUNTY															
Oyster Point		A	A	B	A		A		A	A		C		F	D
Coyote Point		A	A+	A+	A+		A		A	A+		A		B	C
Aquatic Park		A	B	F	D		B		F	D		F		F	F
Lakeshore Park		A	D	D	D		C		D	D		F		F	F
Kiteboard Beach			B						A					F	
ALAMEDA COUNTY															
Alameda Point North			A	A+	A			A	A+	A			A+	A	C
Alameda Point South			A	A	A+			A	A	A			A+	A	A
Crown Beach Bath House		A	A	B	A+		A	C	B	A+		C	A+	A	A
Crown Beach Windsurf Corner		A	A	A	A+		A	A	A	A+		A	A+	B	B
Crown Beach Sunset Road		A	A+	A	A+		A	A	A	A+		F	A	B	B
Crown Beach Shoreline Drive		A	A	A+	A+		A	A	A	A		F	A+	C	B
Crown Beach Bird Sanctuary		A	A	B	A		C	A	B	A		F	B	D	C
CONTRA COSTA COUNTY															
Keller Beach North		B	F	D	F		B	D	D	F		A	A	B	A
Keller Beach Mid-Beach		B	C	D	F		B	C	D	F		B	B	B	A
Keller Beach South		A	C	D	D		A	C	D	D		A	B	C	B
SAN FRANCISCO COUNTY															
Crissy Field Beach West			A+	A+	A+			A+	A+	A			A	C	B
Crissy Field mid-Beach	A	A+				A	A+				B	A			
Crissy field Beach East	A	A	A	A	A+	C	A	B	A	B	D	A	B	B	C
Aquatic Park Beach	A	B	A	A	A	A	C	B	A	B	B	A	C	A	B
Hyde Street Pier	A	A	A	A+	A+	A	A	A	A	A	A	A	A+	A	A
Jackrabbit Beach	A	A	A	A	A	A	A	A	A	A	A	F	D	C	B
CPSRA Windsurfer Circle	A	A	A	A	D	A	A	B	A	F	F	F	F	F	F
Sunnydale Cove	A	A	A	B	D	A	C	A	C	C	F	F	F	F	F
MARIN COUNTY															
Horseshoe Cove NE	A	A	A	A+	A										
Horseshoe Cove NW	A	B	A	A	A										
Horseshoe Cove SW	A	A	A	A	A										
Schoonmaker Beach	A	A+	A+	A	A+										
Paradise Cove	A	A	A+												
China Camp	D	A+	A+	A	A										
McNears Beach	C	A	A												
OVERALL GPA	3.64	3.88	3.61	3.30	3.23	3.71	3.44	3.31	3.12	2.91	2.14	2.05	3.11	2.14	2.38
OVERALL GRADE	B+	A-	B+	B	B	A-	B+	B+	B	B-	C	C	B	C	C+

(year-round = April 1 - March 31)

SOURCES OF INFORMATION ON BACTERIA MONITORING AT BAY BEACHES

ALAMEDA COUNTY

website: www.ebparks.org/stewardship/water

hotline: 510-567-6706 (Crown Beach)

CONTRA COSTA COUNTY

website: www.ebparks.org/stewardship/water

CITY AND COUNTY OF SAN FRANCISCO

website: http://beaches.sfwater.org

hotline: 415-242-2214 or 1-877-SFBEACH (732-3224) toll free

MARIN COUNTY

website: www.co.marin.ca.us/ehs/water/beach_monitoring.cfm

hotline: 415-473-2335

SAN MATEO COUNTY

website: www.smhealth.org/environ/beaches

hotline: 650-599-1266

HEAL THE BAY BEACH REPORT CARDS

website: www.beachreportcard.org

CALIFORNIA SAFE TO SWIM WEB PORTAL

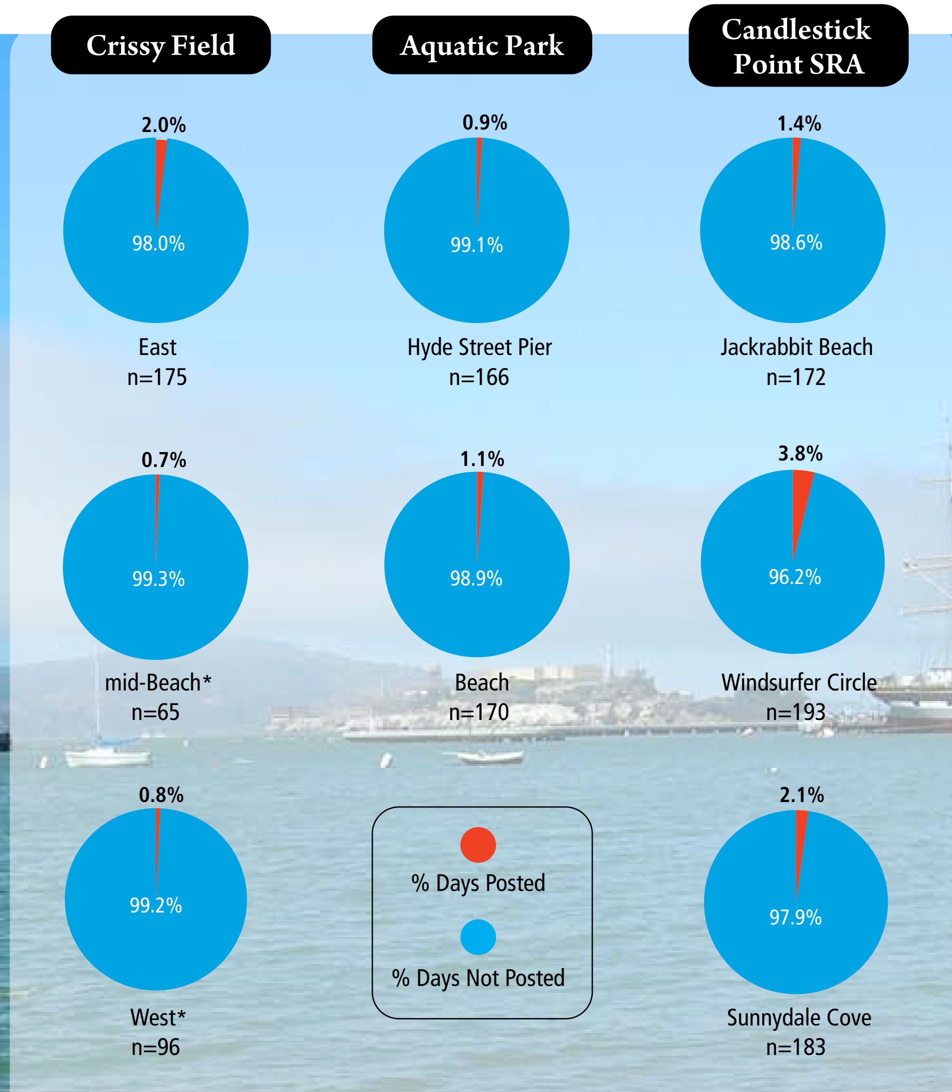
website: www.waterboards.ca.gov/mywaterquality/safe_to_swim

CALIFORNIA BEACH WATER QUALITY INFORMATION PAGE

website: www.swrcb.ca.gov/water_issues/programs/beaches/beach_water_quality/index.shtml

FIGURE 8

County public health and other agencies routinely monitor bacteria concentrations at Bay beaches where water contact recreation is common and provide warnings to the public when concentrations exceed the standards. The county monitoring data represent the longest-term data set from the most locations in the Bay with which to evaluate the question "Is the Bay Safe for Swimming?" Based upon the number of days beaches were closed or posted with advisories warning against water contact recreation, Bay beaches were open 80% to 100% of the time during the prime beach season of April through October from 2006 through 2010. Data for San Francisco beaches are shown here as an example.



Footnote: Percent of days during the prime beach season (April - October) that City and County of San Francisco beaches were posted and not posted due to possible fecal contamination from 2006 through 2010 (n=number of samples). Crissy Field mid-Beach sampled 2006-2007 and Crissy Field West sampled 2008-2010.

Swimmer at Aquatic Park Beach. Photograph by Jay Davis.

SIDEBAR

SWIMMER'S ITCH AND EXOTIC SPECIES

Exotic species, one of the greatest threats to aquatic life in the Bay, also pose a nuisance for people who swim in the Bay. Swimmer's itch, common in some freshwater ponds and lakes, is caused when a parasitic flatworm that normally develops in a water snail and then burrows through the skin and into the circulatory system of a water bird (where it matures and mates) instead burrows into a human swimmer or wader. Symptoms are similar to those caused by exposure to poison oak, with an itchy, red rash that can last for weeks. It is generally unknown in Pacific coastal waters except for a few outbreaks associated with exotic organisms.

An outbreak at Crown Beach in Alameda in the 1950s and another in Surrey, British Columbia that started in 2002 were both caused by an Atlantic Coast flatworm (*Austrobilharzia variglandis*) carried by an introduced Atlantic mudsnail (*Ilyanassa obsoleta*) (Grodhaus & Keh 1958; Leighton et al. 2004). Then in June 2005, approximately 90 elementary school children developed swimmer's itch after a class outing to Crown Beach during the last week of school. Warnings about the new outbreak were issued by the Alameda County Environmental Health Department and posted at the beach, and cases have been reported each spring and summer since.

Naturally, it was initially thought that this outbreak was due to the same exotic snail and flatworm as had caused the previous outbreaks, but this time the carrier turned out to be a recently introduced Japanese bubble snail (*Haminoea japonica*) and the parasite a previously unknown flatworm in the genus *Gigantobilharzia* (Brant et al. 2010). The bubble snail had been reported from a few sites in Washington in the 1980s, probably imported with Japanese oysters, and was found in southwestern San Francisco Bay in 1999. Interestingly, around the same time that a population of the Japanese oyster *Crassostrea gigas* became established in the South Bay, though it's unclear whether there's a connection. In 2003 the snail was discovered on the eastern side of the Bay just south of Crown Beach, and by 2005 it was the most abundant snail at the Beach.

Contact: Andrew Cohen, Center for Research on Aquatic Bioinvasions, acohen@bioinvasions.com

Literature Cited

Grodhaus G. and B. Keh. 1958. The marine dermatitis-producing cercaria of Austrobilharzia variglandis in California (Trematoda: Schistosomatidae). Journal of Parasitology 44: 633-638.

Leighton B.J., D. Ratzlaff, C. McDougall, G. Stewart, A. Nadan and L. Gustafson. 2004. Schistosome dermatitis at Crescent Beach, preliminary report. Environmental Health Review 48: 5-13.

Brant, S.V., A.N. Cohen, D. James, L. Hui, A. Hom and E.S. Loker. 2010. Cercarial dermatitis transmitted by exotic marine snail. Emerging Infectious Diseases 16(9): 1357-1365.

↑ Atlantic mudsnails. Photograph by Andrew Cohen.

↑ Crown Beach, Alameda, California. Photograph by Amy Franz.

THE RV ENDEAVOR

The RMP gratefully acknowledges the significant contribution made by the Bureau of Reclamation to the program through the generous donation of the research vessel, RV Endeavor, and Captain Nick Sakata. Dr. Erwin Van Nieuwenhuyse, Chief of the Science Division of Reclamation's Bay-Delta Office, is Reclamation's coordinator for the Interagency Ecological Program (IEP). Similar to the RMP, the IEP is a consortium of federal and state agencies that monitors and conducts special studies on the physical, chemical, and biological properties of the Bay-Delta to meet the requirements of Biological Opinions and state water right permit conditions that govern the long term operation of the Central Valley Project and the State Water Project. The IEP has recently devoted significant resources to determining the cause of the Pelagic Organism Decline (PAGE 68). The RMP is extremely pleased to have Reclamation's team assisting us in understanding Bay water quality.

MORE INFORMATION ON THE 303(d) LIST AND TMDLS IS AVAILABLE FROM THE FOLLOWING WEBSITES

303(D) LIST FOR REGION 2 (which includes the Estuary)
www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/TMDLs/303dlist.shtml

TMDLs
www.swrcb.ca.gov/sanfranciscobay/water_issues/programs/TMDLs/

THE 303(D) LIST

Section 303(d) of the 1972 Federal Clean Water Act requires that states develop a list of water bodies that do not meet water quality standards, establish priority rankings for waters on the list, and develop action plans, called Total Maximum Daily Loads (TMDLs), to improve water quality.

The list of impaired water bodies is revised periodically (typically every two years). The RMP is one of many entities that provide data to the State Water Board to compile the 303(d) List and to develop TMDLs. The process for developing the 303(d) List for the Bay includes the following steps:

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

In August 2010, the State Water Board adopted the 2010 303(d) List. The 2010 List was approved by USEPA.

The Regional Water Board and State Water Board are now working developing the draft 2012 303(d) List. The primary pollutants/stressors for the Estuary and its major tributaries on the 2010 303(d) List include:

Trace elements
Mercury and Selenium
Pesticides
Dieldrin, Chlordane, and DDT
Other chlorinated compounds
PCBs, Dioxin and Furan Compounds
Others
Exotic Species, Trash, and Polycyclic Aromatic Hydrocarbons (PAHs)

↑ The RV Endeavor. Photograph by Jay Davis.

Regulatory 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	TMDL in early development stage
Legacy Pesticides (Chlordane, Dieldrin,and DDT)	Under consideration for delisting
Mercury	Bay TMDL and site-specific objectives approved in 2008 Guadalupe River Watershed TMDL approved in 2010
Pathogens	Richardson Bay TMDL adopted in 2008 Bay beaches (Aquatic Park, Candlestick Point, China Camp, and Crissy Field) added to 303(d) List in 2006
PCBs	TMDL approved in 2009
Selenium	TMDL in development – completion projected for 2013
Trash	Central and South Bay shorelines added to the 2010 303(d) List

Approved: State Board and USEPA approval

↑ Ducks in San Leandro Bay. Photograph by Jay Davis.

STATUS & TRE
UPDATE

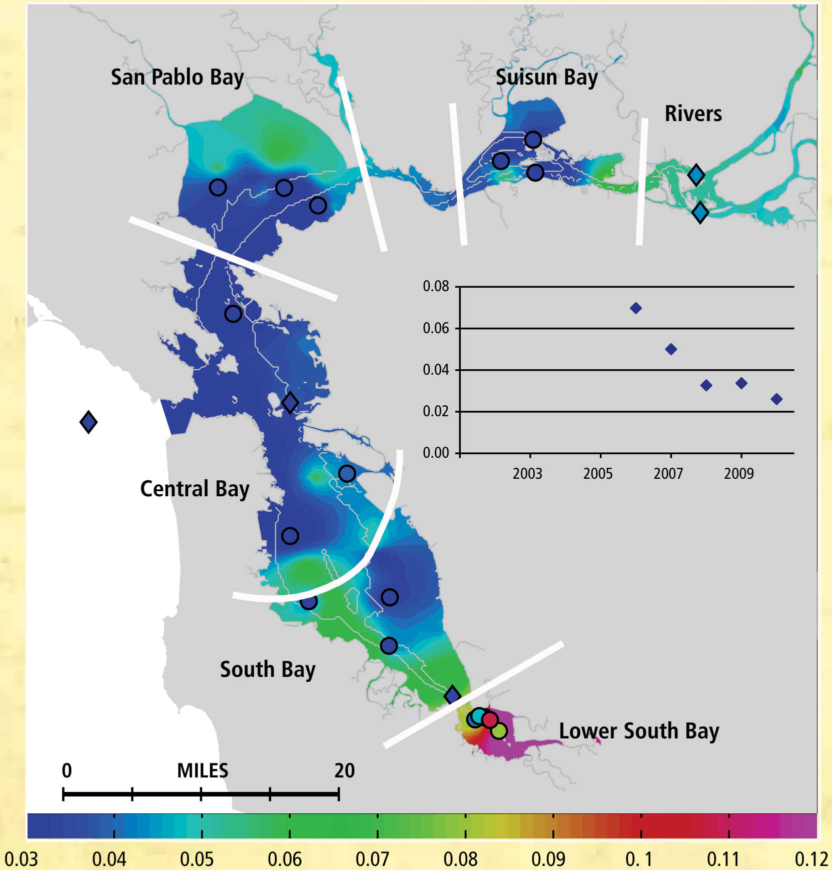
NDS

Latest Monitoring Results

MERCURY

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

Methylmercury in Water (ng/L)

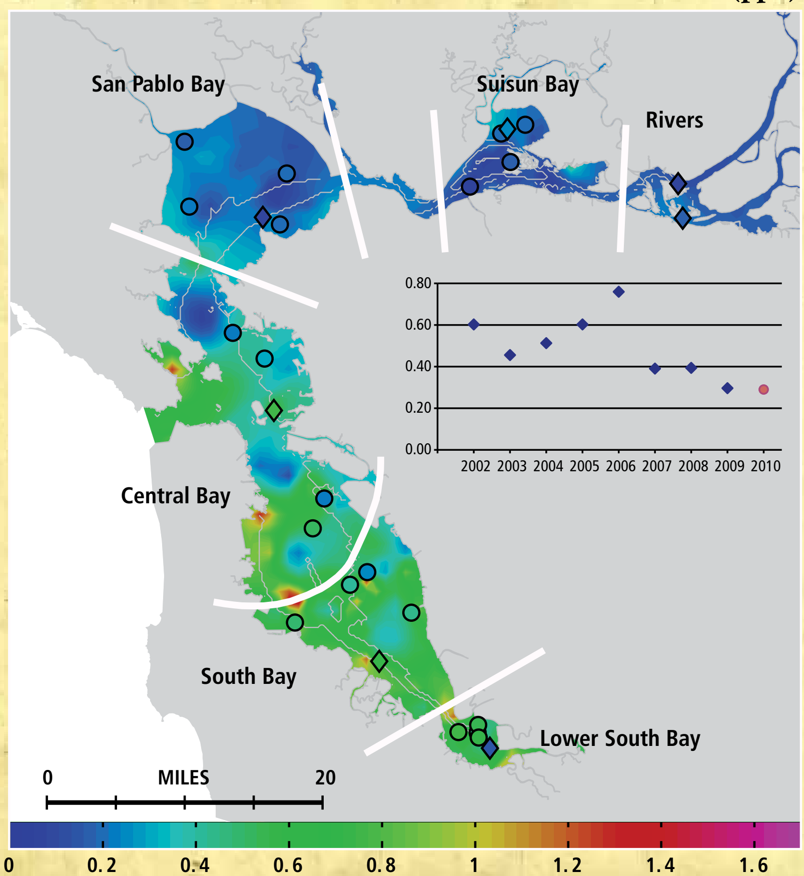


Water from Lower South Bay had the highest average concentration of methylmercury by far (0.11 ng/L) of any segment from 2006 to 2010. South Bay had the next highest average (0.06 ng/L). Methylmercury typically represents only about 1% of the total of all forms of mercury in water or sediment, but it 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. The Bay-wide average in 2010 was 0.03 ng/L. The Bay-wide average for the five-year period was 0.05 ng/L. The Bay-wide averages for 2008-2010 were lower than those observed in 2006 and 2007. Additional data will be needed to determine whether this reflects a real trend.

Footnote: Map plot based on 119 RMP data points from 2006-2010. Earlier years not included because a less sensitive method was employed. The maximum concentration was 0.23 ng/L at a site in Lower South Bay in 2009. Trend plot shows annual Bay-wide averages. Data are for total methylmercury. Colored symbols on map show results for samples collected in 2010. Circles represent random sites. Diamonds represent historic fixed stations.

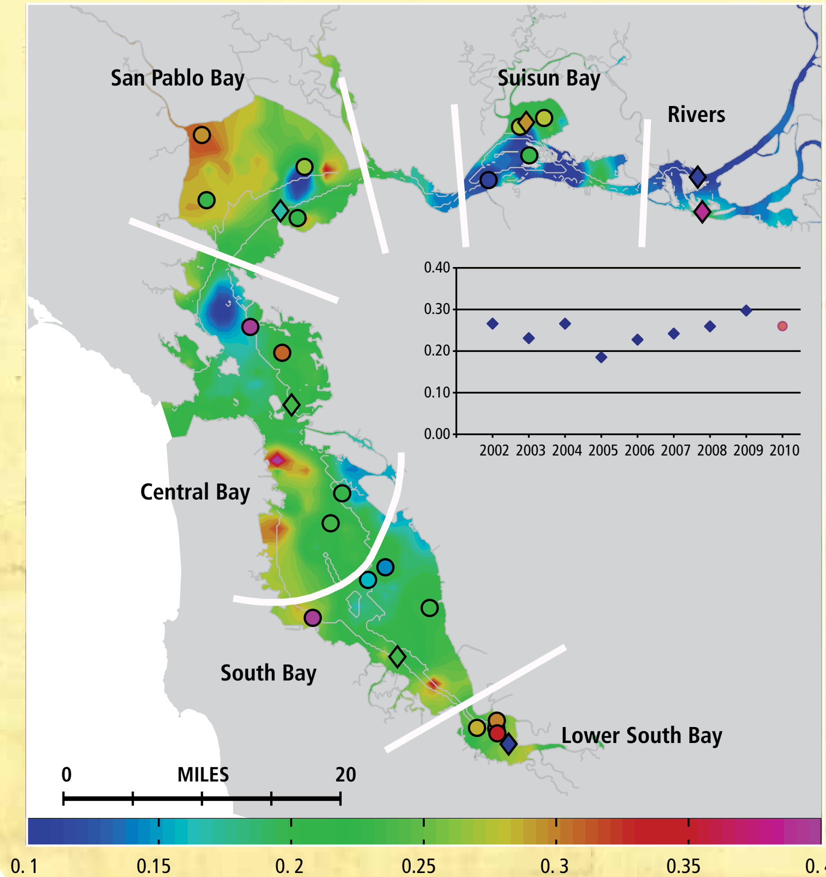
Concentrations of methylmercury in sediment south of the Bay Bridge have been consistently higher than those in the northern Estuary. Mercury is converted to methylmercury mainly by bacteria in sediment. Methylmercury production can vary tremendously over small distances and over short time periods, so the colored contours shown should be viewed as the result of several "snapshots" of Bay conditions at the time of the surveys in the summers of 2002-2009. Circles and diamonds represent results from a first year of wet-season sampling in 2010. The wet-season data show a similar spatial pattern as the long-term average conditions for the dry season. The average for the 2010 wet season (0.29 ppb) was lower than the long-term average for the dry season (0.50 ppb), but similar to the dry season result for 2009 (0.30 ppb). No regulatory guideline exists for methylmercury in sediment.

METHYLMERCURY IN SEDIMENT (ppb)



Footnote: Contour plot based on 378 RMP data points over an eight-year period from 2002-2009. The maximum concentration was 6.1 ppb at a site in Central Bay in 2009. Trend plot shows annual Bay-wide averages. Colored symbols on map show results for samples collected during the wet season (February) in 2010. Circles represent random sites. Diamonds represent historic fixed stations. Red circle on trend plot indicates a wet season sample; other samples were dry season. Concentrations presented on a dry weight basis.

MERCURY IN SEDIMENT (ppm)

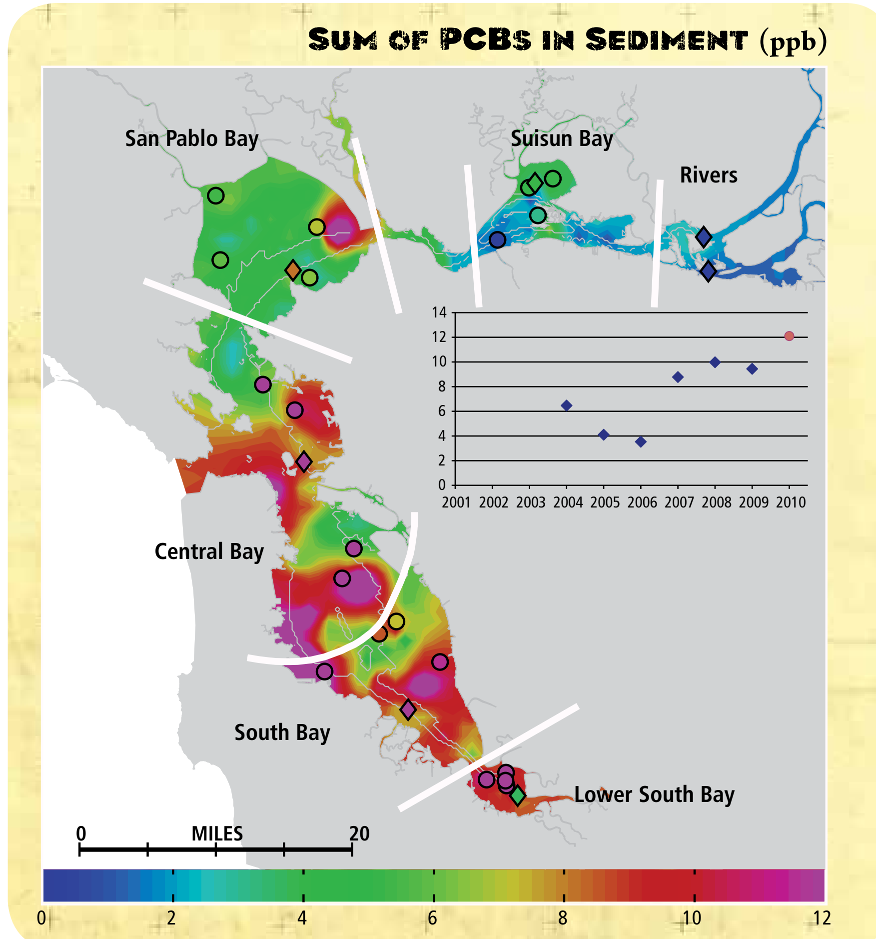


In contrast to methylmercury, long-term average total mercury concentrations in sediment during the dry season have been highest in San Pablo Bay (0.28 ppm). Also in contrast to methylmercury, Bay-wide average dry season concentrations of total mercury in sediment have shown relatively little variability over this period, ranging from 0.19 ppm in 2005 to 0.30 ppm in 2009. The lowest Bay-wide average methylmercury concentration over the eight years of dry season sampling was observed in 2009, coinciding with the highest average total mercury concentration. Circles and diamonds on the map represent results from a first year of wet-season sampling in 2010. The three highest concentrations measured in 2010, ranging from 0.39 to 0.41 ppm, occurred in areas that have had relatively low concentrations in the dry season. The average for the 2010 wet season (0.26 ppm) was similar to the long-term average for the dry season (0.25 ppm) and to annual dry season averages observed from 2002-2009. No regulatory guideline exists for total mercury in sediment.

Footnote: Contour plot based on 378 RMP data points over an eight-year period from 2002-2009. The maximum concentration was 0.94 ppm in Central Bay in 2009. Trend plot shows annual Bay-wide averages. Colored symbols on map show results for samples collected during the wet season (February) in 2010. Circles represent random sites. Diamonds represent historic fixed stations. Red circle on trend plot indicates a wet season sample; other samples were dry season. Concentrations presented on a dry weight basis.

PCBs

PCB contamination remains one of the greatest water quality concerns in the Estuary, and PCB cleanup is a primary focus of the Water Board. PCBs are a problem because they accumulate to high concentrations in some Bay fish and pose health risks to consumers of those fish (PAGE 19).

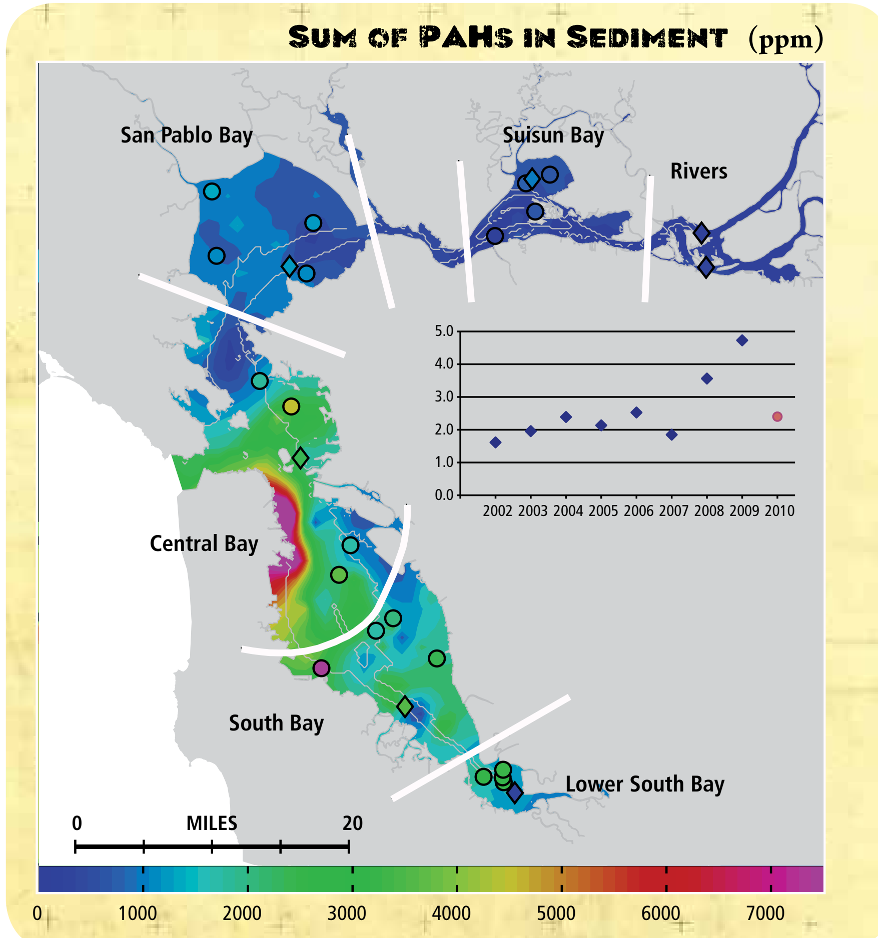


Footnote: Contour plot based on 282 RMP data points from 2004 – 2009. Data from 2002 and 2003 are not available. The maximum concentration was 30 ppb in South Bay in 2008. Trend plot shows annual Bay-wide averages. Colored symbols on map show results for samples collected during the wet season (February) in 2010. Circles represent random sites. Diamonds represent historic fixed stations. Concentrations presented on a dry weight basis.

Average PCB concentrations in Bay sediment have been highest in the southern reach of the Estuary (Central Bay, South Bay, and Lower South Bay). Circles and diamonds on the map represent results from a first year of wet-season sampling in 2010. The spatial pattern observed in the wet season of 2010 was xx consistent with the general pattern observed in dry season monitoring from 2002-2009. The Bay-wide average for the wet season sampling in 2010 was 12 ppb, higher than in any of the other years (dry season) sampled to date. Four of the 10 highest samples in the seven-year period (ranging from 19-24 ppb) were collected in 2010, all in the southern reach. Models suggest that sediment PCB concentrations must decline to about 1 ppb for concentrations in sport fish to fall below the threshold of concern for human health. Suisun Bay dipped below this value in 2006 (0.8 ppb), but averaged 2.9 ppb in 2010.

PAHs

PAHs (polycyclic aromatic hydrocarbons) are included on the 303(d) List for several Bay locations. Concentrations tend to be higher near the Bay margins, due to proximity to anthropogenic sources. In addition to historic industrial sources along the Bay margins, increasing population and motor vehicle use in the Bay Area suggest that PAH concentrations could increase over the next 20 years, due to deposition of combustion products from the air directly into the Bay and from the air to roadway runoff and into the Bay via stormwater.

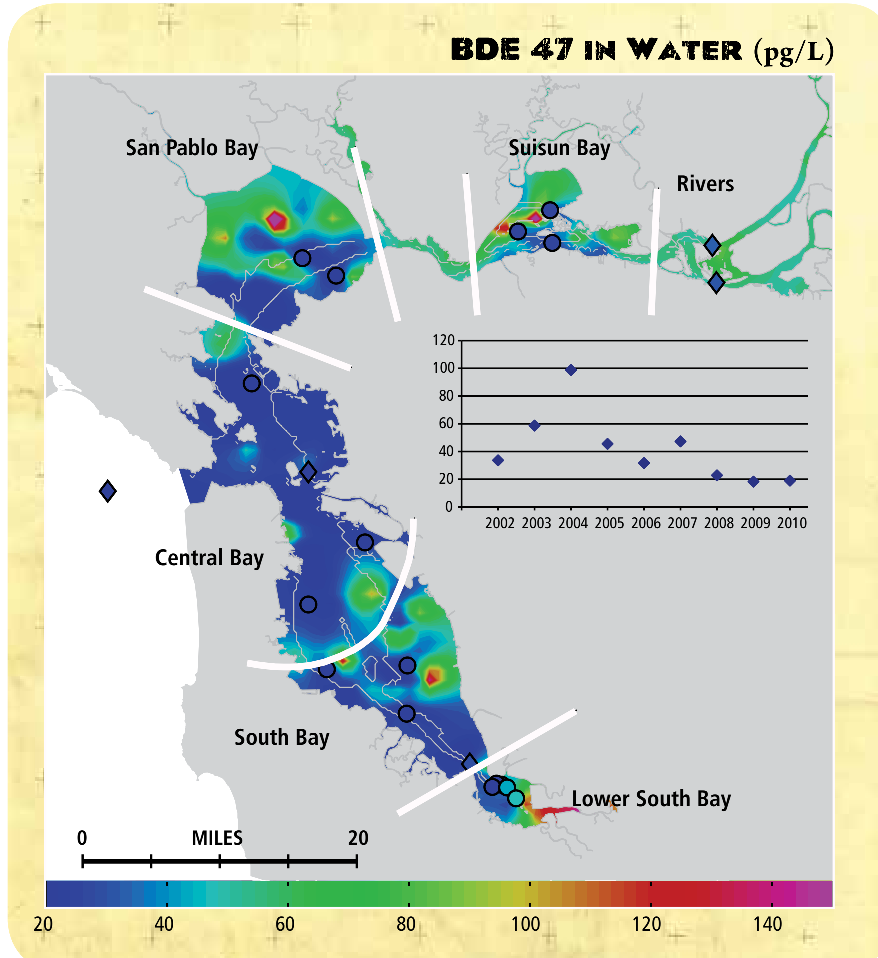


PAH concentrations in sediment have been highest along the southwestern shore-line of Central Bay. Circles and diamonds represent results from a first year of wet-season sampling in 2010. The spatial pattern observed in the wet season of 2010 was consistent with the general pattern observed in dry season monitoring from 2002-2009. The average for the 2010 wet season (2.4 ppm) was similar to the long-term average for the dry season (2.6 ppm) and to annual dry season averages observed from 2002-2007. The high annual average dry season concentrations observed in 2008 and 2009 were largely driven by a few unusually contaminated sites sampled in those years..

Footnote: Contour plot based on 377 RMP data points from 2002-2009. The maximum concentration was 43 ppm at a site on the southwestern Central Bay shoreline in 2009. Seven of the ten highest samples in the nine-year period were from Central Bay. Trend plot shows annual Bay-wide averages. Colored symbols on map show results for samples collected during the wet season (February) in 2010. Circles represent random sites. Diamonds represent historic fixed stations. Red circle on trend plot indicates a wet season sample; other samples were dry season. Concentrations presented on a dry weight basis.

PBDEs

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

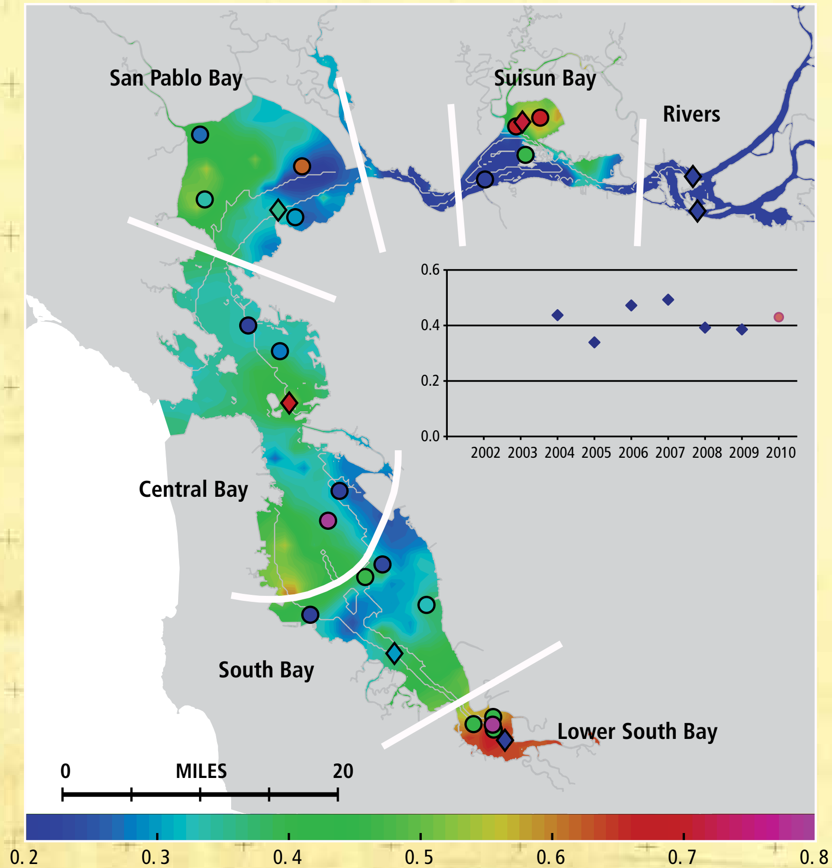


The highest long-term average concentration of BDE 47 (one of the most abundant PBDEs and an index of PBDEs as a whole) from 2002-2010 was found in Suisun Bay (67 pg/L). The maximum concentrations, two samples greater than 300 pg/L, were observed at locations in Suisun Bay and San Pablo Bay, both in 2004. The high concentrations in Suisun Bay suggest the presence of PBDE inputs into the northern Estuary. The Bay-wide average concentration for the nine-year period was 45 pg/L. The Bay-wide average for 2010 was the second lowest recorded (19 pg/L). The three lowest annual average concentrations were measured in 2008-2010.

Footnote: BDE 47 shown as an index of total PBDEs. BDE 47 is one of the most abundant PBDEs and was consistently quantified by the lab. Map plot based on 247 RMP data points from 2002-2010. The maximum concentration was 337 pg/L observed in Suisun Bay in 2004. Trend plot shows annual Bay-wide averages.

Data are for total BDE 47 in water. Colored symbols on map show results for samples collected in 2010. Circles represent random sites. Diamonds represent historic fixed stations.

BDE 47 in Sediment (ppb)

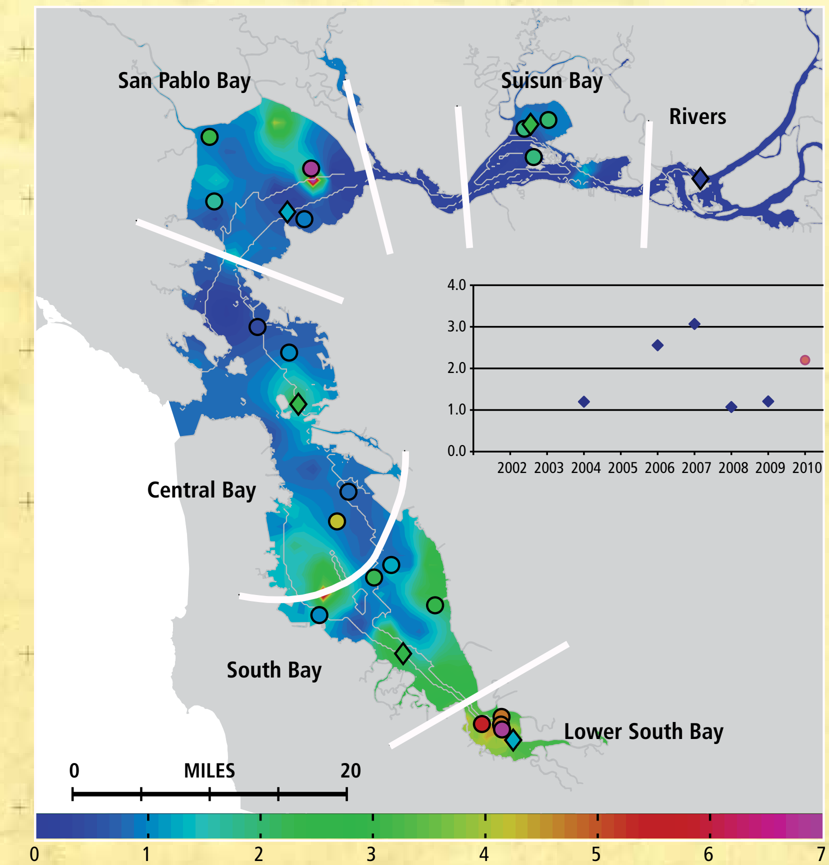


In contrast to the results obtained from water monitoring, long-term average dry season concentrations of BDE 47 in sediment have been highest in Lower South Bay (0.70 ppb). Circles and diamonds represent results from a first year of wet-season sampling in 2010. The spatial pattern observed in the wet season of 2010 was consistent with the general pattern observed in dry season monitoring from 2002-2009. Three samples with relatively high concentrations were observed in northern Suisun Bay, a region that has been consistently elevated in past sampling. The Bay-wide average for the 2010 wet season (0.43 ppb) was similar to the long-term average for the dry season (0.42 ppm) and to annual dry season averages observed in all prior years (2004-2009). The Bay-wide average has shown little fluctuation over the seven-year period, ranging from a low of 0.34 in 2005 to a high of 0.49 in 2007.

Footnote: BDE 47 is one of the most abundant PBDEs and was consistently quantified by the lab. Contour plot based on 282 RMP data points from 2004–2009. Data from 2002 are available but were inconsistent with data for the other years. The maximum concentration, by far, was 3.8 ppb in Lower South Bay in 2005. Trend plot shows annual Bay-wide averages. Colored symbols on map show results for samples collected during the wet season (February) in 2010. Circles represent random sites. Diamonds represent historic fixed stations. Concentrations presented on a dry weight basis.

BDE 209 (also known as decabromodiphenyl ether) represents the one remaining class of PBDEs that can still be used in California. Similar to BDE 47 in sediment, long-term average dry season concentrations of BDE 209 from 2004–2009 were highest in Lower South Bay (4.8 ppb). Circles and diamonds represent results from a first year of wet-season sampling in 2010. The spatial pattern observed in the wet season of 2010 was consistent with the general pattern seen in dry season monitoring from 2002-2009, with the highest concentrations (including samples at 16 ppb in Lower South Bay and 8.4 ppb in San Pablo Bay) occurring in areas previously shown to have relatively high concentrations. The average for the 2010 wet season (2.2 ppb) was similar to the long-term average for the dry season (1.8 ppb) and in the middle of the range of annual dry season averages from 2004-2009.

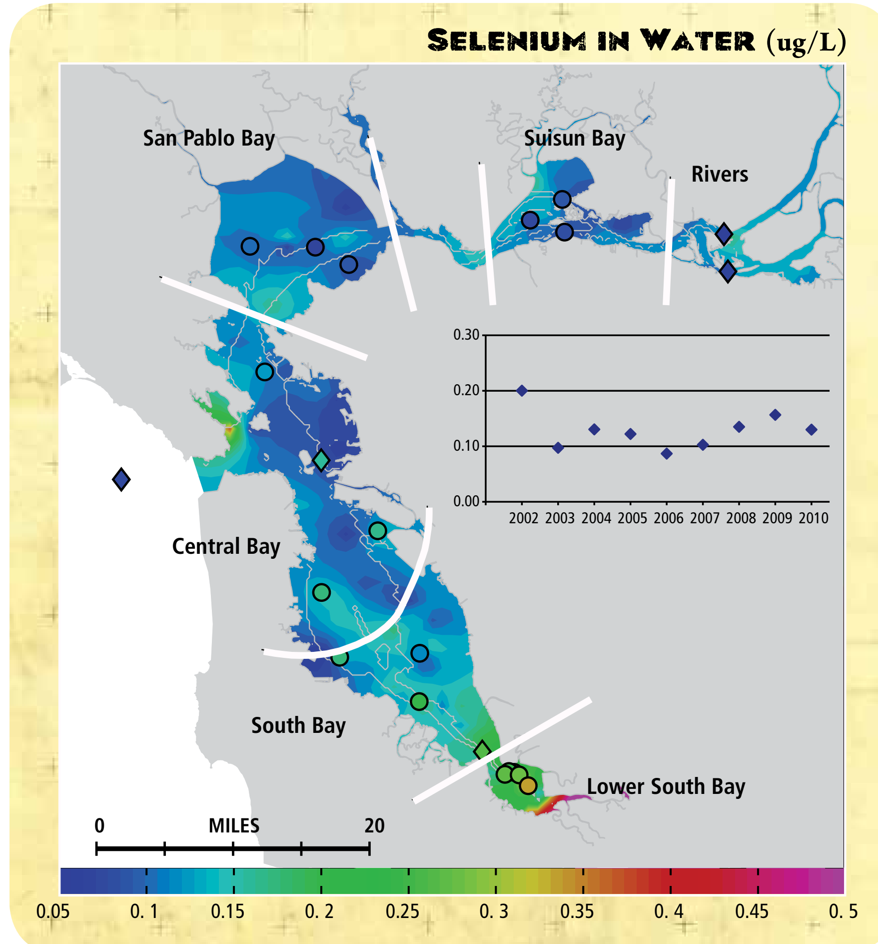
BDE 209 in Sediment (ppb)



Footnote: BDE 209 shown as an index of the "deca" PBDE mixture. Contour plot based on 282 RMP data points from 2004, 2006, 2007, 2008, and 2009. The maximum concentration by far was 52 ppb in San Pablo Bay in 2007 (the next highest concentration was 19 ppb in South Bay in 2006). Trend plot shows annual Bay-wide averages. Colored symbols on map show results for samples collected during the wet season (February) in 2010. Circles represent random sites. Diamonds represent historic fixed stations. Red circle on trend plot indicates a wet season sample; other samples were dry season. Concentrations presented on a dry weight basis.

SELENIUM

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

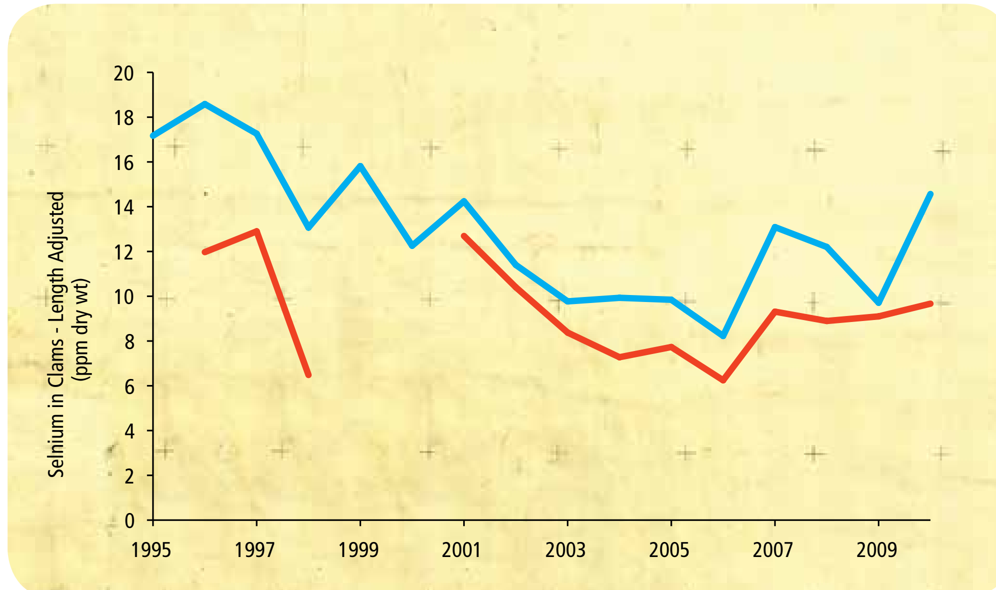


Selenium concentrations in water are well below the water quality objective established by the California Toxics Rule (CTR). However, concerns still exist for wildlife exposure as indicated by studies on early life-stages of fish. The highest concentration observed in water from 2002 to 2010 was 1.15 µg/L, much lower than the CTR objective (5 µg/L). The Lower South Bay had a higher average concentration over this period (0.25 µg/L) than the other Bay segments, which had very consistent average concentrations (all other averages were between 0.12 and 0.14 µg/L). The Bay-wide average concentration in 2010 (0.13 µg/L) was identical to the long-term Bay-wide average (0.13 µg/L).

Footnote: Map plot based on 247 RMP data points from 2002-2010. The maximum concentration was 1.15 µg/L at a historical station in the Southern Sloughs in 2002. Trend plot shows annual Bay-wide averages. Data are for total selenium. Colored symbols on map show results for samples collected in 2010. Circles represent random sites. Diamonds represent historic fixed stations.

SELENIUM IN CLAMS

Selenium concentrations in the North Bay clams continue to fluctuate seasonally and from year to year. *Corbula amurensis* is a dominant clam that accumulates selenium to an unusual 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 project. Since 1995, the U.S. Geological Survey has measured selenium concentrations in *Corbula* 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 to the Bay, including agricultural inputs to the San Joaquin River and refinery discharges, have been reduced over the last decade. After 1998, clam selenium concentrations (adjusted for differences in clam size) declined to levels 50% of pre-1998 concentrations, but have increased in recent years. Selenium burdens remain higher than levels commonly associated with toxicity and reproductive impairment in fish and other wildlife species.



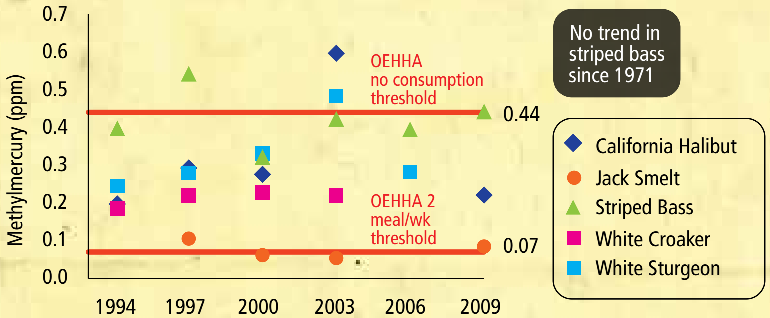
Reference: Kleckner, A.E., Stewart, A.R., Elrick, K., and Luoma, S.N., 2010, Selenium concentrations and stable isotopic compositions of carbon and nitrogen in the benthic clam Corbula amurensis from Northern San Francisco Bay, California: May 1995–February 2010: U.S. Geological Survey Open-File Report 2010-1252, 34 p.

Contact: Robin Stewart, U.S. Geological Survey, arstewar@usgs.gov

Water Quality Trends at a Glance

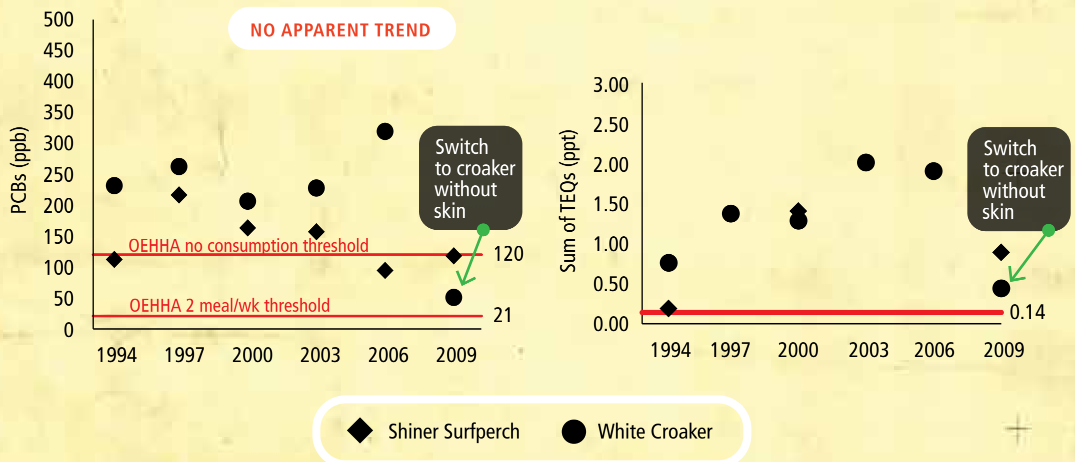
Toxics and Bacteria

1 Methylmercury in Sport Fish

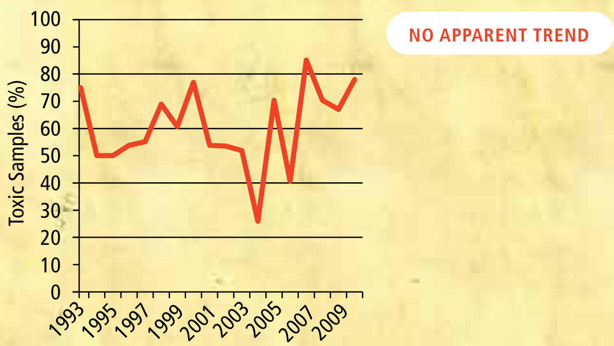


2 PCBs in Sport Fish

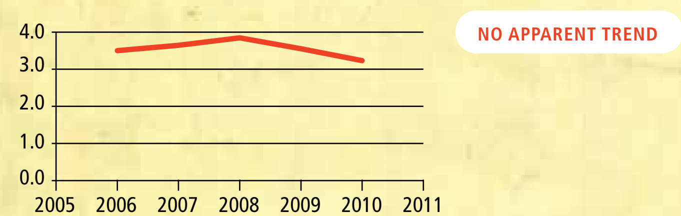
3 Dioxins in Sport Fish



4 Percent Toxic Sediment Samples



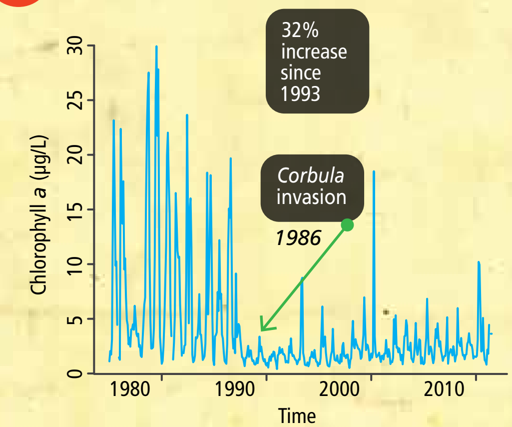
5 Beach Report Card Grades



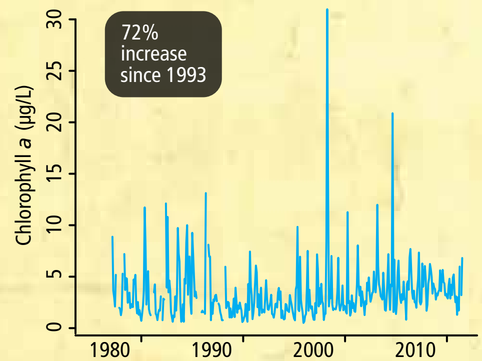
SEE PAGE 45 FOR GRAPH DETAILS

Chlorophyll and Dissolved Oxygen

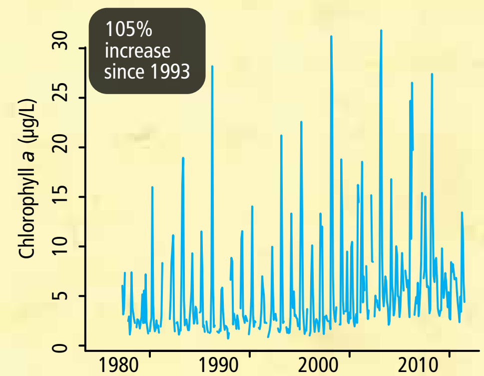
1 Chlorophyll in Suisun Bay



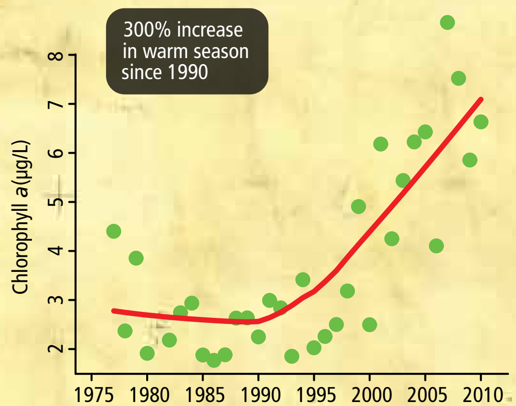
2 Chlorophyll in San Pablo Bay



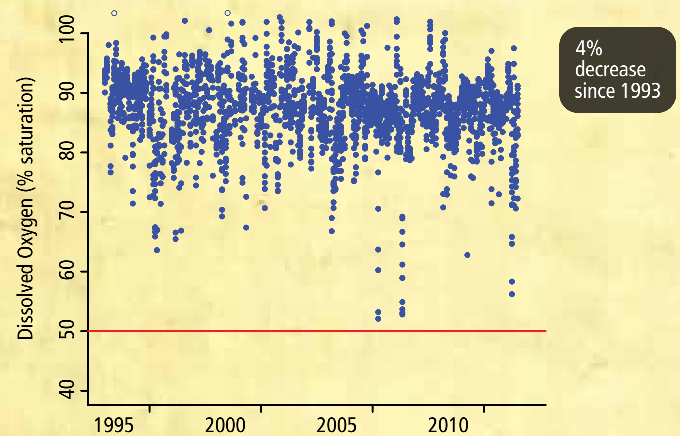
3 Chlorophyll in South Bay



4 Summer Chlorophyll in South Bay



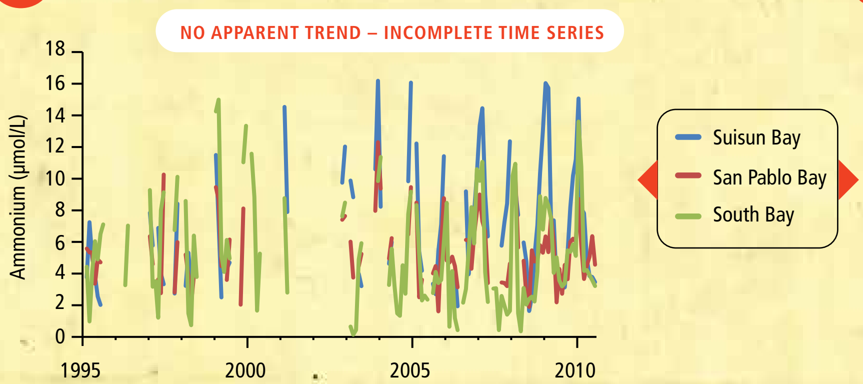
5 Bottom Dissolved Oxygen in South Bay



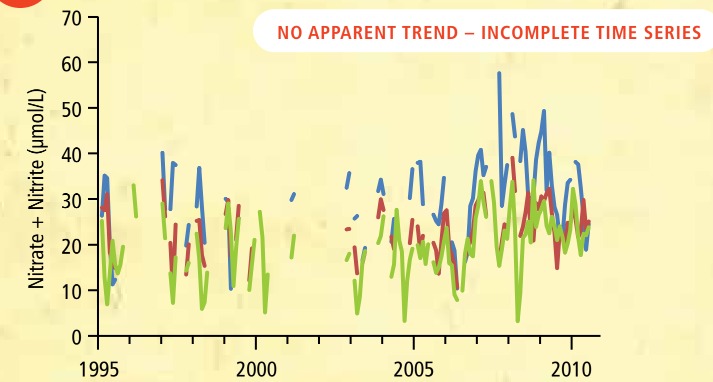
SEE PAGE 45 FOR GRAPH DETAILS

Nutrients and Sediments

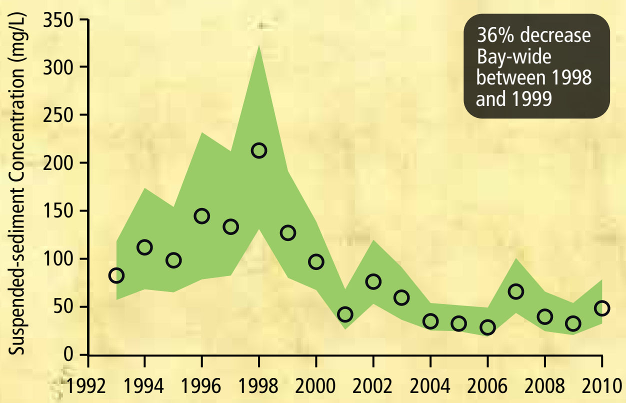
1 Ammonium



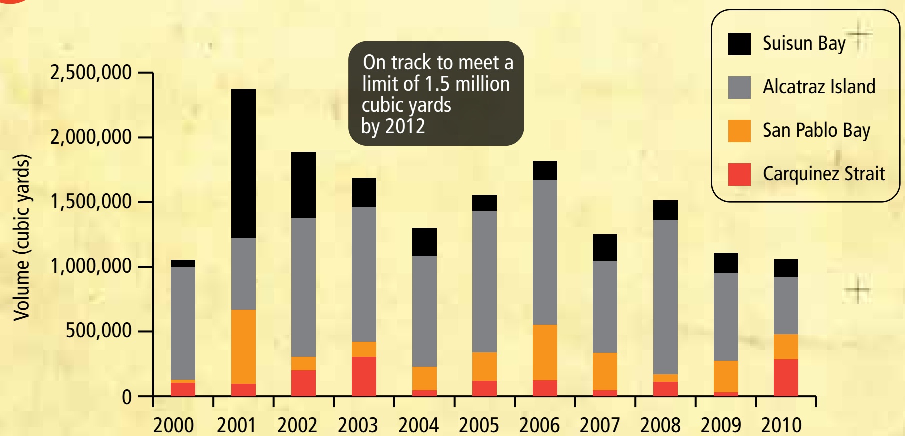
2 Nitrate and Nitrite



3 Suspended Sediment



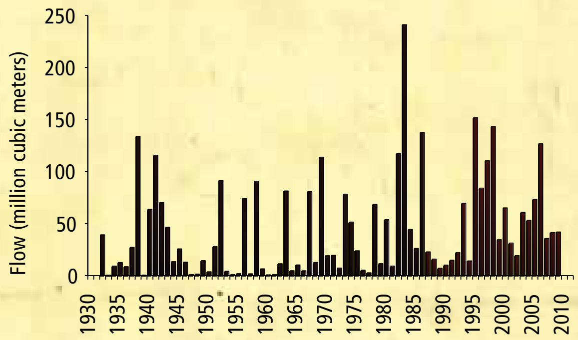
4 In-Bay Disposal of Dredged Material



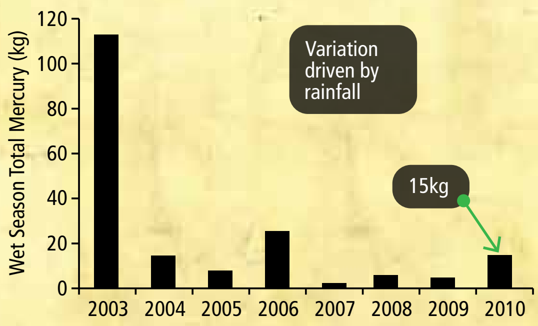
SEE PAGE 45 FOR GRAPH DETAILS

Flows and Loads

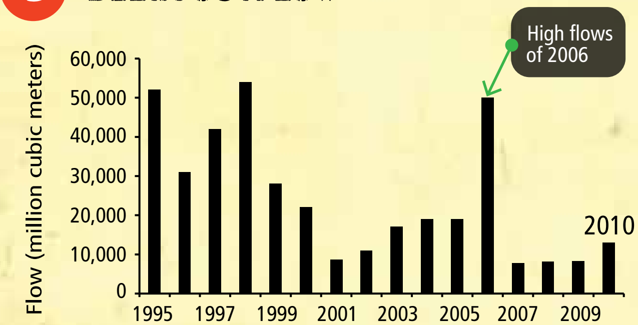
1 Guadalupe River Flow



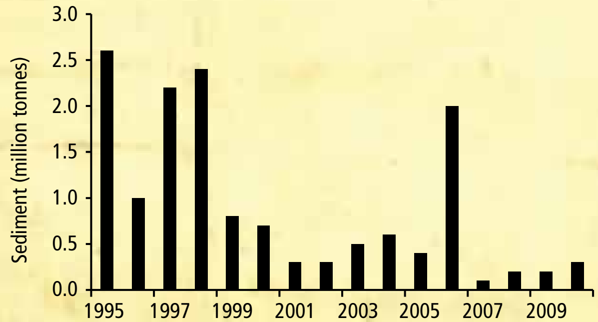
2 Guadalupe River Mercury Load



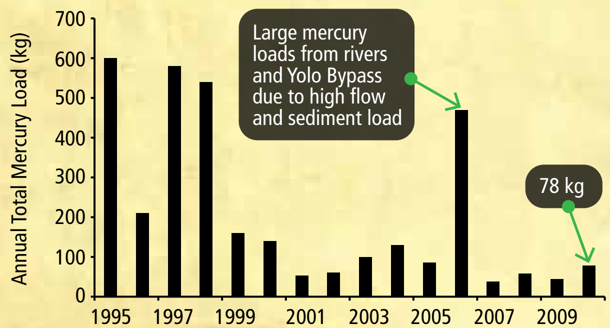
3 Delta Outflow



4 Delta Sediment Load



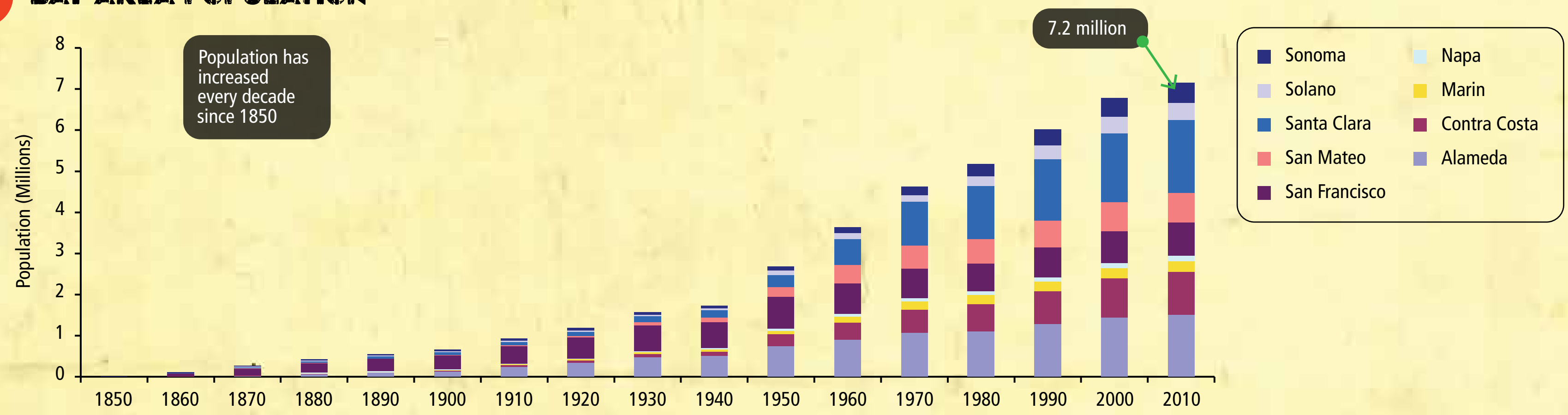
5 Delta Mercury Load



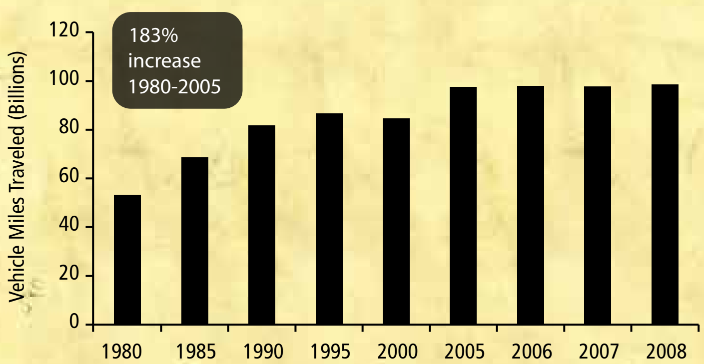
SEE PAGE 45 FOR GRAPH DETAILS

Human Presence

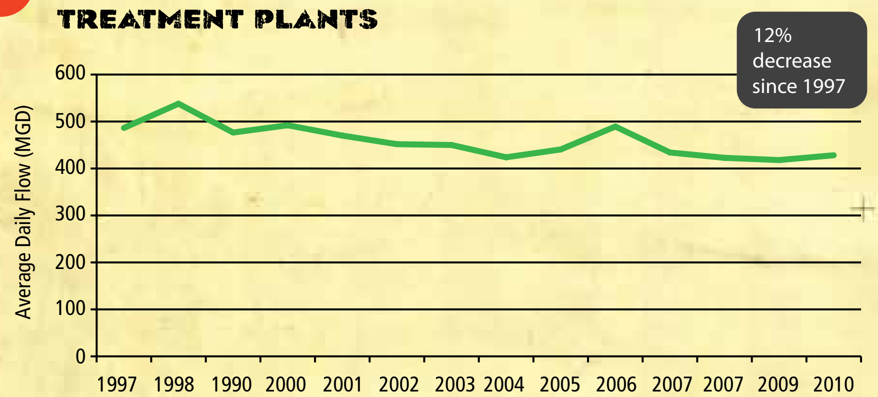
1 Bay Area Population



2 Bay Area Vehicles Miles Traveled



3 Flows from Top Ten Wastewater Treatment Plants

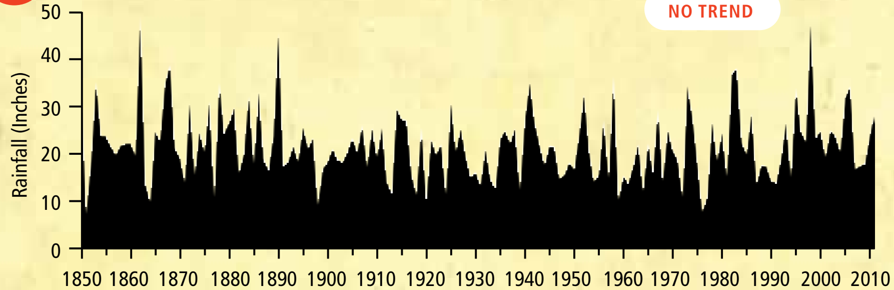


SEE PAGE 45 FOR GRAPH DETAILS

Climate and Habitat

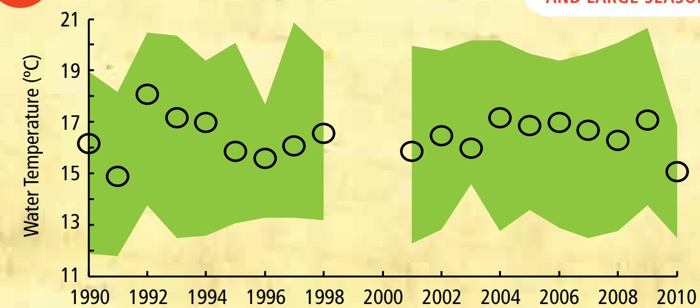
1 Rainfall in the Bay Area

NO TREND



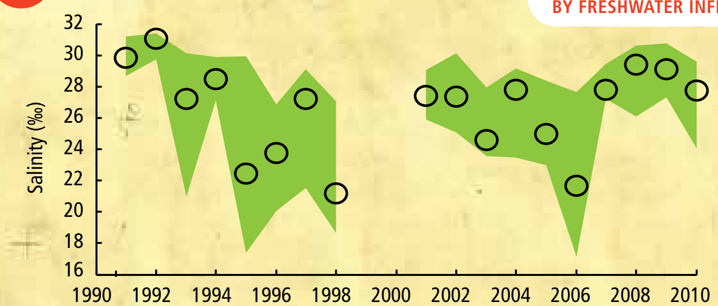
3 Water Temperature

NO TREND – SHORT TIME SERIES AND LARGE SEASONAL VARIABILITY

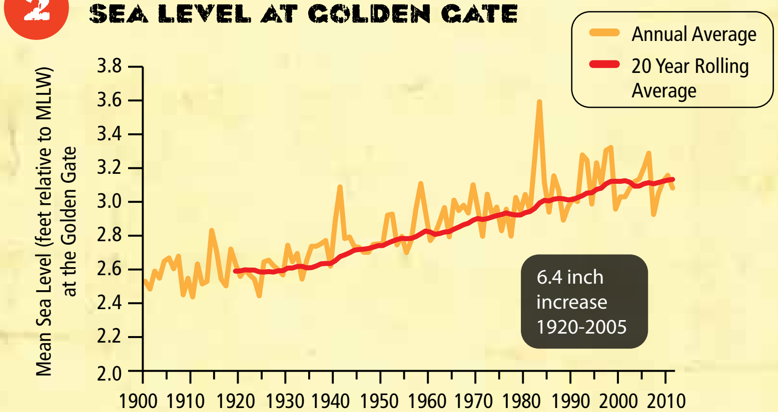


4 Salinity

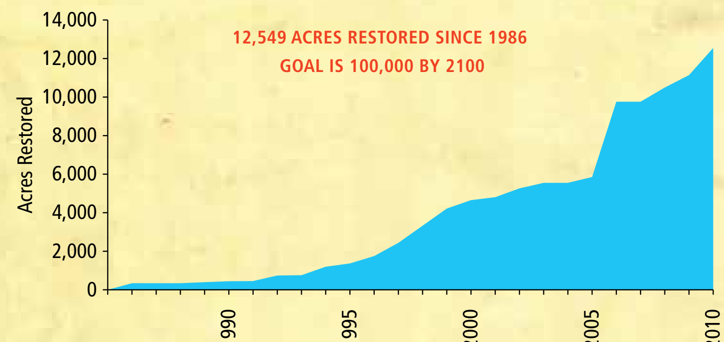
NO TREND – VARIABILITY DRIVEN BY FRESHWATER INFLOW



2 Sea Level at Golden Gate



5 Restored Wetland Opened to Tidal Action

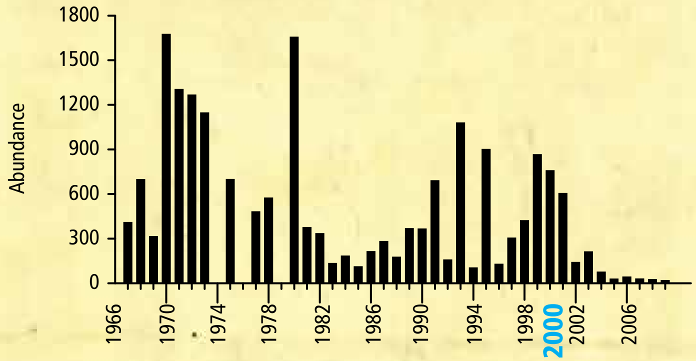


SEE PAGE 45 FOR GRAPH DETAILS

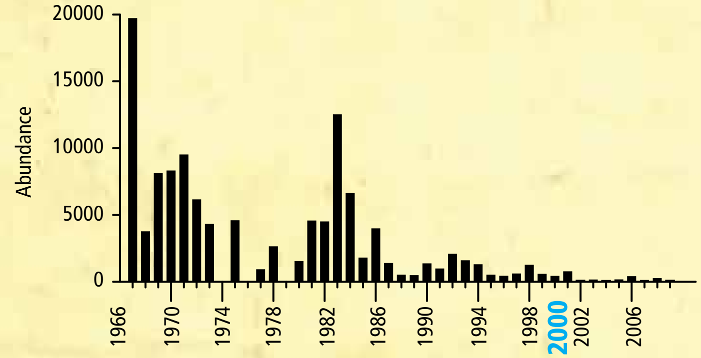
POPULATIONS

PELAGIC ORGANISM DECLINE

DELTA SMELT

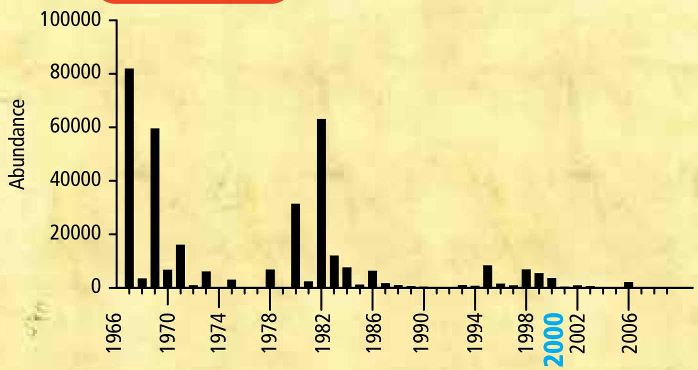


STRIPED BASS

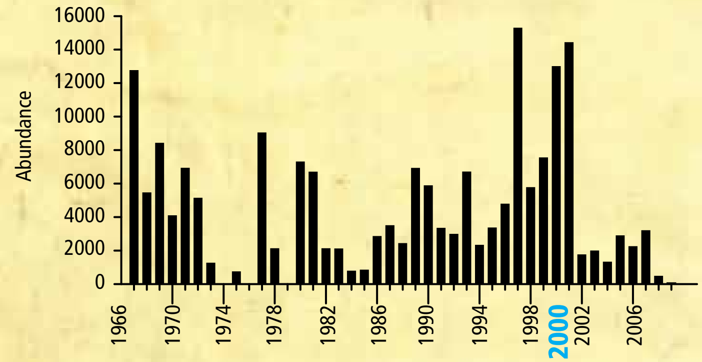


All species have been near record lows since 2002

LONGFIN SMELT



THREADFIN SHAD



SEE PAGE 45 FOR GRAPH DETAILS

Graph Details

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1) Bay-wide average methylmercury concentrations. Averages for striped bass based on concentrations for individual fish normalized to 60 cm. The no consumption advisory tissue level for mercury is 440 ppb, and the two serving advisory tissue level is 70 ppb.

2) Bay-wide average PCB concentrations. The no consumption advisory tissue level for PCBs is 120 ppb, and the two serving advisory tissue level is 21 ppb. White croaker were analyzed without skin in 2009, and with skin in previous years.

3) Bay-wide average dioxin TEQ concentrations. The San Francisco Bay Water Quality Control Board has developed a screening value for dioxin TEQs of 0.14 parts per trillion (ppt). White croaker were analyzed with skin from 1994-2006, and without skin in 2009.

4) Sediment samples are tested using amphipods and mussel larvae.

5) Average of Bay Area summer beach season (April-October) grades from Heal the Bay's annual beach report card (PAGE 23).

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Data from USGS: sfbay.wr.usgs.gov/access/wqdata. Data from prior to 1969 from USGS. Data collected monthly at fixed stations along the spine of the Bay. Data for stations D10, D8, D7, D6, and D41 from IEP: http://www.water.ca.gov/bdma/meta/Discrete/data.cfm.

1) Chlorophyll a, averaged over top 3 meters and all stations, in Suisun Bay (stations D10, D8, D7, D6, s4, s5, s6, and s7).

2) Chlorophyll a, averaged over top 3 meters and all stations, in San Pablo Bay (stations D41, s11, s12, s13, s14, and s15).

3) Chlorophyll a, averaged over top 3 meters and all stations, in South Bay (stations s21, s22, s23, s24, s25, s26, s27, s28, s29, s30, s31, s32, and s33).

4) Chlorophyll a in South Bay, averaged over top 3 meters, all stations, and June-October season for each year. Trend line is a smoothed fit.

5) Minimum dissolved oxygen percent saturation from each South Bay station, averaged over all stations. Minimum dissolved oxygen values typically occur at or near the bottom. Horizontal line indicates 50% saturation.

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1 AND 2) Data from USGS: sfbay.wr.usgs.gov/access/wqdata

3) Suspended-sediment concentration, Dumbarton Bridge, 20 feet below mean lower low water. Based on 15-minute data collected by the U.S. Geological Survey (Buchanan and Morgan 2010). Water years 2008-2010 are provisional data.

4) Data from the U.S. Army Corps of Engineers.

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1) Data from the U.S. Geological Survey. Data for all of these graphs are for water years (Oct 1 to Sep 30).

2) Total loads for each water year. Additional matching funds for this study provided by the CEP, USACE, SCVWD, and SCVURPPP.

3) Daily average Delta outflow from DAYFLOW. DAYFLOW data are available from the California Department of Water Resources (www.water.ca.gov/dayflow/).

4)Total sediment loads for each water year. Loads based on continuous measurements taken at Mallard Island by USGS (http://sfbay.wr.usgs.gov/sediment/cont_monitoring/).

5) Total loads for each water year. Loads from 2002–2006 are based on field data. Loads for earlier and later years are estimated from relationships observed between suspended sediment and mercury in 2002–2006.

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1) Data from the Association of Bay Area Governments and U.S. Census Bureau. http://census.abag.ca.gov/counties/counties.htm

2) Data from Caltrans: http://traffic-counts.dot.ca.gov/

3) Data provided by 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.

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1) Annual rainfall measured at San Jose shown as index for Bay Area rainfall. These 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

2) Data from National Oceanic and Atmospheric Administration: http://tidesandcurrents.noaa.gov/data_menu.shtml?bdate=19000520&edate=20110521&wl_sensor_hist=W5&relative=&datum=6&unit=1&shift=g&stn=9414290+San+Francisco%2C+CA&type=Historic+Tide+Data&format=View+Data

3) Water year median water temperature and interquartile range, San Mateo Bridge, 4 feet below mean lower low water. From 15-minute data collected by the U.S. Geological Survey (Buchanan 2009). 1999-2000 not shown because data were temporarily not collected during bridge construction. Some variation is caused by different periods of missing data.

4) Same information as #3. Salinity reflects freshwater inflow to the Bay with lower values for higher inflows. Ocean water has a salinity of 35.

5) Data from the California Wetlands Portal (www.californiawetlands.net/tracker/).

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All data from: Baxter, R. et al. 2010. Interagency Ecological Program 2010 Pelagic Organism Decline Work Plan and Synthesis of Results. http://www.water.ca.gov/iep/docs/FinalPOD2010Workplan12610.pdf

FEATURE ART

ICLES

CHRISTINE WERME, Independent Consultant
KAREN TABERSKI, San Francisco Bay Regional Water Quality Control Board
LESTER MCKEE, San Francisco Estuary Institute
DICK DUGDALE, San Francisco State University
TOM HALL, EOA, Inc.
MIKE CONNOR, East Bay Dischargers Authority

A GROWING CONCERN: POTENTIAL EFFECTS OF NUTRIENTS ON BAY PHYTOPLANKTON

HIGHLIGHTS

Phytoplankton, the microscopic plants at the base of the food chain, are the focus of a new San Francisco Bay Nutrients Strategy

Nutrient loading to the Bay is high, but phytoplankton biomass has been low compared to other urban estuaries, in part a result of turbid waters that limit light penetration and high grazing pressures, particularly by invasive clams

Since the late 1990s, phytoplankton biomass has increased throughout the Bay, a response to increased water clarity and favorable wider regional oceanographic conditions

In the Sacramento River and northern portions of the Bay, there is evidence suggesting that high levels of one form of nitrogen, ammonium, can inhibit rather than stimulate phytoplankton growth

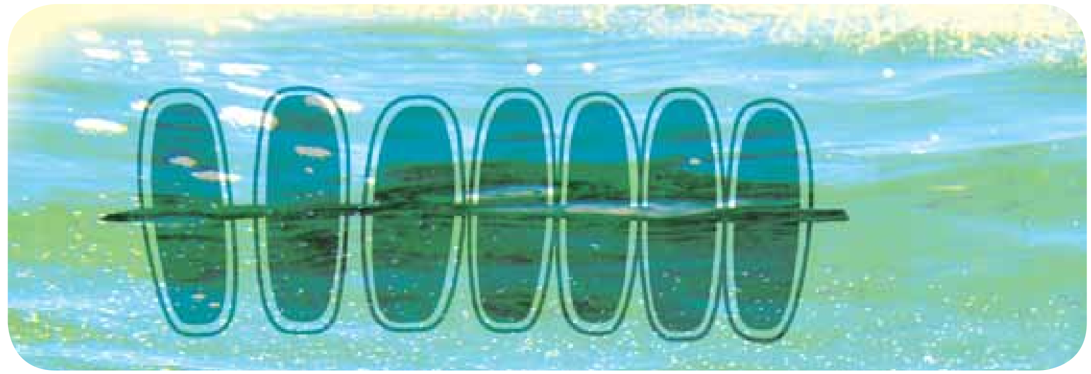
The complexity of the ecosystem and uncertainty about future conditions underlie the growing importance of nutrient and phytoplankton monitoring, research, and modeling

SIGNS OF TROUBLE AT THE BASE OF THE FOOD CHAIN?

At the very base of the food chain in San Francisco Bay and the Delta are the phytoplankton (also referred to as algae), microscopic plants that drift in the water column and provide food for zooplankton, clams, and filter-feeding fishes. In the past, the phytoplankton have not been a major focus of the Regional Monitoring Program for Water Quality in the San Francisco Estuary (RMP). That is changing with the development of a new San Francisco Bay Nutrient Strategy, developed by the RMP in collaboration with other scientists and environmental managers. In the Bay as a whole, phytoplankton biomass is increasing, prompting the question of whether excess phytoplankton growth, which has not been a problem for San Francisco Bay, may become one in the future. Upstream from the Carquinez Straits, where the system is dominated more by riverine than by oceanic conditions, there is another concern, that one form of nitrogen – ammonium – from wastewater treatment plant effluent has reached high enough levels to inhibit growth of a group of desirable phytoplankton species, the diatoms.

ESSENTIAL INDICATORS OF WATER QUALITY

The abundance and species composition of phytoplankton communities are important measures of environmental quality in all freshwater, estuarine, and marine ecosystems. Almost every estuary in populated regions of the United States and around the world shows signs of eutrophication – overstimulation of algal growth by an excess of nutrients – which can lead to low levels of dissolved oxygen, excess turbidity, and nuisance or harmful algal blooms (**SIDEBAR, PAGE 50**). In many U.S. estuaries, the problem of excess nutrients, especially nitrogen from agriculture, urban runoff, and wastewater treatment plants, is a major focus of environmental monitoring and management programs. Phosphorus inputs are also a concern, particularly in areas with low salinity.



↑ *Thalassiosira rotula.* Illustration by Susan Putney.

In typical, healthy coastal ecosystems, phytoplankton populations follow seasonal patterns, blooming when temperature and light levels rise during the spring, then dropping off a little before rising again in the fall, when cooling waters promote mixing, returning nutrients from deeper waters to the surface. However, in San Francisco Bay the water column is usually well-mixed during every season. Seasonal changes in nutrient concentrations are largely determined by changes in inputs. Seasonal spring blooms occur fairly regularly in South Bay, Central Bay, and San Pablo Bays, but less frequently in Suisun Bay.

Nitrogen is the nutrient that usually limits phytoplankton growth in marine and estuarine waters. Nitrogen exists as an abundant gas in the atmosphere. It is also present in terrestrial and aquatic systems, in organic molecules such as proteins and urea, and in inorganic forms, including ammonium, nitrate, and nitrite. Ammonium and nitrate are the forms that usually control phytoplankton growth. Nitrogen enters estuaries from riverine, atmospheric, and groundwater sources and pathways. Dense human populations can greatly increase nitrogen inputs through sewage discharges and runoff of fertilizers applied to agricultural fields, lawns, and other areas.

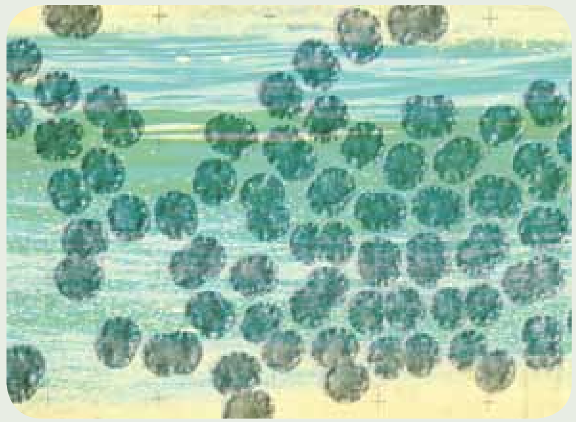
Phytoplankton studies generally include measurements of biomass and sometimes include studies of the species composition of the phytoplankton community. Biomass is measured as chlorophyll, which is the easily measured plant pigment that absorbs light, capturing energy in photosynthesis. Species composition studies can detect changes in the community, such as shifts from larger diatoms to smaller flagellates and blue-green algae (cyanobacteria) or increased incidence of toxin-producing or other nuisance species. Changes in the composition of the phytoplankton community can trigger changes in the community structure of their predator communities, which can influence the rest of the food chain.

SIDEBAR

HARMFUL ALGAL BLOOMS

Take a walk along the Bay's fishing piers and you'll see the posted signs that warn against harvesting mussels during May through October. Similar signs occur along the entire California coastline. An annual preventative quarantine for sport-harvested mussels protects the public from consuming shellfish that have accumulated toxins generated during what are called harmful algal blooms. The California Department of Public Health monitors potentially toxic algae through its volunteer Marine Biotoxin Program and prepares regular reports, available at www.cdph.ca.gov/healthinfo/environhealth/water/Pages/Shellfish.aspx. Compared to some other parts of the world, San Francisco Bay is relatively free from harmful algal blooms, with only six blooms reported since 1995 But some of the toxins produced by a number of local algal species can be deadly.

The historic shellmounds of the San Francisco Bay Area provide evidence of thousands of years of human shellfish consumption. The first documented cases of toxic shellfish poisoning were reported in 1927, and it took ten years to identify the cause (Sommer and Meyer 1937). It was a dinoflagellate, *Alexandrium catanella*. The toxin produced by many *Alexandrium* species, when sufficiently concentrated by shellfish, causes a condition known as paralytic shellfish poisoning. Symptoms can include numbness, lack of muscle control, respiratory failure, and death for marine mammals, fish, and humans. There is no antidote or cure for paralytic shellfish poisoning. *Alexandrium* blooms with paralytic shellfish poisoning occur along the California coast but are rare within the Bay.



↑ *Microcystis aeruginosa.* Illustration by Linda Wanczyk.

Were algal toxins the inspiration for Hitchcock's The Birds? In 1961, hundreds of Sooty Shearwaters went berserk, crashing into roofs and windows near Santa Cruz, and shortly thereafter, Hitchcock began to film Daphne Du Maurier's story of a similar incident, choosing Bodega Bay as his location. The real-life events may have been the result of a toxin produced by another phytoplankton group, diatoms in the genus *Pseudo-nitzchia*. At high densities *Pseudo-nitzchia* species produce sufficient concentrations of the toxin domoic acid to cause a condition known as amnesic shellfish poisoning. Symptoms include gastrointestinal and neurological conditions, including dementia. In 1990, domoic acid poisoning was found in central California sea lions (Scholin et al. 2000). One toxin-producing species, *Pseudo-nitzchia australis*, was blamed for the 1991 deaths of pelicans, cormorants, and sea lions in Monterey Bay. Scientists from The Marine Mammal Center have found that low doses of domoic acid can cause epilepsy in sea lions (Goldstein et al. 2007) and are studying other possible long-term effects.

A blue-green alga or cyanobacterium, *Microcystis aeruginosa*, has recently been implicated in sea otter deaths in Monterey Bay (Fimrite, 2010). *Microcystis* has also been blamed for skin rashes among windsurfers. *Microcystis* blooms have occurred in the Delta and the North Bay every year since 1999 (Lehman et al. 2005, 2008), and they are regarded as a potential threat to humans and wildlife.

Other possibly harmful species known to occur within the Bay include the raphidophyte *Heterosigma akashiwo* and the dinoflagellate *Akashiwo sanguine*. In recent years, *Heterosigma akashiwo* blooms have been detected outside the Golden Gate, in Richardson Bay, and near the Berkeley Pier. The species has been implicated in fish kills in other regions. *Akashiwo sanguine* does not produce a toxin but can clog shellfish gills and lead to fish kills when the bloom ends and decomposing algae deplete oxygen in the water column. *Akashiwa sanguine* also produces a foamy, surfactant-like protein that can coat bird feathers and lead to hypothermia. As San Francisco Bay enters a regime with larger and more frequent phytoplankton blooms, harmful algae may become more frequent or have greater consequences.

Fimrite, P. 2010. Monterey sea otters killed by toxic algae. San Francisco Chronicle September 11, 2010 Page C-1.

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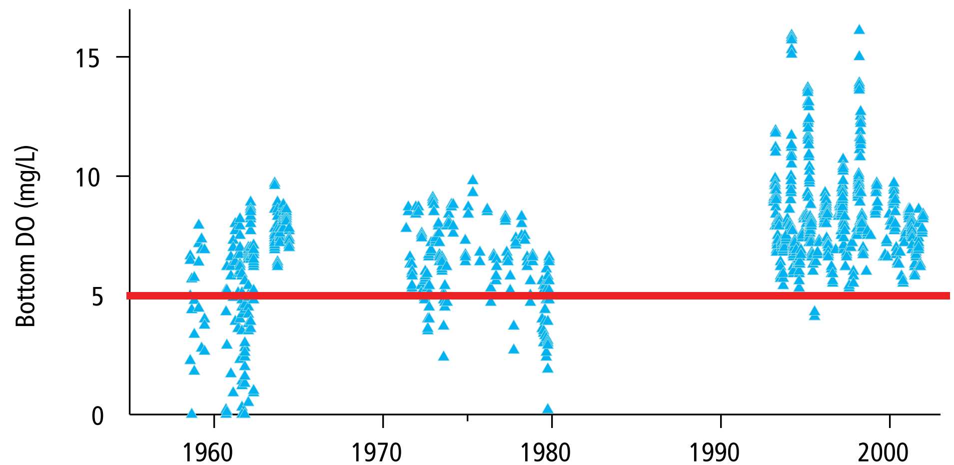
THE HISTORY OF LOW OXYGEN IN SAN FRANCISCO BAY

In the 1950s and 1960s, before upgrades to wastewater treatment facilities, San Francisco Bay experienced oxygen depletion and fish kills, particularly in the South Bay (**FIGURE 1**). In other estuaries, such conditions are often due to decomposing phytoplankton following algal blooms. In the Bay, it was the large inputs of oxygen-depleting organic waste that led to foul conditions.

The passage of the Clean Water Act in 1972 required the conversion from primary to secondary treatment of sewage, which reduced the loads of organic effluents discharged into rivers and the Bay. Primary treatment is a physical process that removes solids through settling, followed by disinfection. Secondary treatment adds bacterial oxidation of remaining particulate and dissolved organic matter and sedimentation, which greatly decreases the amount of oxygen-depleting organic matter. In the late 1970s, municipal dischargers with permits to discharge to shallow waters implemented additional facilities to further reduce oxygen-depleting organic matter. Some of these advanced secondary treatment facilities included filtration and nitrification, a process that changes ammonium to nitrate, changing the balance of these two nutrients and reducing the oxygen demand of the effluent.

FIGURE 1

Implementation of improved wastewater treatment eliminated periods of low oxygen and fish kills in the South Bay. Conversion from primary to secondary and advanced secondary treatment removed oxygen-depleting organic matter from wastewater effluents. J. Cloern, unpublished data.



Footnote: Red line shows 5 mg/L water quality objective.

A FORTUITOUSLY UNUSUAL ESTUARY

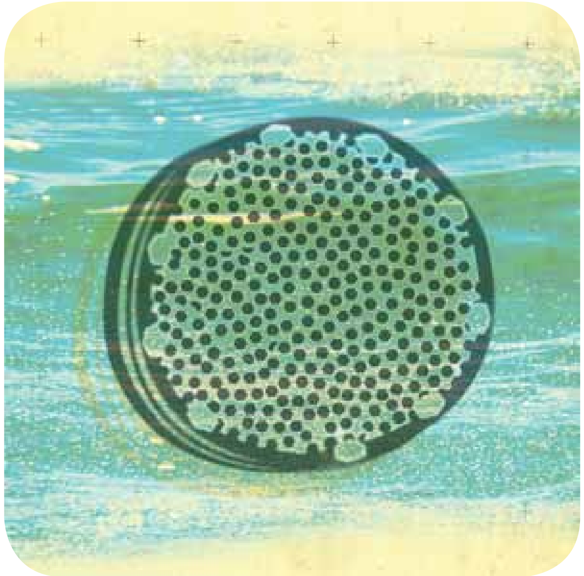
The U.S. Geological Survey (USGS) has studied water quality parameters in the Bay since 1968 and phytoplankton biomass, measured as chlorophyll, since 1977. The thousands of measurements they have made provide valuable insights. For example, the USGS has made more than 8500 measurements of ammonium and more than 9000 measurements of nitrate in Bay waters since 1968. In recent years, these studies have found that nutrient concentrations in San Francisco Bay remain high, but eutrophication has not been a major concern. Nutrients and phytoplankton growth have not been considered an imminent threat to Bay water quality.

Analysis of recent USGS data show a slight decreasing gradient in ammonium and nitrate concentrations from the fresher waters of Suisun Bay in the north to the more saline waters in the Central Bay (reviewed in McKee et al. 2011). The Lower South Bay has the highest levels of nitrate, while high ammonium levels are found in all geographic segments of the Bay. Interestingly, the average concentrations of ammonium, nitrate, and nitrite in many Bay water samples from 1995–2010 (**FIGURE 2**) are in same ranges as results from samples taken throughout the Bay during 1958–1964 and included in San Francisco Bay's first comprehensive Basin Plan (SFBRWCB 1975). The most notable change is a large decrease in average ammonium concentrations in Lower South Bay, a result of advanced secondary wastewater treatment. During 1958–1964, ammonium concentrations were much higher in the Lower South Bay than in other segments. Now ammonium concentrations are more similar throughout all segments of the Bay, although a clear gradient exists from Suisun Bay to Central Bay.

Comprehensive studies of nutrient loads to the Bay have not been completed. Available information suggests that annual nutrient loads to the Bay may be as high or higher than loads to other large U.S. estuaries, but phytoplankton biomass is low (**FIGURE 3**). Small, lagoon-type estuaries, such as Barnegat Bay in New Jersey, the Coastal Bays of Maryland and Virginia, Florida Bay at the southern end of Florida, and Pensacola Bay on the Gulf Coast, receive relatively low loads of nitrogen. Estuaries with large river inputs, such as Delaware Bay and Chesapeake Bay in the mid-Atlantic states, and Narragansett Bay in New England, receive relatively higher loads. San Francisco Bay, particularly the North Bay, receives large river inputs, and its total nitrogen loads are large.

One reason for historically low phytoplankton productivity in San Francisco Bay is the turbid water (Cloern 1982). Historically, large sediment loads from the Sacramento and San Joaquin rivers in the north (McKee et al. 2006) and the local watersheds in the south (Lewicki and McKee 2009), the shallow depth of the Bay, and continual mixing by waves and tides have kept Bay waters turbid, limiting light penetration into the water column and consequently limiting photosynthesis. But light limitation is not the only answer – both Delaware and Chesapeake bays are turbid, but have high chlorophyll levels. Narragansett Bay is relatively clear, with transparency that is two and a half times greater than San Francisco Bay, but chlorophyll levels are relatively low. Nutrient levels trigger eutrophic conditions despite low light levels in some estuaries, but not in San Francisco Bay.

Another reason for low phytoplankton biomass is grazing. Grazing pressure by rapid filtering rates in clams and other animals has long been known to reduce populations of phytoplankton and also zooplankton, the small animals that inhabit the water column. San Francisco Bay had a dramatic illustration of this process in the late 1980s and early 1990s. In 1986, a few specimens of a never-before-seen Asian clam, *Corbula amurensis*, were discovered in Suisun Bay. It quickly became the most common bottom animal in the North Bay, and it also invaded Central and South bays (Cohen 2005). Phytoplankton production in Suisun Bay had already been low before the invasion, but it plummeted afterwards, with the disappearance of any summer bloom (Cloern and Dugdale 2010). Chlorophyll concentrations remained low in Suisun Bay in the wake of the invasion (**FIGURE 4**). Narragansett Bay in New England is also subject to heavy grazing pressure, but in that estuary, it is largely native clams and mussels that keep phytoplankton biomass low.



↑ *Thalassiosira punctigera.* Illustration by Susan Putney.

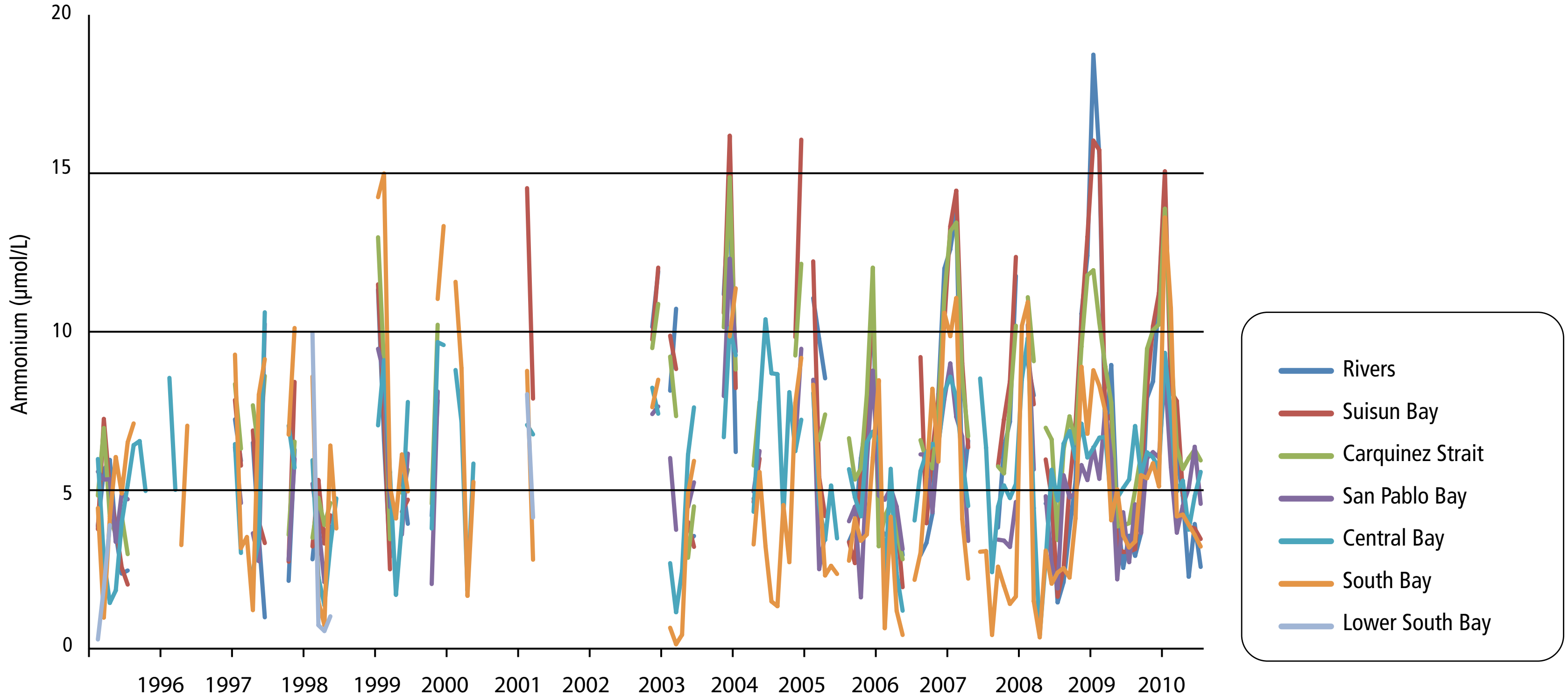


FIGURE 2

Ammonium in water samples from geographic segments of San Francisco Bay, 1995–2010. There is considerable overlap in concentrations between the segments. Concentrations decrease slightly along a gradient from Suisun Bay to Central Bay. Variable concentrations of ammonium can be detected in all segments. (USGS data, http://sfbay.wr.usgs.gov/access/wqdata)

FIGURE 3

Nitrogen loads to San Francisco Bay are high in comparison to other U.S. estuaries, but average Bay phytoplankton biomass (chlorophyll) during blooms is low. (Data from Glibert et al. 2010)

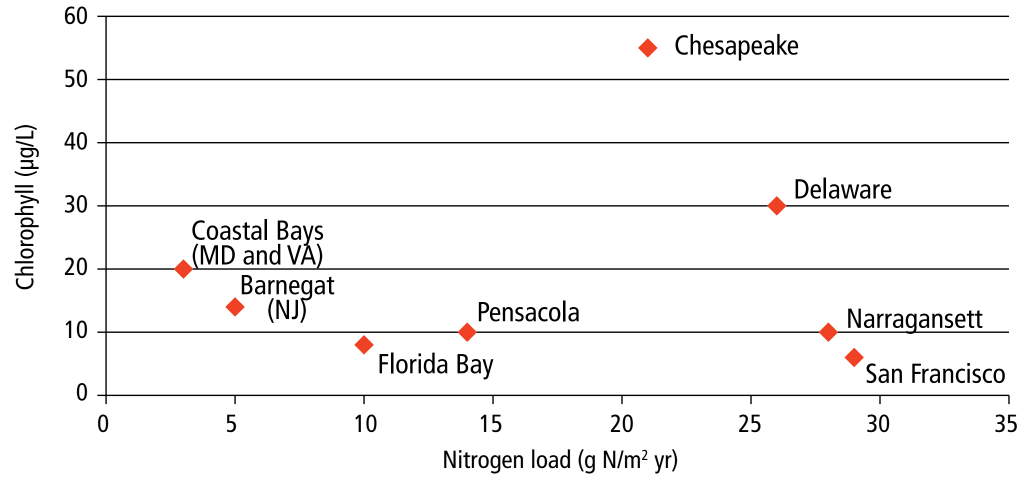
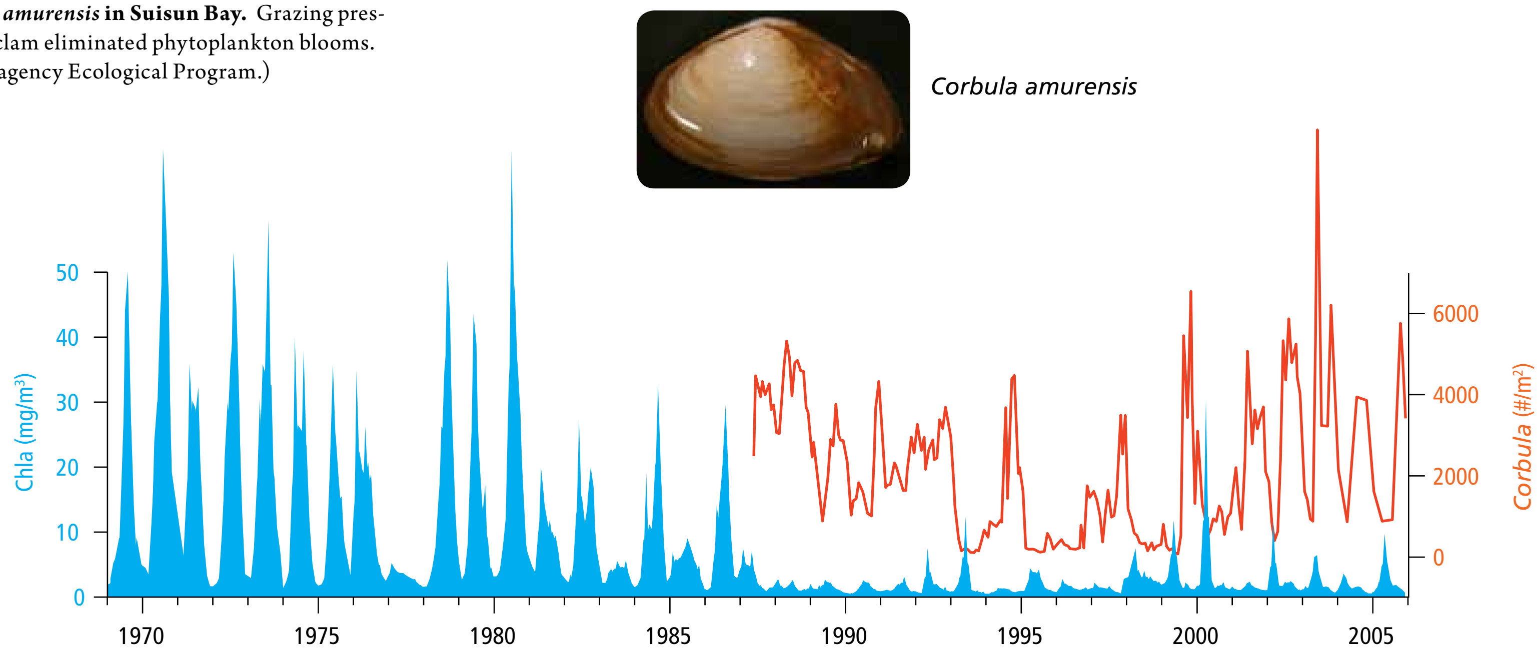


FIGURE 4

Chlorophyll concentrations and abundance of the invasive Asian clam *Corbula amurensis* in Suisun Bay. Grazing pressure by the invasive clam eliminated phytoplankton blooms. (Data from the Interagency Ecological Program.)



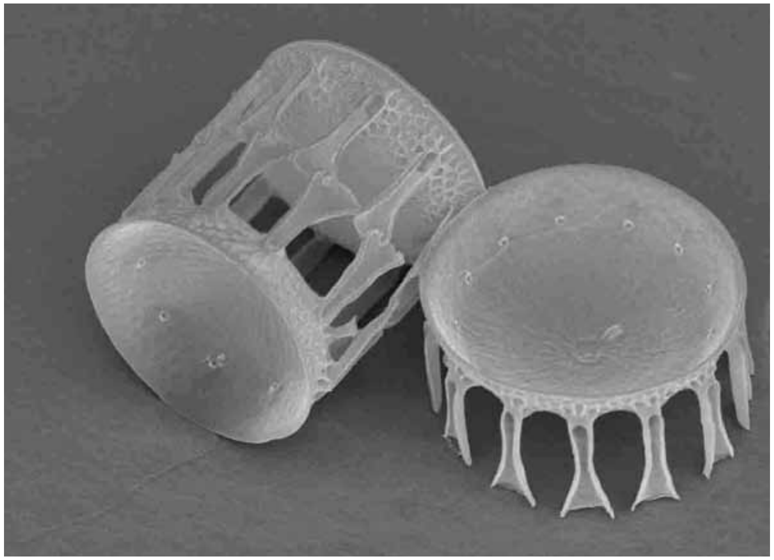
CONCERNS FOR INCREASING PHYTOPLANKTON BIOMASS

Recent data are showing some significant changes to conditions in San Francisco Bay, especially since the late 1990s, and particularly in San Pablo Bay, Central Bay, and South Bay. These changes include larger spring blooms, increased incidence of fall blooms, and increases in the annual biomass minimum (**FIGURE 5**). Although most pronounced in the South Bay, increases have been observed in every region of the Bay (McKee et al. 2011). Evidence is building that the historic resilience of the Bay to potentially harmful effects of eutrophication may be waning.

The 2006 Pulse of the Estuary reported on the increased phytoplankton biomass, presenting several possible hypotheses to explain the trend, including increased transparency, decreased metal toxicity, large-scale oceanographic processes, decreased predator grazing, and changes in the invasive species mix in the Bay (Cloern et al. 2006).

Increased transparency is one logical explanation. The 2009 Pulse of the Estuary focused on a major shift in water quality that occurred in 1999 (Jassby et al. 2002, Schoellhamer 2009). In just one year, suspended sediment concentrations decreased by about 40%, most likely a result of depleting the pool of sediments sent down waterways during the Gold Rush. That increase in water clarity is expected to continue and may serve to fuel increased phytoplankton production.

Continued improvements to municipal wastewater treatment and better controls on industrial discharges may also have contributed to increases in phytoplankton biomass. For example, annual loads of cadmium, copper, and other toxic metals have declined greatly since the 1980s. These metals may affect phytoplankton growth and production.



↑ *Skeletonema costatum.* Photograph by Mariella Saggiomo.

Large-scale processes are also an important driving force. Oceanographic conditions can vary on long time scales, and conditions during 1992–2003 were more favorable to region-wide growth of phytoplankton, particularly diatoms, than conditions during 1975–1986. A change in the California Current System, which extends from Oregon to Baja California, brought stronger upwelling to the region, a situation in which nutrient-rich bottom waters are brought to the surface, promoting increased productivity (Cloern et al. 2007, Cloern et al. 2010). Upwelled seawater entering the Bay at the Golden Gate, contains high levels of nitrate, phosphate, and silicate. Diatoms are characterized by cell walls containing silicate. In those areas of the Bay where conditions are favorable, intrusions of oceanic water are expected to enhance phytoplankton production. In 2011, scientists are learning that such intrusions may have other environmental effects as well (**SIDEBAR, PAGE 58**).

The upwelling in the late 1990s was also good for Dungeness crabs, sanddabs, and other flatfish that feed on the clams that exert great grazing pressure on the phytoplankton populations (Cloern et al. 2007, Cloern et al. 2010). Cold, nutrient-rich waters along the coast drove the increases in Dungeness crabs and flatfish in the marine portions of the Bay. The biomass of clam predators increased four-fold, and particularly in the South Bay, the filter-feeding clam populations plummeted (**FIGURE 6**). These results are especially important, because they point to long-term, broad-scale forces beyond the control of water quality managers.

New invasive species may also have played a role. San Francisco Bay is one of the most invaded estuaries in the world, with new species continually changing community composition, species interactions, and ecological processes. Two new species of predatory zooplankton were found in the late 1990s. These new arrivals reduced the populations of existing zooplankton species that fed on phytoplankton, further reducing grazing pressure (Hoof and Bollens 2004). No matter the cause, be it changing water clarity, grazing, or changing inputs and influences from the Pacific Ocean, recent evidence suggests that the resilience of the phytoplankton populations to high nutrient loads is decreasing, and phytoplankton productivity is increasing, particularly in the South Bay.

FIGURE 5

Throughout the Bay, chlorophyll levels have increased since the late 1990s, particularly in the South Bay. Data are for the South Bay, August-December (Cloern and Dugdale 2010). Bars show the middle 50% of values for each year.

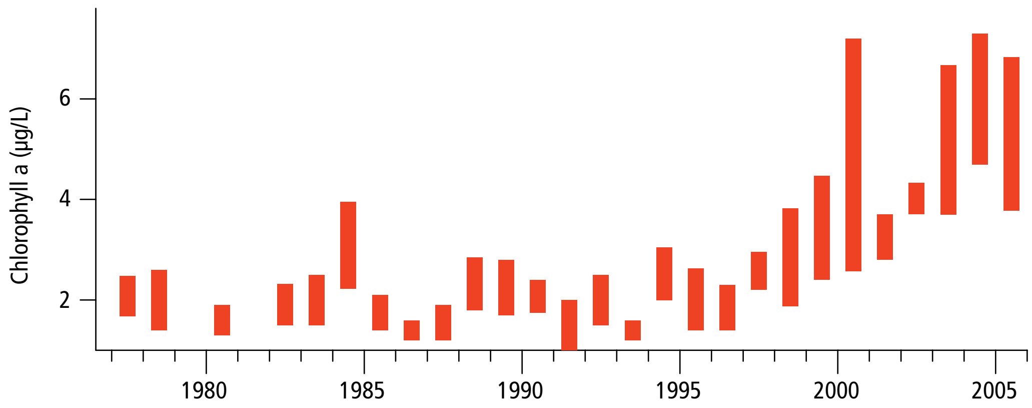
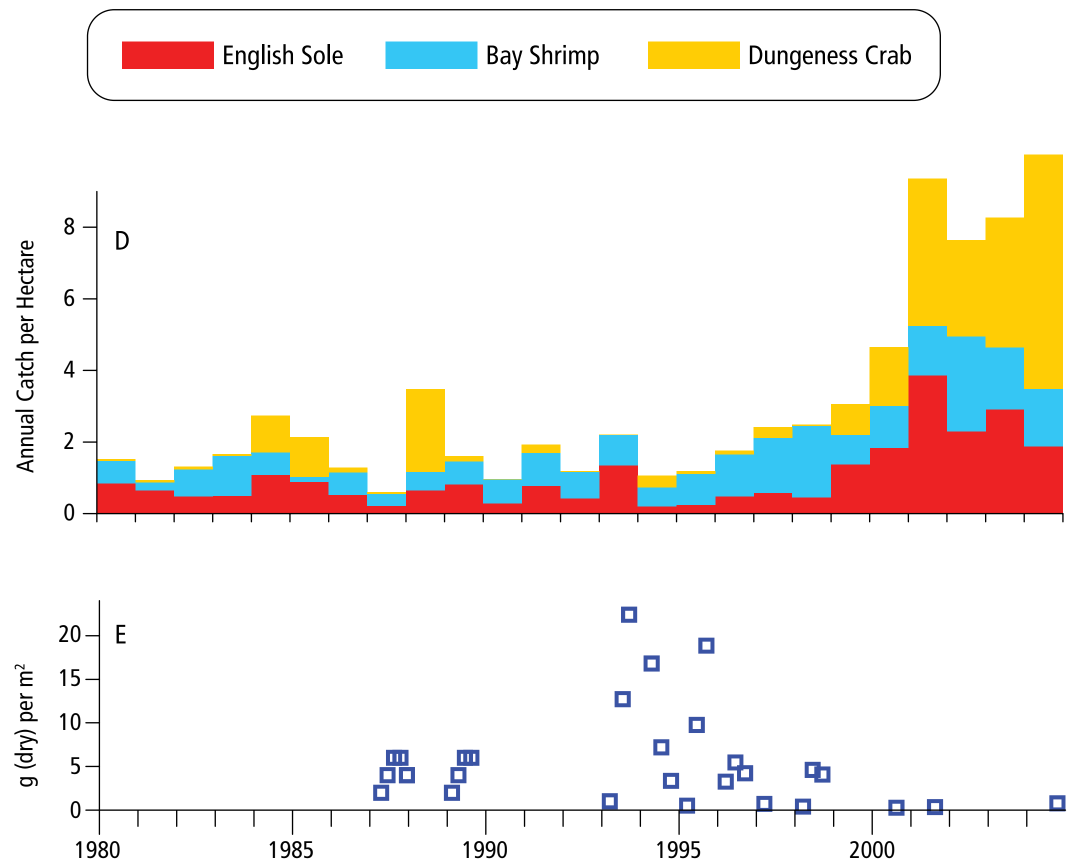


FIGURE 6

Top: Mean annual catch per hectare of the bivalve predators English sole, Bay shrimp, and Dungeness crab from the marine domains of San Francisco Bay. Data from California Department of Fish and Game, presented in Cloern et al. (2007).

Bottom: Annual median biomass of filter-feeding clams across the shallow habitats of the South Bay.



↑ The USGS Research Vessel Polaris. Photograph by Nicole David.

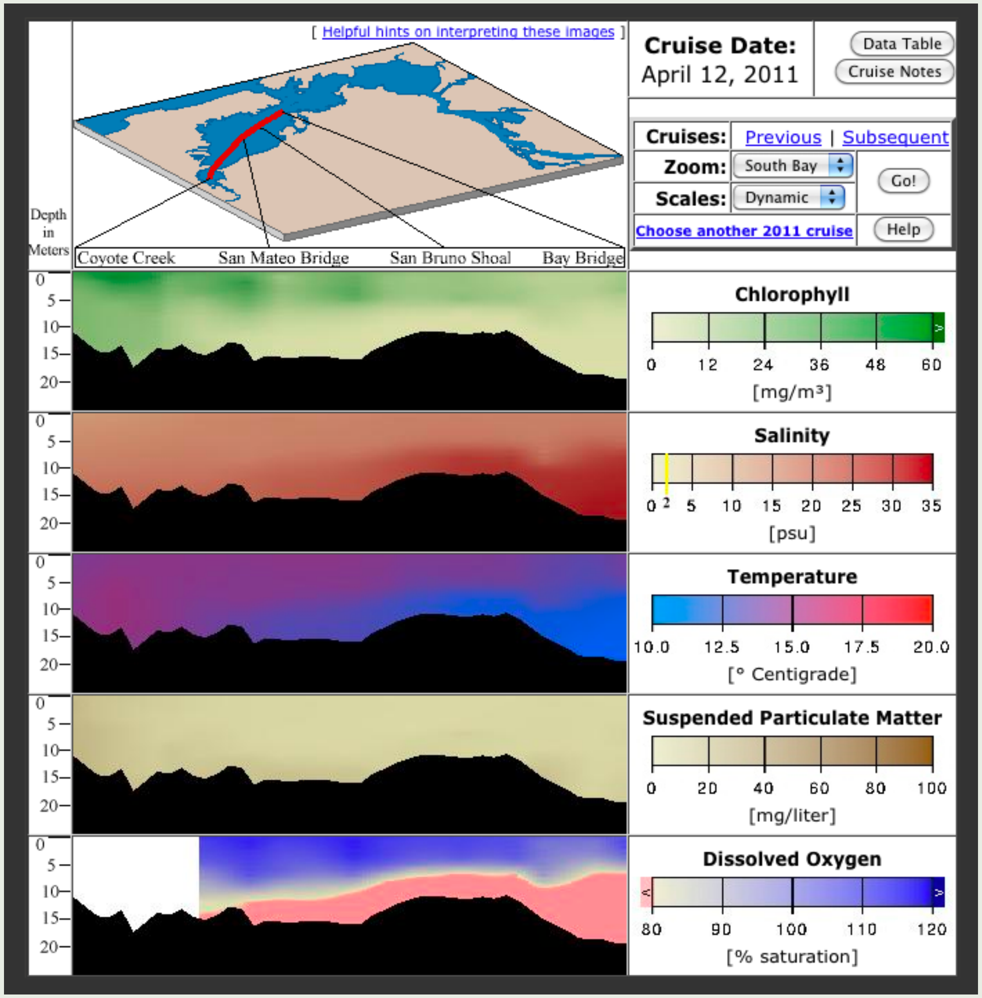
SIDEBAR

EXCEPTIONAL CONDITIONS IN SPRING 2011

San Francisco Bay is usually well mixed. In most other estuaries and coastal waters, seasonal changes in water temperatures and salinities create stratified conditions, which effectively separate surface and bottom waters. Phytoplankton in the surface waters deplete the available nutrients and then die, sinking through the temperature and salinity barrier to the bottom. While oxygen levels remain high in the surface waters, levels fall in the bottom waters, as bottom-dwelling animals respire, and bacteria use up oxygen as the phytoplankton decompose. Such conditions do not usually occur in the Bay.

USGS profiles from the South Bay on April 12, 2011 and throughout the following summer showed a radically different pattern than the usual (FIGURE). There was extremely strong stratification, with high levels of chlorophyll in the surface layer and record low levels of dissolved oxygen in the bottom waters. Scientists from San Francisco State University's Romberg Tiburon Center for Environmental Studies and the Water Board were sampling in Suisun Bay at the same time and also reported strong stratification.

Preliminary analysis of the data suggested that the stratification resulted from an intrusion of ocean water into the Bay. Cold, salty water moved into the Bay and remained at the bottom, isolated from the surface waters. The April 2011 observations were important, as they showed that extremely low levels of dissolved oxygen can occur, even without local eutrophication and phytoplankton blooms. Understanding such interactions of the Bay ecosystem with the wider oceanic regime will be important to understanding the ongoing changes in Bay water quality.



Chlorophyll, salinity, temperature, suspended particulate matter, and dissolved oxygen concentrations in the South Bay on April 12, 2011, during an unusual period of stratification (Screen capture of USGS data, http://sfbay.wr.usgs.gov/access/wqdata) . Graphs show depth profiles along the transect shown on the map at the top.

Concerns for Inhibited Phytoplankton Growth in Suisun Bay

Meanwhile, another, very different, kind of story has been emerging from the Sacramento–San Joaquin Delta and Suisun Bay (Wilkerson et al. 2006). The Sacramento and San Joaquin rivers have high nutrient levels, largely due to the dense and rapidly growing population in the region and agricultural production in the Central Valley. Loads of ammonium discharged from the Sacramento regional wastewater treatment plant, the largest discharger in the region, have more than doubled since 1985 (Jassby 2008).

In the North Bay and the Sacramento River, high concentrations of ammonium appear to inhibit rather than stimulate growth of diatom species (Dugdale et al. 2007), a finding that is counterintuitive, since increased nutrients typically mean increased phytoplankton growth. Wilkerson, Dugdale, and their co-workers monitored nitrogen uptake by diatoms in water samples from the Bay. They found that although nitrate concentrations were consistently high, when ammonium concentrations were also high, the nitrate was not taken up by the phytoplankton. This effect was observed throughout locations in the North Bay and was particularly strong in Suisun Bay, where only one phytoplankton bloom occurred during their three-year study. No similar inhibition has been detected in the South Bay. Reduced phytoplankton productivity under similar conditions of high concentrations of both nitrate and ammonium has also been observed in Delaware Bay and the Scheldt Estuary in western Europe (Yoshiyama and Sharp 2006, Cox et al. 2009).

Community Structure as an Indicator of Change?

From 1992 through 2001, Cloern and Dufford (2005) found 500 distinct phytoplankton taxa, about 400 of which could be identified to species, along a transect from the Sacramento River to the South Bay. The community was dominated by a few species, with the most abundant ten taxa accounting for 77% of the cumulative biomass, and the top 100 accounting for more than 99%. Diatoms contributed the most, accounting for more than 80% of total phytoplankton biomass (**FIGURES 7 and TABLE 1**).

The diatoms are relatively large in size compared to other groups, and large species dominated the community (Cloern and Dufford 2005). Why large species dominate in the Bay is not known. Possible explanations include high growth rates under low light conditions, efficiency in taking up nitrate, and protection from predation by the thick silica shells that are characteristic of diatoms.

Other urban estuaries, such as Chesapeake Bay, have used measures of phytoplankton community structure, such as diversity and relative abundance of species groups, as indicators of changing conditions. Changes in the Bay phytoplankton community could also signal broader environmental change.

In Suisun Bay and the Delta, scientists are increasingly concerned that high concentrations of ammonium may be changing the species mix of the phytoplankton community. Changes in the ratios of ammonium to nitrate and in total nitrogen to total phosphorus (the nutrient that is usually limiting in fresh waters) may favor growth of small cyanobacteria, such as the harmful species *Microcystis aeruginosa* (**SIDEBAR, PAGE 50**), and flagellates over larger diatoms species (Glibert 2010), potentially resulting in less desirable food for larger organisms.

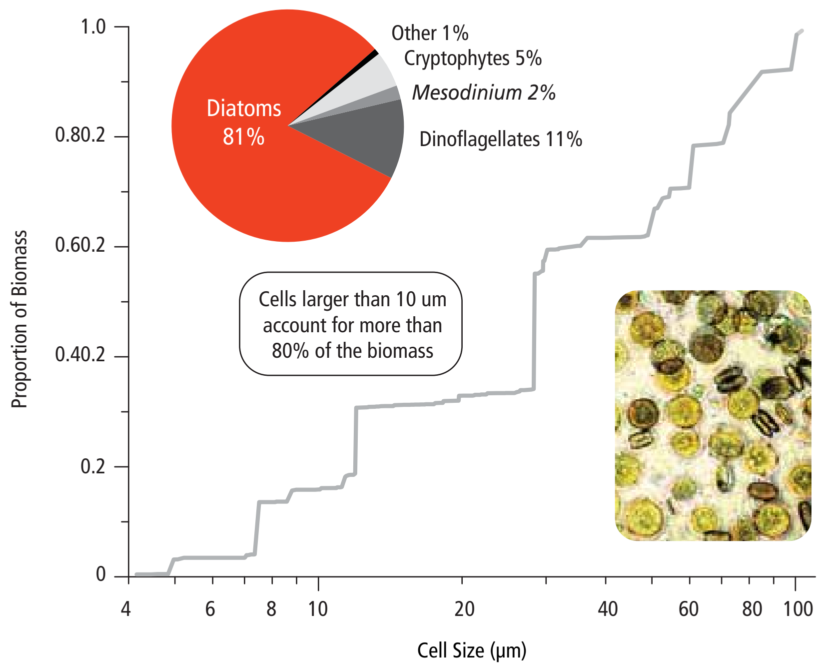
What Makes the North Bay Different?

There are profound differences between the North Bay and the South Bay. The freshwater inputs to the North Bay are dominated by river outflow, while in the South Bay, water inputs from wastewater treatment plants, rainfall, and runoff from small tributaries are also important. Residence times of water masses in the North Bay are much shorter than those in the South Bay. Wastewater treatment plants are the major sources of nutrients to both the North Bay and the South Bay (Hager and Schemel 1996, Smith and Hollibaugh 2006), however wastewater treatment is continually evolving. For example, advanced secondary treatment at the Sunnyvale, San Jose, and Palo Alto treatment plants in the South Bay has substantially reduced the ammonium input but equally increased nitrate input.

↑ *Coscinodiscus oculus-iridis.* Illustration by Susan Putney.

FIGURE 7

Relative contribution to total phytoplankton biomass and cumulative frequency by cell size, showing that San Francisco Bay is dominated by large phytoplankton species. (Data are from USGS samples taken along a transect from the Sacramento River to the South Bay in 1992–2001.)



From Cloern, J.E., R. Dufford. 2005. Phytoplankton community ecology: principles applied in San Francisco Bay. Marine Ecology Progress Series, 285:11-28.

TABLE 1

Twenty most abundant phytoplankton species in the Bay, based on biomass. From Cloern and Dufford (2005).

1. ***Thalassiosira rotula***
2. ***Chaetoceros socialis***
3. ***Skeletonema costatum***
4. ***Ditylum brightwellii***
5. ***Gymnodinium sanguineum***
6. ***Coscinodiscus oculus-iridis***
7. ***Thalassiosira hendeyil***
8. ***Thalassiosira punctigera***
9. ***Plagioselmis prolonga var. nordica***
10. ***Coscinodiscus curvatulus***
11. ***Mesodinium rubrum***
12. ***Teleaulax amphioxeia***
13. ***Chaetoceros debilis***
14. ***Eucampia zodiacus***
15. ***Coscinodiscus radiatus***
16. ***Thalassiosira eccentrica***
17. ***Protoperidinium sp.***
18. ***Thalassiosira decipiens***
19. ***Coscinodiscus centralis var. pacifica***
20. ***Rhizosolenia setigera***

STUDIES UNDERWAY

The USGS continues to study water quality parameters and chlorophyll at 39 fixed sampling locations, located about 3–6 kilometers apart from the southern limit of the South Bay to the Sacramento River (**FIGURE 9**). The program includes monthly measurements of chlorophyll, nitrate, nitrite, ammonium, phosphate, and silicate. Data are available on the USGS website and can be accessed through the RMP.

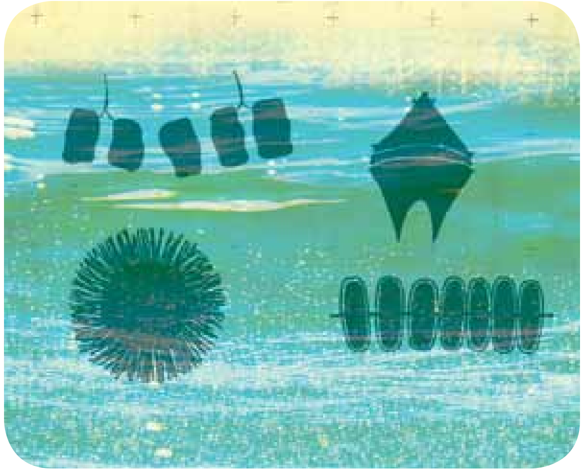
The Interagency Ecological Program (IEP) for the San Francisco Bay/Sacramento–San Joaquin Estuary, with ten member agencies, collects water quality data and other environmental information that can be used to complement the information being gathered by the USGS in the Bay. The IEP Environmental Monitoring Program has 40 years of data from the Delta and the North Bay.

The state and regional water boards, through the Surface Water Ambient Monitoring Program (SWAMP), also continue to monitor nutrients, with a particular focus on ammonium and its affect on phytoplankton blooms in the Delta and in Suisun Bay. During March through July 2010, scientists repeatedly sampled seven stations in Suisun Bay (Taberski et al. 2010). Blooms (defined as chlorophyll concentrations of 30 µg/L or greater) were detected during two of the sampling events, one in mid-April and the other in late May. The analysis of the blooms attributes them to a combination of reduced ammonium loading and increased river flow, resulting in relatively low ammonium concentrations in the river as it flowed into Suisun Bay (Dugdale et al. submitted).

This study is ongoing, and sampling continued in 2011. Its objectives include determining effects of ammonium on phytoplankton production and other topics, including effects of the invasive clam *Corbula* and the composition of the phytoplankton community during bloom and non-bloom sampling events. The study is also identifying springtime sources of ammonium to Suisun Bay and comparing spatial patterns of nutrient concentrations, chlorophyll concentrations, primary production, and nitrogen uptake by phytoplankton. Other goals include investigating the role of greater water transparency and the possible effects of copper, herbicides, and pesticides, through toxicity tests and Toxicity Identification Evaluations (TIEs). A coalition including SWAMP, the State and Federal Water Contractors, the Bay Area Clean Water Agencies (BACWA), and Central Contra Costa County Sanitary District is funding these studies.

Agencies with permits to discharge stormwater to the Bay under the Municipal Regional Stormwater Permit (MRP) are beginning a program to monitor stormwater loads at six stations over three years. Consistent with the MRP and the Small Tributaries Loading Strategy, the RMP plans to collect specific data on nutrients and other contaminants that will support development of a regional model for estimating loads by extrapolation from local studies.

As part of a state-wide effort, the Water Boards are working towards developing nutrient objectives for San Francisco Bay. RMP scientists are currently evaluating available data to identify appropriate indicators of nutrient impacts (McKee et al. 2011). Possible indicators include water clarity, phytoplankton productivity and biomass, incidence of harmful or nuisance algal blooms, and dissolved oxygen. The indicators will be used to build a Nutrient Numeric Endpoint framework to assess the status of nutrients and their water quality impacts throughout the Bay. A workplan, developed in coordination with the new San Francisco Bay Nutrient Strategy, will identify special studies needed to build the assessment framework and better understand nutrient issues.



←

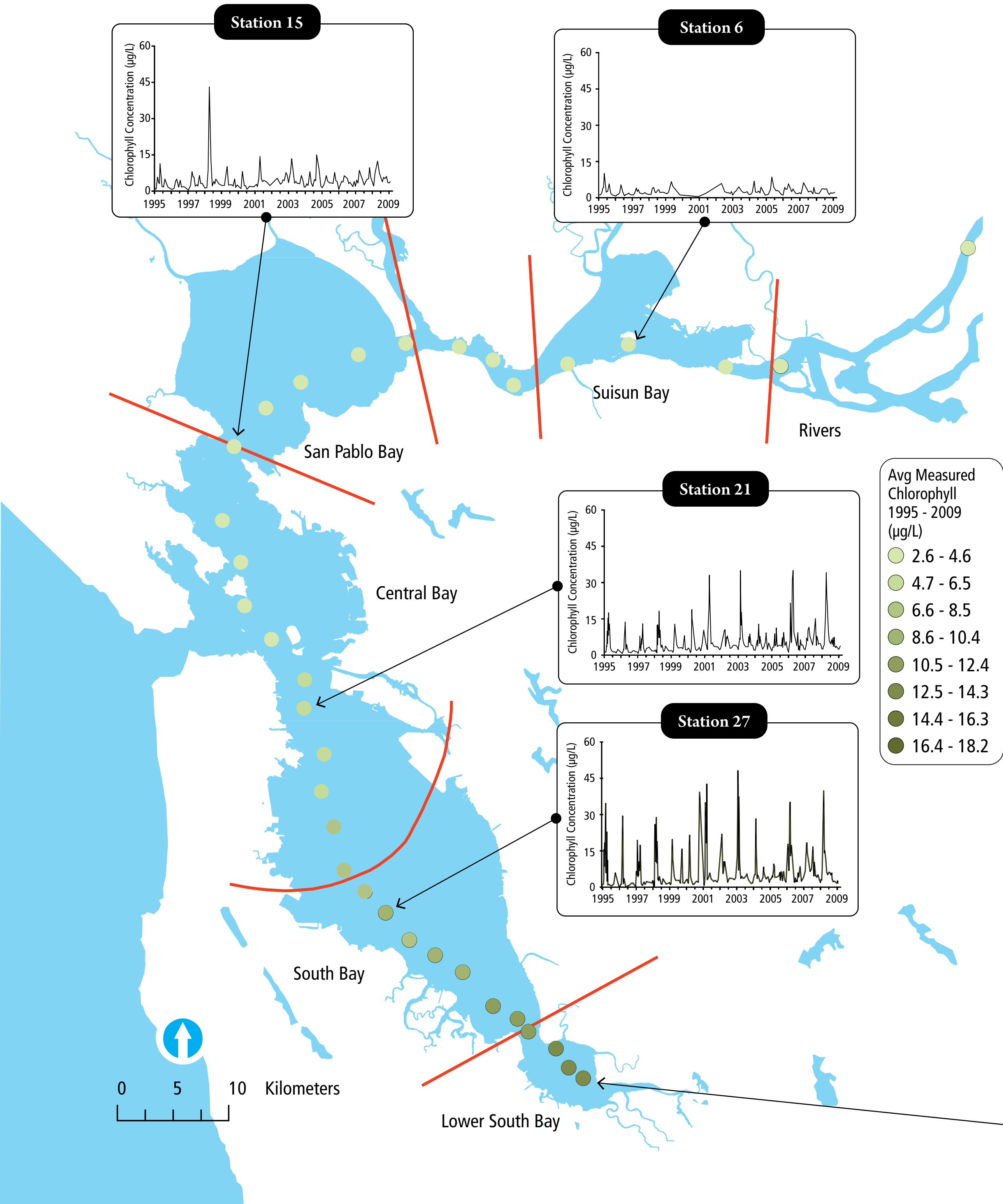
Top left. *Chaetoceros socialis.*

Top right. *Protoperidinium sp.*

Bottom left. *Mesodinium rubrum.*

Bottom right. *Ditylum brightwellii.*

Illustrations by Susan Putney.



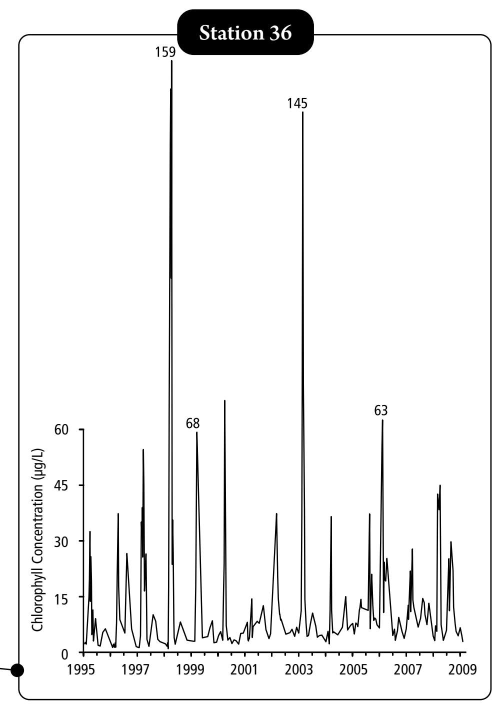


FIGURE 9

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ADDITIONAL SCIENCE NEEDS

The complex and sometimes seemingly paradoxical scenarios emerging from San Francisco Bay show the importance of continued monitoring, research, and modeling. The biggest overall question is whether there are plausible scenarios in which the Bay will start to exhibit the symptoms of eutrophication due to nutrient enrichment that have been observed in so many other estuaries.

Information gaps are many, and future trends are difficult to predict. The lessons from other ecosystems show that each estuary is unique, further emphasizing the importance of local data and modeling. Understanding nutrient and phytoplankton dynamics in San Francisco Bay is especially important, because future conditions could make it necessary to reduce agricultural or sewage loads. Reducing agricultural loads, through enhancement of fringing wetlands and buffer strips, has been an important focus in Chesapeake Bay and the Mississippi River Delta. Advanced secondary treatment has already been implemented at the Palo Alto, Sunnyvale, and San Jose/Santa Clara treatment plants, and additional advanced secondary treatment and/or nitrogen-removal technologies may be warranted. Nitrogen removal has been necessary in many other urban estuaries around the world.

The new San Francisco Bay Nutrient Strategy is increasing the focus on information gaps and the present uncertainty surrounding future projections. One focus is to better understand quantities, timing, and composition of loads. Although it is known that nutrient loading to the Bay is high, there is no detailed understanding of the relative magnitude of loads from individual sources and pathways. Obtaining this information, which will be necessary if future conditions suggest that inputs must decline, is key.

There has also been no systematic assessment of phytoplankton production and species composition within the Bay and no monitoring of phytoplankton outside the Golden Gate. Nor is there systematic monitoring of zooplankton or benthic grazers. Another key need is for predictive simulation models to assess and manage nutrients and phytoplankton in the Bay. The RMP is looking to partner with other programs to rise to the challenge of addressing these substantial information needs and providing a solid technical foundation for the consequential decisions that are on the horizon.

The biggest overall question is whether there are plausible scenarios in which the Bay will start to exhibit the symptoms of eutrophication due to nutrient enrichment that have been observed in so many other estuaries

Understanding the more specific issues, such as possible ammonium inhibition, will also be important to determining appropriate management responses to changing conditions. One hopeful scenario might be the restoration of primary productivity in northern portions of the Bay following controls on ammonium discharges, which are likely to be imposed by the Water Boards. The Scheldt estuary of western Europe, where zooplankton communities are changing in response to nutrient reductions, may provide a glimpse of what could occur in the Bay (Mialet et al. 2011).

↑ View from the Golden Gate Bridge. Photograph by Jay Davis.

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EFFECTS OF POLLUTANTS ON BAY FISH

HIGHLIGHTS

- Many fish populations are declining in the North Bay and Delta; contaminants may play a role
- Fish have life histories that make them vulnerable to pollutants
- PAHs from vehicle exhaust, oil spills, and other sources can reach concentrations that can affect growth, reproduction, and survival of Bay fish
- Pyrethroid pesticides and other pollutants are suspected to have a role in the “Pelagic Organism Decline” in the northern Estuary and Delta
- Studies suggest that endocrine disruption may be occurring in the Bay-Delta, but the causes are not entirely clear

FISH POPULATIONS UNDER SIEGE

Populations of many important fish species in the San Francisco Estuary have declined significantly in recent years. Beginning in 2000, a dramatic decrease in fish populations in the northern portion of the Estuary was observed, pitting fisherman and environmentalists against farmers and water suppliers. Significant declines have also been observed for salmon returning to upstream spawning locations and for Pacific herring, which spawn within the Bay.

One of the largest environmental concerns in the Estuary has been significant declines in the populations of Delta smelt (*Hypomesus transpacificus*), juvenile striped bass (*Morone saxatilis*), longfin smelt (*Spirinchus thaleichthys*), and threadfin shad (*Dorosoma petenense*) (**FIGURE 1**). For example, in 2005–2007, the Delta smelt population index reached the lowest recorded levels for the last 40 years of monitoring. Collectively the decline of these four key species is referred to as the "pelagic organism decline" (POD).

The convergence of the decline of these four species is particularly disturbing because they have different life histories (migratory and nonmigratory) and occupy different habitats (freshwater and estuarine), suggesting that a large-scale phenomenon is occurring. Declines of Delta smelt and longfin smelt are of great concern because they are both endangered species. Interestingly, both the striped bass and the threadfin shad are introduced species .

The returning Sacramento River fall run of chinook salmon (*Oncorhynchus tshawytscha*) was virtually non-existent in 2007, and in 2008 and 2009 commercial fishing for chinook was completely closed due to low runs (in 2009, only 39,500 salmon returned, down from a high of 770,000 in 2002) (Pacific Fisheries Management Council 2010 [**FIGURE 2**]). In addition, two other Estuary salmon populations are so diminished that they are listed as endangered, the winter and spring run chinook salmon and steelhead trout (*Oncorhynchus mykiss*).

Pacific herring (*Clupea pallasii*) is the last commercial fishery in San Francisco Bay. Herring roe, considered a delicacy by the Japanese, is largely exported. The central portion of San Francisco Bay is one of the largest herring spawning sites in California. Herring spend two to three years in the open ocean, and then return to the Bay to lay their eggs on substrates such as eelgrass, algae, rocks, gravel, rip-rap, and pier pilings. In recent years, herring catch declined dramatically from the historic average of 49,000 tons down to a low of 4,800 tons in the winter of 2008-2009. In 2010, the commercial herring season was closed completely, the first time in the 38 years of monitoring the catch (www.dfg.ca.gov/marine/newsletter/1010.asp#herring). The 2009-2010 estimate of 38,409 tons was an improvement, but remains below the historical average of 49,084 tons.

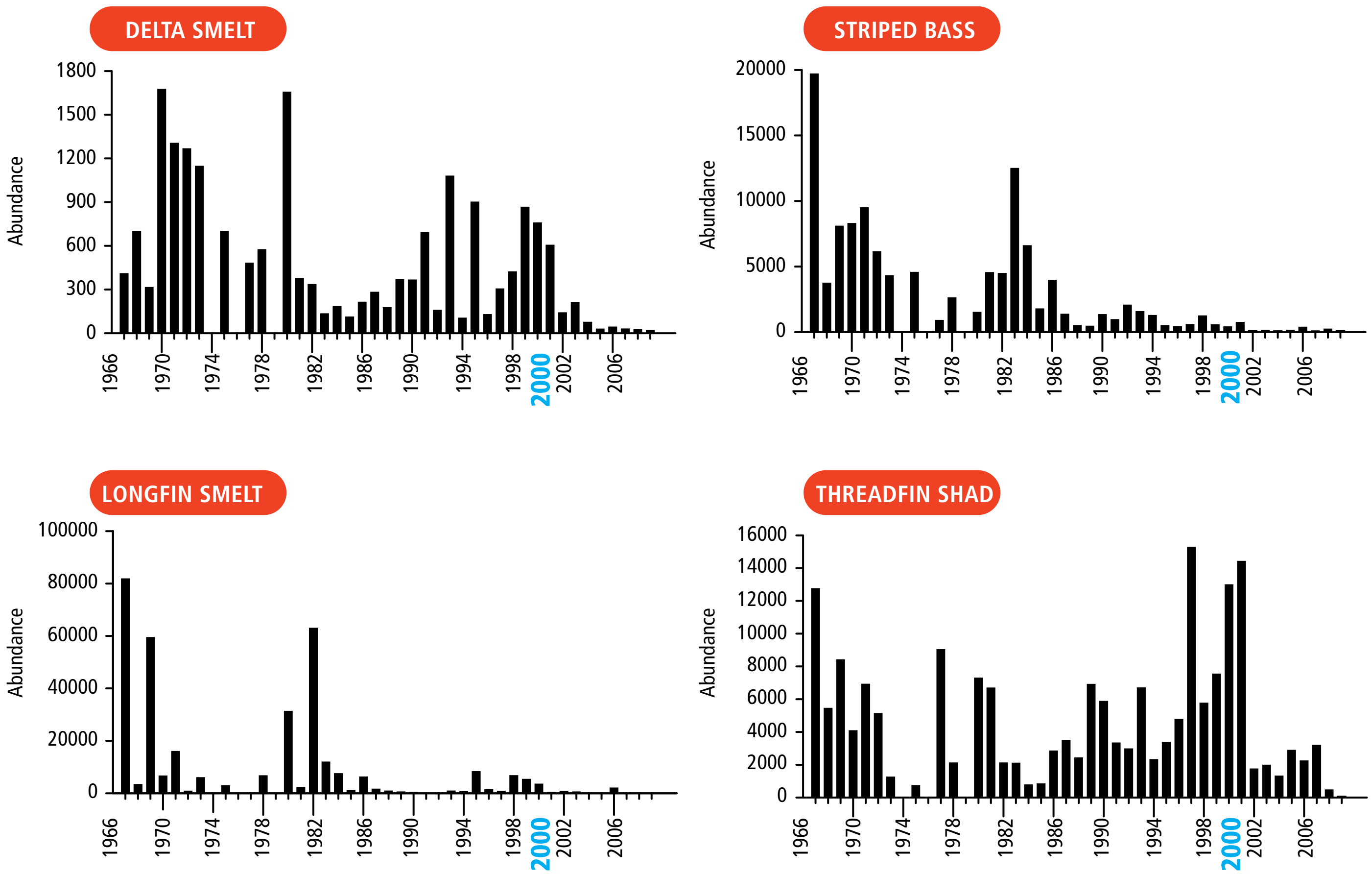
The causes for these dramatic declines in fish populations in the Bay and Delta are unknown. Various factors have been investigated, including habitat loss and reduced water flows; predation; entrainment in Delta pumps for water diversion; limited food supply due to low primary productivity; and toxic effects of pollutants.

The sources of pollutants in the Estuary are diverse and include agricultural runoff, dry weather flows, wastewater treatment plant effluent, storm water runoff, refinery discharges, and resuspension of sediments. In addition to direct effects on fish, there may be indirect effects of pollutants such as the introduction of invasive species which may concentrate pollutants (e.g., selenium in clams – **PAGE 37**) or the inhibition of key food sources (e.g., possible ammonium inhibition of phytoplankton at the base of the food web – **PAGE 60**).

↑ Herring fishing boats in Raccoon Strait. Photograph by Joan Linn Bekins.

FIGURE 1

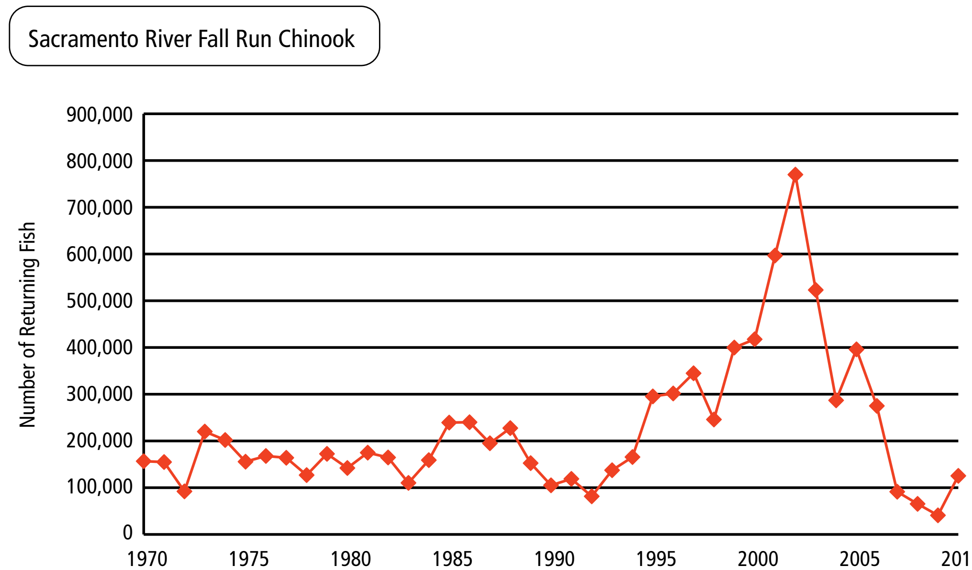
One of the largest environmental concerns in the Estuary has been significant declines in the populations of Delta smelt (*Hypomesus transpacificus*), juvenile striped bass (*Morone saxatilis*), longfin smelt (*Spirinchus thaleichthys*), and threadfin shad (*Dorosoma petenense*). For example, in 2005–2007, the Delta smelt population index reached the lowest recorded levels for the last 40 years of monitoring. Collectively the decline of these four key species is referred to as the "pelagic organism decline" (POD). Declines of Delta smelt and longfin smelt are of great concern because they are both endangered species.



Footnote : From Baxter, R. et al. 2010. Interagency Ecological Program 2010 Pelagic Organism Decline Work Plan and Synthesis of Results.

FIGURE 2

The returning Sacramento River fall run of chinook salmon was at a long-term low in 2007, and in 2008 and 2009 commercial fishing for chinook was completely closed due to low runs (in 2009, only 39,500 salmon returned, down from a high of 770,000 in 2002). The Pacific Fisheries Management Council has set a goal of between 122,000 to 180,000 returning fish.



Footnote: From Pacific Fisheries Management Council. 2010. Stock Assessment and Fisheries Evaluation (SAFE) 2010 Ocean Salmon Fisheries.

FISH ARE SENSITIVE AND IMPORTANT INDICATORS

Fish are very sensitive to pollutants. In part, this sensitivity is attributable to their exposure to waterborne pollutants throughout their lives. The vast majority of Bay fish species are oviparous (egg-laying) , dispersing thousands of eggs directly into the water column or anchoring their eggs on rigid structures such as pier piles. Once the eggs are fertilized, they hatch, and then develop into juvenile fish and adults. Pollutants can disrupt fish life cycles at many stages. For example, exposure to the synthetic estrogen hormone used in birth control pills, ethinylestradiol, at very low concentrations (around 1 part per trillion) can cause male fish to exhibit female characteristics (e.g., expression of the female egg yolk protein, vitellogenin) (Jobling et al. 1998; Rodgers-Gray et al. 2000). Similarly, exposure to part per billion concentrations of the detergent nonylphenol elicits a similar response (Jobling et al. 1996).

↑ Collection of herring for evaluation of effects of oil pollution. Photograph courtesy of John Incardona.

Fish are also particularly sensitive to chemical pollutants because they have multiple routes of exposure, including ingestion, aquatic respiration, and regulation of osmotic pressure. Because water contains less oxygen than air, fish respiration rates are about five times higher than mammals (Van der Kraak et al. 2001). Gill surfaces must be quite large to extract sufficient oxygen, and the active movement of water across the gill increases exposure to waterborne pollutants. Fish in saline and freshwater environments are also subject to changes that may increase their contaminant burden as they move water through their bodies to regulate the osmotic pressure.

Lastly, fish are susceptible to contaminant effects because they exhibit sexual plasticity. Unlike mammals, the gender of fish is not genetically predetermined and may be influenced by social and environmental factors. For example, the California sheephead (*Semicossyphus pulcher*) which resides in the Southern California Bight, has one dominant male and many females. When the dominant male dies, one of the females will change sex to become the next dominant male. Gender changes may also occur upon exposure to a class of chemical pollutants referred to as endocrine disruptors. Municipal wastewater is one source of these compounds, often containing trace amounts of steroid hormones, surfactants such as nonylphenol, and many other chemicals from pharmaceuticals, personal care products, and consumer products. Furthermore, endocrine-disrupting chemicals can affect other physiological systems, and are known to disrupt development and growth, metabolism, immune responses, and other essential processes.

Numerous examples of contaminant effects on fish have been documented throughout the world. Many pollutants found in the Bay can elicit adverse effects at elevated levels, including pesticides, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), dioxins, metals, and endocrine disruptors such as ethinylestradiol, nonylphenol and bisphenol A. The effects of these pollutants on fish are potentially significant and wide-ranging: elimination of an entire fish population (17-α ethinylestradiol) (Kidd et al. 2007), compromised immune systems (Reynaud and Deschaux 2006), liver lesions (Myers et al. 2003), thyroid dysfunction (Brar et al. 2010), and impairment of the sense of smell (McIntyre et al. 2008). Many of these effects occur at concentrations that are observed in the Bay.

One of the challenges in evaluating pollutant effects on fish is identifying a direct link between contaminant exposure and a distinct measurable effect. Few pollutants have had impacts that are as strongly linked to one contaminant as those associated with the bioaccumulation of DDT in birds in the 1970s that resulted in eggshell thinning and population declines. It is usually very difficult to tease out the impacts of a specific pollutant on organisms in an environmental setting, and even more difficult to identify impacts at the population level. The effects of pollutants on organisms are often subtle, such as impairment of neurological functions, growth rate, or immune responses that contribute to adverse outcomes. For example, low concentrations of pyrethroid insecticides can affect the swimming ability of fish, making them more vulnerable to predation (Connon et al. 2009). In addition, fish are exposed to a myriad of other stressors that may exert even greater pressures on populations, such as loss of habitat, disruptions from invasive species, and reduction in prey. Isolating the effects of a specific pollutant or pollutant mixtures with so many other simultaneous stressors is a challenge.

Fish health is an important metric in assessing the health of an estuary as fish are critical components of the food web. Many higher trophic animals, including seals, cormorants, and sturgeon, depend upon small fish as prey. Fish from estuaries are also consumed by humans (**PAGE 15**). Fish health monitoring is frequently included in other major water quality programs, including those in the Southern California Bight, Puget Sound, Great Lakes, and along the Eastern seaboard, and allow us to place Bay results in context.

SIDEBAR

EXPOSURE AND EFFECTS WORKGROUP

The RMP Exposure and Effects Workgroup provides oversight on RMP studies relating to the effects of toxic pollutants on aquatic life, including the work on fish, birds, and seals that is summarized in this edition of The Pulse.

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FINDINGS FROM RECENT BAY AREA STUDIES

COMBUSTION, OIL SPILLS, AND PAHS

Fish are highly sensitive to PAHs, a diverse family of compounds that can cause a number of adverse effects including heart malfunctions, liver lesions, abnormal larval development, and death. Sources of PAHs to the Bay are both natural and anthropogenic and include combustion of fossil fuels and wood, forest fires, petroleum refining, and oil spills. PAHs are made up of linked hydrocarbon rings, ranging from relatively light weight two-ring compounds to heavier compounds with six rings or more. PAHs consisting of two to four rings are typically derived from petroleum compounds (e.g., naphthalene, fluorene, dibenzothiophene, phenanthrene and anthracene), while four- to six-ring compounds are typically the result of combustion (e.g., pyrene, benz(a)anthracene, and chrysene).

Exposure of adult fish to PAHs can cause suppression of immune systems; lesions on gills, skin, and fins; liver lesions; and reproductive dysfunction. The National Oceanic and Atmospheric Administration (NOAA) identified significant adverse effects occurring in English sole (*Parophrys vetulus*) located in areas of PAH-contaminated sediments on the West Coast of the U.S., including San Francisco Bay. They observed an increase in liver lesions, failure to spawn, poor egg quality, and a decline in growth rates (Johnson et al. 2002). Bay sediments commonly exceed 1 ppm, the concentration suggested by NOAA as a sediment-quality threshold.

PAHs are widely dispersed throughout the Bay, with areas of elevated concentrations near the former fuel depots along the San Francisco waterfront and near the industrial port of Oakland Harbor (**PAGE 33**). Oil spills are another source of PAHs to the Bay. Fortunately, oil spills in the Bay occur relatively infrequently. In the last 100 years, there have been three major spills in the Bay: the collision of a passenger steamer and oil tanker in 1937 that caused a release of approximately 2,400,000 gallons; a 1971 collision of two tankers spilling 900,000 gallons of partially refined fuel oil; and, most recently, the Cosco Busan tanker that gouged its hull on a Bay Bridge support releasing 54,000 gallons of bunker fuel oil in 2007 .

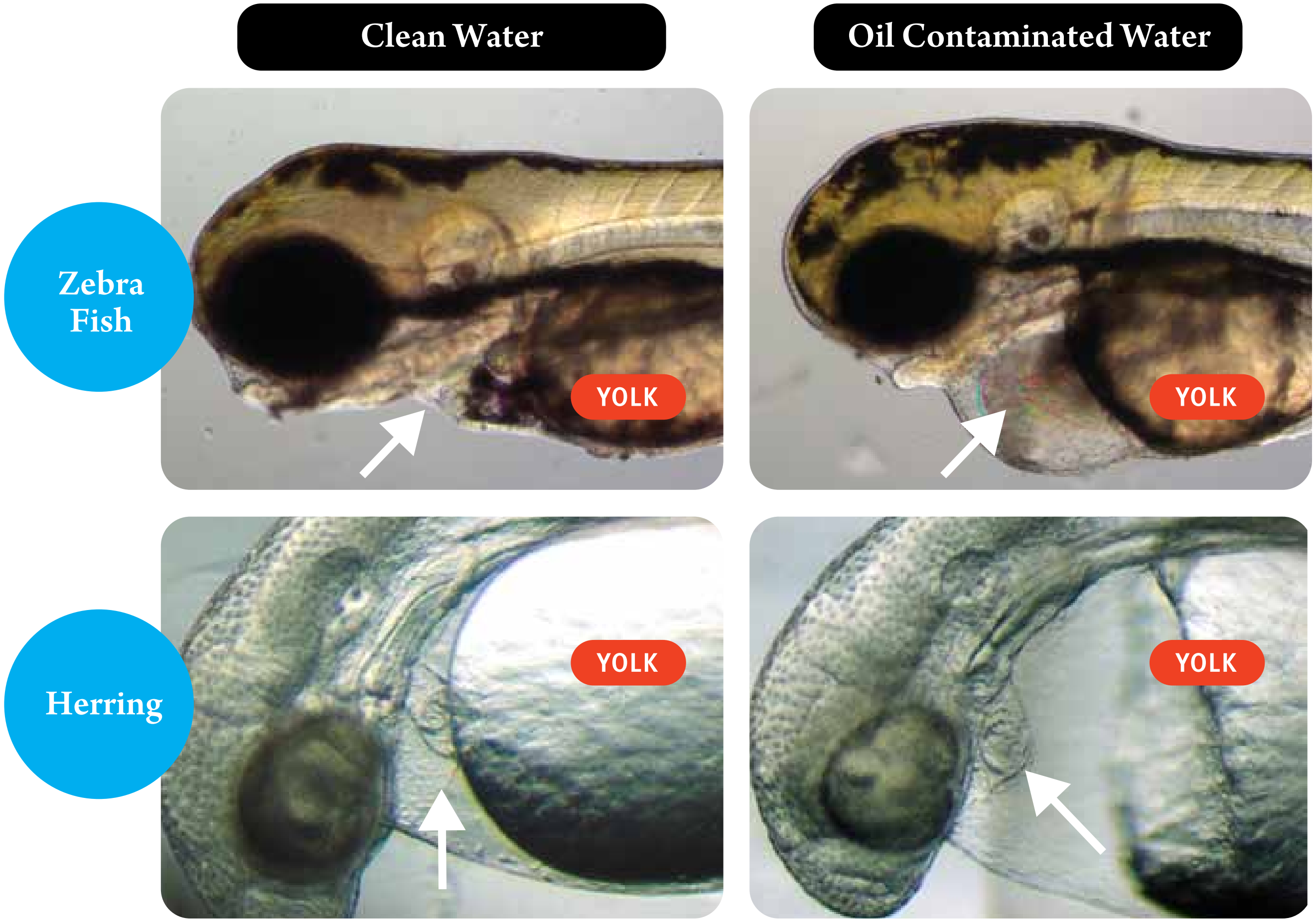
As a result of oil spills around the country, particularly the Exxon Valdez in Alaska and more recently the Cosco Busan in the Bay, the adverse effects of PAH exposure have been extensively studied. The timing of exposure and the type of PAH greatly affect the outcome. Fish larvae exposed to high enough concentrations of the three-ring PAHs present in unrefined crude oil (e.g., fluorenes, dibenzothiophenes, and phenanthrenes) experience swellings in the heart and yolk sac, small jaws, deformed spines, reduced heart rate, and heart arrhythmia (**FIGURE 3**). Pacific herring collected in oiled areas of the Bay after the Cosco Busan spill exhibited many of these effects (Incardona et al. 2008).

The research evaluating the effects of the Cosco Busan spill found higher acute toxicity in intertidal areas where fuel oil was exposed to sunlight. Subsequent laboratory studies have not yet identified the mechanism by which this occurs. Many studies have shown UV light activates PAHs in biota (Oris and Giesy 1985).

With funding from the Regional Monitoring Program for Water Quality in the San Francisco Estuary, NOAA is currently investigating thresholds for PAH effects in juvenile flatfish. The focus is on the higher molecular weight, pyrogenic PAHs that result from combustion of petroleum products and that are endemic to industrial and heavily urbanized estuaries such as San Francisco Bay. The project is divided into three phases. The first phase assessed the effects of individual pyrogenic PAHs on the development of a laboratory model fish, the zebra fish, *Danio rerio*. After these effects were characterized, in the second phase, experiments on the effect of individual PAHs on California halibut, *Paralichthys californicus*, are being conducted. California halibut was selected because it is a resident species that spawns in the Bay. After the effects of individual PAHs on California halibut have been identified, the researchers will use real-world sediments containing similar levels and mixtures of PAHs as Bay sediments to assess the effects to developing California halibut and other flatfish.

ROLE OF POLLUTANTS IN THE POD

Pesticides and their effects on fish have been a major focus of the POD research in the Delta. Pesticides are used extensively in Central Valley agriculture, and the use of pyrethroids for urban applications in California has increased dramatically since 1999 with the phase out of organophosphate pesticides (2006 Pulse of the Estuary, **PAGE 71**). Pyrethroids have been detected in California waters at concentrations that can be harmful to fish. Pyrethroids are particularly toxic to fish, blocking the sodium and potassium channels in nerve cells resulting in tremors, impaired swimming ability, convulsions, and, at high enough concentrations, death. Impairment of swimming ability causes these fish to be more susceptible to predation. The pyrethroid esfenvalerate has been shown to impair swimming ability of larval Delta smelt at concentrations as low as 62 ng/L (Connon et al. 2009). Pyrethroids have also been shown to inhibit growth and immune responses and delay spawning (Connon et al. 2009). The concentrations at which effects can occur are as low as 25 ng/L (Floyd et al. 2008). Laboratory studies found that juvenile chinook salmon exposed to esfenvalerate and a virus had a significantly higher mortal-



Photographs by John Incardona.

FIGURE 3

Fish larvae exposed to high enough concentrations of the three-ring PAHs present in unrefined crude oil (e.g., fluorenes, dibenzothiophenes, and phenanthrenes) experience swellings in the heart and yolk sac, small jaws, deformed spines, reduced heart rate, and heart arrhythmia. Pacific herring collected in oiled areas of the Bay after the Cosco Busan spill exhibited many of these effects.

ity rate than fish exposed to the virus alone, suggesting that fish exposed to low levels of pyrethroids may be more susceptible to disease.

Pyrethroids have generally not been detected in the Bay. However, they have been detected in urban creeks and streams at concentrations that exceed these effect levels. Dr. Don Weston and his team at University of California at Berkeley have studied pyrethroids extensively and have observed concentrations in urban creeks as high as 46 ng/L (Weston and Lydy et al. 2010).

Work conducted by researchers at the University of California at Davis suggests that Bay-Delta species exposed to environmentally relevant concentrations of pollutants are exhibiting toxic responses. Spearow et al. (2010) found that wild fish in the northern portion of the Bay and in the Delta showed a number of responses from exposure to pollutants. Delta striped bass exhibited significantly higher induction of metabolic enzymes when exposed to Delta water. These enzymes are induced by exposure to PAHs, PCBs, dioxins, and other pollutants. Recent work by Dan Schlenk of University of California at Riverside suggests that pyrethroids cause induction of vitellogenin in fish (Nillos et al. 2010 and Wang et al. 2007). Additional laboratory studies have shown that mixtures of detergents significantly enhanced the estrogenic activity of pyrethroids and other pesticides used in surface waters of the Central Valley (Xie et al. 2005). Whether the POD is a direct effect of pollutants on the fish or on their invertebrate food supply remains a mystery. Based on all of the studies collected to date, the consensus is that no one factor is responsible for the POD. Most likely, it is a combination of factors in which pollutants play a role.

POLLUTANTS AND ENDOCRINE DISRUPTION IN FISH

Synthetic reproductive hormones and compounds that mimic reproductive hormones are one of the few cases in which environmentally relevant concentrations have been shown to potentially have significant population-level effects in the wild. It has been well established in field and laboratory studies that very low concentrations of hormones in water can affect the endocrine system of fish. The endocrine systems of all vertebrates including fish are a series of glands that secrete hormones that regulate not only reproduction but also growth and development, stress response, and other processes. Substantial research has documented that fish downstream of wastewater treatment facilities frequently exhibit disruption of the reproductive system. For example, male fish downstream of wastewater treatment plants have been found to have vitellogenin (female egg yolk protein) and eggs present in their testes (Jobling et al. 1998).

Perhaps more disturbing are the results from an experiment conducted in Canada on a series of experimental lakes in which one lake was treated with the synthetic hormone ethinylestradiol at concentrations of 5 to 6 ng/L (Kidd et al. 2007). Both the control lake and the treated lake contained fathead minnows. After the first year, male fish exhibited female characteristics such as expression of the egg protein, vitellogenin, and eggs present in their testes. By the second year, the population of minnows in the treated lake had completely collapsed, linking a contaminant effect to the survival of a population as a whole.

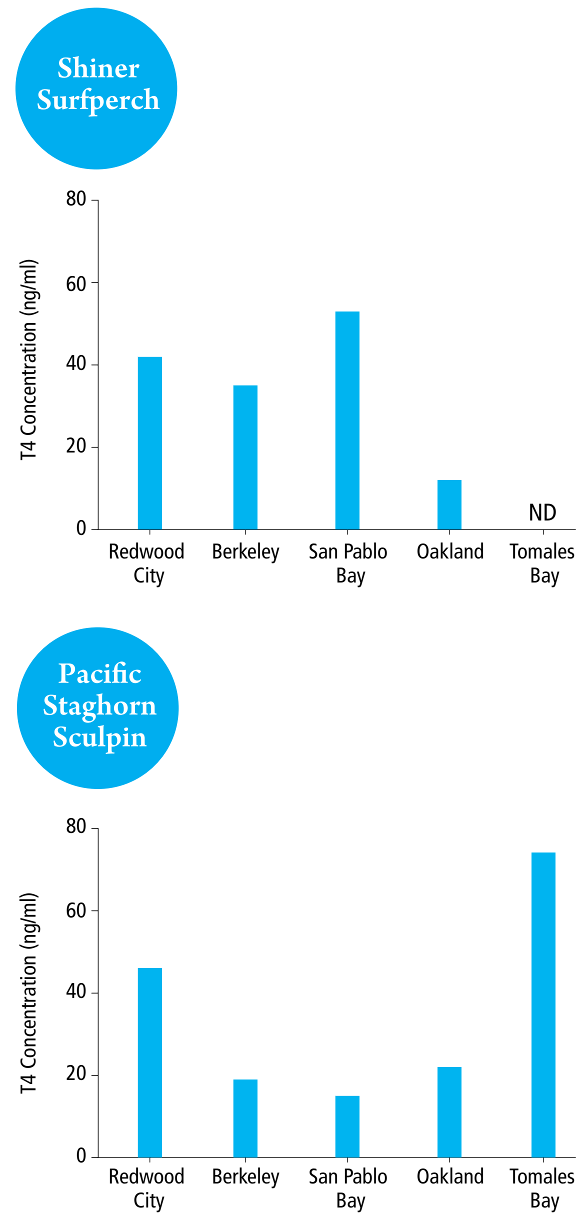
Within the Bay-Delta, there is limited evidence of reproductive endocrine disruption. Dr. Dan Schlenk of U.C. Riverside and Dr. David Sedlak of U.C. Berkeley conducted a study in 2006–2007 to evaluate whether reproductive endocrine disruption was occurring in Bay-Delta fish in laboratory experiments (Lavados et al. 2009). The team collected water from 16 locations throughout the Bay-Delta and extracted pollutants from the samples, and then used the extracts in laboratory exposures. The results indicated significant endocrine disruption potential in the Napa and Sacramento river samples; however, the endocrine disruption not associated with any one contaminant from chemical classes including steroid hormones, pesticides, surfactants such as alkylphenol ethoxylates, or a host of pharmaceutical and personal care products. Ongoing work suggests that the response may be the result of a mixture of pyrethroids and surfactants.

The RMP has sponsored studies to determine whether contaminants are affecting additional components of the endocrine system. Dr. Kevin Kelley and his research team from California State University at Long Beach recently completed a two-year study evaluating non-reproductive forms of endocrine disruption and their relationships to pollutant exposure in two Bay fish species (Brar et al. 2010). In shiner surfperch (*Cymatogaster aggregata*) and Pacific staghorn sculpin (*Leptocottus armatus*), disruptions in the thyroid endocrine system, including significant reductions in thyroid hormones, were found in fish sampled from contaminated industrial and harbor locations (**FIGURE 4**). Further experimental analysis found that specific problems within the thyroid system may be associated with different classes of contaminants (PCBs and chlordanes). Thyroid hormones are critical regulators of development and growth in fish. It was therefore notable that in fast-growing, young of the year sculpin, thyroid hormone concentrations were strongly correlated with concentrations of an important growth hormone (**FIGURE 5**), suggesting that impaired thyroid hormones could translate into growth effects. However, it is not yet understood whether the impacted fish exhibit deficits in growth or survival or in the population at large.

In addition to the thyroid disruption, both fish species also exhibited a dysfunctional adrenal endocrine system, which generates the hormone, cortisol. Cortisol is a critical stress hormone that promotes physiological and behavioral adaptations that help when an animal must deal with intraspecific competitors, predators, poor food availability, or other stressors. Cortisol is also important under normal physiological conditions, and disruptions in cortisol control can have negative effects on metabolism, immune functions, growth, and reproduction (Mommsen et al. 1999, Barton, 2002). In the studies by Kelley's group, fish sampled from harbor locations like the Oakland and Richmond harbors and at the San Francisco waterfront, were significantly impaired in their ability to produce cortisol during a stress challenge (**FIGURE 6**). Further analysis of the surfperch indicated that this endocrine disruption was significantly related to exposures to petroleum-derived PAHs (phenanthrene, anthracene, and fluoranthene). The fish also had increased parasitic infestations, suggesting the cortisol disruptions were related to compromised immune function. It is also notable that the effects on cortisol response did not routinely coincide with thyroid disruptions (**FIGURE 6**). This may reflect differential actions of different contaminant mixtures present at the different Bay locations tested.

COPPER

In conjunction with the RMP, NOAA is also studying the effect of copper on the olfactory system of salmon. Their recent research has shown that metals, particularly copper, inhibit predator avoidance by impairing olfactory nerve cells. Fish have exquisitely sensitive noses with an ability to smell chemicals at the part per billion level to find a mate, find a bite to eat, avoid being a bite to eat, and to locate their birth streams. The fish nose is much more than a nose – it also governs physiological and behavioral responses. In predator avoidance experiments, juvenile salmon exposed to copper had a survival rate three to five times lower than control fish. The concentrations at which this effect was observed were quite low, in the range of 3 µg/L in freshwater (McIntyre et al. 2008). Dissolved concentrations of copper in San Francisco Bay typically range up to approximately 4 µg/L. Water chemistry in estuarine systems is dramatically different than freshwater and there is some evidence to suggest that dissolved organic carbon and salinity may protect salmon in the Bay from the adverse effects of exposure to copper. This work will investigate the threshold at which effects occur in a saltwater environment.



Footnote: From Brar et al. (2010).

FIGURE 4

In shiner surfperch (**TOP**) and Pacific staghorn sculpin (**BOTTOM**), disruptions in the thyroid endocrine system include significant reductions in thyroid hormone (T4) were found in fish sampled from contaminated industrial and harbor locations, including Oakland Harbor.

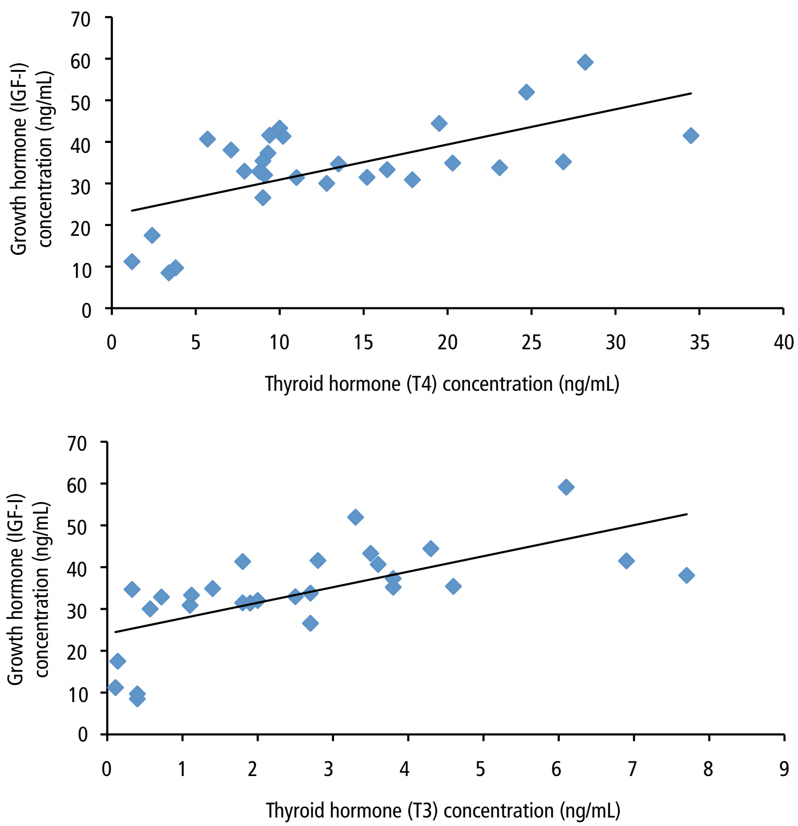


FIGURE 5

Relationships between concentrations of the growth regulatory peptide, insulin-like growth factor-I (IGF-I), and the thyroid hormones, thyroxine (T4, upper panel) and triiodothyronine (T3; lower panel), in Pacific staghorn sculpin.

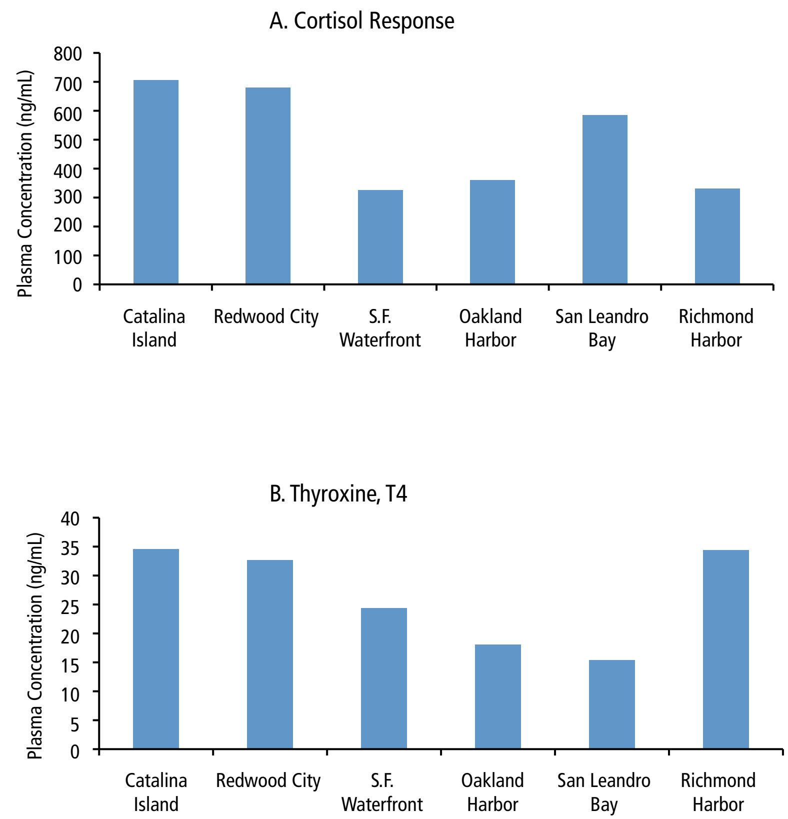


FIGURE 6

Fish sampled from harbor locations like the Oakland and Richmond harbors and at the San Francisco waterfront were significantly impaired in their ability to produce cortisol during a stress challenge. This endocrine disruption was significantly related to exposures to petroleum-derived PAHs (phenanthrene, anthracene, and fluoranthene). The fish also had increased parasitic infestations, suggesting the cortisol disruptions were related to compromised immune function. The effects on cortisol response did not routinely coincide with thyroid alterations, suggesting differential actions of contaminant mixtures present at the different Bay locations.

SELENIUM

Selenium is a naturally occurring element found in geologic formations of the Coast Range. An arid climate and extensive irrigation results in the San Joaquin and Sacramento rivers being the major source of selenium to the Bay, followed by local tributaries, refineries, and wastewater treatment plants (Baginska 2011). A vital nutrient for fish, selenium is critical for the production of thyroid hormones, regulation of the immune system, and management of stress. However the window between necessity and toxicity is one of the smallest known (Baginska 2011).

Selenium can cause embryonic deformities such as malformed spines and impaired feeding systems. In the preliminary North Bay selenium TMDL report, effects thresholds for splittail and white sturgeon are characterized as above 6.0 and 10 µg/g dw, respectively (Baginska 2011). Splittail collected in the Bay in 2000 did not exceed this threshold (Baginska 2011). Between 1997 and 2009, the RMP analyzed 56 sturgeon for selenium with an average of 1.4 ppm wet weight. The Water Board has proposed a sturgeon tissue target of 6.0 to 8.1 µg/g dry weight for the North Bay (Baginska 2011). Few RMP samples (considered on a dry weight basis) have exceeded this range.

The Water Board has proposed a sturgeon tissue target of 6.0 to 8.1 µg/g dry weight for the North Bay - few RMP samples have exceeded this range

Relatively low concentrations of selenium are detected in Bay water; however, the major route of exposure to fish is through their diet. Bottom-feeding fish such as splittail (*Pogonichtuhys macrolepidotus*) and sturgeon (*Acipenser transmontanus*) are considered to be at substantial risk for selenium exposure in the Bay (Beckon and Mauer 2008). Splittail and sturgeon are at risk because their diet consists primarily of the overbite clam (*Corbula amurensis*) (PAGE 37), which are selenium-rich relative to other prey (Stewart et al. 2004). Increased risk factors for sturgeon include their longevity (they can live over 100 years), their year-round resident status, and long egg maturation times (several years) (Beckon and Mauer 2008).

CONCLUSIONS AND PRIORITY INFORMATION GAPS

Our understanding of the effects of individual pollutants on fish growth, development, and reproduction is gradually advancing. However, much of the past work has been conducted by exposing model fish species in a laboratory setting at concentrations that are much higher than what is typically observed in the environment. In the last decade, several research groups have begun to design experiments to evaluate the effects of pollutants at realistic levels on wild fish. This work will be critical for improving understanding of the effects of pollutants on the health of Bay fish.

There is much to be learned and there are many challenges. Future studies will need to address the effects of mixtures that may enhance or ameliorate the potency of individual pollutants. For example, recent work by University of California at Riverside and Davis researchers suggests that commercial formulations of pesticides are more toxic than the active pesticide ingredients, indicating that the inactive carriers (the "inert ingredients") enhance toxicity. Understanding the combined effects of multiple pollutants, including pollutants of emerging concern, will be important. It can be expected that the effect of pollutants on fish will vary among species and habitats. An additional challenge will be to understand the effects of pollutants in combination with other stressors such as food scarcity and other water quality variables (temperature, dissolved oxygen, turbidity, and salinity). Perhaps the hardest issue to address will be the translation of effects on individuals to effects on the population as a whole. It may be that pesticides impair swimming or that pollutants increase susceptibility to disease within individuals, but this may not necessarily translate to impacts at the population level.

The RMP will continue to strive, in collaboration with other Bay-Delta organizations, to provide the scientific understanding needed to reverse the declines that have recently been observed in so many important fish species.

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RECENT FINDINGS ON RISKS TO BIRDS FROM POLLUTANTS IN SAN FRANCISCO BAY

HIGHLIGHTS

Birds are facing significant health risks in San Francisco Bay, due to their exposure to pollutants, and are sensitive indicators of patterns and trends of contamination in the Bay food web

Methylmercury exposure is a major concern for birds in managed ponds and tidal marsh and is suspected of affecting some species at the population level, including special-status species

Available data suggest that PCBs exceed risk thresholds in some birds that forage in the shallow Bay and managed pond habitats

PBDEs are prevalent in species foraging in the shallow Bay and managed ponds, but there are no effects thresholds; PBDE bioaccumulation in tidal marsh birds is largely unstudied

Dioxin and legacy pesticide concentrations in bird eggs are generally below thresholds of concern

AVIAN SENTINELS FOR THE BAY

The extent to which San Francisco Bay birds are affected by pollutants is a topic of great importance to water quality managers and to the public. As the largest estuary on the Pacific Coast of North America, the Bay is a critical habitat for many estuarine bird species. The Bay and its wetlands are a vital refueling stop for large populations of migrating waterbirds and support many species of breeding birds, including several threatened and endangered species and some types of birds found nowhere else in the world. Not only are birds important to the natural heritage of the area, but we also value them as part of our cultural heritage. Birders, hunters, and other nature lovers appreciate birds. The support of wildlife, including birds, is one of many attributes of the Bay that is protected by state and federal water quality regulations.

Aquatic and wetland birds are also important components of the food web; many are predators feeding on fish and invertebrates from several of the main estuarine habitats, including shallow bay, marshes, and managed ponds. In addition, studies have indicated that pollutant impacts are a significant concern for some Bay birds, including special – status species like the California Clapper Rail (*Rallus longirostris obsoletus*) and the California Least Tern (*Sterna antillarum browni*). For all of these reasons, it is important to know the extent to which estuarine birds are negatively affected by chemical pollutants.

Birds are sensitive to environmental contamination, especially during early development as embryos and chicks. Aquatic and wetland birds are exposed to pollutants that are transferred through the food web, and may be harmed by substances such as methylmercury, polychlorinated biphenyls (PCBs), dioxins, selenium, legacy pesticides, and polybrominated diphenyl ethers (PBDEs). The mercury cleanup plan for the Bay (the Total Maximum Daily Load, or TMDL) includes a target for prey fish to protect piscivorous (fish-eating) birds, particularly the endangered California Least Tern. Because many Bay bird species have well-understood life histories in terms of their foraging habitat, home range size, diet, and migratory patterns, they can be excellent sentinels for tracking the spatial and temporal patterns of pollutants in the food web. Birds are commonly used as sentinel species in monitoring programs around the world, including the Great Lakes, the Canadian arctic, the Baltic Sea, and San Francisco Bay, where the Regional Monitoring Program for Water Quality in the San Francisco Estuary has monitored pollutants in birds for nearly a decade.

This article provides an update on what has been learned about the effects of aquatic pollutants on estuarine birds from studies completed in the last decade. These recent findings are organized by estuarine habitat type (**FIGURE 1**), because many pollutants show spatial patterns that differ by habitat. For example, PCBs appear to have higher concentrations in sediments near urbanized and industrialized margins of the Bay (Davis et al. 2007, Ackerman et al. 2008b). Methylmercury, which is the toxic form of mercury in estuarine food webs, exhibits different patterns of bioaccumulation by habitat (Greenfield and Jahn 2010, Grenier et al. 2010), likely due to variation in methylmercury cycling. Furthermore, birds are adapted to forage in particular habitats; therefore, as sentinel species they tend to represent one or two primary habitat types. The species of birds that are the most suited to being used as indicators of pollutant problems in the food webs of different Bay habitats are discussed here. Most of the recent work on avian effects has been on these species, but a few studies on other species are not included in this article (e.g., Takekawa et al. 2002, Hothem and Hatch 2004).

← Cormorants on Seal Rocks. Photograph by Linda M. Wanczyk.

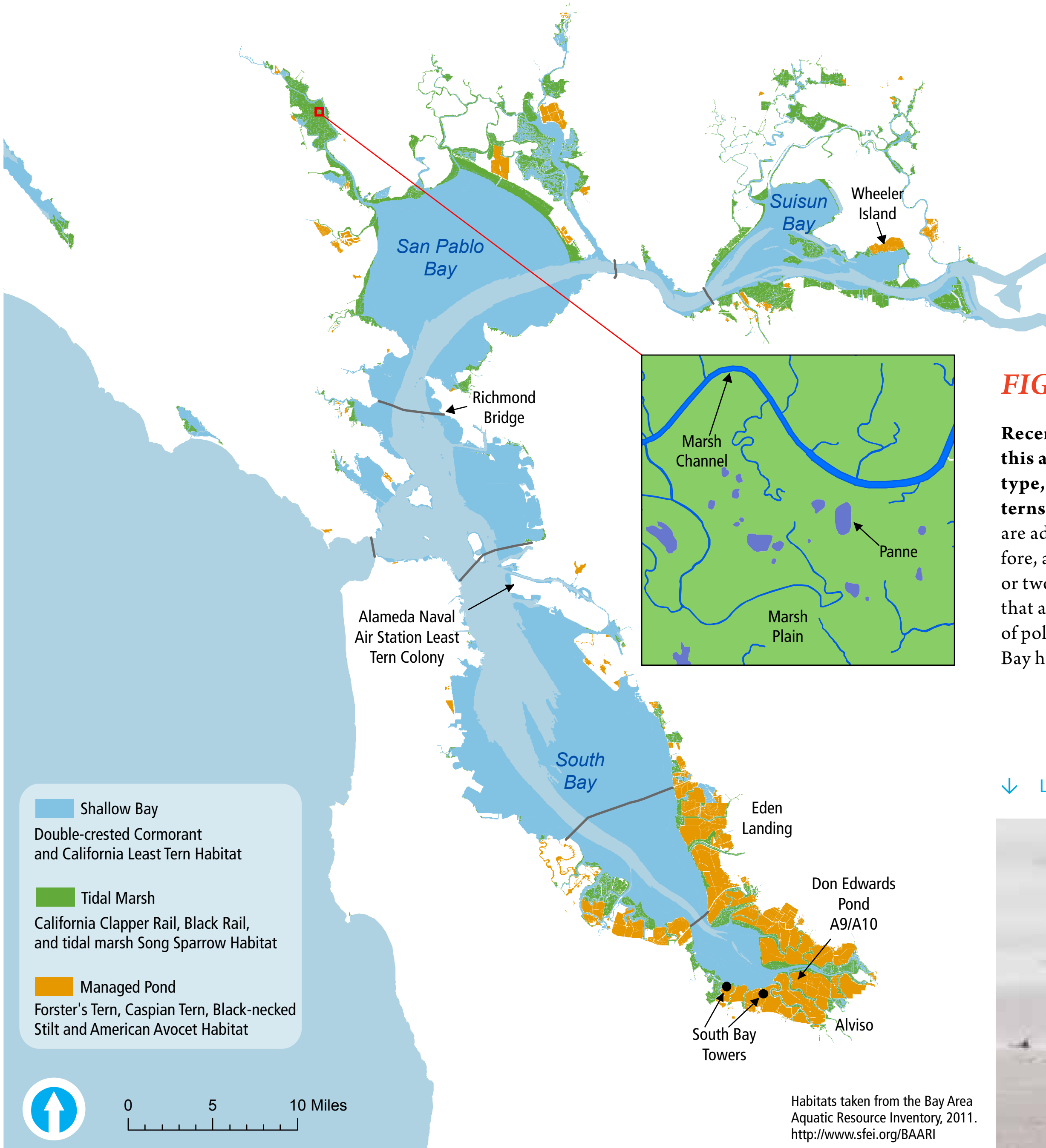


FIGURE 1

Recent findings on pollutants in Bay birds in this article are organized by estuarine habitat type, because many pollutants show spatial patterns that differ by habitat. Furthermore, birds are adapted to forage in particular habitats; therefore, as sentinel species they tend to represent one or two primary habitat types. The species of birds that are the most suited to being used as indicators of pollutant problems in the food webs of different Bay habitats are discussed.

Least Terns. Photograph by Robert Lewis.

SHALLOW BAY

Double-crested Cormorants (*Phalacrocorax auritus*) are used by the RMP as a sentinel species for the open waters of the Bay. Cormorant eggs are sampled Bay-wide every three years for mercury, selenium, PBDEs, PCBs, legacy pesticides, and, starting in 2009, perfluorinated compounds (PFCs). Cormorants forage in a variety of shallow-water habitats (Hatch and Weseloh 1999), including managed ponds (former salt ponds), but they primarily hunt in the subtidal shallows and over mudflats and large sloughs when the tide is in. California Least Terns also forage extensively in these areas, with a preference for shallow Bay habitat near their nesting area (Ehrler et al. 2006). Both species are fish-eaters. Bioaccumulation in Least Terns is more difficult to study, because of the importance of sample collection not adversely impacting this endangered species. The only recent data available for these piscivores come from two small studies of fail-to-hatch eggs from 2000–2002 at the Alameda Naval Air Station colony (Schwarzbach and Adelsbach 2003, She et al. 2008).

METHYLMERCURY

Cormorant eggs have shown regional spatial variation in methylmercury with higher concentrations in the South Bay (**FIGURE 2**), but methylmercury is not likely to be adversely affecting this species. While eggs from San Pablo and Suisun Bays have tended to be at or below adverse effects thresholds for reproductive impairment in Mallards and Ring-necked Pheasants (0.5–0.8 ppm fresh wet weight [fww] - all egg concentrations presented in fww; Fimreite 1971, Heinz 1979), those from the South Bay have tended to exceed those levels. Cormorants, however, are relatively insensitive to methylmercury toxicity compared to other species (Heinz et al. 2009), so it does not appear likely that these concentrations are harming the population. The regional patterns have been consistent over time, with no indication of increasing or decreasing trends within each region. Cormorant eggs also have indicated that there is spatial variation in methylmercury bioaccumulation at a even broader regional scale, with higher concentrations in San Francisco Bay (including Suisun Bay) compared to the Delta (Schwarzbach and Adelsbach 2003).

Very few data are available for methylmercury in California Least Tern eggs. Three fail-to-hatch Least Tern eggs collected in 2000 had an average concentration of 0.3 ppm, which is below the effects thresholds (Schwarzbach and Adelsbach 2003). However, terns as a group may be somewhat more sensitive to methylmercury than the species used to develop the thresholds, based on egg-injection studies, which are difficult to translate into thresholds for wild birds (Heinz et al. 2009). Inclusion of a TMDL target to protect the Least Tern is an indication of the regulatory concern for potential methylmercury impacts on this endangered species.

PCBS

PCB concentrations in cormorant eggs over the last 10 years have occasionally approached an effects threshold of 3.6-6.8 ppm for reproductive impairment in this species (**FIGURE 2**). Concentrations in this species have been variable and not shown distinct regional patterns. Concentrations in San Pablo Bay were relatively high from 2000–2006 (with a maximum of 4.5 ppm in 2002), but lower in 1999 and 2009. Some of the samples from the Richmond Bridge in San Pablo Bay exceeded the lower end of the estimated threshold range for reproductive impairment.

PCB concentrations in Least Tern eggs also indicate potential risks of adverse effects. Average PCBs in ten fail-to-hatch Least Tern eggs collected in 2001 and 2002 (4.0 ppm) were at a published effects threshold for PCBs in terns (also 4.0 ppm), with multiple individual samples exceeding the threshold (She et al. 2008).

PBDES

Effect thresholds for PBDEs in birds are not available, but seemingly high concentrations in some Bay bird egg samples have raised concern. A recent review showed that PBDE concentrations in the eggs of fish-eating birds from the Bay were an order of magnitude higher than those in birds from Chesapeake Bay and the Delaware area (Yogui and Sericano 2009). Concentrations of PBDEs in cormorant eggs varied considerably in space and time among samples collected from the three subembayments (**FIGURE 2**). Concentrations have been highest at Wheeler Island in Suisun Bay, up to a maximum of 800 ppb in 2002. The results from Wheeler Island are interesting as this is the least urbanized sampling location. Concentrations at Wheeler Island and the Richmond Bridge were substantially lower in 2004 and 2006 than in 2002. Continued monitoring will be needed to determine whether this is indicative of a downward trend. Declines in PBDEs are expected as a result of the California Legislature's ban of the use of two types of PBDE mixtures ("penta" and "octa") in 2006.

Least Tern eggs had mean concentrations of 770 ppb in 2001 and 500 ppb in 2002, similar to those observed in cormorants at Wheeler Island (She et al. 2008).

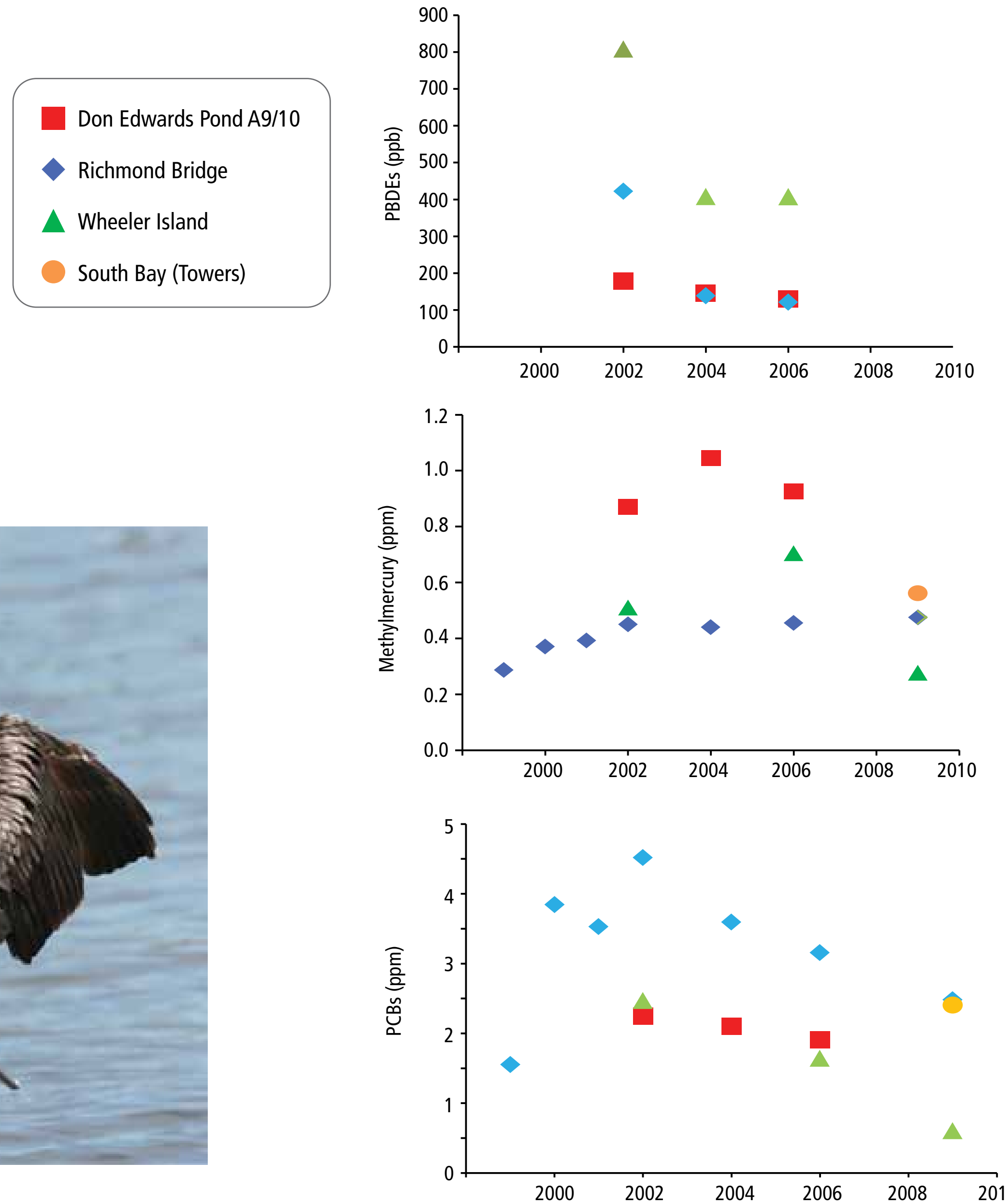
PFOS

Cormorant egg monitoring has shown that fluorinated stain-repellents appear to be reaching concentrations of concern in the Bay food web. Perfluorinated chemicals (PFCs) have been used extensively over the last 50 years in a variety of products including textiles treated with stain-repellents, fire-fighting foams, refrigerants, and coatings for paper used in contact with food products. As a result of their chemical stability and widespread use, PFCs such as perfluorooctane sulfonate (PFOS) have been detected in the environment. PFOS and related PFCs have been associated with a variety of toxic effects including mortality, carcinogenity, and abnormal development.

In 2006, the RMP began analyzing cormorant eggs for PFCs. Consistent with other published studies, PFOS was the dominant PFC detected in cormorant eggs. Concentrations of PFOS were highest in the South Bay, and higher

FIGURE 2

Double-crested Cormorants are monitored by the RMP as a sentinel species for the shallow open waters of the Bay. Cormorant eggs have shown higher concentrations in the South Bay ("Don Edwards Pond A9/10" and "South Bay [Towers]"), but methylmercury is not likely to be adversely affecting this species due to its low sensitivity to this pollutant. PCB concentrations over the last 10 years have been variable and not shown distinct regional patterns, and have occasionally approached an effects threshold for reproductive impairment. Concentrations of PBDEs have varied considerably among the three subembayments and over time, and are high relative to other parts of the world, but a lack of thresholds makes it unclear whether these concentrations are affecting Bay bird species.



↑ Double-crested Cormorant. Photograph by Robert Lewis.

than concentrations reported in other regions (Houde et al., 2006). Concentrations were similar in 2006 and 2009. The concentrations in the South Bay exceeded an estimated no effect concentration of 1 ppm.

OTHER POLLUTANTS

The other bioaccumulative pollutants that have been studied in Double-crested Cormorant eggs have been below effect thresholds, and no recent studies have examined other pollutants in California Least Terns. Since 1999, only one composite cormorant egg sample from Wheeler Island in 2002 exceeded the 5 ppm effects threshold for reproductive impacts for DDT (Weseloh et al. 1983) with a concentration of 7 ppm DDT. No previous or more recent cormorant egg samples approached any effects thresholds for DDT, dieldrin, dioxins, or other pollutants.

MANAGED PONDS

Managed ponds are the former salt ponds around the margin of the Bay that were originally tidal marsh. These ponds are now largely managed to support waterbirds, such as terns, plovers, ducks and shorebirds. Some managed ponds are shallow and seasonal, drying out in the summer and fall. Others are perennially wet and support fish year round. Forster's Tern (*Sterna forsteri*), Caspian Tern (*Sterna caspia*), American Avocet (*Recurvirostra americana*), and Black-necked Stilt (*Himantopus mexicanus*) all feed and breed primarily in and around managed ponds, and all have been studied extensively in recent years, particularly regarding methylmercury accumulation and effects. The terns are piscivores, while stilts and avocets feed on invertebrates in shallower ponds.

METHYLMERCURY

Forster's Terns appear to face significant risk from exposure to methylmercury. Nearly half (48%) of breeding Forster's Terns and approximately 5% of Avocets, Stilts, and Caspian Terns (Eagles-Smith et al. 2009) exceeded a risk threshold developed for Common Loon (*Gavia immer*) blood of (3 ppm wet weight) at which there was a 40% loss in loon reproduction (Evers et al. 2008). Estimated reproductive risks to these species based on egg methylmercury concentrations are very similar (Eagles-Smith et al. 2009). Tissue concentrations are consistently higher in the South Bay near the town of Alviso. Methylmercury concentrations in Forster's Tern eggs have fluctuated considerably over time, with annual averages in the most recent monitoring all exceeding reproductive effects thresholds.

Despite the strong evidence for risk to these populations from methylmercury toxicity, verifying reproductive impacts through field study is difficult. Many other factors influence avian survival and add to noise in the data set. Forster's Tern hatching success shows evidence of impacts from mercury. Fail-to-hatch eggs of Forster's Terns had higher average methylmercury concentrations than abandoned eggs and random eggs sampled from successful nests (Eagles-Smith and Ackerman 2008). Stilt and avocet chicks found dead had higher methylmercury in their feathers than randomly-sampled live chicks of similar age, but chick survival rates varied little based on their methylmercury bioaccumulation (Ackerman et al. 2008a). Similarly, fledgling Forster's Tern survival was not related to blood methylmercury concentration (Ackerman et al. 2008b). A detailed summary of this research can be found in the 2008 Pulse of the Estuary (Eagles-Smith and Ackerman 2008).

PCBS

PCB concentrations in some eggs of Forster's and Caspian Terns appear to be high enough to pose health risks to these species. Average PCB concentrations in Forster's and Caspian Tern eggs collected from 2000-2003 were below a 4 ppm threshold for impacts on reproduction, but many individual eggs exceeded this value (She et al. 2008). Maximum concentrations observed in both Forster's Terns and Caspian Terns were similar and nearly five times greater than the lowest observed adverse effect level for reproduction. The Eden Landing area in South Bay had the highest concentrations of PCBs.

PBDES

Some of the highest concentrations of PBDEs observed anywhere in the world have raised concern for possible impacts on Forster's Terns in the Bay (Shaw and Kannan 2009). There is a growing body of data from many urbanized coasts for comparison, including many species of fish-eating birds from Canada, New England, San Francisco Bay, Delaware Bay, Alaska, Washington state, Europe, South Africa, and China. Annual average PBDE concentrations in eggs of Forster's Terns (ranging from 330–990 ppb) and Caspian Terns (320–580 ppb) were similar to concentrations in Least Terns and cormorants from Wheeler Island (She et al. 2008). A few of the Forster's Tern samples from Eden Landing had the highest PBDE concentrations ever recorded in wildlife (She et al. 2004).

TIDAL MARSH

Tidal marshes are highly organized habitats that are composed of clearly distinguished sub-habitats (marsh plain, marsh channel, and panne) that develop because of the unique hydrology of these wetlands. Food webs may be somewhat separate among these habitats (Grenier 2004), so it is important to understand where sentinel species forage within a tidal marsh. Three tidal marsh bird species have been studied for exposure to methylmercury, although not to the extent of the terns and cormorants in the shallow bay and managed ponds. Thus, information about tidal marsh bird methylmercury exposure and effects is quite limited and tends to come from a few studies completed in different marshes at different times, California Clapper Rail. Photograph by Robert Lewis. →

rather than from long-term programmatic monitoring. The three bird species that have been studied differ in the habitats in which they forage. While tidal marsh Song Sparrows (*Melospiza melodia subspp.*) and California Black Rails (*Laterallus jamaicensis coturniculus*) forage predominantly in the vegetated marsh plain (Grenier 2004, Tsao et al. 2009), California Clapper Rails forage extensively in marsh channels and somewhat in the marsh plain (Moffitt 1941).

METHYLMERCURY

Methylmercury is considered a significant concern for several species of tidal marsh birds. The recovery of the endangered California Clapper Rail, found only in the San Francisco Estuary, may be impeded by methylmercury contamination. A study conducted from 1991-1999 concluded that methylmercury was a likely cause of the unusually high rates of nonviable Clapper Rail eggs (31%; Schwarzbach et al. 2006). Methylmercury was found in rail eggs above effects thresholds at all of the marshes studied; means by marsh ranged from 0.27–0.79 ppm wet weight (Schwarzbach et al. 2006). Furthermore, laboratory studies have indicated that Clapper Rails are more sensitive to methylmercury than the pheasant and Mallard species from which the thresholds of 0.5 and 0.8 ppm fresh wet weight were derived (Heinz et al. 2009).

Tidal marsh Song Sparrows, a state species of special concern, and Black Rail, a state threatened species, both had methylmercury concentrations in blood that indicated potential risks of impaired reproduction. For the sparrows, comparison to a songbird effects threshold is appropriate. A recent study linked blood methylmercury concentrations to reproductive effects in the Carolina Wren (*Thryothorus ludovicianus*), yielding an estimated relationship between reductions in nesting success and maternal blood concentrations (Jackson et al. in preparation). Based on that study, maternal songbird blood methylmercury concentrations of 0.4 ppm wet weight translate to approximately a 5% reduction in reproductive success.

Average Song Sparrow blood methylmercury concentrations in the South Bay ranged from 0.1–0.6 ppm wet weight by marsh, and more than half the sparrows were above the 0.4 ppm threshold in both years of the study (**FIGURE 3**; Grenier et al. 2010). Song Sparrow methylmercury concentrations were lowest in marshes far from the Bay and highest in marshes near the Bay (**FIGURE 3**), which parallels the salinity gradient (Grenier et al. 2010). Blood methylmercury concentrations in Black Rails from North Bay were in the same range as the Song Sparrow concentrations, and about 10% of them were in a range corresponding to a moderate risk for reproductive effects (> 1 ppm and < 3 ppm wet weight), based on the same Common Loon model used to describe the Forster's Tern data above (Tsao et al. 2009).

OTHER POLLUTANTS

A few studies have examined persistent organic pollutants in the eggs of Clapper Rail (PCBs and legacy pesticides: Schwarzbach et al. 2006, dioxins: Adelsbach and Maurer 2007, PCBs and PBDEs: She et al. 2008), and one study measured PCBs and DDT in Song Sparrow eggs from North Bay (Davis et al. 2004). In all cases but one, these pollutants were detected in the marsh bird eggs, but the concentrations were relatively low and did not approach effects thresholds. Adelsbach and Maurer (2007) reported that four fail-to-hatch Clapper Rail eggs from North and South Bay had dioxins at concentrations that might impact reproduction. Thus, based on the few marshes and analytes examined, very little evidence of the potential for adverse effects from persistent organic pollutants on marsh birds in the Estuary has been found. This is an encouraging outcome, in that it indicates that a pervasive, Bay-wide problem is unlikely. However, since these pollutants typically exhibit hotspots near watershed sources, the sampling conducted to date cannot rule out problems in unstudied marshes near industrial and urban areas.

PRIORITY INFORMATION GAPS

Given that there is evidence for potential effects of pollutants on birds in every habitat in the Estuary that has been monitored, where should we focus our efforts? What information is the most important to gain that could reduce exposure and risk through improved management or regulation? A few priority areas stand out.

ARE THERE POPULATION-LEVEL EFFECTS?

In many cases, exposure in birds exceeds an effects threshold for a pollutant. What does this really mean? To what extent are the birds impacted? Can the avian population in this urbanized environment with many other stressors absorb a reproductive loss related to pollutants, or will the population decline?

WHAT ARE EFFECTS THRESHOLDS FOR PBDES, ESPECIALLY IN TERNS?

PBDEs reach seemingly high concentrations in terns, but the adverse effects, if any, are unknown. The RMP has funded a study by the Patuxent Wildlife Research Center to evaluate the relative sensitivity of tern embryos to PBDE exposures. The results will be available at the beginning of 2012.

SHOULD EXPOSURE IN BIRDS BE EVALUATED RELATIVE TO AMBIENT CONDITION RATHER THAN TO SPECIES-SPECIFIC THRESHOLDS?

Bird species vary in their sensitivity to each pollutant, yet species-specific thresholds will not be forthcoming in the near future. Thus, there are uncertainties associated with managing and regulating water quality based on effects thresholds developed with a few laboratory species (e.g., chicken, Mallard, pheasant) that cannot accurately represent the diversity of wild birds that reside in Bay habitats. Therefore, it may be valuable to explore other approaches to evaluating wildlife exposure, particularly comparison to ambient condition. It seems likely that pollutants impact many wildlife species in the Bay to some degree, especially when considered as a compound effect with other pollutants, disturbance, habitat degradation, and other stressors. A reasonable approach might be to manage pollutants so as to improve condition in the worst places or at least not make things worse through management actions, and then re-evaluate the situation every 5 or 10 years. A solid understanding of spatial and temporal patterns in bioaccumulation would be needed to support this type of approach.

HOW CAN SCIENCE BE MORE CLOSELY LINKED TO IMPROVING MANAGEMENT DECISIONS?

This is an ongoing challenge for the environmental community – to get the most out of research and monitoring dollars by making sure that they positively affect decision-making and improve environmental outcomes. The RMP is funding a synthesis of mercury information from the Estuary, which will create conceptual models that tie scientific knowledge to feasible management actions for reducing methylmercury in biota. The report will be available by the end of 2011.

SIDEBAR

ANOTHER DIMENSION OF THE MERCURY PROBLEM

Methylmercury bioaccumulation in songbirds residing along Bay Area streams may also be high enough to cause reproductive impacts at some sites. Song Sparrows (*Melospiza melodia*) were used as a methylmercury biosentinel for riparian (streamside) habitat throughout the Bay Area in 2010. Twenty sites and 140 Song Sparrows were sampled, with blood mercury concentrations spanning more than two orders of magnitude. This project was guided by a group of regional and national scientific experts in mercury, riparian habitat, and songbirds that helped determine the appropriate biosentinel species and sampling approach.

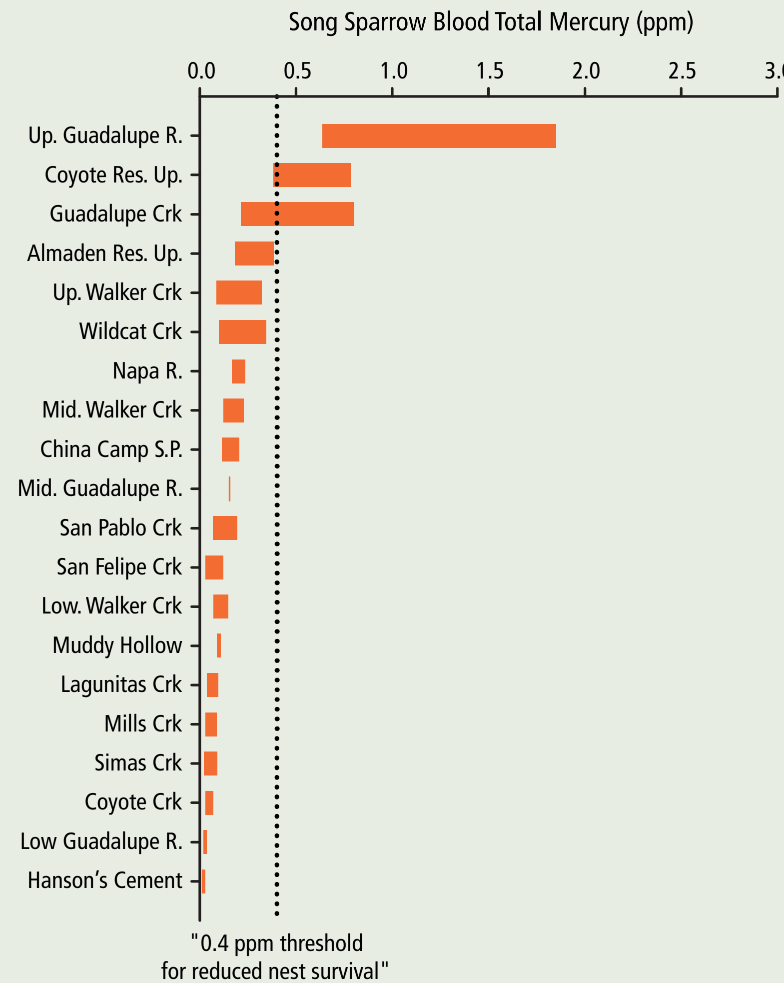
Sampling sites were chosen based on a conceptual model in which the key drivers of songbird exposure were 1) total mercury contamination of sediment and 2) environmental conditions that were thought to affect production of methylmercury. The findings supported the conceptual model in that both total mercury contamination and environmental conditions were related to blood methylmercury concentrations in sparrows. The site with the greatest methylmercury exposure in songbirds was downstream of the New Almaden Mercury Mining District, but the second highest site was not influenced by mining.

More than a dozen other bird species were also sampled, and a few of those species appeared to have higher exposure than Song Sparrows. Thus, Song Sparrows may be an indicator of riparian methylmercury accumulation in the food web, but they may not reflect the greatest impacts that are occurring to riparian wildlife.

Average methylmercury concentrations at two of the 20 sites sampled were above 0.4 ppm (ww). A recent study in Carolina Wrens that examined the relationship between maternal blood mercury concentration and reproductive effects found that concentrations of 0.4 ppm translated to an approximate 5% reduction in nest survival (the number of nests that successfully hatched chicks) (Jackson et al. in prep). The highest mercury concentrations measured in riparian Song Sparrows of the Bay Area were above 2.5 ppm, a level associated with a 50% decline in nest survival.

Many of the sites in this study were in an urbanized environment where wildlife populations are subject to multiple stressors. In these stressed populations, there may be little to no surplus of young birds each year, which would amplify the consequences of reproductive loss from methylmercury effects.

This innovative study, which builds on a nascent body of work on songbird methylmercury east of the Rockies, appears to have revealed another dimension of the mercury problem in the Bay Area. The findings have implications for mercury impacts in habitats across California and beyond that have received little attention to date.



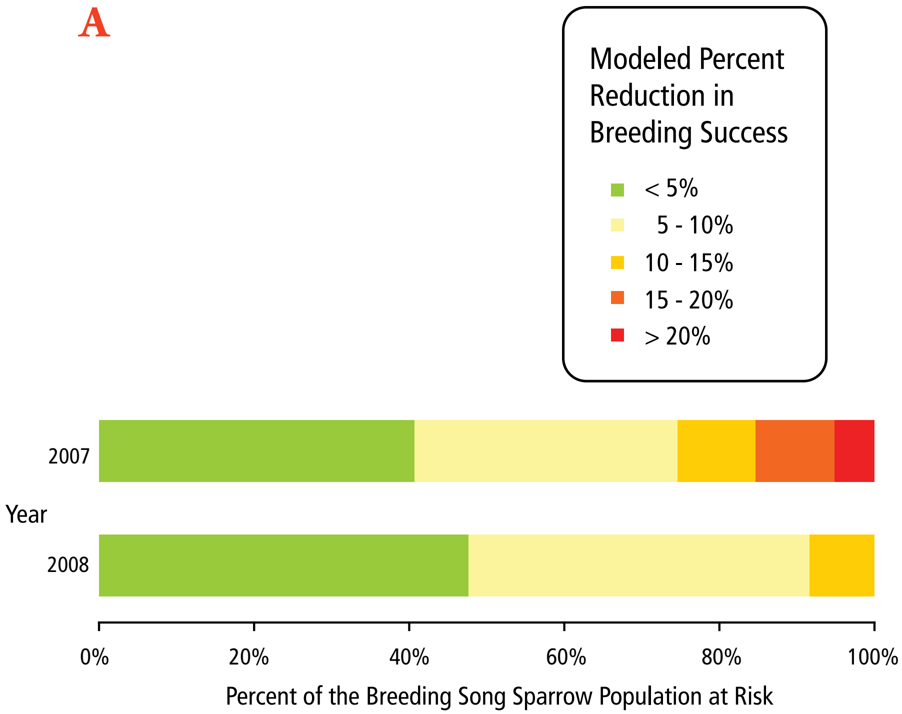
Footnote: Bars show range of the middle 50% of the observations.

FIGURE 3

(A) The estimated risk to the South Bay tidal marsh sparrow population varied somewhat by year. In both 2007 and 2008, more than half of the sparrows were at risk for an estimated 5% or greater reduction in nesting success from methylmercury effects. **(B) Song Sparrow blood methylmercury concentrations (based on 109 birds) were higher in marshes closer to the Bay.** One hypothesis for this pattern is that there may be a relationship between marsh type (brackish versus salt) and methylmercury bioaccumulation.

← Song Sparrow. Photograph by Robert Lewis.

A



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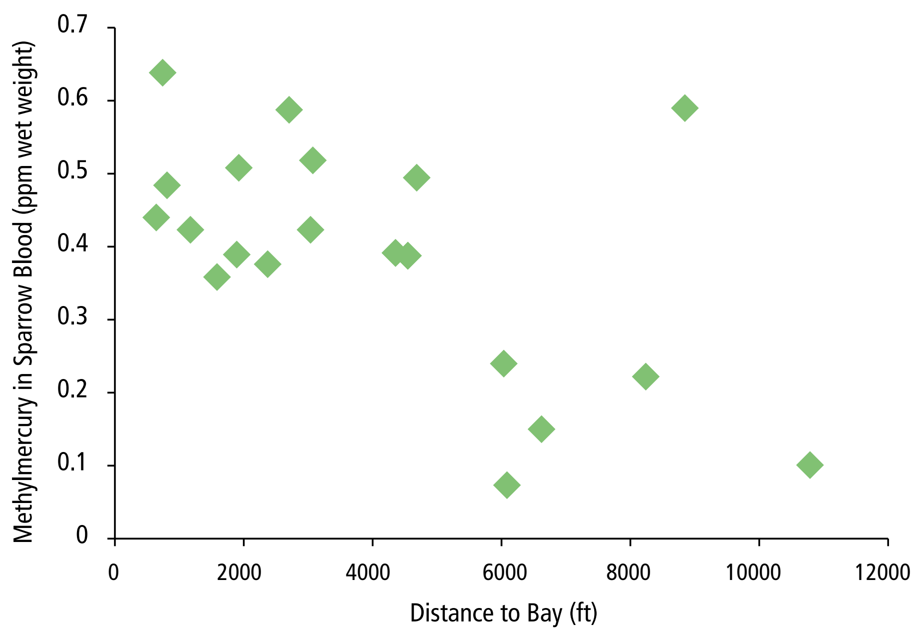

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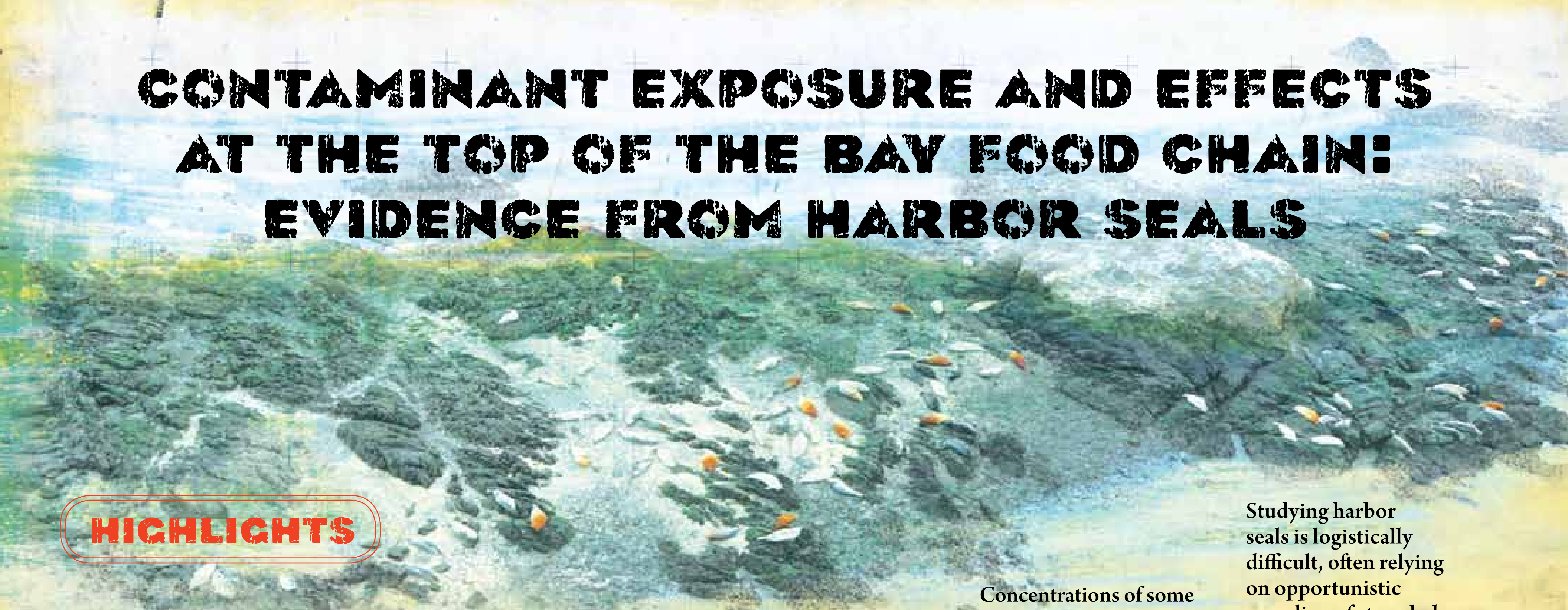
CONTAMINANT EXPOSURE AND EFFECTS AT THE TOP OF THE BAY FOOD CHAIN: EVIDENCE FROM HARBOR SEALS



HIGHLIGHTS

- Pacific harbor seals are found year-round in San Francisco Bay, feed at the top of the food chain, and maintain a large store of fat, all factors that put them at risk of accumulating toxic contaminants and make them good monitoring sentinels
- Along much of the California coast, harbor seal populations rebounded after hunting was banned in the 1970s, but similar increases did not occur in San Francisco Bay
- Concentrations of contaminants such as organochlorine pesticides, PCBs, mercury, and selenium in tissues are elevated to levels that may cause health effects in Bay harbor seals
- Concentrations of some contaminants, such as PBDEs from flame retardants and perfluorinated compounds are elevated in seal tissues to levels as high or higher than those measured in other parts of the world
- Studying harbor seals is logistically difficult, often relying on opportunistic sampling of stranded animals, so there are many data gaps and challenges to be met

THE TOP OF THE BAY FOOD CHAIN

The Pacific harbor seal (*Phoca vitulina richardii*) is a year-round resident of San Francisco Bay and the surrounding coastal waters. It is the area's only permanent resident pinniped, the group that includes seals, sea lions, and walruses. Harbor seals are only semi-aquatic, depending on beaches and other haul-out sites for daily resting and for giving birth during the spring pupping season. Harbor seals can be found throughout the Bay. Major haul-out and pupping sites include Mowry Slough at the Don Edwards San Francisco Bay National Wildlife Refuge in the South Bay, Yerba Buena Island, and Castro Rocks, next to the Richmond-San Rafael Bridge in the North Bay (**FIGURE 1**).

Harbor seals were probably abundant in the Bay until the late 1800s, when hunting for their pelts, oil, and meat began to take a toll. By the 1920s, hunting had seriously reduced the population (Grigg 2003, Neale et al. 2005). Systematic surveys did not begin until the 1970s, when concerns about the effects of pollutants and habitat loss spurred the interest of scientists and the community. Seal hunting ended with the passage of the federal Marine Mammal Protection Act of 1972, and afterwards, numbers dramatically increased along most of the California coast. Population increases have been much slower in the Bay, largely due to habitat loss and other human disturbance, and possibly also due to chemical contaminants. There are currently about 34,000 harbor seals in California. About 400–500 harbor seals lived within the Bay during the 1980s, and the current population remains around 500.

Year-round residency, feeding at the top of the food chain and close to the shore, and maintaining a large mass of fatty tissue over many years put seals at particular risk of accumulating toxic pollutants

Harbor seals are at the top of the Bay food chain, generally feeding close to shore on both bottom and schooling fishes and on squid and crustaceans. Healthy harbor seals have thick blubber, used for insulation and energy reserves, and may live up to 30 years. These factors – year-round residency, feeding at the top of the food chain and close to the shore, and maintaining a large mass of fatty tissue over many years – put seals at particular risk of accumulating toxic pollutants.

Excavation of the large Native American shellmounds found along San Francisco and East Bay shorelines indicates that harbor seals have been present in the Bay for thousands of years.

The Marine Mammal Protection Act prohibits any killing or harassing of seals, elephant seals, sea lions, whales, porpoises, and other marine mammals. Under that mandate, the National Oceanic and Atmospheric Administration's National Marine Fisheries Service (NMFS) leads the Marine Mammal Health and Stranding Response Program to investigate strandings and deaths and analyze tissue samples for toxic substances and diseases. NMFS, in collaboration with the National Institute of Standards and Technology, maintains a tissue bank for samples taken from stranded animals and other sources. The goal of the tissue bank is to provide material for studies of geographic and temporal trends. On the state level, the San Francisco Bay Regional Water Quality Control Board protects the estuarine, marine, and wildlife habitat of the harbor seal.

To scientists, harbor seals are useful sentinels of adverse conditions and have been used to identify regional contaminant hotspots, even when tissue contaminant levels are below those suspected of causing harm. A growing body of literature from the world's five subspecies of harbor seals suggests that exposure to contaminants can reach levels that contribute to population declines (e.g., Marine Environmental Research Institute 2006).

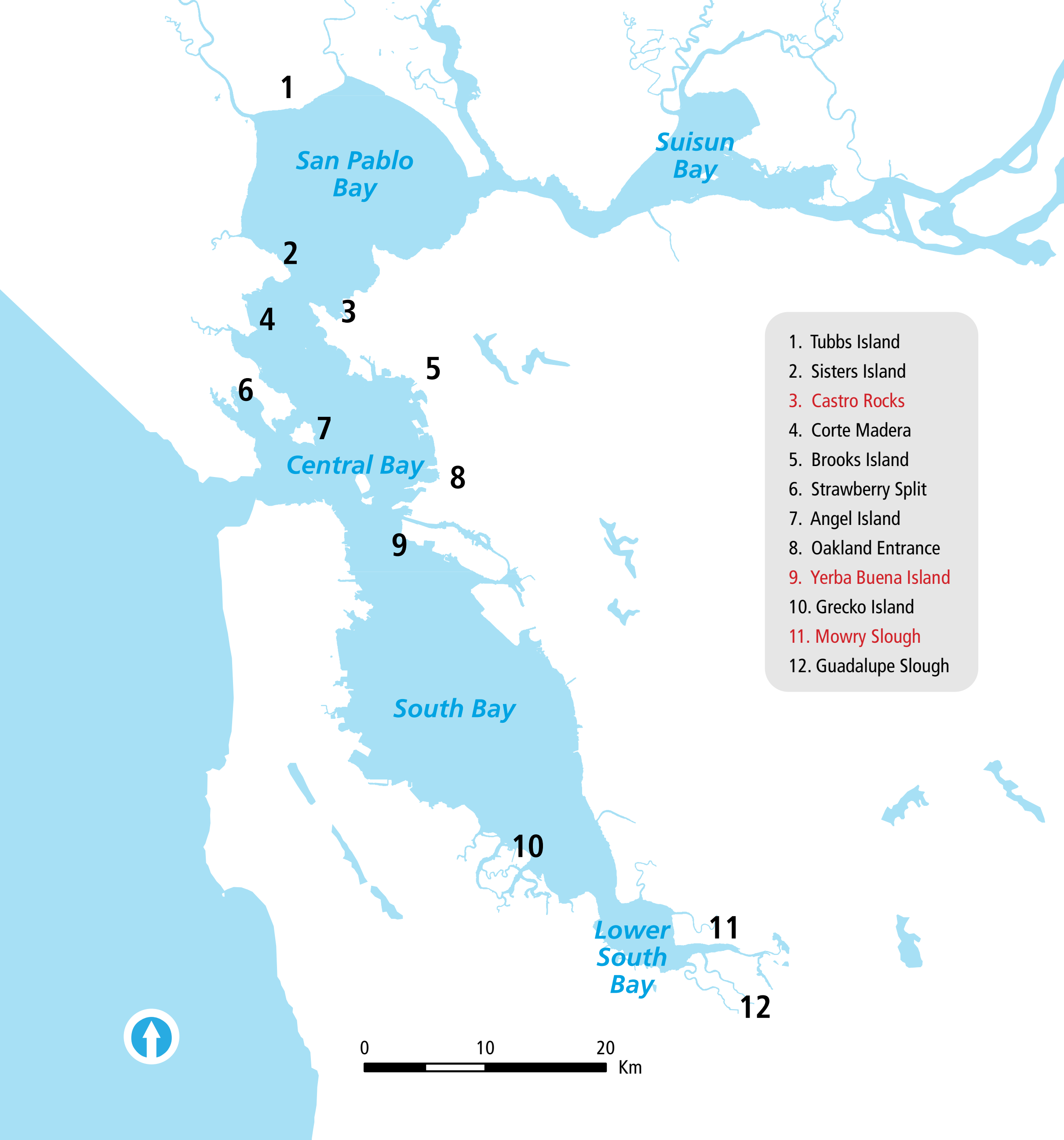
Studies of harbor seals are challenging, making them difficult to include in routine monitoring programs. Some studies acquire samples opportunistically, collecting blood, blubber, and other samples from dead animals or from animals that have been rescued. Capturing healthy live animals for sampling requires federal permits and is logistically challenging because they can be difficult to capture.

The Regional Monitoring Program for Water Quality in the San Francisco Estuary (RMP) has benefitted from collaboration with The Marine Mammal Center in Sausalito and other research scientists. The Marine Mammal Center provides regional expertise and facilities for marine mammal rescue and rehabilitation, serving much of the central California coastline. They treat stranded animals, including harbor seals, at their hospital and when possible, release them back into the wild. In 2010, they treated 132 harbor seals and were able to release 73 of them. The Marine Mammal Center staff works with scientists around the world to learn from the animals they rescue. Their publications (http://www.marinemammalcenter.org/science/publications/), provide a valuable resource for understanding the threats to marine mammals, including the threats from exposure to chemical contaminants.

← Harbor seals on Castro Rocks. Photograph by Suzanne Manugian.

FIGURE 1

Major harbor seal haul-out sites in San Francisco Bay. Castro Rocks, Yerba Buena Island, and Mowry Slough are the most heavily used sites.



Harbor seal mother and pup. Photograph by Suzanne Manugian.

ORGANIC CONTAMINANTS ACCUMULATE IN SEAL BLUBBER AND OTHER TISSUES

Studies of organic contaminants in San Francisco Bay harbor seals began in the 1990s (reviewed for the RMP in Thompson et al. 2007). Those studies documented elevated levels of organic pollutants, such as PCBs and organochlorine pesticides, that persist for long periods in the environment, biomagnify up the food chain, and accumulate in fatty tissues, such as seal blubber. Other studies from the 1990s documented a variety of abnormal health parameters in harbor seals, such as low red blood cell counts and high white blood cell counts, and hypothesized that environmental pollutants might be causing some of those conditions (Kopec and Harvey 1995).

In 2001–2002, scientists from the University of California Davis and other organizations, including The Marine Mammal Center, undertook an integrated study of contaminant levels, immune function, and biological parameters in healthy, wild seals (Neale et al. 2005). Scientists captured and took blood samples from 35 free-ranging Bay harbor seals. The 13 males and 22 females, including pups, yearlings, and adults, were captured with beach seines and tangle nets from haul-out sites. All seals were re-released to the wild after weighing, measuring, and drawing blood samples. The blood samples were then analyzed for DDE (a breakdown product of the pesticide DDT), polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs), and biological parameters.

The investigators found that higher DDE, PCB, and PBDE levels in the blood correlated with white blood cell counts, suggesting that high levels of contaminants might be associated with increased rates of infection. There was an inverse relationship between total PBDEs and red blood cells, although the relation was not strong enough to suggest a clear contaminant link to anemia. When the scientists compared their results with earlier studies, they found some evidence of declining levels of PCBs in Bay seals, although concentrations remained high enough to warrant continuing concerns for reproductive or immunological effects.

Another recent study examined the effects of developmental stages on concentrations of organic contaminants in very young central California harbor seals (Greig et al. 2011). Seal pups are exposed to organic contaminants through the placenta before birth and through milk during the three-to-five weeks nursing period after they are born. The study sampled blubber from 180 wild and stranded young-of-the-year animals, and categorized them by age and source of contamination (for example, placenta, milk, or other diet). Blubber samples were also taken from 23 older seals and two fetuses. The samples were analyzed for a broad range of organic pollutants, including PCBs, PBDEs, and organochlorine pesticides.

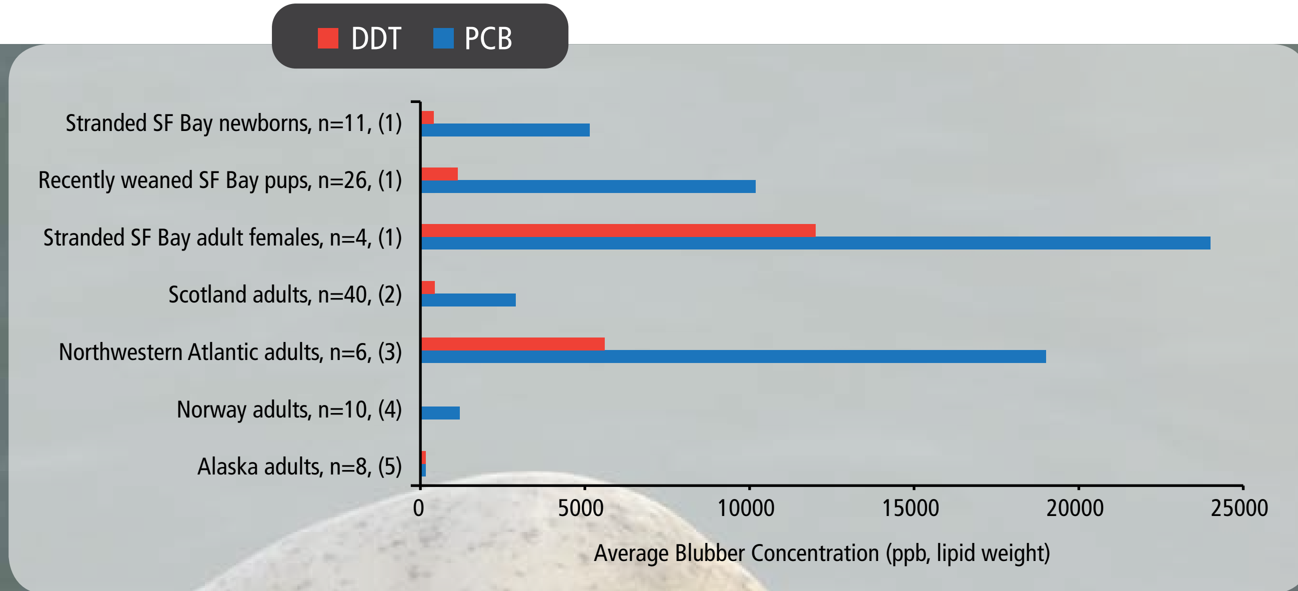
The study found the highest concentrations of organic contaminants in blubber from pups that had been weaned in the wild, lost weight, then stranded and died. These results showed that harbor seals may be at particular risk during a post-weaning period, during which contaminants move from blubber into the blood. Using a subset of the data, newborn pups found dead near the location of birth, the researchers could begin discern some geographic patterns, with pups from San Francisco Bay having contaminant profiles suggestive of more urban inputs and those from Monterey Bay showing more agricultural influence.

These studies began to make a case that levels of organic contaminants in San Francisco harbor seals appeared to be elevated. Comparable studies have suggested that for some pollutants, conditions are similar in other parts of the world (**FIGURE 2**).

> Organic pollutants, such as PCBs and organochlorine pesticides, persist for long periods in the environment, biomagnify up the food chain, and accumulate in fatty tissues, such as seal blubber

FIGURE 2

Average concentrations of blubber PCBs and DDTs from harbor seals sampled in San Francisco Bay and around the world.



Footnote: Where sex is not specified, adults are half male, half female. 1) Greig et al. 2011, 2) Hall and Thomas 2007, 3) Shaw et al. 2005, 4) Wolkers et al. 2004, 5) Wang et al. 2007.

↑ Harbor seals on Castro Rocks. Photograph by Suzanne Manugian.

MERCURY AND OTHER METALS

Just as the human population is concerned about mercury levels in seafood, harbor seals are at risk from the legacy of mercury mining in the South Bay and use of mercury in the Sierra foothills during the Gold Rush. Selenium is another environmental concern in the Bay, but it is especially interesting, because it can counteract some harmful effects of mercury in harbor seals. Changes in relative levels of the toxic form of mercury, methylmercury, in comparison to selenium levels can be indicative of increased mercury toxicity. Seals may also be at risk of toxicity from other metals, such as lead.

Mercury and other inorganic elements were the subject of a 2003–2005 project that analyzed tissue samples from 186 live and 53 dead seals from central and northern California (Brookens et al. 2007). Live seals were captured in Monterey Bay, San Francisco Bay, Point Reyes, and Humboldt County for blood and hair samples. Blood, hair, and liver samples were taken from dead seals found at sites along the coast of central California, including San Francisco Bay. All samples were analyzed for methylmercury, total mercury (methyl mercury plus inorganic mercury), selenium, and lead.

This study found elevated concentrations of mercury and selenium in the blood samples, sometimes higher than levels known to be toxic to mammals. The average total mercury in the blood samples exceeded levels that had previously been recorded for harbor seals, although average values in liver samples were within the known range. Total mercury concentrations in liver tissues increased linearly with age, while methylmercury concentrations increased exponentially for the first five years of life, leveling off in adults. These results suggested that the mechanisms for detoxifying methylmercury are not well developed until harbor seals reach adulthood. Age-related changes in the mercury to selenium ratios corroborated that finding.

Except for samples from one adult female, lead concentrations were uniformly low. That seal was weak and experiencing seizures when it came into The Marine Mammal Center facilities and died four days later. A necropsy found a lead fishing sinker in the seal's stomach and high lead levels in blood and liver tissues (Zabka et al. 2006). The sinker was a common type used by sport and commercial fishermen and was too large to move through the digestive system.

No clear geographic trends in metals concentrations were detected during the Brookens et al. (2007) study, a little surprising to the scientists, who had anticipated finding higher mercury levels in San Francisco Bay and Tomales Bay than the other central California sites. Studies of sediments, oysters, and fish had found clear differences in San Francisco Bay and Tomales Bay, both areas with histories of mercury mining. The scientists attributed the lack of trends in the harbor seal study to difficulties in differentiating sources of exposure in large, mobile animals of varying ages and developmental stages.

A subsequent study of seal pup tissues suggested that muscle samples may be the best tissue for mercury monitoring, when they are available (Brookens et al. 2008). In this study, scientists sampled brain, heart, liver, kidney, muscle, blubber, and other tissues from 26 seal pups that were found dead on the shoreline or that had been admitted for rescue but subsequently died. Total mercury levels were highest in hair samples, but the levels in muscle samples correlated better with results from other tissues, making it the best measure for comparisons with other studies.

> The study found elevated concentrations of mercury and selenium in the blood samples, sometimes higher than levels known to be toxic to mammals

Seals accumulate mercury, in the form of methylmercury, mostly from eating fish. Methylmercury bioaccumulates and biomagnifies through the food chain. Seals and other mammals are able to transform methylmercury in their digestive systems and livers into another form, inorganic mercury. Both methylmercury and inorganic mercury can be retained in the liver, circulated through the blood system, and excreted in urine and feces. Total mercury levels in blood, including both methylmercury and inorganic mercury, are regarded as good indicators of ongoing exposure to contamination within a specific geographic area.

Mercury, particularly methylmercury, can also be incorporated into hair. Mercury levels in hair samples provide a longer term record of exposure than blood samples. Female seals can also transfer methylmercury to across the placenta fetuses and, to a lesser degree, into milk.

SENTINELS FOR BAY CONTAMINANTS

Some recent studies of harbor seals in the Bay have generated considerable public attention. For example, when scientists analyzed seal blubber samples that had been collected and archived from stranded, dead harbor seals during 1989–1998, PBDE levels were among the highest ever reported (She et al. 2002). Of most concern, the highest concentrations came from seals collected in later years (**FIGURE 3**). When normalized for lipid content, the results showed that concentrations were doubling every 1.8 years. These results were reported around the world and were important for making the case to ban two of three classes of PBDEs in California. Oregon has banned all three classes of PBDEs, and the giant retailer Wal-Mart, has also instituted a ban on all PBDEs. Chemical companies in the U.S. have ceased manufacture of the two classes of PBDEs that are banned in California and will begin to phase out manufacture of the third type in 2012.

In 2006–2008, the RMP teamed up with scientists from The Marine Mammal Center to study perfluorinated compounds (PFCs) and other contaminants in blood of harbor seals from sites near the Richmond Bridge in the North Bay and in Mowry Slough in the South Bay (Sedlak et al. in prep). PFCs, which are used in products such as Teflon© and 3M Scotchgard™, bind to proteins and are typically detected in the blood and liver, rather than in fatty tissues. The scientists compared the results from Bay samples to measurements from seals in Tomales Bay, which was considered an uncontaminated reference site for PFCs. Seal blood concentrations of PFCs from both San Francisco Bay sites were about ten times higher than those in seals from Tomales Bay and higher than most comparable measurements in seals anywhere in the world (**FIGURE 3**).

To date, little work has been conducted on the biological effects of PFCs in seals. In general, PFCs in mammals are associated with reproductive problems, suppressed immune systems, and liver cancer. One study of seals in Lake Baikal in Russia suggested that PFCs could affect the signaling pathway related to transforming normal cells into cancers. A recent study of the California sea otter population along the central California coast identified a significant correlation between the presence of PFCs and the incidence of disease.

There was good news in another collaboration with The Marine Mammal Center. The RMP has recently completed a project to quantify a newer brominated flame retardant, hexabromocyclododecane (HBCD), in seal tissues. HBCD is added to polystyrene insulation that is used in building construction. The study found relatively low levels of the compound in Bay seals, lower than levels detected in similar studies in Asia and much lower than levels detected in Europe.

Another recent study showed a possible link between a birth defect and petroleum pollution. This study received attention because it occurred after the 2007 San Francisco bay M/V COSCO Busan oil spill. In April 2008, a newborn male harbor seal came into The Marine Mammal Center with a severe birth defect and was euthanized (Harris et al. 2011). The seal pup was less than three days old, undernourished, and suffering from many soft tissue masses around the mouth, which likely prevented it from nursing. Analysis of bile samples found PAH levels that suggested a recent exposure to diesel or crude oil. How the animal had been exposed to petroleum pollutants was unclear, but the mouth lesions suggested that the exposure occurred before birth. The oil spill occurred about one third of the way through the pup's gestation. Although the mother's movements are unknown, it is possible that she was exposed to oil from the spill.

CONTINUING INVESTIGATION

The Marine Mammal Center continues to perform blood and tissue analyses on the animals within their care. Their facilities and research capabilities have become a valuable resource to federal and state agencies, universities, and other scientific organizations. Their collaborations continue to work towards understanding the effects that chemical pollutants have on harbor seal health and reproduction, determining how and where they enter the food chain, and ultimately determining the risks they pose to wildlife and human health.

One of these studies, a joint project with the RMP and the National Institute of Standards and Technology, is currently identifying a broad range of natural and man-made chemical compounds in seal blood, blubber, and liver samples. Unlike previous studies that targeted specific compounds, this "untargeted" approach takes advantage of recent advances in analytical instrumentation to examine a broader range of contaminants than have been studied before.

In another ongoing study, researchers from Moss Landing Marine Laboratory are evaluating the underlying cause of incidence of a red coat or pelage in harbor seals from the Bay. Harbor seals typically have a light or dark spotted coat, but some seals in the Bay develop a reddish coat, which has been attributed to iron accumulation. In itself, the red pelage does not appear to harm the animals, but some red-pelaged seals have displayed hair loss and shortened vissibrae (whiskers), which could negatively affect foraging success. An earlier study (Kopec and Harvey 1995) suggested that development of red pelage may be the result of selenium toxicity. The goals of the ongoing study are to determine whether selenium toxicity has the potential to cause red pelage and whether there are potential adverse health implications.

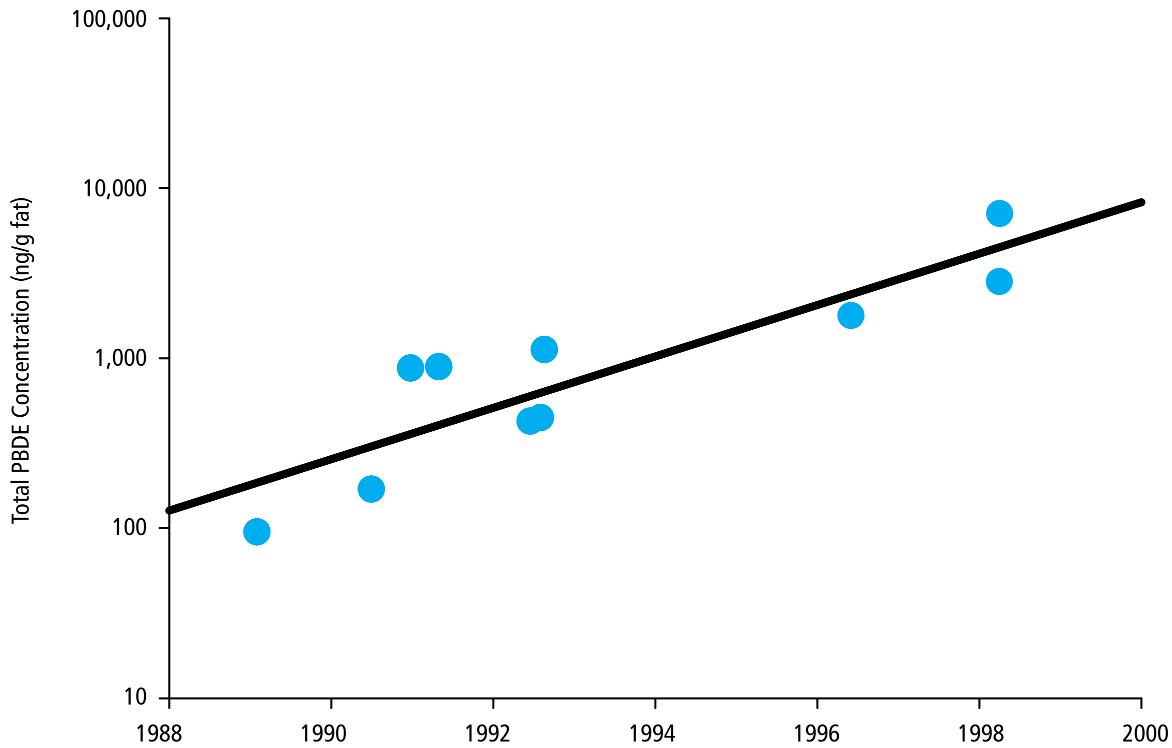
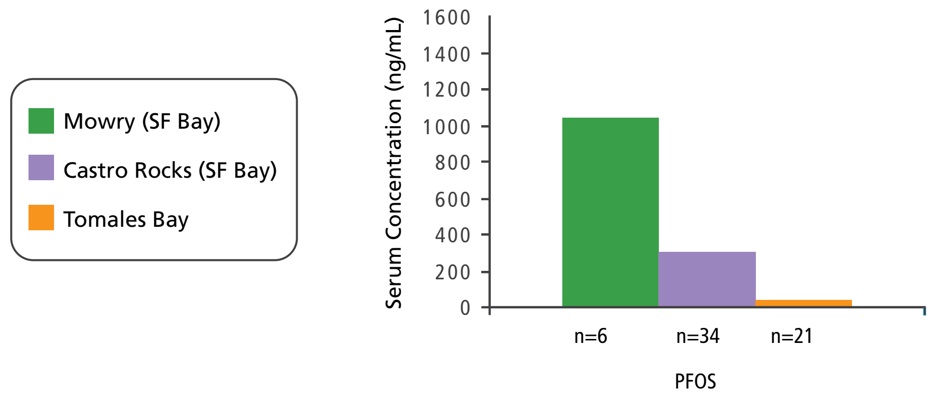


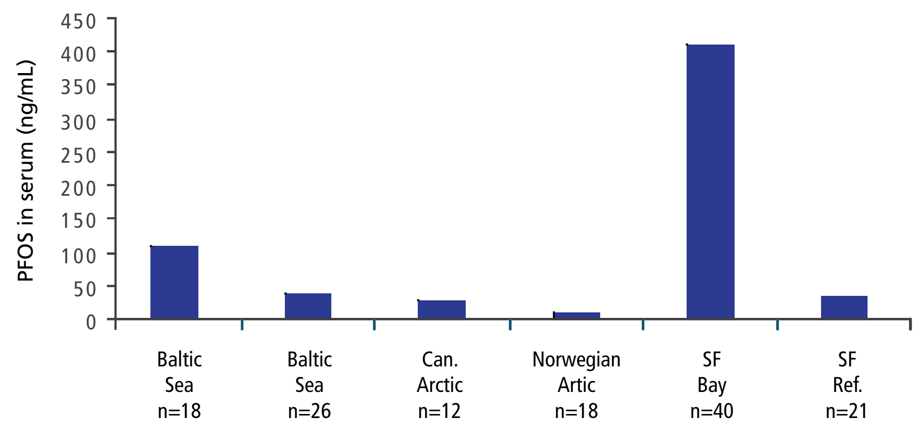
FIGURE 3

Concentrations of total PBDEs in San Francisco Bay harbor seals (from She et al. 2002). The disturbing increase and high levels focused attention on PBDEs throughout the state.

FIGURE 4

In 2006–2008, the RMP teamed up with scientists from The Marine Mammal Center to study perfluorinated compounds (PFCs) and other contaminants in blood of harbor seals from sites near the Richmond Bridge in the North Bay and in Mowry Slough in the South Bay. PFCs have been used extensively over the last 50 years in a variety of products including textiles treated with stain-repellents, fire-fighting foams, refrigerants, and coatings for paper used in contact with food products. Perfluorooctane sulfonate (PFOS) and related PFCs have been associated with a variety of toxic effects including mortality, carcinogenity, and abnormal development. PFCs bind to proteins and are typically measured in the blood and liver, rather than in fatty tissues. The scientists compared the results from Bay samples to measurements from seals in Tomales Bay, which was considered an uncontaminated reference site for PFCs. Seal blood concentrations of PFCs from both San Francisco Bay sites were about ten times higher than those in seals from Tomales Bay and higher than most comparable measurements in seals anywhere in the world.





Source: Giesy, J. and K. Kannan. 2001. Global distribution of pefluorooctane sulfonate in wildlife. Environ. Sci. Technol. vol 35. 1339-1342.

CONTINUED CHALLENGES

There are many data gaps and unanswered questions about harbor seals and the role that contaminants may play in their low population in the Bay. Studies of harbor seals are logistically too difficult to include in routine monitoring programs. The population is small, mobile, and long-lived, and capturing wild animals for sampling requires federal permits. Sampling blood, blubber, and other tissues from stranded animals is opportunistic and represents a biased segment of the population.

Smaller, shorter-lived, less mobile animals, such as mussels and small fish, in many ways are better sentinels for monitoring than seals, but seal monitoring provides essential information about accumulation of pollutants and biological effects at the top of the food chain. Even limited data can contribute valuable insights. Results from projects such as the broad survey of chemicals in seal tissues will be used to direct the RMP and other Bay contaminant studies by identifying specific chemicals that may pose risks to wildlife and humans and that merit close attention.

↑ Harbor seals on Castro Rocks. Photograph by Suzanne Manugian.

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