2023 Outfall Monitoring Overview

Massachusetts Water
Resources Authority
Environmental Quality
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Cover photos:

Top: 2023 Fish and shellfish survey at Deer Island Flats:
Michael Moore, Woods Hole Oceanographic Institution

Bottom: Sea stars feeding on barnacles:
Normandeau Associates, Semper Diving & Marine

2023
Outfall Monitoring Overview

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Executive Summary

The Massachusetts Water Resources Authority (MWRA) provides wastewater services to more than three million people in Greater Boston. MWRA works with industrial dischargers to prevent pollutants from entering the waste stream and provides primary and secondary sewage treatment to remove solid material and ensure that remaining pollutants meet permitted limits before discharge into Massachusetts Bay. The sewage effluent discharge is at depth, below the sunlit portion of the water column, where plant growth occurs, preventing nutrients from overstimulating algal growth.

MWRA's permit to discharge treated effluent requires monitoring the sewage effluent before discharge from Deer Island Treatment Plant and the water column, sea floor, and living communities in Massachusetts Bay. In the more than two decades that MWRA has discharged treated wastewater into Massachusetts Bay, there have been no unanticipated effects or findings of environmental concern.

Deer Island Treatment Plant effluent meets permit conditions

Producing the cleanest possible sewage effluent is the most important way that MWRA strives to protect the marine environment. In 2023, MWRA earned a Platinum Peak Performance Award from the National Association of Clean Water Agencies for a 17th consecutive year with no exceedances of its Deer Island Treatment Plant effluent permit limits.

One important measure of effluent quality is the suspended solids load, that is, the total amount of solid material discharged each year. Primary treatment removes most of the solid material from sewage as sludge, which is processed into fertilizer, but small particles remain suspended in the liquid effluent. The 2023 effluent solids load remained consistent with the past two decades, far lower than the amounts once discharged into Boston Harbor (Figure i, top). Discharges of toxic metals have followed similar patterns, remaining low for more than 20 years (Figure i, bottom).

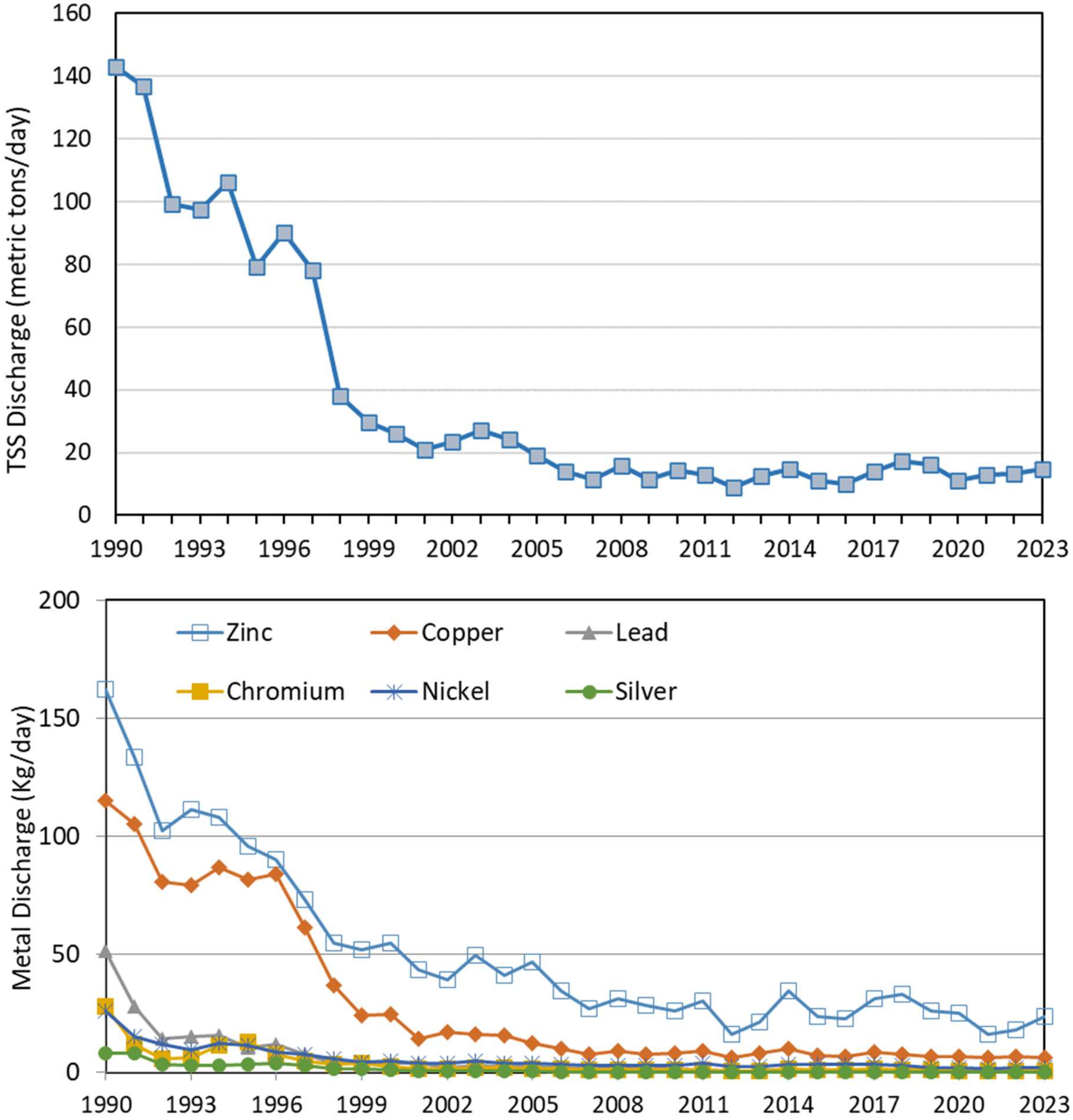

Figure i. Annual discharges of sewage solids (top) and metals (bottom), 1990–2023. Source reduction, including industrial pretreatment, ending sludge discharges, and secondary effluent treatment dramatically decreased solids and metals discharges, and those decreases have been sustained for more than 20 years. TSS = total suspended solids, Kg = kilogram.

MWRA's discharge has not led to eutrophication

Eutrophication occurs when nutrients overstimulate phytoplankton growth, leading to lower levels of oxygen when the phytoplankton die and decompose.

Sewage treatment removes some, but not all, of the nutrients in wastewater, including nitrogen, phosphorus, and silica, so MWRA water-column monitoring focuses on potential effects of nutrient inputs. Monitoring ensures that nutrients do not lead to eutrophication, a condition caused by excessive growth and decay of phytoplankton, the microscopic algae that live in the water column (Figure ii), or stimulate harmful algal blooms.

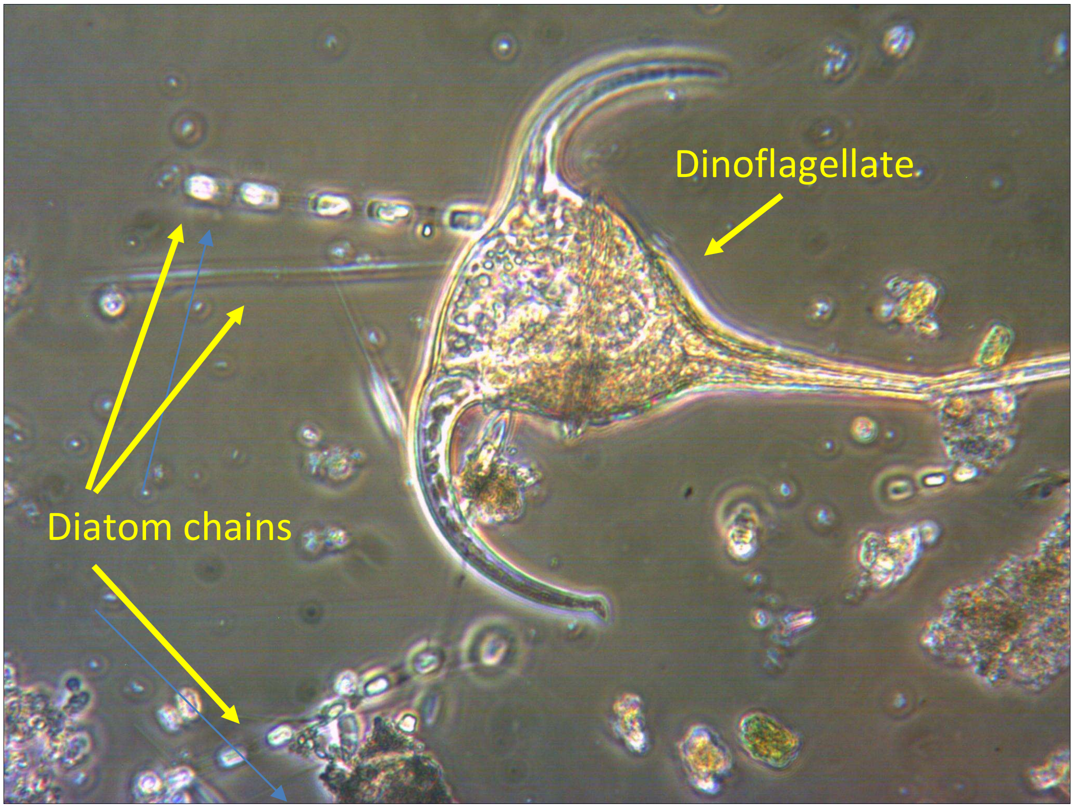

Figure ii. Typical phytoplankton from Massachusetts Bay. Phytoplankton include chains of individual diatoms and larger dinoflagellates, such as this *Tripos muelleri*, which bloomed throughout New England in 2023. Photo credit David Borkman, Pausacaco Plankton, Saunderstown, Rhode Island.

The MWRA discharge has not increased phytoplankton growth or lowered dissolved oxygen levels, even at stations closest to the outfall. In 2023, there was an unusual large bloom of one phytoplankton species, the dinoflagellate *Tripos muelleri*, which did affect phytoplankton biomass and dissolved oxygen levels. The bloom occurred from Maine to Rhode Island, beyond any possible influence of the MWRA wastewater discharge. Fortunately, dissolved oxygen concentrations did not reach extremely low hypoxic levels, and marine life was not noticeably affected. The bloom ended quickly during the summer and did not recur in 2024.

Seafloor communities remain healthy and diverse

MWRA's monitoring of the sediments and animals at the sea floor has shown that bottom-dwelling communities are influenced by sediment types and water depth rather than by the effluent discharge. The total abundance of animals, numbers of species, and the species makeup of bottom-dwelling communities have remained within the ranges of natural variability. Even the outfall diffusers provide habitat to bottom-dwelling animal communities (Figure iii).

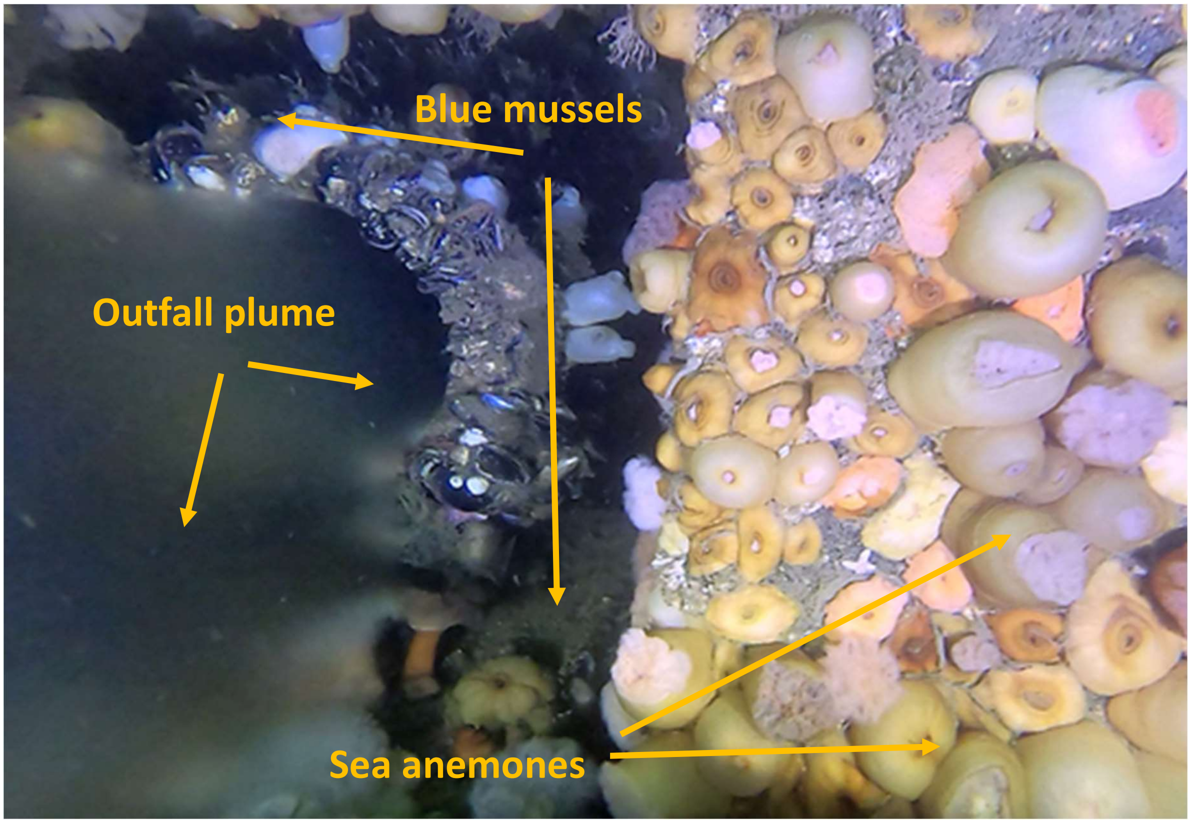

Figure iii. Blue mussels and sea anemones growing on an active outfall diffuser in 2023. Robust communities continue to thrive near the Massachusetts Bay outfall.

Flounder have low rates of liver disease and are cancer-free

Winter flounder, popular commercial and recreational fish that live and feed at the sea floor, are susceptible to contaminant-related physical abnormalities and health risks, such as fin disease, ulcers, and liver conditions. Flounder health has improved both near the outfall and at the former sewage effluent outfall in Boston Harbor (Figure iv), a result of pollution prevention and sewage treatment. Cancerous tumors have never been found in fish taken from near the Massachusetts Bay outfall.

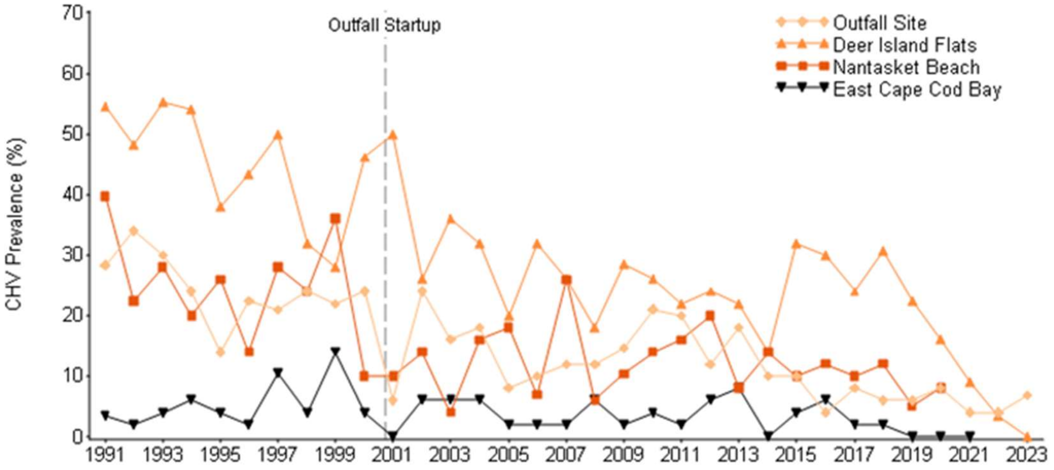

Figure iv. Winter flounder tumor precursors, 1991–2023. Incidence of the tumor precursor CHV has declined throughout the region. Only the outfall site and Deer Island Flats in Boston Harbor were sampled in 2023. Nantasket Beach and East Cape Cod Bay provided additional geographic coverage in previous years. CHV = centrotubular hydropic vacuolation, a key tumor precursor and mild liver condition associated with exposure to pollutants.

Stellwagen Bank Marine Sanctuary remains healthy

MWRA’s permit requires an assessment of monitoring results relevant to the Stellwagen Bank National Marine Sanctuary, about 2000 protected square kilometers, located offshore from the outfall. The Sanctuary’s nearest boundary is about 20 kilometers to the east of the outfall. Stellwagen Bank supports rich recreational and commercial fisheries and is a major feeding ground for whales. There have been no measurable effects of the MWRA outfall discharge on the sanctuary’s water column or sea floor.

The 2023 bottom-water dissolved oxygen concentrations in Stellwagen Basin reached unusually low levels, a result of the wide-spread *Tripos muelleri* phytoplankton bloom and changing physical conditions throughout the region. No environmental harm was observed.

Environmental conditions are changing throughout the region

While MWRA has not found any unexpected or harmful effects of its outfall on marine life, the more than 30 years of monitoring have detected changes. Waters are warmer than they used to be (Figure v), and changes in wind speeds and directions have altered the flow of ocean water into Massachusetts Bay. These physical changes affect summertime dissolved oxygen levels and the biology and ecology of the region. Other scientists and government agencies throughout New England have detected similar changes. MWRA is paying close attention to their own measurements and results reported by other research organizations throughout New England and the Gulf of Maine to better understand regional changes and how they might interact with the outfall in the future.

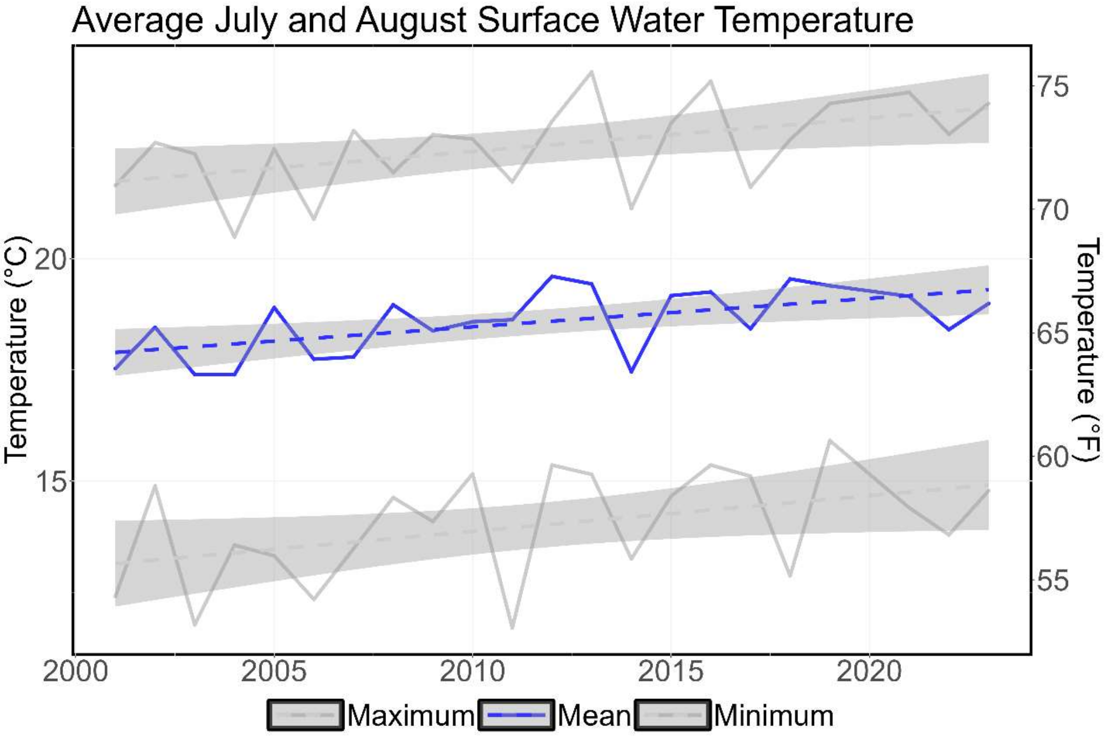

Figure v. Increases in summertime surface-water temperatures in Massachusetts Bay, 2001-2023. Maximum, mean, and minimum values recorded at an instrumented buoy off Cape Ann at the northern limit of the bay.

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1. Introduction

Since 1984, the Massachusetts Water Resources Authority (MWRA) has worked to minimize adverse effects of municipal wastewater on the marine environment through a vigorous pretreatment program, a carefully maintained treatment plant, and vigilant effluent and environmental monitoring. One of the most important milestones in the well-known Boston Harbor Project occurred in September 2000, when the MWRA Deer Island Treatment Plant wastewater effluent discharge was diverted from the shallow, enclosed waters of Boston Harbor to deeper, more open waters in Massachusetts Bay. Since then, the Massachusetts Bay outfall has operated under a National Pollutant Discharge Elimination System (NPDES) permit, jointly issued by the U.S. Environmental Protection Agency (EPA) and the Massachusetts Department of Environmental Protection. An independent Outfall Monitoring Science Advisory Panel has assisted EPA in addressing scientific questions about potential environmental effects of the outfall on Massachusetts Bay.

The NPDES permit requires MWRA to measure effluent quality before discharge and to monitor the seawater, sea floor, and marine life in Massachusetts Bay. A Contingency Plan attached to the permit requires comparing measured conditions against “caution” and “warning” thresholds, developed from state standards and baseline monitoring data. If a caution threshold is exceeded, MWRA must investigate the issue. A warning threshold is a higher level of concern and could require both investigation and a responsive action. Background information about the monitoring program (Werme et al. 2012), the most current monitoring plan (MWRA 2021) and Contingency Plan (MWRA 2001), past plans and overviews, and study-specific technical reports are available on MWRA’s Technical Reports List at www.mwra.com/our-environment/water-quality-reports.

This 2023 Outfall Monitoring Overview fulfills a requirement of the NPDES permit, which stipulates that MWRA produce an annual summary of monitoring results for Massachusetts Bay, including results relevant to the Stellwagen Bank National Marine Sanctuary; the sanctuary’s western boundary is about 20 kilometers offshore from the MWRA outfall.

This overview also discusses special topics selected in response to permit conditions and environmental concerns, often including research completed in cooperation with other agencies and research organizations. This year’s special topics section includes a discussion of changing environmental conditions throughout the broader region of Massachusetts Bay and the Gulf of Maine and a report on a large bloom of a marine phytoplankton species, *Tripos muelleri*, which occurred throughout the region during the summer of 2023. The bloom extended well beyond any possible influence of the MWRA outfall but led to several Contingency Plan threshold exceedances.

2. Effluent

Effective wastewater treatment protects Massachusetts Bay.
MWRA's industrial pretreatment program and its primary and secondary sewage treatment minimize the contaminants discharged into Massachusetts Bay. In 2023, the effluent met all permit and Contingency Plan limits.

MWRA's NPDES permit and Contingency Plan set limits on effluent parameters and pollutants. Contaminants of concern include **pathogens, suspended solids, organic material, nutrients, and toxic contaminants**. Because wastewater entering Deer Island Treatment Plant includes not only municipal sewage but also groundwater infiltration and stormwater inflow, rainfall is an important factor in determining annual wastewater flows and contaminant concentrations in the treated effluent. The Boston area received 50 inches of rain in 2023, more than the 1990–2023 average of 44 inches (Figure 2-1).

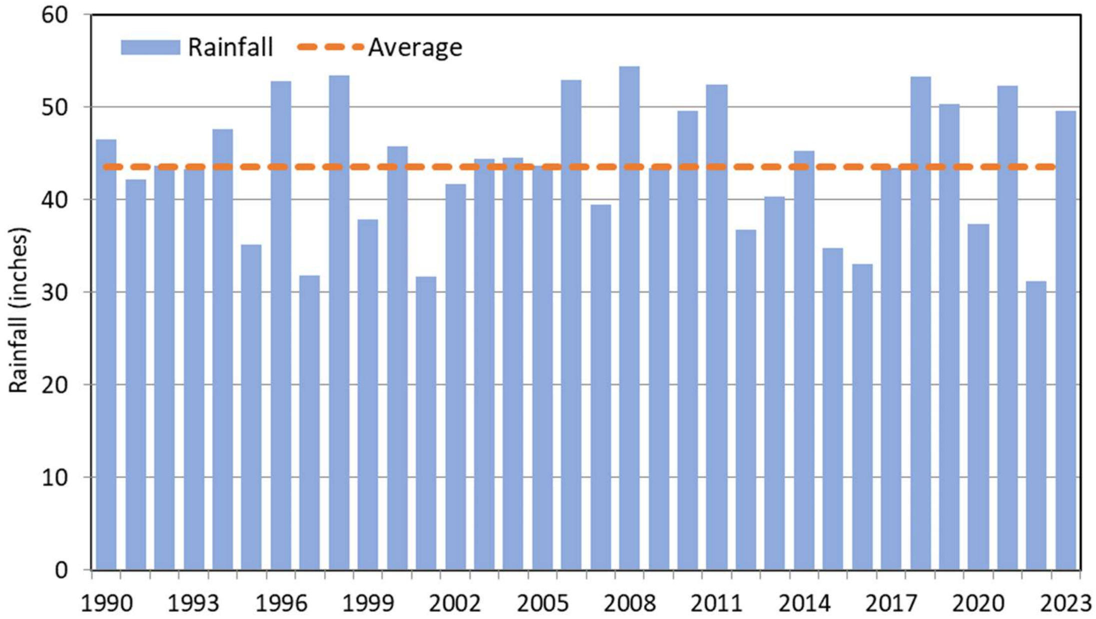

Figure 2-1. Annual and average rainfall in Boston, 1990–2023. Boston received almost 50 inches of rain in 2023. Data are from the National Weather Service rain gauge at Boston Logan International Airport.

Deer Island Treatment Plant continued to meet permit conditions through 2023, marking 17 consecutive years of 100% compliance with permit limits and earning MWRA a National Association of Clean Water Agencies Platinum Peak Performance Award. MWRA's compliance report for Fiscal Year 2023 summarizes data from July 2022 through June 2023 (Davis 2023); this Outfall Monitoring Overview reports on data for January through December 2023.

2023 Effluent Characterization

The high rainfall in 2023 led to an annual effluent flow comparable to other recent wet years (Figure 2-2). Flow averaged 337 million gallons per day, just slightly higher than the average 327 million gallons per day since 1999. As in past years, almost all effluent in 2023 received full secondary treatment, with less than 1% of the total flow consisting of primary-only treated effluent blended into secondary-treated effluent prior to disinfection and discharge (Figure 2-3).

Flow refers to the rate at which wastewater travels through the treatment plant. It may refer to flow entering the plant (influent), but often refers to outflow from the plant (effluent). Once effluent is released to the environment, it is often called the **discharge**.

Primary treatment uses physical process to remove solid material through settling. Secondary treatment adds biological processes that remove most of the remaining organic material and toxic pollutants. Blending occurs during intense rainfall, when flow to the treatment plant exceeds what the secondary treatment process is designed to handle. Diverting some flow around the secondary treatment process prevents street flooding and water backups into homes and businesses. It also protects the secondary treatment system, preventing washout of the beneficial bacteria that are a critical part of the process. Massachusetts regulations require MWRA to notify regulators and the public whenever a blending event occurs. Historically, blended flows have fully met permit limits.

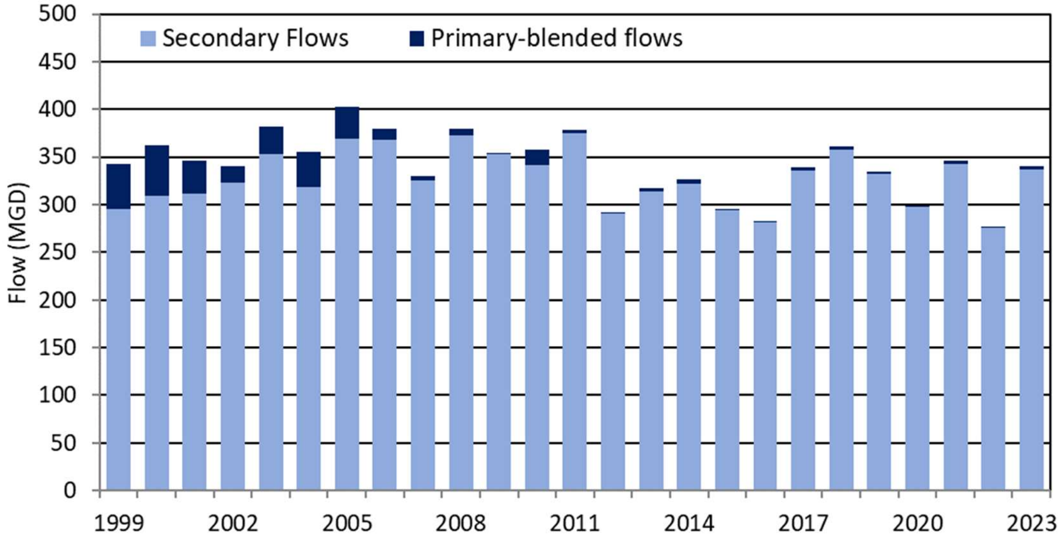

Figure 2-2. Annual full secondary-treated effluent flows and primary-blended flows, 1999–2023. During large storms, flow exceeding the secondary capacity of the plant is diverted around the secondary process; this primary-treated flow is blended with the fully treated flow before disinfection and discharge. Historically, blended flows have been minimal and met all permit limits. MGD = million gallons per day.

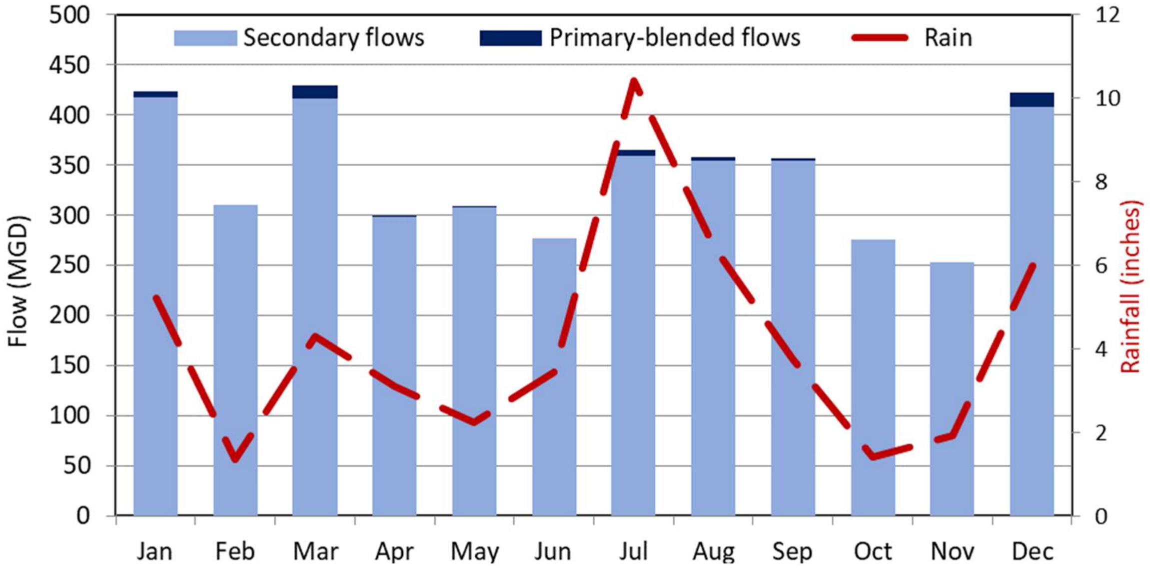

Figure 2-3. Monthly full secondary-treated and primary-blended flows (bars) and rainfall (dashed line) in 2023. Months with primary-blended flows corresponded with months of greater rainfall and snow melt. MGD = million gallons per day.

Most solid material is removed from sewage influent as sludge, and the remaining particles are called total suspended solids. In 2023, about 16 metric tons of total suspended solids were discharged per day, only slightly more than in 2022, despite much higher flow (Figure 2-4). Over the past two decades, the total solids discharges have been only about 10% of what had been discharged to the harbor in 1990–1991.

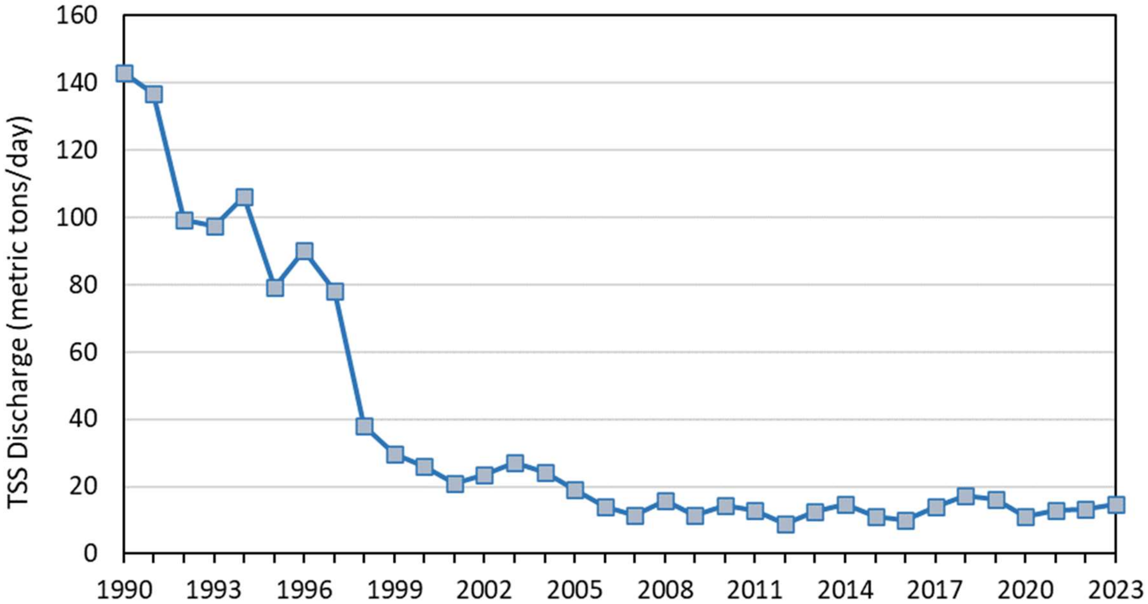

Figure 2-4. Average annual daily discharges of sewage solids, 1990–2023. Solids discharges have remained low. TSS = total suspended solids.

Organic material in effluent consumes oxygen as it decays. Biochemical oxygen demand (BOD), a measure of the amount of oxygen needed to decompose organic material, remained well below levels that would be expected to affect dissolved oxygen in the environment in 2023. MWRA has consistently met its BOD permit limit.

Organic material, a major constituent of untreated sewage that consumes oxygen as it decays, remains at safe levels.

MWRA monitors the effluent for fecal coliform bacteria, one indicator of a variety of pathogens that can make shellfish unhealthy for human consumption. Fecal coliform bacteria levels in the effluent have always been well below permit limits. MWRA also monitors fecal coliform bacteria in Massachusetts Bay, and results at all locations, even those closest to the outfall, meet the stringent shellfishing standards set by the state.

Pathogens include disease-causing bacteria, viruses, and protozoa, and are found in human and animal waste. Effluent bacteria levels continue to meet permit limits.

Nutrients control algal growth and, in excess, can lead to lower oxygen concentrations or stimulate nuisance algal blooms.

MWRA's permit requires reporting on nutrients, toxic metals, and organic compounds. Nutrient measurements include individual components of total nitrogen (ammonium, nitrate, and nitrite). Toxic metals with reporting requirements include zinc, copper, lead, nickel, silver, and mercury. Organic compounds include selected pesticides and polychlorinated biphenyls (PCBs).

The Contingency Plan attached to MWRA's permit includes thresholds for nitrogen discharges. The total nitrogen load for 2023 was 12,103 metric tons, below the Contingency Plan caution threshold of 12,500 metric tons per year (Figure 2-5). This threshold was set conservatively at about 90% of the warning threshold, 14,000 metric tons, which was the amount expected to be discharged annually by 2020, based on population growth projections for the MWRA service area made in the 1990s. Actual population growth has been somewhat higher than projected, but nitrogen loads have remained well below that anticipated amount, a result of water conservation, better controls on groundwater infiltration, and good removal efficiencies during treatment. The caution threshold was exceeded once, in 2019, when the population size of the MWRA service area was about 6% greater than had been predicted for 2020. However, modeling has suggested that nitrogen loads even higher than the more stringent warning threshold would not harm the environment (Deltares 2022). MWRA updates a report on potential nitrogen-removal strategies annually (Davis et al. 2024).

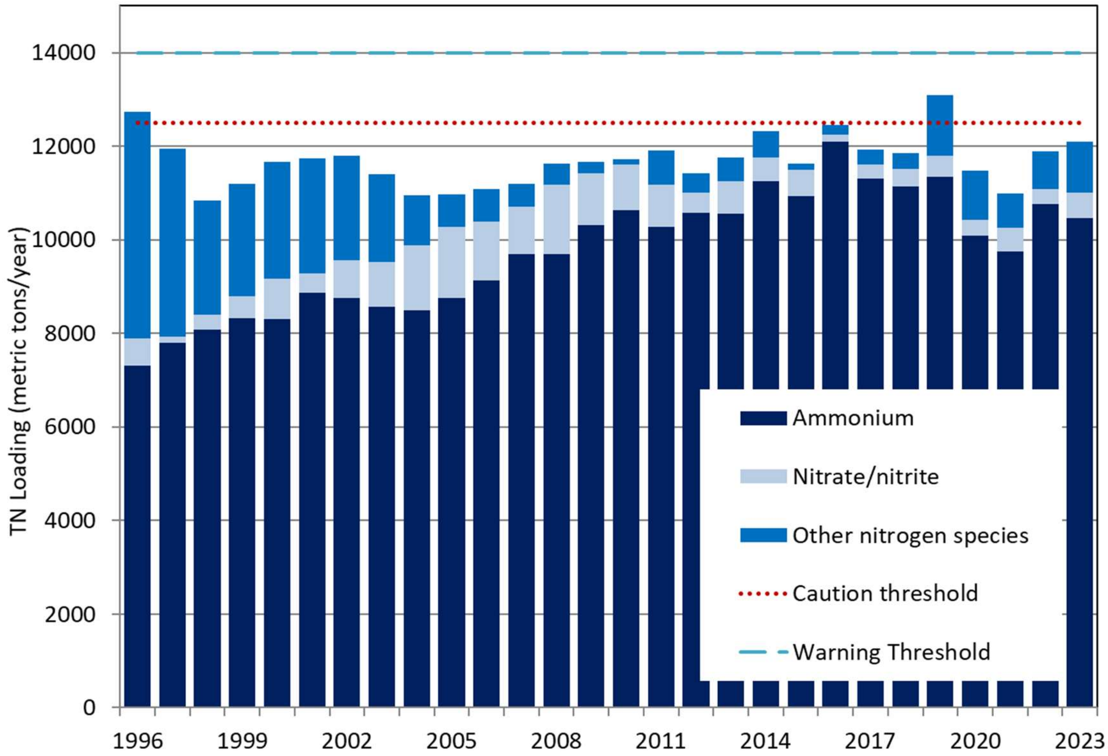

Figure 2-5. Annual nitrogen discharges, 1996–2023. The warning threshold, 14,000 metric tons per year, was set as the load anticipated for 2020; the caution threshold was set at 90% of the warning threshold. Actual loads have remained lower than anticipated. TN = total nitrogen.

Ammonium is the form of nitrogen most readily taken up by phytoplankton and a good effluent tracer. During the late 1990s and early 2000s, ammonium discharges became a larger component of the total nitrogen loading, likely a result of the evolving treatment processes for both sewage sludge and effluent. Those increases have plateaued in more recent years.

Metals discharges remained low in 2023 (Figure 2-6). Zinc continued to be the most abundant metal, followed by copper. Both are present in water pipes and fixtures. Other notable sources of zinc to wastewater include hair salons, automobile-repair shops, and hospitals; residential household products, such as shampoos, ointments, and laundry detergent; and street runoff (MWRA, unpublished data).

Toxic contaminants in the effluent include heavy metals, such as copper and lead, and organic compounds, including some now-banned pesticides and polychlorinated biphenyls (PCBs).

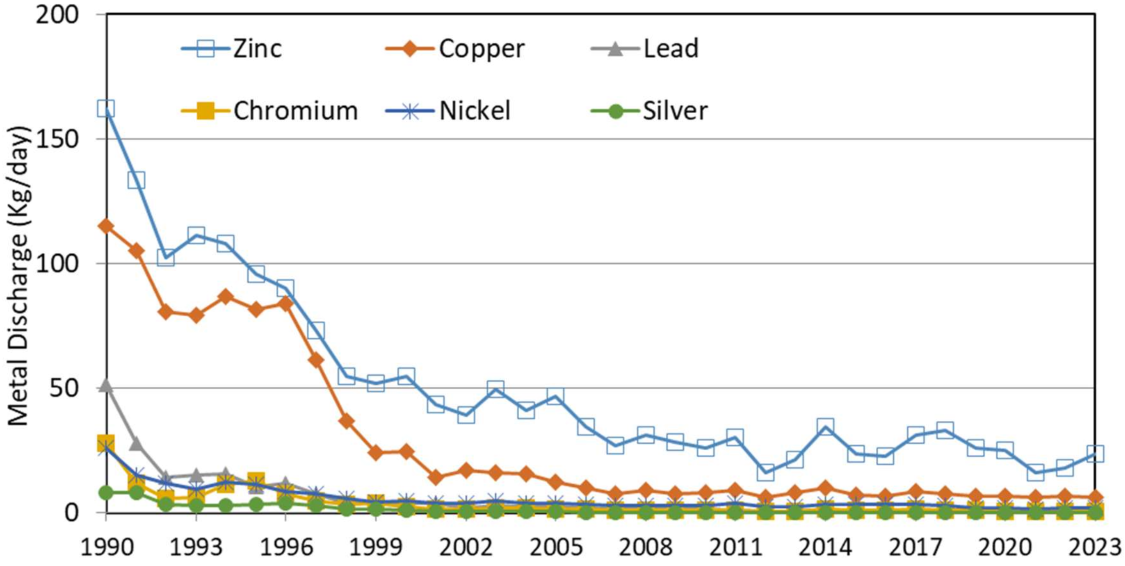

Figure 2-6. Annual metals discharges, 1990–2023. Zinc and copper from water pipes and fixtures remain the most abundant metals. Source reduction, industrial pretreatment, and secondary treatment have dramatically decreased metals loads in the effluent. Kg = kilogram.

Total loads of all metals remained small percentages of what had been anticipated during planning for the Massachusetts Bay outfall. Copper discharges remained less than 20% of what had been predicted would be discharged in 2020, and all other metals discharges were less than 10% of the predictions (summarized in Werme et al. 2021). Except for copper, all metals meet water quality standards even prior to discharge. Initial dilution (the amount of mixing within a strictly defined area near the outfall) further reduces concentrations. Copper discharges, which meet the standard after initial dilution, have declined over time, a result of drinking-water corrosion control, which decreases leaching from water pipes. Removing lead from pipes and service lines has significantly reduced lead levels in the effluent discharge.

Mercury discharges were only 1% of what had been anticipated during planning for the outfall, a result of source-reduction efforts in dental and medical facilities. Silver, once considered an effluent tracer, is now often at levels below detection limits, due to the decline in film-based photography, as well as efficient removal by secondary treatment.

Discharges of organic contaminants have varied slightly from year to year but have been well below loads historically discharged into Boston Harbor. Annual polycyclic aromatic hydrocarbons (PAH) discharges, for example, were the lowest ever measured in 2023, less than 2% of the 3,000 kilograms of PAHs estimated to have been discharged in wastewater effluent into Boston Harbor in 1991 (Rex et al. 1992). PAH concentrations now meet water quality standards at discharge. Effluent data for some other organic compounds, such as 4,4’-DDE, one of the most prevalent breakdown products of the pesticide DDT, show evidence of the very slow declines anticipated in the 1970s, when PCBs and chlorinated pesticides were banned.

Effluent Contingency Plan Thresholds

There were no effluent Contingency Plan exceedances in 2023 (Table 2-1). Exceedances of effluent permit limits have been rare, and none have occurred since 2006. The total nitrogen thresholds, set in the Contingency Plan attached to the permit, were also not exceeded in 2023. Similar to other effluent constituents, total nitrogen discharges have been less than were expected during planning for the treatment plant and the outfall.

Table 2-1. Contingency Plan threshold values and 2023 results for effluent monitoring.

Parameter	Baseline	Caution Level	Warning Level	2023 Results
Permit Condition and Contingency Plan Thresholds				
pH	NA	NA	<6 or >9	Not exceeded
Fecal coliform	NA	NA	>14,000 fecal coliforms/100 mL	Not exceeded
Chlorine, residual	NA	NA	>631 µg/L daily, >456 µg/L monthly	Not exceeded
Suspended solids	NA	NA	>45 mg/L weekly >30 mg/L monthly	Not exceeded
cBOD	NA	NA	>40 mg/L weekly, >25 mg/L monthly	Not exceeded
Acute toxicity	NA	NA	LC50 <50%	Not exceeded
Chronic toxicity	NA	NA	NOEC <1.5% effluent	Not exceeded
PCBs	NA	Aroclor>0.045 ng/L	NA	Not exceeded
Plant performance	NA	5 violations/year	Compliance <95% of the time	100% compliance
Flow	NA	NA	>436 MGD average dry days	Not exceeded
Oil and grease	NA	NA	>15 mg/L weekly	Not exceeded
Contingency Plan Thresholds				
Total nitrogen load	NA	>12,500 mtons/year	>14,000 mtons/year	12,103 mtons

NA = not applicable
cBOD = carbonaceous biological oxygen demand
LC50 = 50% mortality concentration
NOEC = no observable effect concentration
PCB = polychlorinated biphenyl
Aroclor = total for a specified suite of PCB compounds (called Aroclors)
Plant performance = compliance with permit conditions
mL = milliliter
µg/L = micrograms per liter
mg/L = milligrams per liter
ng/L = nanograms per liter
MGD = million gallons per day
mtons = metric tons

3. Water Column

Water-column monitoring focuses on potential eutrophication.
For many parameters, 2023 was a typical year in the water column, following well-established seasonal patterns. However, a large regional bloom of the phytoplankton species *Tripos muelleri* resulted in widespread high summer chlorophyll concentrations and low dissolved oxygen levels.

MWRA's water-column monitoring program measures and evaluates **physical oceanographic conditions, water quality, and phytoplankton and zooplankton communities** at stations in Massachusetts Bay, at the mouth of Boston Harbor, and in Cape Cod Bay. Ship-based field surveys are augmented by data from instrumented buoys and satellite imagery. Organic material, pathogens, and toxic contaminants are largely removed in wastewater treatment, so are mostly undetectable in the water, and unlikely to have any harmful effects. Therefore, water-column monitoring focuses mainly on potential effects of excess nutrients, which are less completely removed by treatment.

Eutrophication occurs when nutrients overstimulate phytoplankton growth, leading to lower levels of oxygen when the phytoplankton die and decompose.

Excess nutrients can cause eutrophication or promote growth of nuisance or toxic algal blooms. One nuisance, but not toxic, phytoplankton species, *Phaeocystis pouchetii*, was a focus in past years, but its presence and abundance have been shown to vary in response to physical oceanographic conditions rather than the outfall, and it is no longer a focus of the monitoring program. Potentially toxic species include *Alexandrium catenella*, which occurs regularly in Massachusetts Bay, and *Pseudo-nitzschia*, a species group that is often present, but usually in low numbers and in its nontoxic forms.

Each monitoring year includes nine ship-based surveys, completed monthly between February and October. Five stations are in the "nearfield," a 12×10-kilometer area centered on the outfall, where some effects of the effluent were expected and have been observed. Nine stations are in the more distant "farfield," including the mouth of Boston Harbor, Cape Cod Bay, and near Stellwagen Bank National Marine Sanctuary (Figure 3-1). Nearfield Station N18, located just to the south of the outfall, is often considered representative of the nearfield, as it has been consistently monitored over time and would be likely to show any effects, should they occur.

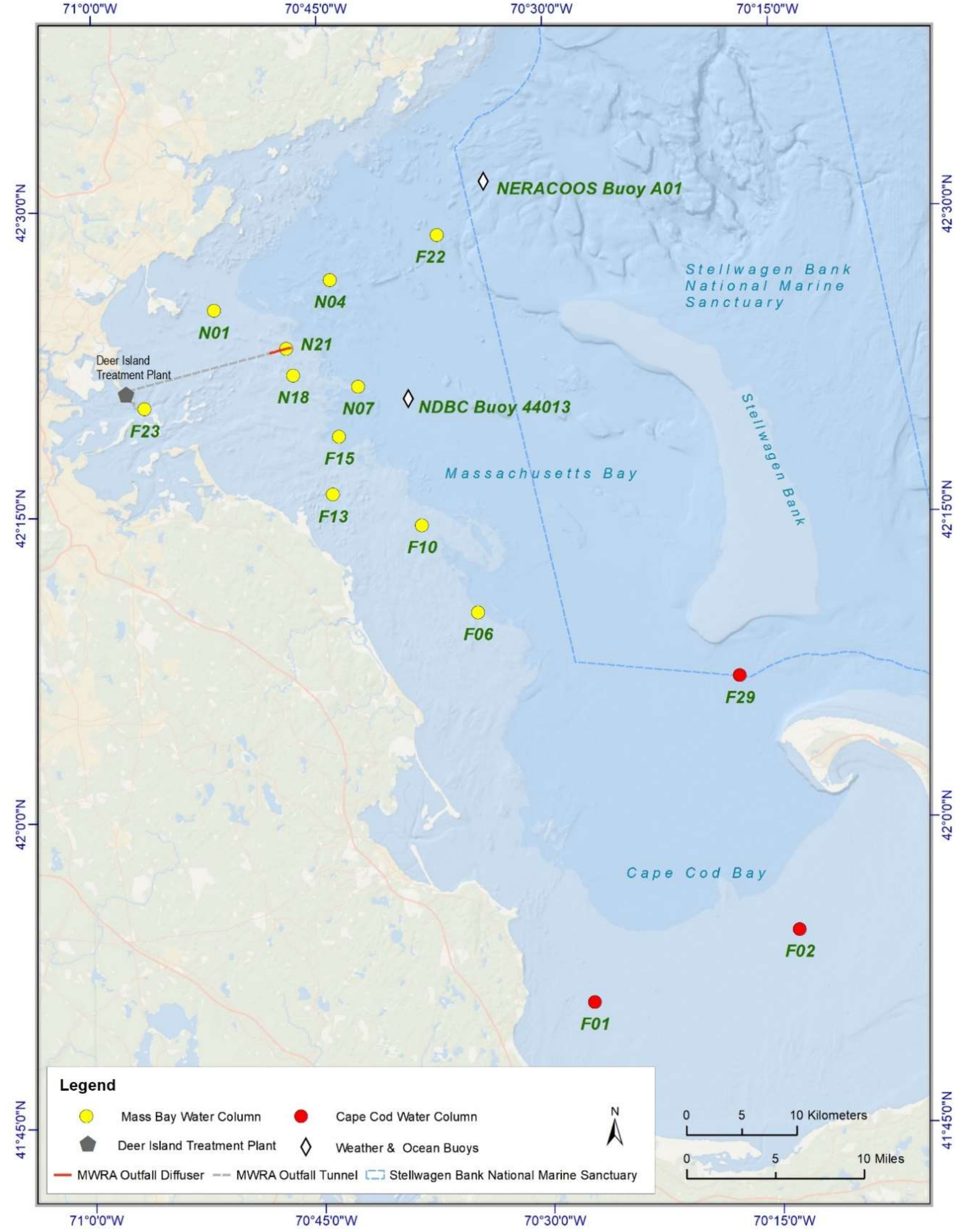

Figure 3-1. Water-column monitoring stations and instrumented buoys in Massachusetts and Cape Cod Bays. Data are obtained from surveys, the NERACOOS A01 and NDBC 44013 buoys, and satellite imagery. Also shown are the outfall and the Stellwagen Bank National Marine Sanctuary. Nearfield stations include a designation N, while farfield stations include a designation F. NERACOOS = Northeastern Regional Association of Coastal Ocean Observing Systems; NDBC = National Data Buoy Center.

Additional surveys may be triggered by elevated abundance of the potentially toxic phytoplankton species *Alexandrium catenella*. These "*Alexandrium* Rapid-Response Study" surveys (Libby et al. 2013) provide in situ hydrographic data and water samples for measuring nutrients and *Alexandrium catenella* abundance at up to 19 stations. No additional surveys were necessary in 2023.

The monitoring program benefits from collaboration with the Center for Coastal Studies in Provincetown, Massachusetts, which samples the three stations in Cape Cod Bay and near Stellwagen Bank National Marine Sanctuary (Figure 3-1, red points). In 2023, all sampling by MWRA and the Center for Coastal Studies occurred within 48-hour windows.

Surveys are supplemented by measurements at two instrumented buoys: the Northeastern Regional Association of Coastal and Ocean Observing Systems (NERACOOS) Buoy A01 off Cape Ann at the northern limit of Massachusetts Bay, and the National Oceanic and Atmospheric Administration (NOAA) National Data Buoy Center (NDBC) Buoy 44013 in central Massachusetts Bay (Figure 3-1, white diamonds). The National Aeronautics and Space Administration provides Moderate Resolution Imaging Spectroradiometer satellite imagery of chlorophyll fluorescence, a measure of phytoplankton biomass.

Physical Conditions

Circulation and physical properties in Massachusetts Bay are driven by the larger patterns of water flow in the Gulf of Maine. Water typically enters Massachusetts Bay from the north, circulates in a counter-clockwise direction, and exits by Race Point, at the tip of Cape Cod. Consequently, Station F22, to the north and east of the outfall, is considered a reference station for water entering the bay, while stations to the south of the outfall are more likely to have detectable outfall influences. Water flows vary from week-to-week and depend on the strength of the current and on wind speed and direction. The coastal current is strongest during spring runoff from rivers and streams.

Stratification separates warm, surface water from colder, denser bottom water. The boundary between layers is called the thermocline or pycnocline.

As in other temperate waters, there are seasonal patterns to the physical structure of the water column, extending from the surface to the sea floor. In the winter, the water column is well mixed, and dissolved oxygen levels are high throughout the water column. Warm water is less dense than cold water, so as surface waters warm, the water column stratifies, effectively separating surface from bottom waters. Bottom waters become isolated from the atmosphere and oxygen production by phytoplankton, which leads to lowered bottom-water dissolved oxygen levels in late summer and fall. In the fall, cooling surface waters and strong winds promote mixing, ending the stratified season and re-oxygenating bottom waters.

Stratification is also affected by rainfall and river flow to Massachusetts Bay. Inputs of freshwater, which is lighter than seawater, contribute to stronger stratification. The Merrimack River, which enters the Gulf of Maine just to the north of Massachusetts Bay, is the largest river in the region and plays an important role in freshwater delivery to Massachusetts Bay. River flow from the smaller Charles, Mystic, and Neponsit Rivers into Boston Harbor also influence conditions in the bay.

Following a dry year in 2022, 2023 was relatively wet, particularly during the summer, when river flows are usually at their lowest (Libby et al. 2024). Flows from both the Merrimack and Charles Rivers were greater than average in the winter, summer, and fall (Figure 3-2), leading to lower-than-average surface salinities and promoting stronger stratification.

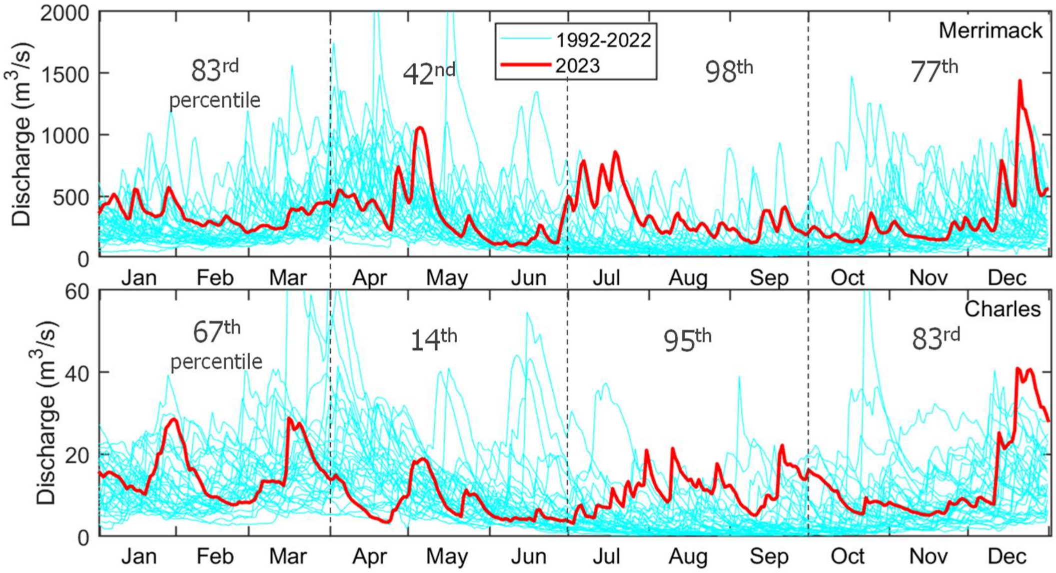

Figure 3-2. Discharges from the Merrimack (top) and Charles (bottom) Rivers. The Charles River flows into Boston Harbor and the much larger Merrimack River flows into the Gulf of Maine just south of the New Hampshire border. The quarterly percentiles represent the 2023 flows in comparison to the entire record. m^3/s = cubic meters per second.

Winter air temperatures measured at the NERACOOS A01 buoy at the northern boundary of Massachusetts Bay, were unusually warm in the winter of 2023. Winter water temperatures, measured at the NDBC 44013 buoy in the middle of the bay, were also warm, and those warm water temperatures persisted into the summer, with a brief cooling episode in August. The same temperature pattern was observed during MWRA surveys. Surface- and bottom-water temperatures were warmer than prior years during most survey months, for example, at Station N18 just south of the outfall (Figure 3-3, top two panels).

Surface- and bottom-water salinities at Station N18 reflected the high river discharges in 2023 (Figure 3-3, bottom panels). Low surface-water salinity was a major factor in establishing especially strong summer stratification throughout Massachusetts Bay (Figure 3-4).

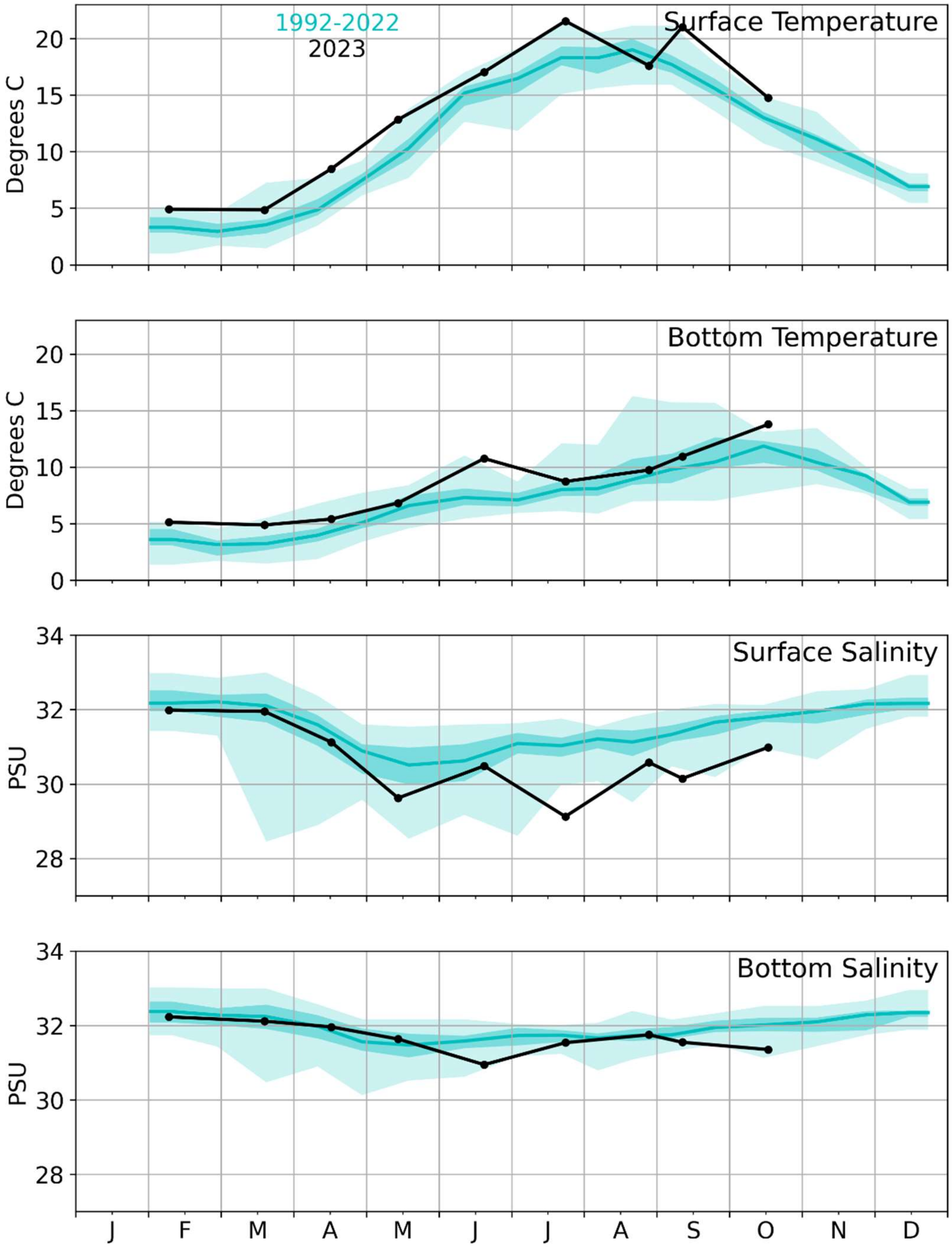

Figure 3-3. Surface- and bottom-water temperature and salinity at Station N18 just to the south of the outfall in 2023 compared to prior years. PSU = practical salinity units or parts per thousand.

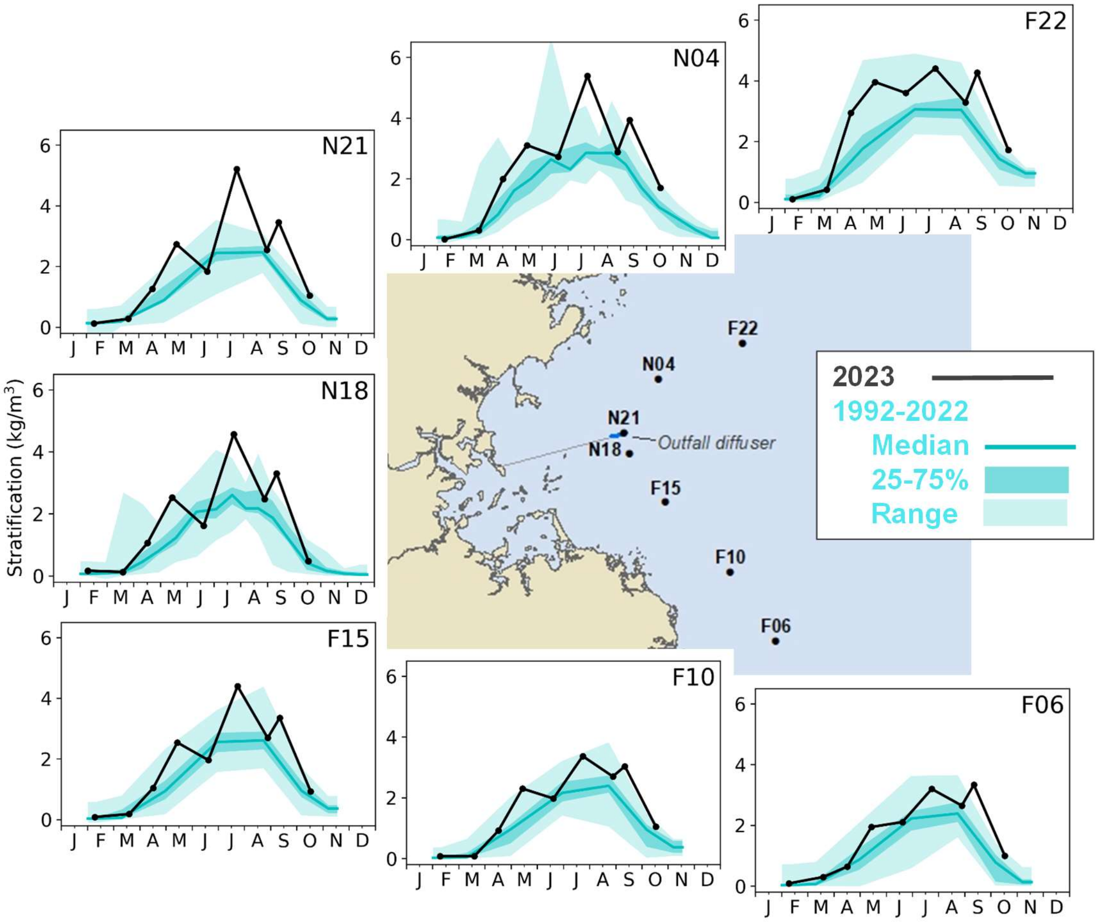

Figure 3-4. Stratification of the water column in 2023, compared to prior years. Greater stratification indicates greater separation between surface and bottom waters. Strong stratification developed early throughout Massachusetts Bay in 2023. kg/m^3 = kilograms per cubic meter.

Wind speeds and directions, which can exert large effects on conditions in the bay, were mostly typical through 2023. No storms produced high winds or large waves capable of resuspending and transporting bottom sediments, which occurs in some years. Winds from the south in July and August promoted upwelling of bottom water to the surface, temporarily disrupting stratification and cooling the surface waters.

Water Quality

Water quality measurements include quantification of **nutrients** (nitrogen, phosphorus, and silica), **phytoplankton biomass** (chlorophyll and particulate organic carbon), and **dissolved oxygen** (concentration and percent saturation). These measurements address the concern that excess nutrients from the effluent discharge could stimulate phytoplankton growth (increase biomass) and exacerbate the low bottom-water oxygen conditions that occur naturally in the late summer and fall.

Results for 2023 continued to confirm measurable outfall influence on some nutrient concentrations at stations near the outfall (Libby et al. 2024). Unlike previous years, plankton biomass reached unusually high levels throughout the bay in April until June, a result of the unprecedented bloom of the dinoflagellate *Tripos muelleri*. This bloom preceded unusually low summer dissolved oxygen levels throughout the bay.

Nutrients

The most important nutrients that fuel phytoplankton growth in Massachusetts Bay are two forms of nitrogen (nitrate and ammonium), phosphate, and silicate. Typical of temperate, coastal waters, nutrient concentrations follow seasonal patterns, naturally varying with phytoplankton uptake, seasonal stratification, water exchange with the Gulf of Maine, and river flow. Concentrations of some of the nutrients near the outfall followed the typical patterns in 2023, but there were also some variations (Figure 3-5), due to effluent inputs, physical conditions, and the *Tripos muelleri* bloom.

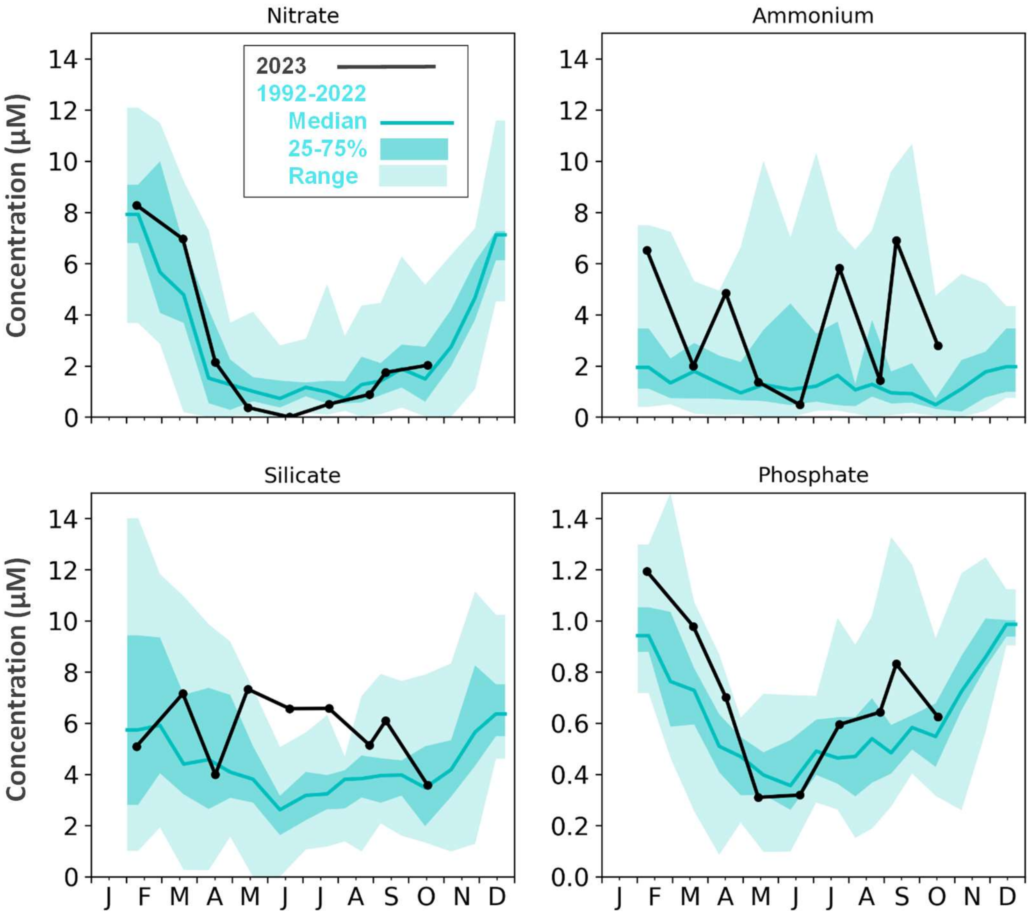

Figure 3-5. Seasonal trends of major water-column nutrient concentrations at Station N18 just to the south of the outfall in 2023 compared to prior years. μM = micromoles.

Following the typical coastal pattern, nitrate and phosphate concentrations were relatively high at the beginning of the survey season, and decreased through the spring, as phytoplankton production and biomass increased. These typical springtime declines were especially steep in 2023, and nitrate levels remained especially low or depleted from April through July.

Silicate concentrations generally follow similar though less pronounced seasonal patterns. In 2023, silicate concentrations were somewhat lower than most years at the start of the survey season, generally an indication that a winter diatom bloom has occurred prior to the February survey. Diatoms are phytoplankton that use silicate to build glass-like, shells, and the first MWRA surveys of the year often occur after the early blooms. Silicate concentrations were unusually high in May to July, with concentrations exceeding the historic maxima at many stations. This anomaly may have resulted from the high river runoff, a major source of silicate. Another factor could be the increasing presence of *Tripos muelleri*, which may have outcompeted diatom species. *Tripos* species are in a different phytoplankton group, dinoflagellates, and do not use silicate to produce exterior shells.

Ammonium concentrations have varied from the typical seasonal pattern at stations nearest the outfall since the discharge began. Ammonium is the largest fraction of the total nitrogen in wastewater (see Figure 2-5, page 6), and ambient concentrations are relatively low for most of the year, making it a good effluent tracer. Since the discharge was relocated from the harbor to the bay in late 2000, variable and elevated levels of ammonium have been detected at stations nearest and immediately to the south of the outfall, in the direction of the predominant currents (Figure 3-6).

Especially high ammonium concentrations at stations closest to the outfall are sometimes a result of a sample being taken directly in the effluent plume before it is completely mixed into the surrounding water. For example, for most of the year, ammonium levels were particularly high at Station N21, located at the outfall. However, during some surveys, ammonium levels were lower at Station N21 and higher at Station N18, just to the south of the outfall. These results indicate possible shifts in water flow, sometimes pushing the plume to the south as it mixes into the water.

Ammonium levels remained lower than the baseline concentrations at Station F23, at the mouth of Boston Harbor. Ammonium concentrations dropped precipitously at Station F23 and at all stations sampled as part of MWRA's separate Boston Harbor monitoring program as soon as effluent discharge in Boston Harbor ended and the Massachusetts Bay outfall discharge began.

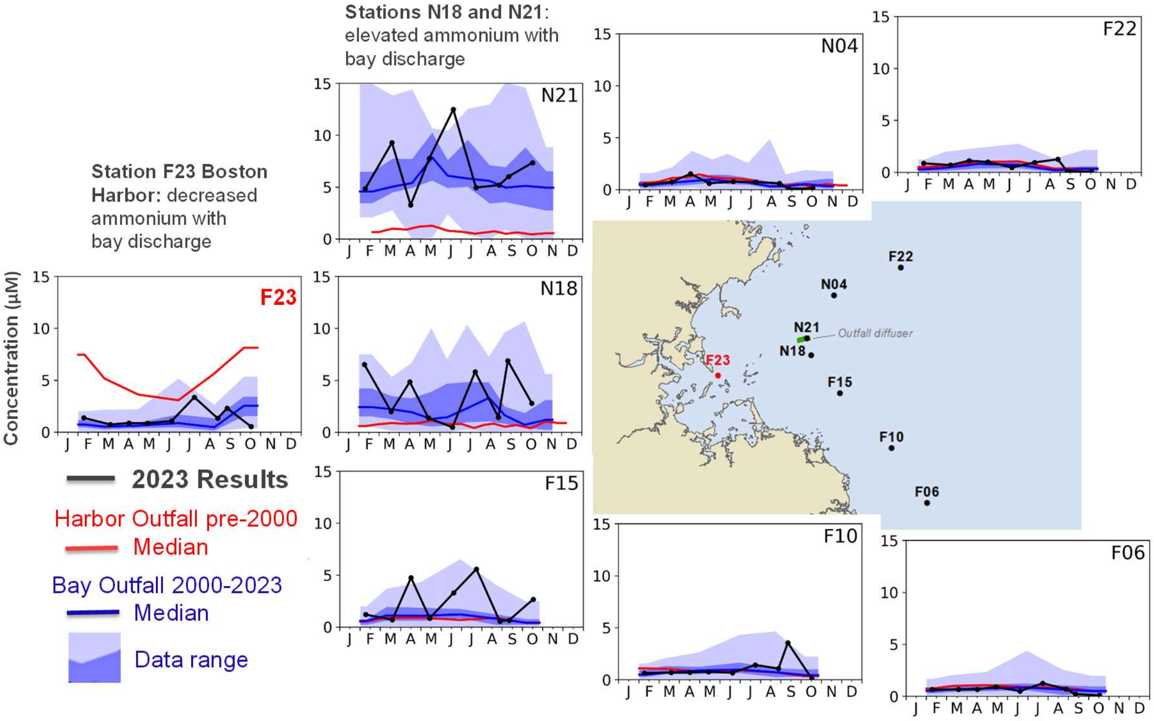

Figure 3-6. Ammonium concentrations at selected stations in 2023 compared to prior years. Increased and more variable concentrations of the sewage tracer ammonium are found at stations closest to the outfall, while stations further away have maintained concentrations similar to pre-outfall levels. Ammonium concentrations at Station F23 (red point) at the mouth of Boston Harbor decreased abruptly when discharge to Boston Harbor ended and have remained low. µM = micromoles.

As is typical, the effluent plume's ammonium signature was evident in surface waters at stations closest to the outfall during the winter surveys, when the water column was relatively well-mixed (Figure 3-7). During the summer, stratified season, the plume was confined beneath the pycnocline, below depths where maximum phytoplankton growth occurs. The plume could be detected as far as 20 kilometers from the outfall under both mixed and stratified conditions.

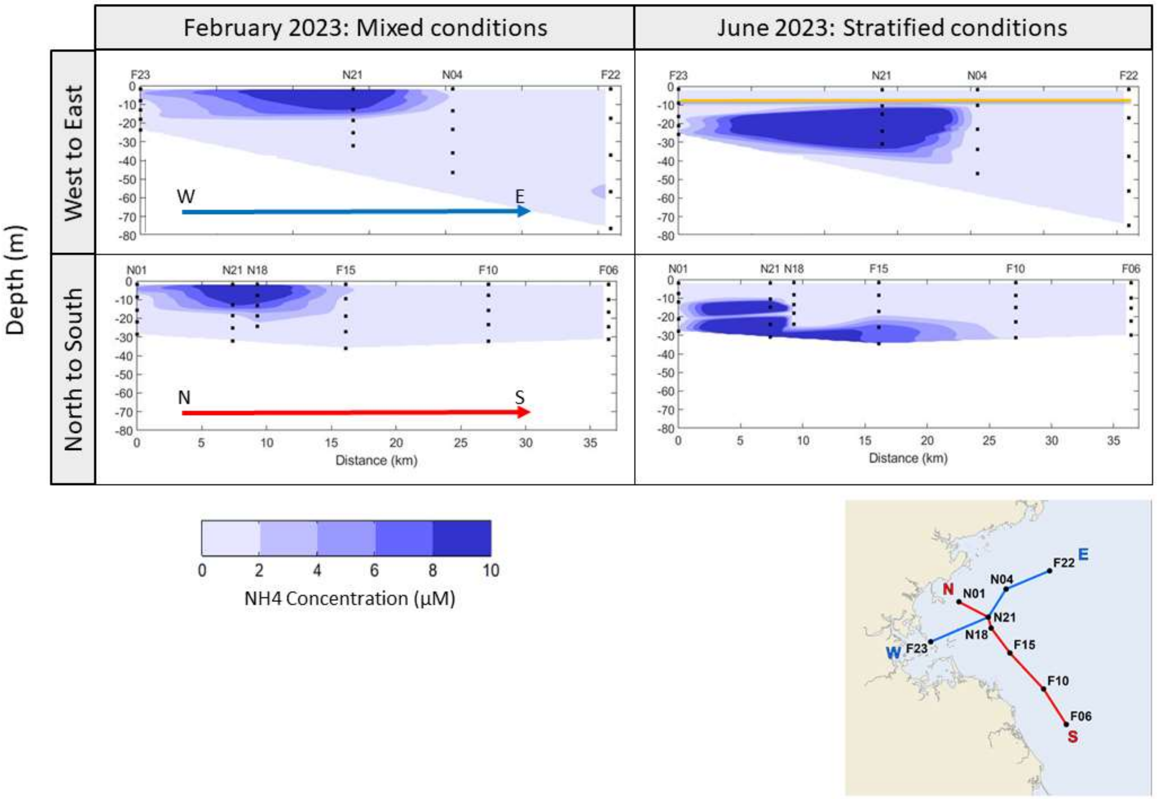

Figure 3-7. Surface- and bottom-water ammonium during mixed and stratified conditions. During winter, well-mixed conditions, the plume was evident in surface waters. The plume was confined below the pycnocline (yellow line), below the depth of most phytoplankton growth, during the summer. Station N21 is directly over the outfall. m = meters; µM = micromoles.

Phytoplankton Biomass

More than two decades of monitoring have shown that the localized ammonium concentration increases from the outfall have not stimulated phytoplankton growth or resulted in increased phytoplankton biomass at any station. Phytoplankton biomass in the water column is determined from chlorophyll concentrations and fluorescence and from particulate organic carbon levels. Unusually elevated chlorophyll concentrations were observed throughout the region in the late spring and early summer surveys, corresponding with the timing of the *Tripos muelleri* bloom (Figure 3-8). Particulate organic carbon concentrations were elevated during the same period. Both chlorophyll and particulate organic carbon concentrations dropped sharply from June to July and remained at or below long-term median levels throughout Massachusetts Bay for the rest of the survey season. Chlorophyll fluorescence data from satellite imagery and the NERACOOS Buoy A01 showed a similar pattern.

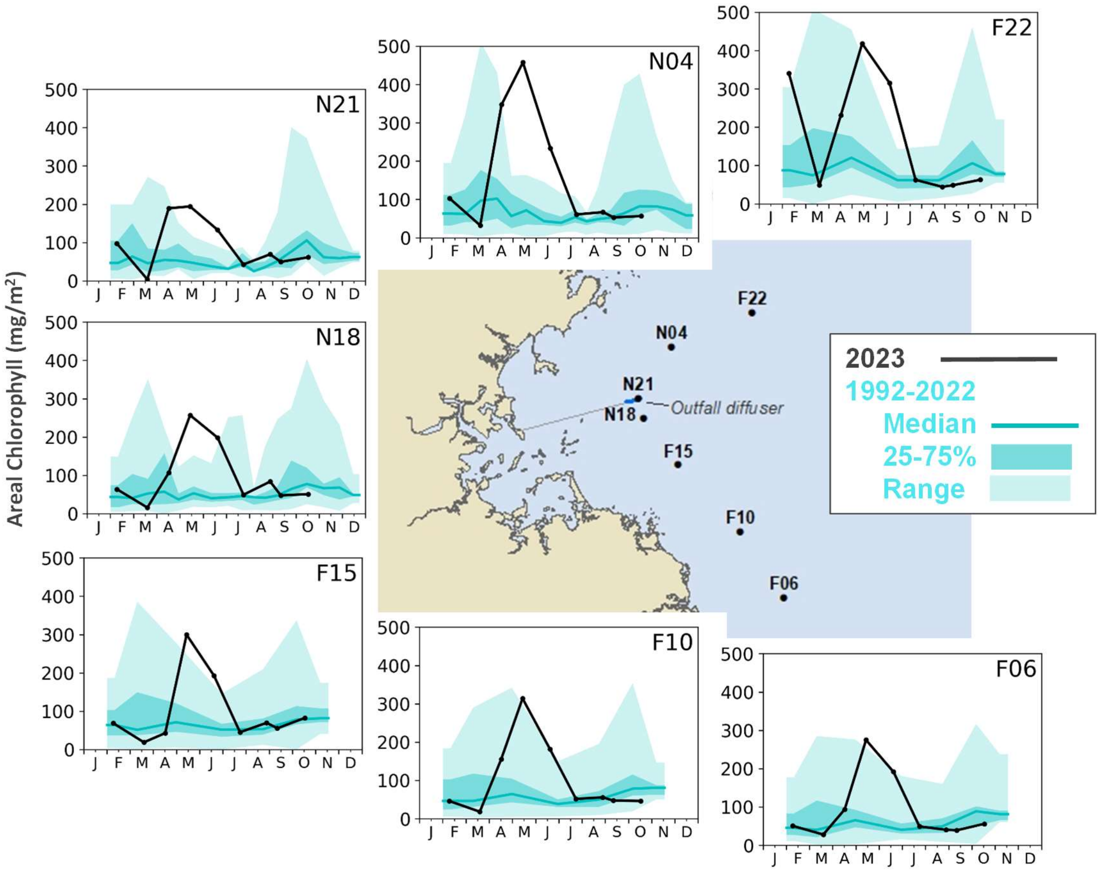

Figure 3-8. Monthly areal chlorophyll concentrations at selected stations in 2023 compared to prior years. Survey phytoplankton biomass is reported as vertically summed (areal) chlorophyll from measurements collected throughout the water column from the surface to the sea floor, rather than as an amount within a fixed volume. mg/m^2 = milligrams per square meter summed over depth.

Dissolved Oxygen

Typically, bottom-water dissolved oxygen levels (concentration and percent saturation) begin the year relatively high and steadily decline throughout the summer. Stratification prevents exchange between the atmosphere and bottom waters, so dissolved oxygen levels naturally decline at depth, as animals and microbes respire. Although that general pattern persisted in 2023, physical parameters (warm waters and strong stratification) and the *Tripos muelleri* phytoplankton bloom affected the timing and extent of the declines (Figure 3-9).

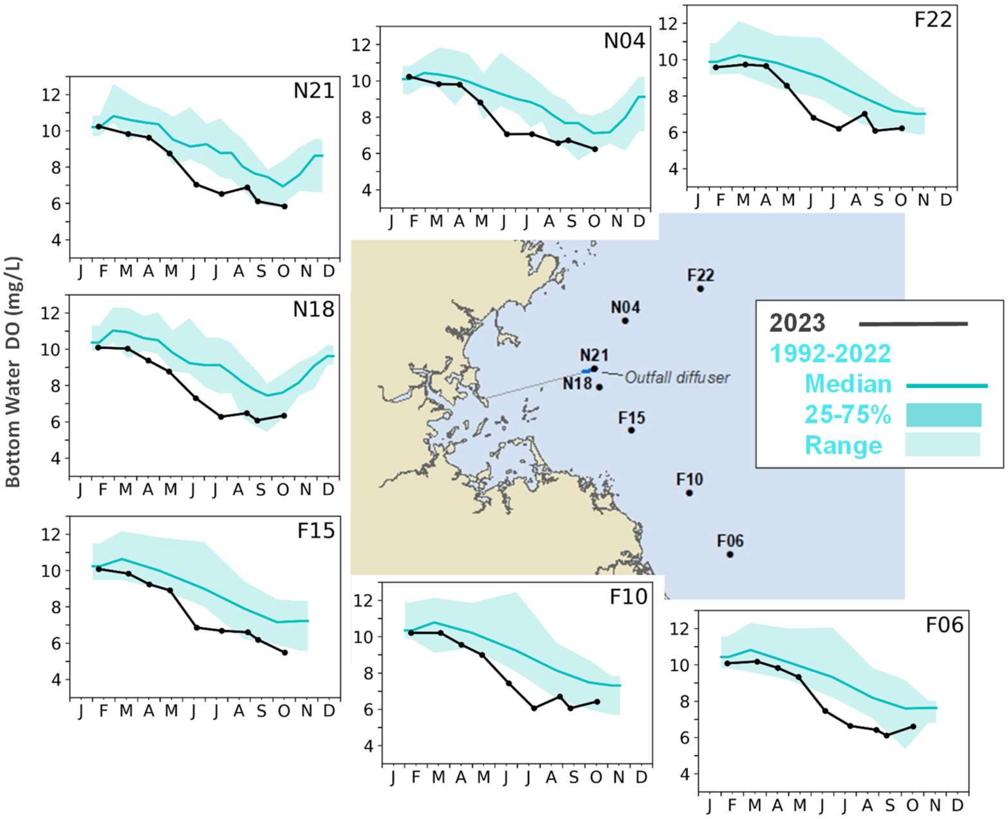

Figure 3-9. Near-bottom water dissolved oxygen concentrations in 2023 compared to prior years. DO = dissolved oxygen; mg/L = milligrams per liter.

Dissolved oxygen concentrations were already relatively low at the start of the survey season in February 2023. These early low levels can be attributed to unusually warm bottom waters (see Figure 3-3 on page 13). Physically, warmer water can dissolve less oxygen than cooler water; warmer water also promotes greater consumption of oxygen by bacteria and other marine organisms. From March to April, dissolved oxygen levels rose in surface waters, remaining high in May and June. During the same period, oxygen levels rapidly declined to well below historic minimums in bottom waters. These results were consistent with what would be predicted for a large phytoplankton bloom. Phytoplankton produce oxygen during photosynthesis, but oxygen is consumed when phytoplankton die and decompose in the water column and at the sea floor. The high chlorophyll and low dissolved oxygen levels observed in 2023 resulted in exceedances of several Contingency Plan thresholds (see page 28).

Plankton Communities

Marine plankton includes plants and animals that have limited mobility on their own and that move through the water with winds, tides, and currents. MWRA monitors **phytoplankton** and **zooplankton** abundance and species composition to detect any changes that might be associated with the outfall discharge (Cibik et al. 1998). A focus on potentially toxic or nuisance phytoplankton species addresses concerns for marine mammal and human health.

Massachusetts Bay phytoplankton includes small algae and other plant-like organisms, such as microflagellates, centric (rounded) and pennate (elongated) diatoms, and dinoflagellates (Figure 3-10). Microflagellates are extremely small and are typically the most abundant phytoplankton type in Massachusetts Bay. Centric and pennate diatoms have silica-rich cell walls and often dominate spring blooms.

Dinoflagellates have two perpendicular whip-like flagella, which propel them up and down in the water column. Dinoflagellates are grouped into the phytoplankton, because many of them photosynthesize. *Tripos muelleri*, the species responsible for the large 2023 phytoplankton bloom, is one common dinoflagellate in the bay. Another common dinoflagellate, *Alexandrium catenella*, often blooms in Massachusetts Bay and the wider Gulf of Maine region and is the species known in New England for causing “red tide.” Other geographic areas designate different species, usually other dinoflagellates, as causing red tides, and many types of phytoplankton can, when abundant, color the water column red or brown.

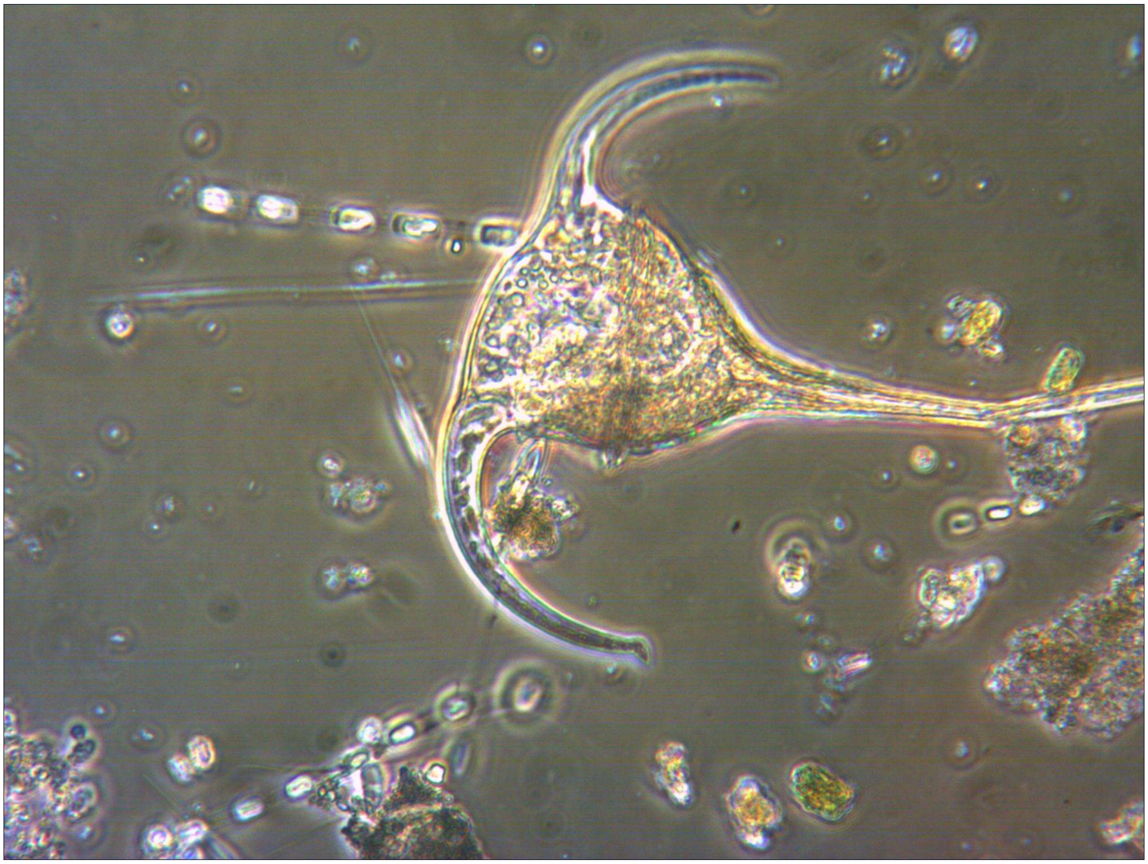

Figure 3-10. Typical phytoplankton from Massachusetts Bay. The long strings are diatoms, and the large, hooked organism is the dinoflagellate *Tripos muelleri*. The boxy diatom chains are species in the genus *Skeletonema*, and the very thin chain is a species of the diatom genus *Pseudo-nitzschia*. Photo credit David Borkman, Pausacaco Plankton, Saunderstown, Rhode Island.

Zooplankton communities in Massachusetts Bay include animal species that live their entire lives as plankton, particularly shrimp-like crustaceans called copepods, and those that live in the plankton for only a part of their life cycles, such as barnacle and clam larvae. Most species are small, but larger animals, including jellyfish, are also part of the zooplankton community. Zooplankton are food for many other species, including other zooplankton, fishes, and the endangered North Atlantic right whale. Zooplankton abundance and species composition are highly variable through the seasons and between years.

Phytoplankton Communities

Total phytoplankton abundance was at or near the long-term mean at most stations and during most surveys in 2023 (Figure 3-11; Libby et al. 2024). Microflagellates were abundant throughout the year. Microflagellates have consistently remained the most numerically abundant plankton group, and in 2023, they made up almost 80% of the phytoplankton community. The diatom species in the genus *Skeletonema* and the species *Asterionellopsis glacialis* were also abundant during the summer.

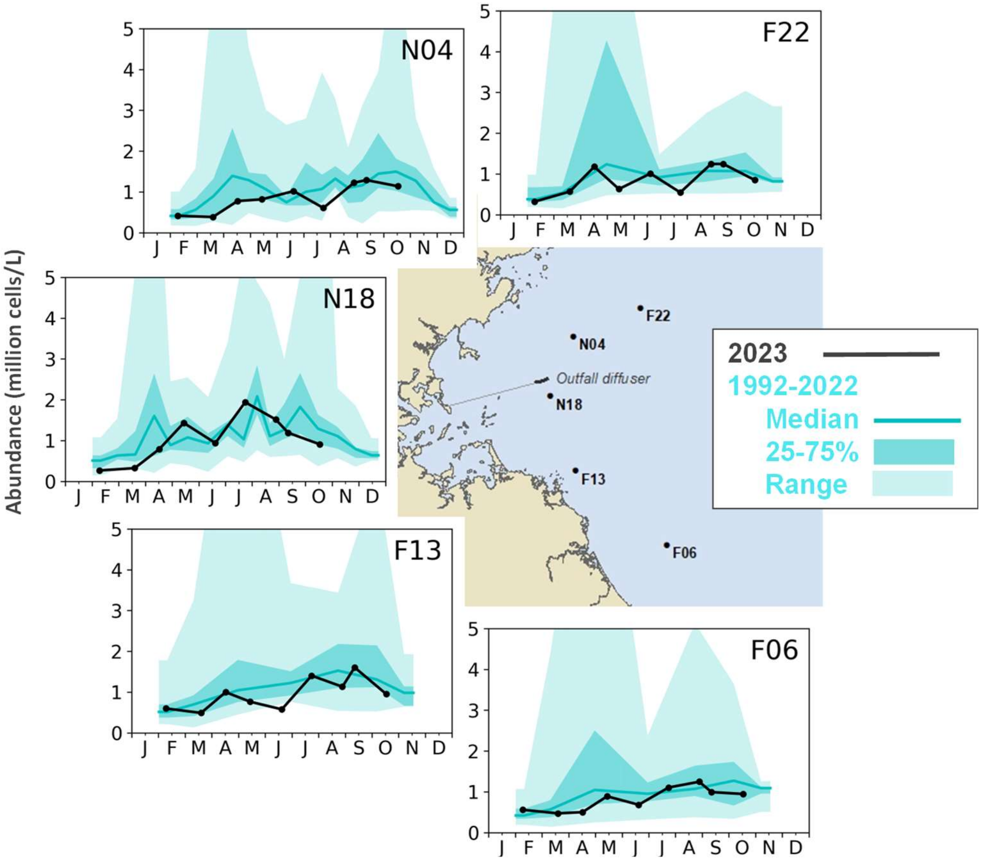

Figure 3-11. Total phytoplankton abundance at selected stations in 2023 compared to prior years. cells/L = cells per liter

Dinoflagellates were more abundant than the long-term average during most of 2023, largely due to the *Tripos muelleri* bloom, which dominated the region from April through July. *Tripos muelleri* abundance far exceeded past maxima throughout Massachusetts Bay (Figure 3-12). The bloom is discussed in greater detail in Section 6, Special Topics.

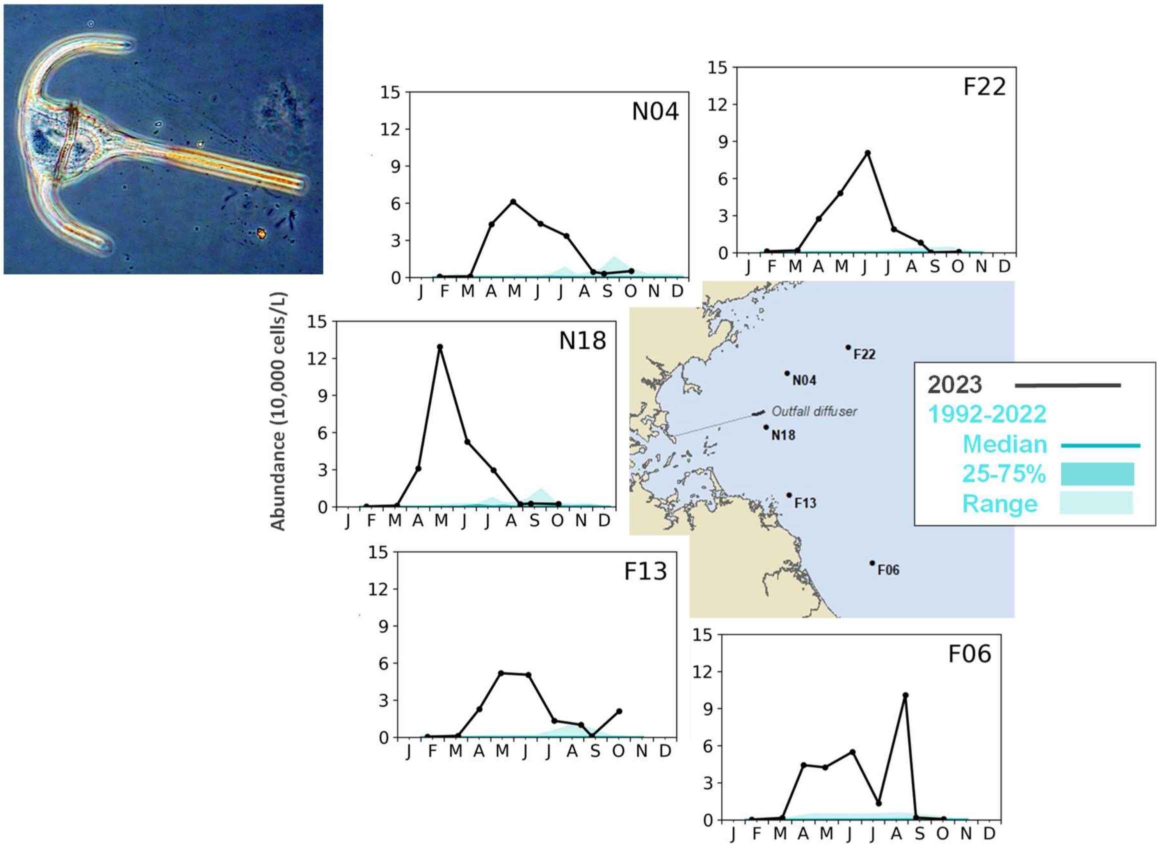

Figure 3-12. *Tripos muelleri* abundance at selected stations in 2023 compared to prior years. Abundance in 2023 was so high that, in many cases, it is difficult to see the historic ranges (blue shading). Photo credit David Borkman, Pausacaco Plankton, Saunderstown, Rhode Island. cells/L = cells per liter

The potentially toxic diatom genus *Pseudo-nitzschia* occurred at one of the lowest abundances observed since monitoring began. Abundance was orders of magnitude lower than the Contingency Plan thresholds. Some *Pseudo-nitzschia* species produce domoic acid, a neurotoxin that causes amnesic shellfish poisoning (ASP), a life-threatening condition in seabirds, marine mammals, and humans that consume contaminated shellfish. Historically, ASP has not caused shellfish closures in Massachusetts or Cape Cod Bays.

Abundance of the potentially toxic dinoflagellate *Alexandrium catenella* was lower in 2023 than in recent years (Figure 3-13), with a maximum abundance of only 32 cells per liter, observed at Station N01 to the north of the outfall in April. Abundances remained well below the Contingency Plan threshold and also below the threshold for conducting *Alexandrium* Rapid-Response Study surveys. The toxin produced by *Alexandrium catenella* causes paralytic shellfish poisoning (PSP), a potentially deadly condition for people and marine mammals that consume shellfish. No PSP toxicity was detected in Massachusetts Bay. *Alexandrium catenella* abundance and PSP toxicity were low throughout the Gulf of Maine in 2023, possibly because of low nutrient levels or other factors related to the *Tripos muelleri* bloom.

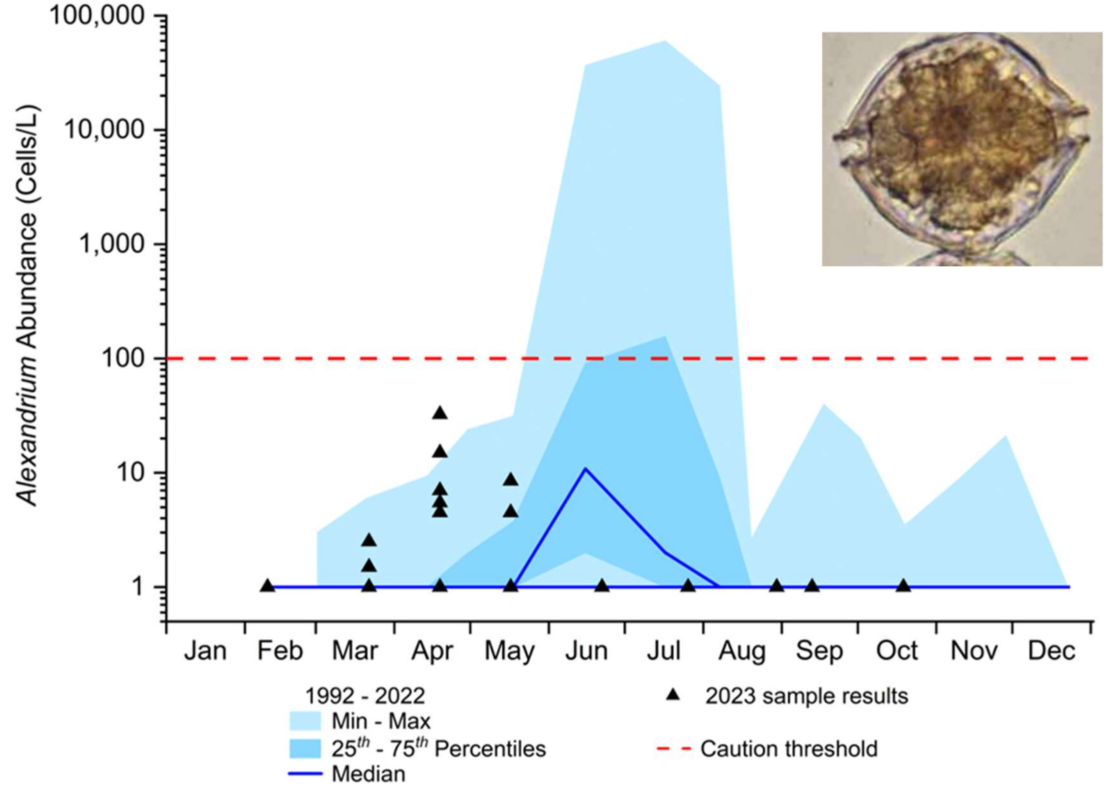

Figure 3-13. A*lexandrium catenella* abundance in 2023 compared to prior years. Photo credit Donald M. Anderson, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts. Cells/L = cells per liter.

Zooplankton Communities

Total zooplankton abundance and seasonal patterns were largely typical in 2023 (Figure 3-14) not reflecting any response to the *Tripos muelleri* phytoplankton bloom. Relatively few zooplankton species consume *Tripos muelleri,* which is spiny and has some ability to move up and down in the water column to avoid predation.

As in past years, copepod adults and younger life stages dominated in every survey. Numerically, the small copepod species *Oithona similis* continued to be the most abundant species in the zooplankton community, as it has since the beginning of the monitoring program. The June and July peak abundance was driven by early life stages of bivalve and gastropod mollusks (clams and snails). The somewhat unusual October peak observed at some stations was largely attributed to early life stages of copepods. The October peaks also reflected high numbers of radiolarians, single-celled protozoans that build ornate silica-rich exoskeletons. Radiolarians are more typically found in offshore waters, and their presence each year since 2020 may reflect an influx of warm water masses from offshore.

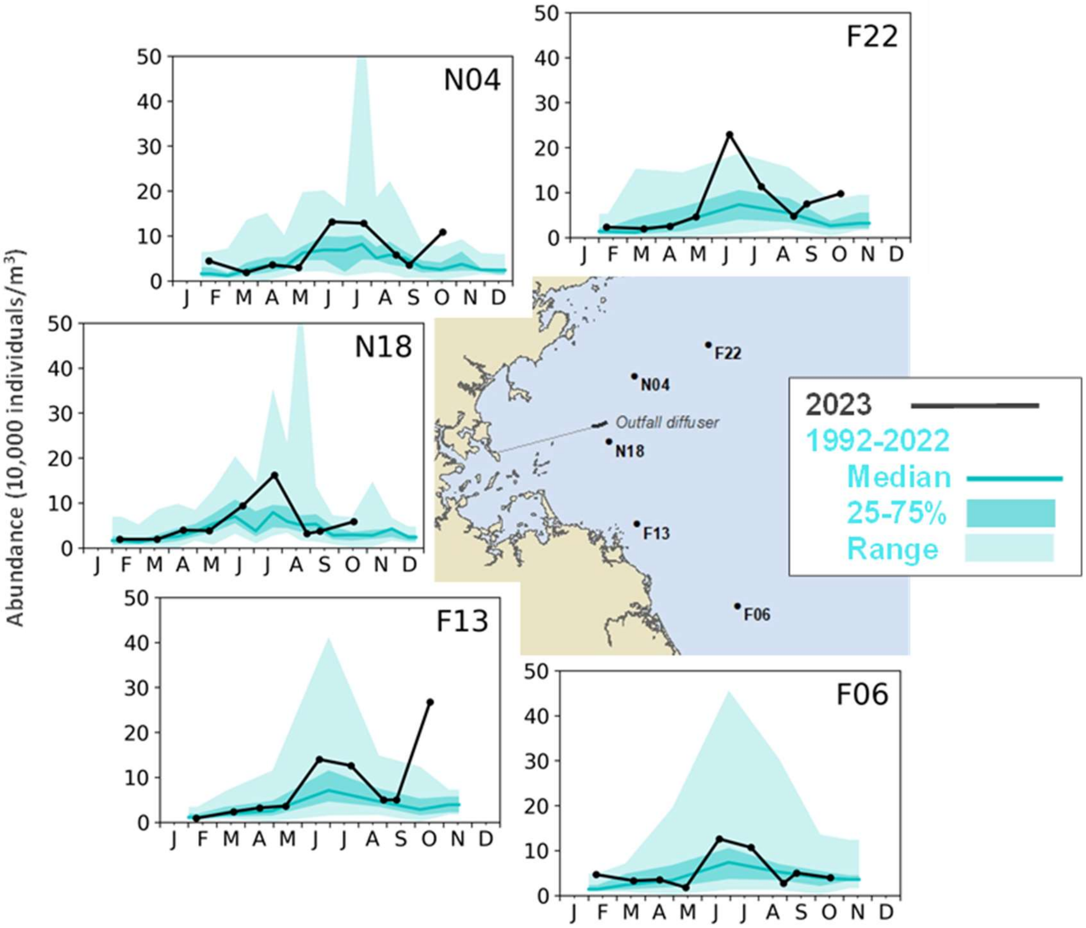

Figure 3-14. Total zooplankton abundance at selected stations in 2023 compared to prior years. The high historical values in July occurred in 2015, when sampling took place after a major bivalve spawning event. Abundances in 2023 were close to average at most stations in most months. The increases in October compared to other years were due to early life stages of copepods and to radiolarians, which are usually found in more offshore waters. individuals/m^3 = individuals per cubic meter

Stellwagen Bank National Marine Sanctuary

The NPDES permit requires MWRA to report on results relevant to Stellwagen Bank National Marine Sanctuary. Water-column Station F22 is just north of Stellwagen Basin, to the west of the sanctuary, and is representative of offshore conditions. The instrumented NERACOOS Buoy A01 is located in the northwest corner of the sanctuary.

Ammonium levels have not increased at Station F22 in the years since the outfall began to discharge (see Figure 3-6, page 17). However, like elsewhere throughout the region, the *Tripos muelleri* phytoplankton resulted in abnormally high chlorophyll concentrations in 2023. Physical conditions, as well as the bloom, led to low summertime oxygen levels and consequent Contingency Plan threshold exceedances.

Measurements at the NERACOOS Buoy A01 and at Station F22 documented the rapid increase in chlorophyll concentrations in the spring, followed by a rapid decline with the end of the *Tripos muelleri* bloom (Figure 3-15). Similar buoy and shipboard measurements documented the decline in oxygen concentrations though the summer months (Figure 3-16).

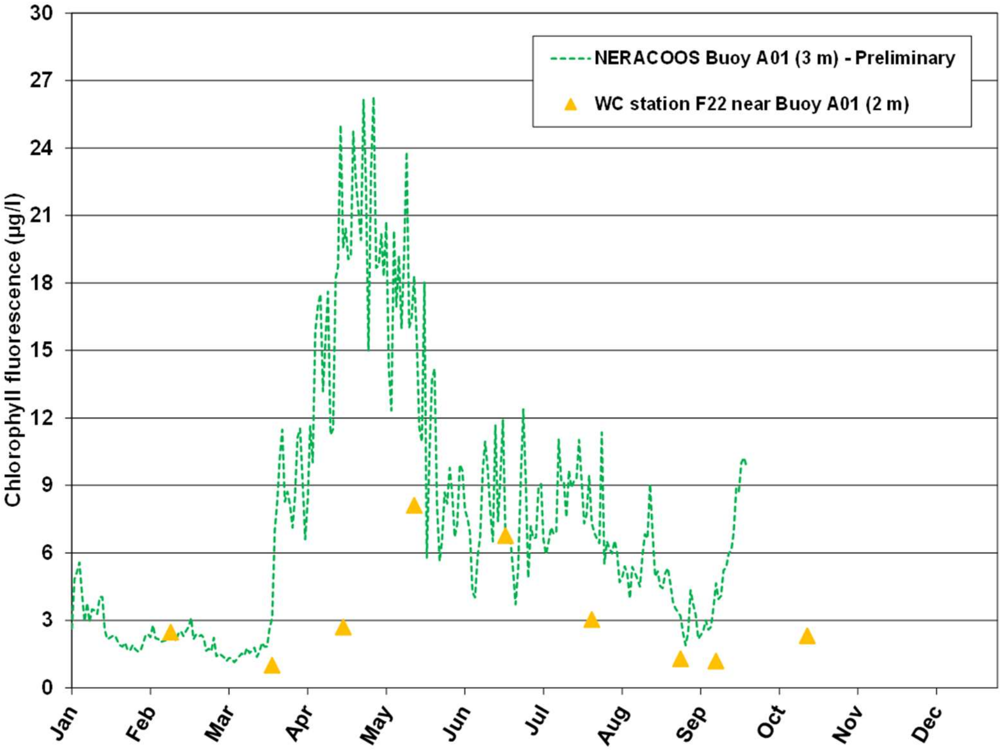

Figure 3-15. Surface chlorophyll measured at the NERACOOS Buoy A01 and nearby MWRA station F22 in 2023. Buoy values are daily means. µg/l = micrograms per liter.

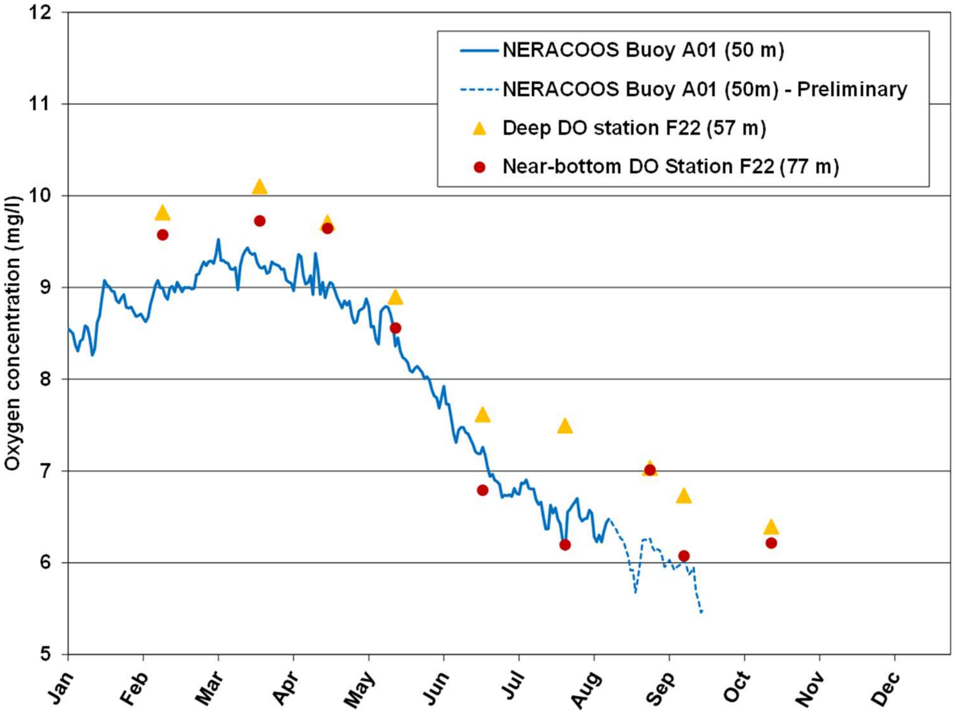

Figure 3-16. Dissolved oxygen concentrations at the NERACOOS Buoy A01 and at nearby deepwater MWRA survey Station F22 in 2023. Buoy values are daily means. The state water quality standard for dissolved oxygen is 6.0 milligrams per liter. mg/l = milligrams per liter.

The sanctuary's most recent condition report rated water quality within its borders as "good," and its most recent management plan agrees with MWRA's assessment that the outfall is not adversely affecting its waters (NOAA Office of Marine Sanctuaries 2020, 2023). The management plan notes that "ongoing monitoring suggests that the MWRA outfall is currently not adversely influencing monitored water quality parameters, and no evidence suggests that eutrophication is occurring." Sanctuary staff and scientists will continue to collaborate with MWRA and other organizations, viewing the sanctuary as a sentinel site for water quality monitoring in the Gulf of Maine.

Boston Harbor Water Quality

Water quality in Boston Harbor greatly improved during the Boston Harbor Project, and those advances remained evident in 2023. Perhaps the most dramatic improvement in Boston Harbor was the decrease in ammonium levels, which dropped precipitously in 2000 after the effluent discharge was diverted from the harbor to the bay. Ammonium levels have remained low. The decreases in nutrient inputs have been accompanied by decreases in primary production and phytoplankton biomass, an abatement of the harbor's historically high level of eutrophication (Werme et al. 2018, Taylor et al. 2020).

Water-Column Contingency Plan Thresholds

There were exceedances of five water-column thresholds in 2023, including caution-level exceedances for annual and summer chlorophyll concentrations, a warning-level exceedance for nearfield dissolved oxygen concentration, and caution- and warning-level exceedances for Stellwagen Bank dissolved oxygen concentration and percent saturation (Table 3-1).

Table 3-1. Contingency Plan threshold values and 2023 results for water-column monitoring.

Parameter	Baseline	Caution Level	Warning Level	2023 Results
Chlorophyll				
Annual	72 mg/m^2	>108 mg/m^2	>144 mg/m^2	116 mg/m^2
Winter/spring	50 mg/m^2	>199 mg/m^2	NA	96 mg/m^2
Summer	51 mg/m^2	>89 mg/m^2	NA	163 mg/m^2
Autumn	90 mg/m^2	>239 mg/m^2	NA	54 mg/m^2
Dissolved oxygen*				
Nearfield concentration	6.05 mg/L	<6.5 mg/L	<6.0 mg/L	5.96 mg/L
Nearfield percent saturation	65.3%	<80%	<75%	68.0%
Stellwagen concentration	6.23 mg/L	<6.5 mg/L	<6.0 mg/L	6.08 mg/L
Stellwagen percent saturation	67.2%	<80%	<75%	62.7 %
Nearfield depletion rate	0.024 mg/L/d	>0.037 mg/L/d	>0.049 mg/L/d	0.008 mg/L/d
Nuisance algae nearfield *Pseudo-nitzschia*				
Winter/spring	6,735 cells/L	>17,900 cells/L	NA	13 cells/L
Summer	14,635 cells/L	>43,100 cells/L	NA	591 cells/L
Autumn	10,050 cells/L	>27,500 cells/L	NA	472 cells/L
Nuisance algae nearfield *Alexandrium catenella*				
Any nearfield sample	Baseline maximum 163 cells/L	>100 cells/L	NA	32 cells/L
PSP toxin extent	NA	New incidence	NA	No new incidence

"Nearfield" refers to the five stations closest to the outfall, where effects might be detected, if they were to occur. Red shading shows a warning-level exceedance; orange shading shows a caution-level exceedance. For dissolved oxygen parameters, "exceedances" refer to values less than the threshold.
*Dissolved oxygen caution and warning levels represent numerical criteria, with the caveat "unless background conditions are lower." Results are therefore compared to the baseline as well as the caution and warning levels.
PSP = paralytic shellfish poisoning
NA = not applicable
mg/m^2 = milligrams per square meter
mg/L = milligrams per liter
mg/L/d = milligrams per liter per day
cells/L = cells per liter

Chlorophyll Exceedances

Nearfield summer chlorophyll levels were almost twice the caution level, and those high summer values drove an exceedance of the annual chlorophyll concentration threshold as well (Figure 3-17). Summer average chlorophyll concentrations in 2023 far exceeded those observed in any prior monitoring year, a result of the *Tripos muelleri* bloom. To a lesser extent, summer chlorophyll levels were also elevated during the baseline year 2000, in 2006 and in 2016. Annual chlorophyll levels were higher in the baseline years 1999 and 2000 than in 2023. The somewhat high summer chlorophyll level in 2006 resulted from a bloom of the diatom *Dactyliosolen fragilissimus*, which was stimulated by an unusually high period of upwelling of nutrients from deep waters. Elevated levels in 2000 and 2016 were attributed to multi-species blooms.

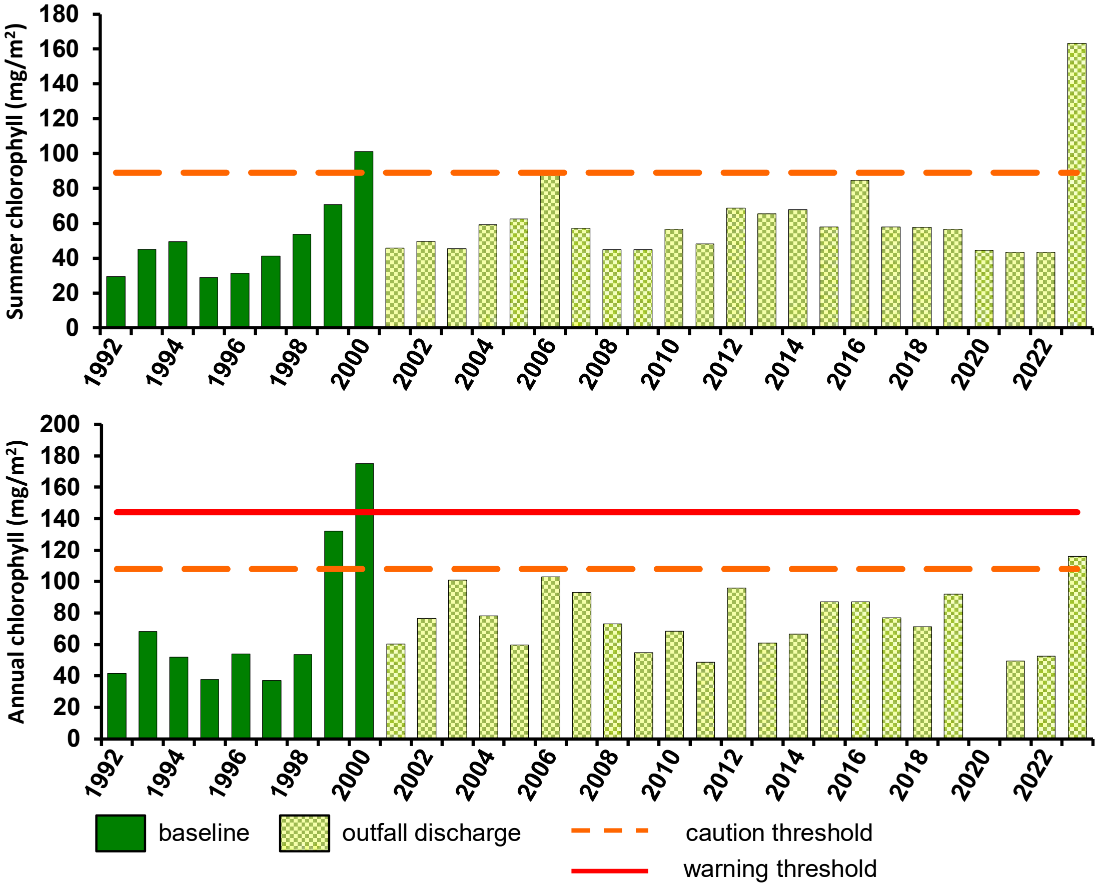

Figure 3-17. Summer (top) and annual (bottom) average chlorophyll concentrations, 1992–2023. No annual chlorophyll threshold could be calculated for 2020 due to COVID-19 restrictions on sampling in March and April. mg/m^2 = milligrams per square meter.

Dissolved Oxygen Exceedances

The Contingency Plan includes caution and warning thresholds for concentration, percent saturation, and the rate of oxygen depletion during the summer months at the nearfield stations close to the outfall and in Stellwagen Basin. The concentration is the amount of oxygen dissolved per liter water, and the percent saturation is the amount dissolved in the water compared to the maximum possible under the given physical conditions (temperature, salinity, and depth). Those stations closest to the outfall would be most likely to show an effect of the discharge, while the thresholds in Stellwagen Basin provide information about the wider region. (Note that for the dissolved oxygen parameters, the regulatory term “exceedance” refers to values that are lower than the Contingency Plan thresholds.)

The Contingency Plan thresholds were developed in the mid-1990s and were based on the established Massachusetts regulatory standards of the time. For some parameters, such as dissolved oxygen concentrations in both the nearfield and Stellwagen Basin, baseline levels were lower than those standards, so the thresholds direct that monitoring results be compared to the baseline values. Since the 1990s, New York and New England states other than Massachusetts have lowered their regulatory standards to make them more representative of the levels now thought to potentially harm marine life. Current standards for oxygen concentrations in those states now range from 4.8 to 5.0 milligrams per liter.

Percent saturation thresholds were also based on the Massachusetts standards of the 1990s, but field measurements fell below the caution levels in seven of eight baseline years, 1992–1999, and also in 2000, the year that the Massachusetts Bay outfall began to discharge. No further excursions below the caution thresholds occurred until 2021. Massachusetts removed percent oxygen saturation from its state standards in 2008, after research showed that percent saturation was not strongly associated with ecosystem health, but it remains a Contingency Plan parameter.

The first 2023 exceedances occurred in measurements made in July in Stellwagen Basin. There were no exceedances in August, following a period of winds from the south, which promoted upwelling and some mixing of the water column. In September, there were exceedances in both the nearfield and Stellwagen Basin (Figure 3-18). These exceedances have not been attributed to the outfall, but instead appear to be the result of widely recognized regional physical conditions, particularly warming waters, which have been broadly documented in the Gulf of Maine, and to the aftermath or the *Tripos muelleri* phytoplankton bloom. Changing physical conditions and the phytoplankton bloom are discussed further in Section 6, Special Topics.

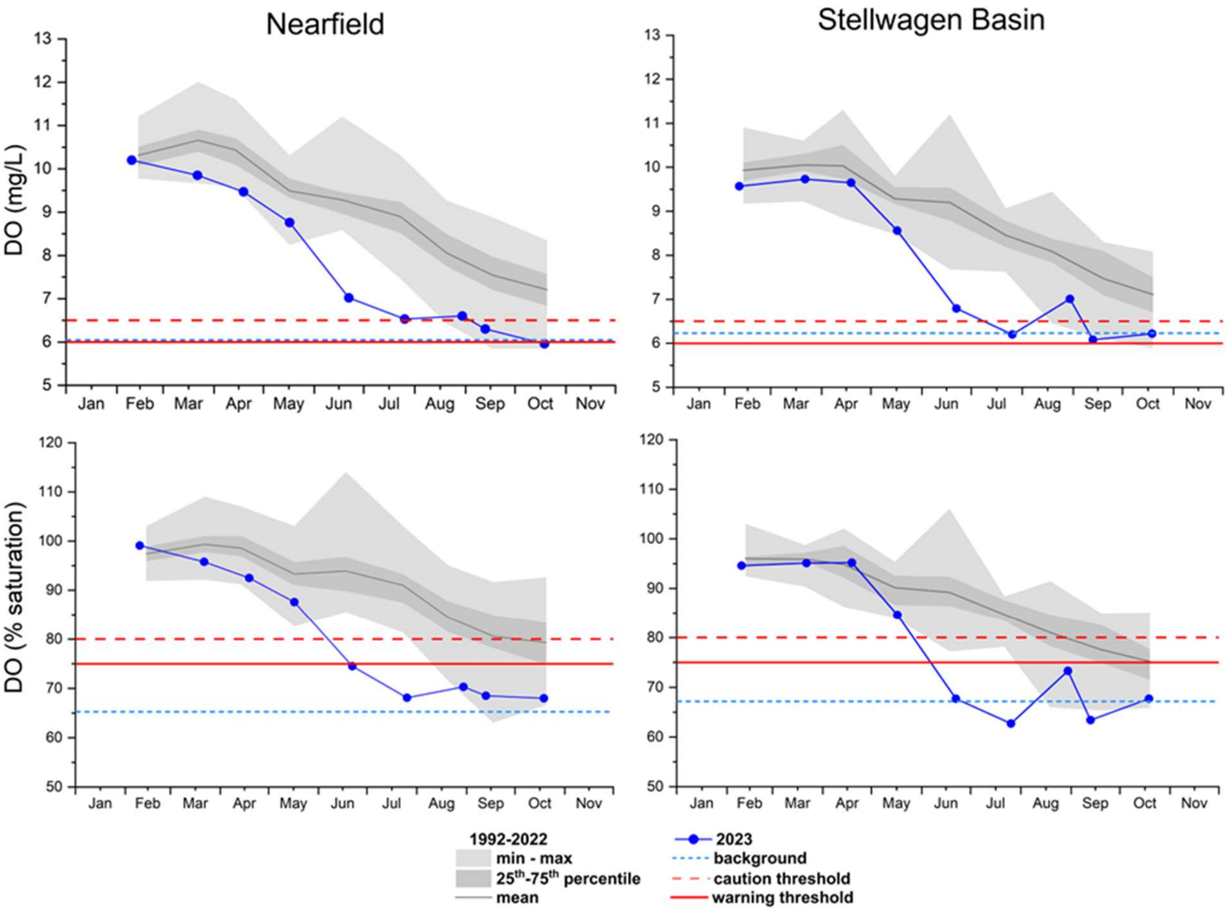

Figure 3-18. Bottom dissolved oxygen concentrations and percent saturation in the nearfield and Stellwagen Basin, 2023. Nearfield = the five stations closest to the outfall; DO = dissolved oxygen; mg/L = milligrams per liter.

4. Sea Floor

Seafloor monitoring assesses the health of habitats and communities. MWRA measures sediment characteristics and assesses animal communities living in soft-bottom and hard-bottom habitats. Because of consistently good results, some sediment-contaminant monitoring has been reduced. Seafloor animal communities vary within typical natural cycles, influenced by sediment types and water depths.

The sea floor of Massachusetts Bay was shaped by glaciers, which scoured the bottom and created Stellwagen Basin to the east of the outfall, deposited rocky debris in elongated hills called drumlins, and left sand and gravel on what is now Stellwagen Bank. Tides and currents continue to shape the bay, particularly during major storms with waves large enough to resuspend and transport sediments. Seafloor habitats range from mud in soft bottom depositional areas to rocky cobbles and boulders on the hard-bottom tops and flanks of the drumlins.

Seafloor monitoring assesses potential outfall effects on the health of both the soft-bottom areas and the hard-bottom drumlins. Most seafloor-monitoring studies focus solely on soft-bottom sediments made up of sand, silt, and clay, but such depositional sites are somewhat rare in the immediate vicinity of the outfall, so MWRA also conducts hard-bottom surveys. Massachusetts Bay soft-bottom sampling surveys are conducted annually, while photographic and video assessments of the hard-bottom areas occur at three-year intervals, including 2023. A separate program in Boston Harbor includes annual soft-bottom surveys and photographic sediment-profile imagery.

In August 2023, MWRA sampled 14 soft-bottom stations for analysis of sediment grain-size distribution, the wastewater tracer *Clostridium perfringens* spores, percent total organic carbon, and infauna (animal) abundance and species composition (Figure 4-1). The stations included four “inner nearfield” stations located within two kilometers of the outfall; six “outer nearfield” stations in western Massachusetts Bay somewhat farther from the outfall; one station in the “transition” area between Boston Harbor and the nearfield; and three “farfield” reference stations in Massachusetts and Cape Cod Bays. For the purposes of testing Contingency Plan thresholds for the sea floor, “nearfield” includes both nearfield groups and the transition station, for a total of 11 stations. Note that water-column and seafloor monitoring sample different stations and have different definitions of nearfield and farfield.

Hard-bottom surveys of 23 stations were completed in mid-June 2023 (Figure 4-2). The stations included one active and one inactive outfall diffuser cap. The surveys yielded 487 minutes of analog video, which were analyzed for physical parameters and species composition.

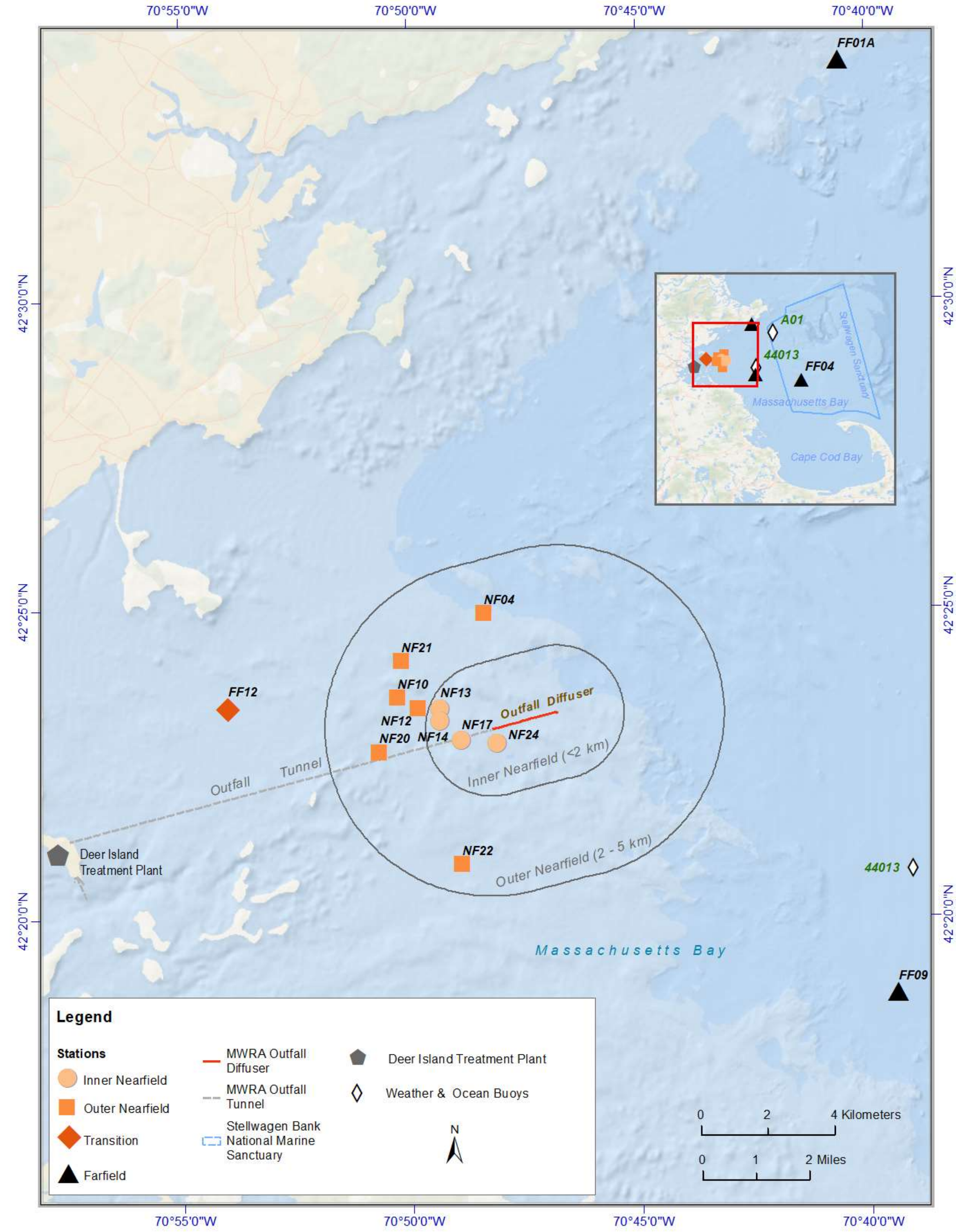

Figure 4-1. Soft-bottom monitoring stations. Also shown are the instrumented buoys, the MWRA outfall diffuser, and Stellwagen Bank National Marine Sanctuary. Nearfield stations include a designation NF, while farfield stations and the transition station include a designation FF. The transition station FF14 is included with the nearfield stations to calculate Contingency Plan thresholds.

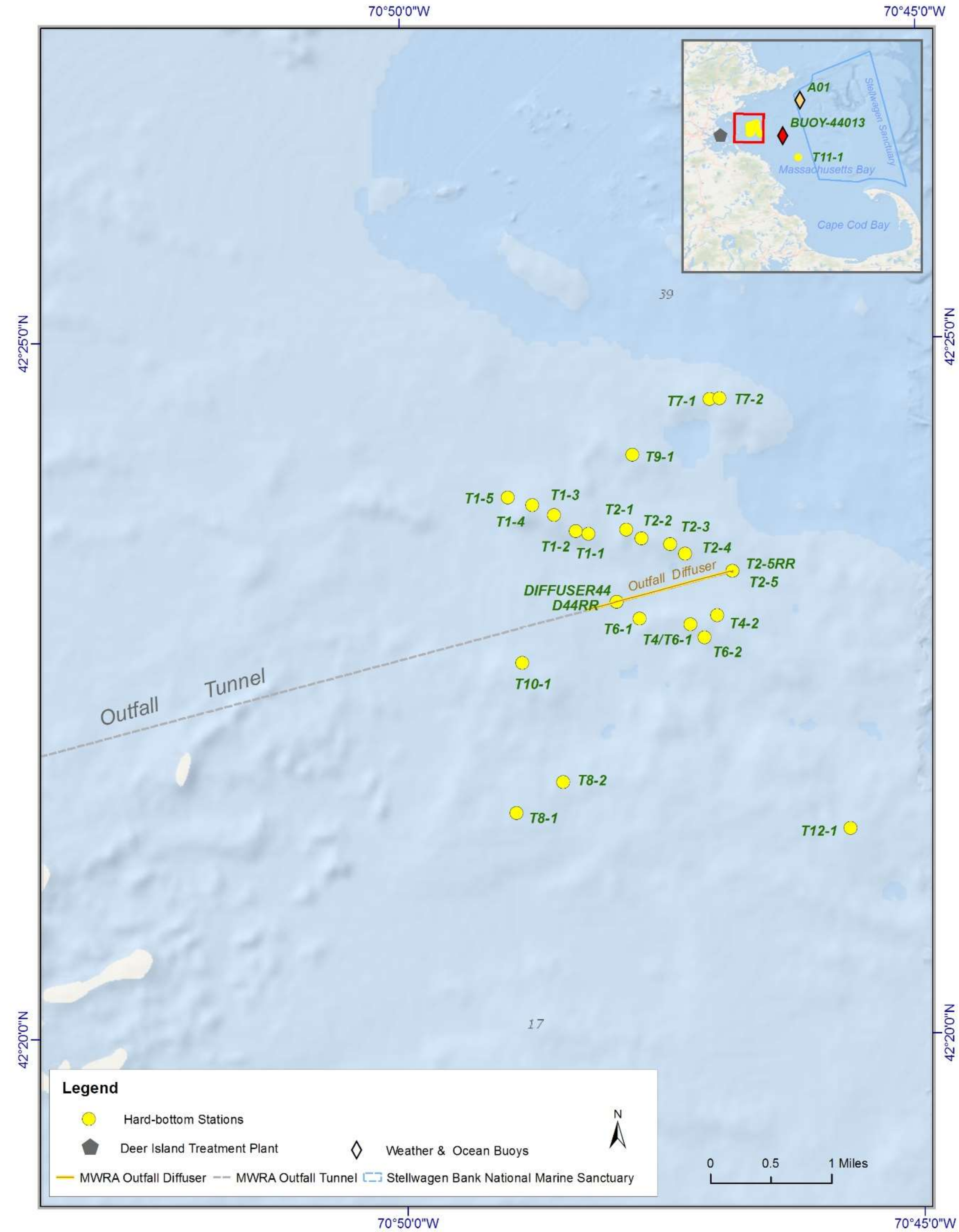

Figure 4-2. Hard-bottom monitoring stations. Also shown are the instrumented buoys, the MWRA outfall diffuser, and Stellwagen Bank National Marine Sanctuary.

Sediment Characteristics and Tracers

As in past years, sediment grain-size distributions in 2023 varied broadly, ranging from silt and clay at some stations (particularly Station FF04 within Stellwagen Basin) to almost entirely sand at others (Nestler et al. 2024). Within individual stations, sediment textures have remained generally stable over the years of monitoring, with occasional changes following large storms.

Clostridium perfringens is an anaerobic bacteria species, which is found in the digestive tracts of humans and other mammals and is not completely removed by wastewater treatment. It forms resting spores, and in sediments, those spores provide a sensitive tracer of sewage effluent. Since spores can persist for decades, they do not reflect immediate deposition onto the sea floor; instead, they integrate results over years.

In 2023, as in other years, elevated abundance of *Clostridium* spores was detected at some stations located closest to the outfall (Figure 4-2). In most years, *Clostridium* spore concentrations have been elevated at stations located within two kilometers of the outfall. In 2022, some anomalously high concentrations were measured at two sites farther from and out of the projected range of the outfall, but measurements from those sites returned to more typical values in 2023.

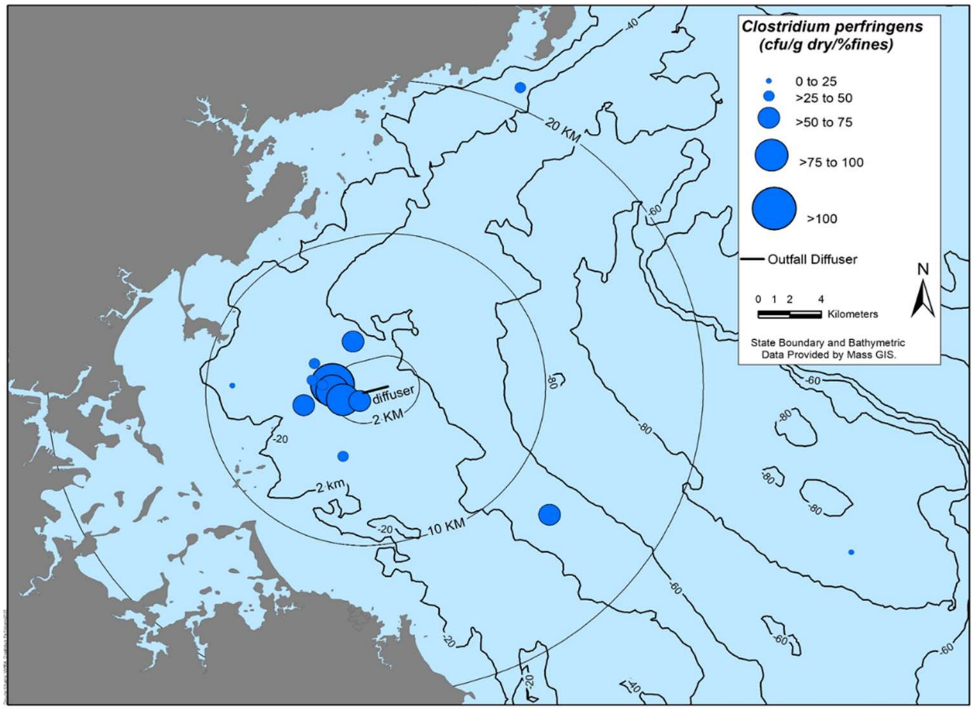

Figure 4-3. Concentrations of the effluent tracer *Clostridium perfringens* spores in 2023. Concentrations represent spore counts normalized to the percent of the sediment made up of fine silt and clays, removing any effect of grain size from the analysis. As anticipated during outfall planning, *Clostridium* spore concentrations are elevated at stations closest to the outfall. cfu = colony forming units, the measure used in spore counts.

Percent total organic carbon content in the sediments was consistent with past results, with no increased organic carbon from sewage effluent at stations near the outfall (Figure 4-4). In general, stations with finer sediments, such as Station FF04, to the east of the outfall in Stellwagen Basin, have higher mean total organic carbon concentrations, while stations with coarser sediments, such as Station NF17 just to the south of the outfall have lower concentrations. Overall, the total organic carbon data continued to show no signs of organic enrichment from wastewater effluent, consistent with predictions made before the outfall began to discharge and also consistent with a special study of sediment metabolism, which was completed in 2010 (Tucker et al. 2010, Tucker et al. 2014). No sample showed increased organic carbon concentrations following the large 2023 *Tripos muelleri* phytoplankton bloom, a somewhat surprising result that remains under study.

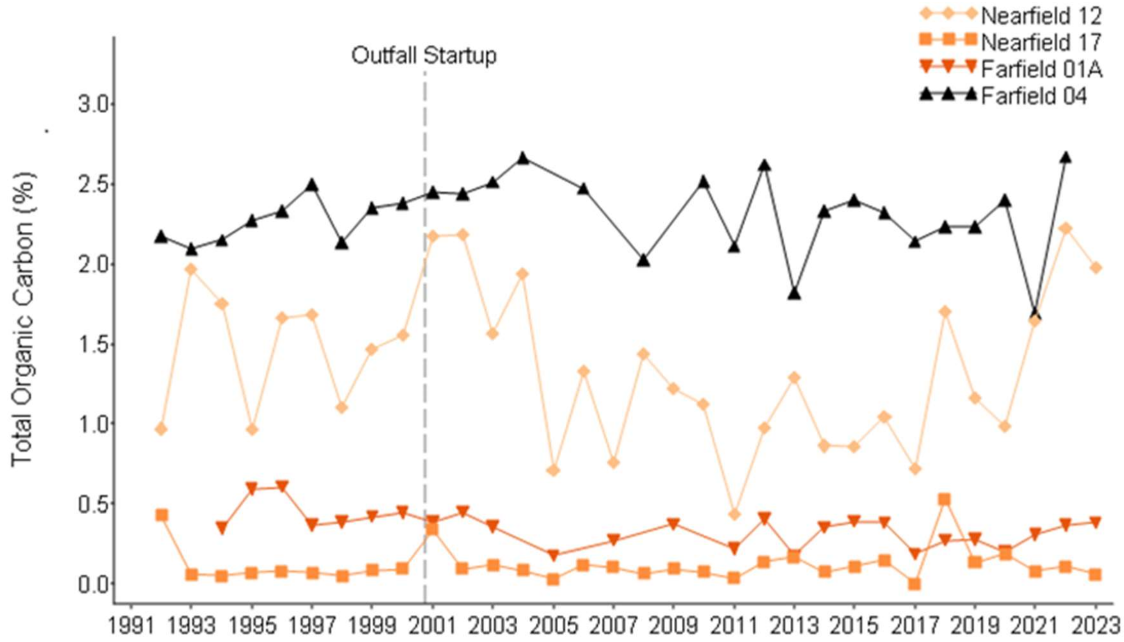

Figure 4-4. Total organic carbon at selected stations, 1992–2023. Nearfield 12 (NF12) is more than two kilometers northwest of the outfall, and Nearfield 17 (NF17) is in closer proximity and southwest of the outfall, where the effects of the discharge might be expected but have not been found. Farfield 01A (FF01A) is the northern reference station, and Farfield 04 (FF04) is in Stellwagen Basin; both farfield stations are farther than 20 kilometers from the outfall. No effects of the discharge have been observed at any station; total organic carbon content is correlated with sediment type rather than distance from the outfall. (Note that 2023 data from Station FF04 are currently unavailable.)

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Soft-bottom Communities

A variety of small animals live in the sediments, including segmented polychaete worms, mollusks, and crustaceans. MWRA monitors abundance and species composition of animals living within soft-bottom communities to document any changes that might be associated with the outfall discharge, such as altered species composition, decreased biodiversity, or increased presence of the opportunistic species typically found in disturbed habitats.

The 14 soft-bottom samples collected and analyzed in 2023 contained 27,099 organisms, classified into 174 species and 23 other discrete taxonomic groups of animals that could not be identified to the species level (Nestler et al. 2024). Total abundance of organisms was slightly higher in 2023 than in 2022 in all regional groups, but remained within expected ranges (Figure 4-5). The several community diversity measures calculated for nearfield samples remained at levels typical of past years.

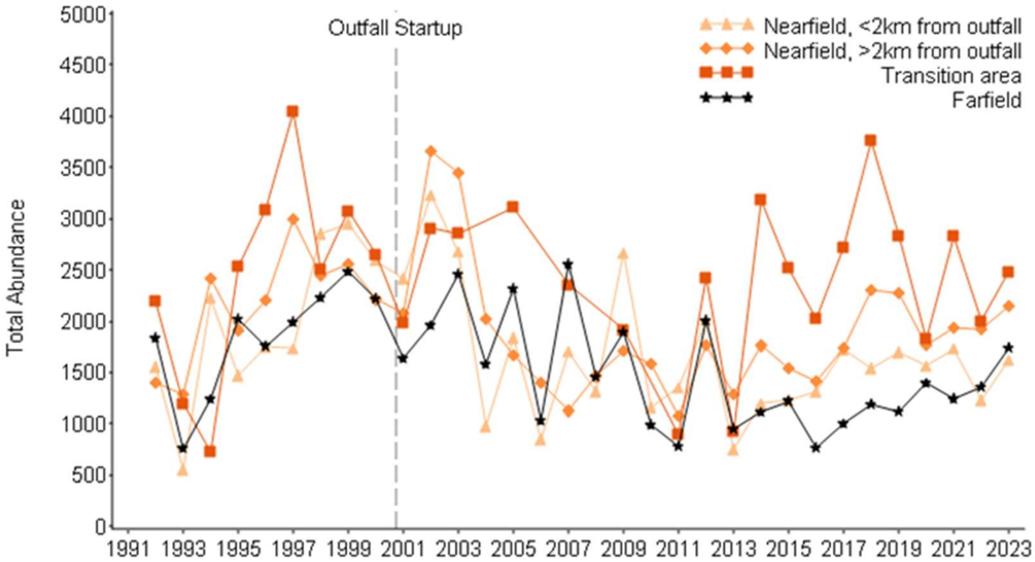


Figure 4-5. Total abundance of soft-bottom organisms by region, 1992–2023. Regions include the inner nearfield within two kilometers of the outfall, the outer nearfield farther than two kilometers from the outfall, the transition area between Boston Harbor and the outfall, and the farfield.

Small polychaete worms (sometimes known as bristle worms, Figure 4-6), dominated the samples at most stations, as they have for the duration of the monitoring program. These segmented worms are among the most common marine organisms. The polychaete *Prionospio steenstrupi*, which was the numerically dominant species in 1997–2005, has declined in abundance over recent years, but remained among a group of dominant species. Other common polychaetes, including *Aricidea catherinae* and *Mediomastus californiensis*, were present in numbers comparable to other recent years.

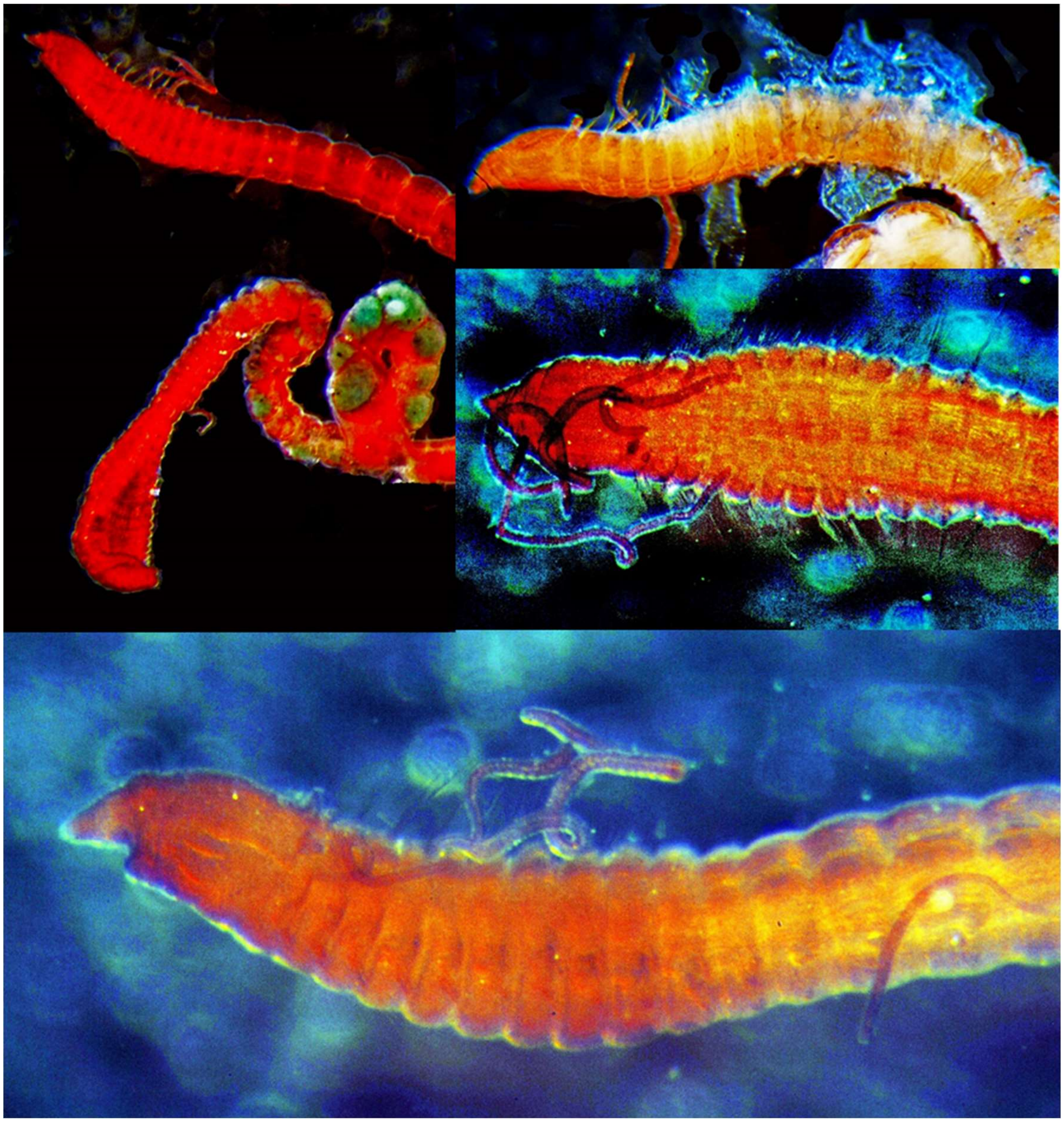


Figure 4-6. Polychaete worms dominate the soft-bottom habitats in Massachusetts Bay. Polychaetes can range in size from less than a millimeter to several meters, but most are very small. This species, *Kirkegaardia baptistae*, is about 14 millimeters long and frequently found in fine-grained, offshore sediments. MWRA samples were used in its original description. Photo credits James A. Blake, Museum of Comparative Zoology, Harvard University, Cambridge, Massachusetts.

Community analyses continued to show no effects of the outfall on total abundance of animals, relative abundance of species, or community composition. A series of analyses assessed patterns in the soft-bottom communities over space and time and found no particular species or type of community specifically associated with the outfall.

One type of community analysis, called cluster analysis, groups stations by similarity in species composition and abundance. Similar to prior years, cluster analysis of the 2023 samples identified two main groups (I and II) and one “outlier” group (III). Group I was dominated by crustaceans and polychaete worms. Group II included a greater abundance of polychaetes and also mollusks. Group II could be subdivided into three subgroups (IIA, IIB, and IIC). The very small bivalve mollusk *Crenella decussata* was a dominant species at Station FF09, the only station within Group IIA. As in past years, the outlier Group III included only the offshore station located within Stellwagen Basin, which has consistently supported a unique polychaete community, typical of the other deepwater, offshore stations sampled in the past.

Further analysis, called ordination analysis, provides a picture of how closely the bottom communities identified in the cluster analysis relate to each other. The 2023 ordination analysis continued to show no indication of any relation between community composition and proximity to the outfall (Figure 4-7). Both main Groups I and II included stations located at various distances and directions from the outfall. Group II included stations from both nearfield station groups, the transition station between the harbor and the outfall, and farfield stations to the northeast and southeast of the outfall.

As in past years, further assessment of the ordination analysis demonstrated that variations in species distributions largely followed differences in sediment grain size (Figure 4-8). Water depth was another important factor in determining community structure. Seafloor animal communities at stations with similar sediment textures and water depths tended to be more closely related, as shown by closer proximity on the ordination plots. These results continued to validate past findings that the Massachusetts Bay seafloor communities are driven by physical factors rather than by the discharge. The strong physical forces in the bay, as well as the low pollutant levels in the effluent discharge, have helped to maintain healthy soft-bottom habitats throughout Massachusetts Bay.

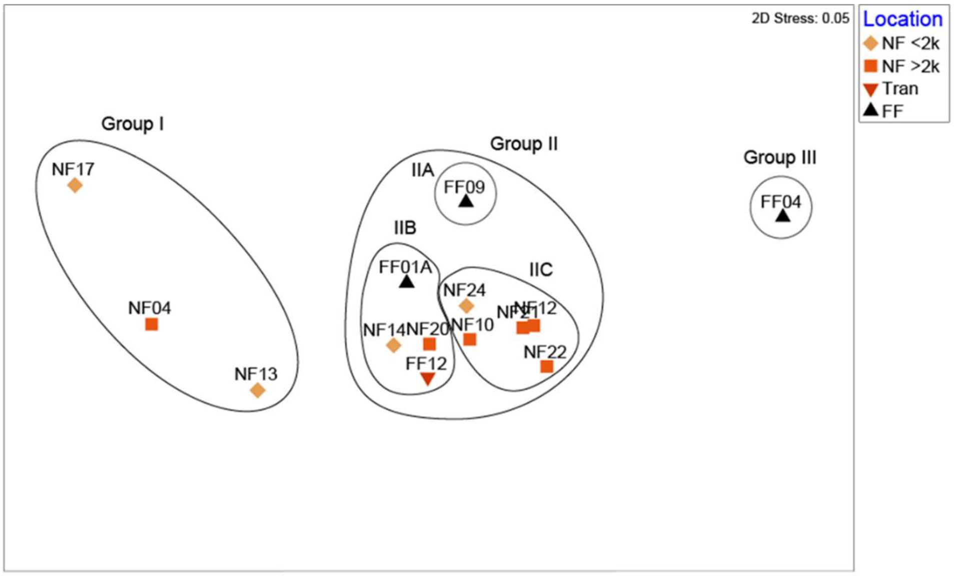


Figure 4-7. Ordination plot of 2023 Massachusetts Bay samples by location. The ordination analysis shows that the distance from the outfall does not correspond with bottom community composition. Each point on the plot represents one of 14 stations, and varying colors and shapes depict locations. Placement of the points indicates similarity of the communities—the nearer two points are to each other, the more similar their seafloor communities. NF<2k = stations within two kilometers of the outfall; NF >2k = stations near but more than two kilometers from the outfall; Tran = the one station between Boston Harbor and the outfall; FF = stations far from the outfall. (The 2D Stress value noted in the upper right is a measure of good confidence in the analysis.)

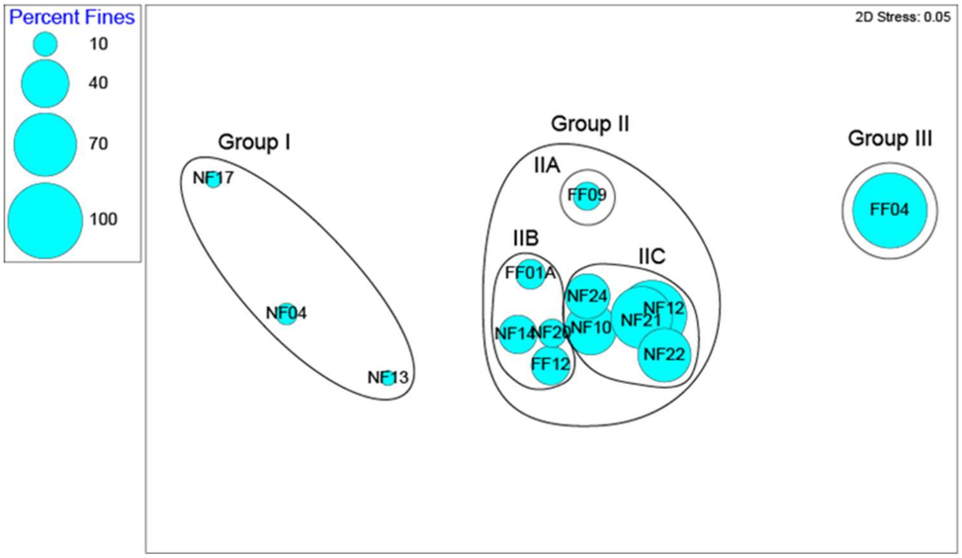


Figure 4-8. Percent fine sediments superimposed on the ordination plot of the 2023 samples. Combining the ordination analysis with sediment grain-size data shows that sediment texture is likely a strong driver of community composition. Data are shown as in Figure 4-7, with the size of each station marker indicating the percentage of fine sediments (percent fines). Stations with similar sediment grain size tend to be represented in the same groups. Group I included only stations with coarser sediments, and Group II subgroups reflected a range of finer-grained sediments. The offshore outlier Group III in Stellwagen Basin has the finest-grained sediments (The 2D Stress value noted in the upper right is a measure of good confidence in the analysis.)

Hard-bottom Communities

Past monitoring has shown that the hard-bottom habitats near the Massachusetts Bay outfall are spatially diverse but relatively stable over time. The changes that have occurred have not been associated with the outfall. For example, abundance of encrusting coralline algae was once proposed as a potential indicator of outfall effects, supposing that abundance could decline in response to increased deposition of solid matter in the wastewater discharge. In fact, coralline algas abundance has decreased throughout the area, but those decreases have been region-wide and first occurred at northern reference locations, outside the projected influence of the discharge.

Sporadic sets of juvenile barnacles, as they transition from the zooplankton to immobile adults, have been common over time, but in 2023, for the first time, they were observed at almost every station. At some locations, the barnacle sets were followed by unprecedented numbers of the sea star *Asterias rubens*, feeding on the young barnacles (Figure 4-9, top). These sorts of events likely occur more frequently than can be detected by periodic monitoring and illustrate the natural variability of the environment.

The active outfall diffuser head included as a monitoring station continued to support a healthy seafloor community (Figure 4-9, bottom). Sea anemones have historically been abundant on both active and inactive diffuser heads. The blue mussel *Mytilus edulis*, which has traditionally been more common in shallower waters, was first seen on the active diffuser head in 2005 and appears to be increasing in numbers throughout the area. Blue mussels are now co-existing with the more typically deepwater horse mussel *Modiolus modiolus*. Over the same years, intertidal and shallow-water blue mussel populations have declined throughout the region. Some researchers speculate that a shift to deeper water is a response to warming waters; the Gulf of Maine Research Institute is currently mapping this change (Mussel Bed Mapping - Gulf of Maine Research Institute).

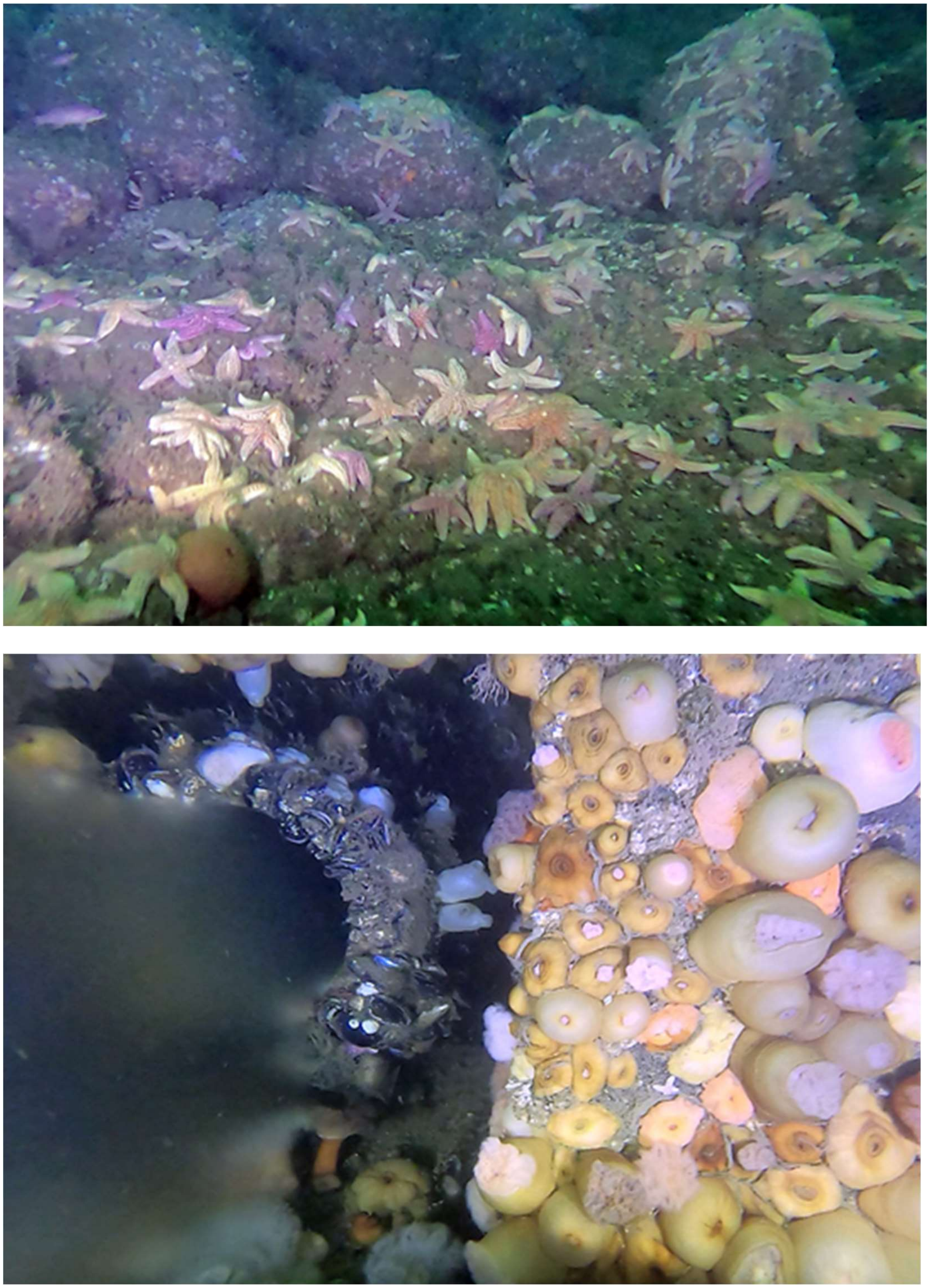


Figure 4-9. Top: Large numbers of sea stars feeding on barnacles in 2023. Bottom: Blue mussels and sea anemones growing on an active outfall diffuser. Large barnacle sets occur periodically throughout the study area, including 2023. Blue mussels, which have been disappearing from shallower habitats throughout New England, were first detected on the diffuser in 2005 and have been found on large boulders throughout the area since 2011.

Stellwagen Bank National Marine Sanctuary

The NPDES permit to discharge from Deer Island Treatment Plant into Massachusetts Bay requires annual reporting on results relevant to Stellwagen Bank National Marine Sanctuary. MWRA's seafloor deepwater reference Station FF04 lies within the depositional part of the sanctuary, Stellwagen Basin, where long-term accumulation of pollutants could feasibly occur.

Station FF04 is typical of deepwater, offshore habitats and is representative of a larger group of stations that was monitored in earlier years of the program. It continues to support a soft-bottom community typical of what had been found at the larger suite of deepwater stations. Communities at those stations have always shown distinct differences from those found in shallower areas, probably due to the distance from shore, as well as greater depth and fine-grained sediments (Figures 4-7 and 4-8, above). Superimposing percent grain size on the ordination plot for 2023 samples continued to show those natural differences. Analysis of data from 1992–2023 has demonstrated the temporal consistency of the seafloor community at that station.

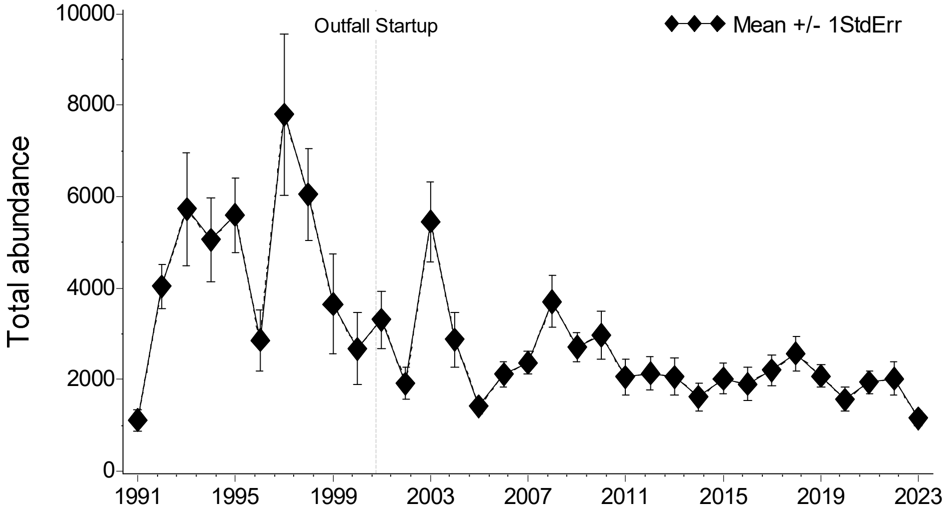
The most recent management plan for the sanctuary (NOAA Office of Marine Sanctuaries 2023) includes an action plan to assess all the major habitats within its borders, including sand, boulder, gravel, mud, rocky areas, and shipwrecks. Their most recent environmental assessment (NOAA Office of Marine Sanctuaries 2020) found that changes to seafloor habitats and animal communities came mostly from fishing. Fishing gear physically scrapes the sea floor, and fishing pressures can change the species makeup of both seafloor and fish communities.

Boston Harbor Seafloor Monitoring

Seafloor conditions are much better in Boston Harbor than they were in the 1970s and 1980s. Boston Harbor received sewage sludge discharge until 1991 and effluent discharge until September 2000. MWRA has conducted ongoing seafloor monitoring in Boston Harbor since 1991. Each year, sediment samples are taken from nine stations, and sediment-profile images are taken at 61 stations throughout the harbor.

Over time, sediment textures within individual harbor stations have become stable, ranging from mostly sand at some stations to silt and clay at others. Percent total organic carbon in harbor sediments has declined over time, reflecting the lowered wastewater inputs.

Over the past decade, the total abundances of organisms and number of species per sample have also stabilized (Figure 4-10), a sign of sustained improvement in seafloor habitat conditions. In 2023, samples contained 19,686 specimens, classified into 122 species and 17 other discrete taxonomic groups.



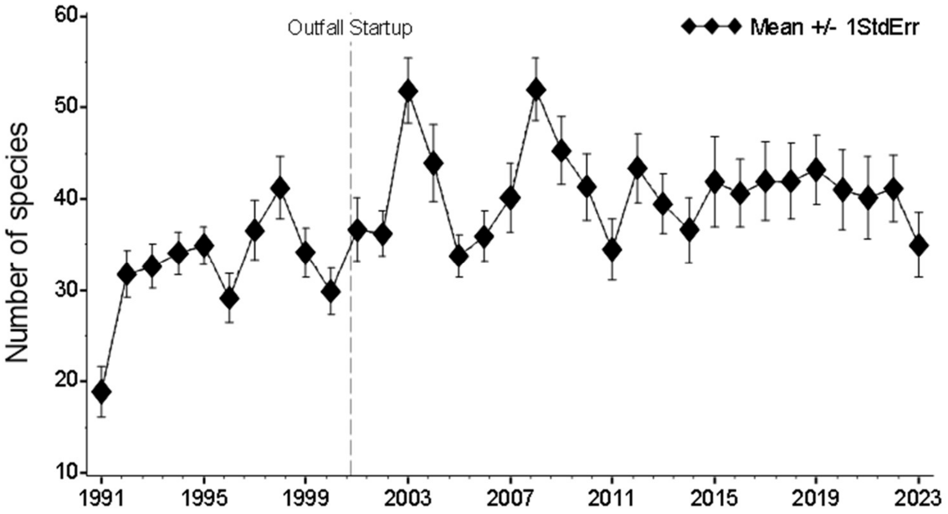


Figure 4-10. Total abundance of soft-bottom animals (top) and number of species (bottom) per sample in Boston Harbor samples, 1991–2023. Both total abundance and numbers of species have stabilized as the harbor has recovered from past inputs of sewage sludge and effluent. Data are from eight harbor stations that have been consistently monitored since 1991. "Outfall startup" refers to the beginning of effluent discharge from the Massachusetts Bay outfall and the end of discharge to the harbor.

As in past years, the communities in 2023 varied along an outer-to-inner harbor gradient, reflecting the greater stream and river inputs to the inner harbor and greater tidal flushing at the outer-harbor stations. Sediment-profile imaging has confirmed the gradient and clearly documented sustained improvements to habitat conditions throughout the harbor over time.

Sediment-profile images from 2023 (Figure 4-11) depicted the continuing healthy conditions. Some locations in 2023 had been disturbed by recent dredging activity, but in general, sediments continued to be well-oxidized, with no evidence of excess organic matter.

Figure 4-11. Example of a sediment-profile image, showing a large mantis shrimp burrow at Station R07, at Deer Island Flats, near the location of the former Boston Harbor effluent outfall. Scales at the sides of the image are in centimeters.

Seafloor Contingency Plan Thresholds

There were no threshold exceedances for the seafloor Contingency Plan thresholds in 2023 (Table 4-1). For the purposes of threshold testing, “nearfield” includes stations from both nearfield groups (both nearer and farther than two kilometers from the outfall) and the station in the transition area between Boston Harbor and the Massachusetts Bay outfall.

All threshold parameters continued to confirm that Massachusetts Bay maintains healthy seafloor habitats, unaffected by the wastewater discharge. Number of species per sample and the several diversity and evenness indices used to evaluate community structure remained higher than Contingency Plan limits, while the percent opportunistic species, a concern for disturbed or polluted habitats, remained far below any level of concern, only 0.21% compared to caution and warning thresholds of 10% and 25%.

Table 4-1. Contingency Plan threshold values and 2023 results for seafloor monitoring.*

Parameter	Baseline	Caution Level	Warning Level	2023 Results
Species per sample	NA	<42.99	NA	60.8
Fisher’s log-series alpha	NA	<9.42	NA	12.4
Shannon diversity	NA	<3.37	NA	3.94
Pielou’s evenness	NA	<0.57	NA	0.67
% opportunists	NA	>10%	>25%	0.21%

NA = not applicable

* Number of species per sample is often referred to as species richness. Fisher’s log-series alpha and Shannon diversity are indicators of diversity, calculated from both numbers of species and numbers of individuals per species. Pielou’s evenness assesses how evenly numbers of individuals are distributed among the species in the sample. Percent opportunists is the percentage of the total number of animals that are indicators of disturbed habitat. The percent opportunist threshold is a maximum; all other thresholds are minimum values.

5. Fish and Shellfish

Fish and shellfish are healthy.
MWRA monitors winter flounder health and fish and shellfish tissues for chemical pollutants that occur in wastewater effluent. Over time, flounder health has improved, and contaminant concentrations have declined in flounder, lobster, and mussel tissues from both Boston Harbor and Massachusetts Bay.

Fish and shellfish are important to the regional identity and economy of Massachusetts and can be good indicators of overall environmental health. The monitoring program focuses on winter flounder, lobster, and cage-deployed blue mussels. Flounder and lobster are important commercial and recreational species that live on the sea floor and feed on bottom-dwelling animals, likely sources for contaminant exposure. Mussels filter large volumes of water and can concentrate toxic metals and organic compounds in their tissues. Sampling and deployment locations vary by species (Figure 5-1). Sampling locations for winter flounder and lobster were selected to be far enough away from each other to maximize the likelihood of sampling separate populations. Winter flounder are unlikely to range farther than about two kilometers in areas with ample food; lobster migration is less well understood.

Timing and parameters measured vary by species. MWRA monitors winter flounder health each year and conducts chemical contaminant analyses of flounder, lobster, and mussel tissues every three years, most recently in 2021. Flounder health assessment was the only monitoring activity in 2023. It measured external conditions and liver disease, including precancerous conditions and tumors.

In 2023, flounder monitoring was conducted at two locations, the Massachusetts Bay outfall site and Deer Island Flats, near the location where wastewater effluent was once discharged into Boston Harbor. Through 2021, fish were also collected from eastern Cape Cod Bay, which was considered a relatively pristine control site. In earlier years, other locations provided greater geographic representation. That past monitoring concluded that there had been no adverse effects of the Massachusetts Bay outfall and that instead, conditions have improved throughout the region, a result of improved contaminant source reduction and better sewage treatment. Consequently, a formal study with a control site was deemed no longer necessary. However, the regulatory agencies maintain a continued interest in documenting flounder health in Massachusetts Bay and sustained improvements in Boston Harbor, so MWRA continues to sample sites at those two locations.

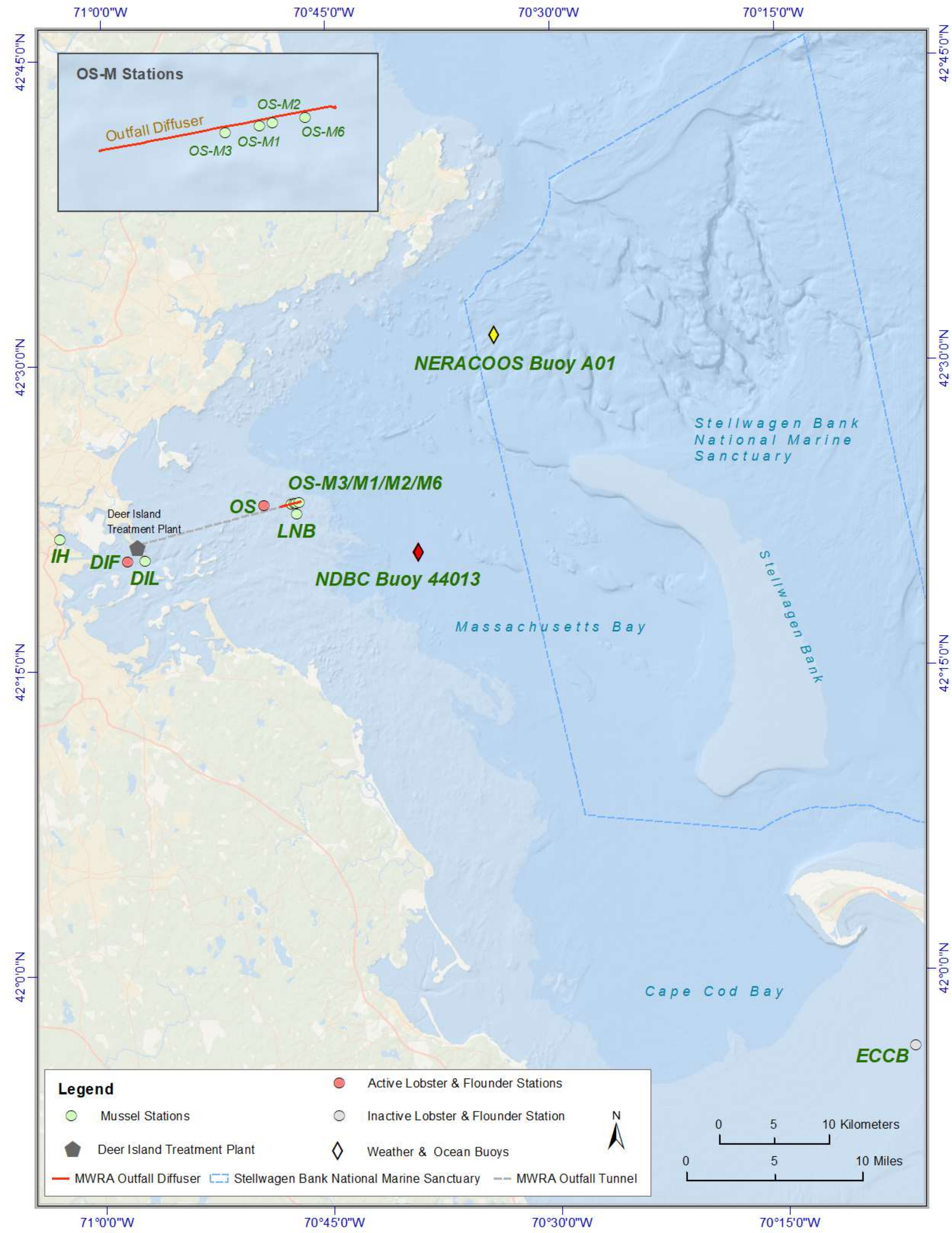


Figure 5-1. Fish-and-shellfish monitoring stations. IH = Inner Harbor; DIF = Deer Island Flats; DIL = Deer Island Light; OS = Outfall Site; OS-M = Outfall Site, Mussels; LNB = Large Navigation Buoy (buoy south of the outfall); ECCB = Eastern Cape Cod Bay. Also shown are the outfall, the instrumented buoys, and the Stellwagen Bank Marine Sanctuary.

Commercial fishing boats conducted flounder sampling over several days in April and May 2023. Sampling was hampered by entangled lobster traps and other “ghost” fishing gear, an abundance of seaweed (kelp), and a torn net (Moore et al. 2024; Figure 5-2). Even accounting for entangled fishing gear and abundant algal growth, which have regularly stalled fishing efforts, catches have been relatively low throughout the region in the past several years. Winter flounder populations throughout southern New England and the Mid-Atlantic have declined since the 1980s, probably a result of overfishing rather than pollution or warming waters (Frisk et al. 2018). It has also become increasingly difficult to engage the fishing boats that MWRA uses for sampling, particularly during time periods when commercial catches may be more lucrative for the boat owners. Following a back-up plan, the 2023 MWRA catch was supplemented by fish collected by the Massachusetts Department of Marine Fisheries.

Despite the extra effort, only 29 fish were taken from near the Massachusetts Bay outfall and only 15 fish from Deer Island Flats, marking the first year that the full complement of 50 fish was not reached in Massachusetts Bay. Catches from Deer Island Flats have fallen short in four of the past five years, but the 2023 catches were the lowest in more than three decades of monitoring. The low catch numbers, while still valuable, make comparisons with prior years more challenging.

Flounder Characteristics

The mean age of fish in 2023 was about 5.7 years at both stations, and standard length (length from the tip of the head to the base of the tail fin) ranged from 281 to 299 millimeters, within the historical ranges. Weights were also within the typical range for the program. As is common throughout northeast coastal populations (Moore et al. 2016), the catches were dominated by females.

Figure 5-2. Top: Lost lobster traps and other "ghost" fishing gear interfere with flounder collection. Bottom: Excess kelp also interferes with sampling. Photos taken at Deer Island Flats, near the former harbor outfall, in 2023. Photo credits Michael Moore, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts.

Flounder Health

In 2023, no CHV liver disease was found in the 15 flounder from Deer Island Flats in Boston Harbor. In contrast, in the late 1980s, more than 75% of Boston Harbor flounder had CHV.

Measures of external condition, such as bent fin rays and occurrence and severity of fin erosion, remained variable, but continued to reflect improved conditions since the 1980s and 1990s. Incidence of fin erosion, which has been associated with excess ammonium and other pollutants, remained low at both the Massachusetts Bay outfall site and Deer Island Flats. Ulcers, which are observed on the bottom or "blind side" of the fish in some years, were not present in 2023.

Incidence of centrotubular hydropic vacuolation (CHV), a key tumor precursor and mild liver condition associated with exposure to contaminants, was only 6.9% at the Massachusetts Bay outfall and completely absent within the small catch at Deer Island Flats (Figure 5-3). Although the low catch makes comparisons difficult, the continued decrease in CHV incidence at Deer Island Flats is a major environmental success. More than 75% of Boston Harbor flounder livers in the late 1980s showed at least some level of CHV. Incidence has decreased across all age groups in both the harbor and the bay, alleviating the concern prior to the Massachusetts Bay outfall startup that there could be increased liver disease in the bay. In the few fish where CHV has been found, severity of the condition has also declined over time.

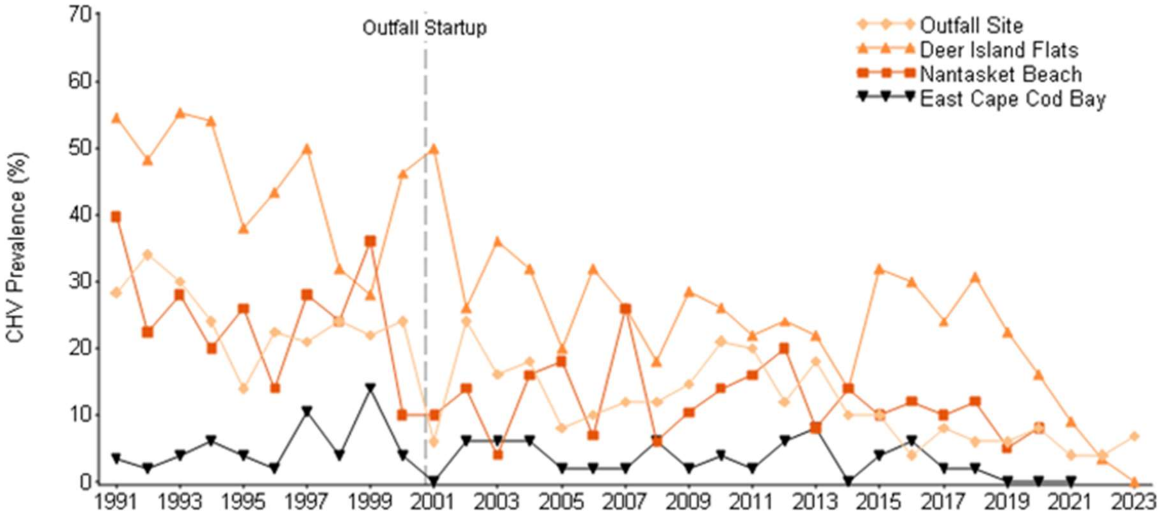


Figure 5-3. Annual prevalence of the tumor precursor centrotubular hydropic vacuolation (CHV) in winter flounder from the Massachusetts Bay outfall site and Deer Island Flats, 1991–2023. Nantasket Beach and East Cape Cod Bay are no longer sampled. CHV incidence and severity have declined throughout the region.

Cancerous liver tumors, also called neoplasia, which were present in up to 10% of flounder from Boston Harbor in the 1980s, remained absent, as they have since 2004. Tumors have never been found in fish taken from near the Massachusetts Bay outfall site (Figure 5-4; see also Moore et al. 2018).

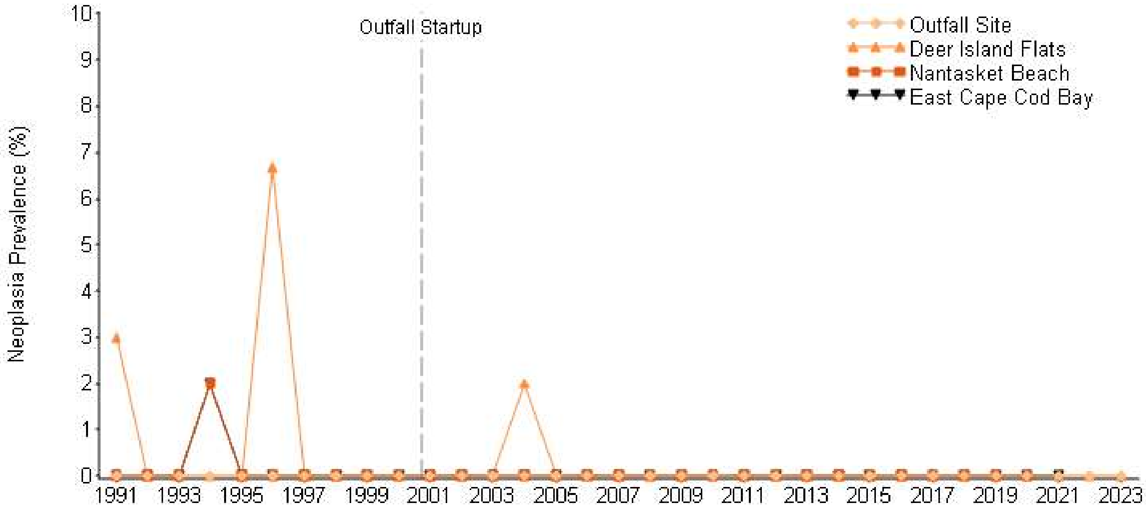


Figure 5-4. Annual prevalence of liver tumors (neoplasia) in winter flounder, 1991–2023. No tumors have ever been recorded in fish taken from near the Massachusetts Bay outfall.

Winter Flounder Contingency Plan Thresholds

There was no Contingency Plan threshold exceedance for the only parameter measured in 2023, flounder liver disease, measured as percent fish caught near the Massachusetts Bay outfall with CHV (Table 5-1). CHV occurred in only 6.9% of the fish, compared to the 24.4% baseline and a caution threshold of 44.9%.

Table 5-1. Contingency Plan threshold values and 2023 results for winter flounder monitoring.

Parameter	Baseline	Caution Level	Warning Level	2023 Results
Flounder disease				
Liver disease (CHV)	24.4%	>44.9%	NA	6.9%

CHV = centrotubular hydropic vacuolation, a liver tumor precursor associated with degraded habitats

6. Special Topics

In addition to the permit-required monitoring of the effluent and the water column, sea floor, and fish and shellfish in Massachusetts Bay, MWRA also initiates or collaborates on studies of Massachusetts Bay and the wider Gulf of Maine. These studies assess the physical conditions, biology, and ecology of the region. They also better inform interpretations of MWRA monitoring results. MWRA evaluates a range of topics in response to information from its routine monitoring programs, its directed studies, and research conducted by other institutions. This year’s report presents information about long-term environmental trends detected by MWRA and other institutions and the large regional *Tripos muelleri* dinoflagellate bloom that occurred in the spring and summer of 2023.

Regional Environmental Trends

Some components of MWRA’s monitoring program in Massachusetts Bay began in 1991, and the full program launched in 1992. As planned from the outset, the monitoring program has evolved over time, but the same suite of parameters has been measured at many of the same locations for more than 30 years. Such long-term programs are rare, and MWRA’s monitoring program has yielded decades of information about physical conditions and environmental trends in Massachusetts and Cape Cod Bays.

For example, MWRA’s long-term monitoring and studies by other agencies and scientists have documented increasing water temperatures in Massachusetts Bay and the broader Gulf of Maine. Increased water temperatures can lead to lower dissolved oxygen concentrations, both locally and regionally. Within the MWRA monitoring area, increased water temperatures may be one factor leading to decreases in dissolved oxygen levels and subsequent Contingency Plan threshold exceedances in recent years. Some scientists believe that increasing temperatures and changing ocean currents may be affecting the North Atlantic right whale population, which was already imperiled by historic whaling, ship collisions, and entanglement (for example, Meyer-Gutbrod et al. 2021).

In 2022, following two years of dissolved oxygen Contingency Plan exceedances, MWRA began an internal review of water temperature and dissolved oxygen concentrations over its 1992–2022 monitoring period (Codiga and Wu 2022). The analyses focused on eight stations in Massachusetts Bay near and far from the outfall, one station at the mouth of Boston Harbor, and one offshore station near Stellwagen Basin. Each of these stations had been monitored during six surveys each year, all completed during April through October, over 31 years. All measurements were made at five depths and occurred within the same calendar weeks per year.

MWRA's analyses showed clear and consistent increasing temperatures and declining dissolved oxygen concentrations across all stations and all water depths. Average April–October warming rates were about 0.4–0.6°C per decade. Dissolved oxygen concentrations declined about 0.17–0.23 milligrams per liter per decade.

At the NERACOOS Buoy A01, located at the northern limit of Massachusetts Bay (see Figure 3-1 on page 10), mean surface-water temperatures in July and August have also risen steadily for more than 20 years (Figure 6-1). Maximum, mean, and minimum temperatures increased by 0.7°C, 0.6°C, and 0.8°C per decade, respectively. Similar data from the NDBC Buoy in central Massachusetts Bay show the same pattern over an even longer time period.

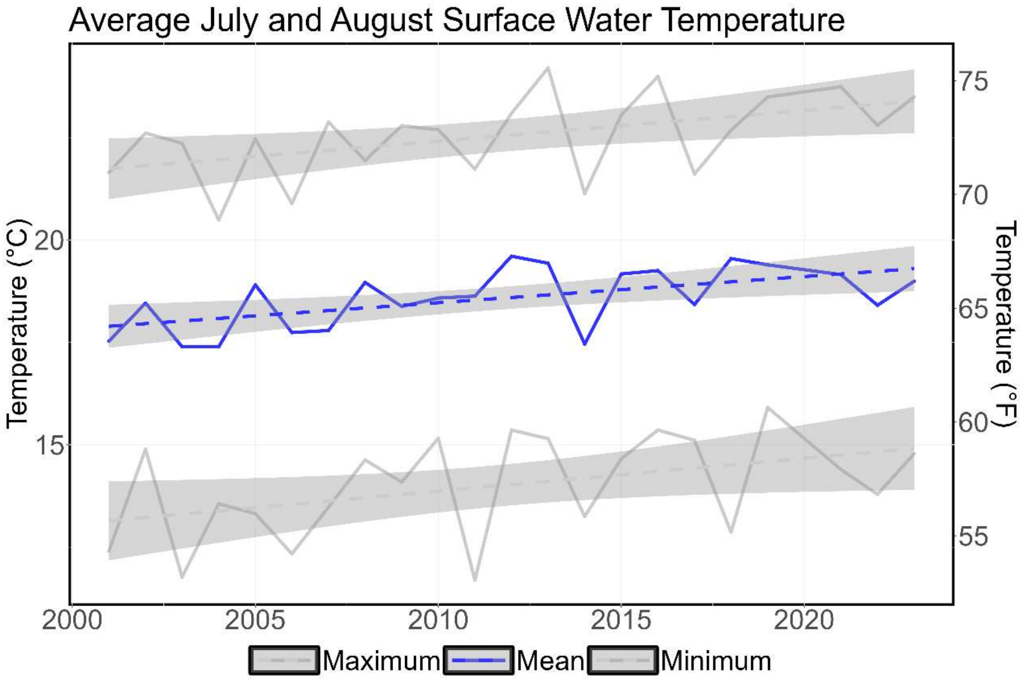


Figure 6-1. Increases in summertime (July and August) water temperatures in Massachusetts Bay, 2001-2023. Data are from the NERACOOS Buoy A01, located in northern Massachusetts Bay. The dashed lines show the linear trends: Maximum (slope = 0.6ºC or 1.3ºF/decade, $P<0.01$), mean (slope = 0.7ºC or 1.1ºF/decade, $P<0.05$), minimum (slope = 0.8ºC or 1.4ºF/decade, $P<0.05$). The shaded area shows the 95% confidence interval surrounding the trend lines. P = probability. $P<0.01$ and $P<0.05$ indicated that the measured changes are statistically significant.

Water temperatures have increased more quickly than air temperatures, possibly due to changes in wind conditions, which can bring warmer, saltier, and less oxygenated, water masses into Massachusetts Bay from offshore. In recent years, summertime winds have increasingly come from the southeast rather than the southwest (Figure 6-2). Preliminary analysis by Malcolm Scully at the Woods Hole Oceanographic Institution in Woods Hole, Massachusetts suggests that these changes in wind direction may be influencing long-term warming of the water column. The changes in wind directions and subsequent influx of water from offshore have been reflected in MWRA zooplankton samples, which have documented increasing presence of offshore zooplankton species since 2020 (see Section 3, Water Column).

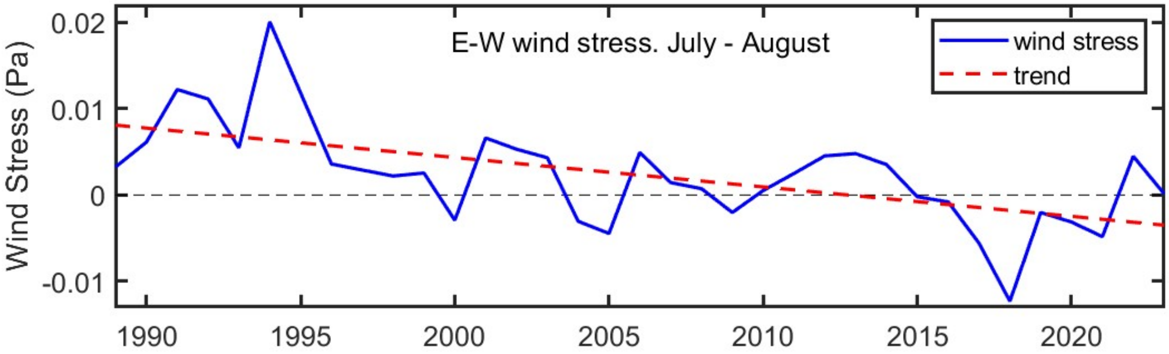


Figure 6-2. Wind stress, 1989-2023. Summertime winds increasingly come from the southeast; in past years, winds more typically came from the southwest. E-W = east to west, Pa = Pascal, a unit of pressure used to quantify wind stress and other pressure-related measurements.

MWRA colleagues from Bowdoin College in Brunswick, Maine have been studying trends in chlorophyll fluorescence and turbidity at the NERACOOS Buoy A01, off Cape Ann at the northern boundary of Massachusetts Bay (Roesler et al. 2024). Bowdoin College, along with the University of Maine, helps to maintain the buoy and has, over the years, added increasingly sophisticated sensors. Their recent measurements in 2022–2023, combined with data collected since 2005, found that spring and fall phytoplankton blooms are beginning earlier and lasting longer than they did in the past. To date, these changes have not affected total annual phytoplankton biomass, but the peak chlorophyll levels in the fall blooms appear to be increasing.

MWRA will continue to track these region-wide physical trends, particularly as they affect Boston Harbor and Massachusetts and Cape Cod Bays. Some of the changes could alter the assumptions made during planning for the Massachusetts Bay outfall or change data interpretation. Those assumptions and interpretations may have to be re-evaluated in the face of the changing environment.

2023 *Tripos muelleri* Bloom

The biggest story of 2023 was the *Tripos muelleri* phytoplankton bloom, which occurred in the spring and summer throughout much of New England (Figure 6-3). *Tripos muelleri*, formerly known as *Ceratium tripos*, is a frequently abundant dinoflagellate species found around the world and is not considered a nuisance species. *Tripos muelleri* abundance dominated the April–July MWRA phytoplankton samples in 2023 and led to Contingency Plan threshold exceedances for chlorophyll and dissolved oxygen. Other phytoplankton species, including other dinoflagellates in the genus *Tripos* were not included in the bloom and were present in numbers typical of other years of monitoring. The bloom was not repeated in 2024.

Figure 6-3. A plankton tow near the mouth of the North River, Marshfield, Massachusetts, during the 2023 *Tripos muelleri* bloom. Photo credits Joseph Vallino, The Ecosystems Center, Marine Biological Laboratory, Woods Hole, Massachusetts, who described the sample as being “like peanut butter.”

Tripos species blooms have occurred around the world, from Europe and Africa, to the Americas and Asia. *Tripos muelleri* blooms were documented in the Gulf of Maine in the 1910s and 1920s. Some MWRA team members were working marine scientists in 1976, when a *Tripos muelleri* bloom occurred in the New York Bight (Malone 1978, Mahoney 1978, Falkowski et al. 1980). That bloom has been attributed to a year with warm winter water temperatures, large river inputs, few storms, a deep summer pycnocline, persistent winds from the south, inputs of carbon from offshore waters, and low grazing pressure by zooplankton (Falkowski et al. 1980). It resulted in widespread anoxia and a $60 million loss to the shellfish industry along the New Jersey coast. The bloom may have impacted a wider geographic area than was studied at the time.

Tripos muelleri abundance was higher than the average during every MWRA survey in 2023, but was extremely high in the spring and summer months (Figure 6-4). In April through June, abundance was 13–20 times the long-term average. In May and June, peak abundance reached 100,000 cells per liter.

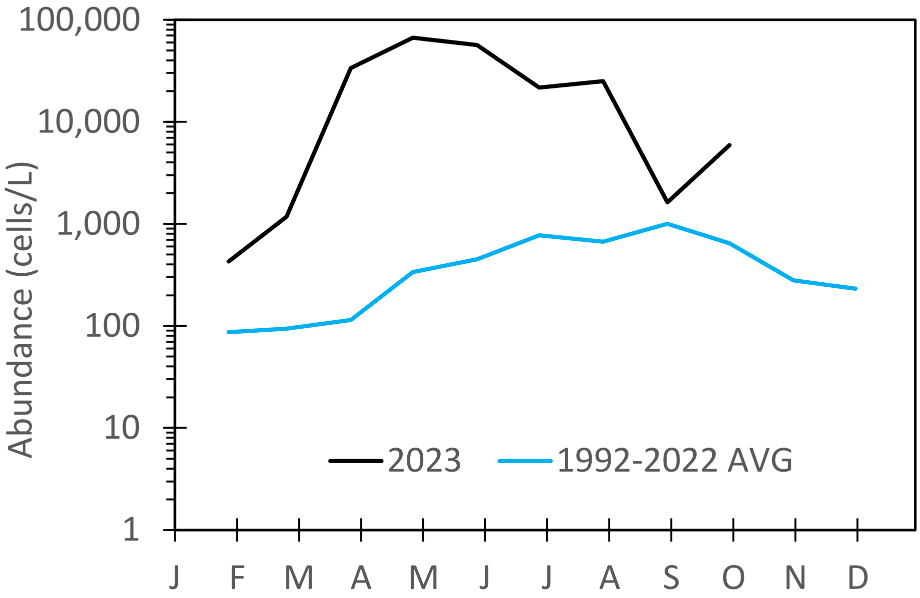
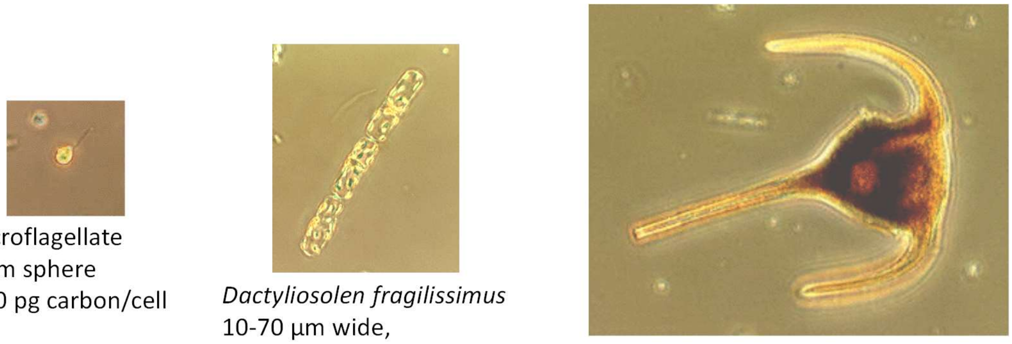


Figure 6-4. Average abundance of *Tripos muelleri* in 2023 MWRA samples compared to 1992–2022. Note log scale on the y-axis. AVG = average.

Tripos muelleri is larger than most other phytoplankton species, and it grows more slowly (Figure 6-5). Microflagellates, which are the most abundant phytoplankton in Massachusetts Bay, are about three micrometers long and wide, while *Tripos muelleri* is at least 20 times wider, about 100 times longer, and contains about 1,000 times the amount of carbon (one measure of biomass) in each cell. It grows more slowly than other types of phytoplankton, although there is evidence that growth rates in the region were higher than usual during the spring of 2023, perhaps a response to warming waters.



Microflagellate
3 µm sphere
< 10 pg carbon/cell

Dactyliosolen fragilissimus
10-70 µm wide,
40 – 300 µm long
332 pg carbon/cell

Tripos muelleri
60-90 µm wide, 200-400 µm long
About 10,000 pg carbon/cell
Maximum 50,000 pg carbon/cell

Figure 6-5. *Tripos muelleri* is much larger, contains more biomass, and grows more slowly than other types of phytoplankton. Photo credits David Borkman, Pausacaco Plankton, Saunderstown, Rhode Island. µm = micrometer; pg = picogram.

Strong and persistent stratification of the water column is correlated with *Tripos muelleri* abundance in Massachusetts Bay, because stable conditions are best for slow-growing species (Figure 6-6 and Hunt et al. 2010; see also Figure 3-4 on page 14, which shows stratification in 2023 compared to past years). More turbulent conditions make it difficult for *Tripos* species to maneuver in the water column, impeding their typical daily upward and downward migrations, which maximize light and nutrient acquisition and increase predator avoidance. Early and persistent stratification, driven by warm temperatures and low salinities in the surface waters, may have been the main factor driving *Tripos muelleri* growth in 2023.

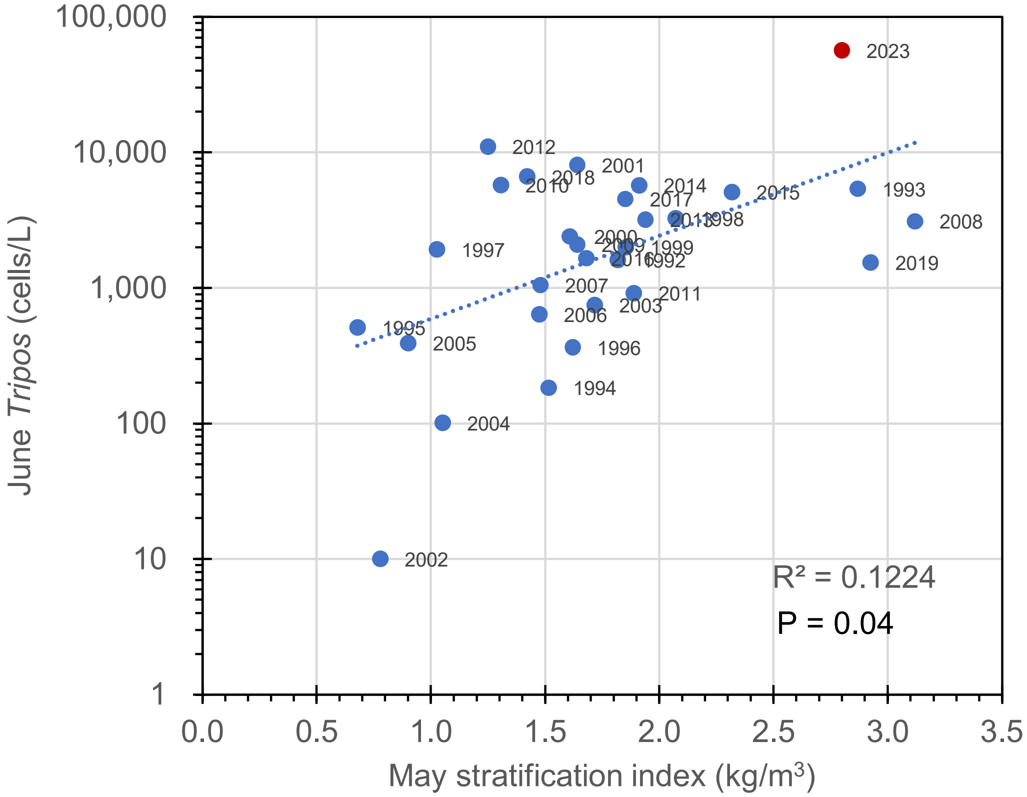


Figure 6-6. *Tripos muelleri* abundance in June compared to water-column stratification during May, 1992–2023. Greater stratification of the Massachusetts Bay water column in May is correlated with *Tripos muelleri* abundance in June. cells/L = cells per liter. kg/m^3 = kilogram per cubic meter.

Massive phytoplankton blooms, such as the *Tripos muelleri* event of 2023 are rare. It is hard to determine not only why they occur, but also why they are rare. Ecologists who study phytoplankton communities have long tried to understand how such blooms develop and why they are not more common, as individual species should regularly outcompete others for sunlight, nutrients, and other necessary resources. MWRA participates in workshops and shares data with agencies and research organizations that continue to assess the 2023 bloom.

7. Update on the NPDES Permit

MWRA’s permit to discharge treated sewage effluent into Massachusetts Bay became effective in August 2000. EPA issued the permit for a period of just five years, but it has been administratively continued ever since.

EPA issued a new draft permit, NPDES Permit No. MA0103284, in May 2023 and received public comments through November 28, 2023 (EPA's Permit for the Massachusetts Water Resources Authority (MWRA) Deer Island Treatment Plant Outfall and CSOs | US EPA). The Massachusetts Department of Environmental Protection issued a companion Surface Water Discharge permit which, by reference, incorporated the EPA NPDES permit requirements. After the close of the public comment period, EPA began its review and response, required steps prior to issuing a final permit. The issuance of the final NPDES permit by EPA is still pending.

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List of Acronyms

ASP	Amnesic shellfish poisoning
AVG	Average
BOD	Biochemical oxygen demand
cBOD	Carbonaceous biochemical oxygen demand
cells/L	Cells per liter
cfu	Colony forming units
CHV	Centrotubular hydropic vacuolation
DDT	Dichlorodiphenyltrichloroethane
DIF	Deer Island Flats
DO	Dissolved oxygen
ECCB	Eastern Cape Cod Bay
EPA	U.S. Environmental Protection Agency
E-W	East to west
kg	Kilograms
kg/m^3	Kilograms per cubic meter
IAAC	Inter-Agency Advisory Committee
LC50	50% mortality concentration
LNB	Large navigation buoy
m	Meters
m^3/s	Cubic meters per second
mg/L	Milligrams per liter
mg/m^3	Milligrams per cubic meter
mL	Milliliters
MGD	Million gallons per day
mtons	Metric tons
MWRA	Massachusetts Water Resources Authority
µg/L	Micrograms per liter
µm	Micrometer
µM	Micromoles
NA	Not analyzed/not applicable
NDBC	National Data Buoy Center
NERACOOS	Northeastern Regional Association of Coastal and Ocean Observing Systems
ng/L	Nanograms per liter
NOAA	National Oceanic and Atmospheric Administration
NOEC	No observed effects concentration
NPDES	National Pollutant Discharge Elimination System
OS	Outfall site
P	Probability
Pa	Pascal
PAH	Polycyclic aromatic hydrocarbon
PCB	Polychlorinated biphenyl
Pg	Picogram
PSP	Paralytic shellfish poisoning
PSU	Practical salinity units
TN	Total nitrogen
TSS	Total suspended solids

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