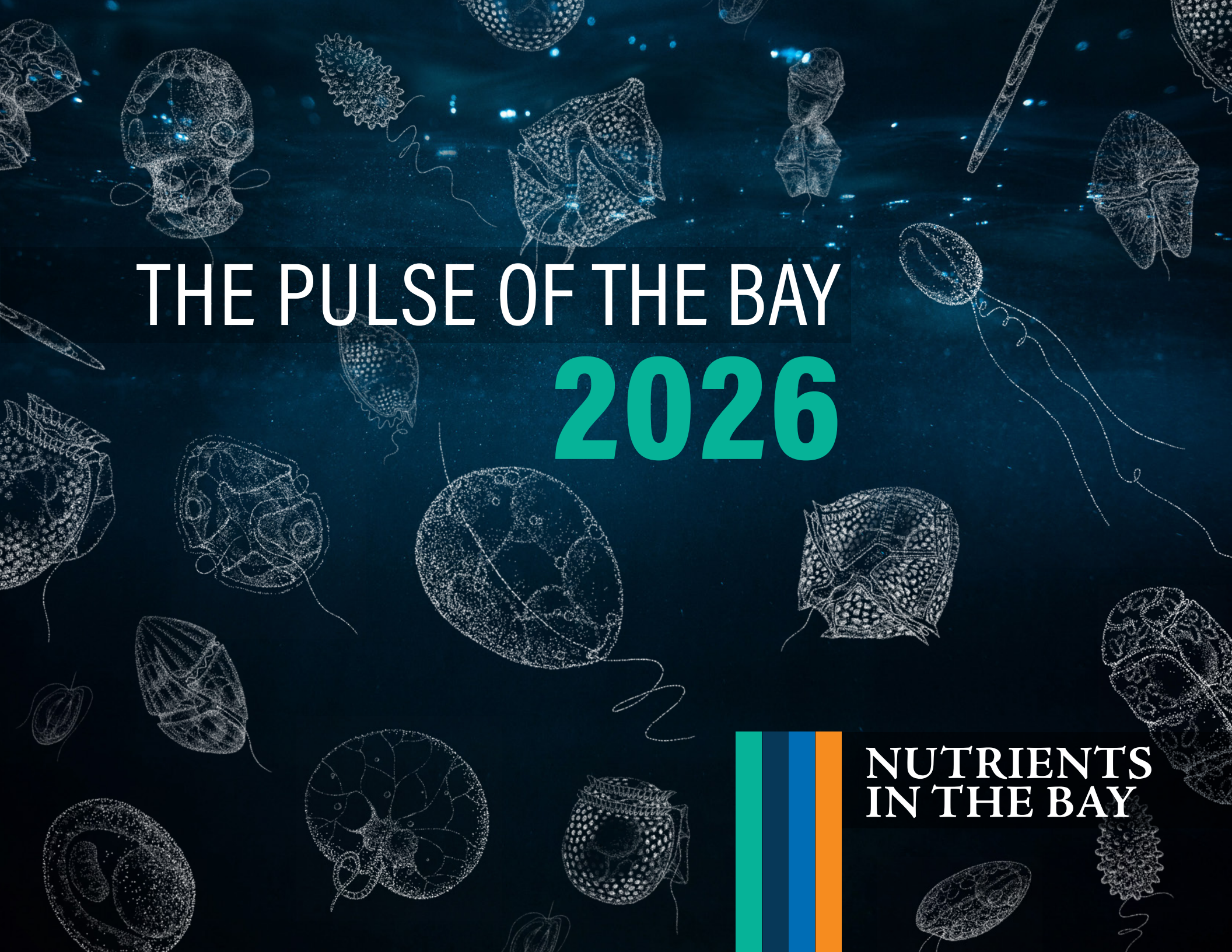


THE PULSE OF THE BAY

2026

NUTRIENTS IN THE BAY

THE PULSE OF THE BAY

2026



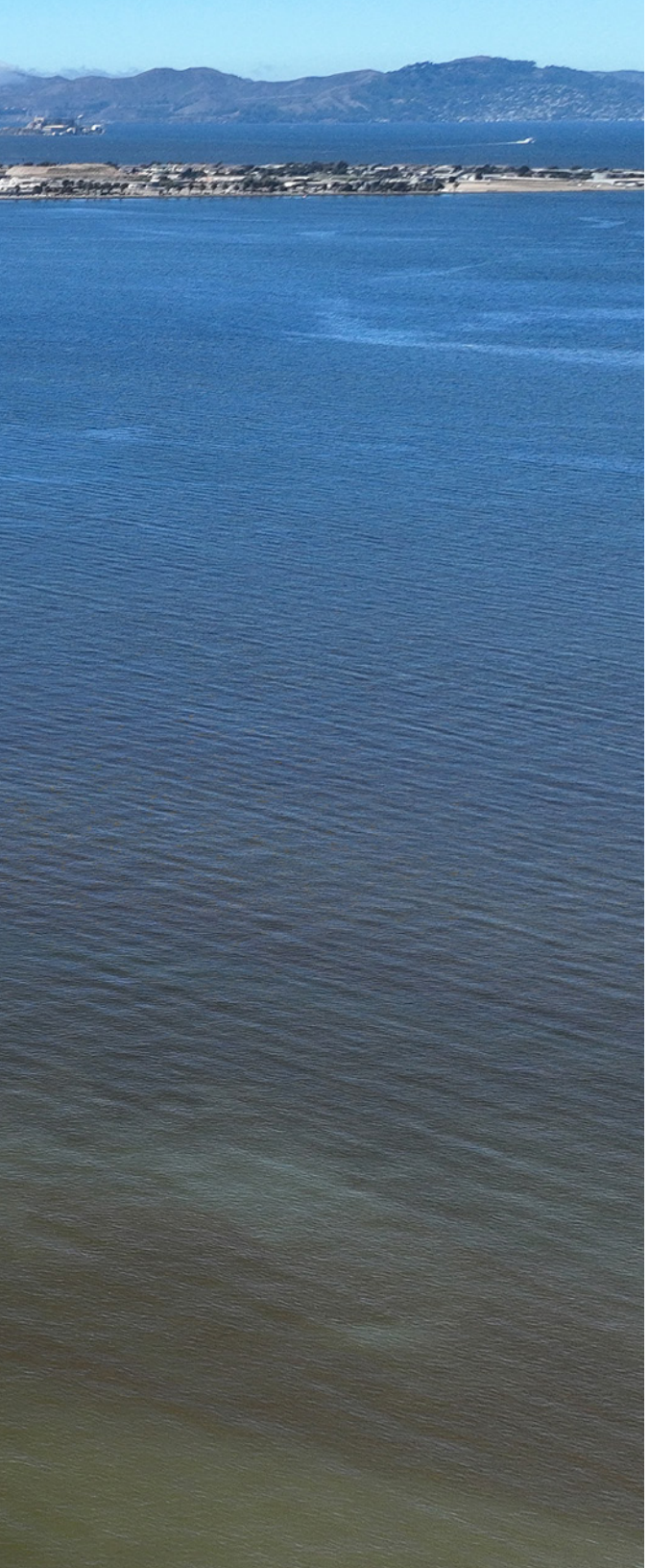
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NUTRIENTS IN THE BAY

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





OVERVIEW

Jay Davis, San Francisco Estuary Institute

The San Francisco Bay Area has begun making its biggest investment in municipal wastewater infrastructure since the 1970s. Billions of dollars will be spent over the next decade to upgrade the region's wastewater treatment infrastructure to remove more nitrogen from the water that is discharged into the Bay. This nitrogen removal will go a long way toward protecting the Bay from harmful algal blooms (HABs) that can have devastating effects on Bay water quality. Bay Area residents are the main source of the nitrogen that must be reduced, and will also be the main source of the funds for the huge investment needed for the infrastructure improvements.

The Bay Area has been slower than many other regions to invest in nitrogen removal because other regions have been suffering from HABs for longer periods of time. HABs driven by emissions of nitrogen are common in many aquatic ecosystems across the country and the globe. In general, sources of nitrogen include fertilizers, animal waste, municipal wastewater, urban runoff, and atmospheric deposition. In the densely populated Bay Area, municipal wastewater is the primary source. The nitrogen in wastewater comes mostly from human urine.

Although the Bay has long received relatively large nitrogen inputs from the population of millions of Bay Area residents, algal growth from the 1980s through the 1990s was persistently low. The abundance of algae in the Bay showed a consistent pattern of generally being low except for mild, non-harmful blooms in spring, usually between February and May. This pattern was well-documented thanks to a robust long-term monitoring program implemented by the US Geological Survey (USGS). USGS initiated this ship-based monitoring program in 1969 and it has continued to the present day, representing one of North America's longest water quality records and providing a strong

◀ **View of the 2022 harmful algal bloom at the Bay Bridge on August 22.**
Photo by Justin Sullivan / Algae Bloom Fills Bay Area Waters via Getty Images.

foundation for Bay nutrient science. The Regional Monitoring Program for Water Quality in San Francisco Bay (RMP) began to contribute a portion of the funding needed for this monitoring from the RMP's very inception in 1993 and continues to sustain this support.

From 1976 into the 2020s the USGS Bay monitoring program was led by Jim Cloern, who passed away in November 2025. Jim's outstanding career as a world expert in estuarine science grew out of his role as leader of this monitoring (page 70).

In the early 2000s, Jim noticed that the stable pattern of the 1980s and 1990s was starting to change. Jim described these changes in a 2006 *Pulse of the Estuary* article: "What is Causing the Phytoplankton Increase in San Francisco Bay?" The changes included more intense spring blooms, blooms in the fall, and a progressive increase in the "baseline" or annual minimum abundance of algae. The increase in baseline algae was particularly noticeable in South Bay. In 2006 Jim posited that the causes of the changes might be a shift in currents in the Pacific Ocean bringing more algae from the ocean into the Bay, improved wastewater treatment of toxic metals, reduced sediment inputs, and introductions of new predator fish species that reduced populations of clams and mussels that consume algae.

The general increase in algae abundance continued from 1995 through 2005, and then appeared to level off, but at a higher baseline than prior to 1995. This decade of increase was enough to raise a great deal of concern that the Bay might be losing its historic resilience to the adverse impacts of high algae concentrations.

In the next few years after the algae increase was recognized, Bay Area municipalities and water quality regulators were keenly interested in developing a solid understanding of Bay nutrients. They realized that wastewater infrastructure upgrades would cost billions and needed a sound basis for deciding whether and how to make these investments.

One of the most valuable aspects of the RMP is that it provides a forum for regulators, dischargers, scientists, and the public to regularly discuss information needs for the Bay. The RMP had been supporting some nutrient-related studies (including the USGS work) since 1993, but it was clear that a much greater investment in nutrient science was needed. Discussions of a strategy for planning and implementing a larger effort on nutrient science began in the RMP in 2011. Early workplans cobbled together funding from the RMP, USGS, the State and Regional Water Boards, and the Bay Area Clean Water Agencies (BACWA - a regional association



▲ **Dead fish at Lake Merritt, a tidal lagoon of San Francisco Bay, August 30, 2022.** Photo by Justin Sullivan / Algae Bloom Fills Bay Area Waters via Getty Images.

that represents Bay Area municipal wastewater agencies). An RMP Nutrient Strategy Team began to identify management drivers and priority management questions. In June 2011 the RMP convened a workshop to discuss the current state of understanding and critical information needs. David Senn was hired by the San Francisco Estuary Institute in the latter part of 2011 as a leader on nutrient science. The Regional Water Board and BACWA quickly realized that nutrient science needed a level of attention and investment that merited the formation of a separate program from the RMP, and the Nutrient Management Strategy (NMS) was established in 2012, with David Senn as the NMS Lead Scientist. The budget (and associated science portfolio) for the NMS grew quickly in the years that followed, reaching approximately $3 million per year by 2019 (page 6).

All of the actions to establish and grow the NMS were taken in a highly proactive manner, in the absence of any major harmful blooms. It was very fortunate, however, that this program was in place when a devastating bloom did occur in the Bay in the summer of 2022 (page 37). The 2022 *Heterosigma akashiwo* harmful algal bloom resulted in thousands of dead fish throughout most of the Bay, including high profile species such as white and green sturgeon. This signal that the Bay was no longer immune to harmful blooms compelled the Regional Water Board to require the Bay Area's 35 wastewater agencies to collectively reduce dry-weather nitrogen inputs to the Bay by 40% by 2034. This reduction goal is the impetus for the large investment in wastewater infrastructure that is now underway (page 15).

The NMS had its origins in the RMP and the two programs continue to be closely linked.

The RMP contributes funding to two important elements of the Bay nutrient science plan: 1) the monthly cruises that have been conducted by USGS since 1969 (as mentioned above) and 2) a network of moored sensors that provide data with high temporal resolution on key water quality parameters. The RMP also benefits from opportunities to piggyback on work that is done under the NMS, such as the robust framework the NMS has developed for modeling the movements of Bay water and sediment.

This edition of the *Pulse* is further evidence of the partnership between the two programs. Given the importance of the topic and the large amount of activity in nutrient science and management, this *Pulse* is entirely dedicated to the subject of nutrients in the Bay. The updates on other water quality parameters that are usually included in the *Pulse* have still been prepared and are accessible online via the new RMP data dashboard (page 100).

In 2024 the RMP and the NMS joined forces to propose a project to the US Environmental Protection Agency's San Francisco Bay Program Office called Tracking Bay Health. The proposal was approved and is providing $38 million that will double the budgets of these programs for a five-year period. This is one of the biggest developments in the history of Bay water quality monitoring, and even more firmly establishes the Bay as one of the best-monitored water bodies in the world.

The story of nutrients in the Bay demonstrates the importance of this monitoring. Baseline data generated by long-term monitoring, combined with targeted studies to address other information needs, provide the understanding that is essential to recognize when management is needed, and what level and kind of management. The Bay's community of proactive and well-informed water quality managers will continue to act wisely to protect the Bay from nutrients and the many other pollutants that pose threats. §



Nutrient sample collection at the Dumbarton Bridge. Photo by Alex Braud.

CONTENTS

OVERVIEW iii

FEATURE ARTICLES 1

FROM RESILIENCE TO RED ALERT:
The Origin and Evolution of the San Francisco Bay Nutrient Management Strategy
by the San Francisco Bay Regional Water Board 1

PROTECTING THE BAY'S FUTURE:
A Regional Effort to Reduce Nutrients
by the Bay Area Clean Water Agencies 15

Inside the 2022 San Francisco Bay Algal Bloom
by the San Francisco Estuary Institute 37

Algae of Concern in San Francisco Bay
by the San Francisco Estuary Institute 50

Science Priorities to Inform Management of Nutrients in San Francisco Bay
by the San Francisco Estuary Institute 67

ADDITIONAL INFORMATION 92

References 92
303(d) List /Status of Pollutants of Concern 98
RMP Committee Members and Participants 99
Credits and Acknowledgements 100



FROM RESILIENCE TO RED ALERT:

The Origin and Evolution of the San Francisco Bay Nutrient Management Strategy

Richard Looker, Kevin Lunde, and Eileen White
San Francisco Bay Regional Water Board

THE NMS ORIGIN STORY

San Francisco Bay has long been recognized as a nutrient-enriched estuary with higher nitrogen and phosphorus loads and concentrations than most estuaries around the world. Most nutrient loads to San Francisco Bay come from municipal wastewater treatment plants, and the main source of nutrients in wastewater is human waste. Other nutrient-enriched estuaries often experience nuisance phytoplankton growth and the associated problems (low dissolved oxygen, toxic algae blooms) that can result from excessive nutrient enrichment.

For the past five decades, the United States Geological Survey (USGS) has made ship-based measurements of water quality along a 145 kilometer water transect that spans the length of the entire estuary system from San José to Antioch. Despite receiving some of the highest nitrogen loads among estuaries worldwide, the USGS data were showing that phytoplankton abundance in the Bay was consistently lower than would be expected in a nutrient-enriched system. Scientists attributed the Bay's resilience against excessive algae growth to several factors, including strong tidal mixing; high turbidity, which limits light penetration; and high filtration of phytoplankton by clams. Starting in the early 2000s, a new pattern began to emerge in the data that suggested that the Bay's resilience might be weakening. For the first time, the data were starting to show an increasing trend in phytoplankton biomass and a corresponding small decline in dissolved oxygen concentrations in many areas of the estuary, especially the South Bay (Figures 1 and 2).

View of upper South Bay from the USGS *Landsteiner* station maintenance cruise.
Photo by Sierra Garcia.

HIGHLIGHTS

- Concern about increasing phytoplankton abundance and decreasing dissolved oxygen detected in USGS long-term Bay data beginning in the early 2000s motivated the initiation of the Nutrient Management Strategy (NMS) in 2012
- The NMS Science Program combines monitoring, modeling, and special studies to inform regulatory decisions like the Nutrient Watershed Permit for Municipal Wastewater Dischargers (NWP)
- The severe algae bloom in 2022 led the Water Board to institute a protective 40% reduction in nitrogen loads in the 2024 NWP re-issuance
- The collaborative joint-fact finding of the NMS will provide the information needed by managers to make informed decisions about expensive infrastructure upgrades to reduce nutrients in the face of scientific uncertainty and environmental change

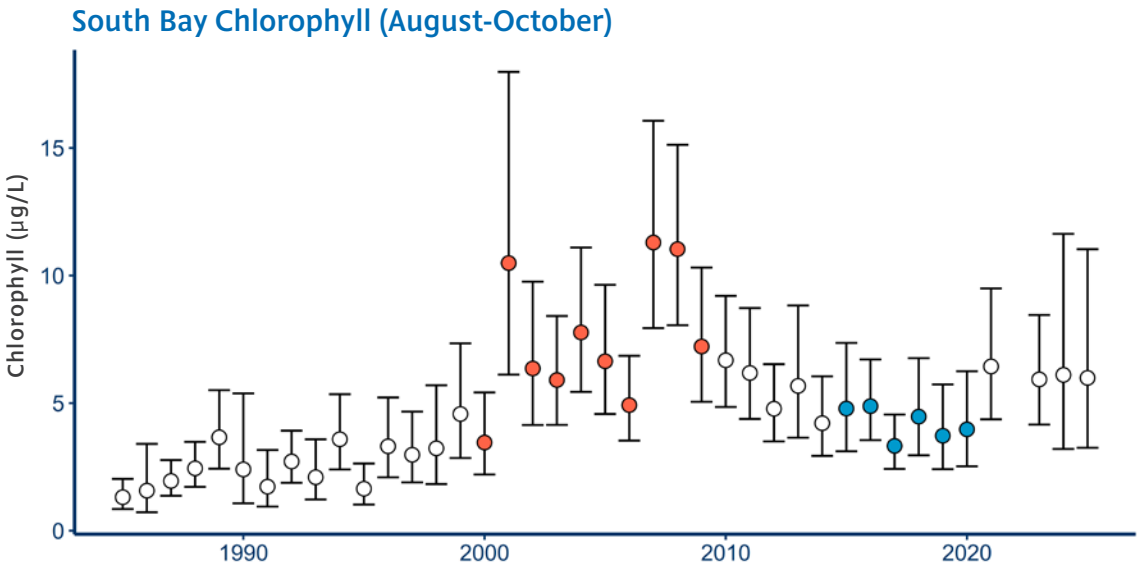


Figure 1. August–October average chlorophyll concentrations, 1985–2025. Algal growth in the Bay from the 1980s through the 1990s was persistently low, as observed at this station in South Bay. Average chlorophyll concentrations progressively increased from 2000–2009 (orange symbols). After 2009, concentrations leveled off, including a period of decline (blue symbols), but have remained at a higher baseline than in the 1980s and 1990s.

FOOTNOTE: Estimated mean August–October chlorophyll concentrations, 1985-2025 (vertical lines: 95% confidence intervals), in South Bay (station 30, midway between the San Mateo and Dumbarton Bridges). Symbol color represents the long-term trend in August-October chlorophyll-a concentrations (orange = increasing, blue = decreasing) based on an 11-year rolling window (right justified). For additional information on the approach see Beck et al. (2021) and SFEI (2022). Data: USGS (Schraga and Cloern 2017).

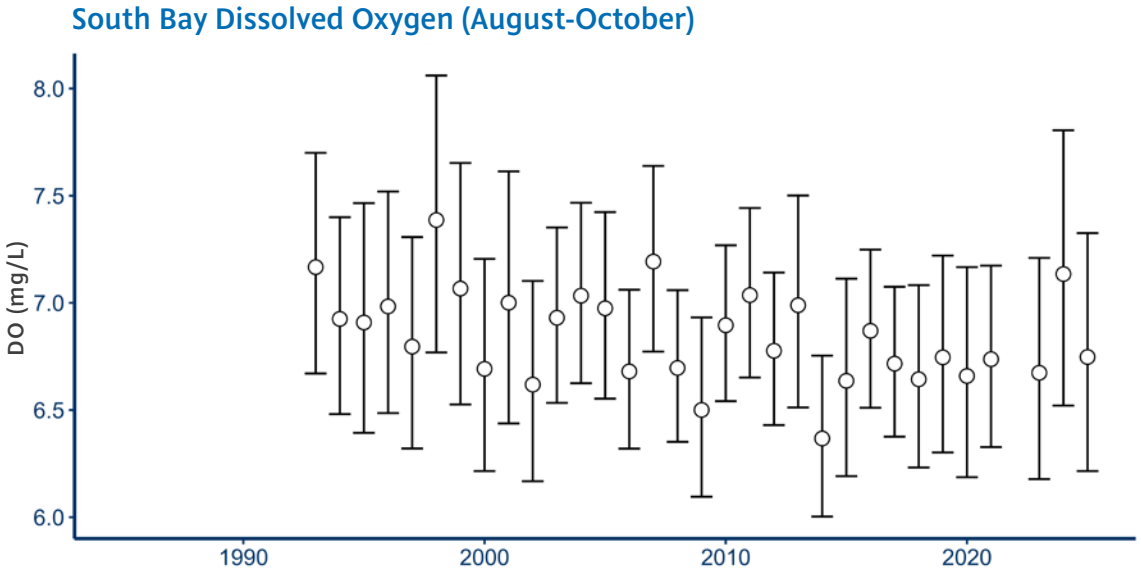


Figure 2: August–October average depth-averaged dissolved oxygen (DO) concentrations, 1993–2025. Along with the increase in chlorophyll in from 2000-2010, dissolved oxygen showed a slight decline, though it was not statistically significant.

FOOTNOTE: Estimated mean August-October depth-averaged dissolved oxygen (DO) concentrations, 1993–2025 (vertical lines: 95% confidence intervals), in South Bay (station 30, midway between the San Mateo and Dumbarton Bridges). Symbol color represents the long-term trend (white = no trend) in August-October DO, based on an 11-year rolling window (right justified). For additional information on the approach see Beck et al. (2021) and SFEI (2022). Data: USGS (Schraga and Cloern 2017)

This warning sign in the data indicating a possible weakening of the Bay's resilience against excessive phytoplankton growth was part of the motivation for the generation of *The San Francisco Bay Nutrient Management Strategy* technical report produced in 2012. This report served as the initial roadmap for how the San Francisco Bay Regional Water Quality Control Board (Water Board) could work collaboratively with interested parties to develop the science needed to make informed decisions about managing wastewater nutrient loads to protect beneficial uses in San Francisco Bay.

In 2014, the Water Board established the Nutrient Management Strategy (NMS) to implement the collaborative approach outlined in the 2012 technical report. The Water Board recognized that meaningful nutrient management decisions would require a shared scientific foundation developed jointly with regional partners and that strong governance for the program would be instrumental to success. To this end, the NMS created a charter in 2014 that explains how the NMS operates, and outlines its core purpose, organizational framework, and guiding principles that shape the program.

Central to the governance of the NMS is the Steering Committee, which is a formal stakeholder body convened by the Water Board to represent the interests affected by the NMS. The Steering Committee spans a range of perspectives and includes representatives from the wastewater discharger community, state and federal resource agencies, environmental NGOs, the Ocean Protection Council, the Central Valley Regional Water Board, the Interagency Ecological Program, and others. The Water Board participates in and chairs the Steering Committee, and the Water Board's Executive Officer maintains ultimate decision authority. The Steering Committee serves as the decision-making body for most NMS decisions, oversees implementation of the NMS Science Program, promotes information sharing, and supports public outreach related to nutrient management in the Bay.

In the summer of 2022, a massive harmful algal bloom changed the warning light from yellow to flashing red

The core purpose of the NMS is to inform ongoing regulatory efforts, the most important of which is the San Francisco Bay Nutrient Watershed Permit for Municipal Wastewater Dischargers (NWP). Beginning with the first NWP in 2014, the Water Board required wastewater dischargers to fund the NMS scientific activities. The Bay Area wastewater agencies are committed to protecting the Bay and have contributed over $15 million over the past decade on water quality monitoring, modeling, and studies to further the understanding of the impacts of nutrients in the Bay. The NMS used this funding to pursue answers to two broad management questions: 1) do nutrient loads to the Bay cause a problem now or might they in the future and, 2) if so – what can be done about it using load reductions or other measures? The NMS science team translated those broad management questions into several more specific scientific questions, which it seeks to resolve through an ambitious science program that combines monitoring, modeling, and special studies (page 67).

Because rising phytoplankton abundance and periodic harmful algal blooms signaled a "yellow warning light" of reduced resilience against excessive phytoplankton growth, the 2014 NWP also required each permittee to identify options for how their facility could, if necessary, reduce nutrient loads. The 2019 NWP further required an evaluation of nutrient reductions that could be achieved through wastewater recycling and nature-based solutions. The 2019 NWP also required permittees to plan for nitrogen load caps, roughly at current performance, in the subsequent permit. The hope was that the Bay would continue to maintain its resilience against excessive phytoplankton growth, but these facility-specific nutrient reduction plans could be put into action if conditions worsened. In the summer of 2022, a massive harmful algal bloom changed the warning light from yellow to flashing red.

A NUTRIENT SCIENCE TIMELINE FOR SAN FRANCISCO BAY

From the first USGS monitoring in 1969 to the Nutrient Management Strategy's 2025–2030 Science Plan

The San Francisco Bay Nutrient Management Strategy grew from decades of local research, led by the US Geological Survey, focused on why a nutrient-rich estuary long resisted eutrophication and tracking mounting evidence that this natural resistance was weakening. Since 2012, the program has built a high-resolution observing system, a Bay-scale biogeochemical model, and a body of knowledge to inform a regulatory mandate aimed at reducing nitrogen loads. The milestones below track the origins of the NMS through the present.

1969 – 2012
Foundations

1969

USGS begins monitoring San Francisco Bay. The US Geological Survey initiated a ship-based monitoring program that continues today, building one of North America's longest water quality records and providing the empirical basis for subsequent nutrient science.

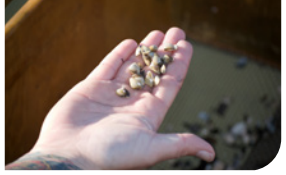


1979

San Francisco Bay: The Urbanized Estuary. Book consolidating Bay estuarine science; includes an early synthesis of the current understanding of Bay phytoplankton ecology by Jim Cloern (Conomos et al. 1979).

1986

The Bay's transformation, and an early account of its resistance to nutrient enrichment. **A *Science* synthesis shows how diking, diversion, invasions, and waste discharge reengineered San Francisco Bay.** Despite high sewage-derived nutrient loads, filter-feeding grazers and turbidity kept algal biomass low, sparing the Bay the classic symptoms of eutrophication (Nichols et al. 1986).



1986 - 1992

The overbite clam invades the North Bay. Following its 1986 introduction via ballast water (Carlton et al. 1990), the invasive overbite clam *Potamocorbula amurensis* rapidly expanded to a point where it grazed phytoplankton so heavily that it suppressed the northern estuary's summer phytoplankton blooms (Alpine and Cloern 1992).

1993

The Regional Monitoring Program (RMP) is established. Funded by regional wastewater, industrial, and stormwater dischargers and run by SFEI, the RMP began long-term support for the USGS water quality monitoring program, including the collection of chlorophyll data that later revealed escalating phytoplankton levels in the late 1990s.

2001

A new conceptual model of coastal eutrophication. Jim Cloern's synthesis showed how an estuary's response to nutrient enrichment is modulated by physical and biological factors, such as turbidity, tidal exchange, grazing, and residence time, rather than nutrients alone (Cloern 2001).

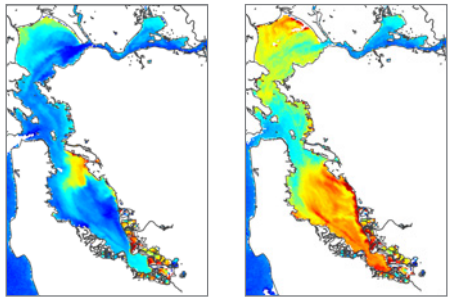
2011

A numeric nutrient endpoint framework for the Bay. As part of a statewide initiative led by the State Water Board with **US Environmental Protection Agency (USEPA)** Region IX, San Francisco Bay Water Board staff and SFEI began developing numeric nutrient endpoints for the estuary, starting with a literature review and data-gaps analysis (McKee et al. 2011) that recommended quantifying loads, building models, and sustaining monitoring.

2007 - 2012

Warning signs and the case for management. Research documented a step increase in phytoplankton biomass and new blooms after 1999 (Cloern et al. 2007), associated spring-bloom suppression to wastewater-derived ammonium (Dugdale et al. 2007), and distilled four decades of change into a framework of ecosystem drivers (Cloern and Jassby 2012), which established the scientific basis for a coordinated nutrient program.

2012 – 2016
Establishing the Program and its Scientific Basis



2012
The Nutrient Management Strategy is established. The San Francisco Bay Regional Water Quality Control Board formally establishes the NMS, concluding that additional science is needed before setting nutrient water-quality objectives. The program is housed at SFEI and guided by a 15-member Steering Committee of dischargers, regulators, environmental groups, and scientists.

2013
Governance and the first high-frequency sensors. The NMS Charter and Steering Committee are formalized, and the first two continuous water-quality sondes are deployed in Lower South Bay, forming the basis of the moored sensor network.



Moored sensor retrieval. Photo by Sierra Garcia.

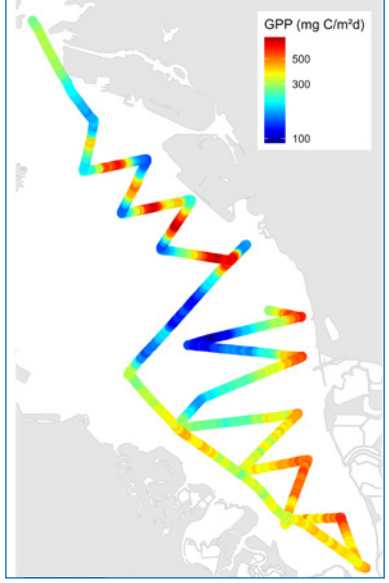
2014
Scientific foundation, first Science Plan, first permit. A convening of national experts (Senn and Novick 2014) establishes the conceptual model, the program's management questions, and an overall framework for the NMS. The first Nutrient Watershed Permit (Order R2-2014-0014, 2014–2019) dedicates $800K per year to the program, representing its first sustained funding stream.

2015
Molecular harmful algal bloom (HAB) surveillance and toxin monitoring begin. The program launches molecular surveillance of harmful algae, biweekly monitoring of algal toxins in mussels at eight sites, and continuous dissolved oxygen monitoring in South Bay sloughs. Numerous priority harmful algal species are detected, and mussel sampling shows that multiple freshwater and marine algal toxins co-occur Bay-wide (Peacock et al. 2018).



2016
Satellite record enhanced, assessment framework initiated, and Science Plan updated. Operational Sentinel satellites enable the Bay's remote-sensed chlorophyll record, and the Science Plan is updated with a tiered, risk-based approach to prioritizing HAB investigation. Sutula et al. (2017) provide an assessment framework for the Bay, deriving chlorophyll thresholds that link phytoplankton biomass to eutrophication risk.

2017 – 2021
Building the Observing System



2017

High-speed shoal mapping and automated phytoplankton imaging. The NMS and USGS initiate high-speed mapping of water parameters in South Bay shoals, confirming that shoals and channels differ substantially in productivity and nitrogen dynamics. An Imaging FlowCytobot is used to rapidly identify the phytoplankton community.

2018

Chronic slough hypoxia quantified in shallow habitats. Continuous monitoring documents persistent hypoxia in South Bay sloughs (Guadalupe Slough below 5 mg/L for roughly 60–70% of summer; MacVean et al. 2018).



2019

Moored sensor network reaches 12 stations; second permit. The moored network grows from two stations (2013) to 12; the second Nutrient Watershed Permit (Order R2-2019-0017, 2019–2024) raises dedicated NMS funding to $2.2M per year and adds evaluation of nature-based solutions and recycled water as management alternatives.

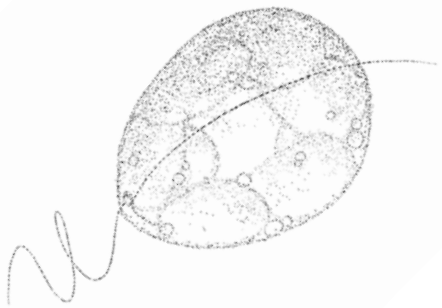
2020

Further evidence that the Bay's resistance to nutrients can't be assumed. A USGS-led synthesis (Cloern et al. 2020) placed the Bay among the most nutrient-enriched estuaries worldwide (the 87th percentile for nitrogen and 91st for phosphorus among 163 systems) and attributed a two- to three-fold rise in Central Bay productivity to the post-1999 loss of bivalve grazing control following a North Pacific meteorological shift.

2021

Routine shoal mapping and moored sensor network reaches 15 stations. The NMS begins regular high-speed mapping of the shoals (six cruises, March to October), and the moored sensor network expands to 15 stations, establishing routine Bay-wide coverage of nutrients, chlorophyll, and dissolved oxygen.

2022 – 2023
The 2022 Bloom and the Pivot to Acute Conditions



2022 - 2023
***Heterosigma akashiwo* blooms.** The 2022 bloom, the largest HAB in the Bay's recorded history, peaked near 500 µg/L of chlorophyll on August 23. It drove the largest recorded sturgeon kill in the estuary, killing numerous white and green sturgeon and raising serious concern for the Bay's already-declining population. A smaller *H. akashiwo* bloom the following summer (2023) again killed sturgeon, signaling that these events may pose a recurring threat to the species.

2023
A surge in federal funding. The NMS receives an influx in investment following the 2022 bloom: a NOAA MERHAB grant ($2.2M, 2023–2028) for an integrated HAB detection system combining molecular, satellite, and real-time methods, and a USEPA San Francisco Bay Water Quality Improvement Fund (WQIF) award for the Destination Clean Bay project ($3M total, split 50/50 with the Regional Monitoring Program, 2023–2027).

2023
Independent review of the Bay model. A Model Advisory Group of external experts reviews the San Francisco Bay Biogeochemical Model, affirms its strengths as a management-support tool, and recommends targeted improvements.

2023 - 2024
Load reduction modeling for worst-case conditions. The San Francisco Bay Biogeochemical Model, a coupled hydrodynamic–water quality model is used to evaluate how nitrogen load reductions would affect dissolved oxygen under acute scenarios based on the 2022 bloom.

2024
40% nitrogen load reduction requirements. The San Francisco Bay Biogeochemical Model informs the third Nutrient Watershed Permit (Order R2-2024-0013), which requires a 40% reduction in dry-season nitrogen loads over 10 years and continues the $2.2M-per-year science allocation. Draft acute and chronic dissolved-oxygen thresholds developed for Lower South Bay sloughs (Chelsky et al. 2024) and a remote-sensing algorithm for chlorophyll in the Bay (Kudela et al. 2024) are completed. Two USEPA awards — BayInsight ($3.0M, 2024–2028) and Tracking Bay Health ($15M to the NMS, 2024–2031) — serve to sustain the science for several years.

2025
A synthesis year and a new Science Plan. Several NMS publications are released, spanning Bay-wide productivity and dissolved-oxygen trends (Foley et al. 2025), slough oxygen gradients (Montgomery et al. 2025), salt-pond drivers of low oxygen (Volaric et al. 2025), and HAB metabarcoding (Killam et al. 2025). The Steering Committee approves the 2025–2030 Science Plan, and SFEI publishes the State of the Science Report (SFEI Contribution #1290).

2026
Turning the Tide. A USEPA award ($2.7M to the NMS of a $4.1M total, 2026–2031) supports nutrient and HAB monitoring through 2031 and assesses nutrient removal in the Bay's tidal wetlands.

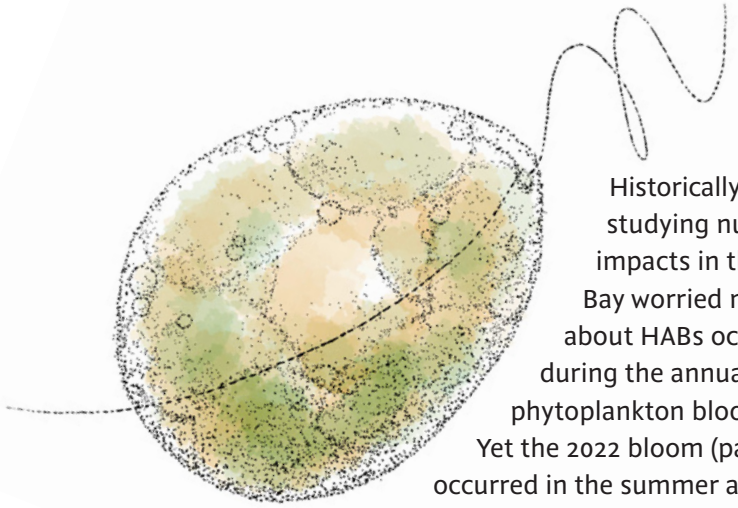
2023 – 2026
From Science to Mandate

THE 2022 BLOOM – THE GAME-CHANGING WAKE UP CALL

Large phytoplankton blooms can harm beneficial uses in the Bay by causing low dissolved oxygen when the algae die and are digested by bacteria, or by directly impacting aquatic organisms through toxin production or physical effects (e.g., clogging fish gills, smothering). Blooms that can cause direct impacts are known as harmful algal blooms or "HABs". NMS managers and scientists knew that the risk of a HAB was always present and even growing based on the data collected during the first two decades of the 21st century, yet the *Heterosigma akashiwo* bloom covering a vast portion of the Bay and lasting several weeks in the summer of 2022 was a shock.



▲ **View of the algal bloom over the Richmond-San Rafael Bridge on August 22, 2022 near San Rafael.** Photo by Jason Sullivan / Algae Bloom Fills Bay Area Waters via Getty Images.



Historically, scientists studying nutrient impacts in the Bay worried more about HABs occurring during the annual spring phytoplankton blooms. Yet the 2022 bloom (page 37) occurred in the summer and was the most extreme HAB in living memory. The bloom resulted in nuisance odors and thousands of dead fish, including protected species such as white and green sturgeon. The precise combination of physical and biological factors that contributed to the initiation and spread of the 2022 bloom is not yet fully understood and is still the subject of active scientific investigation. However, it was clear that high nutrient concentrations in the Bay provided the fuel for the growing phytoplankton, and these nutrients were primarily from wastewater discharges.

Therefore, in 2024 when the Water Board reissued the NWP, it required the Bay Area's 40 wastewater agencies to collectively reduce dry-weather nitrogen loads to the Bay by 40% from 2022 levels within 10 years. It also included associated effluent limits for each of the municipal wastewater treatment plants designed to achieve the load reductions.

The aggregate load reduction used in the derivation of the effluent limits in the 2024 NWP was determined through the data and information collected and interpreted by the NMS science team as well as an NMS numerical model developed and calibrated against those data.

In 2013, the NMS established a network of fixed monitoring stations (sondes) to collect continuous dissolved oxygen, pH, nitrate, and chlorophyll data in Central Bay, South Bay, and the South Bay sloughs (Figure 3). This sonde network provided the

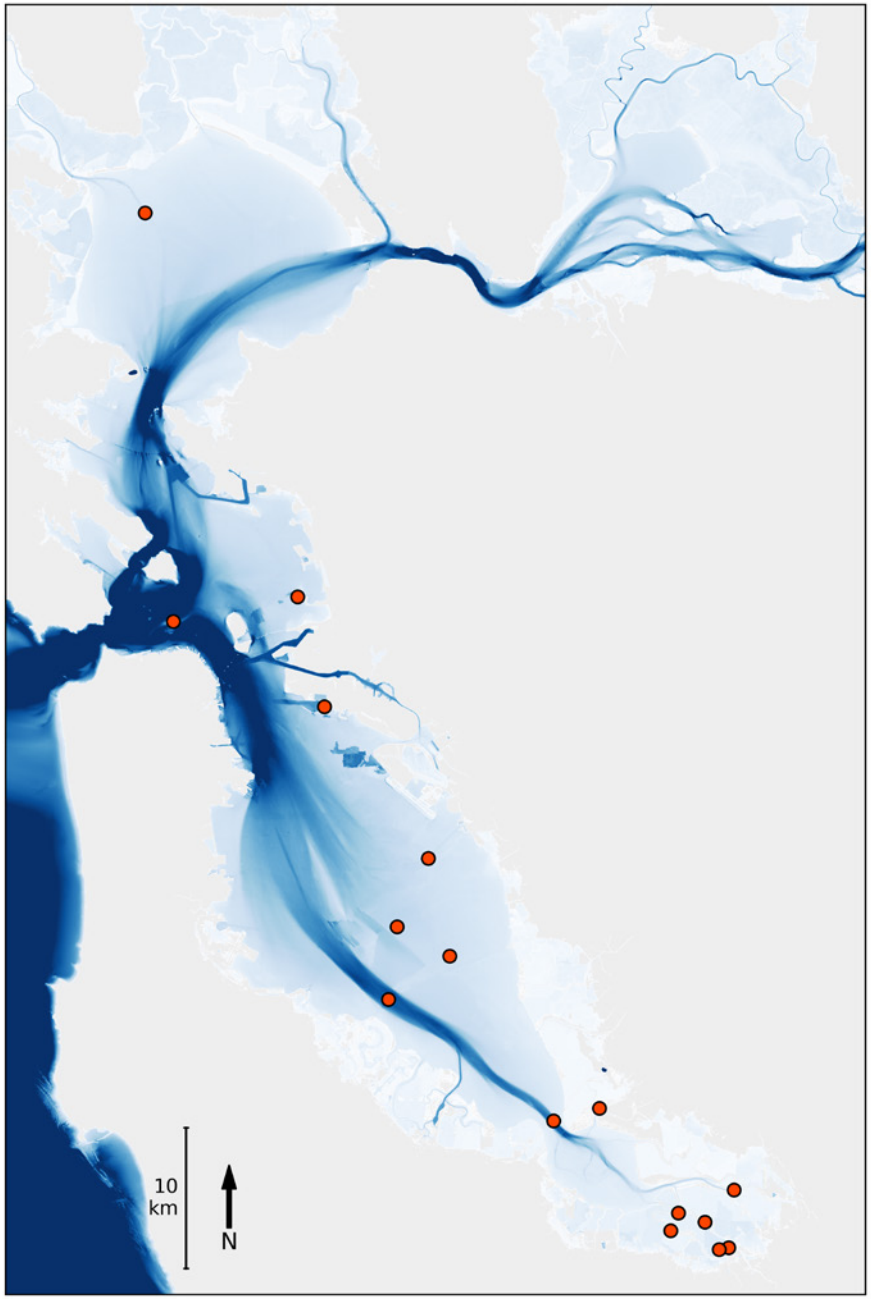
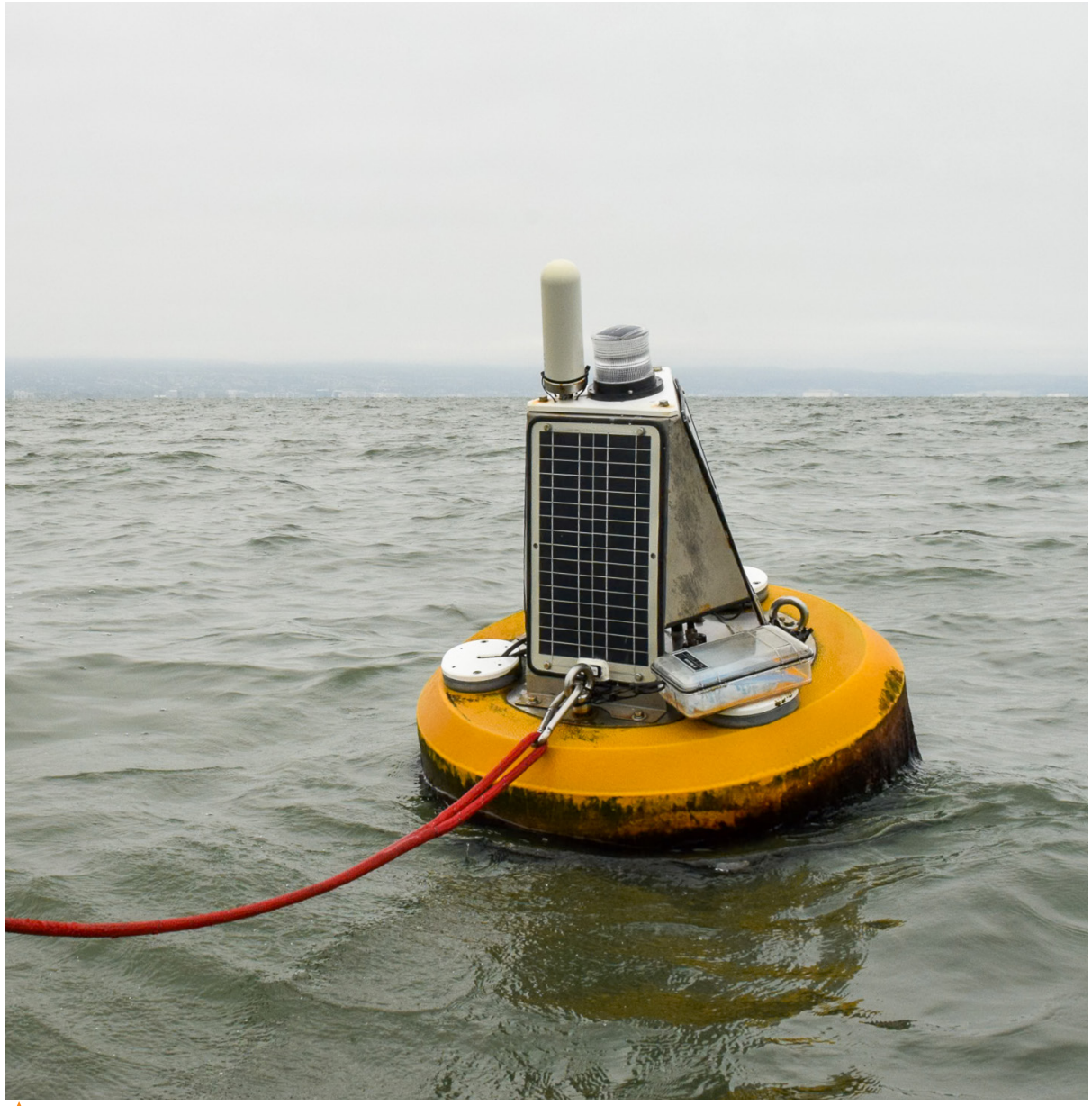


Figure 3. NMS fixed monitoring station locations in 2026. Blue shading indicates depth of the Bay.



Sonde monitoring buoy at the South Bay Shoal station. Photo by Sierra Garcia.

NMS science team with a continuous record of how these parameters behaved throughout the evolution of the bloom and its ultimate abrupt termination. These data allowed NMS scientists to demonstrate that the bloom was so severe that virtually all nitrogen in the Bay at the start of the bloom and discharged during the bloom was incorporated into phytoplankton biomass. Moreover, the oxygen depletion observed in the network of fixed station sondes in the later stages of the bloom generally agreed with what one would expect if all the produced biomass were aerobically digested with a corresponding depletion of oxygen.

Water Board staff made use of the straightforward quantitative relationships between the observed nitrogen uptake, phytoplankton growth, and oxygen depletion as well as the numerical modeling of nitrogen concentrations leading up to the start of the bloom to derive the effluent limits in the 2024 Permit. The limits were based on a technical analysis aimed at protecting Bay fish from acute impacts of low dissolved oxygen caused by a severe HAB. The Water Board focused on the 2022 bloom's excessive-bloom/low-dissolved oxygen pathway of harm because our understanding of that pathway allowed the effluent limits to be quantitatively determined with greater confidence.

The Permit also required the wastewater agencies to continue to fund studies to

address the potential impacts of nutrients on Bay beneficial uses. The NMS Steering Committee has responded to the challenge wrought by the bloom by revising the fundamental management questions of the program and adopting a new set of science priorities for 2025–2030 to address these questions (page 67). Included in these priorities is an expansion of the sonde monitoring network to new Bay segments. The NMS, through funds provided through a grant from the National Oceanic and Atmospheric Administration, added telemetry to the sondes to enable real-time monitoring of HABs to allow for more nimble management response and risk communication.

The 2022 bloom also underscored the need for the NMS to improve numerical modeling capabilities to take on the challenge of simulating a dynamic bloom event, and to develop the scientific information to establish relationships between nutrients and the direct effects of HABs.

BASIN PLAN AMENDMENT TO SUPPORT NUTRIENT REDUCTIONS

When the Water Board issued the 2024 NWP requiring the nitrogen load reductions, it recognized the ten-year compliance schedule could discourage dischargers from taking the risk to embark on multi-benefit solutions and innovative technologies to reduce nitrogen loads because it is generally not feasible for those projects to be completed within ten years. Ten years is the longest compliance schedule duration allowed by the State Water Resources Control Board Policy for Compliance Schedules in NPDES Permits (Compliance Schedule Policy). Therefore, the Regional Water Board adopted Resolution R2-2024-0014 to *Identify and Consider Regulatory Mechanisms to Extend Compliance Schedules for Nutrient Effluent Limitations*. That resolution discussed various regulatory options available to the Water Board to permit certain projects that will take longer than 10 years. After careful consideration, the Water Board decided to proceed with a non-TMDL Basin Plan amendment to grant a narrow set of projects extended compliance schedules. This Basin Plan amendment will facilitate nutrient reductions from municipal wastewater treatment plants by encouraging multi-benefit projects such as nature-based solutions (e.g., horizontal levees), water recycling projects, and projects using innovative technologies that promote environmental co-benefits. The Basin Plan amendment is a Water Board top priority.

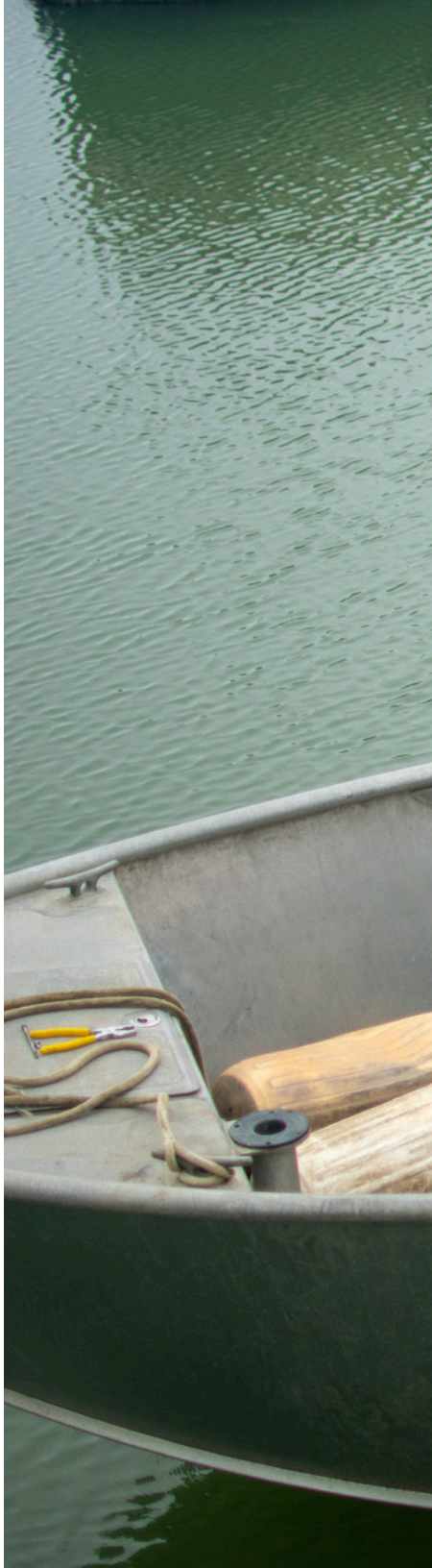
> The Basin Plan amendment will encourage multi-benefit projects such as nature-based solutions (e.g., horizontal levees), water recycling projects, and projects using innovative technologies that promote environmental co-benefits

NUTRIENT REGULATION IN THE FUTURE

The 2029 NWP will incorporate new scientific findings resulting from implementation of the 2025–2030 Science Plan.

The NMS science program is actively engaged in developing the scientific information needed by managers to make decisions about nutrients in San Francisco Bay. Among these important decisions is determining whether the load reductions required in the 2024 permit are sufficient to protect beneficial uses against low dissolved oxygen impacts and also from HAB direct effects. To make this decision, the Water Board will be relying on the NMS science team's efforts to unpack the mysteries of how blooms get started in the Bay, how they grow and spread, and how nutrient concentrations and loads affect these processes. That alone constitutes a monumental challenge, but environmental managers will need to make difficult decisions about expensive nutrient management options as the Bay Area's population grows, weather changes, sea level rises, and large-scale changes to the Bay occur from wetland restoration in South Bay and other Bay segments.

The stakes of managing nutrients to protect San Francisco Bay are high. The Water Board is charged with protecting water quality, and failing to act effectively or not acting in time could leave the Bay vulnerable to the devastating impacts of harmful algal blooms. At the same time, regulation carries real costs, and significant resources are already being committed to upgrading wastewater facilities to meet the 2024 effluent limits (page 15). Nutrient-related management decisions will be informed by the science developed by the NMS program. Bay Area wastewater dischargers are working diligently toward the load reductions required to improve water quality and protect beneficial uses. As those reductions come to fruition, NMS monitoring is positioned to observe how the Bay ecosystem responds, and that evidence, combined with improved scientific understanding achieved through the NMS science program, will inform the Water Board's future regulatory actions. The collaborative fact-finding ethos of the NMS combined with a commitment to science-based decision-making will enable managers to navigate the scientific and regulatory complexities.



NMS scientists sampling in Newark Slough. ▶
Photo by Alex Braud.


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PROTECTING THE BAY'S FUTURE:

A Regional Effort to Reduce Nutrients

Lorien Fono
Bay Area Clean Water Agencies

A NEW INITIATIVE TO REDUCE BAY NUTRIENTS

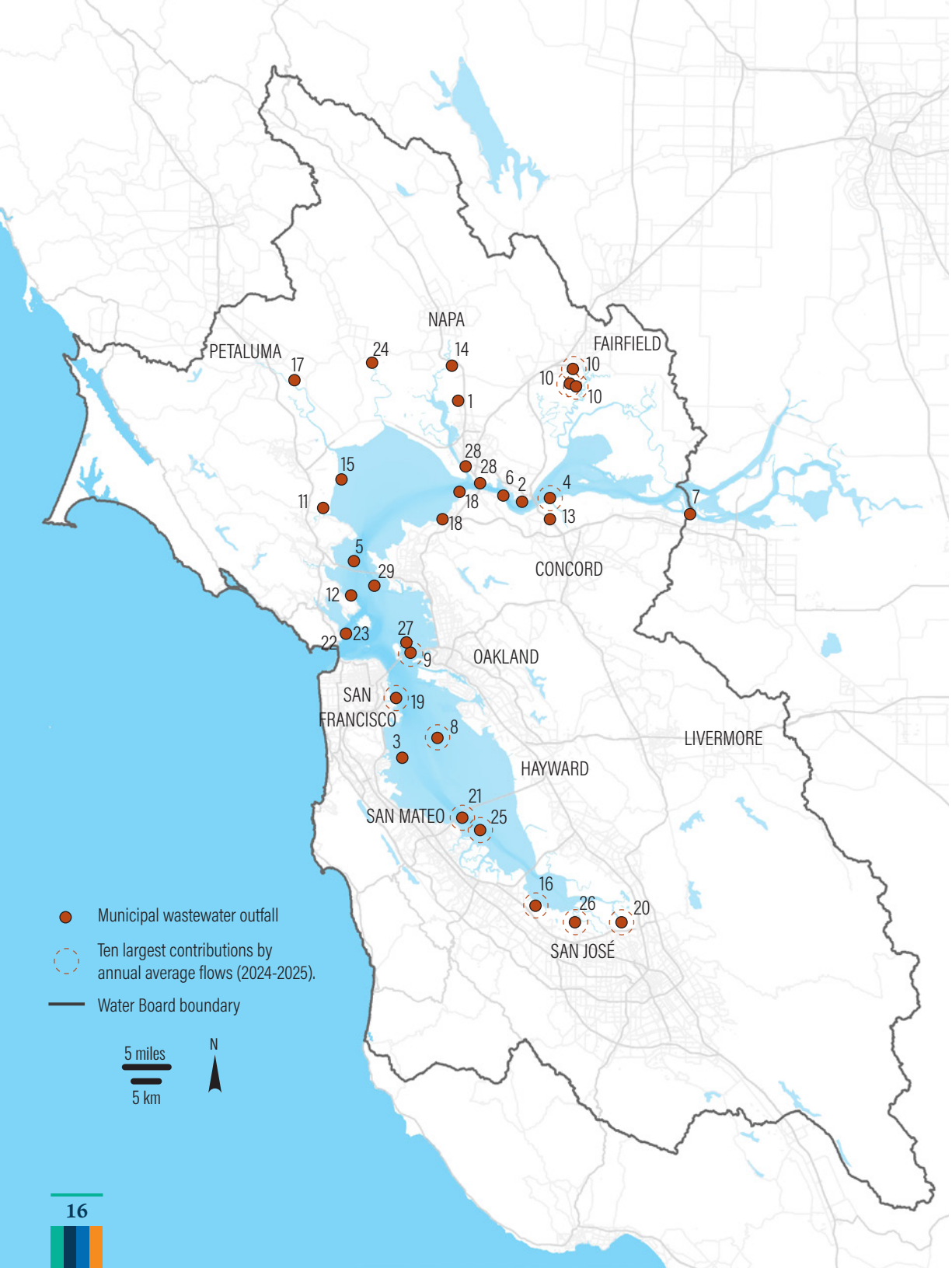
Early in the 20th century, taking a dip in San Francisco Bay could mean swimming through raw sewage. Beginning mid-century, wastewater treatment plants were constructed to remove solids from wastewater before it reached the Bay. The 1972 Clean Water Act spurred mass investment in implementing modern municipal wastewater treatment in the 1970s, transforming the Bay within a decade even as the population grew. The region's wastewater agencies are now turning to the next environmental challenge, this time with little federal support: diverting excess nutrients in the treated wastewater from reaching the Bay.

Historically, San Francisco Bay has been resilient to harmful algal blooms and other impacts from excess nutrients observed in estuaries around the world. Much of the nutrient input into the Bay today comes from 35 municipal wastewater facilities that serve a total population of more than 7 million (Figure 1). While no regulations previously limited nutrient discharges to the Bay, the regional wastewater and regulatory communities had the foresight to project that regulating nutrients could become necessary. The wastewater community collaborated with the San Francisco Bay Regional Water Quality Control Board (Water Board) to adopt a Regional Nutrients Watershed NPDES Permit (Watershed Permit) in 2014 that required permittees to monitor and report nutrient discharges (Figure 2). It also required the wastewater agencies to fund studies on the possible impacts of nutrients on the Bay and to investigate the feasibility of a suite of nutrient reduction alternatives at each facility, including optimization, upgrades, water recycling, and nature-based solutions. The Bay Area Clean Water Agencies (BACWA), a joint powers authority that serves as the regional

◀ **The East Bay Municipal Utility District wastewater treatment facility and the Emeryville Crescent.**
Photograph courtesy of EBMUD.

HIGHLIGHTS

- Most excess nutrients entering San Francisco Bay come from treated municipal wastewater
- The region's municipal wastewater agencies are collaborating to cut nutrients 40% by 2034
- Innovations to reduce nutrients entering the Bay include wastewater facility upgrades, nature-based solutions, and recycling treated wastewater
- Upgrades in progress are the region's largest investment in wastewater infrastructure since the 1970s



Municipal Dischargers[1]:

1. City of American Canyon* (1.4)
2. City of Benicia (1.86)
3. City of Burlingame (2.54)
   City of Millbrae (1.6)
   City/Co. of SF, Int'l Airport (1.02)
   So. SF/San Bruno WQCP (8.42)
4. Central Contra Costa S.D. (34.8)
5. Central Marin Sanitation A.G. (9.83)
6. Crockett Community Services District, Port Costa (0.02)
7. Delta Diablo (9.34)
8. East Bay Dischargers Authority (62.3):
   -City of Hayward
   -Oro Loma S.D.
   -Castro Valley S.D.
   -City of San Leandro
   -Union S.D.
   Livermore-Amador Valley WMA:
   -Dublin/San Ramon S.D.
   -City of Livermore
9. EBMUD (Main wastewater plant) (51.2)
10. Fairfield Suisun Sewer District* (15.5)
11. Las Gallinas Valley S.D. (1.88)
12. Marin Co. S.D. No. 5 (Paradise) (0.01)
13. Mountain View S.D.* (1.09)
14. Napa S.D. (5.38)
15. Novato S.D. (3.89)
16. City of Palo Alto* (21.8)
17. City of Petaluma (3.86)
18. Cities of Pinole & Hercules Rodeo S.D. (3.42)
19. City/Co. of SF, Southeast (47.3)
20. San José-Santa Clara RWF* (83.8)
21. City of San Mateo (10.7)
22. Sausalito-Marin City S.D. (1.14)
23. Sewarage Agency of S. Marin (2.52)
    Marin Co. S.D. No. 5 (Tiburon) (0.578)
24. Sonoma Valley County S.D.* (1.47)
25. Silicon Valley Clean Water* (14.1)
26. City of Sunnyvale* (11.9)
27. San Francisco Public Utilities Commission – Treasure Island (0.547)
28. Vallejo Sanitation & Flood Control (9.86)
29. West County Agency (8.38):
    -City of Richmond
    -West County Wastewater District

[1]Average daily discharge in millions of gallons per day for 2024-2025 indicated in parentheses
* Performs advanced secondary treatment

Figure 1. Locations of the 29 Bay Area municipal wastewater outfalls of the 35 municipal wastewater treatment plants covered by the Watershed Permit. Flow data from BACWA (2026).

municipal wastewater association that convenes the Watershed Permittees, provides the required compliance reporting and special studies.

A large harmful algal bloom in 2022 (page 37) prompted regional decision-makers to reexamine long-standing assumptions about the Bay's resilience to excess nutrients. In July 2024, the Water Board reissued the Watershed Permit with a new requirement to reduce total inorganic nitrogen discharged to the Bay during the May through September dry season by 40%, in aggregate. The Watershed Permit requires nutrient reduction projects to be completed as soon as possible, but within a maximum of ten years.

HOW IS NITROGEN REMOVED FROM WASTEWATER DISCHARGES?

Most of the nitrogen entering wastewater treatment plants comes from human urine. Some also is derived from food waste. The urea from urine is quickly converted to ammonia in the sewer system and early in the wastewater treatment process.

Because decreasing the region's flow of urine is not a viable strategy, wastewater agencies have two primary options for lowering nitrogen inputs to the Bay. The first is to use bacteria to convert the ammonia through a series of transformations to nitrogen gas, called biological nutrient reduction (BNR). This biological process can happen in special treatment units within the wastewater plant or in a constructed treatment wetland, which is a nature-based solution. The second option to reduce the amount of nitrogen flowing to the Bay is water recycling. This diverts the wastewater to be reused as irrigation water, where the nitrogen can offset fertilizer use in agriculture or landscaping.

The Water Board calculated individual limits on nitrogen in treated wastewater based on wastewater agencies' performance, with a benchmark of 20.5 milligrams of nitrogen per liter. An agency that discharges much higher concentrations would need to reduce their total nitrogen outputs by more than 40%, but an agency already discharging less than 20.5 mg/L nitrogen would not need to reduce their nitrogen output at all. Agencies also have the option to meet their limit by diverting their treated wastewater via water recycling to reduce total nutrient outputs.

CHALLENGES AND OPPORTUNITIES

The special studies required by previous iterations of the Watershed Permit provided an $11 billion estimate for the cost of complying with the permit via traditional upgrades. Most of the wastewater infrastructure in the region was built in the 1970s using federal grants that came with the adoption of the 1972 Clean Water Act. Since then, there has not been significant federal or state investment in these types of infrastructure projects, so the costs of nutrient reduction measures are expected to fall on community members as increases in their utility rates.

Because these costs are so high, the wastewater community must seek innovative solutions, often by maximizing the use of existing infrastructure or identifying projects that reduce nitrogen but also provide additional benefits. For example, investments in water recycling can enhance drought resilience, while projects such as treatment wetlands can improve shoreline resilience, support habitat restoration, and create new recreational opportunities for the community.

Two years into the 2024 Watershed Permit, several agencies are evaluating nutrient reduction alternatives. For example, the San Francisco Public Utilities Commission has budgeted $1.5 billion for a nutrient reduction project with a progressive design-build team. They are evaluating a suite of pathways, including a major facility upgrade for BNR, and exploring synergies for future recycled water expansion. However, many agencies have already begun implementation. This article provides a sampling of some of these initiatives at the largest facilities in the region. These projects are part of the largest investment in wastewater infrastructure since the 1970s.

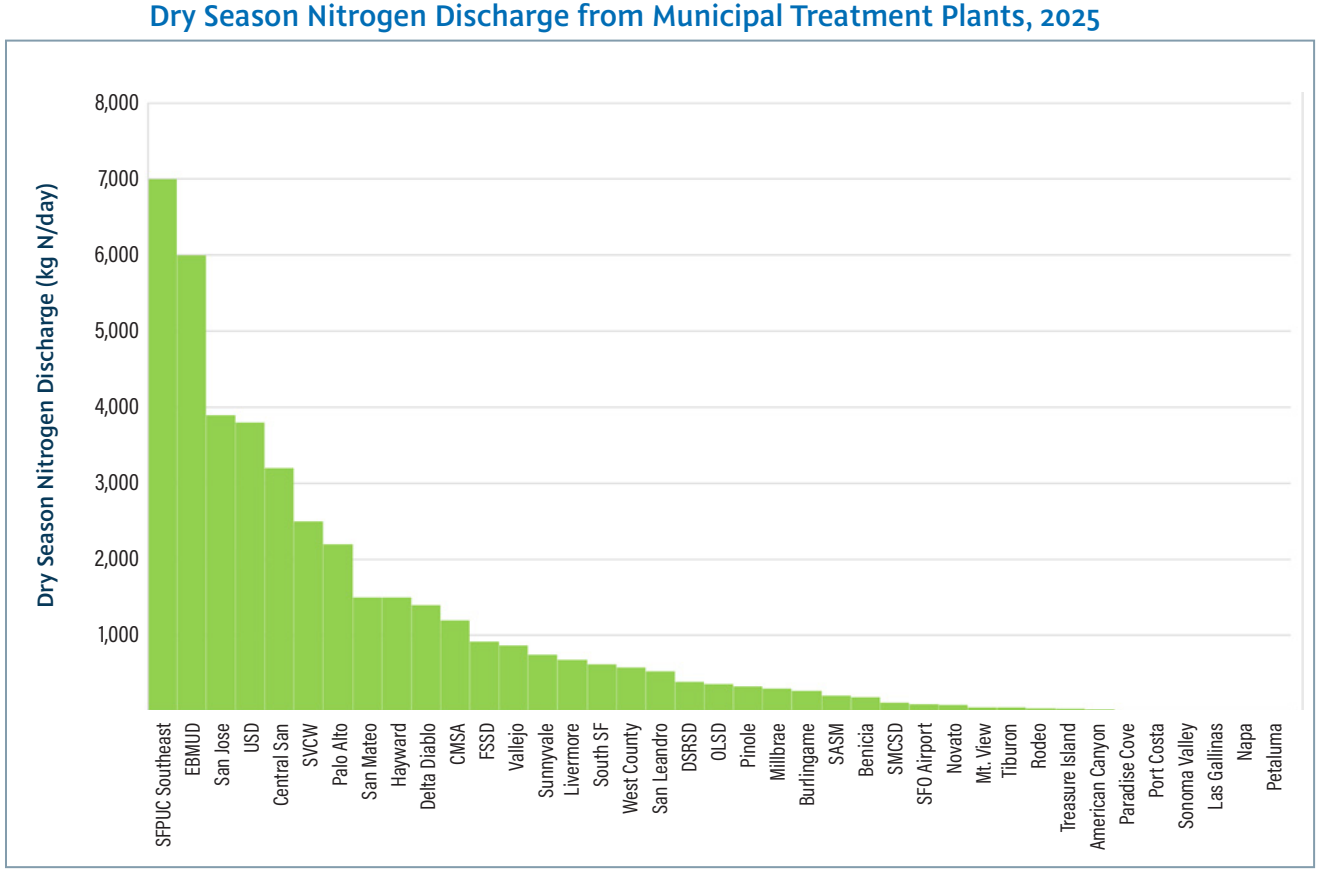


Figure 2. Dry season nitrogen discharge from municipal treatment plants, 2025. The municipalities are required to monitor and report their nutrient discharges.

MAKING THE MOST OF EXISTING INFRASTRUCTURE

Upgrading wastewater facilities that were not originally designed to reduce nutrients can be a challenge, especially in a dense urban area like the San Francisco Bay region. Each of the facilities in our region has a unique combination of processes with various ages and particular site constraints. In some cases, there is literally no space to add on BNR process units, so engineers need to employ creative problem solving.

For some agencies whose existing processes have decades of life left in them, there may be an opportunity to implement innovations to reduce nutrients using that existing infrastructure. Some agencies, such as the City of Benicia, have had early successes in optimizing their treatment processes by changing how the bacteria that provide secondary treatment (biological treatment that harnesses bacterial metabolism to break down organic matter) are recirculated in their systems. East Bay Municipal Utility District has been successful piloting nutrient reduction within their existing basins using excess dry weather capacity (page 27).

One promising technology to provide nitrogen removal within existing facilities is a Membrane Aerated Bioreactor (MABR), where oxygen is delivered to a biofilm via a gas-permeable membrane, rather than by bubbling air through the water. The City of Palo Alto is in the midst of a multi-year construction project that will implement MABR, and Central Contra Costa Sanitation District launched a demonstration-scale test in 2026 after a successful pilot in 2025 (page 29).

MAKING OPPORTUNISTIC UPGRADES

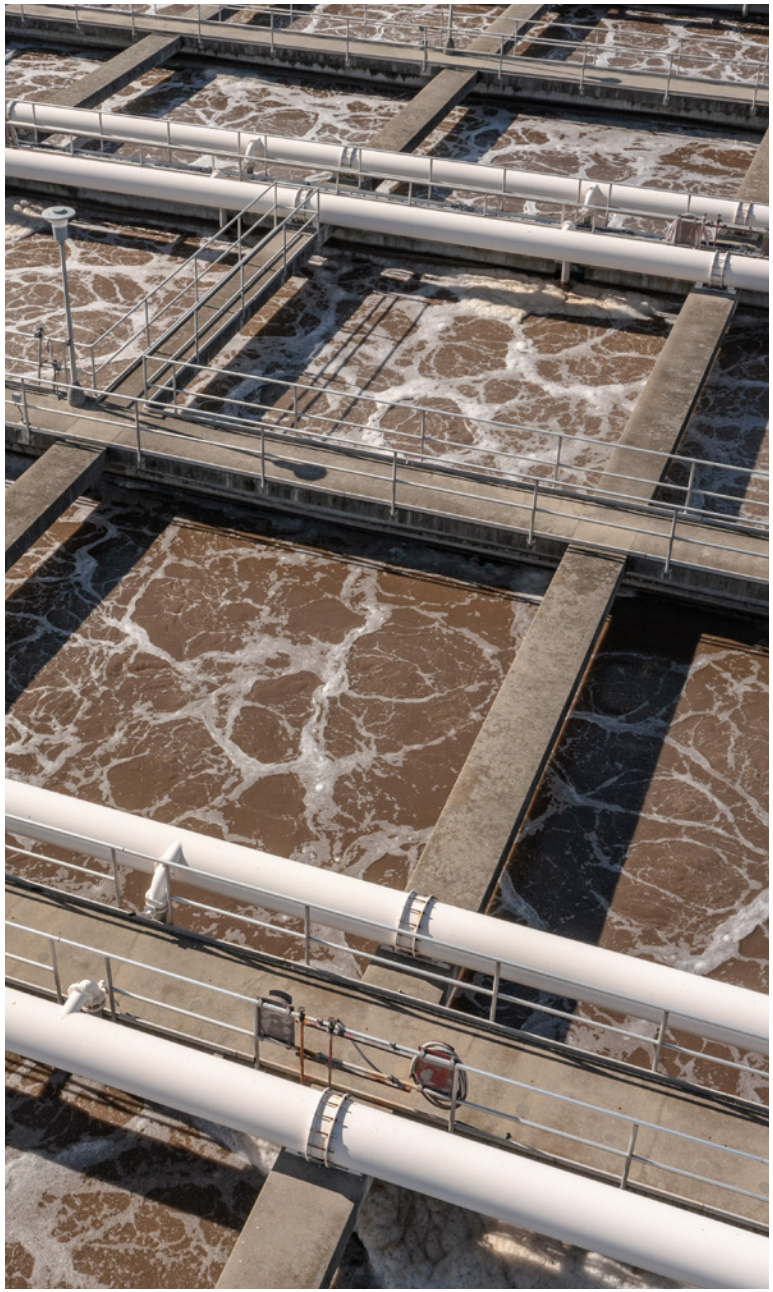
Because many facilities were built in the 1970s, they are reaching the end of their usable lifespan. In some cases, separate infrastructure improvement priorities may dovetail with nutrient reduction solutions. Several agencies, including the City of Palo Alto, the City of Sunnyvale, and Union Sanitary District (page 25), are in the midst of major upgrades to replace aging infrastructure while incorporating nitrogen reduction. The City of San Mateo recently completed construction of new BNR facilities.

MAXIMIZING RECYCLED WATER TO BENEFICIALLY REUSE NUTRIENTS

Using recycled water for irrigation can achieve multiple goals by conserving potable (drinking) water, diverting nutrients from the Bay, and beneficially reusing those nutrients while offsetting fertilizer use. Among stakeholder communities in the region, there is general support for recycled water as a means to address multiple challenges. However, recycled water programs often involve collaborative partnerships between multiple agencies, including both wastewater and water agencies. The time required to form and develop agreements substantially lengthens the timeline for project implementation. Furthermore, many agencies located in built-out urban areas have limited opportunities for recycled water deliveries near their facilities.

Even with these challenges, many agencies plan to incorporate new non-potable recycled water programs into their nutrient reduction plans. Dublin San Ramon Services District (DSRSD) is a regional leader in recycled water, and plans on further increasing its recycled water deliveries in the future (page 31).

Potable water reuse is a promising avenue for increasing our region's resilience to drought. Recycling water to drinkable quality requires reverse osmosis (RO), which is a membrane technology that produces exceptionally high-quality water. RO separates the incoming treated wastewater into two streams: the "permeate," which constitutes about 85% of the total incoming flow but only 5% of the pollutants, such as nitrogen, and an "RO concentrate," which is the remaining 15% of the flow and 95% of the pollutants. This RO concentrate must be managed, and if it is simply discharged through a wastewater outfall without additional process modifications, this approach does not address nutrients.



▲ **Aeration basins at Central Contra Costa Sanitary District.**
Photo by Joseph Zumbo.

Mike Connor

1951–2025



▲ **Mike Connor and colleagues at the 2006 RMP Annual Meeting.** Photo by Jay Davis.

Michael (Mike) Connor, who passed away in June 2025, was another key figure in the development of the Nutrient Management Strategy (NMS) and nutrient science in San Francisco Bay. Mike was a catalyst for Bay nutrient science in his roles as Executive Director of the San Francisco Estuary Institute (SFEI) from 2002-2008, General Manager of the East Bay Dischargers Authority (EBDA) from 2008 until his retirement in 2018, and member of the Bay Area Clean Water Agencies (BACWA) Executive Board (and Board Chair from 2013-2015). Mike's impactful career had a sharp focus on using science to improve coastal urban water management.

Mike established roots in the Bay Area early in his career, earning a BA in Biology from Stanford University in 1974. He then moved to the East Coast where he gained experience working at the intersection of science, management, and policy at a range of institutions. He received a PhD in Biological Oceanography from a joint Massachusetts Institute of Technology/Woods Hole Oceanographic Institution program in 1980. He then did postdoctoral fellowships with the National Science Foundation and at the Harvard School of Public Health. In 1982, Mike became a National Estuary Program Coordinator for the US Environmental Protection Agency, where he worked to develop management plans for Long Island Sound, Narragansett Bay, and Buzzards Bay. From 1988-1998 he served as the first Director of the Environmental Quality Department at the Massachusetts Water Resources Authority, where he developed a Massachusetts Bay monitoring plan to address Endangered Species Act concerns and built research partnerships with NOAA and USGS to create a Bay eutrophication (excessive algae growth) model. From 1998-2002 Mike was Vice President of Programs and Exhibits at the New England Aquarium. Under the

Mike will be remembered for his tireless efforts to protect the Bay

leadership of Mike and his mentor, Aquarium President Jerry Schubel, the Aquarium doubled its grant funding and opened three new exhibits.

These experiences on the East Coast prepared Mike well for his roles as a regional leader in the Bay Area at SFEI, EBDA, and BACWA. At SFEI, given his background in coastal water quality, Mike was actively engaged in the governance and science of the RMP. And given his knowledge and experience with nutrients and eutrophication, he was very receptive to Jim Cloern's warnings about increasing Bay algae concentrations. After Mike moved to EBDA in 2008, he remained involved in, and a driving force behind, nutrient discussions within the Regional Monitoring Program and the NMS.

As Board Chair for BACWA, which includes all Bay wastewater agencies, Mike oversaw BACWA's strategic response to nutrient concerns in the Bay. Mike, in his role as General Manager of EBDA, received a Bay Hero award with his partners for the "First Mile Horizontal Levee Project", a green engineering strategy using wetlands to reduce nutrients and emerging contaminants in municipal wastewater (pages 32-33). The first large-scale, fully functional horizontal levee in the Bay Area, the project integrates water quality improvement, flood protection, habitat enhancement, and public access into a single, multi-benefit system.

Mike also worked internationally. As a Fulbright Specialist for the US Department of State from 2016-2018, he worked in both Myanmar and Mauritius on connecting coastal science, management, and policy. He also served as an advisor to agencies in Japan, Korea, and Hong Kong.

Mike will be remembered for his intelligence, love of science, candor, mentorship, humor, and tireless efforts to protect the Bay and other coastal ecosystems.

He was a world-class thinker and scientist. In meetings he was very engaged, one of the brightest people in the room, and could be counted on to be a provocateur and make sure discussions were meaningful and focused on the things that really mattered. He had a huge impact on Bay water quality, most notably by setting in motion the major investments in treatment plant upgrades now being made to manage nutrients. Mike is missed, but his impact and legacy live on. §



▲ **Mike Connor describing the Oro Loma Horizontal Levee.** Still from Oro Loma Horizontal Levee: Interview: Mike Connor, East Bay Dischargers Authority, General Manager. YouTube video posted by Oro Loma Sanitary District, October 29, 2015.

WORKING WITH NATURE TO IMPROVE WATER QUALITY AND PROTECT THE SHORELINE



The Oro Loma Horizontal Levee.
Photo by Ian Wren.

Nature-based solutions, such as engineered treatment wetlands and horizontal levees, are attractive alternatives for nutrient management, as they bring the co-benefits of flood risk reduction and habitat enhancement. A handful of agencies around the region, such as Mountain View Sanitary District and the City of Petaluma, have longstanding open-water treatment wetlands that have "polished" wastewater outflow for decades. These ponds mimic natural wetlands and support wildlife.

Horizontal levees are a relatively new concept. Horizontal levees are plant-covered slopes built along the waterline to buffer the areas behind them from flooding. Treated wastewater released behind these levees moves toward the Bay below the surface and is "polished" as it passes beneath the soil through a series of raised beds (berms). Nutrients are taken up or transformed by soil microbes and plants.

Oro Loma Sanitary District worked with researchers at the University of California Berkeley to pilot a horizontal levee test bed that was 97% effective in reducing nitrogen, metals, and contaminants of emerging concern. The City of Palo Alto recently completed construction of the region's first demonstration-scale horizontal levee. The East Bay Dischargers Authority (EBDA) is building on these early successes and is in the planning stage of the "First Mile" project that will remove nitrogen from treated wastewater from the City of Hayward and Union Sanitary District (page 33).

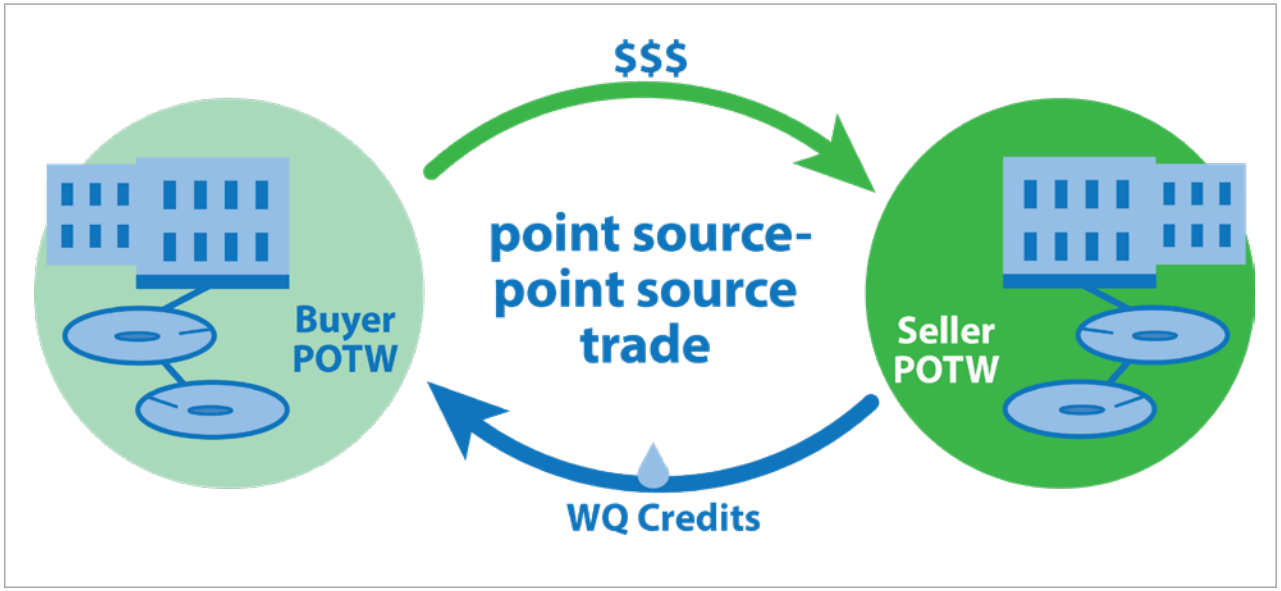
While nature-based solutions are an exciting opportunity where feasible, land requirements for nutrient reduction through wetlands are very large, and land adjacent to the Bay is expensive and often unavailable. This challenge, and the challenge of removing nutrients from RO concentrate, as described in the previous section, provide an interesting potential synergy. The RO process concentrates nitrogen into a smaller volume, which requires less land area if treated through a constructed wetland. Treating RO concentrate via horizontal levees is an area of active research. The City of San José, which is collaborating with Valley Water on a potable water reuse project, is initiating a feasibility study to treat RO concentrate through a horizontal levee on its property.

NUTRIENT TRADING AND THE BENEFITS OF REGIONAL COLLABORATION

The Watershed Permit allows for developing a trading program for wastewater agencies to meet nutrient reductions by buying credits from other agencies who achieve nutrient reduction beyond what is required. By looking beyond individual facilities to consider nutrient reduction opportunities throughout the watershed, participants in a trading program can pursue the most efficient and cost-effective compliance strategies while reducing nutrients discharged to the Bay. BACWA commissioned a trading feasibility assessment in 2025 (The Freshwater Trust 2025). The study found that trading is feasible, and could account for up to 20% of the total nitrogen reduction required by the Watershed Permit by encouraging wastewater treatment facilities with large site-specific opportunities for nutrient removal to take advantage of their full potential. As a next step, BACWA will evaluate specific credit buyer and seller scenarios and develop a framework to govern a trading program. They may eventually incorporate offsite green engineering alternatives to reduce nutrient levels in the Bay, such as tidal marsh restoration or expansion of shellfish beds.

A Varied Array of Projects

Many agencies are taking a mixed approach to nutrient reduction, especially in cases where upgrades and process optimization were already implemented or where a multi-benefit project or optimizing may not reduce nutrients enough to achieve permit limits. The City of San José, which has already upgraded to BNR and optimized the existing process, is pursuing further upgrades, including potable and non-potable recycled water, and considering nature-based solutions (page 35). This mixed approach where each agency can develop a portfolio of approaches to address its individual needs helps our region achieve long-term, sustainable nutrient reductions while continuing to serve a growing population.



▲ Illustration courtesy of The Freshwater Trust.

The following pages provide profiles of six municipal wastewater treatment plants and their plans to implement enhanced nutrient reduction measures.



Nutrient Reduction Project Profiles: UNION SANITARY DISTRICT (USD)

Authors: Armando Lopez and Paul Eldredge

USD began evaluating wastewater treatment infrastructure needs in 2015 as major plant components approached the end of their useful life and operational constraints emerged. Although overall flows were declining, solids loading continued to increase, creating treatment capacity challenges. This early planning effort incorporated potential future nutrient requirements, even though no formal nutrient limits were in place at the time. The analysis focused on achieving meaningful nutrient reduction without triggering excessive cost escalation, ultimately targeting a 50% reduction in total inorganic nitrogen.

In 2018, this effort evolved into the Enhanced Treatment and Site Upgrade (ETSU) program. Phase 1A includes modifications to all existing aeration basins and construction of a new aeration basin to enable BNR, along with a new campus building to relocate existing facilities and create space for subsequent construction. Phase 1B consists of constructing new secondary clarifiers and effluent facilities, which are essential to achieving reliable BNR performance, while Phase 1C focuses on flow equalization and emergency storage upgrades.

Implementation of the ETSU program has occurred during an exceptionally challenging period. The COVID-19 pandemic, global supply chain disruptions, escalating inflation, and severe labor shortages significantly affected both costs and schedules. Equipment delivery times increased dramatically, bids far exceeded estimates, and construction progress slowed across multiple elements of the program. As a result, the program budget increased incrementally – from $348 million to $482 million, then to $541 million, and ultimately to $670 million following receipt of Phase 1B construction bids in 2025.

Despite these challenges USD has continued to advance the program as efficiently as possible, with design and construction activities overlapping where feasible and extensive engineering optimization completed throughout the process. Early action enabled planning and design of nutrient removal infrastructure ahead of regulatory mandates, positioning the facility to meet long-term watershed permit expectations. While significant work remains, USD has committed substantial resources over the past decade to achieve nutrient reduction goals, and that commitment will continue through the completion of the ETSU program.

FACILITY:	Alvarado Wastewater Treatment Plant, Union City
SERVICE AREA:	Fremont, Newark, Union City, southern Alameda County (60 sq mi)
POPULATION SERVED:	348,000 (2025)
DRY-WEATHER FLOW, 2025:	23 MGD
DATE ORIGINALLY BUILT:	1981
DAILY DRY-WEATHER TOTAL NITROGEN LOAD, 2025:	3,600 kg

◀ **Construction in progress as part of USD's Enhanced Treatment and Site Upgrade program.**
Photo courtesy of USD.



Nutrient Reduction Project Profiles:
EAST BAY MUNICIPAL UTILITY DISTRICT (EBMUD)

Author: Justin Shih

EBMUD has made significant progress in reducing nutrient discharges through a phased and integrated approach to wastewater treatment improvements. In 2021, EBMUD completed an Integrated Master Plan that evaluated a wide range of nutrient reduction strategies while balancing operational, regulatory, and infrastructure priorities across the wastewater treatment plant.

Beginning in 2020, EBMUD initiated in-house testing of a BNR process using existing full-scale reactor decks and clarifiers. During summer dry-weather months, the secondary treatment system was operated as a split plant, with one side converted to BNR mode. Over successive summers, staff steadily increased the portion of influent treated through BNR, reaching up to 75% of secondary flow. In parallel, EBMUD limited the acceptance of animal blood wastes, which had contributed approximately 8% of the District's total inorganic nitrogen discharge.

These early efforts produced measurable results. In a major milestone for protecting Bay water quality, summer nitrogen loads declined by nearly 50% relative to interim limits. In 2024 and 2025, EBMUD expanded BNR operation to year-round use to accelerate process startup and improve performance ahead of dry weather. This expanded operation resulted in the lowest nitrogen discharge to the Bay since required monitoring began in 2012. Continued testing is underway to define upgrades needed for reliable long-term performance.

Recent process modeling and capacity assessments indicate that the existing high-purity oxygen activated sludge BNR configuration is unlikely to consistently meet future nitrogen targets without substantial improvements to the secondary treatment process. In response, EBMUD initiated a Nutrients Master Plan update in mid-2025. This focused effort aims to identify nutrient removal alternatives capable of meeting Watershed Permit limits that take effect in October 2034, with an approach that leverages existing infrastructure supported by targeted capital investments.

FACILITY:	Main Wastewater Treatment Plant, Oakland
SERVICE AREA:	Alameda, Albany, Berkeley, El Cerrito, Emeryville, Kensington, Oakland, Piedmont, part of Richmond (88 sq mi)
POPULATION SERVED:	740,000
DRY-WEATHER FLOW, 2025:	44 MGD
DATE ORIGINALLY BUILT:	1951
DAILY DRY-WEATHER TOTAL NITROGEN LOAD, 2025:	6,000 kg

The EBMUD Main Wastewater Treatment Plant located in Oakland, California.
Photo courtesy of EBMUD.



Nutrient Reduction Project Profiles:
CENTRAL CONTRA COSTA SANITARY DISTRICT (CENTRAL SAN)

Authors: Nitin Goel and Lori Schectel

Central San is advancing a multi-year, integrated strategy to comply with future nutrient regulations while managing costs, energy use, and long-term operational impacts across its wastewater treatment plant. Because more than half of Central San's treatment processes and related facilities will ultimately be affected, it is essential to fully evaluate the most effective and efficient technology pathway before committing to full-scale construction for nutrient compliance.

Following the successful completion of a small-scale pilot in early 2025, Central San began implementation of a full scale demonstration of Membrane Aerated Biofilm Reactor (MABR) technology in the summer of 2026. This demonstration will assess whether MABR can reliably achieve the required 40% nutrient reduction using a lower-energy and more cost-effective approach than conventional treatment alternatives. If successful, MABR could allow Central San to meet regulatory requirements without constructing new aeration basins, potentially avoiding significant capital investment while reducing long-term operations and maintenance costs for our customers.

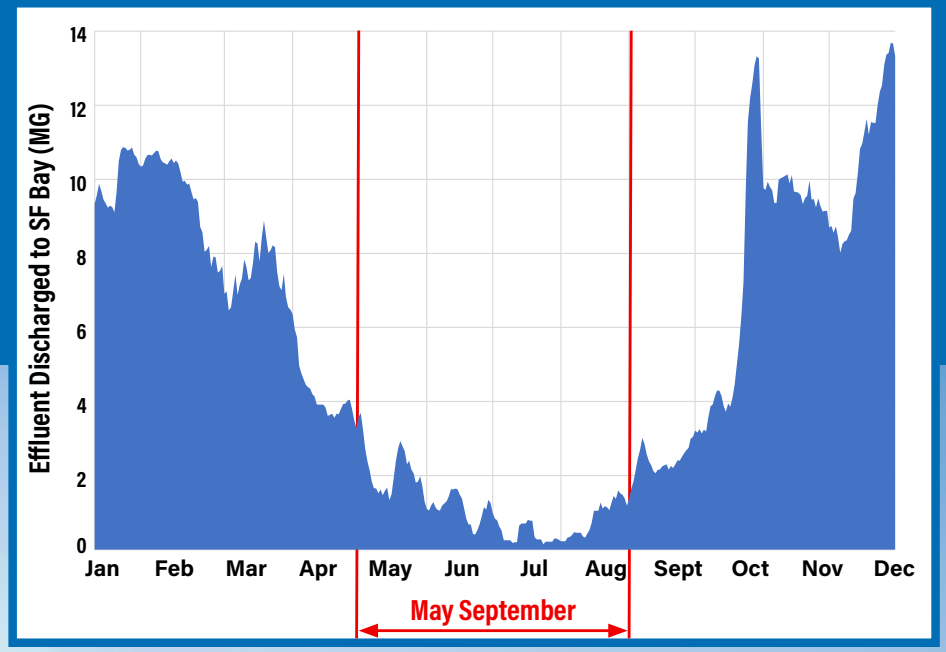
The MABR demonstration period must run its full course – shortening it risks stranded or prematurely built infrastructure. From 2026 through 2027, Central San plans to install and operate demonstration-scale MABR modules across multiple seasons to evaluate real-world performance. In parallel, they will assess system reliability, treatment efficiency, and integration with existing facilities. In 2027, they also plan to initiate a densified activated sludge pilot to enhance MABR performance. Densified activated sludge (DAS) can increase treatment capacity and improve clarifier loading and settling efficiency, potentially reducing or deferring the need for additional secondary clarifiers.

If the MABR demonstration in 2026 and the DAS demonstration in 2027 confirm performance at scale, Central San will proceed with a phased buildout between 2028 and 2034, integrated with planned clarifier and aeration basin upgrades, followed by startup and commissioning through 2036. If MABR and DAS do not prove viable, they will shift to a conventional BNR approach, requiring major new infrastructure and a substantially longer and more costly timeline.

This deliberate, flexible approach allows Central San to minimize risk, avoid unnecessary capital investment, and pursue a nutrient compliance strategy that delivers the greatest long-term benefit to their community and the region.

FACILITY:	Central San Treatment Plant, Martinez (Suisun Bay)
SERVICE AREA:	13 cities/towns, central Contra Costa County (146 sq mi)
POPULATION SERVED:	500,000
DRY-WEATHER FLOW, 2025:	31 MGD
DATE ORIGINALLY BUILT:	1948
DAILY DRY-WEATHER TOTAL NITROGEN LOAD, 2025:	3,200 kg

Crews install one of 44 MABR cassettes into an aeration basin at Central San (inset); broader view of the aeration basins. Photos by Joseph Zumbo.



(Left) Effluent discharged to the Bay by DSRSD, 2021. DSRSD recycles up to 80% of its wastewater in the dry season, greatly reducing the amount discharged to the Bay.

Nutrient Reduction Project Profiles:
DUBLIN SAN RAMON SERVICES DISTRICT (DSRSD)

Authors: Jan Lee, Corinne Ferreyra, and Dan Gill

DSRSD operates one of the most successful recycled water programs in the Bay Area, recycling up to 80% of wastewater during the dry season. Recycled water comprises 20–25% of their service area's total water demand, and two-thirds of their irrigation demand. Through the DSRSD-EBMUD Recycled Water Authority (DERWA), a joint powers authority formed in 1995, DSRSD's program has produced over 20 billion gallons of recycled water for customers within the San Ramon Valley, supported by over $250 million in infrastructure investment and more than 73 miles of recycled water pipeline.

Recycled water is DSRSD's primary nutrient management strategy and substantially reduces nitrogen discharges to the Bay. Between May and September, when harmful algal blooms are most likely, recycled water has displaced treated wastewater discharges (see graph), resulting in the removal of over 3,300 tons of total inorganic nitrogen since 2006. Seasonal irrigation demand aligns well with the Watershed Permit dry season, making it an effective multi-benefit approach to regulatory compliance, water supply resilience, and environmental protection. However, during wet springs when irrigation demand is lower, there is less of an opportunity to divert nutrients.

Future expansion of water recycling is constrained by declining wastewater flows driven by aggressive indoor water conservation requirements and statewide efficiency standards. In response, DSRSD and DERWA instituted a moratorium on new recycled water connections in 2019 and shifted focus toward supplemental supply strategies, most notably a temporary diversion receiving up to 0.7 million gallons per day of wastewater from Central San. This partnership is being evaluated for long-term expansion to increase available recycled water supplies up to 2.7 million gallons per day to meet projected future demands, which would improve water resiliency and further reduce nitrogen discharges to the Bay.

FACILITY:	DSRSD Regional Wastewater Treatment Facility (Jeffrey G. Hansen Water Recycling Plant), Pleasanton
SERVICE AREA:	Dublin, San Ramon, and Pleasanton
POPULATION SERVED:	194,600
DRY-WEATHER FLOW, 2025:	11.7 MGD of influent
DATE ORIGINALLY BUILT:	1961
DAILY DRY-WEATHER TOTAL NITROGEN LOAD, 2025:	392 kg

◀ **Dublin Sports Grounds Park landscaping irrigated with recycled water.**
Photo courtesy of City of Dublin.



Nutrient Reduction Project Profiles:
EAST BAY DISCHARGERS AUTHORITY (EBDA) FIRST MILE

Author: Jackie Zipkin

EBDA is a joint powers agency made up of the cities of San Leandro and Hayward, and the Castro Valley, Oro Loma, and Union Sanitary Districts. EBDA manages the sustainable disposal of wastewater from one million East Bay residents and businesses to the Bay, including contract flows from the Livermore-Amador Valley Water Management Agency.

The First Mile Horizontal Levee Project is EBDA's landmark nature-based shoreline adaptation project located along the eastern edge of Oro Loma Marsh on the Hayward shoreline. Designed as the first large-scale, fully functional horizontal levee of its kind in the Bay Area, the project integrates flood protection, water quality improvement, habitat enhancement, and public access into a single, multi-benefit system.

Unlike traditional vertical levees, the First Mile uses a broad, gently sloping "living levee" that mimics the Bay's historic shoreline. The levee absorbs wave energy and rising tides while providing an upland transition zone that allows marsh habitats to remain resilient as sea level rises. This design will reduce flood risk to nearby neighborhoods in Hayward and San Lorenzo, as well as protect critical regional assets such as parks, infrastructure, and the Bay Trail.

A defining feature of the First Mile is its subsurface treatment layer, which uses engineered soils and native vegetation to "polish" treated wastewater and stormwater before discharge to the Bay. Based on research and local demonstration projects, the horizontal levee is expected to remove as much as 900 kilograms per day of nitrogen.

The project will also create or enhance wet meadow, tidal marsh, and transition-zone habitat, providing high-tide refugia habitat for wildlife and strengthening shoreline resilience. The top of the levee will include a new segment of the Bay Trail, expanding public access and community connection to the shoreline.

As a priority project within the Hayward Regional Shoreline Adaptation Master Plan, the First Mile serves as a regional demonstration, helping establish permitting pathways, design guidance, and governance models needed to scale multi-benefit nature-based solutions throughout the Bay.

FACILITY:	First Mile Horizontal Levee Project, receiving flow from combined EBDA outfall
SERVICE AREA:	San Leandro, Oro Loma SD, Castro Valley SD, Hayward, USD; also Livermore-Amador Valley Water Management Agency (Pleasanton, Livermore, DSRSD)
POPULATION SERVED:	1,000,000
DRY-WEATHER FLOW, 2025:	37.9 MGD (combined)
DATE ORIGINALLY BUILT:	Not applicable
DAILY DRY WEATHER TOTAL NITROGEN LOAD, 2025:	900 kg

◀ **First Mile Horizontal Levee Project on the Oro Loma Marsh on the Hayward shoreline.**
Illustration by Nate Kauffman.



Nutrient Reduction Project Profiles: CITY OF SAN JOSÉ

Author: Eric Dunlavey

The City of San José is taking a comprehensive, long-term approach to reducing nutrient discharges from the San José–Santa Clara Regional Wastewater Facility. The facility serves approximately 1.5 million residents and more than 17,000 businesses across Santa Clara County and receives an average of about 22,000 kilograms of nitrogen per day in the dry season. The facility removes 75% to 80% of that nitrogen through a combination of treatment processes and reuse, resulting in an average outflow of roughly 4,000 kilograms of nitrogen per day.

A major milestone in San José's nutrient reduction efforts occurred in 1998, when they converted their secondary treatment process to an integrated BNR system with denitrification. Today, the BNR process produces high-quality treated wastewater, and removes about 50% of incoming nitrogen, or approximately 11,000 kilograms per day.

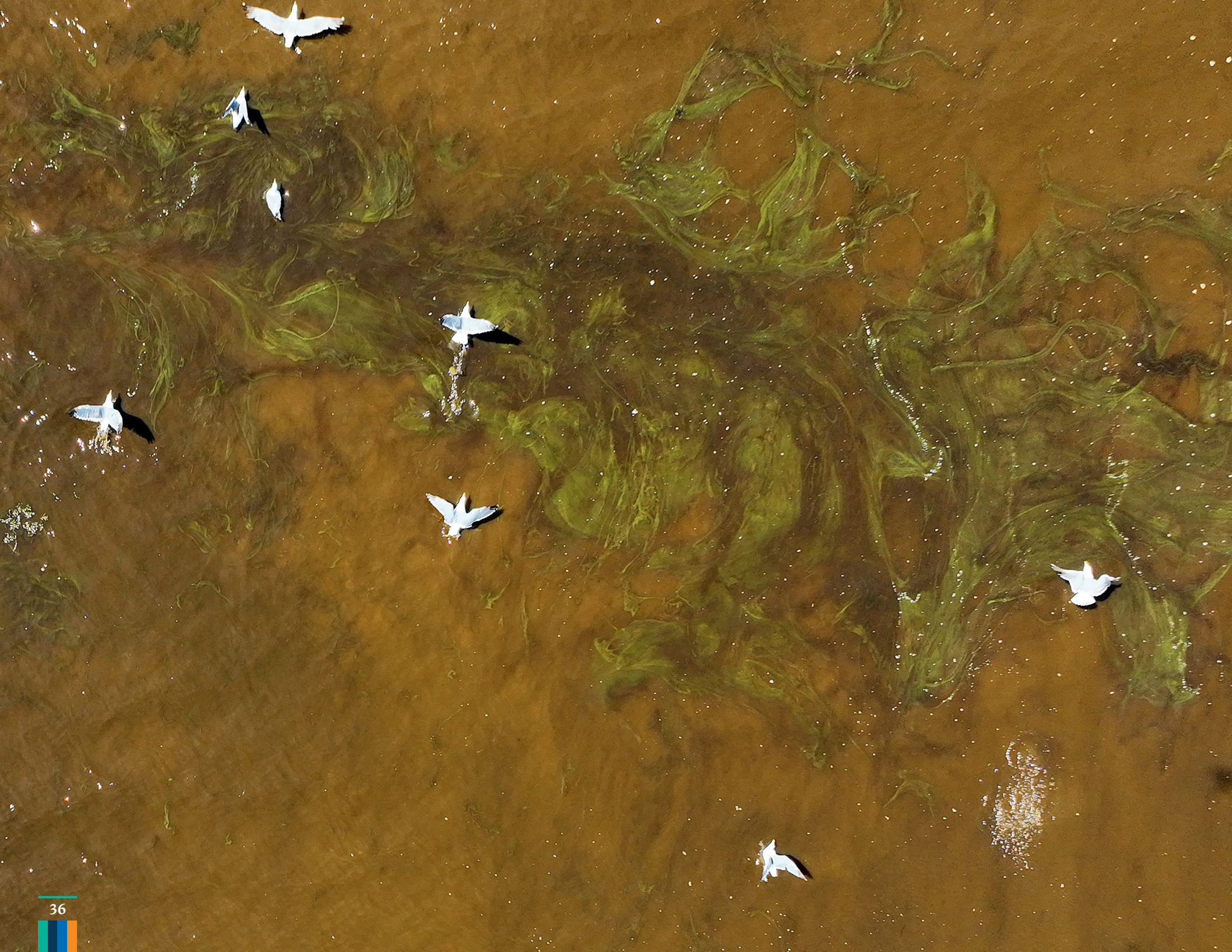
San José also operates a large non-potable recycled water program, originally launched to reduce discharges to Lower South Bay during the dry season. The program now diverts an average of nearly 17 million gallons per day in the dry season, reducing nitrogen loads by roughly 1,000 kilograms per day.

San José's existing biosolids processing using lagoons and drying beds has historically prevented about 4,400 kilograms of nitrogen per day from entering the Bay. However, they are transitioning away from this land- and time-intensive biosolids process to a modern mechanical dewatering system to meet new regulatory requirements to reduce methane emissions from landfills. While necessary, this change will reduce nitrogen removal from biosolids processing by about half, resulting in an interim increase in nitrogen in treated wastewater of about 1,800–2,400 kilograms per day.

San José is addressing this anticipated increase through a multi-decade, $2 billion capital improvement program that includes phased upgrades to their secondary aeration basins and expanded recycled water use. They are also planning future potable reuse in collaboration with Valley Water, possibly in conjunction with a nature-based solution to treat the resultant RO concentrate.

FACILITY:	San José–Santa Clara Regional Wastewater Facility
SERVICE AREA:	San José, Santa Clara, Milpitas; Cupertino SD; West Valley SD; County SD 2-3; Burbank SD
POPULATION SERVED:	1,500,000
DRY-WEATHER FLOW, 2025:	83 MGD
DATE ORIGINALLY BUILT:	1956
DAILY DRY-WEATHER TOTAL NITROGEN LOAD, 2025:	3,900 kg

◀ **Aerial image of San José–Santa Clara Regional Wastewater Facility.**
Photo courtesy of the San José-Santa Clara Regional Wastewater Facility.



Inside the 2022 San Francisco Bay Algal Bloom

Will Geiken, David Senn, Ian Wren, and Sierra Garcia
San Francisco Estuary Institute

In July 2022, San Francisco Baykeeper received reports of rusty brown water in the channel between Alameda and Oakland. Staff like Baykeeper scientist Ian Wren, now with SFEI, soon became concerned as the messages from community members piled up. "We often see discolored water in that area and around that time of year, but this was far more than usual," recalls Wren.

Baykeeper alerted colleagues at SFEI, other regional water quality experts, and state officials, who diagnosed the problem as a fast-growing bloom of one algae species, called *Heterosigma akashiwo (H. akashiwo)* (page 58). Within days, dead fish began lining the Bay shore by the dozens, then hundreds, then thousands. By mid-August, the brownish tinge of quintillions (millions of trillions) of individual algae cells stretched from the Dumbarton Bridge to San Pablo Bay.

Before 2022, scientists, wastewater agencies, and regulators understood that the Bay was susceptible to harmful algal blooms (HABs), but none anticipated a bloom of the magnitude that followed. Between the 1990s and 2010s, algae growth nearly tripled in some areas of the Bay. In 2002 and 2004, algae in the Bay reached levels that indicated potential HABs, but no fish mortality or water quality impairment was reported (Patil 2022, Cloern 2005). Year after year, major harmful blooms did not materialize.

Despite indicators that the Bay's resistance to HABs had been decreasing, the 2022 bloom still took the region by surprise. The most impactful bloom in the Bay's recent history, the 2022 HAB initiated a paradigm shift for regional managers, who went from asking, "Will it happen?" to "How do we make sure it doesn't happen again?" In the years since, scientists in the region have investigated the factors that led to the bloom, how it progressed, and potential tools to protect the Bay in the future.

◀ **Gulls flying over algae-laden water during the 2022 *H. akashiwo* bloom** in San Francisco Bay on August 24, 2022 near Berkeley. Photo by Jason Sullivan / Algae Bloom Fills Bay Area Waters via Getty Images.

HIGHLIGHTS

- The 2022 *Heterosigma akashiwo* harmful algal bloom (HAB) resulted in large-scale fish mortality throughout most of the Bay
- The bloom was fueled by the abundant nutrients available in the Bay and the continued nutrient inputs from wastewater treatment plants and other sources during the bloom
- The bloom's spread was likely enhanced by periods of weak tides, clearer than usual water, layering ("stratification") in the water column, and key adaptations that improved *Heterosigma akashiwo's* ability to sustain the bloom
- What initiated and abruptly ended the bloom remains uncertain, but new findings suggest that viruses may have played a major role
- In the wake of the bloom, collaborators are developing a regional monitoring program to detect future HABs and rapidly inform the region

HISTORIC BLOOM RESISTANCE

The term "algae" includes a wide range of photosynthetic aquatic life, from single-celled phytoplankton to giant kelp. They are the base of the food web, and nutritious algae populations are necessary for healthy aquatic ecosystems.

During a HAB, however, algae populations grow to levels that harm other organisms. They can cause harm in three ways.

1. **TOXIN PRODUCTION:** Some algae produce toxins that affect other organisms. These toxins can contaminate shellfish and cause amnesic shellfish poisoning and other illnesses in humans. They can also kill fish and marine mammals.
2. **OTHER DIRECT IMPACTS:** Some algae species adversely impact marine life through other direct (but non-toxic) mechanisms. For example, they can produce mucus that clogs or irritates fish gills, or detergent-like chemicals that strip the protective water-resistant coating from bird feathers.
3. **DECREASED DISSOLVED OXYGEN:** Under some conditions, HABs can grow dense enough that the bloom collapse results in low dissolved oxygen, due to respiration by other organisms feasting on dead algae biomass.



Several algae species of concern that could could trigger a HAB in San Francisco Bay.

In San Francisco Bay, there are 24 algae of concern that scientists are monitoring (page 50). Included among HABs are so-called "red tides," which refers to the reddish-brown color that coastal waters can exhibit when some types of algae grow to high concentrations. However, not all HABs are red.

Across this wide variety of algae, HABs all share at least one key factor – they need nutrients to grow. San Francisco Bay, Chesapeake Bay, and many other water bodies receive nutrient-rich outflows from human activities, including municipal wastewater treatment plant discharges, agricultural runoff, and stormwater runoff. Such water bodies are "nutrient-enriched," and those nutrients can result in HABs.

Unlike many other nutrient-enriched estuaries, San Francisco Bay has rarely experienced severe blooms over the past few decades. This resistance has been attributed to three main factors that limit overall algae production (Cloern et al., 2007; SFEI 2014, 2025).

1. **There is limited light available in the water column** due to high suspended sediment concentrations. Sediment is churned up by tidal currents that mix the water continuously, and without light, algae cannot photosynthesize.
2. **Algae cannot remain in the light-rich surface water** for extended periods of time due to that same vigorous mixing, which further reduces their ability to grow.
3. **Dense populations of filter-feeding clams and other bivalves** feed on algae and keep their populations in check.

EARLY WARNING SIGNS

Despite those protective features, in the early 2000s, scientists observed several concerning trends that hinted the Bay's resistance to HABs was weakening. Most prominently, long-term monitoring data showed significant increases in algae growth, particularly in South Bay and Central Bay, where annual algae growth more than doubled between the early 1990s and the 2010s (Cloern et al. 2007, Foley et al. 2025). Like the blooms of 2002 and 2004, this increase didn't cause any observed harm, but it suggested that changes were occurring in the system that allowed algae to grow more easily.

In addition, multiple lines of evidence showed that harmful algae species were consistently present in the Bay. DNA surveillance documented the presence of 19 harmful algae species between 2015 and 2021 (Otten et al. 2021), and mussel tissue testing found multiple HAB toxins, including domoic acid, microcystin, saxitoxin, and diarrhetic shellfish toxins (Peacock et al. 2018). The presence of harmful species combined with increasing total algae growth and abundant nutrients added to "growing concerns that there were some cracks in the armor of the system's resistance to high nitrogen levels," says Nutrient Management Strategy (NMS) Lead Scientist David Senn.

The presence of harmful species combined with increasing total algae growth and abundant nutrients added to growing concerns

CURRENT UNDERSTANDING OF THE 2022 BLOOM

In late July 2022, Alameda residents observed a reddish-brown algal bloom forming offshore. In the following weeks, the bloom spread throughout all of South Bay and expanded northward into Central and San Pablo Bays, leading to tens of thousands of fish deaths and other ecosystem impacts.

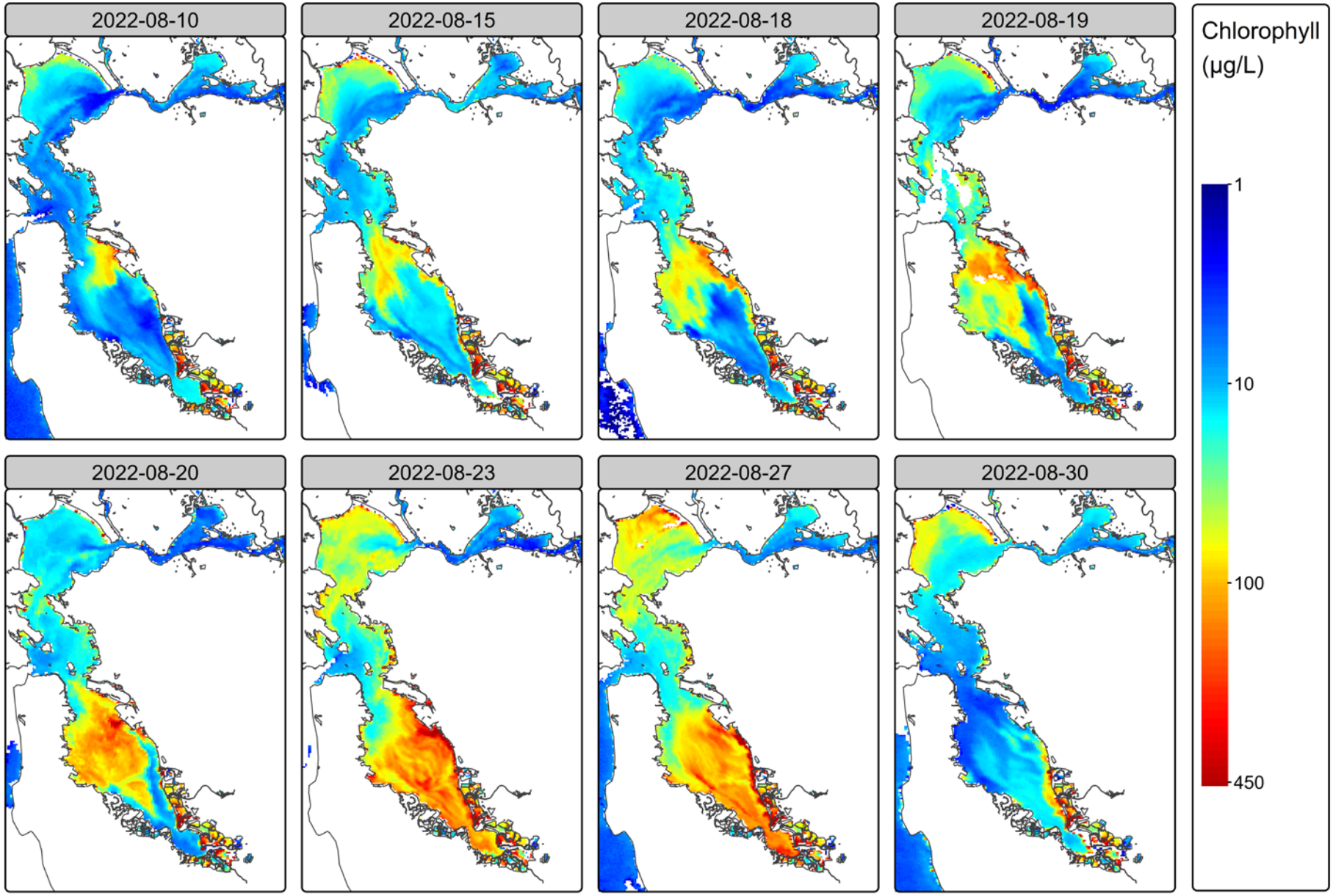
Scientists and community members alike leapt into action sampling shoreline water, collecting data on research cruises, and chronicling dead fish found along the shoreline. The culprit was quickly determined to be *H. akashiwo,* but outside of continued observation, there was little to be done in the face of the bloom.

"I will never forget being on the boat off of San Lorenzo watching gobies swimming up to breathe air, because oxygen was undetectable even in the surface layer of the water," recalls NMS scientist Dan Killam. "We passed several 6 to 7 foot long sturgeon floating belly up. The water was full of brown clumps of dead algae, and the area smelled like rotting fish."

Then, more suddenly than it had appeared, the bloom vanished. In a crash that consumed nearly all the dissolved oxygen in South Bay, *H. akashiwo* disappeared in a matter of days.

In the years since, scientists in the NMS and throughout the region have investigated what exactly allowed *H. akashiwo* to do what few other harmful algae species had done before. While some critical unknowns remain, scientists are now closing in on answers to some of the most pressing questions.

The Timeline: The Rise and Fall of Chlorophyll Concentrations

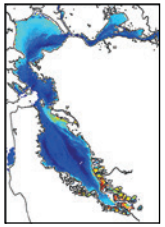


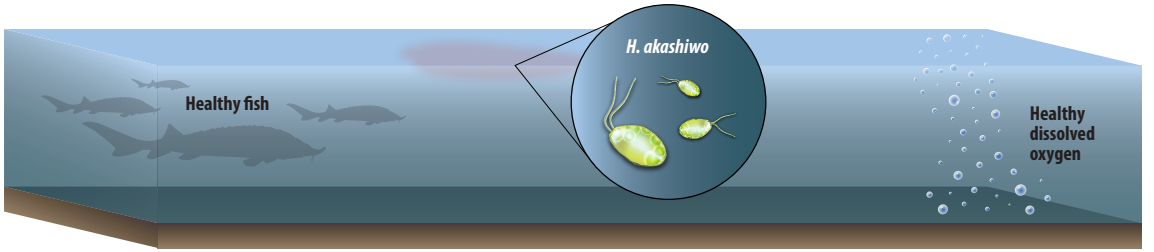
Estimated chlorophyll concentrations show the timing and extent of the bloom's progression before its abrupt collapse. Estimates created using satellite data. Chlorophyll concentrations in micrograms/liter.

The Progression of the 2022 Bloom

1 Bloom initiation
Late July to early August

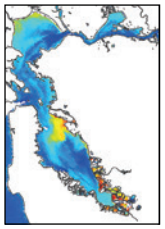
H. akashiwo began rapid growth near Alameda.

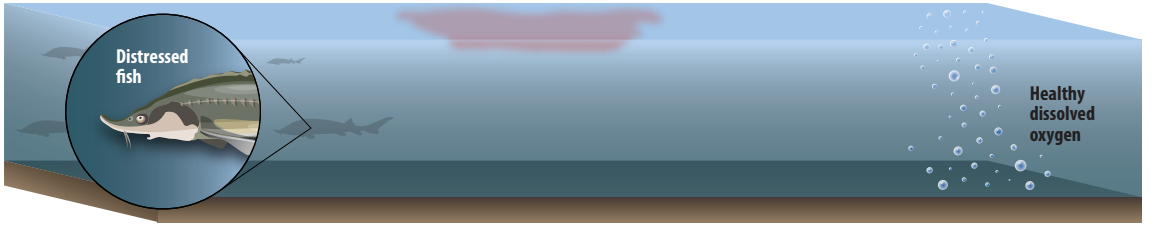




2 Expansion and sustained growth
August 3–9

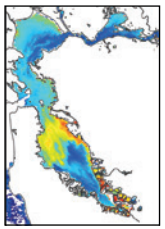
The bloom expanded into the open Bay west of Alameda, where it achieved sufficiently rapid growth to sustain and increase its biomass.

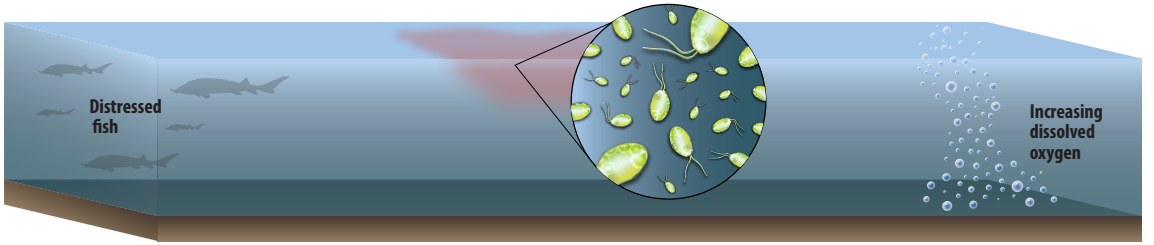




3 Stalled spread
August 11–17

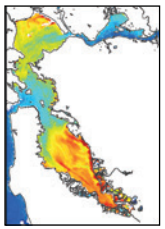
After its initial rapid growth, growth appeared to slow over the next week, with the bulk of the bloom confined to the northern third of South Bay.

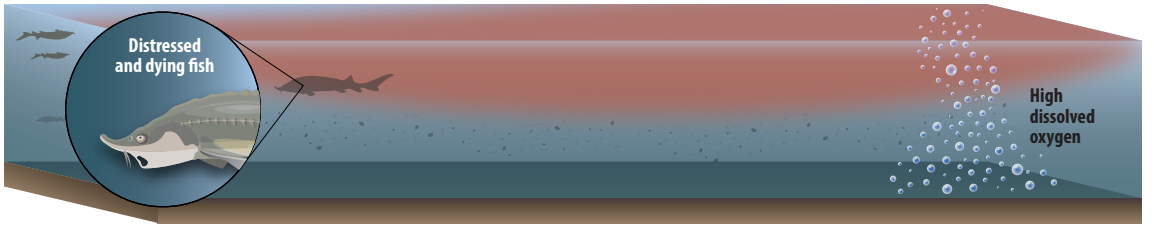




4 Rapid expansion
August 18–27

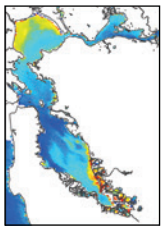
Instead of petering out, the bloom rapidly expanded into the remainder of South Bay, and biomass levels increased roughly tenfold in the newly occupied areas.

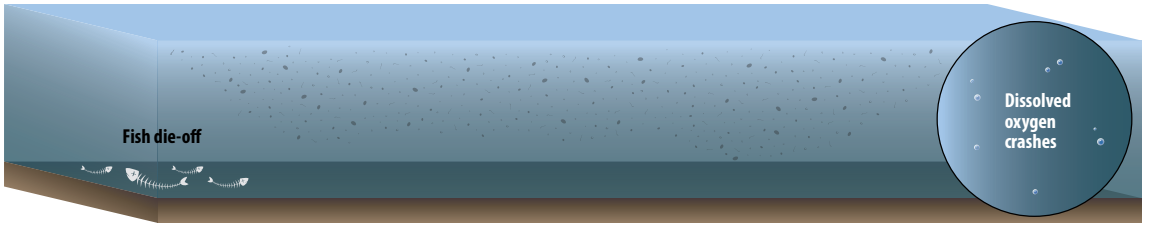




5 Abrupt collapse
August 29–31

After dominating the system for nearly a month, the bloom died off over the course of just three days. The collapse throughout South Bay was nearly simultaneous.





The Impacts

In Central Bay and South Bay, community scientists and researchers from UC Davis documented dead rays, leopard sharks, and sturgeon (including green sturgeon) floating in the Bay and washed up on shore. Because slow-growing green sturgeon are listed as threatened under the Endangered Species Act, these deaths were especially troubling. By the end of the bloom, at least 691 sturgeon (both white and green) were reported dead (Hobbs et al. 2026).

"A lot of people were really emotional seeing these prehistoric fish washing up on shore all over the Bay," says Wren.

Scientists estimate that many more sturgeon died due to the bloom and sank or washed into the ocean undetected (Blackburn et al., 2019, Hobbs et al. 2026). Recent population assessments suggest that the number of legal-size white sturgeon was much lower after the bloom (California Department of Fish and Wildlife, 2024). Because sturgeon take ten or more years to reach sexual maturity, the severe reduction in reproductive-aged sturgeon will elevate risk to the populations for years to come. White sturgeon are now also a candidate for listing as threatened under the California Endangered Species Act (California Department of Fish and Wildlife "White Sturgeon").

The bloom also drove a major fish-kill In Lake Merritt in Oakland, which is connected to the Bay and the Oakland/Alameda estuary near where the bloom started. Tens of thousands of fish in Lake Merritt died (San Francisco Bay Regional Water Quality Control Board 2023).

During the 2022 bloom, dissolved oxygen levels dropped to near zero across much of South Bay in the days following the end of the bloom. However, the majority of documented sturgeon deaths occurred before dissolved oxygen levels fell (Hobbs et al. 2026). Because of that, scientists suspect that a toxic mechanism was particularly harmful to fish populations. New research at UC Santa Cruz tested *H. akashiwo* from the 2022 strain for a variety of harmful compounds produced by HABs. The preliminary findings suggest that *H. akashiwo* may produce multiple harmful compounds, including peroxides, brevetoxins, reactive oxygen species, and polyunsaturated fatty acids (Kudela et al. in prep). Although inconclusive, this finding helps refine understanding of the ways *H. akashiwo* can cause harm.



Dead fish in Lake Merritt. Photo courtesy of San Francisco Baykeeper.

Factors Influencing Bloom Progression

The *H. akashiwo* bloom grew explosively at its outset. Under normal conditions in the Bay, algae does not grow unchecked for that long or reach those levels; something severely altered the balance between algae growth and death rates. Without an obvious 'smoking gun' to point to what started the bloom, the NMS examined the course of the bloom for clues about its origins. These considerations suggest that an interplay of biological and environmental factors influenced the progression, size, and duration of the bloom.

Factor	Possible Influence on 2022 HAB
Nutrients	Excess nutrients fueled growth
Algae Adaptation: Swimming	Swimming to stay in surface waters gave *H. akashiwo* a leg up
Weak Tides	Weak tides allowed *H. akashiwo* to swim towards sunlit surface waters
Distinct Water Column Layers (Stratification)	Warmer water floating on top of denser, colder water kept algae closer to the sunlit surface
Lower Water Clarity (Turbidity)	More sunlight reaches algae through clearer water; In the middle of the bloom, growth slowed for a week when wind stirred up sediment in the water
Algae Adaptation: Energy	*H. akashiwo* can both photosynthesize and "eat" other microbes, making it able to grow even when other algae might not
Viruses	Lower viral infection rates in *H. akashiwo* may have influenced the start of the bloom, and rapid viral spread may have helped end the bloom
Lower Grazing Pressure	Lower grazer abundances may have enabled *H. akashiwo* to proliferate at the start of the bloom

> A lot of people were really emotional seeing all these prehistoric fish washing up on shore all over the Bay



Dead sturgeon washed up on shore near the Dumbarton Bridge during the 2022 *H. akashiwo* bloom. Photo courtesy of San Francisco Baykeeper.

NUTRIENTS

Algae need nutrients to grow. Over the course of the bloom, *H. akashiwo* used virtually all of the available nutrients in South Bay along with virtually all of the additional nutrients from wastewater treatment plant discharges (Figure 1) (Volaric et al. 2026). Although it doesn't explain why *H. akashiwo* started to bloom, available nutrients were an essential ingredient in fueling its continued growth.

> Over the course of the bloom, *H. akashiwo* used all of the available nutrients in South Bay along with virtually all of the additional nutrients from wastewater treatment plants

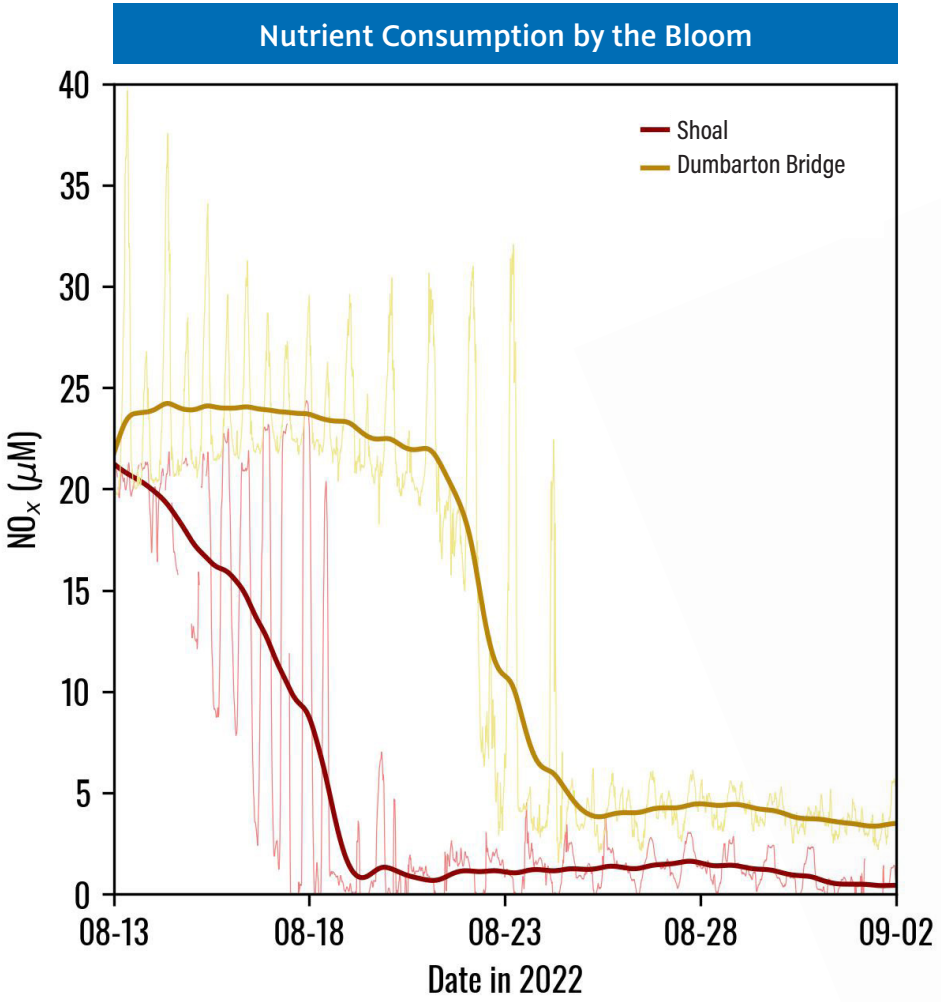
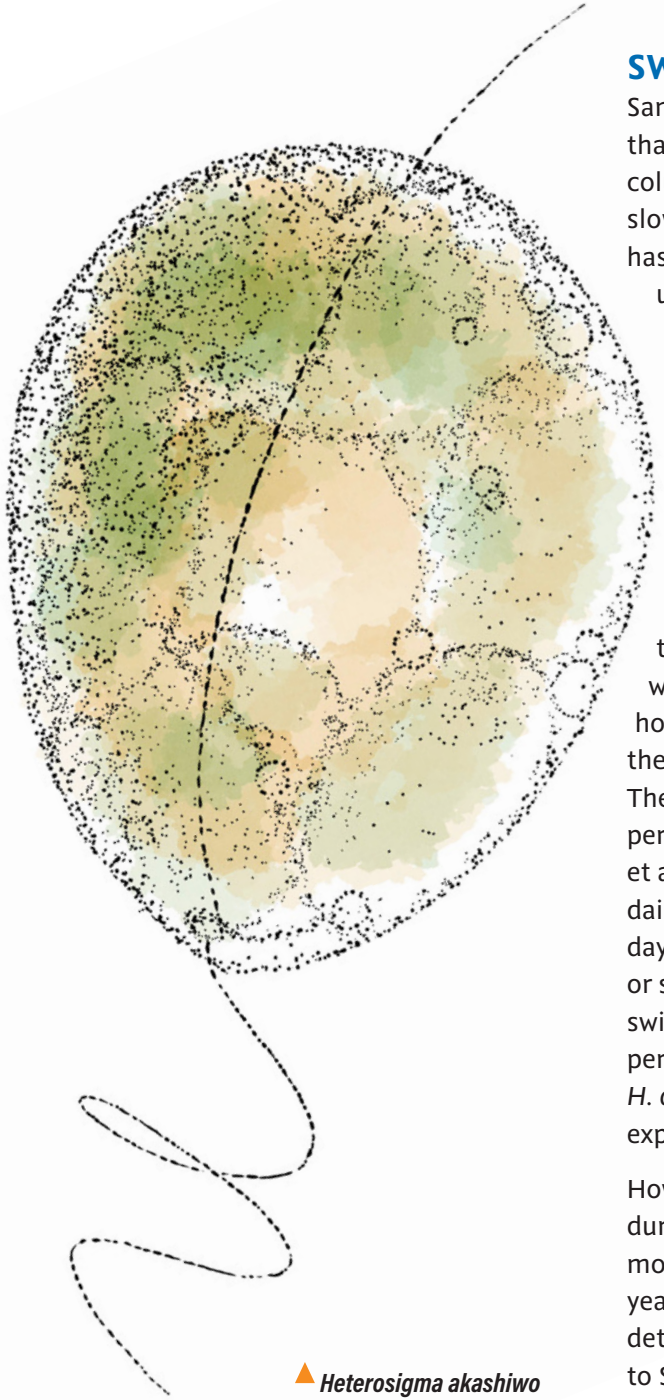


Figure 1. Measurements at moored sensor stations in South Bay show the bloom rapidly consumed available nutrients as it expanded. Nutrient measurements displayed as micromolar NOx (nitrate + nitrite) concentrations at the Shoal station north of the San Mateo-Hayward Bridge and the Dumbarton Bridge station. Light lines show data from measurements taken every 15 minutes. Dark lines show tidally filtered data.



Heterosigma akashiwo

SWIMMING, TIDES, AND STRATIFICATION

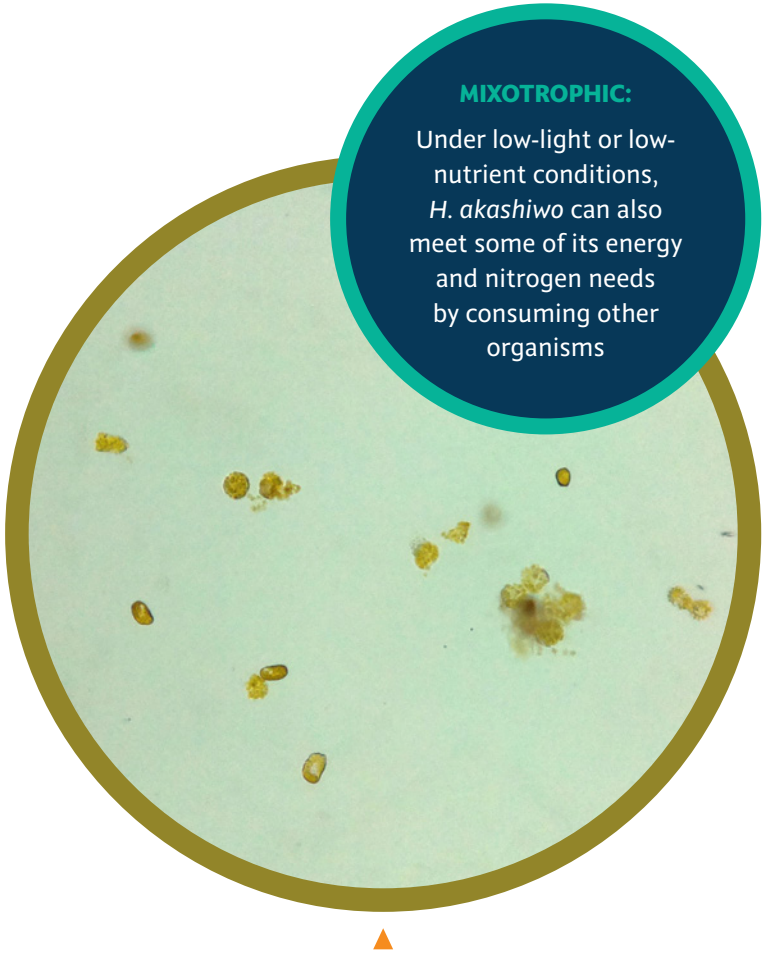
San Francisco Bay is known for strong tides that vigorously mix algae through the water column, limiting their light exposure and slowing their growth. *H. akashiwo*, however, has two tails, or flagella, that allow it to swim upwards. NMS scientists hypothesize that, under the right conditions, swimming allowed *H. akashiwo* to increase the proportion of cells in shallower waters and exposed to higher light levels, thereby increasing the population's overall growth rate.

NMS scientists calculated that *H. akashiwo* could swim strongly enough to overcome tidal mixing during two periods when the weakest daily tides occurred during daylight hours (August 5–9 and 18–22). This allowed for the bloom's growth rate to more than double. These two windows aligned with the two periods of most rapid bloom expansion (Senn et al. 2026). From August 10–17, when strong daily tides mixed the water column during daylight hours, the bloom's growth slowed or stalled. These observations indicate that swimming upward to shallow waters during periods with weak daytime tides supported *H. akashiwo* growth after the bloom had expanded into the open Bay.

However, multi-day windows with weak tides during daylight happen roughly twice per month every summer in the Bay. For seven years before the bloom, *H. akashiwo* was detected in the Bay 60% of the time from July to September (SFEI 2024), along with multiple other swimming HAB species, but no blooms occurred. Swimming and weak tides therefore supported the bloom but didn't trigger it.

There is also evidence that water column stratification contributed to the 2022 HAB. Stratification happens in the Bay when a layer of fresher less-dense water floats on top of saltier, denser water. This can help algae grow if they can remain in the relatively light-rich surface layer. While short-lived algae blooms are common in the spring during brief periods of stratification, salinity-driven stratification rarely occurs in the summer in Central Bay and South Bay because most freshwater has been flushed from the system.

Temperature-driven stratification is also possible, with warmer water forming a layer on top of dense colder water, but is usually less relevant in the Bay due to strong tidal mixing. However, in early August 2022, the NMS detected conditions that suggested the potential for temperature stratification, and later conducted a series of model simulations to evaluate its contribution to the bloom. The results identified the possibility of strong interactions between swimming, weak daytime tides, temperature stratification, and bloom progression. Current work is focused on better understanding the importance of these interactions, and factors contributing to summertime temperature stratification and how frequently it occurs.



***H. akashiwo* under a microscope.**
Photo: Keith Bouma-Gregson USGS-WSC.

TURBIDITY

In the week of August 10–17, the bloom's progress suddenly stalled. During this lull, strong winds stirred up sediment, and strong tides kept it suspended. The resulting murky, highly turbid conditions prevailed throughout most of South Bay from August 9–15. The water column cleared rapidly over the next few days though, and within a week the bloom had spread throughout the remainder of South Bay. The timing of increased light penetration coincided with weak daytime tides between August 19–21 (as described above) which allowed for higher growth rates.

H. AKASHIWO GROWTH CHARACTERISTICS

Evidence suggests that the 2022 bloom's progression was influenced by *H. akashiwo's* ability to grow well under a wide range of conditions. For example, growth experiments using a *H. akashiwo* strain isolated from the 2022 HAB found that it was capable of growing quickly over a wide range of light levels (R. Kudela, pers. comm.). Other experimental studies using *H. akashiwo* isolated from other systems found that some strains can maintain relatively high growth rates even when nitrogen concentrations are low.

In addition, *H. akashiwo* is mixotrophic: under low-light or low-nutrient conditions, *H. akashiwo* can also meet some of its energy and nitrogen needs by consuming other organisms. Data collected during the bloom and results from modeling indicate that *H. akashiwo* continued to grow for extended periods when light levels and/or nutrient concentrations were low. These growth traits likely contributed to the bloom's duration and overall impacts.

TOP-DOWN CONTROLS

Algae populations are kept in check by both bottom-up and top-down controls. Bottom-up factors influence how fast algae grow. The factors highlighted above – nutrient concentrations, influences on light availability (strength of tides, swimming, stratification, turbidity, cloud cover, fog) – are all bottom-up controls. Top-down factors remove algae from the water column, e.g., zooplankton feeding on algae cells and other processes that cause cell death.

Multiple lines of evidence suggest that top-down controls on *H. akashiwo* growth were weaker than usual during the bloom. Perhaps the clearest evidence emerges from how the bloom ended: sharp drops in chlorophyll concentrations (>90%) that occurred during the same one to two day period throughout South Bay (based on field and satellite data), accompanied by rapidly decreasing dissolved oxygen concentrations (Figure 2). Field data and model results both point to the same interpretation: a top-down biological factor caused rapid cell death (Senn et al. 2026). The synchronized timing and rapid rates of biomass reduction and oxygen consumption all support the hypothesis that the bloom ended because marine viruses infected and burst *H. akashiwo* cells. Research from other coastal systems has shown that marine viruses are often responsible for holding *H. akashiwo* populations in check and that, when blooms do occur, marine viruses are often responsible for ending them.

The leading hypothesis is therefore that during the early stages of the bloom, the dominant *H. akashiwo* strain was resistant to the existing viruses present in the Bay. An infectious virus strain emerged over a few weeks of mutations and ultimately caused the bloom's collapse. Early findings from work conducted in collaboration with researchers at Moss Landing Marine Laboratories suggest that the 2022 strain was genetically distinct from a previously observed strain from 2002 (Bowers et al. in preparation). If further testing finds that the 2022 strain was new to the Bay, it would support the idea that introducing new algae strains poses a unique threat due to their potential virus resistance. In addition, NMS scientists are collaborating with the USGS to explore the hypothesis that there were lower grazer abundances and grazing pressure on *H. akashiwo* at the start of the 2022 bloom (Nardelli et al. 2025).

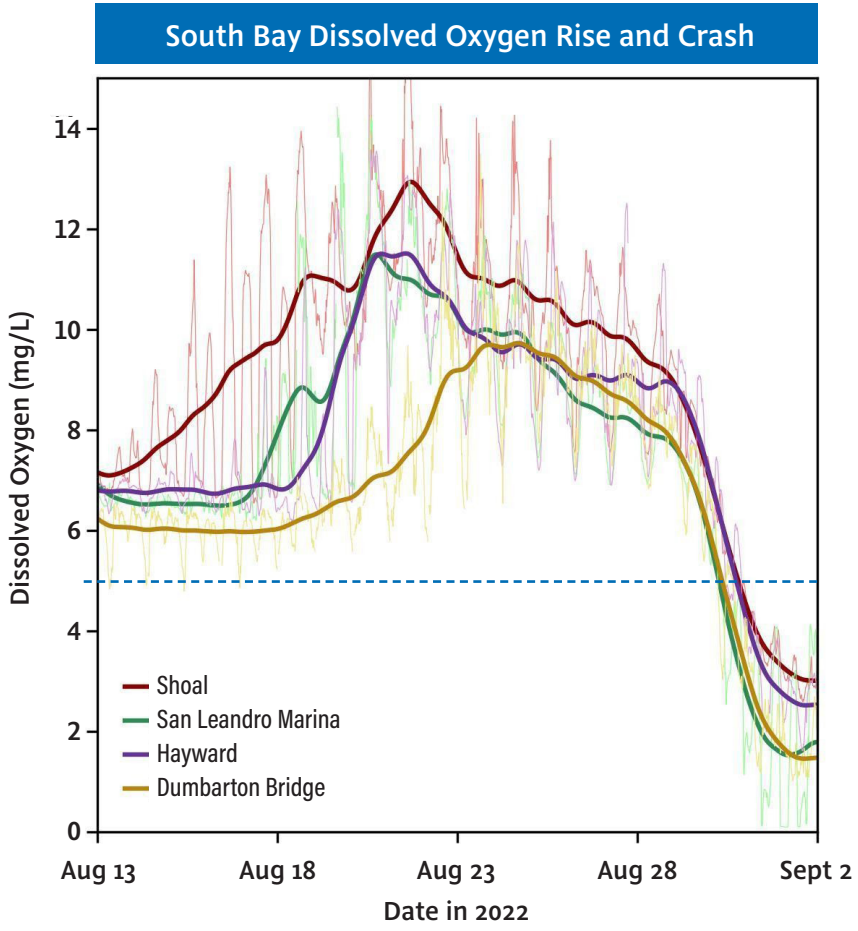


Figure 2. Measurements at moored sensor stations in South Bay show delayed dissolved oxygen increases as the bloom spread South and the synchronized collapse as the bloom ended. Dissolved oxygen measurements displayed as milligrams per liter. Light lines show data from measurements taken every 15 minutes. Dark lines show tidally filtered data.

CONTINUING INVESTIGATIONS FOR THE NMS PROGRAM

In addition to continuing to work on resolving the remaining questions about the 2022 bloom, the NMS is pursuing several broader investigations about HABs.

The 2023 Bloom

After the 2022 bloom, the region was on high alert for potential blooms during summer months. In the summer of 2023, like a recurring nightmare, scientists observed a surge in *H. akashiwo* growth from Seaplane Lagoon in Alameda and extending north to San Pablo Bay. Response measures included satellite monitoring, direct sampling, and continuous observation. After several days the bloom petered out and in its wake, the Water Board and California Department of Fish and Wildlife reported 88 dead fish, including at least 15 white sturgeon and one green sturgeon.

While the region was elated to avoid devastation similar to the 2022 bloom, the 2023 bloom left even more questions. Why did the bloom start? Why did it end so quickly? What were the impacts?

To date, studies have focused on the 2022 bloom. As capacity allows, the NMS will investigate the 2023 bloom to glean additional insights.

HAB Control Measures

Regional managers are interested in exploring a range of potential HAB control measures. As a preliminary effort, the NMS is pursuing several projects to refine the understanding of *H. akashiwo's* biology and lethality. By understanding its biology, NMS scientists may identify strategies to limit its growth. Similarly, by understanding and quantifying how *H. akashiwo* kills fish, the NMS aims to provide information that helps regional managers define regulatory thresholds for nutrients to protect the Bay.

Upcoming NMS projects will study the effectiveness of growing eelgrass to reduce nutrients, applying clay to kill algae, and other proposed control measures. Other regions are exploring such measures, but their applicability in San Francisco Bay is a critical unknown.

H. akashiwo is not the only algae of concern in the Bay (page 50). The NMS intends to conduct studies incorporating additional harmful algae species and assess the risks they pose to the region.

Coordinated HAB Monitoring

In the wake of the bloom, the NMS and regional partners applied for and received a grant through the Monitoring and Event Response for Harmful Algal Blooms (MERHAB) Research Program at the National Oceanic and Atmospheric Administration to support the development of regionally coordinated HAB monitoring. The grant supports expanding monitoring for HAB species, refining satellite data processing, advancing genetic sequencing tools for HAB samples, supporting a community monitoring program led by the San Francisco Baykeeper (page 78), and building a dashboard to easily share satellite- and water-based HAB data with the public. The San Francisco Bay Regional Water Board also formed a technical advisory group to coordinate regional HAB monitoring and response using NMS and MERHAB monitoring tools.

HAB Modeling

Building on advances to the existing biogeochemical model (page 82), the NMS reconstructed the 2022 bloom to test varying hypotheses and learn more about the bloom's dynamics. Refining the model will help resolve remaining questions, especially regarding how the bloom started and collapsed.

The NMS also aims to model the effects of changing conditions on potential blooms. With guidance from expert HAB modelers, the NMS will explore the effects of changing temperature and weather patterns, salinity, wastewater treatment plant outputs, and other potential future conditions on HAB growth.

LOOKING FORWARD

Studies of the 2022 *Heterosigma akashiwo* bloom have provided a wealth of data and many lessons to inform ongoing scientific investigations, as well as raising a host of further questions. The initial findings from the NMS and partners are beginning to explain how such an exceptional event occurred. The NMS will continue studying the 2022 HAB, and HABs in the Bay more generally, to support management efforts to prevent the kind of devastation that occurred in 2022.



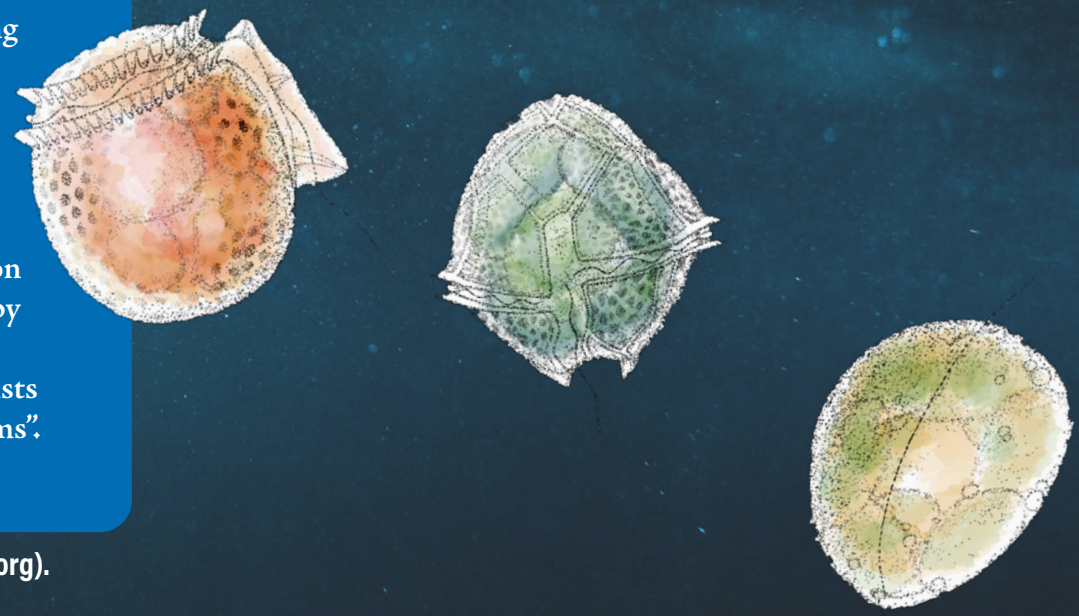
Algal bloom near the Berkeley Marina on August 1, 2023. Photograph by Jason Sullivan / Red Tide Leaves Water Around East Bay Brown via Getty Images.

Algae of Concern in San Francisco Bay

Algae are vital to the health of San Francisco Bay. They serve as the base of the food web and support life throughout the ecosystem. At the same time, some algae species can threaten to devastate the Bay. Floating among the many beneficial algae, such as diatoms, that are prevalent throughout most years are a few species that can cause harm under the right conditions. When these algae populations grow dense enough, they can poison the water, smother aquatic life, and cause oxygen levels to collapse. These are the algae the NMS keeps tabs on: the "algae of concern."

Algae versus Plankton: What's the Difference?

The majority of species that cause harmful algal blooms are phytoplankton (meaning "wandering plants" in Greek), which are photosynthetic organisms that are considered both algae and plankton. However, some of the species mentioned in this section have evolved to lose their photosynthesis, becoming heterotrophic (eating other organisms to live, like zooplankton and other animals do). While this means that by some definitions they are no longer considered phytoplankton, they can still bloom and scientists still refer to such events as "harmful algal blooms".



Algae illustrations by Corlis Schneider (www.corlis.org).

ALGAE ADAPTATIONS

Evolution has produced a variety of traits to help algae survive. In the individual profiles, five of the most common adaptations are represented with the icons below.

Trophism

A H M

Trophism is how organisms get energy.

- **Autotrophic** organisms obtain energy from sunlight through photosynthesis.
- **Heterotrophic** organisms eat other microorganisms for energy.
- **Mixotrophic** organisms can both photosynthesize and eat other microorganisms.

Toxicity

Toxic algae produce harmful compounds (toxins) to eliminate potential competitors and predators. These toxins can harm aquatic life and even humans.

Swimming

Swimming algae propel themselves through the water using flagella (tail-like protrusions). Some plankton can also draw water in and expel it to propel themselves through the water. The ability to move allows algae to stay closer to the surface where light is available and outcompete other algae for sunlight, food, and nutrients.

Armor

Armored algae have a hard outer shell that protects them from predators and harsh environmental conditions. The armor can also increase buoyancy, which helps the algae remain closer to the sunlight-rich surface waters.

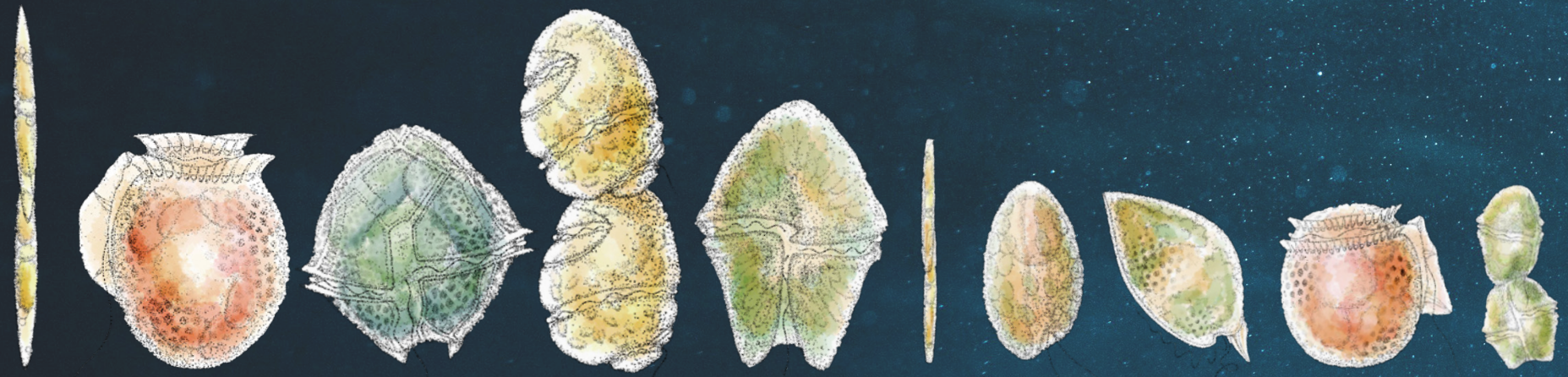
Cyst Formation

When environmental conditions become harsh, some algae morph into a thick-walled cyst that sinks to the Bay floor. This cyst acts like a seed, allowing the algae to lie dormant until conditions become favorable again. At that point, the algae germinates and moves into the water column. This adaptation allows algae to survive variable conditions and means that even if they are not detected in the water column, they may still be lingering in the Bay.

HOW BIG ARE HARMFUL ALGAL SPECIES?

A size comparison of algae of concern

Most harmful algae species in the Bay are smaller than a grain of table salt. The largest species (*Noctiluca scintillans*, not pictured) would be larger than the salt grain pictured and can grow to up to two millimeters, which would take up four pages at this scale. The smallest, *Aureococcus anophagefferens*, is a single micron. That's a millionth of a meter, or the width of a human mitochondrion. Many of these species have wide size ranges, and are shown here near the upper end of how large they can grow.



Pseudo-nitzschia australis | *Dinophysis acuminata* | *Peridinium bipes* | *Margalefidinium fulvescens* | *Akashiwo sanguinea* | *Nitzschia bizertensis* | *Cryptomonas ovata* | *Prorocentrum micans* | *Phalacroma rotundatum* | *Gymnodinium catenatum*

SCALE

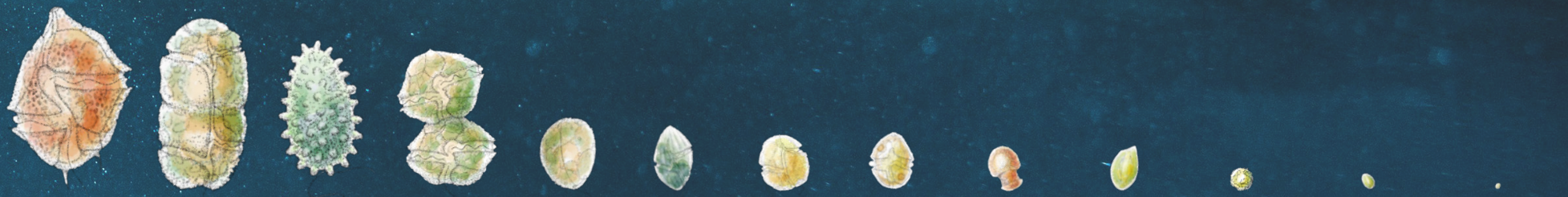
1 in = 48 microns



(Left) A single grain of table salt as seen under a scanning electron microscope. Courtesy of Chhe, Wikimedia Commons.

(Background) A close-up view of water. Courtesy of Marcos Paulo Prado, Unsplash.

Width of one grain of table salt



Gonyaulax spinifera | *Polykrikos hartmannii* | *Pseudochattonella verruculosa* | *Alexandrum catenella* | *Heterosigma akashiwo* | *Gyrodinium jinhaense* | *Karlodinium veneficum* | *Azadinium poporum* | *Heterocapsa rotundata* | *Prymnesium parvum* | *Phaeocystis pouchetii* | *Chrysochromulina leadbeateri* | *Aureococcus anophagefferens*

ALGAE OF CONCERN IN SAN FRANCISCO BAY

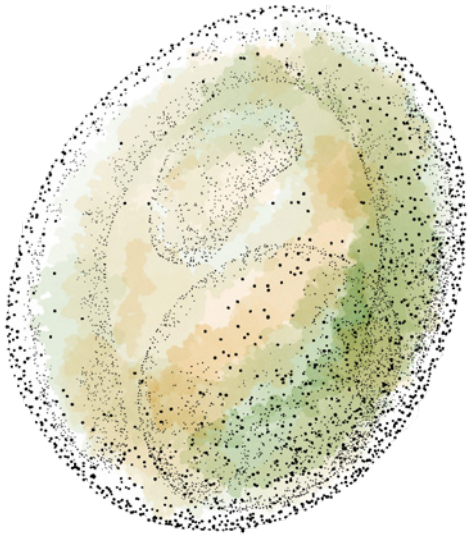
- A — **Trophism:** Autotrophic
- H — **Trophism:** Heterotrophic
- M — **Trophism:** Mixotrophic
- **Toxicity**
- **Swimming**
- **Armor**
- **Cyst Formation**

Aureococcus anophagefferens

M

Length:	1-2 micrometers
Width:	1–2 micrometers
Distribution:	Temperate oceans and estuaries worldwide.

Unlike some harmful algae that produce a single type of toxin, *Aureococcus anophagefferens* instead produces a mix of compounds that generate a toxic effect by inhibiting the ability of shellfish to move their cilia, the small hairlike appendages that they use to feed. This effectively starves them, which is where the name *anophagefferens* (Latin for 'causing a halt to feeding') comes from.



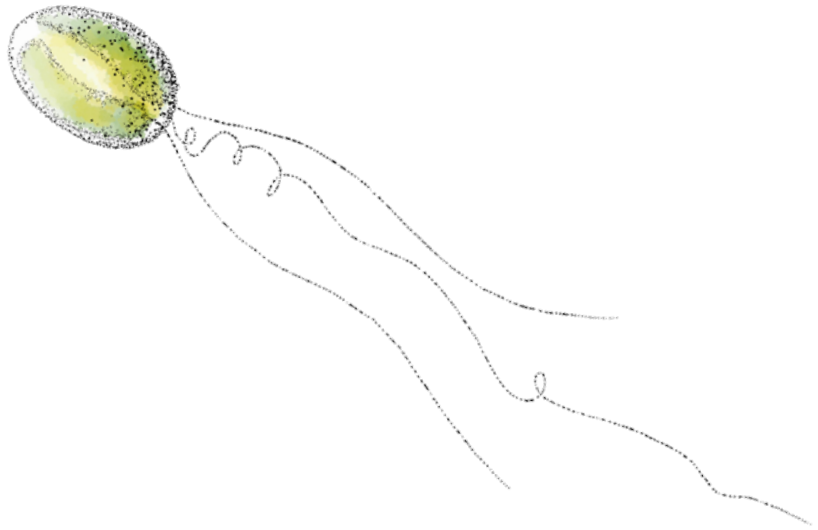
Chrysochromulina leadbeateri

M

Length:	3-8 micrometers
Width:	1–4 micrometers

Distribution: *Chrysochromulina* species are found in polar to tropical oceans, estuaries, and fresh water bodies worldwide. Individual species distributions vary. For example, *Chrysochromulina leadbeateri* (depicted here) is found in subpolar to temperate coastal waters and estuaries worldwide.

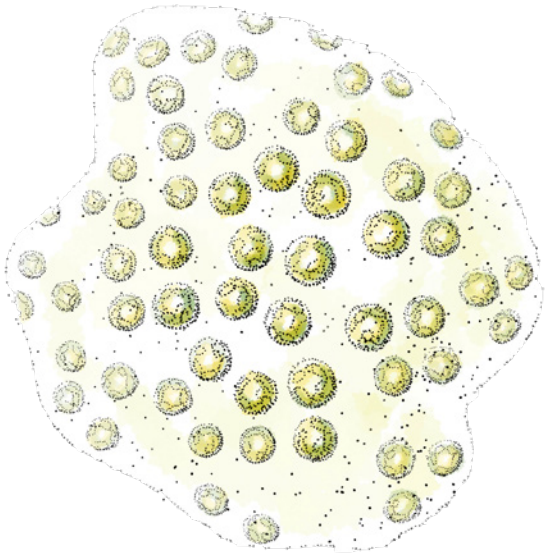
Chrysochromulina leadbeateri is not confirmed in San Francisco Bay, but there are several undescribed strains of *Chrysochromulina* that scientists are working to identify. *Chrysochromulina leadbeateri* produces leadbeaterins, toxins that are dangerous to fish and killed 14,500 tons of salmon off the coast of Norway in 2019, the most devastating fish-killing algal bloom ever recorded in Norway.



Phaeocystis pouchetii

Length:	2-8 micrometers
Width:	2-8 micrometers
Distribution:	Polar to temperate coastal waters and estuaries worldwide.

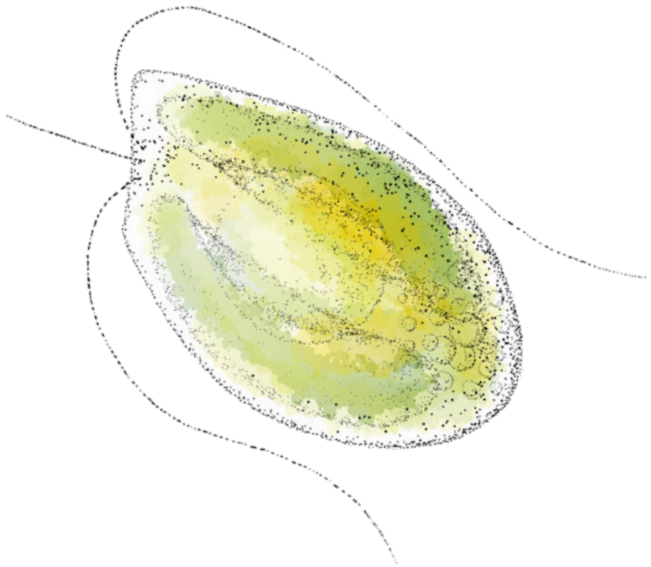
Phaeocystis pouchetti has two distinct life stages: one as a free-floating cell and the other as part of a large gelatinous colony. These colonies can be 1.5 to 2 millimeters across – about the thickness of a penny to that of a nickel. There is ongoing debate on whether it is mixotrophic. It produces volatile organic compounds and polyunsaturated aldehydes that are toxic to fish.



Prymnesium parvum

Length:	6-16 micrometers
Width:	3-10 micrometers
Distribution:	Subpolar to tropical coastal waters and estuaries. It prefers brackish water (a mix of salty and fresh) and in our monitoring is more prevalent farther inland from the Golden Gate, where water is less salty.

Known as “golden alga” for its gold-colored chloroplasts, *Prymnesium parvum* produces prymnesins, toxins that are dangerous to any gill-breathing organism. *Prymnesium parvum* cells have a unique appendage called a haptonema located between its two flagella, which helps it attach to prey and other surfaces. A harmful algal bloom of *Prymnesium parvum* was reportedly responsible for the death of approximately 400 tons of fish in the Oder River in Poland in 2022.



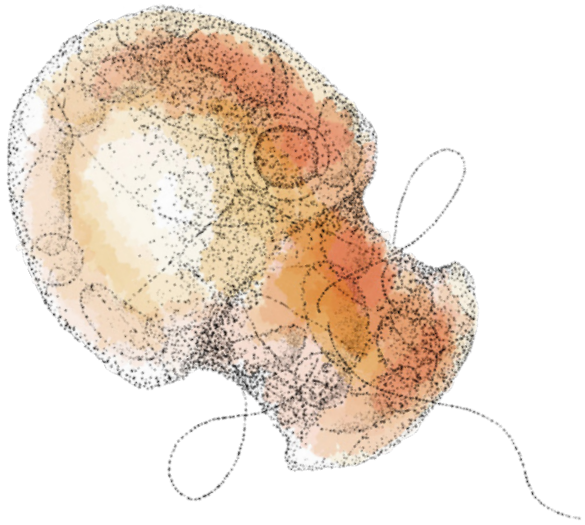
ALGAE OF CONCERN IN SAN FRANCISCO BAY

- **Trophism:** Autotrophic
- **Trophism:** Heterotrophic
- **Trophism:** Mixotrophic
- **Toxicity**
- Swimming
- Armor
- Cyst Formation

Heterocapsa rotundata

Length:	9-14 micrometers
Width:	7-12 micrometers
Distribution:	Polar to tropical oceans and estuaries worldwide.

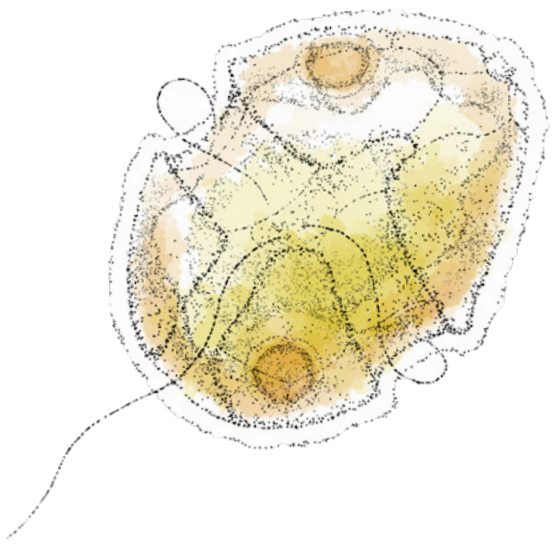
Unlike other *Heterocapsa* species, *Heterocapsa rotundata* does not produce toxins. Its threat is the result of its dense blooms that choke other organisms and reduce oxygen levels. *Heterocapsa rotundata* is also known to bloom during winter months in some places, which is unusual among HAB-forming species. Scientists believe this is due to its ability to thrive in low-light conditions. It is known to produce large blooms during winter and early spring in Chesapeake Bay.



Azadinium poporum

Length:	10-17 micrometers
Width:	7-13 micrometers
Distribution:	Temperate coastal waters and estuaries worldwide.

Azadinium poporum produces toxins called azaspiracids, which cause azaspiracid shellfish poisoning (symptoms include chills, headaches and gastronomic distress) when humans consume tainted shellfish. There is a wide variety of azaspiracids, which vary between different strains of *Azadinium poporum*.

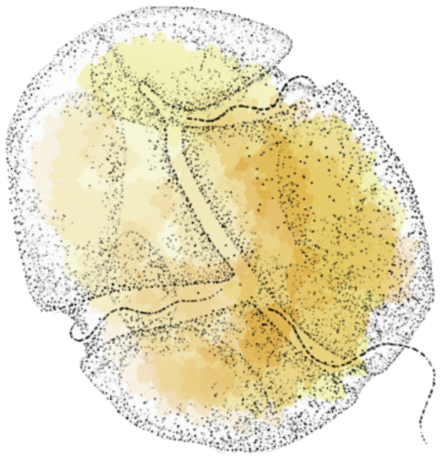


M

Karlodinium veneficum

Length:	9-18 micrometers
Width:	7-12 micrometers
Distribution:	Temperate coastal regions and estuaries worldwide.

A culprit of fish kills around the world, *Karlodinium veneficum* produces compounds called karlotoxins that help it capture prey. In sufficient quantities, as happens during a bloom, karlotoxins become lethal to fish and other marine life.

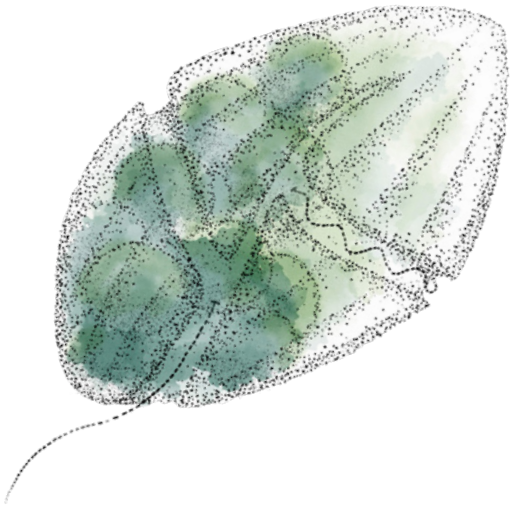


H

Gyrodinium jinhaense

Length:	13-26 micrometers
Width:	7-12 micrometers
Distribution:	Temperate to tropical oceans and estuaries worldwide.

Various *Gyrodinium* species consume other algae of concern, including *Akashiwo sanguinea* and *Heterosigma akashiwo*, making *Gyrodinium jinhaense* potentially both a protector and threat in the Bay. It was originally thought to occur only in Jinhae Bay, South Korea, but has since been observed worldwide. Although it has genes similar to those that produce saxitoxin (the cause of paralytic shellfish poisoning), the toxicity of *Gyrodinium jinhaense* is an open question.

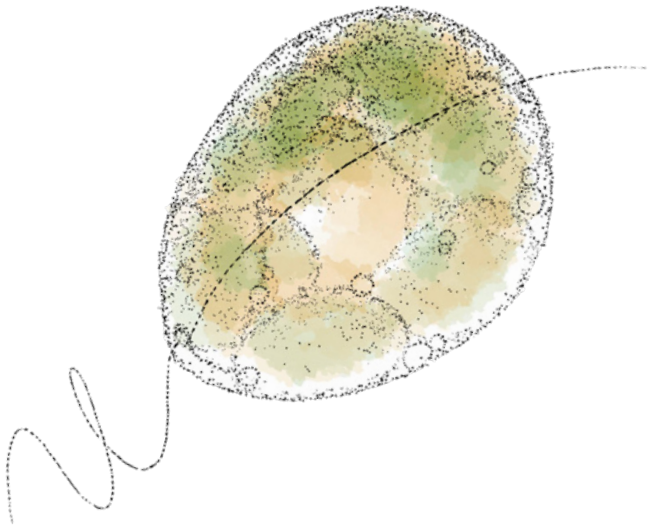


H

Heterosigma akashiwo

Length:	19-25 micrometers
Width:	6-17 micrometers
Distribution:	Coastal regions worldwide.

Heterosigma akashiwo is affectionately referred to as the "flying potato," an innocent-sounding nickname which belies the many fish-killing blooms it has caused. After the 2022 *Heterosigma akashiwo* bloom in the Bay (page 37), it is now the primary focus of many scientific investigations. Although the exact toxins it produces are unknown, recent results suggest it may produce a particularly nasty cocktail of brevetoxins, peroxides, reactive oxygen species, and polyunsaturated fatty acids. *Heterosigma akashiwo* is a leading cause of fish die-offs in Puget Sound: recurring blooms have caused extensive damage to the wild and net-penned (mostly salmon) fish industry.

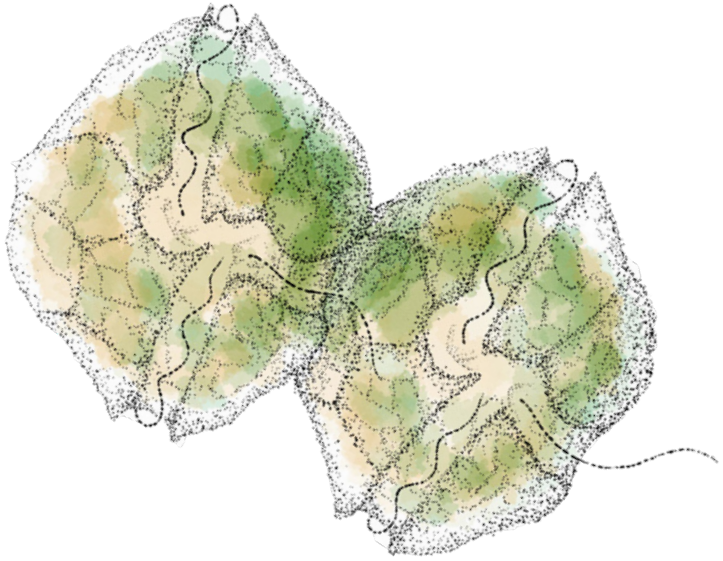


M

Alexandrium catenella

Length:	20-28 micrometers
Width:	18-34 micrometers
Distribution:	Polar to temperate coastal waters and estuaries worldwide.

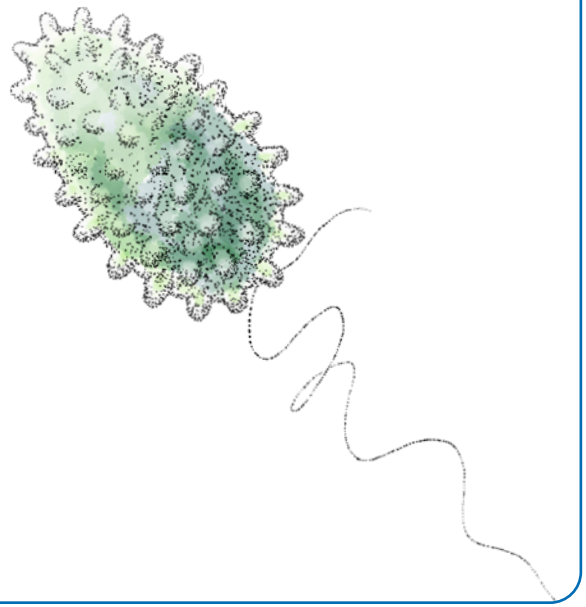
A single-celled beauty and the beast, *Alexandrium catenella* produces bioluminescence (causing swirling light shows in coastal surf) and saxitoxins (the cause of paralytic shellfish poisoning). The individual cells often form chains of two, four, or eight cells that hold themselves together using their flagella. The first reported paralytic shellfish poisoning event occurred in San Francisco in 1927: six people died and over 100 were sickened from eating shellfish contaminated by saxitoxin from an *Alexandrium catenella* bloom. Saxitoxin produced by *Alexandrium* is one of the main drivers of an annual quarantine on consumption of shellfish on the entire California coast (including bays, inlets, and harbors) that is normally in effect from May 1 through October 31.



Pseudochattonella verruculosa

Length:	12-45 micrometers
Width:	12-45 micrometers
Distribution:	Temperate coastal regions and estuaries worldwide.

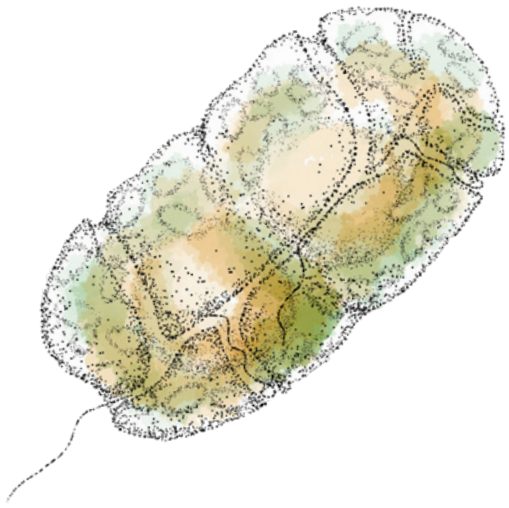
Pseudochattonella verruculosa gets its name from the Latin word verruculosa, which roughly translates to 'covered in small warts.' It is responsible for the largest farmed fish mortality in the world. In 2016, a bloom in the Reloncavi Sound in Chile killed 12% of the country's farmed salmon and resulted in an estimated $800 million in losses. Despite its impact, the toxin produced by *Pseudochattonella verruculosa* has not been definitively characterized.



Polykrikos hartmannii

Length:	30-35 micrometers
Width:	40-45 micrometers
Distribution:	Temperate to tropical coastal waters and estuaries worldwide.

Like microscopic Captain Ahabs, *Polykrikos hartmannii* use a ballistic, harpoon-like appendage to spear other microorganisms. Their white whales are chain-forming algae like *Gymnodinium catenatum*. *Polykrikos hartmannii* generally exists as two-celled chains or singular cells. *Polykrikos* has been observed to form dense blooms in the Eastern Mediterranean. This exact species is not confirmed in San Francisco Bay, but there are several undescribed strains of *Polykrikos* scientists are working to identify.



ALGAE OF CONCERN IN SAN FRANCISCO BAY

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- H — **Trophism:** Heterotrophic
- M — **Trophism:** Mixotrophic
- **Toxicity**
- **Swimming**
- **Armor**
- **Cyst Formation**

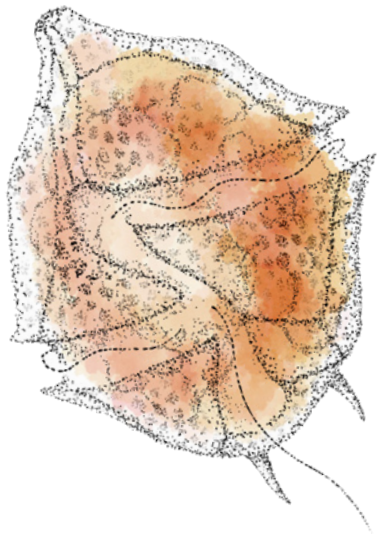
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- **Cyst Formation**

Gonyaulax spinifera

Length:	24-50 micrometers
Width:	20-40 micrometers
Distribution:	Temperate to tropical oceans and estuaries worldwide.

Gonyaulax spinifera produces yessotoxins, which are a compound of ongoing study. At present, the exact mechanism by which yessotoxins create harm is unknown. Blooms of *Gonyaulax* have produced mass deaths of abalone in California in 2011 and South Africa in 2017. There are also other harmful *Gonyaulax* species present in the Bay, which have a similar appearance to *Gonyaulax spinifera*.



Gymnodinium catenatum

Length:	25-40 micrometers
Width:	24-65 micrometers
Distribution:	Temperate to tropical oceans and estuaries worldwide.

Gymnodinium catenatum cells form chains that typically range from four to 32 cells long, although some chains more than 60 cells long have been observed. It produces saxitoxins that accumulate in shellfish and other animals. If consumed, those shellfish can cause paralytic shellfish poisoning in humans. *Gymnodinium catenatum* has produced harmful blooms leading to fish kills on the Mexican coast, the Arabian Gulf, Korea, and other coastal environments around the world.

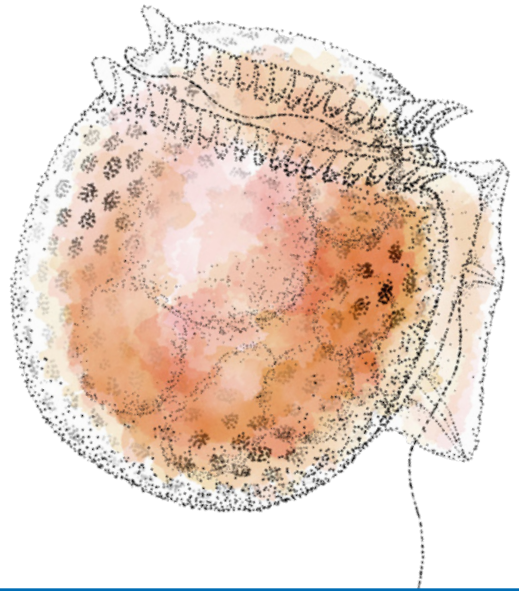


H

Phalacroma rotundatum

Length:	36-56 micrometers
Width:	36-53 micrometers
Distribution:	Polar to tropical oceans and estuaries worldwide.

As a heterotroph, *Phalacroma rotundatum* consumes other algae to survive. To do so, it pierces their cell membranes and sucks out the contents, sometimes of cells two to three times larger than itself. Although it has not been proven to produce toxins, because of its eating habits, *Phalacroma rotundatum* can absorb toxins from other microorganisms and pass them along to predators that consume it. Due to its similarity to *Dinophysis*, it is also being investigated around the world as a potential producer of diarrhetic shellfish poisoning, but it's currently much less studied.

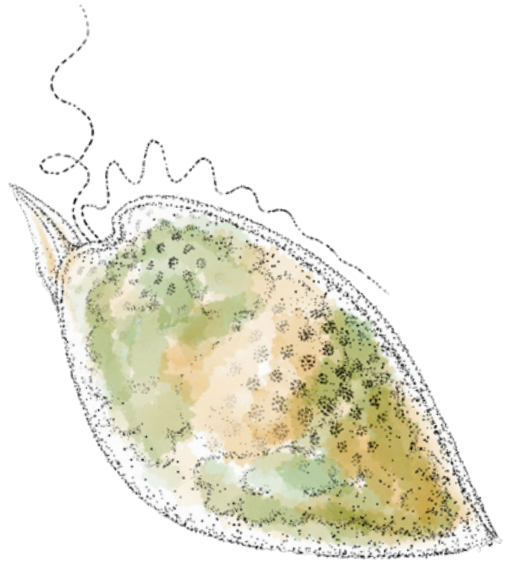


M

Prorocentrum micans

Length:	35-70 micrometers
Width:	20-50 micrometers
Distribution:	Polar to tropical coastal waters and estuaries worldwide.

Although they don't produce toxins, *Prorocentrum micans* blooms can deplete dissolved oxygen to dangerous levels for marine life. A unique spine at the end of the cell serves as both a stabilizing rudder while swimming and as an anchor during sexual reproduction. *Prorocentrum lima*, a close relative of *Prorocentrum micans*, produces okadaic acid and can cause diarrhetic shellfish poisoning. Fortunately, *Prorocentrum lima* is not present in California.



ALGAE OF CONCERN IN SAN FRANCISCO BAY

A **Trophism:** Autotrophic

H **Trophism:** Heterotrophic

M **Trophism:** Mixotrophic

Toxicity

Swimming

Armor

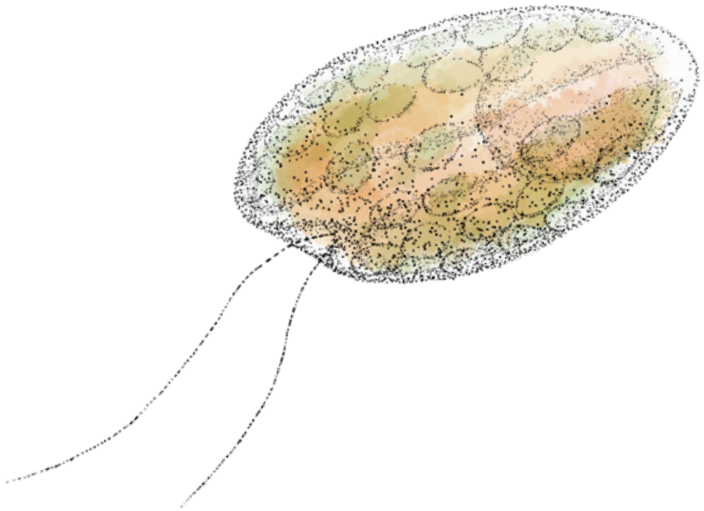
Cyst Formation

M

Cryptomonas ovata

Length:	20-80 micrometers
Width:	6-20 micrometers
Distribution:	Freshwater bodies and estuaries worldwide.

Cryptomonas ovata is a freshwater species that threatens the Sacramento-San Joaquin Delta portion of the San Francisco Estuary. Blooms do not produce toxins, but they can create low-oxygen zones that suffocate aquatic life. *Cryptomonas ovata* and its relatives have an opening called a gullet or crypt that functions like a mouth. The crypt often contains trichocysts, or poisons, that kill the microbial prey. *Cryptomonas* has produced large blooms in Chesapeake Bay and other estuaries, and can produce additional hazards by serving as food for toxic bloom-formers like *Gymnodinium*.

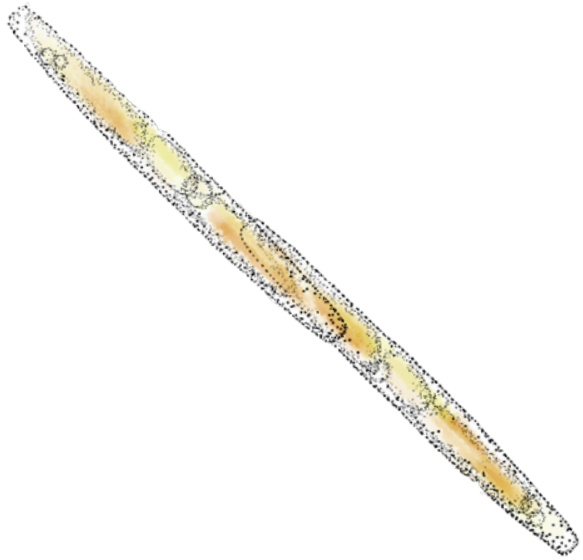


A

Nitzschia bizertensis

Length:	33-82 micrometers
Width:	1-3 micrometers
Distribution:	*Nitzschia* species are found in polar to tropical oceans and estuaries worldwide.

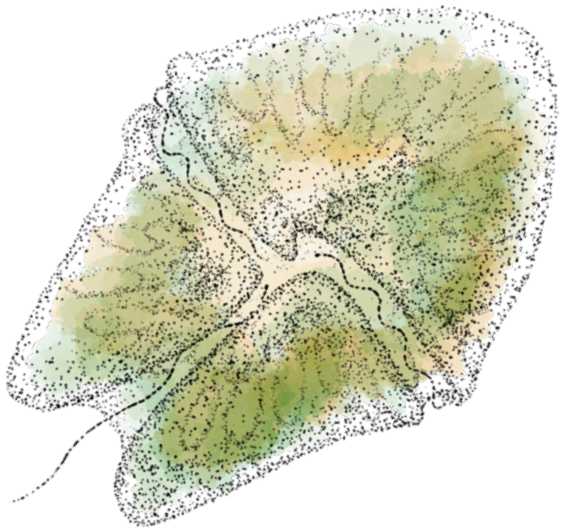
Individual species distributions vary and can be highly specific. For example, *Nitzschia bizertensis* (depicted here) has only been found so far in the Bizerte Lagoon, Tunisia and off the coast of Tunisia. The *Nitzschia* species in the Bay are unclassified. Although they do not form cysts, *Nitzschia* can enter a dormant state where they slow their energy use to survive short periods of environmental stress. *Nitzschia* have also been known to survive being consumed and excreted by mussels, likely due to their dense cell walls.



Akashiwo sanguinea

Length:	40-80 micrometers
Width:	35-50 micrometers
Distribution:	Temperate to tropical coastal waters and estuaries worldwide.

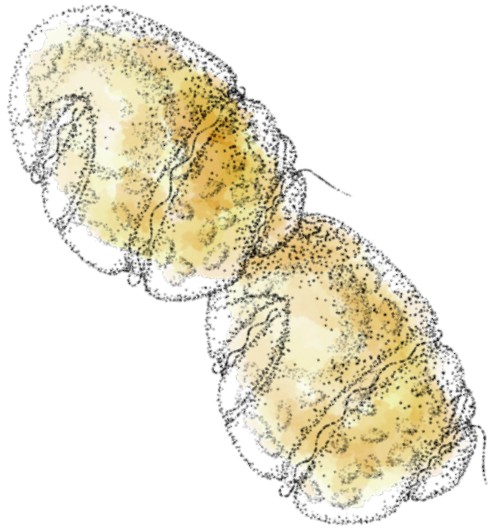
The genus *Akashiwo* gets its name from the Japanese word for red tide, as their cells can be rich in reddish-brown pigments. Their blooms form yellowish-green foams resembling dish soap bubbles and are full of surfactant compounds. The foam washes away the water-repellent oils in seabird feathers, reducing their insulation and putting them at risk of hypothermia. *Akashiwo* also produces a thick mucus that can suffocate fish and other marine life. *Akashiwo* caused a large bloom in San Francisco Bay in 2004, which produced record-breaking levels of biomass at that time, though fortunately no animal deaths were observed during that event.



Margalefidinium fulvescens

Length:	60-80 micrometers
Width:	20-40 micrometers
Distribution:	Temperate to subtropical coastal waters and estuaries worldwide.

Margalefidinium fulvescens frequently forms chains of two, four, or more cells to move through the water column. While it is known to be toxic, scientists have yet to identify the exact toxin(s) it produces. Previously classified under the genus *Cochlodinium, Margalefidinium fulvescens* and other species in its genus have produced harmful blooms with fish kills in estuaries throughout the world.



ALGAE OF CONCERN IN SAN FRANCISCO BAY

A **Trophism:** Autotrophic

H **Trophism:** Heterotrophic

M **Trophism:** Mixotrophic

Toxicity

Swimming

Armor

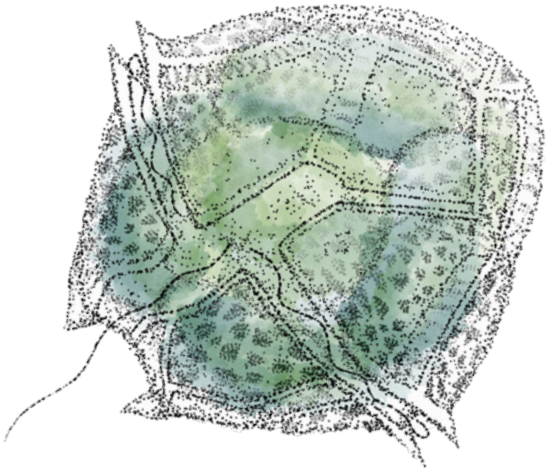
Cyst Formation

M

Peridinium bipes

Length:	40-85 micrometers
Width:	35-76 micrometers
Distribution:	Freshwater bodies worldwide.

As a freshwater species, *Peridinium bipes* can proliferate in the Sacramento-San Joaquin Delta, the Oakland Estuary, and various sloughs and tributaries of San Francisco Bay, particularly when flows are high in spring and salinity is low. Its blooms can reduce dissolved oxygen to dangerously low levels. Some species of *Peridinium* produce a fish-killing toxin, glenodinine. *Peridinium bipes* also produces toxins that harm other algae and allow it to grow with less competition. *Peridinium* is common and monitored as a bloom-former of concern in the freshwater portions of other estuaries such as the Chesapeake and Mississippi Delta.

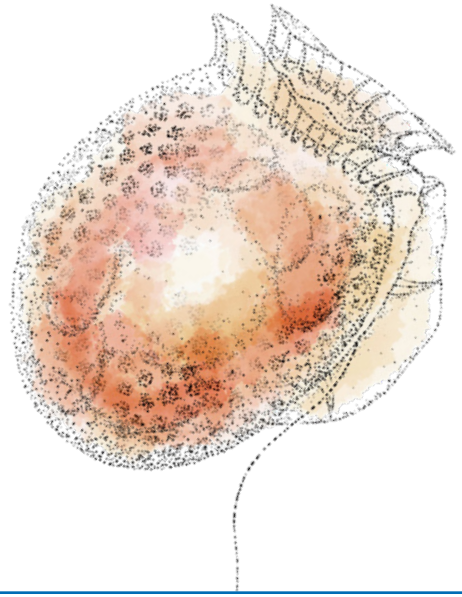


M

Dinophysis acuminata

Length:	20-100 micrometers
Width:	30-60 micrometers
Distribution:	Subpolar to warm coastal waters and estuaries worldwide.

Dinophysis acuminata cannot produce its own chloroplasts. Instead, like a chloroplast pirate, it sucks them out of prey plankton to survive. Its cells also produce okadaic acid and other toxins leading to diarrhetic shellfish poisoning, sickening tens of thousands of people worldwide every year. There are multiple harmful *Dinophysis* species in the Bay that look similar to *Dinophysis acuminata*.

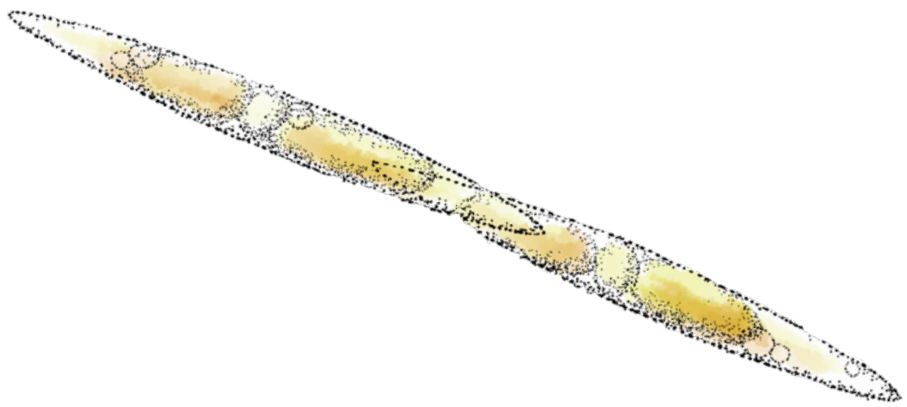


A

Pseudo-nitzschia australis

Length:	68-144 micrometers
Width:	3-8 micrometers
Distribution:	Temperate to subtropical coastal waters and estuaries worldwide.

Pseudo-nitzschia australis produces domoic acid, a neurotoxin that causes amnesic shellfish poisoning in marine mammals and humans. In 1961, a *Pseudo-nitzschia australis* bloom off the coast of Capitola, California caused seabirds to display frenzied behavior after consuming contaminated anchovies, which is rumored to have inspired Alfred Hitchcock's movie *The Birds*. On the US West Coast (California, Oregon and Washington), a toxic bloom of *Pseudo-nitzschia* shut down the Dungeness crab fishery in 2015 causing a $97.5 million loss in landings compared to the previous year. Domoic acid produced by *Pseudo-nitzschia* is one of the main drivers of an annual quarantine on consumption of shellfish on the entire California coast (including bays, inlets, and harbors) that is normally in effect from May 1 through October 31. Although they do not form cysts, *Pseudo-nitzschia* can enter a dormant state that helps them survive short periods of harsh conditions.

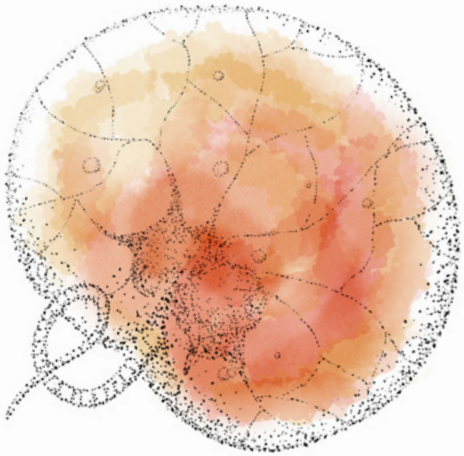


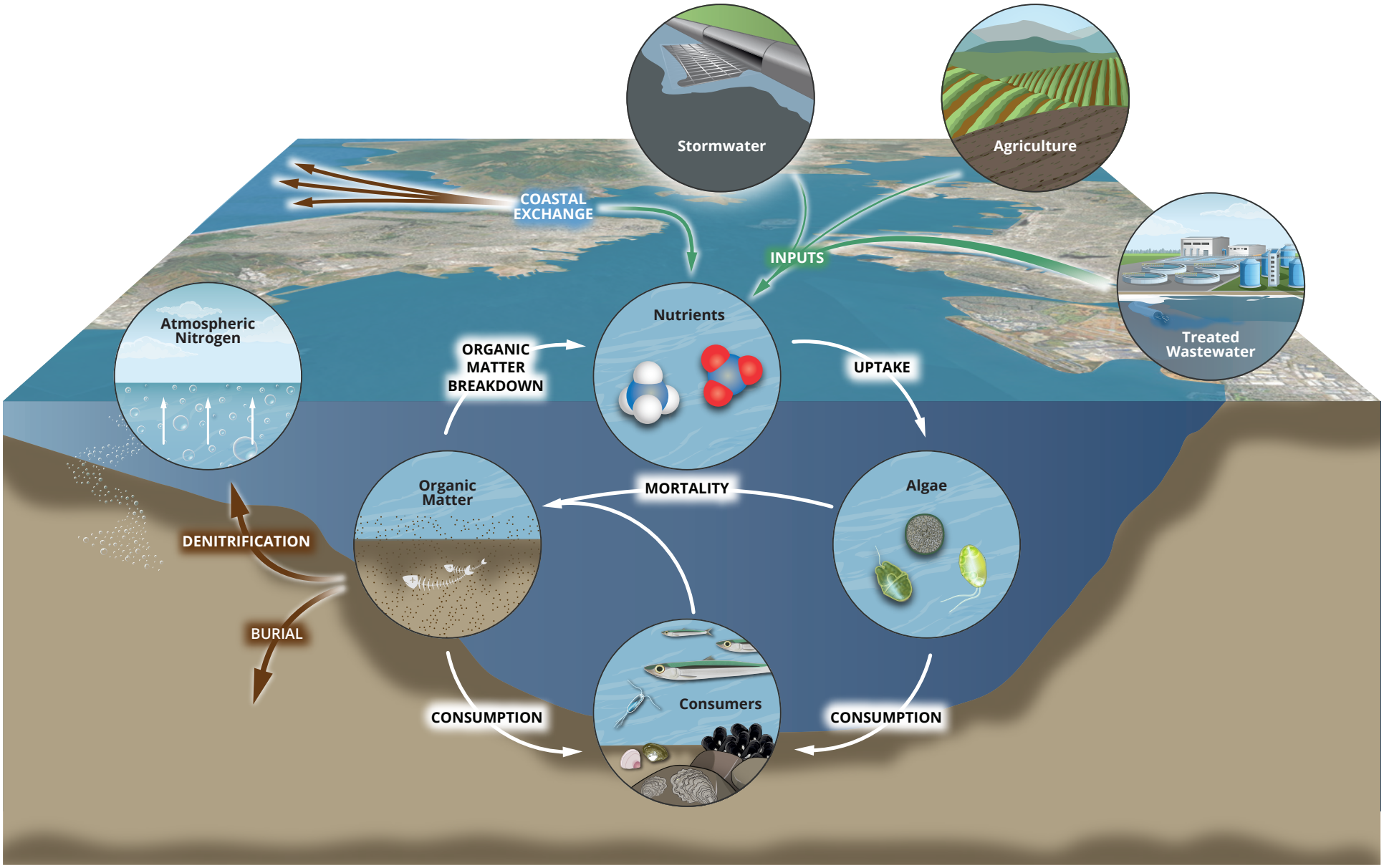
H

Noctiluca scintillans

Length:	200-2,000 micrometers
Width:	200-1,200 micrometers
Distribution:	Temperate to subtropical coastal waters and estuaries worldwide.

Noctiluca scintillans is also known as 'sea sparkle' due to its bioluminescence. When moved by waves or other motion, the cells emit a blue-green light that is visible at night. *Noctiluca scintillans* has two variants based on its bloom color: red and green. Neither variant produces chloroplasts, but green *Noctiluca scintillans* sometimes houses smaller photosynthetic organisms that live within their cell and produce energy they can use. In regions such as the English Channel, the Black Sea, the east coast of India, the Seto Inland Sea, and the East China Sea, multiple *Noctiluca scintillans* blooms have been reported almost annually. Although *Noctiluca scintillans* does not produce toxins that can kill marine organisms or threaten human health, massive blooms of this species do have negative environmental impacts. Aquaculture losses of oysters, scallops, razor clams, and shrimp have been reported, possibly due to mechanical damage, increased ammonia concentration, or low oxygen content during the degradation phase.





▲ **An overview of the major inputs, transformations, and exports that influence nitrogen in San Francisco Bay.** Nitrogen is the limiting nutrient for algae growth in the Bay. Inputs are shown as green arrows, transformations as white arrows, and exports as brown arrows.

Science Priorities to Inform Management of Nutrients in San Francisco Bay

Will Geiken, Ariella Chelsky, Daniel Killam, Martin Volaric, Ian Wren, and David Senn
San Francisco Estuary Institute

For most of the Bay Area's nearly 8 million residents, the nutrients we all flush into the Bay are out of sight and out of mind. But for scientists with the Nutrient Management Strategy program (NMS) at the San Francisco Estuary Institute, studying the fate of those nutrients – and how to protect the Bay from an overload – is top of mind. While there have been many advances, events like the 2022 harmful algal bloom (HAB) (page 37) emphasize that there is still plenty to learn.

The NMS began in 2012 with growing concerns over San Francisco Bay's decreasing resistance to the harmful impacts of adding nutrients to the Bay. At its outset, the NMS took a broad approach and developed foundational science, like identifying the major sources of nutrients, characterizing how nutrients move through the Bay, assessing how the Bay responds to nutrient levels, and evaluating management strategies to protect the Bay.

In pursuit of these goals, the NMS developed a three-pronged research approach based around monitoring, modeling, and synthesis (next page). The findings from each prong influence the directions of the others, and together form a comprehensive research program. For example, monitoring data help build and validate models, which in turn generates estimates for areas that are not monitored. Similarly, synthesis work generates the nutrient cycling rates used in modeling, and model output identifies the process descriptions that require further refinement.

After the 2022 *Heterosigma akashiwo* HAB, NMS priorities shifted to targeted studies designed to inform near-term management. The NMS is now working to uncover the conditions that allowed *H. akashiwo* to bloom, quantify the relationships between nutrient inputs and potential HABs, and assess how well wastewater treatment plant nutrient reductions could protect the Bay from future blooms.

HIGHLIGHTS

- Since its inception in 2012, the Nutrient Management Strategy (NMS) has implemented a robust, multi-faceted science program to inform management of nutrients in San Francisco Bay
- The NMS applies increasingly advanced monitoring techniques to measure nutrients, dissolved oxygen, algae, and other parameters in the Bay
- NMS modeling experts have created foundational numerical models of the Bay and are now developing tools to assess the impacts of management actions and future environmental conditions
- NMS scientists synthesize the data generated by monitoring and modeling efforts to identify key relationships between nutrient levels and the health of the Bay
- Increased funding for the NMS from the San Francisco Bay Program Office of the US Environmental Protection Agency is significantly enhancing the capacity of the program to answer management questions regarding nutrients in the Bay

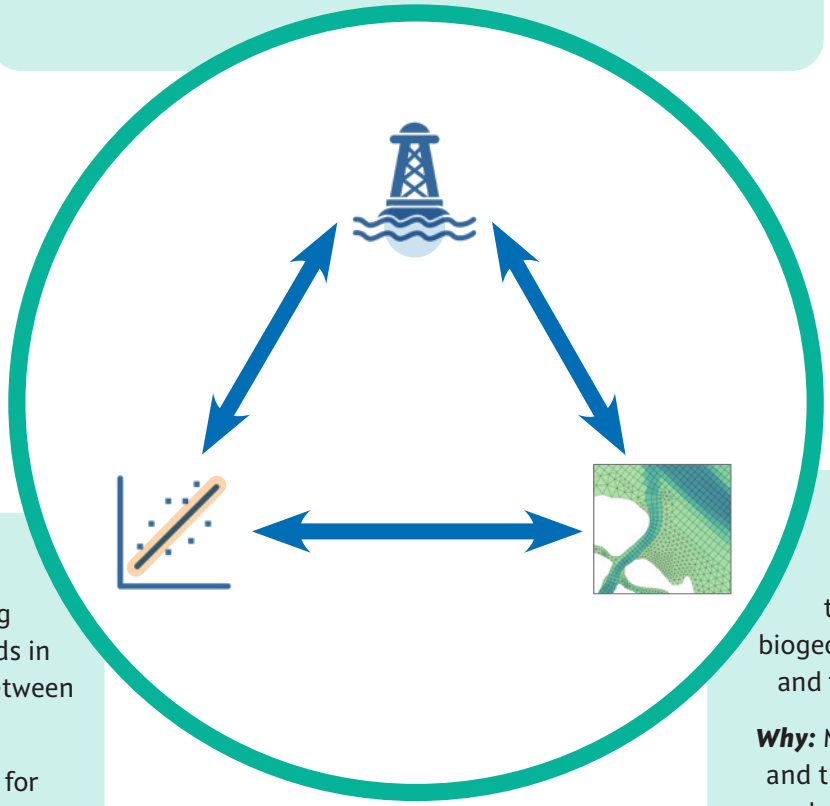
THE THREE PRONGS OF THE NMS

The NMS has developed a three-pronged research approach based around monitoring, modeling, and synthesis. The findings from each prong influence the directions of the others, and together form a comprehensive research program.

Monitoring

What: Building on decades of ship-based monitoring by USGS, the NMS and its partners generate an expansive suite of data that covers water quality, algae growth, toxin presence, and more.

Why: Monitoring quantifies changes in priority water quality parameters and provides the data needed to assess trends (part of synthesis) and to develop models.



Synthesis

What: Using the results of monitoring and modeling, synthesis assesses trends in nutrients and algae and relationships between water quality parameters.

Why: Synthesis determines rates used for processes in models and identifies priority gaps in monitoring. It also provides decision-makers with information they can use to protect the Bay.

Modeling

What: The NMS built and continues to refine hydrodynamic models and biogeochemical models of San Francisco Bay and the Sacramento-San Joaquin Delta.

Why: Modeling shows how nutrients move and transform in the Bay, their influence on algae and dissolved oxygen, and allows forecasting of future conditions. Models provide information for synthesis efforts and help identify monitoring priorities.

MONITORING

Within the network of agencies, universities, and research institutes that monitor conditions in the Bay, the NMS monitoring program is unique in its focus on nutrient-related parameters. The comprehensive program supports a combination of channel sampling cruises, high-frequency moored sensors, shoal mapping cruises, mussel tissue sampling, satellite data, and community-driven sampling. These activities provide a suite of information on water quality, algae growth, toxins, and other priority indicators of ecosystem health. In recent years, the program has received substantial support from US Environmental Protection Agency (USEPA) grants and a National Oceanic and Atmospheric Administration (NOAA) Monitoring and Event Response for Harmful Algal Blooms (MERHAB) research program grant. This funding is allowing the NMS to expand the monitoring network to fill in critical gaps across the Bay and promote regional collaboration in HAB monitoring.

Water quality sampling near the Dumbarton Bridge. Photo by Alex Braud.

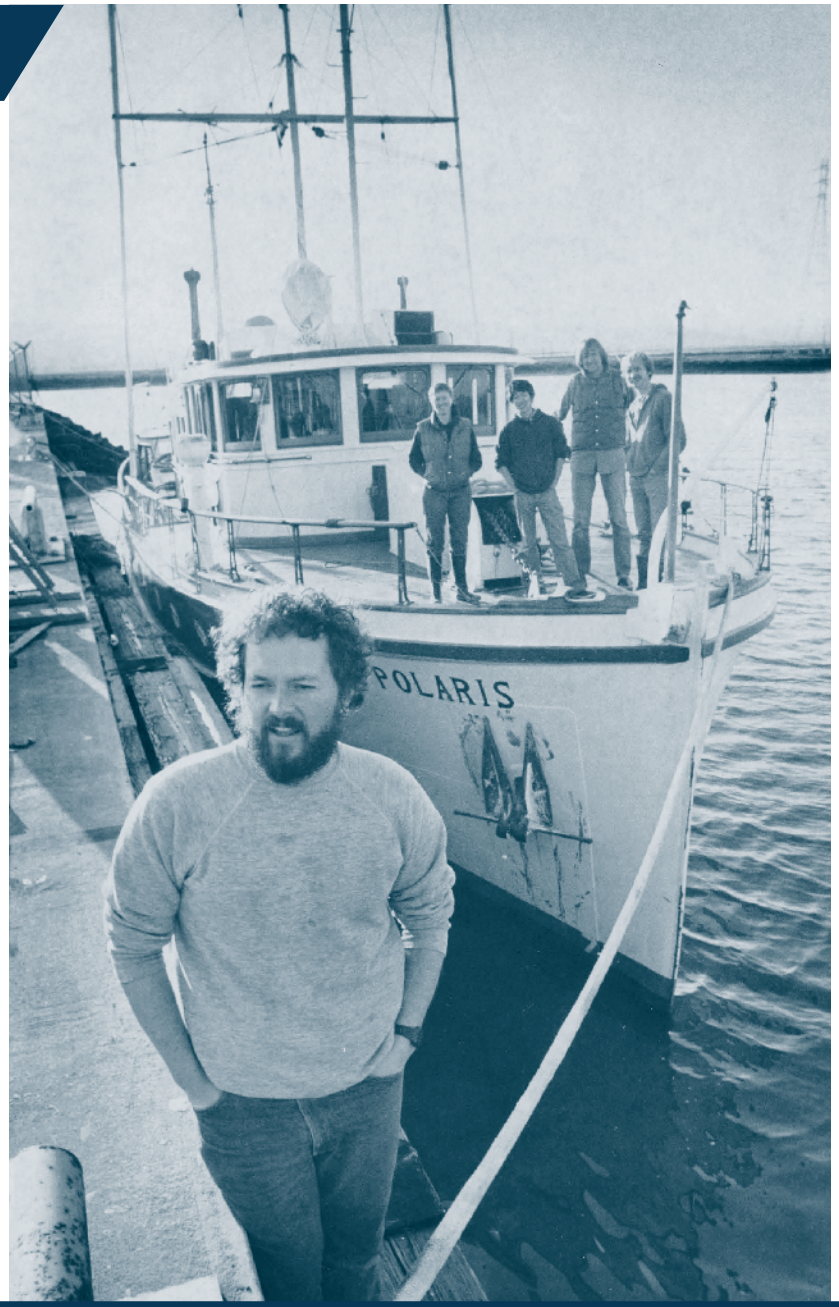


IN MEMORIAM

Jim Cloern

1948–2025

Jim Cloern died on November 3, 2025, after nearly 50 years with the US Geological Survey. To understand the debt of gratitude that San Francisco Bay and the people in the region owe him, start with the program he led. On April 10 and 11, 1969, USGS oceanographers ran the first hydrographic research cruise along the salinity gradient of San Francisco Bay. By the team's own later account, they had no intention of starting a permanent program. But that two-day survey became the first entry in what is one of the longest continuous programs of observation and research in any US bay or estuary – a record still growing month after month at the same network of stations along the Bay's spine.



The USGS hired Cloern in 1976 as a modeler for the then-developing San Francisco Bay Water Quality Research Program. He led it for the rest of his career. Decades of monthly transects produced the conceptual framework that became foundational to estuarine ecology: the way turbidity and strong tidal mixing limit the light available to phytoplankton, the way abundant benthic grazers remove algae from the water column, and the way processes gave San Francisco Bay an unusual resistance to the potential adverse impacts of nutrient loading despite receiving wastewater from a region of more than seven million people.

He synthesized that understanding in his landmark 2012 paper, "Drivers of change in estuarine-coastal ecosystems: Discoveries from four decades of study in San Francisco Bay." The 2012 paper followed his 2001 framing of the global coastal eutrophication problem, which has been cited more than three thousand times. His work was anchored in the Bay but ranged far beyond it. Across nearly 200

◄ **Jim Cloern and the USGS *R/V Polaris*, circa 1983.** Courtesy of Tara Schraga.

The scientist who made San Francisco Bay a living laboratory for the world

published contributions, he led or joined collaborations and comparative studies in the Thames, the Baltic, the Potomac and Chesapeake, the Yangtze Estuary, and coastal systems in Egypt. That body of work earned wide recognition: the Bostwick H. Ketchum Award (Woods Hole, 2010), the American Society of Limnology and Oceanography (ASLO) Ruth Patrick Award (2015), the Coastal and Estuarine Research Federation's Odum Lifetime Achievement Award, the Delta Science Program's Brown-Nichols Award, the Interior Department's Distinguished Service Award, and election as a fellow of both ASLO and the American Geophysical Union. For a fuller portrait by colleagues who knew him longest, see Luoma et al. in the June 2026 issue of *San Francisco Estuary and Watershed Science*.

For decades, the program documented a system that defied expectations. The Bay received nutrient loads comparable to those of Chesapeake Bay, yet phytoplankton stayed low. In the late 1990s, that pattern began to break down. In Cloern et al. (2007, 2010), the USGS team documented that summer and fall phytoplankton biomass in South Bay rose sharply after 1999. August–December primary production more than doubled, and new autumn blooms appeared at concentrations not seen in the program's first two decades of record. They traced the cascade of processes that allowed phytoplankton to begin drawing on the Bay's abundant nutrient supply. That early warning prompted the Water Board to establish the Nutrient Management Strategy in 2012. Without Jim's long record, the 2022 bloom would have been the first sign that anything had changed. With it, the region had a structure in place to respond.



▲ **Jim Cloern at the 2017 RMP Annual Meeting.** Photo by Shira Bezalel.

The Regional Monitoring Program has co-funded the USGS Bay cruises since 1993. The NMS contributed to the purchase and outfitting of the *R/V Peterson* in 2016 and continues to support joint USGS, UC Santa Cruz, and SFEI work on harmful algal blooms. Throughout this time Jim kept contributing: RMP Annual Meeting presentations in 2003, 2006, 2009, 2013, and 2017; *Pulse* articles in 2003 and 2006, State of the Estuary keynote talks in 2009, 2013, and 2019; service on the Delta Independent Science Board; co-editorship of *Estuaries and Coasts* (2007–2012) and the editorship of *Limnology and Oceanography Letters*; testimony to Congress on the importance of sustained long-term monitoring; and a steady stream of reviews and counsel to the people picking up the work.

The cruises continue. ASLO has renamed its L&O Letters Early Career Publication Honor in his name. The program Cloern led from 1976 onward, built on cruises that began in 1969, is now in its 57th year. Today's questions and answers about nutrient management, harmful algae, and a warming Bay rest directly on the record he kept. §

Channel Sampling Cruises

As the monitoring program's steady plowhorse, channel sampling cruises provide a historic record of changes in the Bay. The US Geological Survey (USGS) began regular water quality sampling along the Bay's deep, central channel in 1969. More than 50 years later, the NMS works directly with the USGS to continue extending this dataset at 38 stations along the channel on one to two cruises each month. Data collection covers basic water quality (e.g., temperature, salinity), a complete suite of nutrient parameters (e.g., nitrate, ammonium, phosphate), and algae species and density. Using these long-term data, the NMS tracks shifts in algae growth and water quality as well as localized differences between the Bay's subembayments.



▲ **The *R/V Peterson.*** Photo by Shira Bezalel.

KEY FINDINGS

- Cruise data alerted scientists and regional managers to a steady increase in algae growth from the 1990s through the 2010s in Central Bay and South Bay (Cloern et al. 2007, Foley et al. 2025). This observation and growing concerns over nutrient enrichment prompted the foundation of the NMS.
- Channel monitoring has shown that many HAB-forming algae species are long-term residents in the Bay (page 50), increasing concerns about potential blooms (Otten et al. 2021). They also show seasonal and regional variation in species prominence, which offers insights into the factors that promote and limit growth.
- Channel cruises provide insights on spatial patterns in water quality, such as varying nutrient concentrations by subembayment, which is valuable for informing and verifying modeling efforts.
- Channel data alerted the region to elevated algae growth during the spring, which suggested it was a season of concern for nutrient managers (Cloern et al. 1985, Cloern 1996).

ONGOING PRIORITIES

- The NMS is expanding algae monitoring to include refined identification processes, which provide a more accurate record of species presence and abundance.
- The NMS is adding a water quality sensor and nitrate sensor to the research vessel to collect continuous nutrient data while underway. An additional nitrate sensor will also measure nitrogen at depth, which is a key data gap for developing Bay nutrient budgets.
- The NMS is adding a new carbon dioxide sensor to the cruise to understand carbonate chemistry, which is helpful in refining understanding of biological processes and changes in the Bay's pH.
- The NMS is reinstating a station near the Golden Gate Bridge to better characterize exchange with the coastal ocean, which is critical information for modeling and synthesis work.

High-frequency Moored Sensors

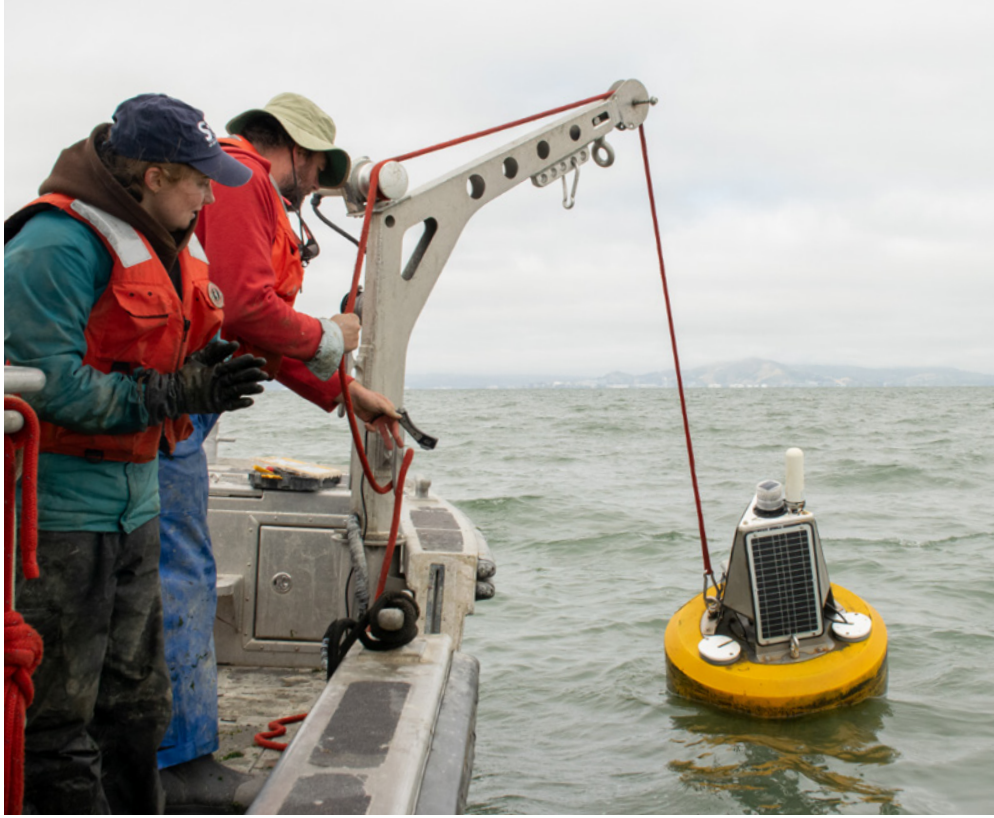
What started in 2013 as two stations in Lower South San Francisco Bay now includes 16 stations in key locations, from San Pablo Bay all the way to the Lower South Bay salt ponds and sloughs. These sensors generate data every 15 minutes for parameters that include temperature, salinity, dissolved oxygen, chlorophyll-a, blue-green algae, turbidity, dissolved organic matter, pH, and more. This coverage allows the NMS to understand how water quality changes on a daily, seasonal, and sub-regional basis. Five stations are now equipped with telemetry systems that transmit continuous data for real-time observation.

KEY FINDINGS

- Stations located on the shallow shoals of the Bay show that algae growth is generally higher and more variable than in the deep channel. This highlights that observing the perimeter of the Bay is key for understanding algae growth and nutrient impacts (Killam et al. 2023).
- Stations in the managed salt ponds and sloughs show large swings in dissolved oxygen, which is a concern for fish and other organisms (Chelsky et al. 2024, Volaric et al. 2025).
- Moored sensors provided critical data during the 2022 HAB, including recording the unprecedented hypoxia and anoxia that occurred following the bloom's collapse (Volaric et al. 2026).

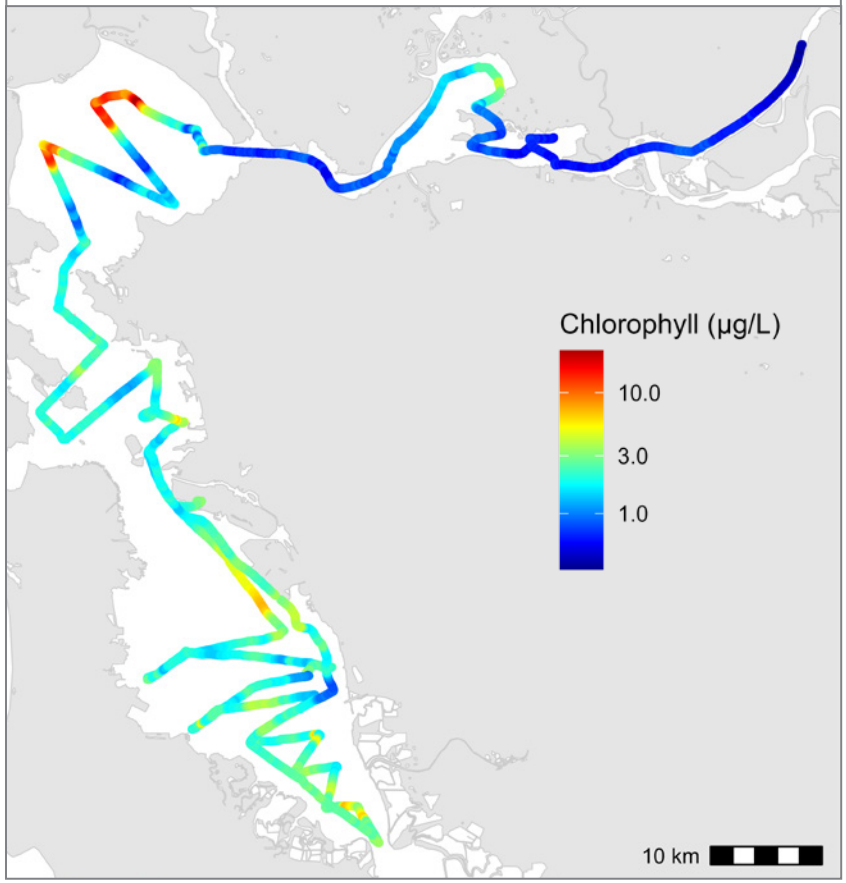
ONGOING PRIORITIES

- The NMS is collaborating with the UC Davis Bodega Marine Lab to establish a sensor near the Golden Gate Bridge to help quantify exchange with the coastal ocean.
- The North Bay received less attention during early sensor deployments due to the high total nutrient inputs from wastewater treatment plants in South Bay. The NMS is expanding the network in the North Bay to round out the understanding of the system.
- The NMS is adding telemetry systems to sensors to provide real-time data for the entire Bay.



▲ **NMS and USGS staff pulling up a moored sensor station for routine servicing and data downloading.** Photo by Sierra Garcia.

Mapping Chlorophyll in Bay Shoals



Shoal mapping cruises follow a zig-zag route. Chlorophyll measurements in micrograms per liter from August 13 and 14, 2025 are shown as an example.

Shoal Mapping Cruises

Incorporating water quality monitoring over the broad shoals of South, San Pablo, and Suisun Bays was a longstanding NMS priority (SFEI 2014, 2016). Pilot study cruises that zig-zagged over South Bay's eastern shoal showed that shoal conditions differ substantially from those in the channel. Beginning in 2021, SFEI collaborated with the USGS to begin regular South Bay shoal mapping cruises during the spring and summer to measure chlorophyll, nutrients, turbidity, temperature, salinity, algae species density, and more. In 2024, cruises were extended to cover the San Pablo and Suisun Bay shoals. Because the shoals represent a large percentage of the Bay's total area, these surveys in understudied and highly variable regions provide much needed detail.

KEY FINDINGS

- Algae growth over the shoals is both higher than the channel (on average) and more variable, which emphasizes the shoals' importance for understanding algae in the Bay (Killam et al. 2024).
- Cruises have found high variability in nutrient levels between years (Killam et al. 2024), which helps characterize nutrient dynamics and provides data for estimating nutrient mass over the shoals.
- Algae growth on the shoals varies with pH and nutrient availability, and more data will help scientists synthesize more exact relationships (Killam et al. 2024).
- Cruises during the 2022 HAB informed nutrient dynamics during the event, including the nearly complete drawdown of nutrients in South Bay (Volaric et al. 2026).

ONGOING PRIORITIES

- The NMS is adding alkalinity measurements to better understand algal growth and respiration.
- While early cruises were limited to South Bay, the NMS continues to add cruises that cover the San Pablo and Suisun Bay shoals.

Mussel Tissue Monitoring

Between 2015 and 2022, mussels were collected from eight floating docks at marinas around the Bay every two weeks. Collaborators at UC Santa Cruz analyzed them for saxitoxin, domoic acid, and microcystin, which are toxins produced by HAB species. The toxin data provide a record of HAB toxins over time throughout the Bay.

KEY FINDINGS

- Testing identified the regular presence of multiple toxins, indicating the presence of the corresponding HAB species in the Bay.
- Saxitoxin levels were generally well below advisory levels (Peacock et al. 2018), but exceeded advisory levels at Central Bay sites in spring 2018, which contributed to a California Department of Public Health advisory against shellfish consumption.
- Domoic acid levels are typically much lower than human consumption advisory levels (Peacock et al. 2018).
- Microcystin levels regularly approached and sometimes exceeded human consumption advisory levels, which merits further study (Peacock et al. 2018).

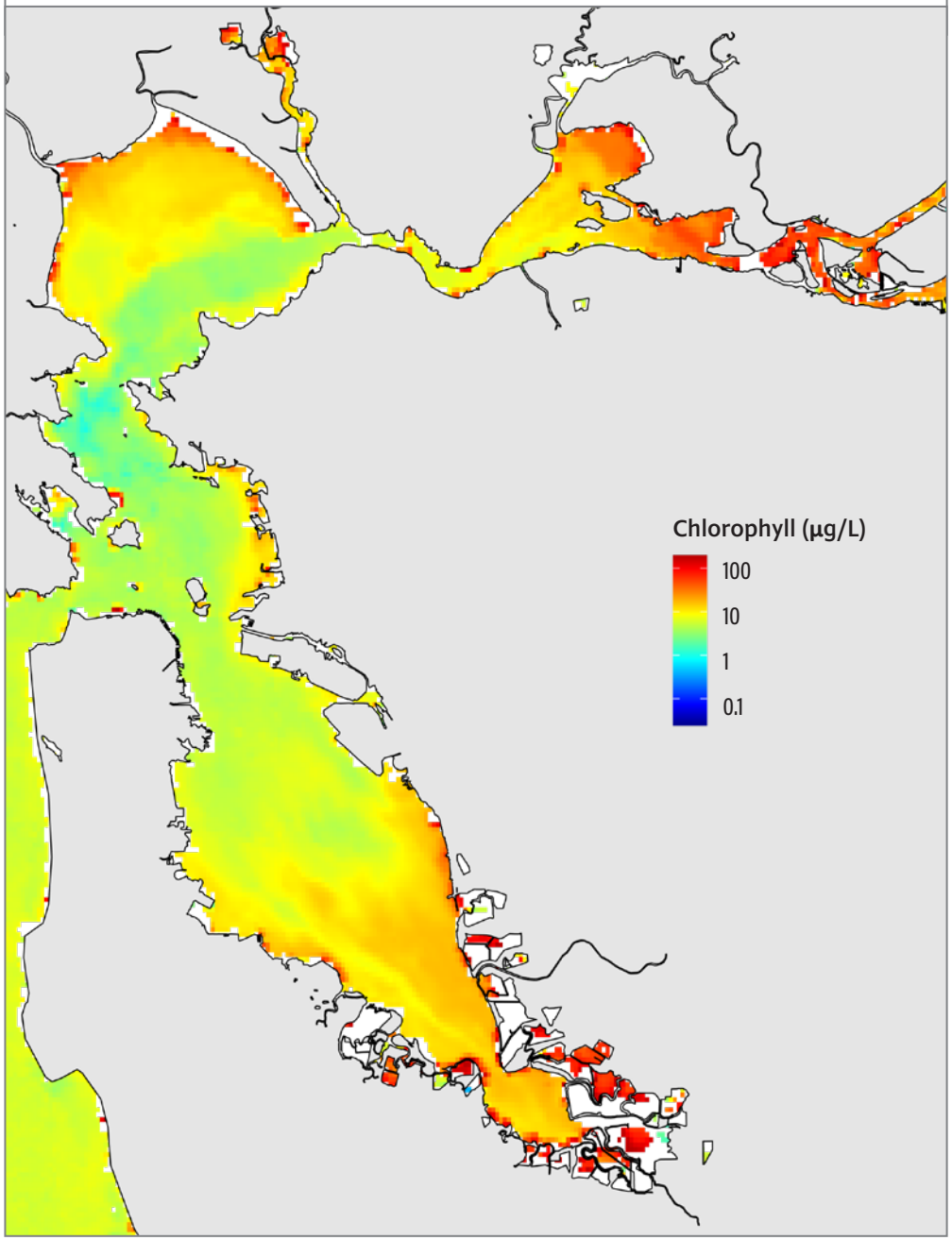
ONGOING PRIORITIES

- While sampling is not slated to resume, the NMS is continuing to analyze the archived mussel tissue to assess the presence of additional HAB toxins and species.
- The NMS is interested in studying how wildlife are impacted by regular exposure to these toxins, which is a significant unknown for wildlife managers.



Mussels at an NMS sampling station. Photo by Dan Killam.

Satellite Monitoring of Bay Algae



Satellite Data

Collaborators at UC Santa Cruz developed an algorithm that uses satellite imagery from the European Space Agency's Envisat-1 environmental research satellite and Sentinel 3A and 3B satellites to estimate algae growth (based on chlorophyll-a abundance), turbidity, and cyanobacteria (blue-green algae) presence. This technique allows the NMS to generate years of datasets that cover the entire Bay, including water quality conditions in the past.

KEY FINDINGS

- In collaboration with UC Santa Cruz and NOAA, the NMS refined the processing algorithm to create a turbidity dataset for the entire Bay from 2002 to present and fill a longstanding data gap (Kudela 2024).
- Satellite imagery from the 2022 bloom provided data on the size and concentration of the HAB as it progressed, as well as a striking visual representation (Killam et al. 2025).

ONGOING PRIORITIES

- The NMS continues to collaborate with satellite experts with the intent to generate additional historic datasets for other parameters of interest. These will provide untold insights into long-term changes in the Bay and their causes.
- The NMS is assessing new satellite products and additional comparisons with existing data to glean further insights about past conditions, including characterizing the types of algae present.

◀ **Chlorophyll measurements generated using satellite imagery** from June 19, 2026 show the scale and resolution of data provided using this technique.

Data Sharing

With mountains of data being collected, the NMS is committed to sharing data with collaborators and colleagues. Moored sensor datasets are available on the SFEI website, and algae eDNA and toxin datasets are available on the Environmental Data Initiatives website. Data are also regularly shared in reports and in a series of data visualization tools available online. A new data dashboard under development with support from NOAA MERHAB and USEPA grants will replace the existing data visualization tools by 2028. The dashboard will provide real-time water quality data for regional managers and interested members of the public in a condensed and easily accessible format.

Data Links

- Moored sensor data:
  bit.ly/4guVCGU
- Phytoplankton and toxin data:
  bit.ly/4x4btkC
- Data visualization tools:
  bit.ly/4iF2nar



Scientists explore data with the public at the Exploratorium in San Francisco.
Photo by Dan Killam.

Community Scientists on the Frontline of Harmful Algae Bloom Detection

Cheryl Patel and Jonathan Rosenfield, Baykeeper

The San Francisco Bay shoreline stretches 500 miles and is beloved by many of the millions of people who live nearby. This makes community members invaluable in augmenting the limited capacity of agency scientists to monitor rapid changes, including during the 2022 harmful algal bloom (HAB) response. The initial reports of a reddish-brown algae mass growing off Alameda came from local residents, and dozens of individuals recorded valuable observational data when fish started dying en masse.

"The Nutrient Management Strategy and the region were investing in increased monitoring efforts before the bloom, but without previous blooms to learn from, predicting exactly where and when a bloom might occur was outside our capabilities," recalls David Senn, the lead scientist for the Bay's Nutrient Management Strategy.

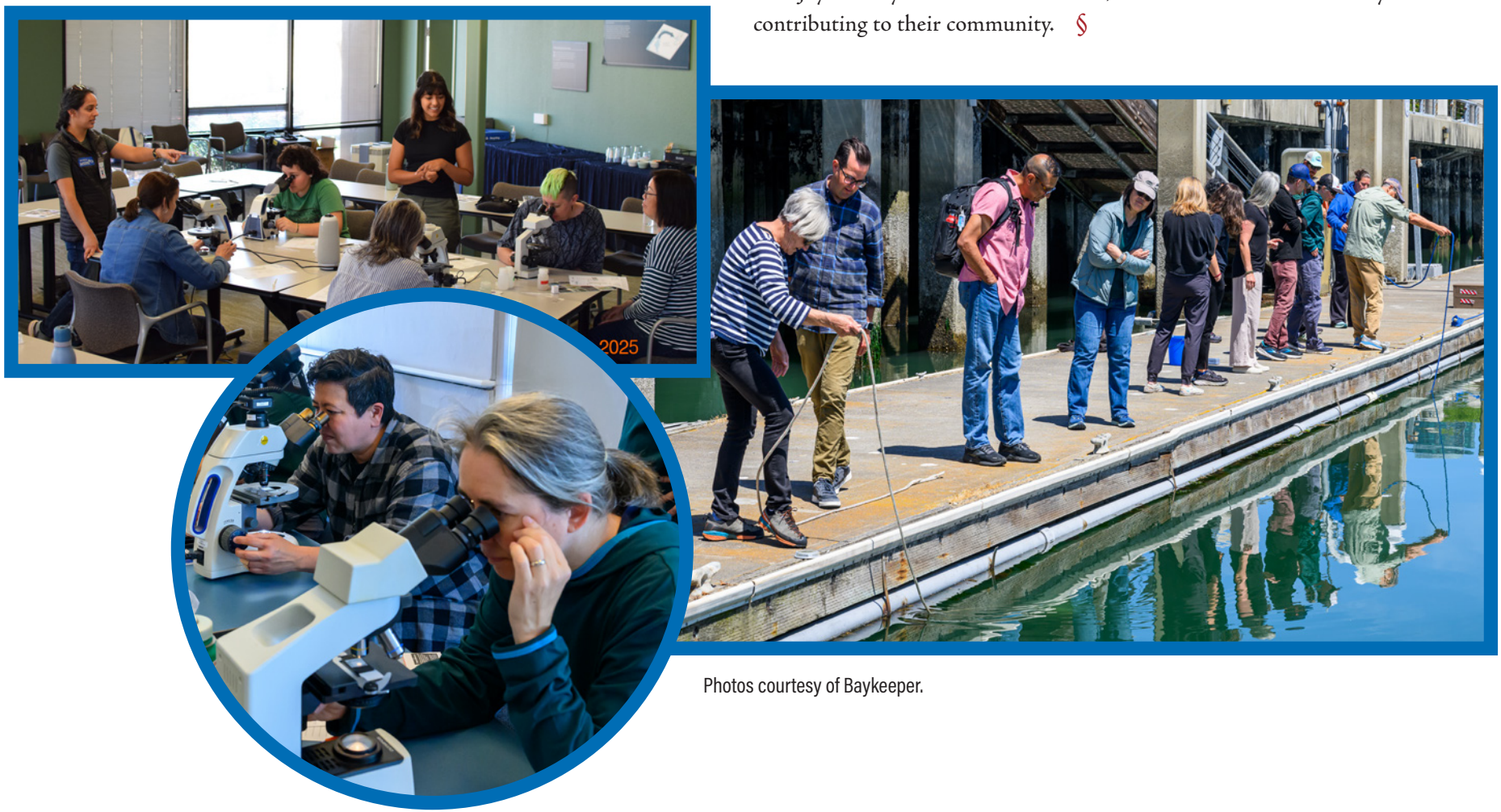
The sheer volume of public reports prompted San Francisco Baykeeper, a local nonprofit dedicated to defending the Bay, to create a Community Monitoring Program whose volunteers are on the frontline of early bloom detection.

"Community members extend Baykeeper's eyes on the Bay, and in 2022 that added vigilance proved to be critical in responding early to the harmful bloom," says Baykeeper field investigator and community science coordinator Cheryl Patel.

Now in its third year, Baykeeper's Community Monitoring Program is funded through a National Oceanic and Atmospheric Administration (NOAA) grant that supports a multifaceted HAB research and monitoring effort among collaborating agencies. The Program is built on the existing HAB monitoring structure of NOAA's Phytoplankton Monitoring Network, which consolidates data collected from volunteers around the country. A second harmful bloom in the summer of 2023 underscored the value of coordinated community monitoring. Ever since, Baykeeper has channeled the community's enthusiasm into an increasingly formalized program.

Community Monitoring Program participants monitor nine sites around San Francisco Bay on a weekly basis during the summer, and monthly during the rest of the year. Baykeeper selected the monitoring sites based on conditions most likely to support algae growth, including shallow water that is shielded from high winds and strong currents. The sites include areas of San Francisco Bay that large research vessels cannot access and where satellite image resolution can miss on-the-ground details. Because blooms can originate in these pockets of the Bay, the data Baykeeper volunteers collect are an essential complement to other regional monitoring efforts.

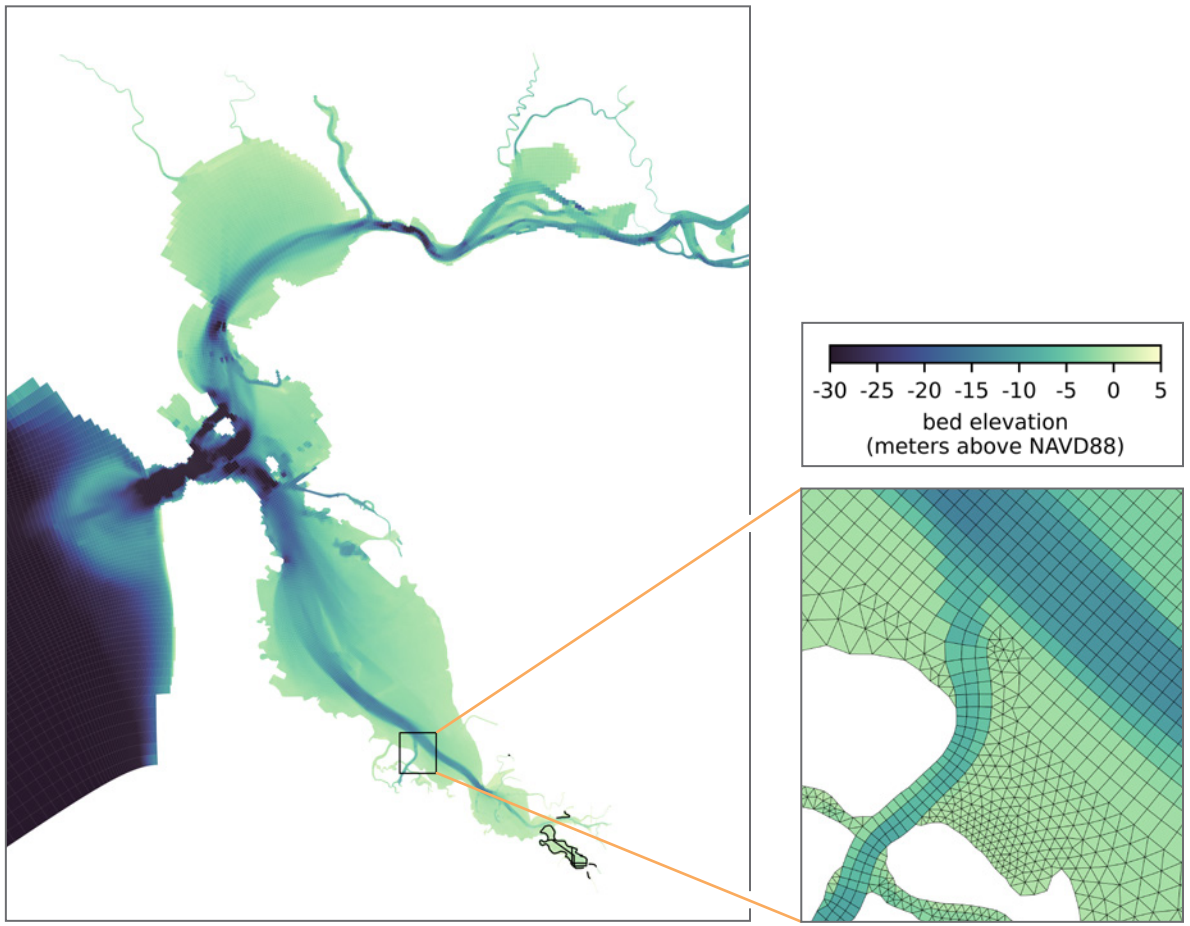
With each passing year, Baykeeper has strengthened the Program's efficiency and improved the experience for volunteers. Volunteers gather for a full-day workshop each spring where the Phytoplankton Monitoring Network program coordinator and Baykeeper staff train them to collect samples, gather environmental data, and identify harmful algal species. The program coordinator also evaluates the successes and challenges of each sampling season. Post-season volunteer surveys help Baykeeper evaluate the effectiveness of Program protocols and growth areas for the future. Volunteers report that participating in the Program feels rewarding, gives them the opportunity to enjoy the Bay's shoreline more often, and makes them feel like they are contributing to their community. §



Photos courtesy of Baykeeper.

MODELING

Since its founding, the NMS has prioritized developing numeric models to quantitatively characterize the Bay's response to added nutrients, explore ecosystem response under future environmental conditions, and test the effectiveness of nutrient reductions and other actions that could reduce or prevent future HABs. Beginning in 2016, the NMS has been steadily developing models that combine hydrodynamics (movement of water, nutrients, phytoplankton) and biogeochemistry (reactions involving nutrients, phytoplankton, oxygen, etc.) to predict Bay water quality, quantify important processes, and investigate water quality changes in response to potential management scenarios. While studies simulating extreme events and environmental change scenarios were identified among the early NMS science priorities (SFEI 2014) and included in the 2019 NMS science plan, they became urgent priorities after the 2022 HAB.



▲ **The high resolution grid used in the San Francisco Bay Hydrodynamic Model allows for accurate, detailed predictions of water quality parameters.**

> Since its founding, the NMS has prioritized developing numeric models to quantitatively characterize the Bay's response to added nutrients, changing environmental conditions, and nutrient reductions

San Francisco Bay Hydrodynamic Model

Although multiple hydrodynamic models of the Bay existed when NMS modeling work began, there were no integrated hydrodynamic and water quality models that could quantitatively explore ecosystem responses to nutrients under existing or future conditions (Senn et al. 2014). To address this need, the NMS used the D-Flow Flexible Mesh module from Deltares to develop a hydrodynamic model specific to San Francisco Bay that could be readily coupled to a biogeochemical model (Holleman et al. 2017).

The resulting hydrodynamic model computes water level, velocity, salinity, temperature, and turbulent mixing on a grid that extends from the lower reaches of the Sacramento and San Joaquin Rivers where they enter Suisun Bay, to Lower South Bay in the south, and the coastal ocean to the west. Along with the large freshwater flows entering Suisun Bay from the Sacramento-San Joaquin Delta (the Delta), the model incorporates predicted daily freshwater flows from Bay Area watersheds at 88 locations (Wu and McKee 2019; Zi et al. 2021) and treated discharges from the region's 40 wastewater treatment plants.

The NMS continues to develop the model (King et al. 2020, 2023, 2026) to support investigations targeting NMS science and management questions, including a recent major update that substantially extended the years modeled, and improved and tested model performance across the wide range of conditions that will be needed to support ongoing NMS science needs (King et al. 2026).

KEY FINDINGS

- The NMS extended the simulation period to span water years 2013 through 2023, a window that includes some of the driest (2013, 2014, 2021, 2022) and wettest (2017, 2019, 2023) years on record.
- The NMS took advantage of the range of water years to test and improve model predictions relative to the wide range of observed conditions, which led to substantial improvements to temperature predictions.
- The NMS evaluated model performance across 11 years, comparing model output with a broad set of observational datasets, and determined that the model performed well.

ONGOING PRIORITIES

- The NMS is incorporating refinements to the grid and hydrodynamics based on insights from recent targeted modeling in Lower South Bay.
- The NMS plans to test opening the coastal boundaries of the model, which were previously closed to avoid erroneous predictions. If feasible, this will improve modeling exchange with the ocean.
- The NMS will test using higher vertical resolution in the model to improve phytoplankton growth predictions, including HABs, and to investigate the potential importance of temperature stratification during summer.
- The NMS will refine salinity and evaporation rates in South Bay to improve model accuracy.

San Francisco Bay Biogeochemical Model

Using the outputs from the hydrodynamic model, the biogeochemical model solves for key nutrient-related parameters, including nutrient levels, algae growth, and dissolved oxygen. To do so, the model includes various modules, each of which captures a critical process within the Bay. To date, efforts have focused on accurately representing the biogeochemistry of recent years. NMS monitoring data are used to validate modeling results and inform priority areas of improvement. As with all models, the biogeochemical model is a significantly simplified version of the system it represents. However, the model can now reproduce the observed seasonal dynamics of nutrient cycling and algae growth for 2013 through 2023 with reasonable accuracy, which is no small feat for such a large, complex system.

KEY FINDINGS

- In 2023 and 2026, the NMS convened a Modeling Advisory Group made up of modeling experts from a variety of organizations and agencies. The Modeling Advisory Group assessed the capabilities of the biogeochemical model and found that it had many strengths (Sutula et al. 2023).
- The coupled hydrodynamic and biogeochemical model represents nitrogen sources and how they move with high confidence.
- The model generates reasonable predictions of gross primary production (algae growth) and respiration.
- The model captures seasonal and spatial trends in dissolved oxygen, but reproducing bloom-like events requires improvement.

ONGOING PRIORITIES

- Biogeochemical modeling efforts were initially focused on accurately representing past conditions, and the NMS is shifting to forecasting future conditions.
- The NMS will quantify the model's uncertainty to convey the value of results for informing management decisions.
- The 2023 Modeling Advisory Group report identified several areas for improvement that the NMS continues to address (Sutula et al. 2023).
    - Refining estimated denitrification rates and other sediment processes is key for increasing confidence in the model.
    - Developing the Bay's sediment model will more accurately represent how much light penetrates the water.
    - Grazing rates for organisms in the water column and the sediment can be refined to better represent biological uptake of nutrients and algae consumption.
    - Updating the ocean module to better reflect oceanic conditions will improve model accuracy as well as elucidate the Bay's impact on the coastal ocean.
- The NMS is collaboratively developing hydrodynamic and biogeochemical models of the Delta, which will be used to assess load reduction scenarios there. The Delta model can be coupled with the San Francisco Bay models to assess the entire Bay-Delta system.

Using the output from the hydrodynamic model, the biogeochemical model solves for key nutrient-related parameters, including nutrient levels, algae growth, and dissolved oxygen

Nutrient Load Reduction Scenarios

The 2022 HAB provided the region with a clear example of a near-worst-case scenario for nutrient management in the Bay. As a result, the San Francisco Bay Regional Water Board (Water Board) began assessing potential nutrient output reduction requirements to include with the 2024 reissuance of the Nutrients Watershed Permit, which governs nutrient discharge by the region's wastewater treatment plants. To assist with this assessment, the NMS modeling team used the hydrodynamic and biogeochemical models to develop and apply approaches for simulating scenarios with reduced nutrient output from wastewater treatment plants. By modeling conditions that mirrored the 2022 HAB, the NMS assessed the impact of various percent reductions in nutrient inputs on the dissolved oxygen levels (Karimpour et al. 2024).

KEY FINDINGS

- The results of the NMS assessment informed the Water Board's 2024 decision to require wastewater treatment plants to collectively reduce the nitrogen released to the Bay by 40% during the dry season.

ONGOING PRIORITIES

- The NMS assessment relied on models to simulate nitrogen levels and estimate a change in dissolved oxygen using literature-based conversions. In future iterations, those conversions can be replaced with modeling processes that directly estimate dissolved oxygen.
- The assessment used the models to replicate previous conditions. For forecasting, the model will need to include uncertainty estimates.
- As wastewater agencies plan their reductions, they are developing a potential trading program that would allow individual plants to pay other plants to reduce their nutrient outputs to a greater extent (page 23). This would allow the region to cover the 40% total reduction in the most cost-effective manner. The NMS is working with wastewater agencies to assess potential localized impacts under various trading scenarios.
- The NMS intends to investigate environmental change scenarios such as increasing average temperatures, periods of intense rainfall or drought, and water stratification. Doing so will require identifying priority scenarios as well as continued refinement of the underlying models.

Harmful Algal Bloom Modeling

The NMS reconstructed the 2022 bloom using models and investigated the various hydrodynamic and biogeochemical factors that contributed to its progression. This contributed to a suite of findings, which are detailed in the article on the 2022 bloom (page 37). Overall, the NMS's efforts to model HABs are in their infancy, and considerable future work is planned.

KEY FINDINGS

- NMS modelers reconstructed the 2022 bloom and identified the various factors that likely contributed to the bloom progression. The simulation requires algae growth to be effectively uncontrolled at the outset to represent the observed growth levels, which is unrealistic in well-regulated ecosystems. This growth pattern suggests that one or more controlling presences, such as viruses, were ineffective at the outset at the bloom. This is discussed in greater detail in the article on the 2022 bloom (page 37).
- Model results helped support the hypothesis that weak tides during daylight hours augmented the bloom's expansion.

ONGOING PRIORITIES

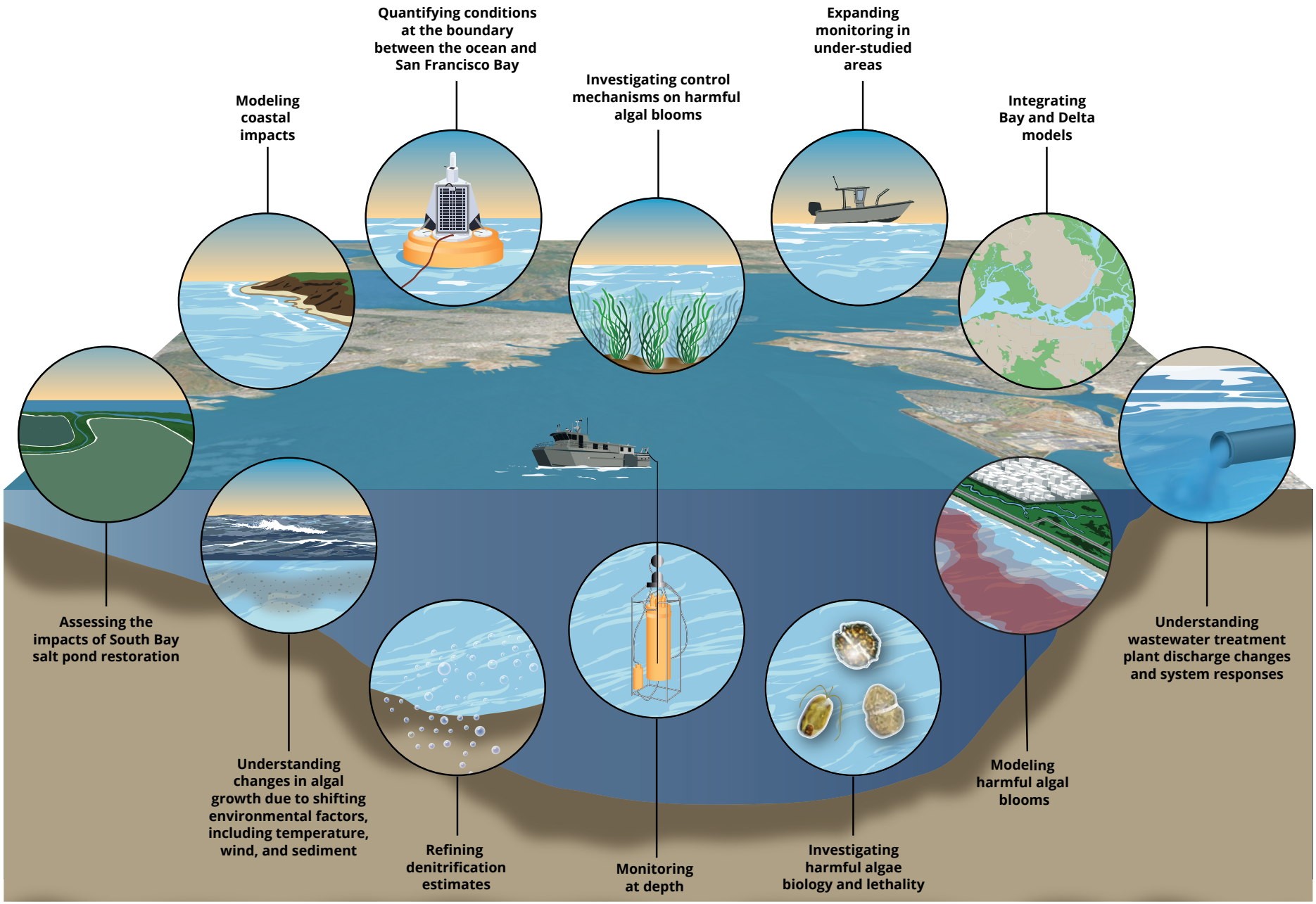
- The NMS plans to convene an expert meeting of HAB modelers to advise on improving HAB modeling. The goals of these improvements will include more accurately representing a *Heterosigma akashiwo* bloom, modeling other HAB species, and forecasting future events.

SYNTHESIS

Models and datasets in isolation aren't useful – scientists must interpret what these combined findings can reveal about the Bay. With the myriad of data produced and unknowns identified by the monitoring and modeling work, synthesis is a crucial part of the NMS workplan. In addition to nutrient cycling, NMS team research often targets specific habitats (central channel, shoals, sloughs, and salt ponds), subembayments (Lower South Bay, South Bay, Central Bay, San Pablo Bay, Suisun Bay), or combinations of the two (e.g., South Bay shoals). This approach teases out important differences within the Bay as well as conclusions about the region as a whole.



Examining NMS sensor data in the field. ▶
Photo by Alex Braud.



The ongoing priorities for the NMS. By targeting these topics, the NMS will provide impactful information for nutrient managers in the region.

Bay Channel Dynamics

The deep central channel of the Bay has a multi-decade monitoring dataset. This detailed record allows the team to assess long-term shifts in nutrients, algae growth, and other key parameters.

KEY FINDINGS

- From the 1990s to 2010, algae growth increased across the entire Bay. The increase was especially pronounced in Central Bay and South Bay where algae growth more than doubled (Cloern et al. 2007, Foley et al. 2025).
- While nutrients fueled the growth, the increase in production was likely due to increased water clarity from reduced sediment, a multi-year decrease in wind mixing in the Bay, and fewer bivalves like clams and oysters (Cloern et al. 2007, Foley et al 2025).
- After 2010, algae growth leveled off across Central Bay and the North Bay, but in South Bay and Lower South Bay it decreased to levels similar to the 1990s (Foley et al. 2025). The reasons for this difference remain a topic of investigation.
- Dissolved oxygen, which is key for the survival of most species, remains at consistently healthy levels along most of the central channel. Strong tidal mixing thoroughly circulates the channel's water column, which maintains oxygen levels despite variable algae growth and grazing. The exception is shallow portions of Lower South Bay, where dissolved oxygen periodically drops below the 5 mg/L threshold established in the San Francisco Bay Basin Plan.

ONGOING PRIORITIES

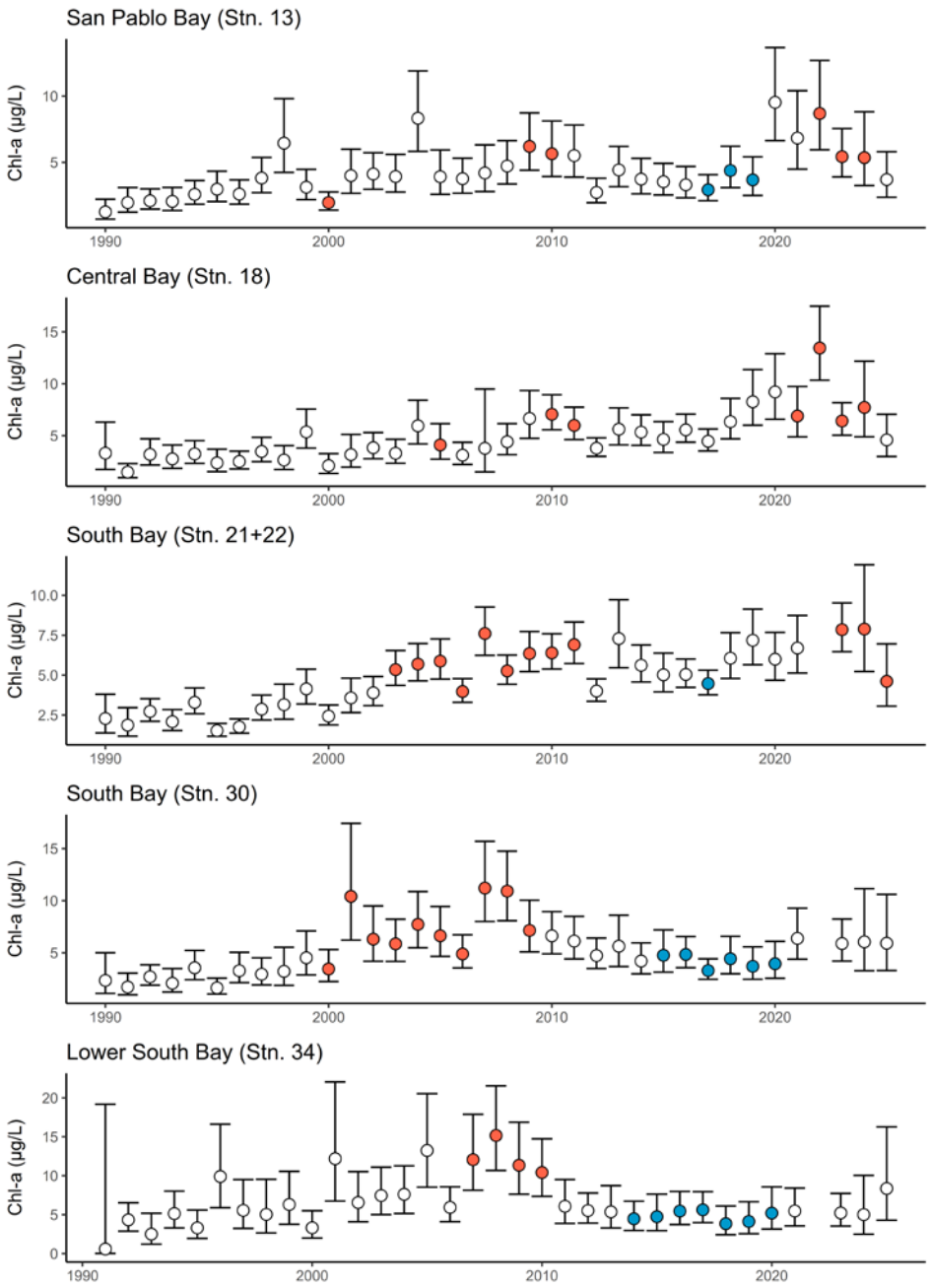
- The NMS is studying whether any additional long-term trends are impacting algae growth in the Bay. Satellite data will be especially helpful in assessing changes in key parameters and their relationship to algae growth over time.
- The NMS continues to monitor different algae species and their total growth. As wastewater treatment plants upgrade and other management actions are taken, synthesis efforts will assess the relative impacts of those actions.

> The deep central channel of the Bay has a multi-decade monitoring dataset that allows assessment of long-term shifts in nutrients, algae, and other key parameters

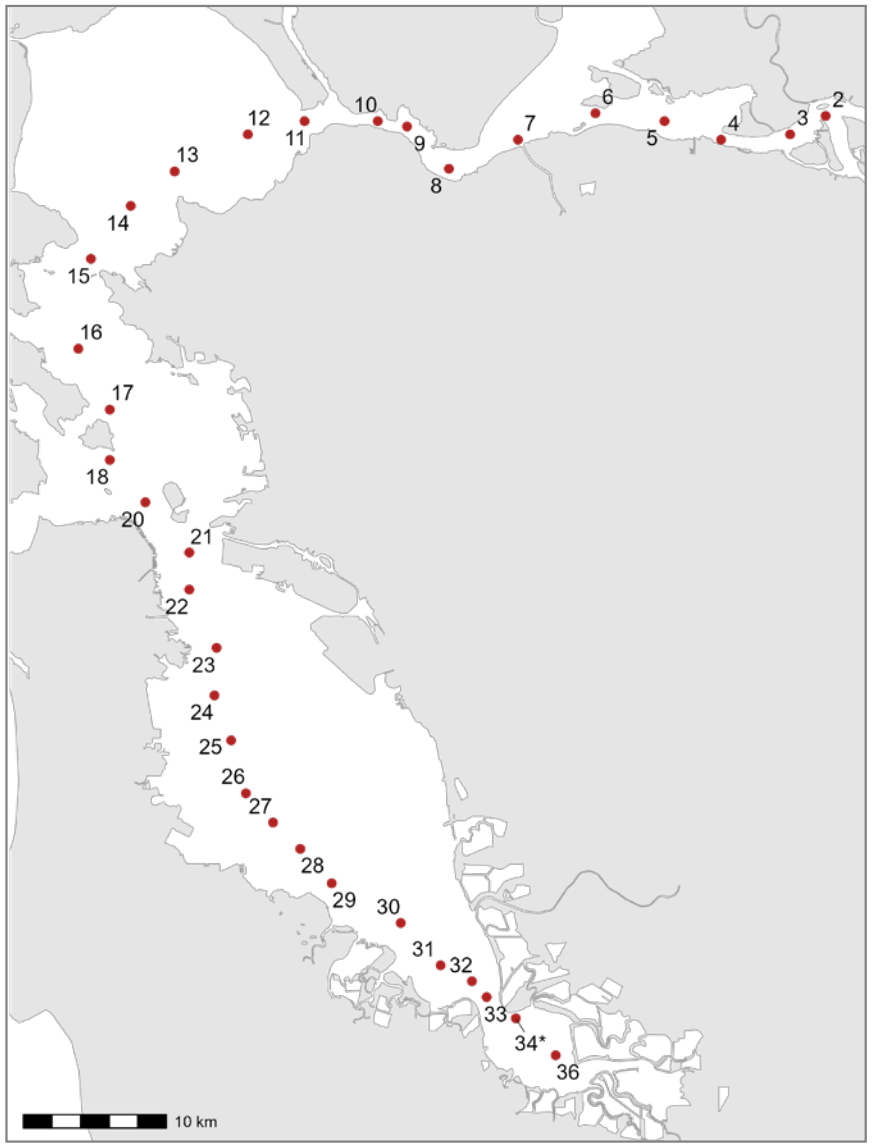
(Right) Trends in algae concentrations (based on chlorophyll) in the Bay from the 1990s to the present. In general, concentrations showed some increases between 2000 and 2010 (orange symbols) and showed some declines between 2010 and 2020.

FOOTNOTE: Estimated mean annual chlorophyll-a concentrations at channel cruise monitoring stations, 1990-2025. Symbol color represents the long-term trend in August-October (orange = increasing, blue = decreasing) based on an 11-year rolling window (right justified). For additional information see Beck et al. (2021) and SFEI (2022). Data: USGS (Schraga and Cloern 2017).

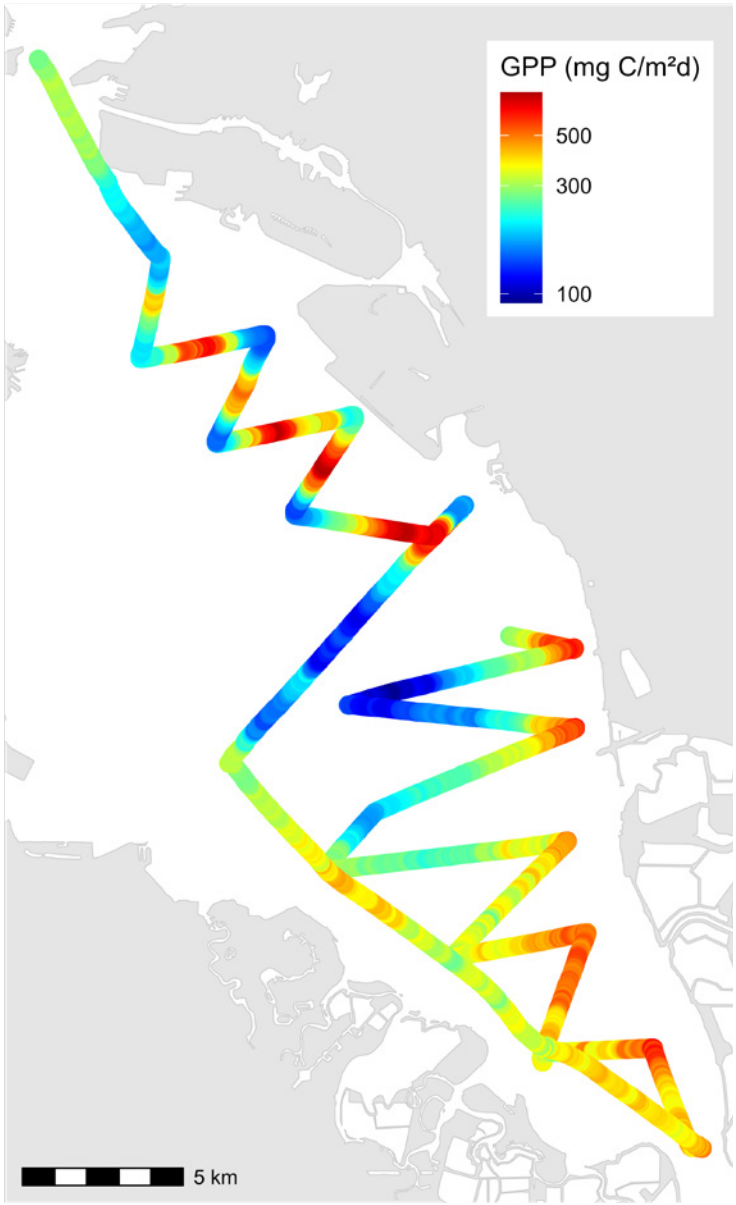
Trends in Algae Concentrations



Channel Cruise Station Locations



Algae Growth Rates in South Bay Shoals



Algae growth rates, expressed as gross primary productivity (GPP), are higher over the shoals and shallower areas of South Bay as compared to the central channel. GPP in milligrams of carbon per meter squared per day calculated using data from the May 5, 2021 shoal mapping cruise.

Shoal Dynamics

The shoals, or shallow regions, of the Bay cover a large area. Early studies found that nutrient concentrations and the amount of algae over the shoals was markedly different from the central channel (Cloern et al. 1989, Huzzey et al. 1990). This matched the intuition that strong tidal influence and shallower water columns increase variability, but limited data prevented drawing larger, regional conclusions. With the advent of NMS shoal mapping surveys and the installation of sensors on the shoals, the NMS now has far more information about just how variable these areas are.

KEY FINDINGS

- Algae growth rates over South Bay shoals are higher than those in the channel (Killam et al. 2024). This is likely because algae have more consistent access to light in shallower environments, where they can't be pushed below the sunlit zone.
- Algae growth rates are also more variable over South Bay shoals, and the amount of algae swings dramatically over time (Killam et al. 2023, Killam et al. 2024). This is likely due to the periods of high turbidity (from suspended silt and sand) that result from tidal mixing and limit light availability.
- Due in large part to the algae growth patterns, dissolved oxygen over South Bay shoals is higher on average than in the channel, but also more variable. This means dissolved oxygen in the shoals can drop to dangerous levels.

ONGOING PRIORITIES

- North Bay shoal mapping surveys and moored sensors have been active for about one year. More data will be valuable for understanding differences between the North and South Bay shoals. The new data will also support investigating the differences between the shoals and other habitats.

Pond and Slough Dynamics

Several former salt ponds in South Bay and Lower South Bay are now managed restoration sites and provide habitat for many local and migrating species. The water is warmer in these shallow and partially enclosed ponds, which can promote algae growth. Many of the ponds are connected to the open Bay by sloughs, which experience high variability as tides push and pull water between these habitats.

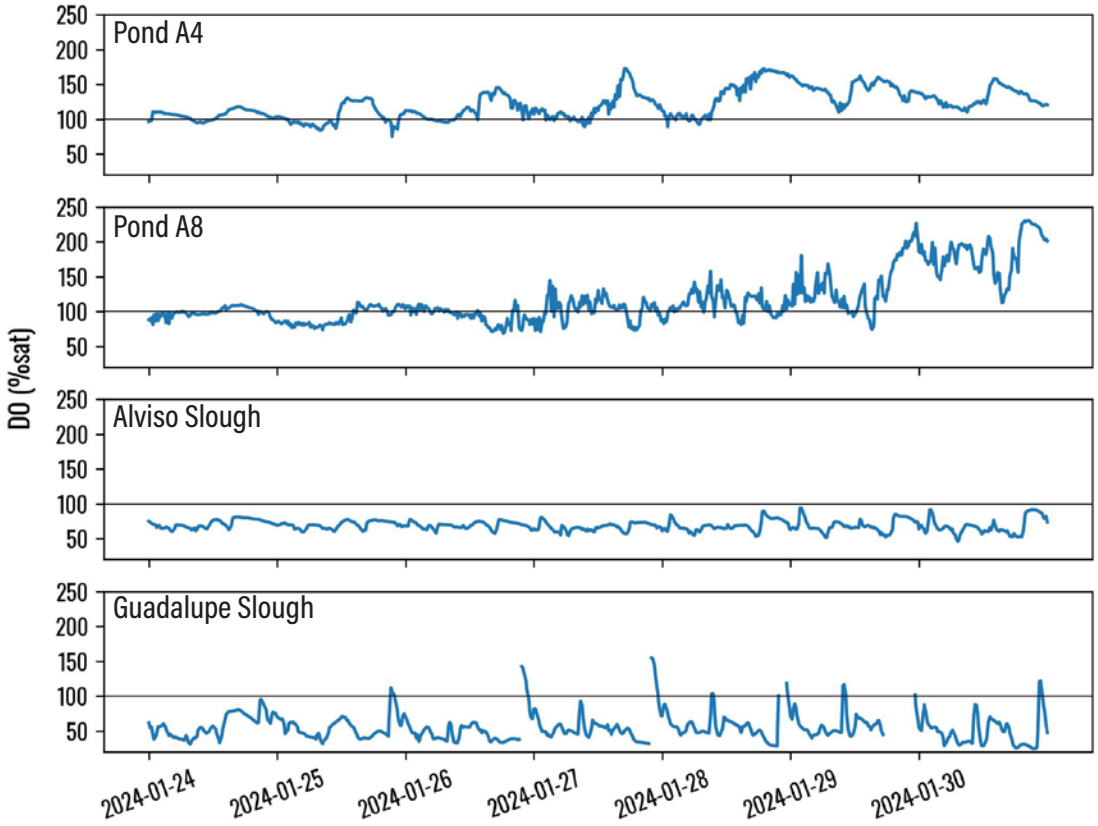
KEY FINDINGS

- Warmer temperatures, shallow waters, and reduced vertical mixing in the ponds allow for increased algae growth (Volaric et al. 2025).
- Tides pull algae from the ponds into the sloughs where it dies and decomposes, reducing dissolved oxygen in the sloughs (Chelsky et al. 2024, Volaric et al. 2025).
- Dissolved oxygen in sloughs frequently drops below 5 mg/L, which could negatively impact fish and other organisms (Chelsky et al. 2024).

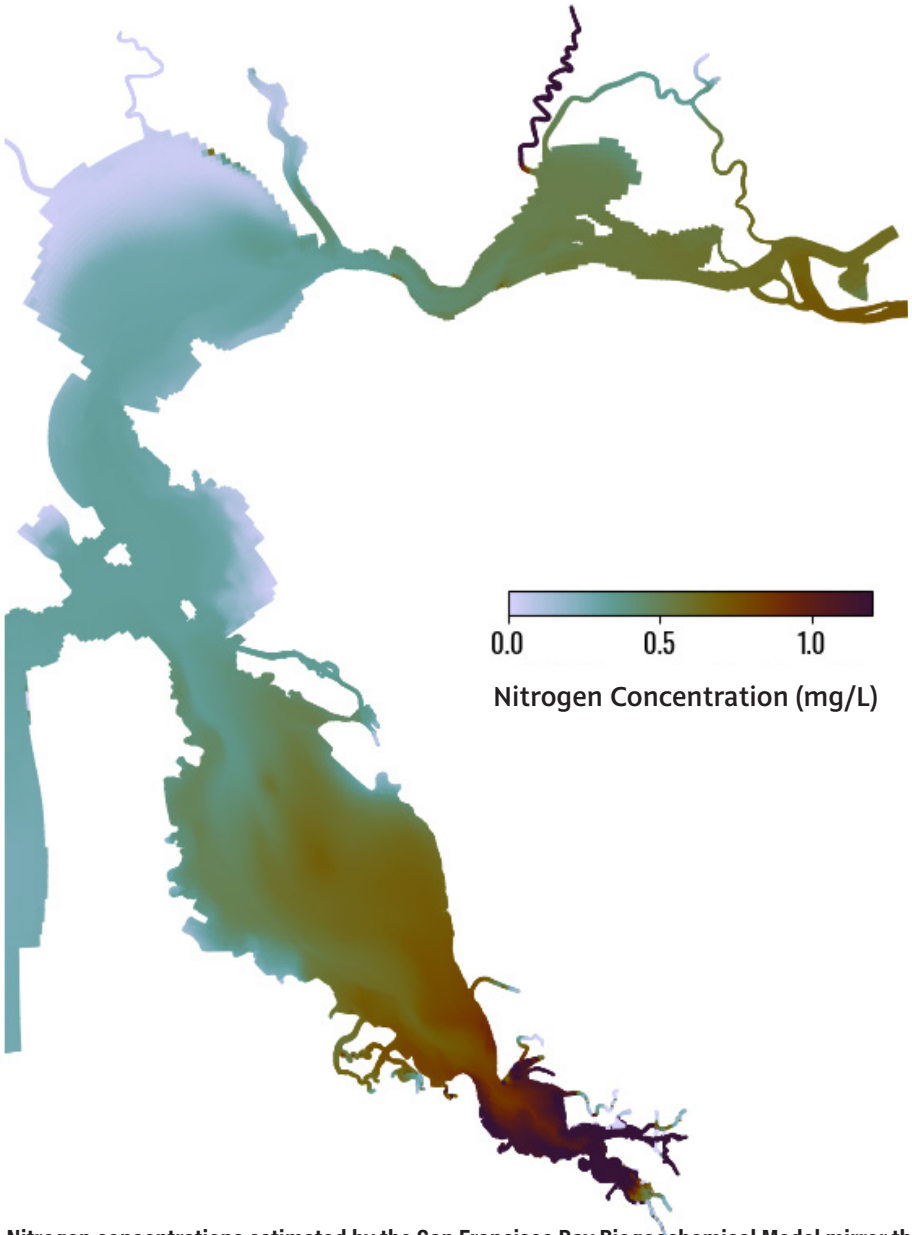
ONGOING PRIORITIES

- Further analysis of existing data and more monitoring are needed to evaluate whether the periodic low dissolved oxygen levels negatively impact aquatic life.
- The NMS will investigate how different levee breach patterns influence algae growth and release to the Bay.

Dissolved Oxygen in South Bay Managed Salt Ponds and Sloughs



Dissolved oxygen measurements often show high levels in managed salt ponds and low levels in sloughs, reflecting the high algae productivity relative to respiration in the ponds and the high respiration relative to algae productivity in the sloughs. Swings in dissolved oxygen measurements also reflect the variable nature of these habitats. Dissolved oxygen measurements expressed as percent saturation.



▲ **Nitrogen concentrations estimated by the San Francisco Bay Biogeochemical Model mirror the higher levels observed in monitoring of South Bay and Lower South Bay.** Nitrogen concentrations shown as dissolved inorganic nitrogen in milligrams per liter.

Nutrient Cycling

A core element of the NMS is understanding how nutrients cycle within the Bay. This includes both their physical movement as well as the biogeochemical processes that alter their form. Nitrogen is the limiting nutrient in the Bay, which means that as algae grows it will use up the nitrogen supply and cease growing before exhausting other nutrients. As such, the NMS focuses on nitrogen, but phosphorus and other nutrients are also considered.

KEY FINDINGS

- San Francisco Bay is nutrient-enriched, which means there is a sufficient nutrient mass to fuel abundant algae growth. The reasons why that growth is not regularly observed are discussed in greater detail on page 38.
- The vast majority of nutrients in San Francisco Bay come from wastewater treatment plant discharges (Novick and Senn 2014). The extent of that influence differs by subembayment. For example, Suisun Bay receives substantial nutrients from the Delta, which is highly influenced by agricultural runoff (Novick and Senn 2014).
- Nutrient inputs to the Bay vary by season. A greater proportion comes from wastewater treatment plants during dry summer months when blooms are more likely to occur, meaning that changing wastewater treatment plant nutrient outputs during the summer has a stronger impact on potential blooms (Novick and Senn 2014).
- The nitrogen released each year from the region's five largest wastewater treatment plants increased 25–30% between 2000 and 2018, reflecting both population growth and the expansion of wastewater infrastructure (SFEI 2025). After 2018, nitrogen from wastewater treatment plants began decreasing.
- Nutrient concentrations in the Bay vary greatly spatially and over time. One consistent trend is higher levels in South Bay and especially in Lower South Bay (see Figure left). This is likely the result of multiple high-volume wastewater treatment plants in the region as well as limited flushing of this area.

- Nitrification is the process by which bacteria convert ammonium (the main form of nitrogen in wastewater) to nitrate (the kind of nitrogen most algae prefer), so nitrification rates partially control algae growth. Scientists measured nitrification across the Bay and at various depths to categorize how temperature, oxygen availability, and microbial community dynamics all influence nitrification rates (Damashek et al., 2016). Those observations defined the nitrification rates used in modeling.
- Denitrification is the process by which bacteria convert nitrate and nitrite to nitrogen gas, which is released from the Bay to the atmosphere. Estimates indicate that denitrification rates in South Bay accounted for about 14% of nitrogen losses, but other regions remain understudied (Czapla et al. 2025).

ONGOING PRIORITIES

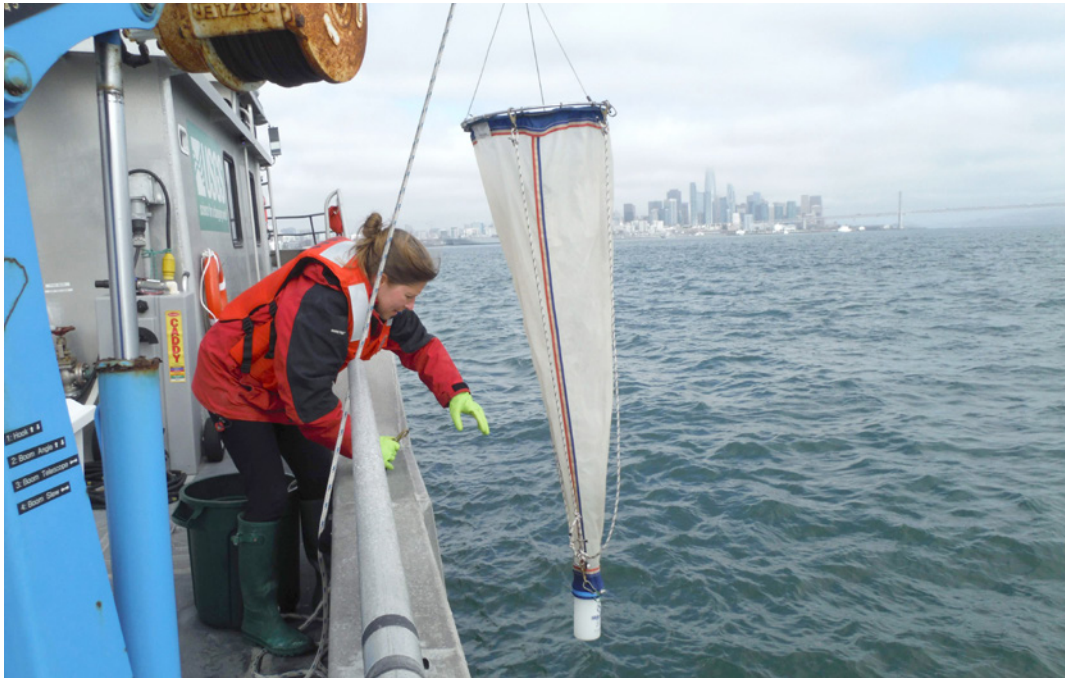
- The NMS is pursuing a study to generate more accurate Bay-wide denitrification rate estimates to understand how much nitrogen leaves the Bay as nitrogen gas.
- The NMS is prioritizing understanding nutrient exchange with the coastal ocean, which combines monitoring and modeling work with synthesis efforts.
- The NMS is synthesizing nutrient data from monitoring efforts to assess the impacts of reduced nutrient output from wastewater treatment plants.
- The NMS is assessing potential studies on biological nutrient removal, such as organisms consuming algae in the Bay before they leave to the open ocean. However, this is likely a relatively small factor in the overall Bay nitrogen cycle.

LOOKING FORWARD

NMS science spans scales from single-cell algae to satellite views, from individual salt ponds to the Bay boundaries at the Delta and ocean, and from tracking change over hours to decades. This array of investigations provides critical information for the regional decision-makers who create policies to protect the Bay.

The NMS has built on decades of work by the region's scientists to create a foundation of understanding of how water and nutrients move through the Bay. The program will continue to develop that foundation, while shifting increasingly toward assessing the future impacts of nutrients within a changing Bay.

For the next several years, funding for the NMS will be substantially augmented by grants from the San Francisco Bay Program Office of the USEPA. This increase in funding will significantly enhance NMS science across the many scientific focus areas outlined in this article. This investment will allow the NMS to provide an even better scientific basis to guide the billions of dollars that are being spent by municipalities to manage nutrients in the Bay.



▲ **Sampling with a plankton tow net in Central Bay.** Photo by Anna Rasmussen.

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303(d) LIST

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

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

- preparation of a draft list of listing/delisting recommendations by Regional Water Board staff;
- adoption by the State Water Board; and
- approval by USEPA.

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

Trace elements: Mercury and Selenium

Pesticides: Dieldrin, Chlordane, and DDT

Other chlorinated compounds:
PCBs
Dioxin and Furan Compounds

Others: Exotic Species, Trash, Polycyclic Aromatic Hydrocarbons (PAHs), and Indicator Bacteria

STATUS OF POLLUTANTS OF CONCERN

PARAMETER	STATUS
Copper	Site-specific objectives approved for entire Bay San Francisco Bay removed from 303(d) List in 2002
Dioxins / Furans	Monitoring recovery (synthesis report prepared in 2018)
Legacy Pesticides (Chlordane, Dieldrin, and DDT)	Monitoring recovery
Mercury	Bay TMDL and site-specific objectives approved in 2008; TMDL revision underway, targeted for 2028 Guadalupe River Watershed TMDL approved in 2010
Bacteria	Richardson Bay TMDL approved in 2008 Bay beaches (China Camp, McNears Beach, Crissy Field, Aquatic Park, Candlestick Point, and Marina Lagoon); TMDL approved in 2017 Bay beaches (Oyster Point, Coyote Point Park, Kiteboard Beach, Gull Park, Marlin, and Erckenbrack Park); Advance Restoration Plan approved in June 2026 Bay beaches (Crown Beach, Encinal Beach, Fort Baker [Horseshoe Cove], Keller Beach, Oakland Inner Harbor, and Paradise Cove); not currently covered by a TMDL
PCBs	Bay TMDL approved in 2010; TMDL revision underway, targeted for 2030
Selenium	North Bay TMDL approved in 2016
Trash	Municipalities required to implement trash load controls in 2009
Dissolved Oxygen	Site-specific objectives for Suisun Marsh approved in 2019

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PBF Martinez Refining Company

Phillips 66 Company

Schnitzer Steel Industries

USS-POSCO Industries

Valero Refining Company

STORMWATER

Alameda County Clean Water Program

California Department of Transportation

City and County of San Francisco

Contra Costa Clean Water Program

Fairfield-Suisun Urban Runoff Management Program

Marin County Stormwater Pollution Prevention Program

Santa Clara Valley Urban Runoff Pollution Prevention Program

San Mateo Countywide Water Pollution Prevention Program

Vallejo Sanitation & Flood Control District

DREDGERS

Aeolian Yacht Club

Benicia Port Terminal, Pier 95

Berkeley Marina

Chevron Richmond Long Wharf

City of Benicia Marina

Glen Cove Marina

Larkspur Marina

Port of Oakland

Port of Richmond

Port of San Francisco

Valero Refinery Terminal

Vallejo Yacht Club



◀ **The RMP Emerging Contaminant Workgroup, 2026.** Photo by Anna de Lopez.

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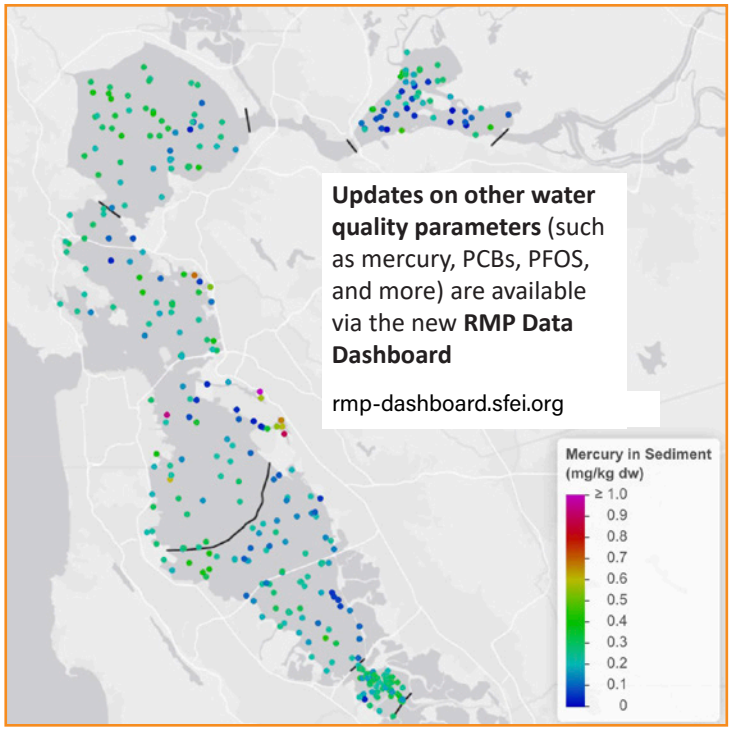
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