2015 Outfall monitoring overview

Massachusetts Water Resources Authority
Environmental Quality Department
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2015
Outfall Monitoring Overview

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Summary

Each year, the Massachusetts Water Resources Authority (MWRA) prepares an overview of environmental monitoring related to the discharge of municipal wastewater effluent from Deer Island Treatment Plant through an offshore outfall tunnel into Massachusetts Bay. The report presents monitoring results and information relevant to MWRA's permit-required Contingency Plan, including threshold exceedances and permit violations, responses, and, if needed, corrective actions. The overview also includes monitoring results relevant to the Stellwagen Bank National Marine Sanctuary and information on special studies conducted in response to specific permit requirements, scientific questions, or public concerns.

This report for the 2015 monitoring year marks more than fifteen years since September 2000, when MWRA ceased discharge of wastewater effluent to the relatively confined waters of Boston Harbor and began to discharge into deeper, less confined waters in Massachusetts Bay. Before September 2000, MWRA had completed almost nine years of baseline monitoring. This report for 2015 includes results of effluent analyses; water-column, seafloor, and fish-and-shellfish monitoring in the vicinity of the outfall (the "nearfield") and at reference stations; and results pertinent to Stellwagen Bank and to Boston Harbor. This year's report on special studies focuses on eelgrass in Boston Harbor, bacterial water quality in Boston Harbor and Massachusetts Bay, winter flounder sex ratios, and ongoing Cape Cod Bay studies.

Operations at the Deer Island Treatment Plant continued to be exceptional in 2015, earning MWRA a National Association of Clean Water Agencies (NACWA) Platinum 9 Peak Performance Award. This NACWA award recognizes facilities with 100% compliance with permit effluent limits for nine consecutive years. Nearfield and reference-station monitoring results from 2015 were consistent both with predictions made during the outfall siting process and with past results, showing no unanticipated effects of the discharge (Tables i through iv). No Contingency Plan "warning-level" exceedances were observed. A "caution-level" exceedance[*] occurred for one water-column parameter, summer levels of the nuisance algal species *Phaeocystis pouchetii*. This exceedance was due to presence of *Phaeocystis* at a low abundance in one sample during the May survey and was likely caused by a weather-related delay of the seasonal phytoplankton cycle. Except for a number of exceedances of the *Phaeocystis* thresholds, which resulted from wide regional blooms, water-column exceedances have been rare throughout the course of monitoring and have not been indicative of problems at the treatment plant or in the environment.

[*] MWRA's discharge permit includes Contingency Plan thresholds, indicators that may signal a need for action. The thresholds are based on permit limits, state water quality standards, and expert judgment. "Caution-level" thresholds indicate a need for a closer look at the data to determine the reason for an observed change. "Warning-level" thresholds are a higher level of concern, and the permit requires a series of steps to evaluate whether adverse effects occurred and if so, whether they were related to the discharge. If exceedances were related to the discharge, MWRA might need to implement corrective action. All thresholds based on effluent discharge permit limits are warning-level. Some ambient parameters have both caution- and warning-level thresholds, and others have only caution-level thresholds.

Table i. Contingency Plan threshold values and 2015 results for effluent monitoring.

Parameter	Baseline	Caution Level	Warning Level	2015 Results
pH	NA	None	<6 or >9	Not exceeded
Fecal coliform	NA	None	>14,000 fecal coliforms/100 mL	Not exceeded
Chlorine, residual	NA	None	>631 µg/L daily, >456 µg/L monthly	Not exceeded
Suspended solids	NA	None	>45 mg/L weekly >30 mg/L monthly	Not exceeded
cBOD	NA	None	>40 mg/L weekly, >25 mg/L monthly	Not exceeded
Acute toxicity	NA	None	LC50 <50%	Not exceeded
Chronic toxicity	NA	None	NOEC <1.5% effluent	Not exceeded
PCBs	NA	Aroclor >0.045 ng/L	None	Not exceeded
Plant performance	NA	>5 violations/year	Compliance <95% of the time	Not exceeded
Flow	NA	None	>436 MGD average dry days	Not exceeded
Total nitrogen load	NA	>12,500 mtons/year	>14,000 mtons/year	Not exceeded
Oil and grease	NA	None	>15 mg/L weekly	Not exceeded

NA = not applicable
cBOD = carbonaceous biological oxygen demand
LC50 = 50% mortality concentration
NOEC = no observable effect concentration
PCB = polychlorinated biphenyl
Plant performance = compliance with permit conditions

Table ii. Contingency Plan threshold values and 2015 results for water-column monitoring.

Parameter	Baseline	Caution Level	Warning Level	2015 Results
Dissolved oxygen*				
Nearfield concentration	6.05 mg/L	<6.5 mg/L	<6.0 mg/L	7.56 mg/L
Nearfield percent saturation	65.3%	<80%	<75%	84.5%
Stellwagen concentration	6.23 mg/L	<6.5 mg/L	<6.0 mg/L	7.44 mg/L
Stellwagen percent saturation	67.2%	<80	<75%	79.6%
Nearfield depletion rate	0.024 mg/L/d	>0.037 mg/L/d	>0.049 mg/L/d	0.018 mg/L/d
Chlorophyll				
Annual	72 mg/m^2	>108 mg/m^2	>144 mg/m^2	87 mg/m^2
Winter/spring	50 mg/m^2	>199 mg/m^2	None	122 mg/m^2
Summer	51 mg/m^2	>89 mg/m^2	None	58 mg/m^2
Autumn	90 mg/m^2	>239 mg/m^2	None	94 mg/m^2
Nuisance algae *Phaeocystis pouchetii*				
Winter/spring	622,000 cells/L	>2,860,000 cells/L	None	13,800 cells/L
Summer	72 cells/L	>357 cells/L	None	408 cells/L, caution level exceedance
Autumn	370 cells/L	>2,960 cells/L	None	Absent
Nuisance algae nearfield *Pseudo-nitzschia*				
Winter/spring	6,735 cells/L	>17,900 cells/L	None	51 cells/L
Summer	14,635 cells/L	>43,100 cells/L	None	925 cells/L
Autumn	10,050 cells/L	>27,500 cells/L	None	294 cells/L
Nuisance algae nearfield *Alexandrium fundyense*				
Any nearfield sample	Baseline maximum 163 cells/L	>100 cells/L	None	3 cells/L
PSP toxin extent	NA	New incidence	None	No new incidence

*Dissolved oxygen caution and warning levels represent numerical standards, with the caveat “unless background conditions are lower.” Results are therefore compared to the baseline rather than to the caution and warning levels.
PSP = paralytic shellfish poisoning
NA = not applicable

Table iii. Contingency Plan threshold values and 2015 results for seafloor monitoring.

Parameter	Baseline	Caution Level	Warning Level	2015 Results
Sediment parameters				
RPD depth	NA	<1.18 cm	None	5.51 cm
Benthic community parameters				
Species per sample	NA	<42.99 or >81.85	None	61.0
Fisher's log-series alpha	NA	<9.42 or >15.8	None	13.1
Shannon-Wiener diversity	NA	<3.37 or >3.99	None	3.93
Pielou's evenness	NA	<0.57 or >0.67	None	0.66
% opportunists	NA	>10%	>25%	0.39%

HMW = high molecular weight; LMW = low molecular weight
NA = not applicable; RPD = redox potential discontinuity

Table iv. Contingency Plan threshold values and 2015 result for fish-and-shellfish monitoring.*

Parameter	Baseline	Caution Level	Warning Level	2015 Results
Flounder disease				
Liver disease (CHV)	24.4%	44.9%	None	10%
Flounder meat				
PCB	0.033 ppm	1 ppm wet weight	1.6 ppm wet weight	0.0153 ppm
Mercury	0.074 ppm	0.5 ppm wet weight	0.8 ppm wet weight	0.0694 ppm
Flounder meat, lipid normalized				
Chlordane	242 ppb	484 ppb	None	19 ppb
Dieldrin	63.7 ppb	127 ppb	None	0 ppb
DDT	775.9 ppb	1552 ppb	None	170 ppb
Lobster meat				
PCB	0.015 ppm	1 ppm wet weight	1.6 ppm wet weight	0.0121 ppm
Mercury	0.148 ppm	0.5 ppm wet weight	0.8 ppm wet weight	0.102 ppm
Lobster meat, lipid normalized				
Chlordane	75 ppb	150 ppb	None	2.3 ppb
Dieldrin	161 ppb	322 ppb	None	0 ppb
DDT	341.3 ppb	683 ppb	None	44.8 ppb
Mussel tissue				
PCB	0.011 ppm	1 ppm wet weight	1.6 ppm wet weight	0.00276 ppm
Lead	0.415 ppm	2 ppm wet weight	3 ppm wet weight	0.147 ppm
Mercury	0.019 ppm	0.5 ppm wet weight	0.8 ppm wet weight	0.00879 ppm
Mussel tissue, lipid normalized				
Chlordane	102.3 ppb	205 ppb	None	16.1 ppb
Dieldrin	25 ppb	50 ppb	None	0 ppb
DDT	241.7 ppb	483 ppb	None	26.3 ppb
PAH	1080 ppb	2160 ppb	None	1580 ppb

* Exceedances are values greater than (>) all thresholds.
CHV = centrotubular hydropic vacuolation

1. Introduction

Since its creation by the Massachusetts state legislature in 1984, the Massachusetts Water Resources Authority (MWRA) has worked to minimize the effects of municipal wastewater discharge on the marine environment. The mission of what became known as MWRA's Boston Harbor Project included reducing inflow of contaminants into the waste stream, ending biosolids discharge, improving wastewater-treatment facilities, and providing better dilution of the effluent discharge. Starting during its early years, MWRA conducted environmental monitoring in Boston Harbor, where both biosolids and effluent were discharged, and also in Massachusetts Bay, at what would become the site of a relocated wastewater-effluent discharge.

By 2000, most of the Boston Harbor Project had been completed. Biosolids discharges ended in December 1991, all discharges to the southern portion of the harbor ended in 1998, and upgrades to the Deer Island Treatment Plant (DITP) were completed in 1995–2001. A major milestone was reached in September 2000, when all effluent discharge was diverted from Boston Harbor to the deeper, less confined waters of Massachusetts Bay. The relocated outfall operates 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 (MassDEP).

The NPDES permit requires monitoring of effluent and receiving waters to assess compliance with permit conditions and with a permit-required Contingency Plan. Results are presented in annual outfall monitoring overviews, such as this report. Background information about the monitoring program (Werme et al. 2012), the monitoring plan (MWRA 2010), the Contingency Plan (MWRA 2001), past plans and overviews, and area-specific technical reports are available in MWRA's technical report list, http://www.mwra.state.ma.us/harbor/enquad/trlist.html.

This year's outfall monitoring overview presents results from 2015, marking the twenty-fourth year of Massachusetts Bay monitoring and more than fifteen years of outfall discharge from the deep-water outfall. The report presents information relevant to permit and Contingency Plan conditions in effluent, water-column, seafloor, and fish-and-shellfish parameters, as well as special studies conducted in response to permit conditions and environmental concerns. Data relevant to the Stellwagen Bank National Marine Sanctuary, located offshore from the outfall, are presented in the overview's water-column and seafloor sections. The report also includes pertinent information from MWRA's separate monitoring efforts in Boston Harbor.

2. Effluent

2015 Characterization

The Deer Island Treatment Plant continued to operate as designed through 2015, earning MWRA the National Association of Clean Water Agencies (NACWA) Platinum 9 Peak Performance Award. This NACWA award recognizes facilities with 100% compliance with effluent permit limits over nine consecutive years.

The Boston area received almost 10 inches less rain than the long-term average in 2015, one of the driest years since 1990 (Figure 2-1). Consequently, total effluent flow in 2015, 295 million gallons per day, was lower than flows in 2013 or 2014, but about the same as the record low flow of 2012 (Figure 2-2). Virtually all the flow, 99.7%, received full primary and secondary treatment, with only trace discharges of primary-only effluent blended with fully treated effluent prior to discharge in any month (Figure 2-3).

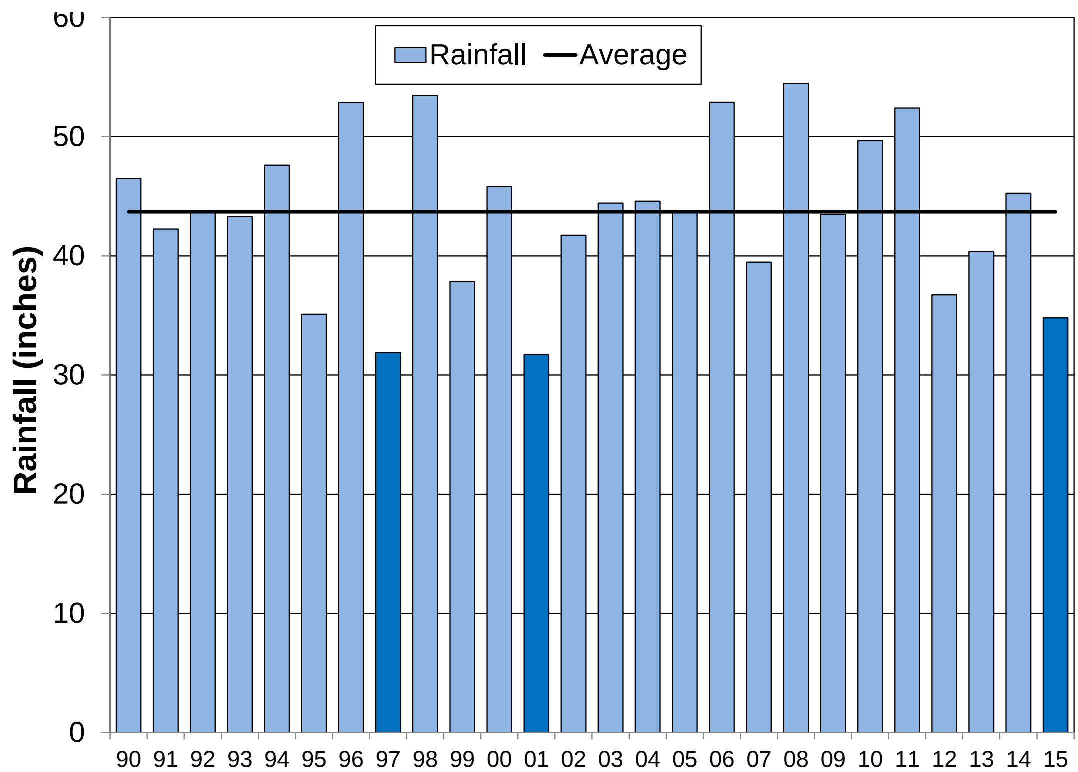

Figure 2-1. Annual rainfall in Boston, 1990–2015. Note the lowest rainfall years in 1997, 2001, and 2015. The horizontal line denotes the long-term average.

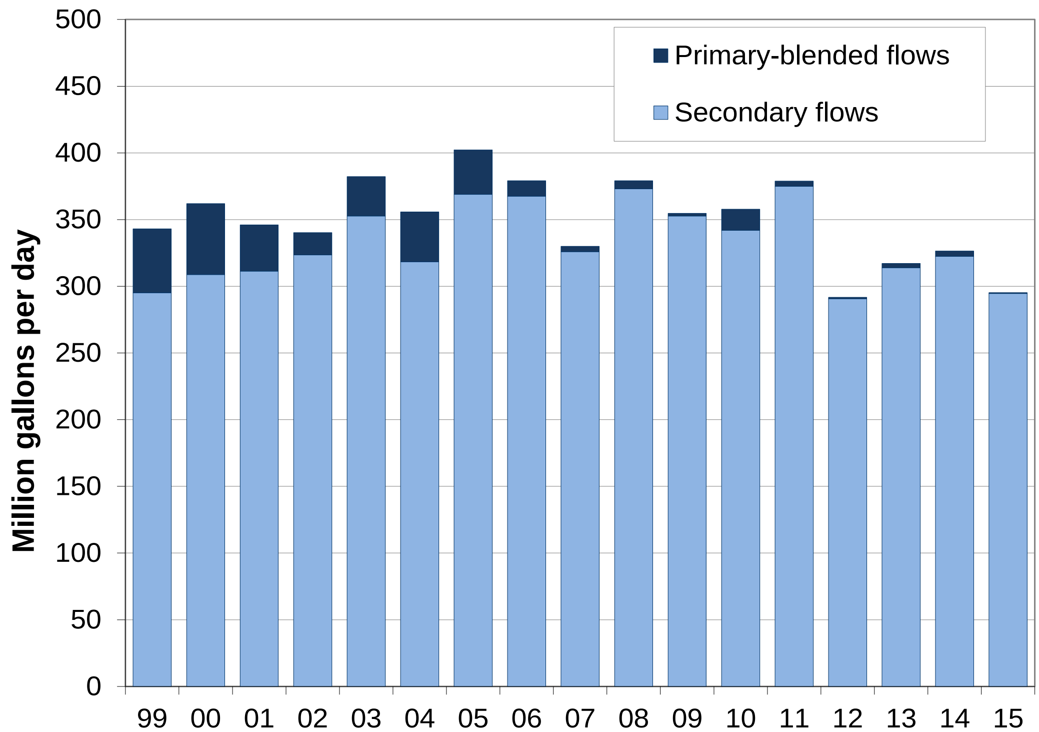

Figure 2-2. Annual primary-blended and full secondary effluent flows, 1999–2015. During large storms, flow exceeding the secondary capacity of the plant is diverted around the secondary process to prevent washing out the essential microbes that carry out secondary treatment. These primary-treated flows are then combined ("blended") with full secondary flows before disinfection and discharge. All 2015 discharges met permit limits.

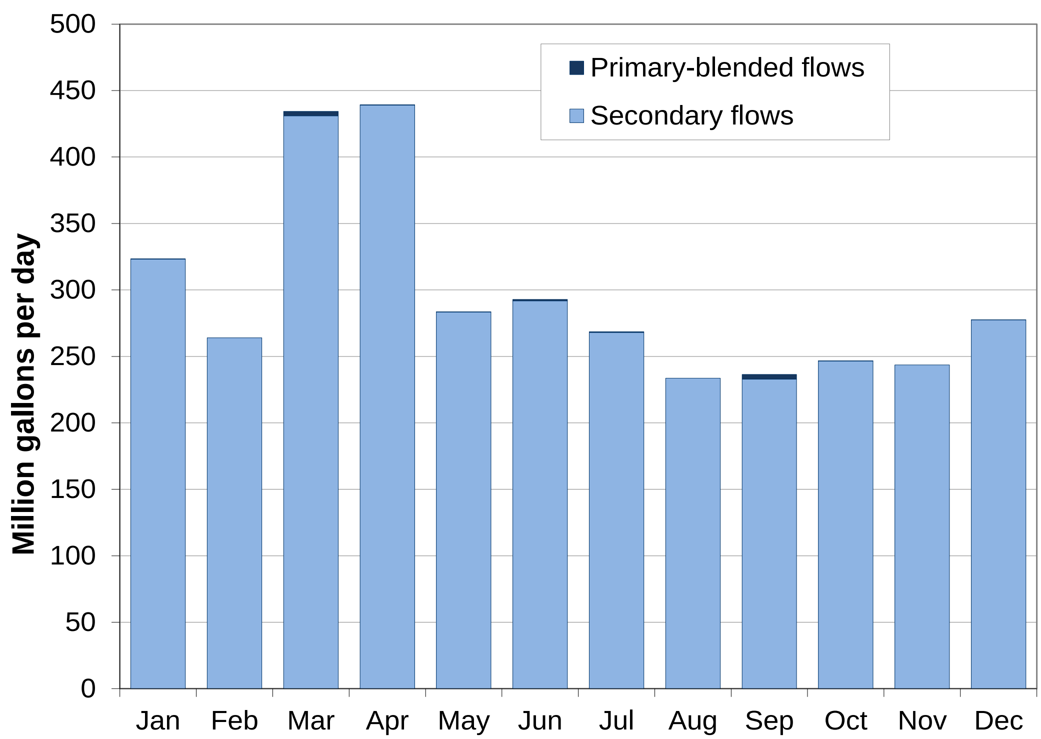

Figure 2-3. Monthly primary-blended and full secondary effluent flows during 2015.

The total suspended solids load to Massachusetts Bay remained well below the loads discharged to Boston Harbor before the relocated outfall began operation in 2000, 12.4 tons per day, compared to almost 160 tons per day in 1990 and 28.5 tons per day in 2000 (Figure 2-4). Carbonaceous biological oxygen demand, a measure of the amount of oxygen consumed by microorganisms, also remained low, well below levels that would be expected to affect dissolved oxygen at the discharge (not shown).

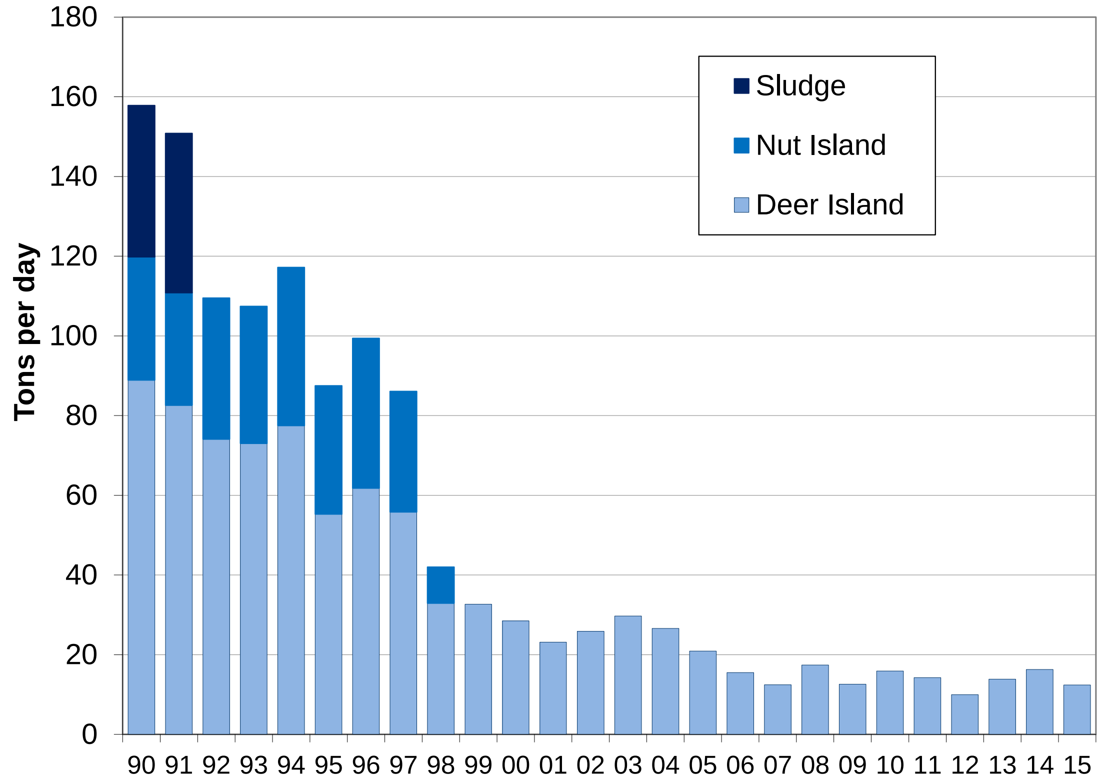

Figure 2-4. Annual solids discharges, 1990–2015. Solids discharges remained low in 2015. (Ending biosolids (sludge) disposal and effluent discharge to the southern portion of the harbor from Nut Island and the implementation of secondary treatment were important steps in the Boston Harbor Project. All effluent discharge was diverted from Boston Harbor to Massachusetts Bay in September 2000.)

The total nitrogen load also remained below its threshold in 2015 (Figure 2-5) and was close to the 1999–2015 average. The portion of the load made up of ammonium remained high, as it has since earlier years of the Boston Harbor Project. About 10% of the ammonium in the wastewater influent is removed by secondary treatment, but the biological treatment process converts some organic forms of nitrogen to ammonium. Also, ammonium-rich liquids from the biosolids pelletizing (fertilizer) plant, built as part of the Boston Harbor Project to end biosolids discharge to the harbor, are reintroduced to DITP for treatment, adding to the ammonium load.

As required by its permit, MWRA continually evaluates nitrogen-removal technologies, so that removal could be quickly implemented, should a need arise (Smolow 2016). Because nitrogen loads have remained below the Contingency Plan caution threshold, and there have been no adverse environmental effects due to nitrogen, nitrogen removal has not been pursued.

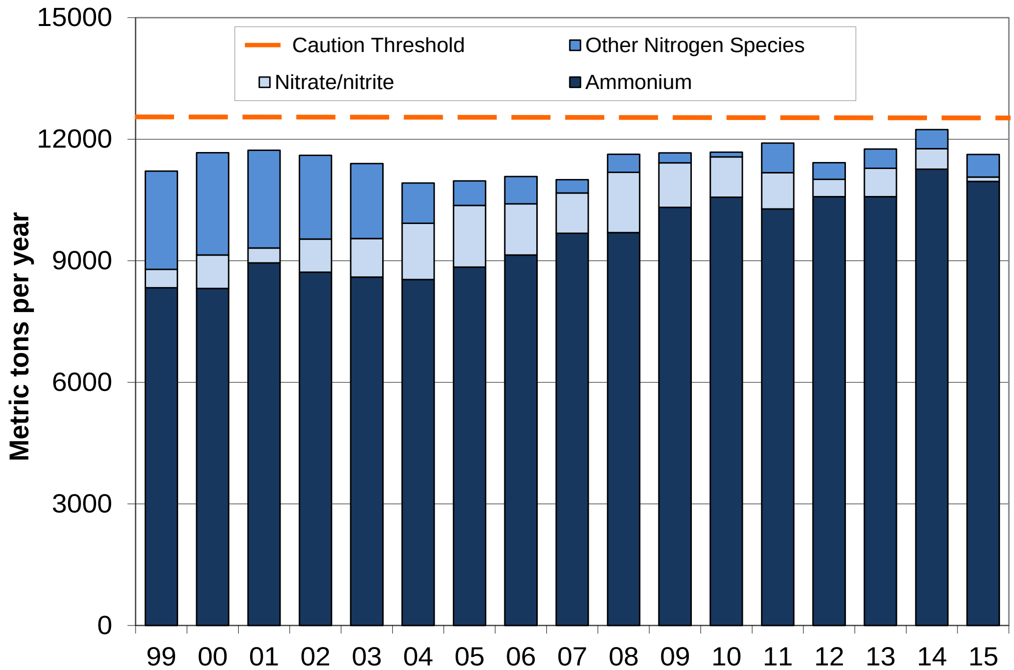

Figure 2-5. Annual nitrogen discharges, 1999–2015. Most of the nitrogen in the effluent is in the form of ammonium.

Metals loads remained low in 2015, with zinc and copper continuing to comprise most of the annual discharges (Figure 2-6). Metals loads are now mostly a factor of rainfall and flow rates rather than variations in inputs to the waste stream. Total discharges in 2015 were about 80 pounds per day, a fraction of what they were before the Boston Harbor Project began, when more than 750 pounds of metals were discharged to Boston Harbor each day. Except for copper, metals meet water quality standards prior to discharge, while copper meets the standard after initial dilution at the Massachusetts Bay outfall. Once considered a sewage tracer, silver is no longer detected in the effluent in appreciable amounts, a result of improved removal efficiencies and the change from film to digital photography. Annual mercury discharges (not shown) are only about 10% of what had been anticipated during the outfall planning process. Most mercury inputs to New England waters now come from atmospheric sources.

Polycyclic aromatic hydrocarbon (PAH) and other organic contaminant loads were also much lower than had been anticipated during the outfall planning process. Annual PAH discharges in 2015 were less than 200 pounds per year (Figure 2-7), whereas in 1988, MWRA projected annual discharges would be about 3,100 pounds of total PAHs per year, even with full secondary treatment.

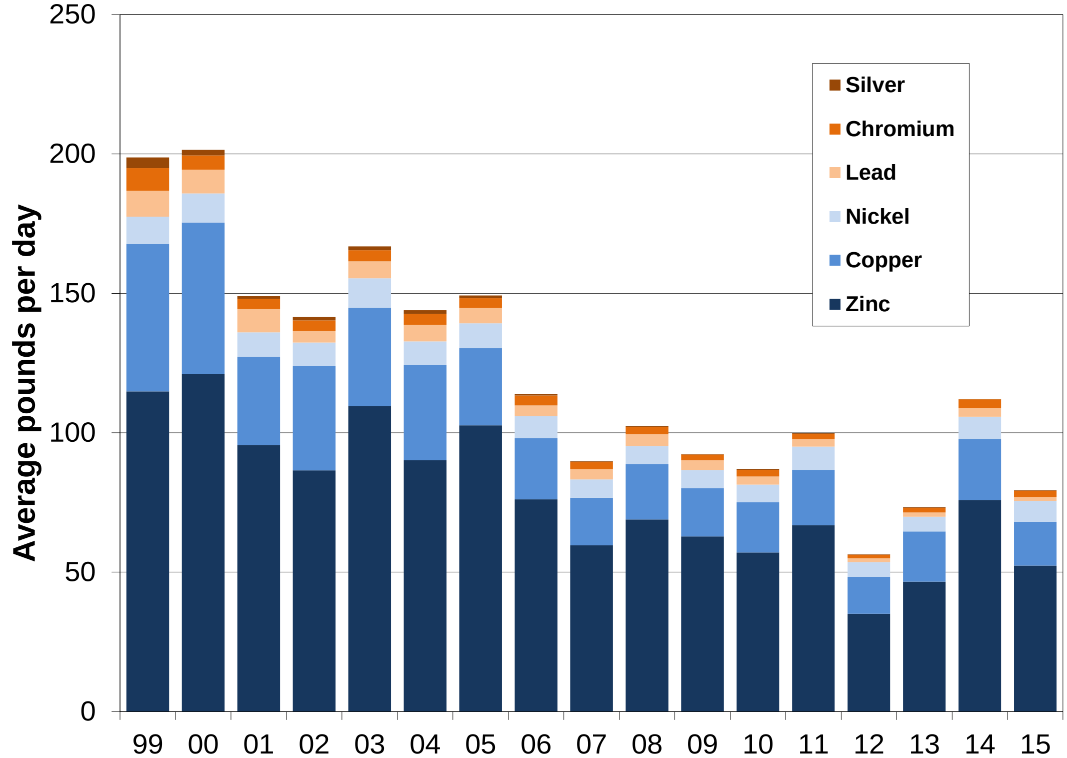

Figure 2-6. Annual metals discharges, 1999–2015.

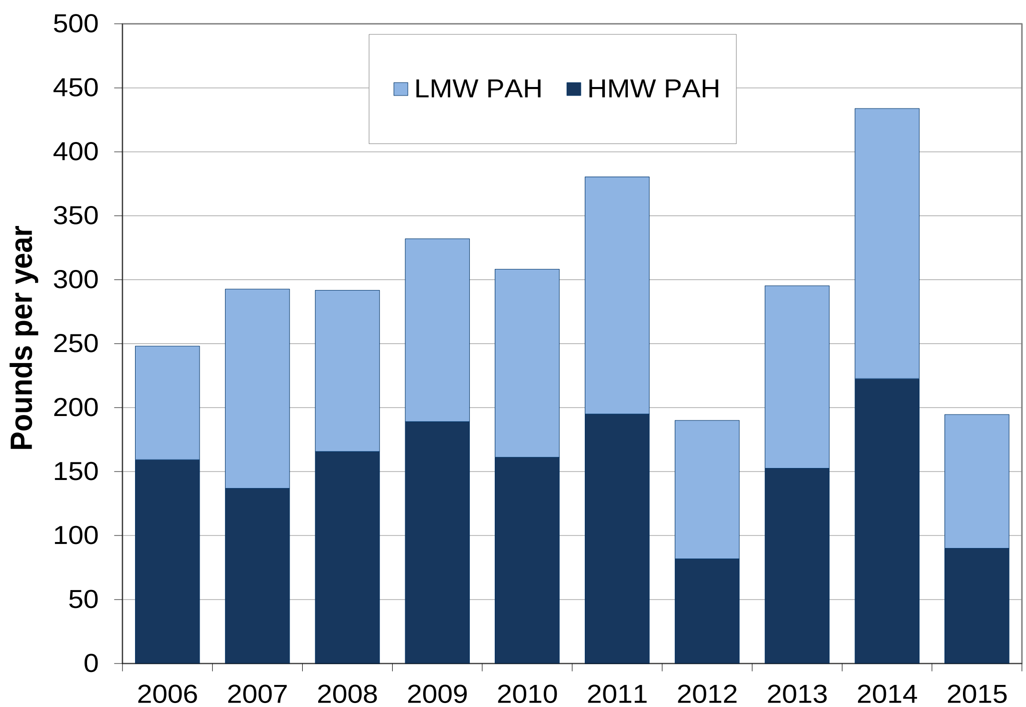

Figure 2-7. Annual PAH discharges, 2006–2015. LMW PAH = lower molecular weight PAH, HMW PAH = high molecular weight PAH

Contingency Plan Thresholds

There were no permit violations in 2015 and no exceedances of the Contingency Plan effluent thresholds (Table 2-1). Effluent threshold exceedances have been rare throughout the duration of the monitoring program, and none have occurred over the past nine years.

Table 2-1. Contingency Plan threshold values and 2015 results for effluent monitoring.

Parameter	Caution Level	Warning Level	2015 Results
pH	None	<6 or >9	Not exceeded
Fecal coliform	None	>14,000 fecal coliforms/100 mL	Not exceeded
Chlorine, residual	None	>631 µg/L daily, >456 µg/L monthly	Not exceeded
Suspended solids	None	>45 mg/L weekly >30 mg/L monthly	Not exceeded
cBOD	None	>40 mg/L weekly, >25 mg/L monthly	Not exceeded
Acute toxicity	None	LC50 <50%	Not exceeded
Chronic toxicity	None	NOEC <1.5% effluent	Not exceeded
PCBs	Aroclor >0.045 ng/L	None	Not exceeded
Plant performance	5 violations/year	Compliance <95% of the time	Not exceeded
Flow	None	>436 MGD average dry days	Not exceeded
Total nitrogen load	>12,500 mtons/year	>14,000 mtons/year	Not exceeded
Oil and grease	None	>15 mg/L weekly	Not exceeded

NA = not applicable
cBOD = carbonaceous biological oxygen demand
LC50 = 50% mortality concentration
NOEC = no observable effect concentration
PCB = polychlorinated biphenyl
Plant performance = compliance with permit conditions

3. Water Column

The water-column monitoring program evaluates relevant physical-oceanographic processes, water quality, and phytoplankton and zooplankton communities at stations in Massachusetts Bay, at the mouth of Boston Harbor, and in Cape Cod Bay (Figure 3-1).

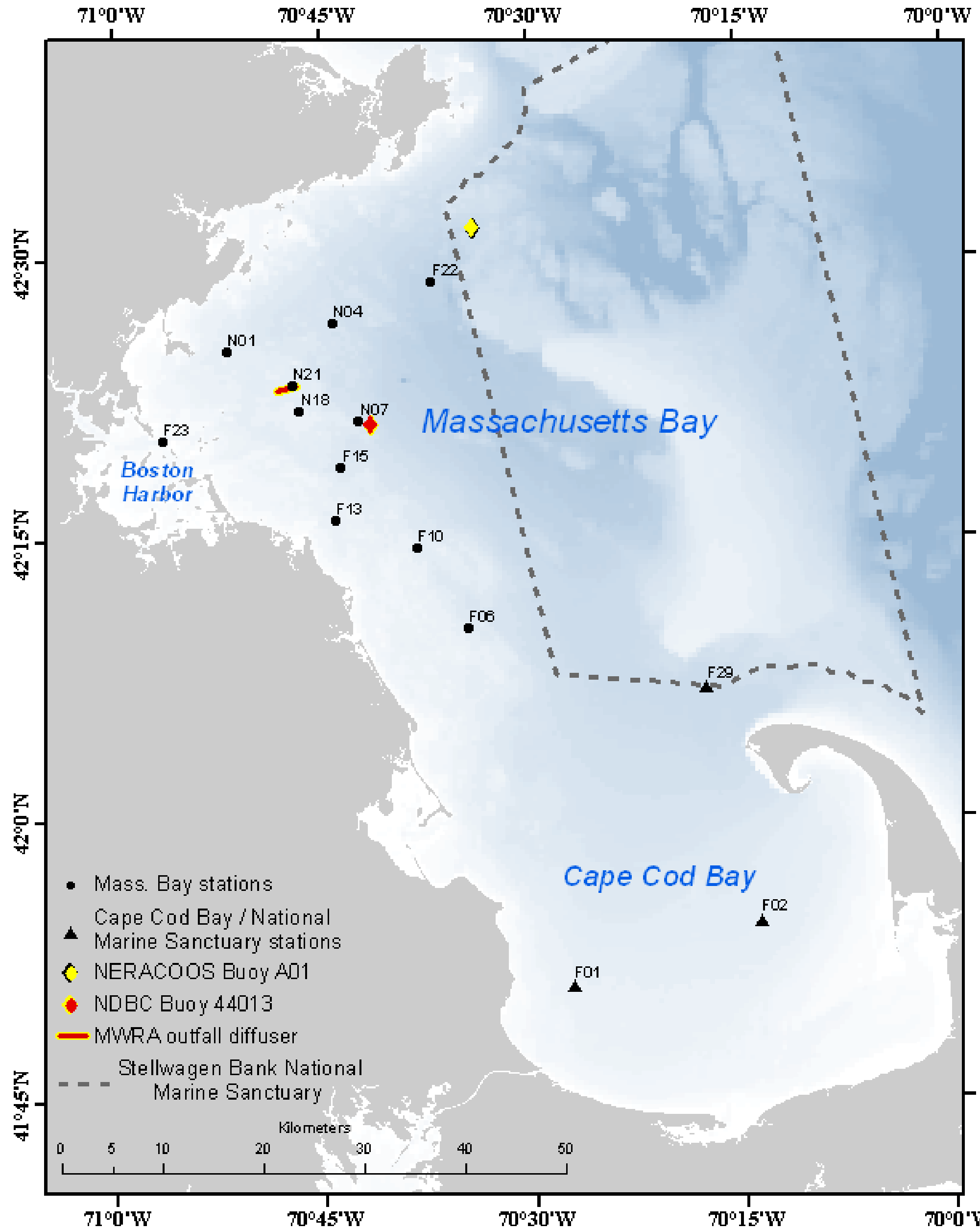

Figure 3-1. Water-column monitoring stations. Also shown are two instrumented buoys, one operated by the Northeastern Regional Association of Coastal and Ocean Observing Systems (NERACOOS) and the other by the National Data Buoy Center (NDBC); the MWRA outfall diffuser; and the Stellwagen Bank National Marine Sanctuary.

Sampling during the nine surveys of fourteen stations in 2015 included vertical profiles of physical, chemical, and biological characteristics in the area around the outfall (the nearfield), where some effects of the effluent were expected and have been observed, and at farfield reference stations, including stations in Cape Cod Bay and near the Stellwagen Bank National Marine Sanctuary. Analyses included data from ten additional stations, sampled as part of MWRA's Boston Harbor water-quality monitoring program when sampling dates were within a few days of the outfall-monitoring surveys. In some years, special surveys are conducted in response to *Alexandrium fundyense* red tide blooms, but no additional surveys were necessary in 2015.

The program continued to benefit from collaboration with the Center for Coastal Studies at Provincetown, Massachusetts, which conducts a monitoring program in Cape Cod Bay. As part of the MWRA monitoring program, the Center for Coastal Studies samples water-column stations in Cape Cod Bay and the Stellwagen Bank National Marine Sanctuary. Regulators have set a target that, whenever possible, sampling in Cape Cod Bay should occur within 48 hours of MWRA Massachusetts Bay sampling and that any failure to meet that schedule should be reported in this annual outfall monitoring overview. In February 2015, ice coverage in Cape Cod Bay delayed sampling until four days after the Massachusetts Bay sampling date. All other sampling was completed within the required time frame.

The field monitoring program was augmented by measurements on two instrumented buoys, the Northeastern Regional Association of Coastal and Ocean Observing Systems (NERACOOS) Buoy A01 and the National Oceanic and Atmospheric Administration's National Data Buoy Center (NDBC) Buoy 44013. The National Aeronautics and Space Administration provided Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery for chlorophyll and for sea-surface temperature.

Physical Conditions

Monitoring has shown that the water quality in the vicinity of the outfall and throughout Massachusetts and Cape Cod bays is heavily influenced by river inflows, weather, and other physical factors. Information about physical conditions has proven key to interpreting the annual monitoring data.

Corresponding to the low rainfall in the Boston area in 2015, discharges from the Merrimack and Charles rivers were low throughout much of the year (Figure 3-2; Libby et al. 2016). There were spring peaks in discharge, corresponding to snow melt at the end of winter, but overall, discharges were low. The low flows led to the highest surface- and bottom-water salinities in February through April ever measured by the monitoring program.

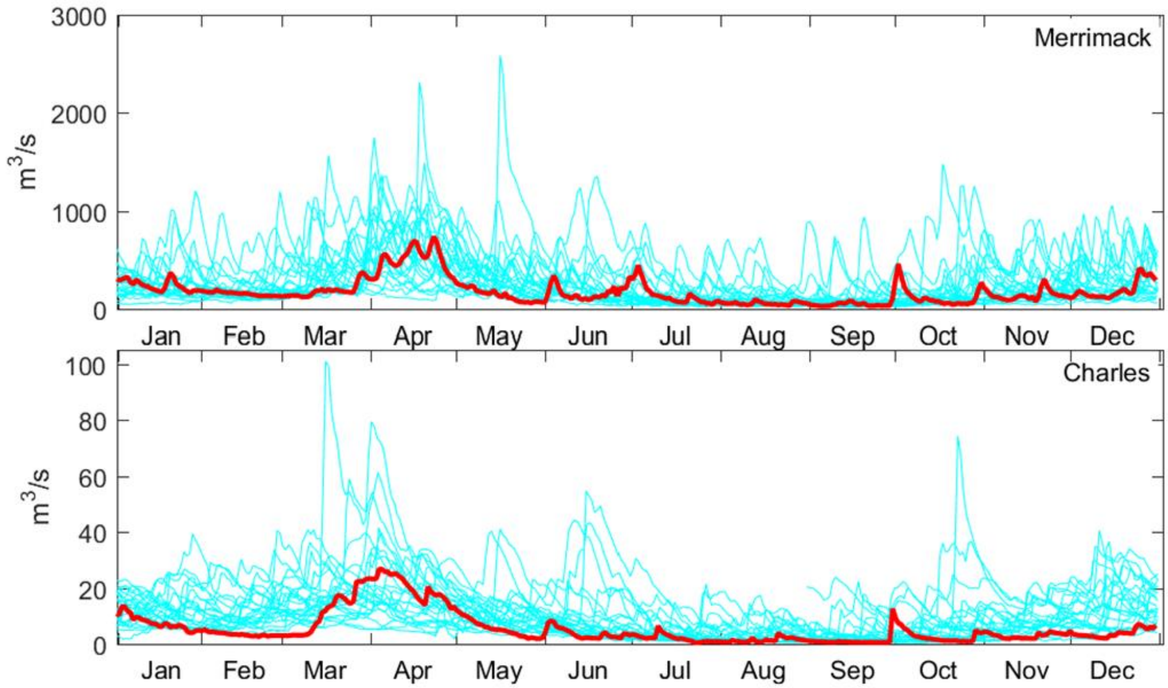

Figure 3-2. Flows of the Merrimack (top) and Charles (bottom) rivers. Flow from the Charles River was the lowest measured in 24 years of monitoring. Dark red lines are 2015 data. Results from 1992–2014 are in light blue.

Surface water temperatures, measured at the NDBC Buoy 44013 and at nearby Station N18, were slightly above average at the beginning of the year, dropping to near the minima for the monitoring program in February and March, and climbing to the monitoring-program maxima by the end of the year (Figure 3-3). Abrupt warming began in May. It was interrupted by a major cooling event at the end of the month, but then continued into the summer.

The winter storms promoted very strong downwelling in February (Figure 3-4). Typically moderate upwelling conditions persisted through the summer, with a return to downwelling conditions in the fall. Stratification, the difference in density between surface and bottom waters, began to develop in late April, with the onset of upwelling conditions. Destratification, the re-mixing of the water column that occurs as waters cool in the autumn, was early, the result of downwelling-favorable wind conditions in early October.

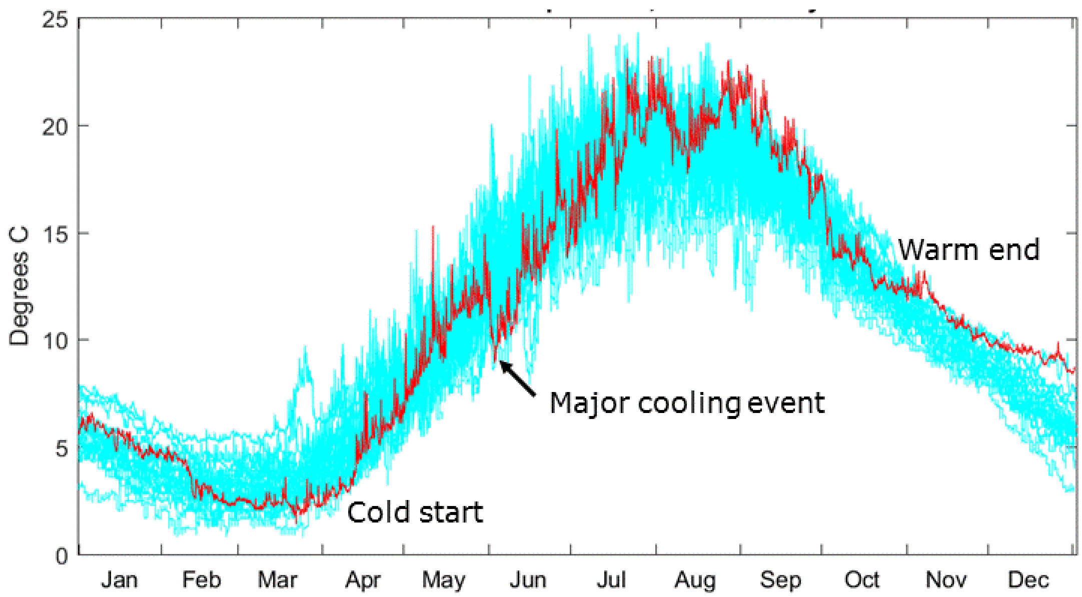

Figure 3-3. Nearfield surface water temperature at the NDCB Buoy 44013. Surface water temperatures were cold in the early months and warm at the end of 2015. Red line is 2015. Results from 1989–2014 are in blue.

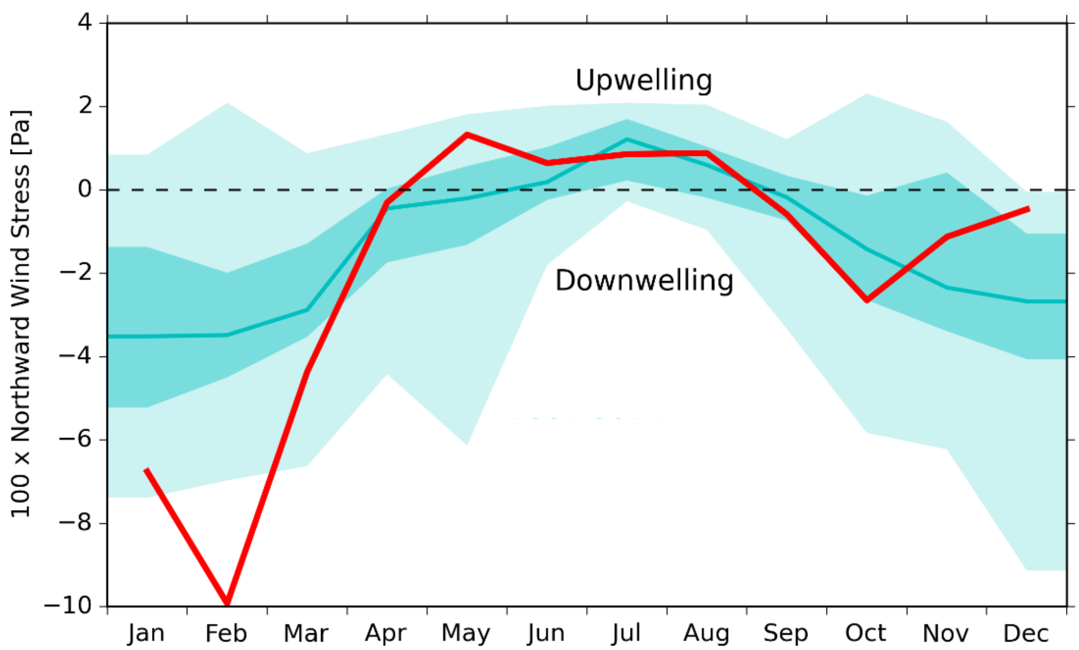

Figure 3-4. Average north-south component of wind stress at NDBC Buoy 44013. Winter storms produced the strongest February downwelling conditions ever measured in the monitoring program. Negative values indicate winds from the north, which favor downwelling; positive values indicate winds from the south, which result in upwelling-favorable conditions. Red line is 2015. Results from 1992–2014 are in blue: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

Water Quality

Water quality measurements for 2015 included quantification of nutrients, phytoplankton biomass (measured as chlorophyll and particulate organic carbon), and dissolved oxygen. Results continued to confirm predictions of measurable outfall influence in some parameters at stations very near the outfall but no unexpected adverse effects (Libby et al. 2016).

At Station N18, located in the nearfield one kilometer south of the outfall, dissolved inorganic nutrient concentrations (nitrate, ammonium, silicate, and phosphate) fell mostly within the ranges seen in previous years (Figure 3-5). During certain of the summer surveys, ammonium concentrations were slightly elevated, at or above the monitoring-program range for those months. Nitrate, silicate, and phosphate concentrations at Station N18 typically show a seasonal pattern of lowered concentrations during the summer. This pattern also occurs in other areas of the bay.

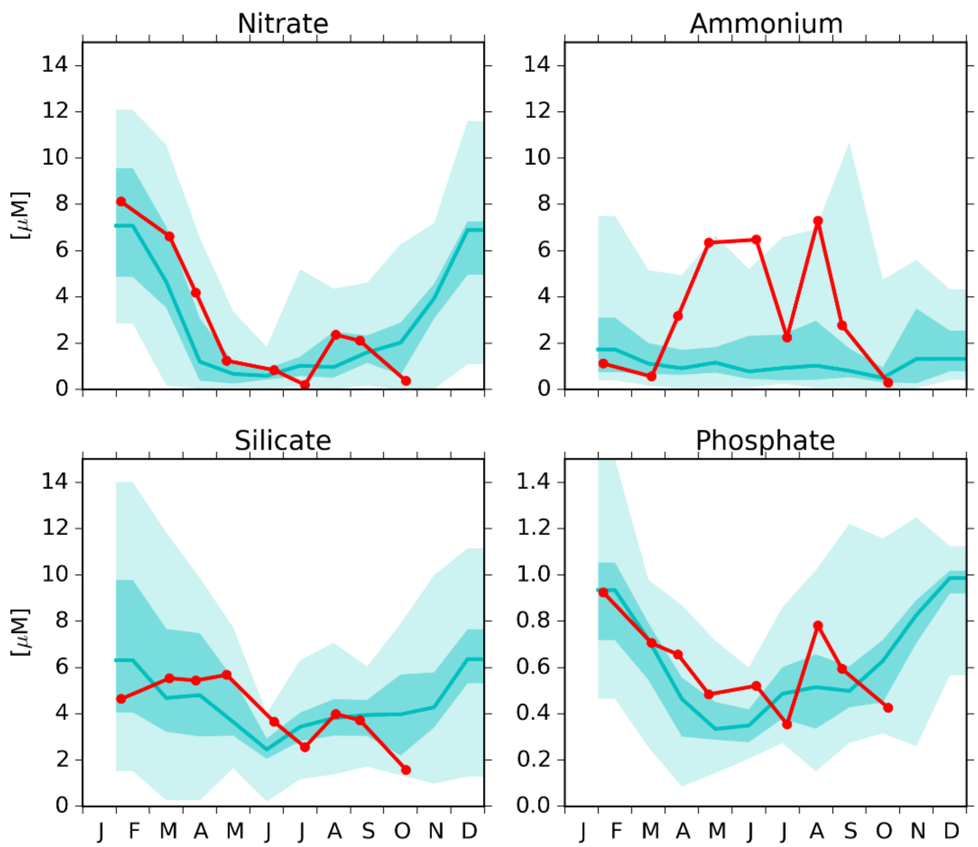

Figure 3-5. Depth-averaged dissolved inorganic nutrient concentrations at Station N18, one kilometer south of the outfall, in 2015 compared to prior years. Note difference in scale for phosphate. Red points are results from individual surveys in 2015. Results from 1992–2014 are in blue: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range.

As has been typical since the offshore outfall began to discharge, elevated ammonium concentrations were found in the immediate vicinity of the outfall throughout the year (Figure 3-6). The plume signature could be detected during both stratified and mixed seasons. Ammonium is the largest fraction of the total nitrogen in wastewater and provides a tracer to identify possible effects of the outfall.

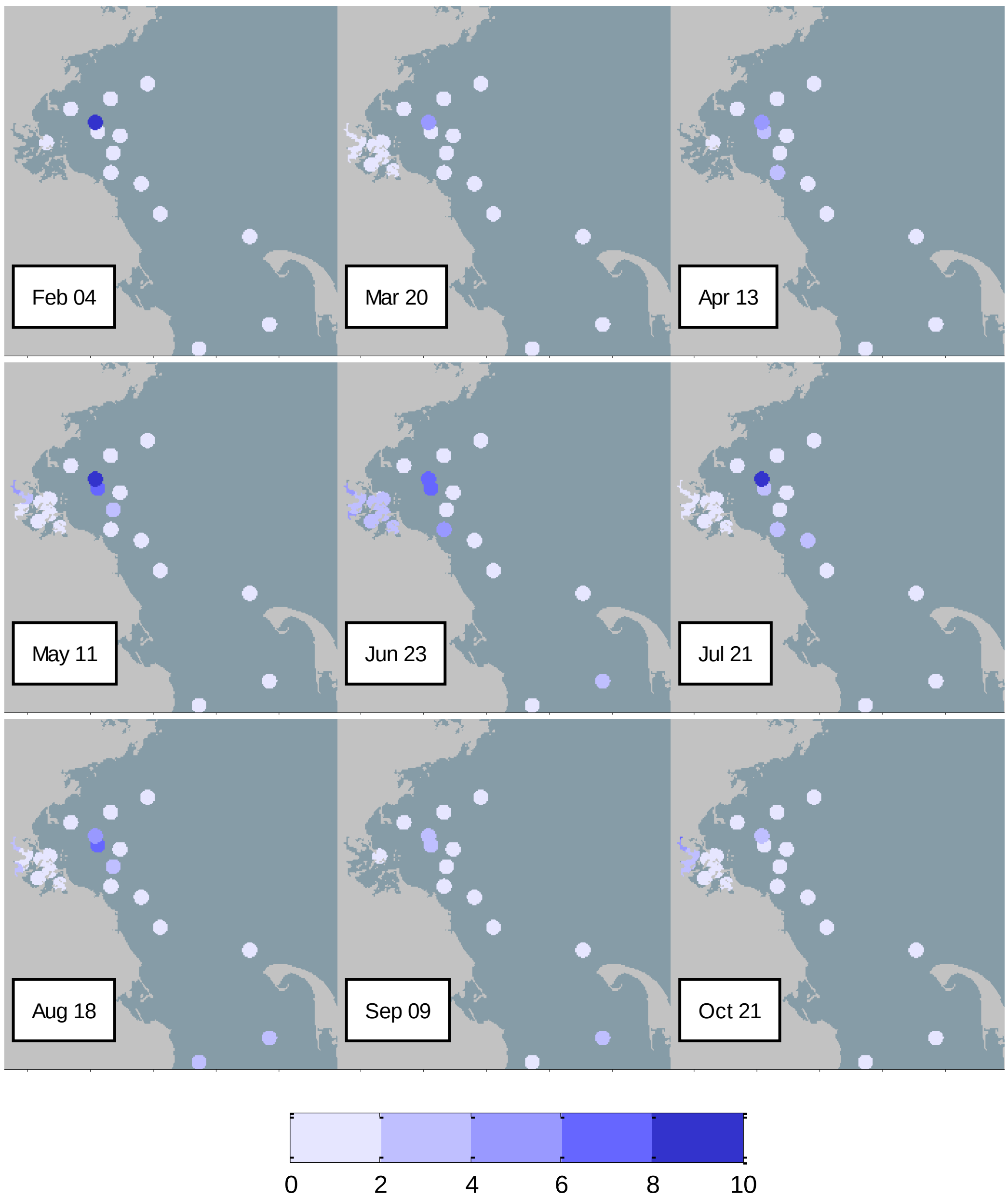

Figure 3-6. Depth-averaged ammonium concentrations (µM) by station in Massachusetts and Cape Cod bays in 2015. Several panels show additional data from MWRA's in-house Boston Harbor monitoring surveys when those surveys were within a few days of the outfall-monitoring surveys.

As in previous years, the plume's ammonium signature was evident in surface waters during the winter and spring (Figure 3-7), but was confined beneath the pycnocline during the summer, stratified season (Figure 3-8). The ammonium signature could be detected only within 10–20 kilometers of the outfall in both well-mixed and stratified seasons, consistent with predictions made during the outfall siting process.

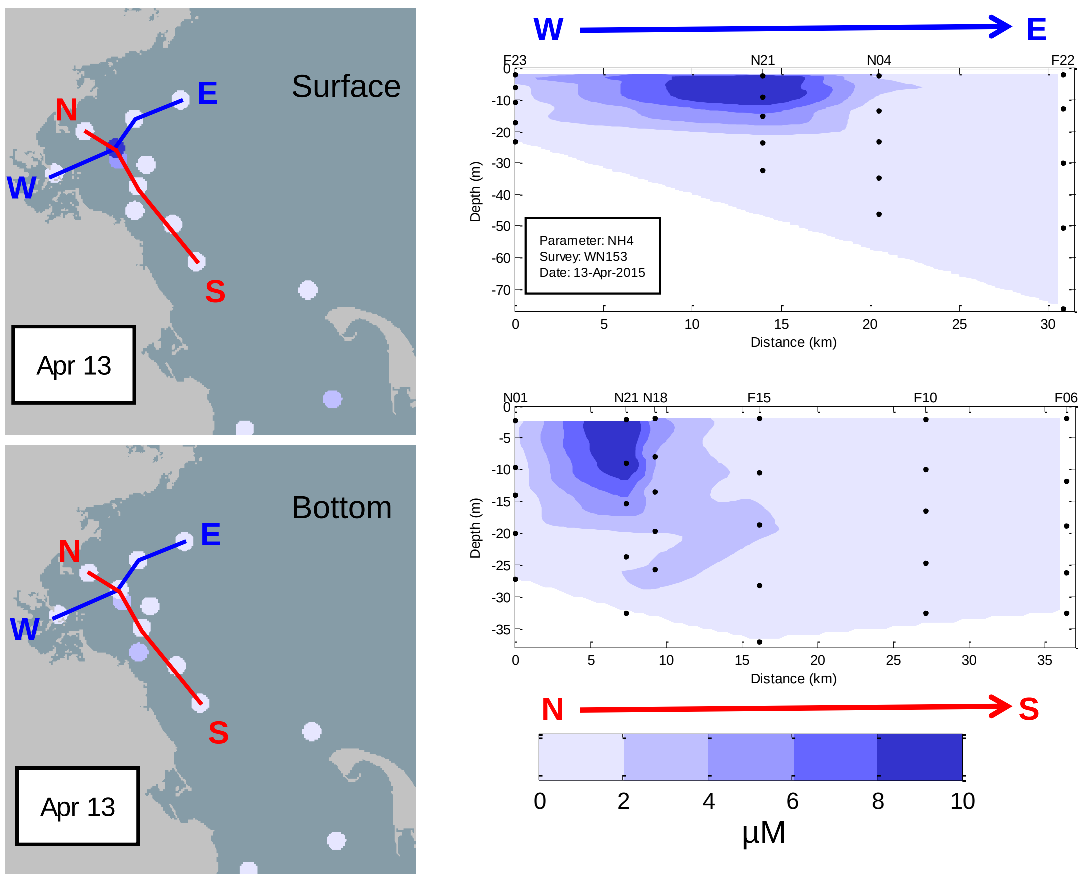

Figure 3-7. (Left) Surface- and bottom-water ammonium on April 13, 2015 at the monitoring stations during mixed conditions. (Right) Cross-sections of concentrations throughout the water column along transects connecting selected stations.

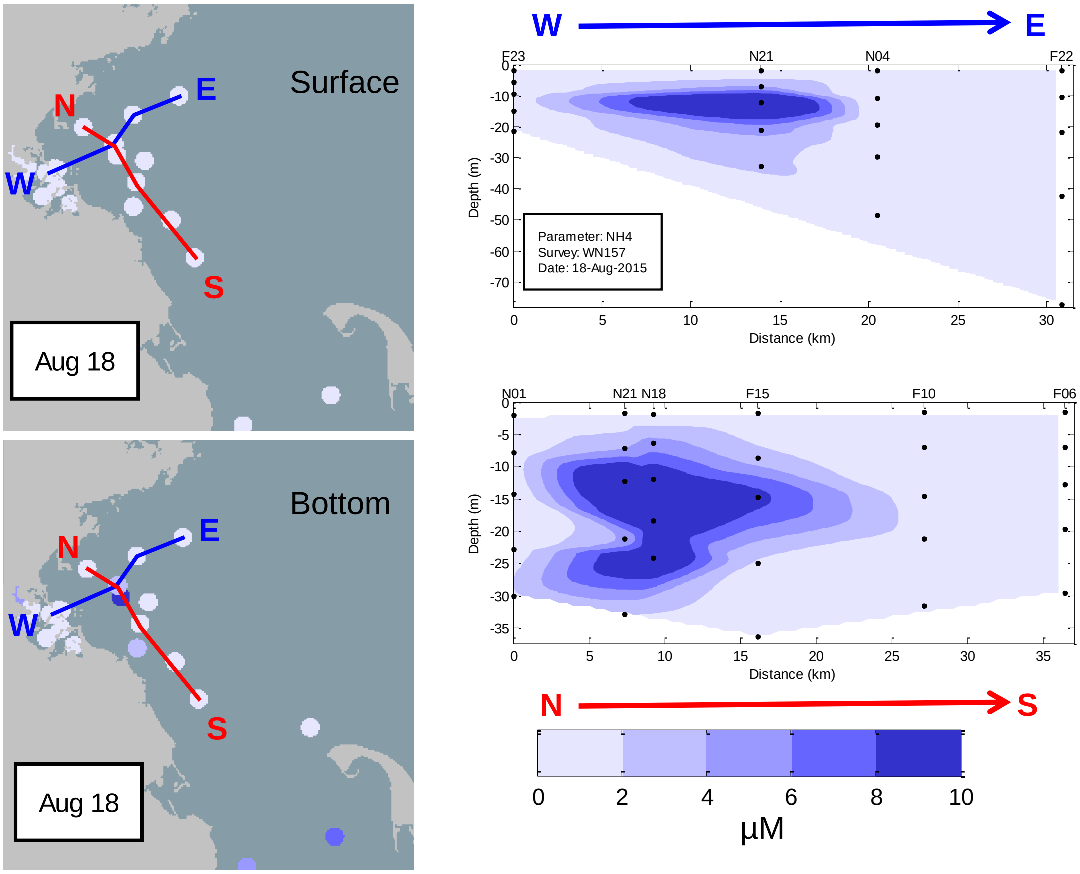

Figure 3-8. (Left) Surface- and bottom-water ammonium on August 18, 2015 at the monitoring stations during stratified conditions. (Right) Cross-sections of concentrations throughout the water column along transects connecting selected stations.

No increase in phytoplankton biomass, measured as chlorophyll or particulate organic carbon, was evident at the outfall. Typically, chlorophyll levels in Boston Harbor and the shallower coastal stations of Massachusetts Bay are elevated in summer months, but during summer 2015, areal chlorophyll levels were relatively low throughout the region, especially in the harbor (Figure 3-9). During months when the water column was vertically well mixed, chlorophyll concentrations were slightly greater. Even at Station N18 near the outfall, chlorophyll levels were at the low end of the historic range during most surveys.

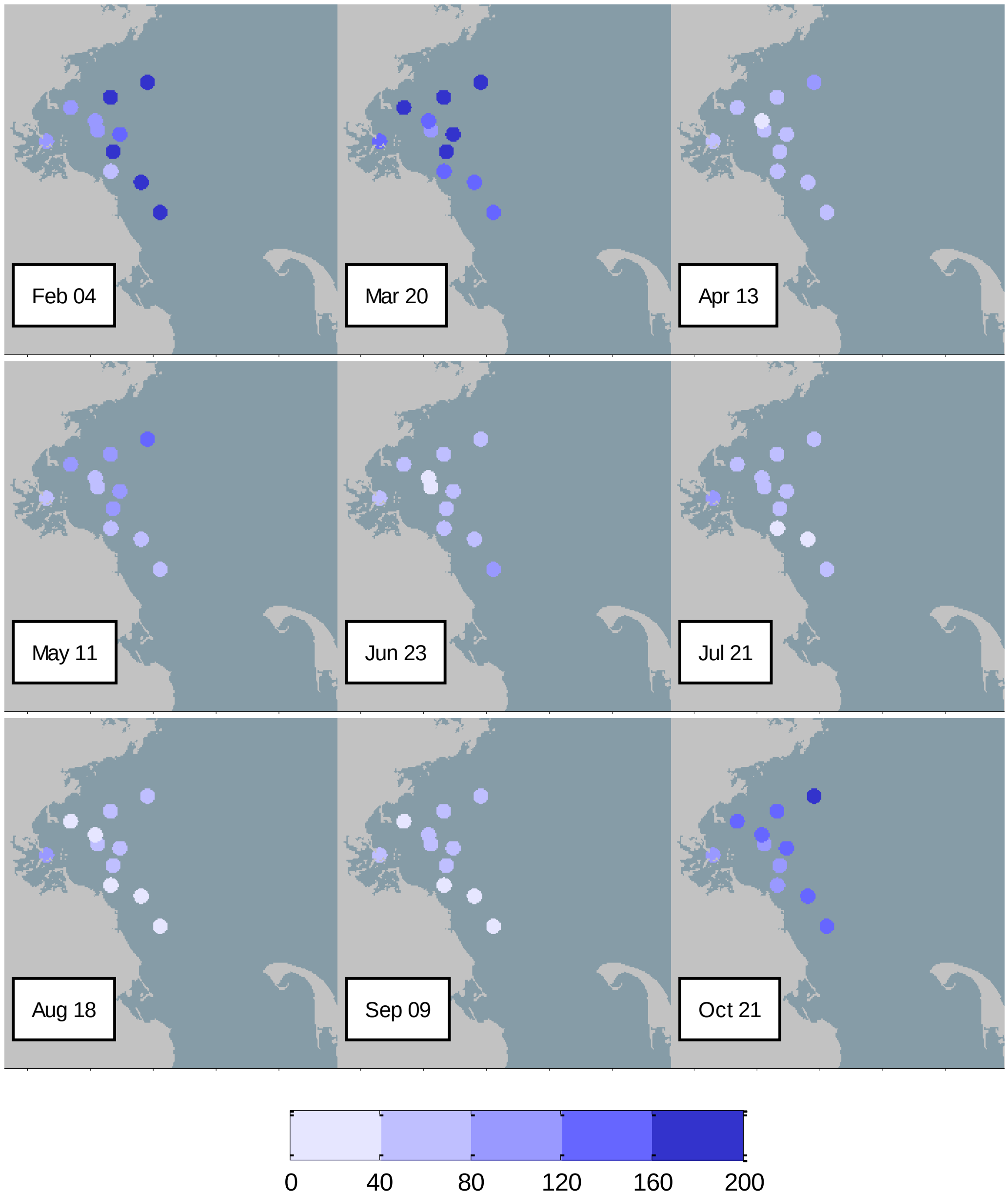

Figure 3-9. Average areal chlorophyll (mg/m^2) by station in Massachusetts Bay in 2015.

Satellite imagery confirmed that phytoplankton were relatively abundant prior to the February 2015 survey, particularly inshore and in Cape Cod Bay (Figure 3-10), as they had been in November and December of 2014 (not shown). Biomass levels were low in February and into March, then relatively elevated in May, variable through the summer, and relatively elevated in the fall, corresponding to a mixed diatom bloom.

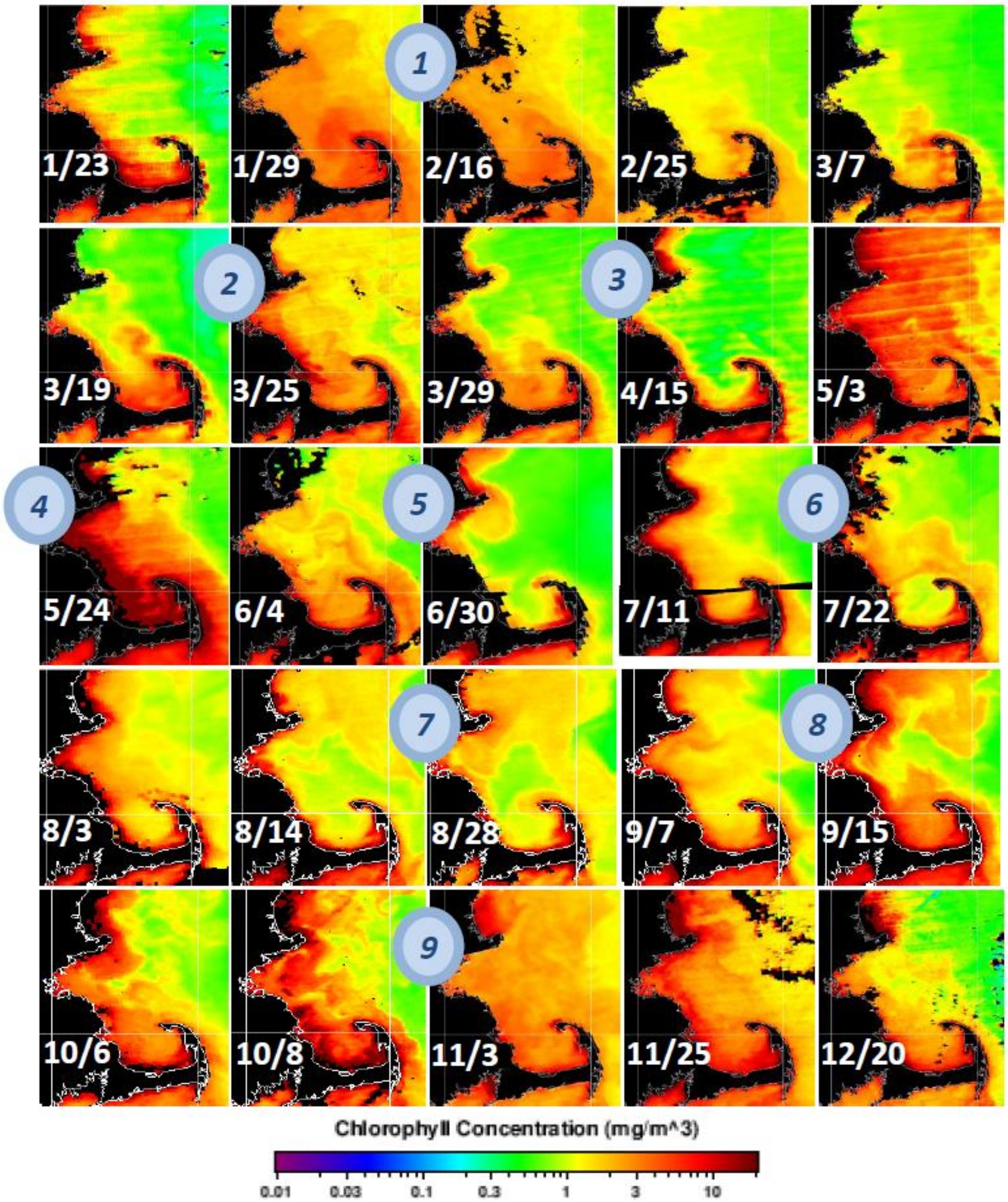

Figure 3-10. Satellite imagery of surface chlorophyll concentrations in 2015. These images, from at NASA satellite, are heavily weather-dependent and do not represent consistent intervals of time. The numbers show the timing of the nine MWRA surveys.

Nearfield surface- and bottom-water dissolved oxygen concentrations were at the low end of the historic range in February (Figure 3-11). Levels were typical from the spring to fall, with brief increases in the summer. Early mixing during September re-oxygenated bottom waters. The fall bottom-water oxygen minimum was relatively high in 2015 compared to past years, continuing to show that the effluent discharge has not caused oxygen depletion near the outfall.

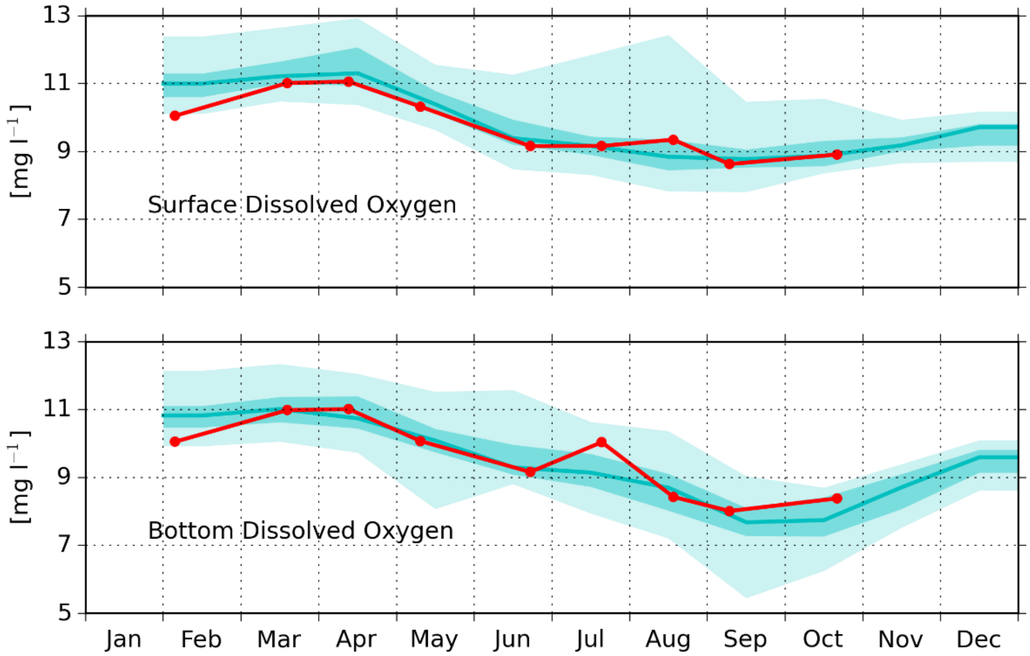

Figure 3-11. Surface- and bottom-water dissolved oxygen concentrations at nearfield Station N18 in 2015 compared to prior years. Red points are results from individual surveys in 2015. Results from 1992–2014 are in blue: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range.

Phytoplankton Communities

Total phytoplankton abundances were low throughout the year and throughout Massachusetts Bay (Figure 3-12), with overall total annual abundance only 56% of the long-term mean (Libby et al. 2016). The typical summer diatoms *Skeletonema* spp. were present at only 39% of their long-term mean. The low observed abundances were partly due to the timing of the surveys, as the satellite imagery in Figure 3-10, above, suggested peaks occurring between survey dates. Other explanations include weather patterns and zooplankton grazing (see Zooplankton Communities, below).

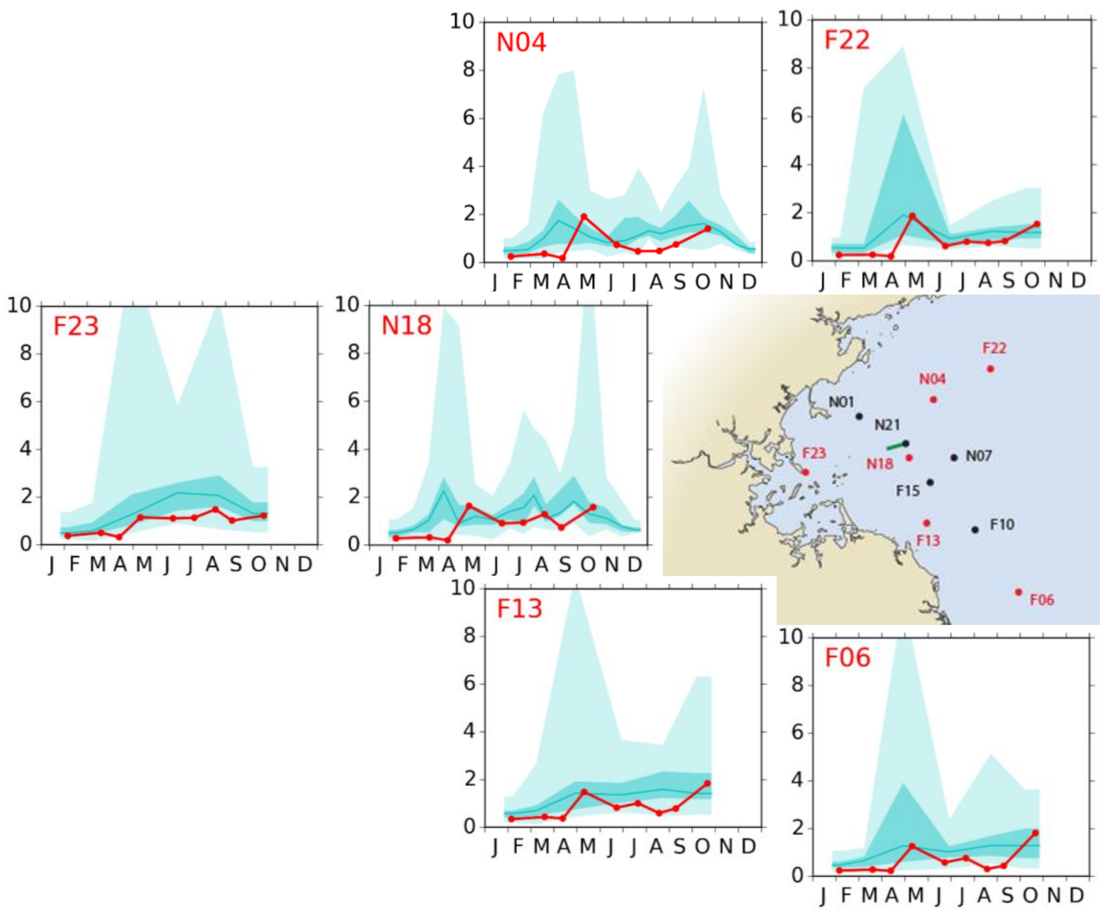

Figure 3-12. Total phytoplankton abundance (million cells per liter) at selected stations in 2015 compared to prior years. Red points and line are results from individual surveys in 2015. Results from 1992–2014 are in blue: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range.

Annual abundance (not shown) of the nuisance species *Phaeocystis pouchetii* was low compared to most previous years. Winter-spring 2015 nearfield abundance was moderate or low in the nearfield, but for a second consecutive year, summer nearfield abundance exceeded the very low summer Contingency Plan caution threshold (Figure 3-13). As in 2014, the cold winter and spring in the region delayed the onset of the bloom by about a month. The Contingency Plan exceedance was triggered by a single sample during that delayed bloom (see Contingency Plan Thresholds, below).

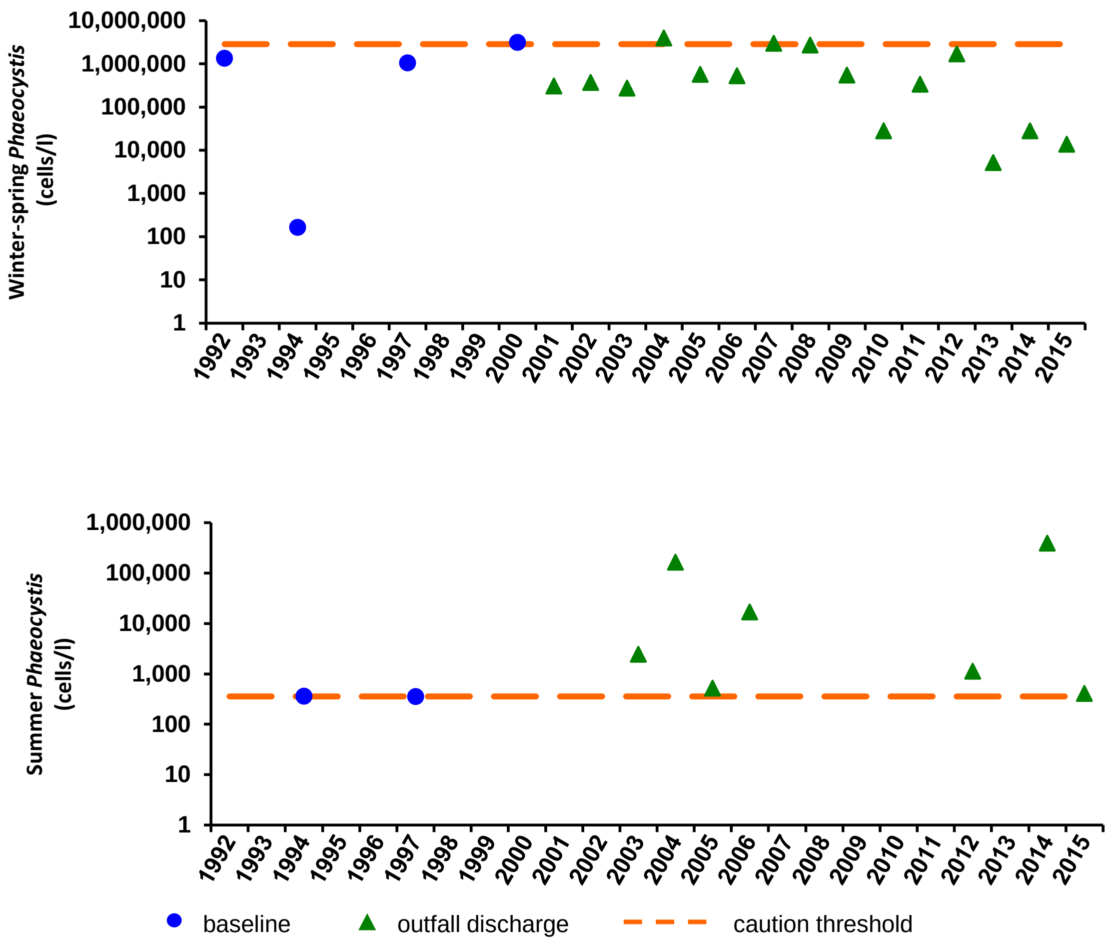

Figure 3-13. Mean nearfield abundance of *Phaeocystis pouchetii*, 1992–2015. (Top) Winter-spring. (Bottom) Summer. (No *Phaeocystis* were detected in years with no symbol.) Note the difference in scales for winter-spring (caution-level threshold of 2.86 million cells per liter) and summer (caution threshold of 357 cells per liter).

Toxic dinoflagellate *Alexandrium fundyense* counts were low in 2015 (Figure 3-14). No paralytic shellfish poisoning (PSP) toxicity was measured in Massachusetts Bay or along the coast from Gloucester, Massachusetts to the New Hampshire border. PSP toxicity was noted in New Hampshire and western Maine waters, but the bloom was minor and short-lived. In previous years, when *Alexandrium* counts in Massachusetts Bay were elevated, cells had been transported into the bay from the north. During 2015, a lack of storms with winds from the northeast in late April and May reduced the chances of *Alexandrium* cells entering Massachusetts Bay.

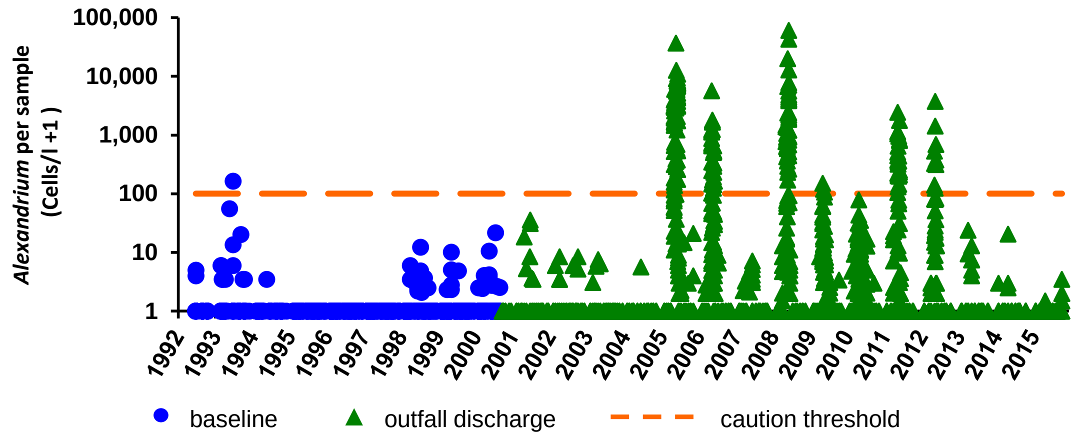

Figure 3-14. Nearfield abundance of *Alexandrium fundyense,* 1992–2015.

Zooplankton Communities

Annual abundances of total zooplankton and many dominant species groups in 2015 were high and continued a trend of increased abundances since lows in the mid-2000s (Figure 3-15, Libby et al. 2016). In July, abundances of total zooplankton at some stations were as much as ten times higher than in other years of the monitoring program (Figure 3-16). The high peaks were partially attributable to extremely high abundances of bivalve veligers (larvae) in July and August, particularly in Boston Harbor. At some stations, abundances of a wide variety of copepods, including adults and copepodites of *Pseudocalanus* spp., *Oithona similis*, and *Calanus finmarchicus*, were also at or above previous maxima from June through October (not shown).

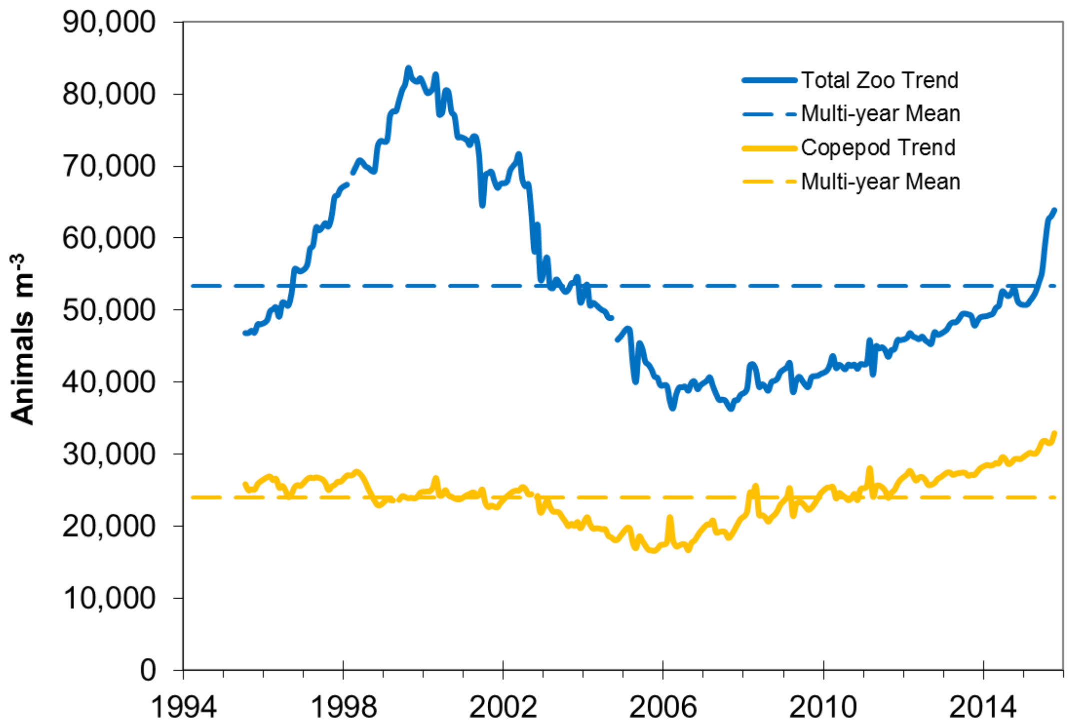

Figure 3-15. Long-term trend (1998–2015) in nearfield total zooplankton and copepods, derived from a time-series analysis, compared to the multiyear means. Data are from Stations N04 and N18.

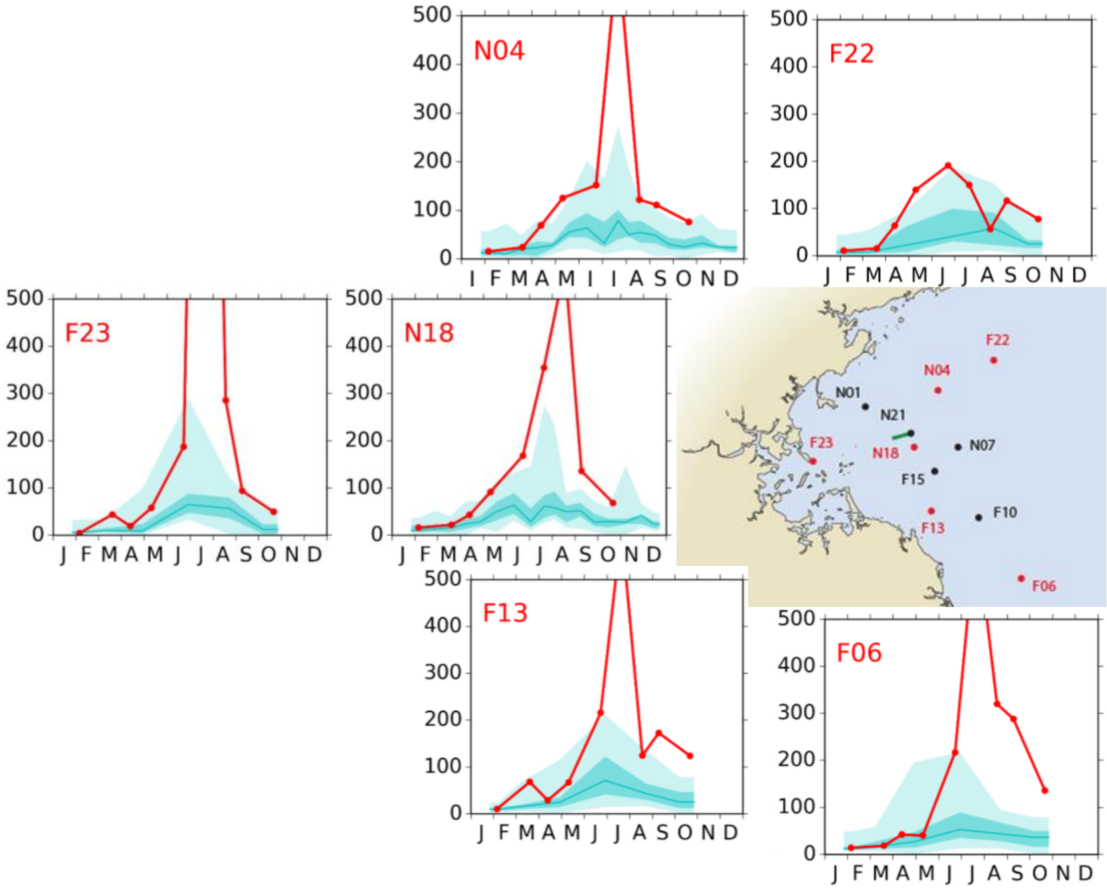

Figure 3-16. Total zooplankton abundance (1,000 animals per cubic meter) at selected stations in 2015 compared to prior years. Red points are data from individual surveys in 2015. Results from 1992–2014 are in blue: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range. Peak values for 2015 exceeding the length of the y-axis maximum of 500,000 were Stations N04 = 630,000; F23 = 2,400,000; N18 = 570,000; F13 = 610,000; and F06 = 700,000 animals per cubic meter.

Long-term trend analysis has shown inverse trends in phytoplankton and zooplankton abundances (Figure 3-17). Reasons for the relatively high zooplankton abundances in recent years and the long-term trends in both phytoplankton and zooplankton abundances are not well understood. Increased zooplankton abundance since 2005 may have contributed to the decline in phytoplankton abundance over the same period. Large-scale regional patterns are likely a major factor.

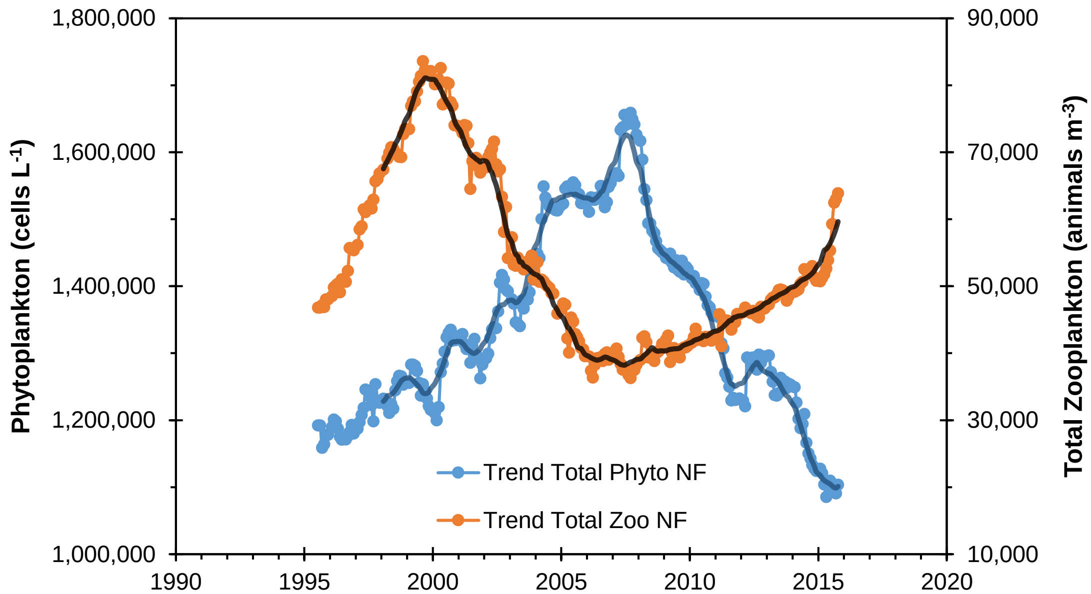

Figure 3-17. Long-term trend (1998–2015) in annual total phytoplankton and total zooplankton in the nearfield. Colored dots and lines based on a smoothing window of 15% of the length of the time series (~3.5 years) and black lines on a 25% smoothing window (6 years). Data are from Stations N04 and N18.

Stellwagen Bank National Marine Sanctuary

The NPDES permit to discharge from DITP into Massachusetts Bay requires annual reporting on results that are relevant to the Stellwagen Bank National Marine Sanctuary. Water-column Station F22 is in Stellwagen Basin, to the northwest of the sanctuary and is considered to be representative of northern, offshore conditions.

Ammonium levels have remained low at Station F22 since the outfall began to discharge (see, for example, 2015 results in Figures 3-6, 3-7, and 3-8, above). Levels have also remained low at Station F06 located to the south and offshore. In contrast, increased ammonium levels have been detected in the nearfield, while decreases have been detected at representative harbor and coastal stations.

Sampling at Station F22 and data from NERACOOS Buoy A01 (Figure 3-18), as well as satellite imagery (see Figure 3-10, above) detected no unusual chlorophyll levels in offshore regions in 2015. No effects on chlorophyll levels in the offshore were predicted, and none have been measured.

Bottom-water dissolved oxygen concentrations at Station F22 were healthy throughout 2015, with survey data showing the typical decline during the stratified season (Figure 3-19). Data from the NERACOOS Buoy A01, located within the sanctuary, documented the return to oxygenated conditions with fall mixing.

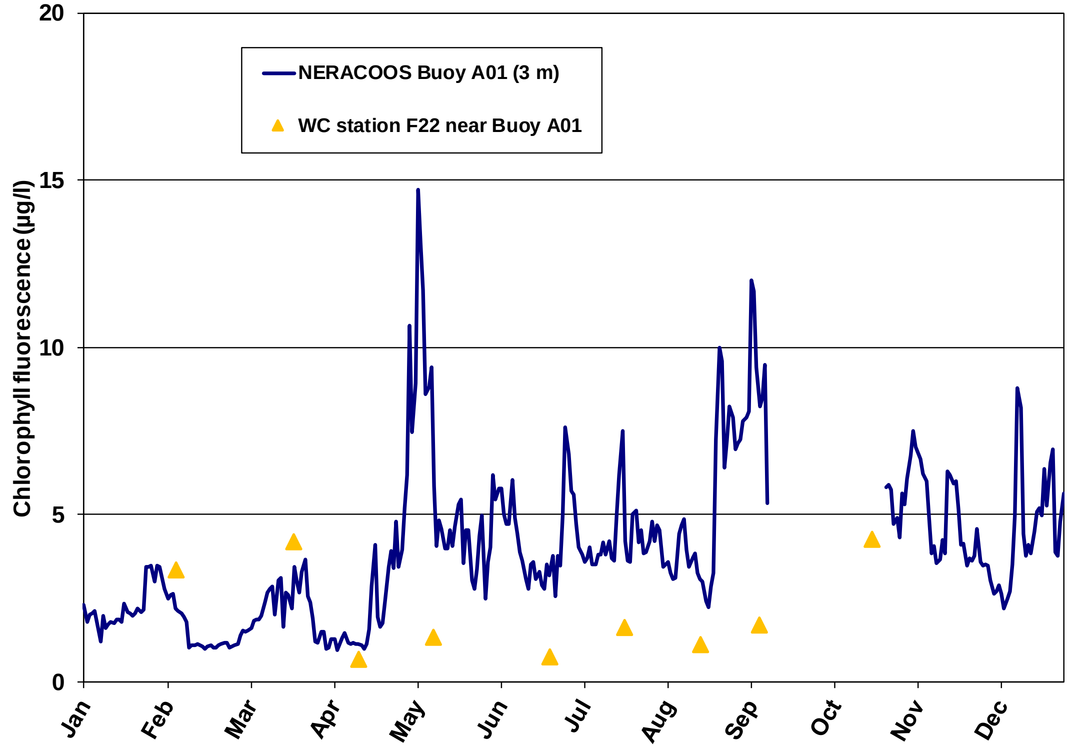

Figure 3-18. Chlorophyll measurements at NERACOOS Buoy A01, inside Stellwagen Bank Marine Sanctuary, and at nearby Station F22. Blanks in the time series represent missing data.

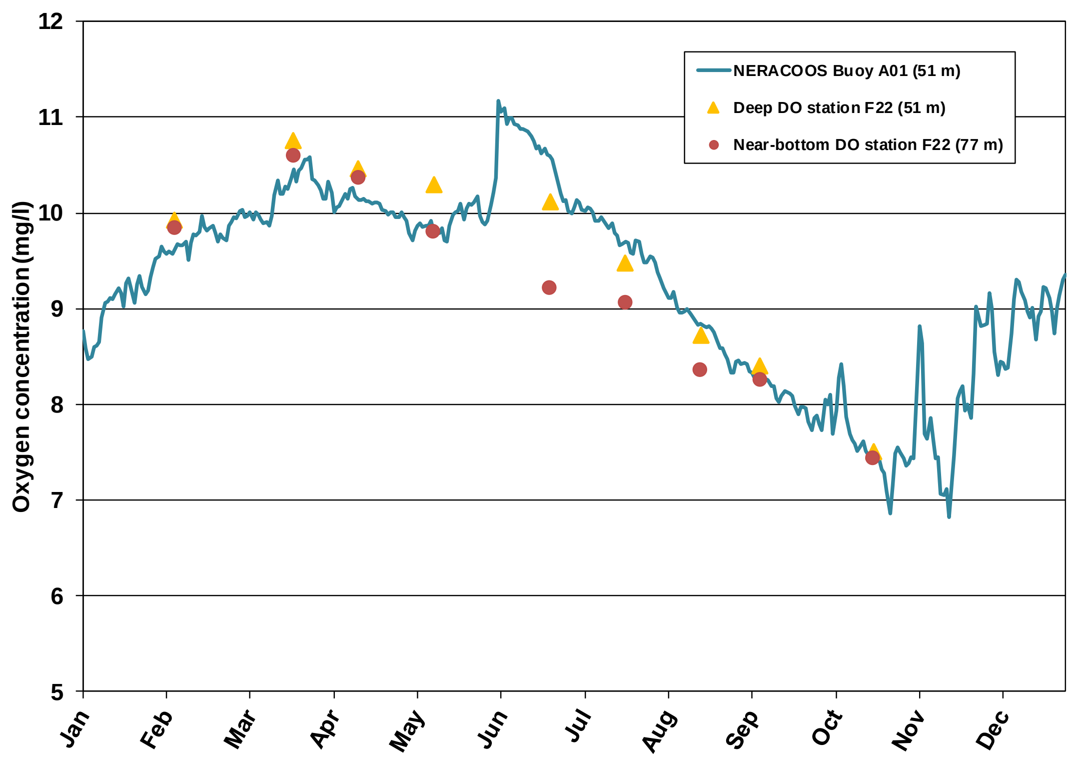

Figure 3-19. Bottom water dissolved oxygen concentrations at NERACOOS Buoy A01, inside Stellwagen Bank Marine Sanctuary, and at nearby Station F22. The NERACOOS measurement is at 51 m, the deep Station F22 at 54 m, and the near-bottom Station F22 at 78 m. DO = dissolved oxygen

Boston Harbor

Water quality in Boston Harbor has improved during the past 20 years, and those improvements were sustained in 2015. MWRA's in-house Boston Harbor monitoring program confirmed that harbor-wide concentrations of total nitrogen and phosphorus remained low, as they have since discharges to the harbor ended (Taylor 2016).

Perhaps the most dramatic improvement in Boston Harbor has been the decrease in ammonium levels (Figure 3-20, top; Libby et al. 2016). Ammonium concentrations dropped precipitously when the effluent discharge was diverted from the harbor to Massachusetts Bay in 2000 and have remained low. In 2015, ammonium levels at Station F23, at the harbor mouth, were typical for the post-diversion years. In contrast, ammonium levels have increased at stations closest to the Massachusetts Bay outfall, such as Station N18 (Figure 3-20, bottom). However, because of increased dilution at the offshore outfall, those increases have been substantially smaller than the concurrent decreases in ammonium concentrations in the harbor.

While total zooplankton abundance peaked in June and July in Massachusetts Bay, in Boston Harbor, there was one major peak in July. *Acartia* spp., which are common in the lower-salinity waters found in the harbor, peaked once in June–July and a second time in September at Station F23 at the mouth of the harbor (Figure 3-21). Prior to the outfall diversion, *Acartia* spp. peak abundances usually occurred in August and September, and since then, peaks have occurred earlier. Overall abundance of *Acartia* spp. in 2015 was about twice that in 2014.

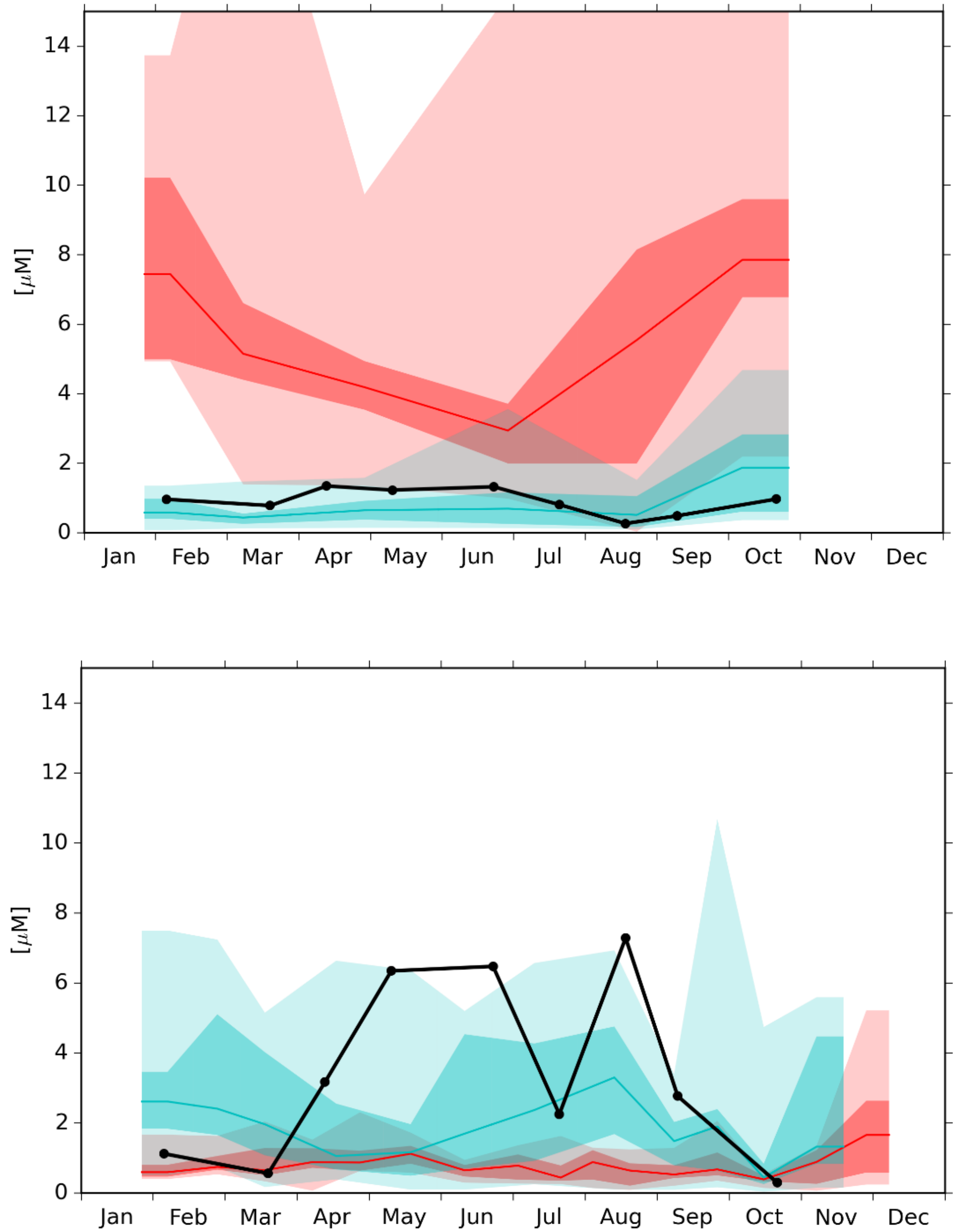

Figure 3-20. (Top) Depth-averaged ammonium levels at Station F23 in Boston Harbor. (Bottom) Depth-averaged ammonium levels at Station N18 near the Massachusetts Bay outfall. Black line shows 2015 results. Red line and shading show data from Boston Harbor discharge years. Blue line and shading show data from Massachusetts Bay discharge years. Lines are the 50th percentile; dark shading spans the 25th to 75th percentile; light shading spans the range.

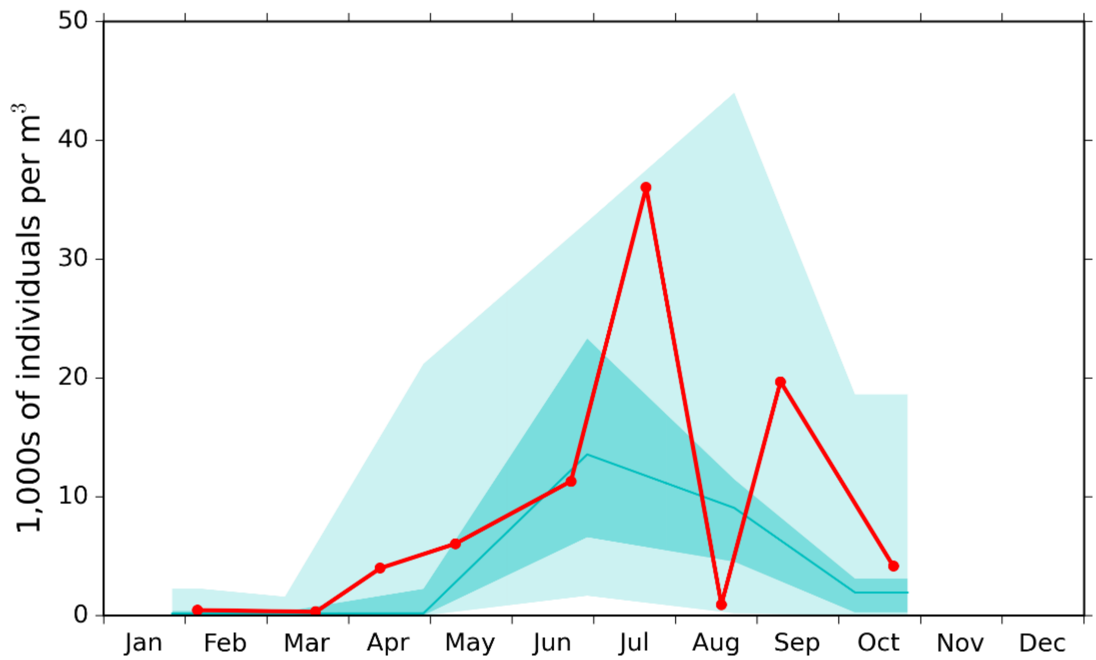

Figure 3-21. ***Acartia*** **spp. abundance at Station F23 in Boston Harbor in 2015 compared to prior years.** Red points are results from individual surveys in 2015. Results from 1992–2014 are in blue: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range.

Contingency Plan Thresholds

All water-quality parameters were within normal ranges during 2015. There was one Contingency Plan caution-level threshold exceedance for a nuisance algae measure, summer *Phaeocystis pouchetii* abundance (Table 3-1). A delay in the spring *Phaeocystis* population increase, caused by cold March and April water temperatures, was responsible for the exceedance. A summer *Phaeocystis* caution level exceedance was also observed during 2014. Neither year's exceedance caused measurable aesthetic or other adverse effects.

Table 3-1. Contingency Plan threshold values and 2015 results for water-column monitoring.

Parameter	Baseline	Caution Level	Warning Level	2015 Results
Dissolved oxygen*				
Nearfield concentration	6.05 mg/L	<6.5 mg/L	<6.0 mg/L	7.56 mg/L
Nearfield percent saturation	65.3%	<80%	<75%	84.5%
Stellwagen concentration	6.23 mg/L	<6.5 mg/L	<6.0 mg/L	7.44 mg/L
Stellwagen percent saturation	67.2%	<80	<75%	79.6%
Nearfield depletion rate	0.024 mg/L/d	>0.037 mg/L/d	>0.049 mg/L/d	0.018 mg/L/d
Chlorophyll				
Annual	72 mg/m^2	>108 mg/m^2	>144 mg/m^2	87 mg/m^2
Winter/spring	50 mg/m^2	>199 mg/m^2	None	122 mg/m^2
Summer	51 mg/m^2	>89 mg/m^2	None	58 mg/m^2
Autumn	90 mg/m^2	>239 mg/m^2	None	94 mg/m^2
Nuisance algae *Phaeocystis pouchetii*				
Winter/spring	622,000 cells/L	>2,860,000 cells/L	None	13,800 cells/L
Summer	72 cells/L	>357 cells/L	None	408 cells/L, caution level exceedance
Autumn	370 cells/L	>2,960 cells/L	None	Absent
Nuisance algae nearfield *Pseudo-nitzschia*				
Winter/spring	6,735 cells/L	>17,900 cells/L	None	51 cells/L
Summer	14,635 cells/L	>43,100 cells/L	None	925 cells/L
Autumn	10,050 cells/L	>27,500 cells/L	None	294 cells/L
Nuisance algae nearfield *Alexandrium fundyense*				
Any nearfield sample	Baseline maximum 163 cells/L	>100 cells/L	None	3 cells/L
PSP toxin extent	NA	New incidence	None	No new incidence

*Dissolved oxygen caution and warning levels represent numerical standards, with the caveat "unless background conditions are lower." Results are therefore compared to the baseline rather than to the caution and warning levels.
PSP = paralytic shellfish poisoning
NA = not applicable

4. Sea Floor

Seafloor monitoring in 2015 included sampling and analysis of soft-bottom sediment conditions, tracers, and infauna at 14 stations and sediment-profile imaging at 23 stations (Figures 4-1, 4-2).

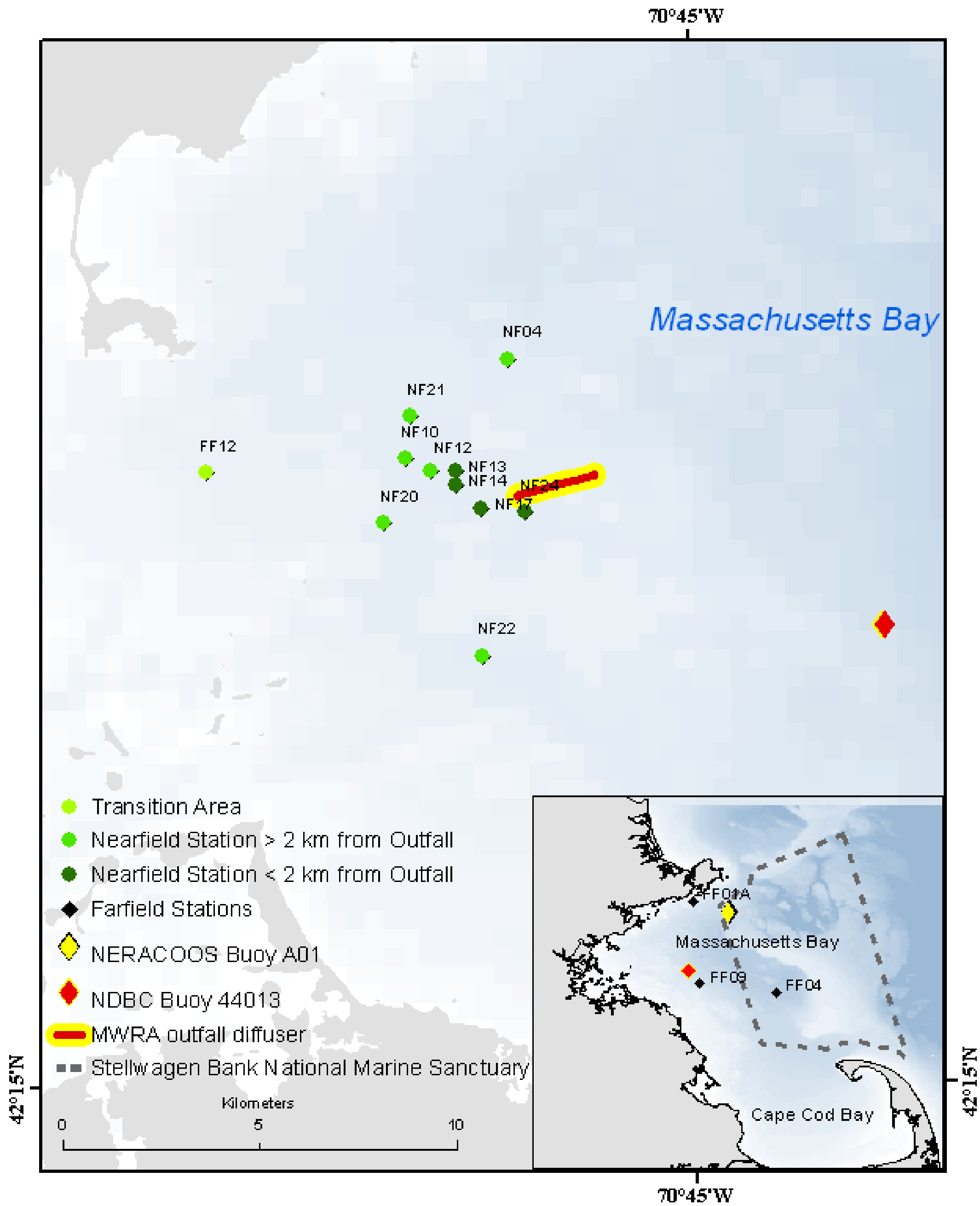

Figure 4-1. Soft-bottom monitoring stations. Benthic community parameters and sediment characteristics are measured in samples from 14 stations. Also shown are the instrumented buoys, the MWRA outfall diffuser, and the Stellwagen Bank National Marine Sanctuary.

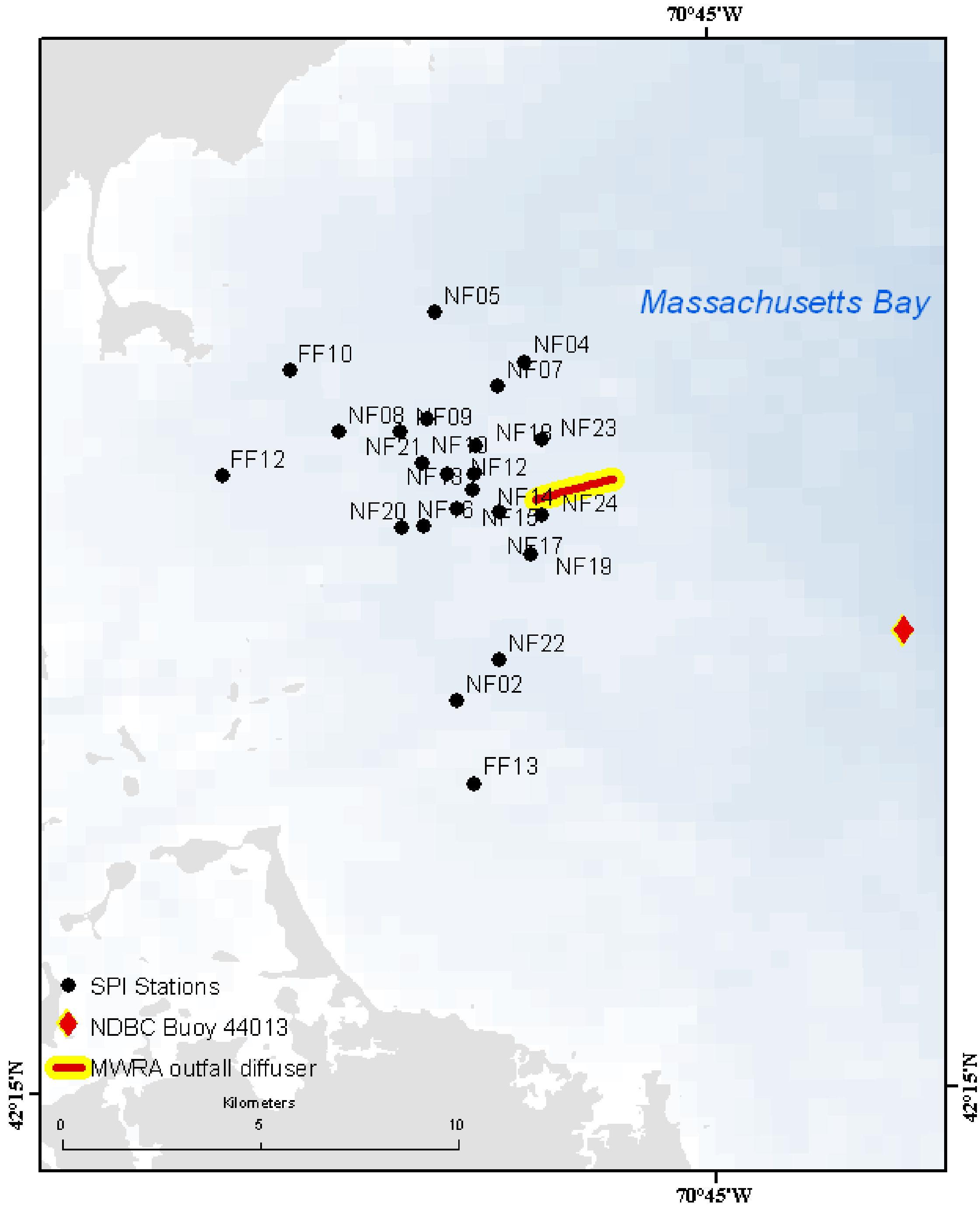

Figure 4-2. Sediment-profile imaging stations. Images are taken at 23 stations and provide rapid assessments of benthic habitats. Also shown are the NDBC buoy and the MWRA outfall diffuser. SPI = sediment-profile imaging

Soft-bottom sediment sampling was completed over two days in early August 2015, with samples analyzed for grain-size distribution, total organic carbon, the effluent tracer *Clostridium perfringens* spores, and benthic infauna. The 14 stations included one station in the "transition" area, located between Boston Harbor and the nearfield stations (FF12); four nearfield stations located within two kilometers of the outfall (NF13, NF14, NF17, NF24); six nearfield stations located within Massachusetts Bay but farther than two kilometers from the outfall (NF04, NF10, NF12, NF20, NF21, NF22); and three farfield reference stations located in Massachusetts Bay and Cape Cod Bay (FF01A, FF04, and FF09). For the purposes of threshold testing, "nearfield" includes the transition station, as well as both nearfield groups, for a total of eleven stations.

Sediment-profile imaging was also completed in August. Triplicate images from 23 stations were used to measure the apparent reduction-oxidation (redox) potential discontinuity (RPD) depth, apparent successional stage of the community, and an organism-sediment index which is derived from the RPD depth and the successional stage.

Sediment Characteristics and Tracers

Sediment grain-size distributions in 2015 varied broadly among stations, ranging from silt and clay at some stations to mostly sand at others (Nestler et al. 2016). Sediment grain-size distributions have remained generally consistent at individual stations over the years of the monitoring program. Changes that have occurred over time have been mostly associated with large storms, with wave-driven currents sufficient to re-suspend bottom sediments. There were some storm-related changes in 2015, but those changes were reflected more in the imaging portion of the monitoring program than in the grab samples (see Sediment-profile Imaging, below).

Percent organic carbon content, which tracks closely with fine material in the samples, was consistent with past results at most stations, with higher mean total organic carbon concentrations at stations with finer sediments. Total organic carbon concentrations showed no signs of organic enrichment from the effluent discharge, even at stations closest to the outfall.

As in past years since the offshore outfall began to discharge (except 2006), it was possible to detect elevated levels of *Clostridium perfringens* spores at the stations located closest to the outfall (Figures 4-3 and 4-4). Past years' statistical analyses have shown that these increases close to the outfall are statistically significant and consistent with predictions made during the outfall siting process.

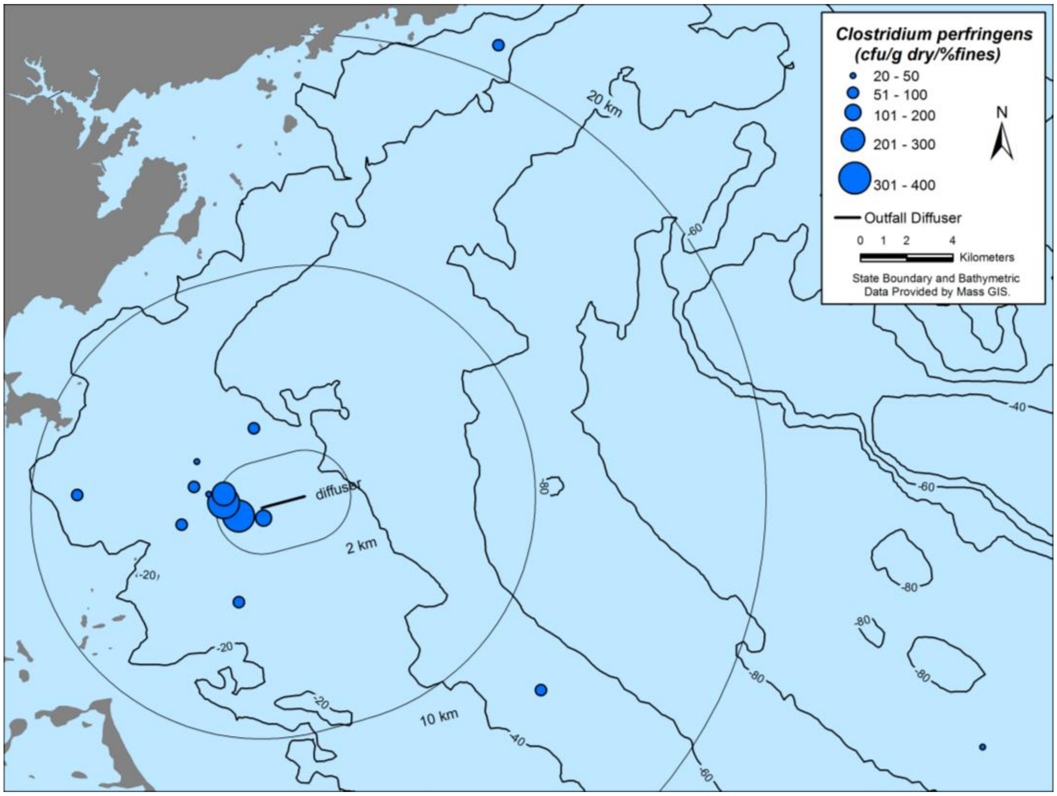

Figure 4-3. Concentrations of *Clostridium perfringens* spores, corrected for sediment grain size, in 2015.

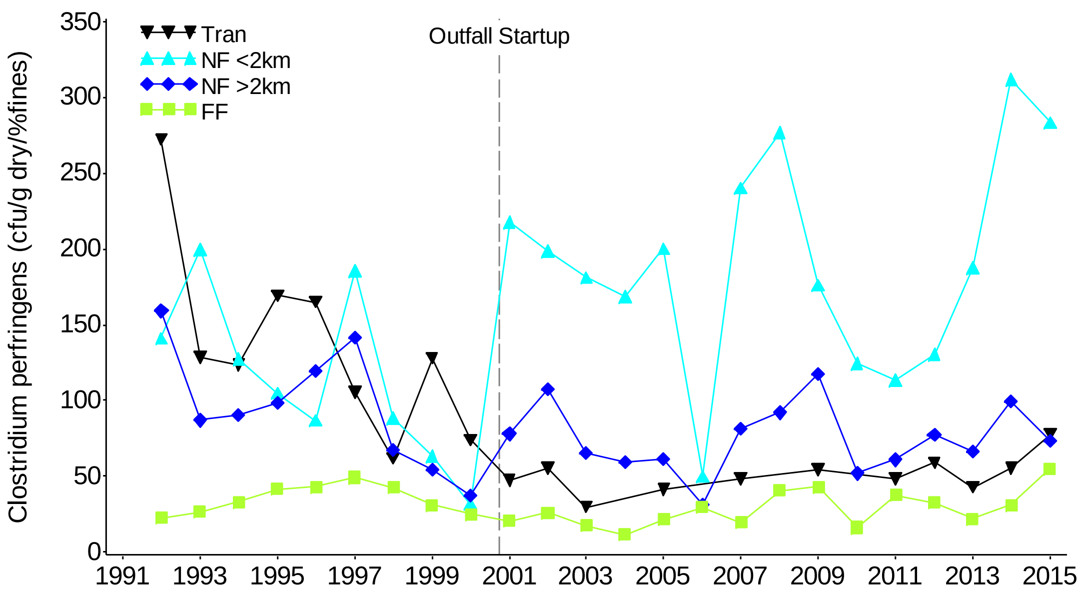

Figure 4-4. Mean concentrations of *Clostridium perfringens* spores during the baseline and outfall discharge years. Tran = transition area, stations located between Boston Harbor and the outfall; NF<2km = nearfield stations located within 2 km of the outfall diffusers; NF>2km = nearfield stations located further than 2 km from the diffusers; FF = farfield stations offshore from the outfall

Soft-bottom Communities

The 14 soft-bottom samples collected and analyzed in 2015 yielded 20,341 organisms, classified into 164 species and 22 other discrete taxonomic groups (Nestler et al. 2016). In recent years, infaunal abundance has been at the lower end of the range observed over the monitoring program, but it was higher in 2014 and 2015 than in 2011 and 2013, particularly in the transition area (Figure 4-5).

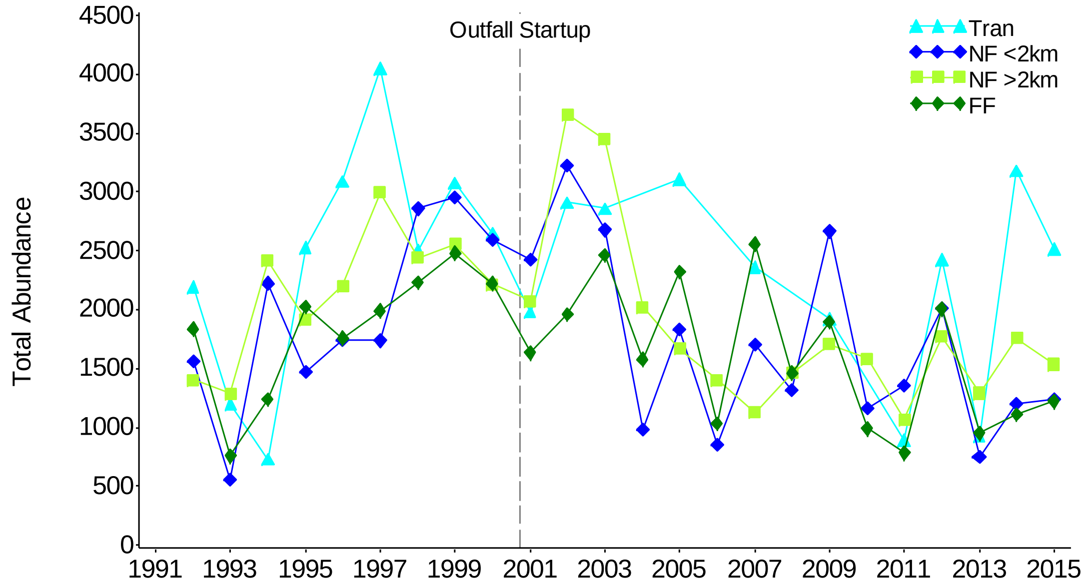

Figure 4-5. Mean infaunal abundance per sample in four areas of Massachusetts Bay, 1992–2015. Tran = transition area, stations located between Boston Harbor and Massachusetts Bay; NF<2km = stations within 2 km of the outfall; NF>2km = nearfield stations greater than 2 km from the outfall; FF = farfield stations offshore from the outfall

A series of multivariate analyses assessed spatial and temporal patterns in the soft-bottom benthic communities and found no particular species or type of community that could be specifically associated with the outfall. As in past years, a cluster analysis identified two main infaunal assemblages, with an outlier at Station FF04, which is offshore in Stellwagen Basin and has consistently had a distinct community. Also continuing the pattern of past years, an ordination analysis demonstrated that variations in species distributions largely followed differences in sediment type (Figure 4-6). The multivariate analyses have shown no indication of any relation of species composition to proximity to the outfall.

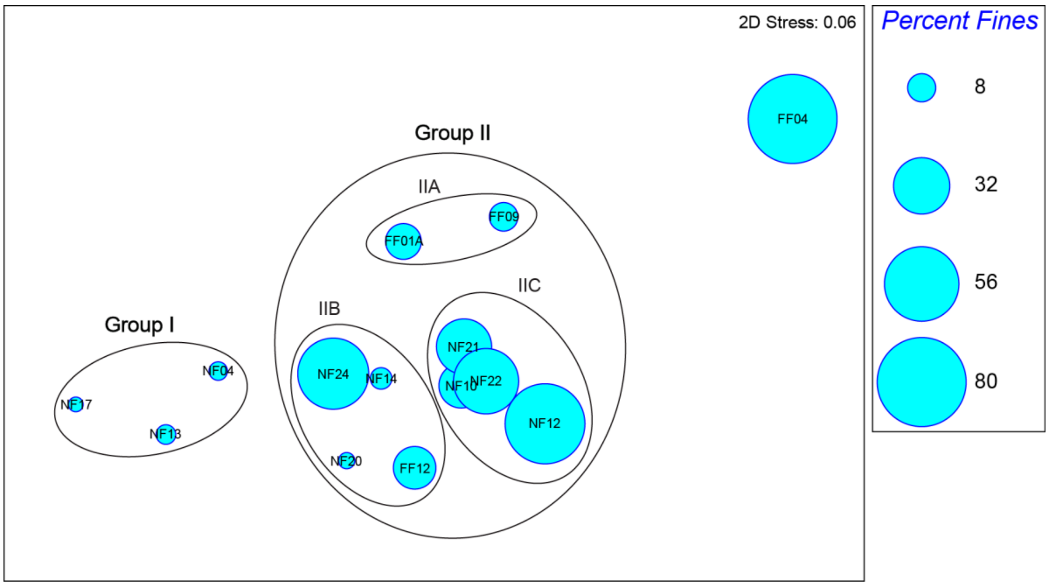

Figure 4-6. Percent fine sediments superimposed on the ordination plot of the 2015 infauna samples. Each point on the plot represents one of the 14 stations; similarity of species composition is indicated by proximity of points on the plot. Faunal assemblages (Groups I-II, and sub-groups) identified by cluster analysis are circled on the plot.

Sediment-profile Imaging

Sediment-profile images continued to show no adverse effects of the outfall (Nestler et al. 2016). Images from five of the 23 nearfield stations appeared to be sandier, with coarser-grained sediments, than in 2014, consistent with storm-induced sediment redistributions (Figure 4-7). The images also showed an increase in surface features indicative of physical structuring of the sediments at some stations. Storms with winds strong enough to re-suspend sediments occurred in October 2014 and February, March, and June 2015.

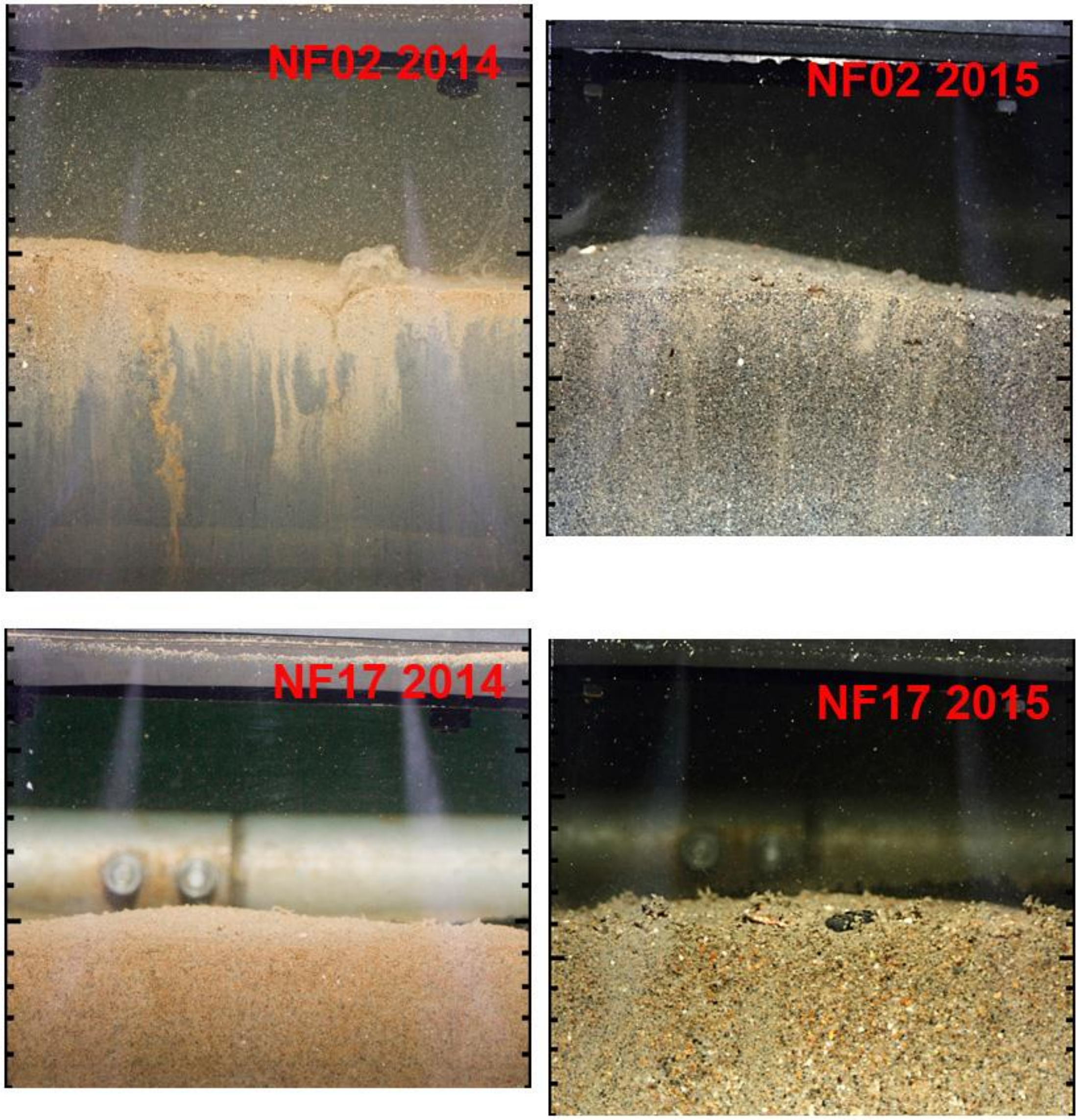

Figure 4-7. Apparent change in sediment grain-size distribution between 2014 and 2015 at Stations NF02 and NF17. Station NF02 is more than 5 km to the southwest of the outfall and changed from fine sand and silt to medium sand; NF17 is immediately to the southwest of the outfall and changed from fine-medium sand to medium sand.

The average RPD depth (the depth to which oxygen penetrates into sediments as determined by color changes) was the deepest ever measured during the monitoring program (Figure 4-8). At 14 of the 23 stations, the RPD was deeper than the bottom of the images. The environmental concern before the outfall began operation was that the RPD depth would become shallower, due to increases in sediment organic matter causing stress on sensitive sediment-dwelling organisms. A deeper RPD depth continued to indicate that there has been no adverse effect from the discharge.

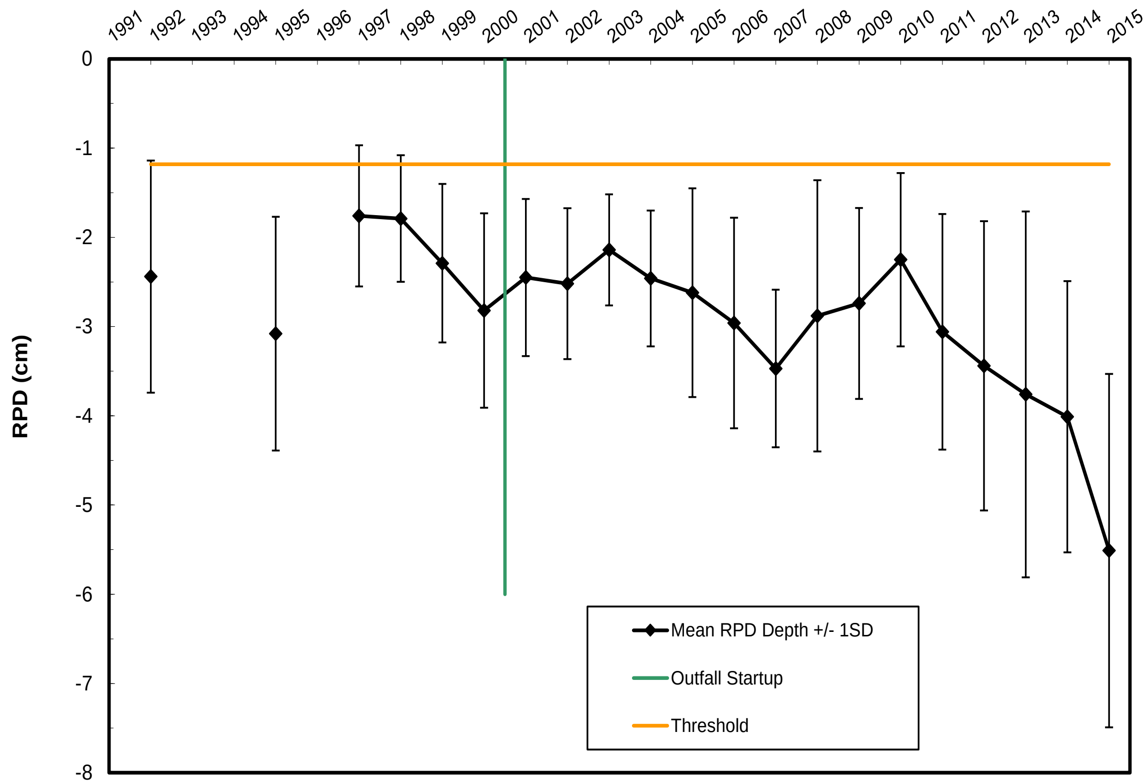

Figure 4-8. Annual apparent color RPD depth for data from nearfield stations. The average RPD discharge-period mean has been deeper than the baseline mean, continuing to indicate that there has been no adverse effect from the discharge.

Secondary treatment effectively reduces contaminants that might affect the sediments, and monitoring has shown that physical processes, such as storms and storm-induced sediment transport, are the primary stressors on the Massachusetts Bay sea floor. The dominance of physical forces may be considered typical of outfalls that have been located in high-energy areas that promote rapid dispersion of the effluent discharge.

Counterintuitively, the camera images detected a trend beginning in 2013 towards increased numbers of "pioneering" or "Stage I" organisms. This finding would be unexpected where there are deepening RPD depths. It was also not anticipated from the infaunal organism analyses presented above, either from the identification of individual animals or from the diversity and other community-parameter measurements. The change appears to be related to a slight coarsening of sediment grain-size and a resulting decline in visible biogenic structures in the sediment-profile images, a factor in determining successional stage.

Sediment-profile imaging and community analyses have been used to investigate effects of numerous coastal ocean effluent outfalls around the world (Puente and Diaz 2015). Those studies have found that, in general, outfalls that are dominated by high-energy physical processes, with little accumulation of organic matter, such as the MWRA outfall, have low or no detectable adverse effects on benthic infauna. Adverse effects on the bottom communities, where they do occur, are manifested primarily as changes in the ratio of opportunistic to sensitive species and as decreases in diversity or species richness (Figure 4-9). Opportunistic species remain rare in Massachusetts Bay, and any changes in diversity measures have been increases rather than the decreases typical of responses to adverse conditions. Changes, when they have been detected, have been analyzed and are thought to represent normal variation for the region.

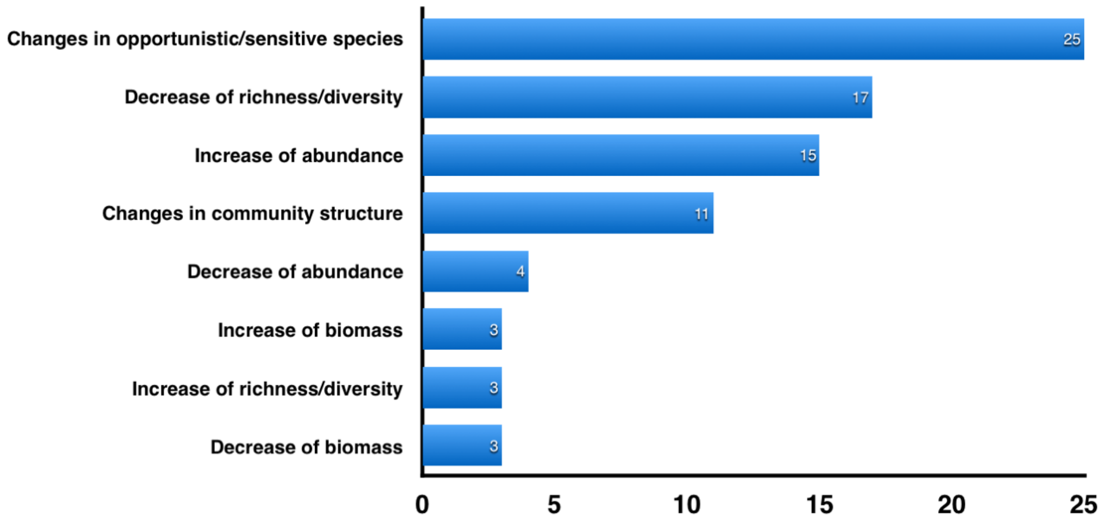

Figure 4-9. Numbers of studies showing types of adverse effects on benthic communities observed in studies of effluent outfalls on coastal and ocean communities. The graph is based on data from 44 outfalls around the world (redrawn from Puente and Diaz 2015).

Stellwagen Bank National Marine Sanctuary

The NPDES permit to discharge from DITP into Massachusetts Bay requires annual reports on results that are relevant to the Stellwagen Bank National Marine Sanctuary. MWRA's deepwater reference Station FF04 lies within the depositional part of the sanctuary, in Stellwagen Basin, where long-term accumulation of pollutants and their effects could be detected if they were to occur.

Station FF04 is typical of the deep waters offshore from the outfall, representative of a number of stations monitored in earlier years of the monitoring program, and it continues to support an infaunal community typical of what was found at the larger suite of deepwater stations. The deepwater stations, including Station FF04, have always shown distinct differences from those found at shallower stations, probably due to their depth, their fine-grained sediments, and their distance from shore. Superimposing depth on the ordination plot for 2015 infauna samples continued to show these differences (Figure 4-10; see also Figure 4-6, which superimposed percent fine sediments on the ordination plot).

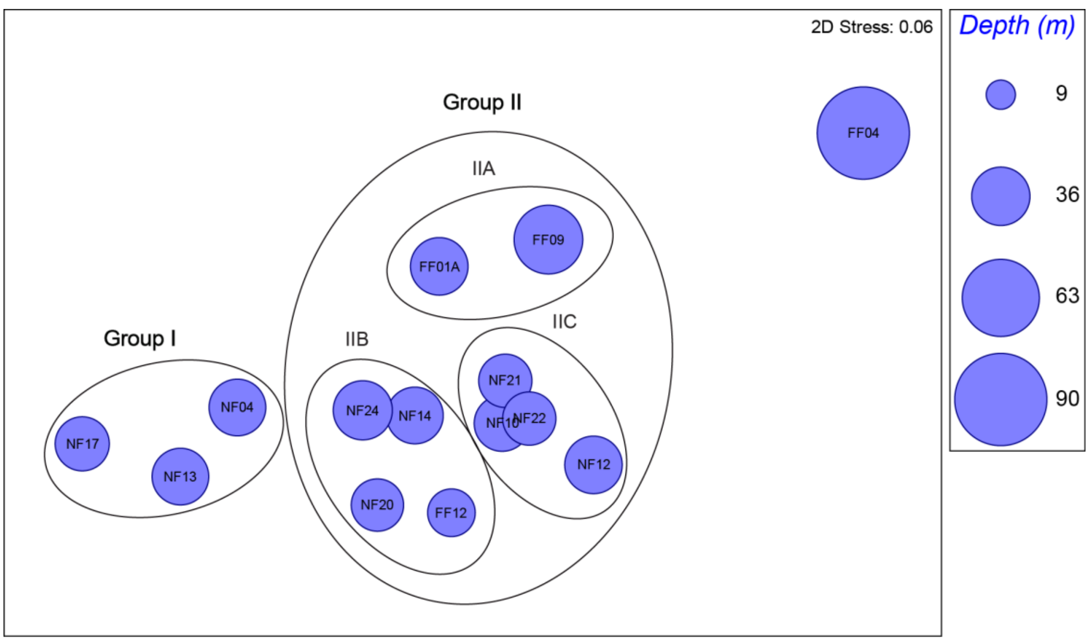

Figure 4-10. Depth superimposed on the ordination plot of the 2015 infauna samples. Each point on the plot represents one of the 14 stations; similarity of species composition is indicated by proximity of points on the plot. Faunal assemblages (Groups I-II, and sub-groups) identified by cluster analysis are circled on the plot.

Boston Harbor

While the chemistry and biology of the Massachusetts Bay sea floor have not been affected by the relocated outfall, conditions have greatly improved and continue to improve in Boston Harbor as a result of the Boston Harbor Project and more recent enhancements to treatment and remediation of combined sewer overflows. MWRA has conducted ongoing seafloor monitoring in Boston Harbor since 1991. Annual sediment and infauna samples are taken from nine stations (Figure 4-11).

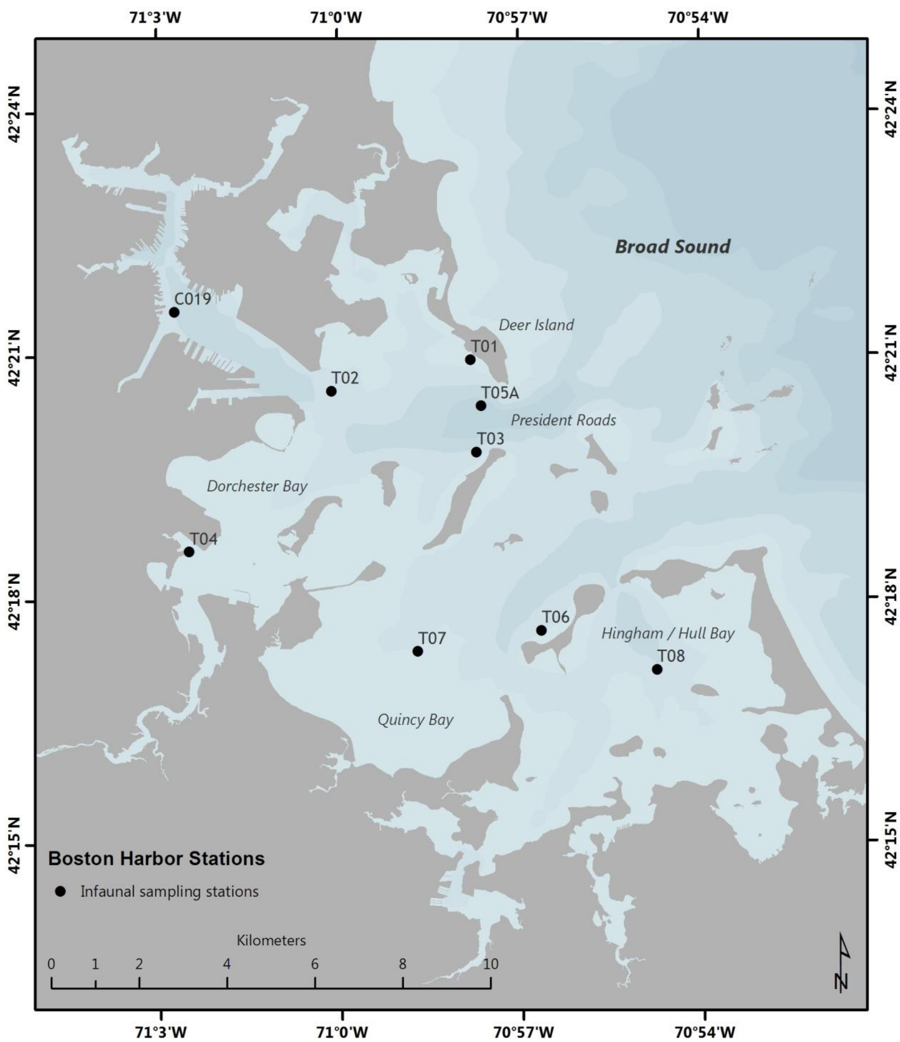

Figure 4-11. Soft-bottom sampling stations in Boston Harbor. Nine stations are sampled each year for sediment characteristics and infauna analyses.

Concentrations of total organic carbon (not shown) and *Clostridium perfringens* spores (Figure 4-12) have declined over time. Infaunal diversity has increased, reflecting continued improvement in habitat conditions. An ordination plot of Boston Harbor infaunal samples shows a separate community in stations in the outer harbor and a most unique fauna at Station T04 at the mouth of Savin Hill Cove, a location recognized as one of the most polluted sites in the harbor (Figure 4-13). Sediment-profile imaging also confirmed an inner- to outer-harbor gradient.

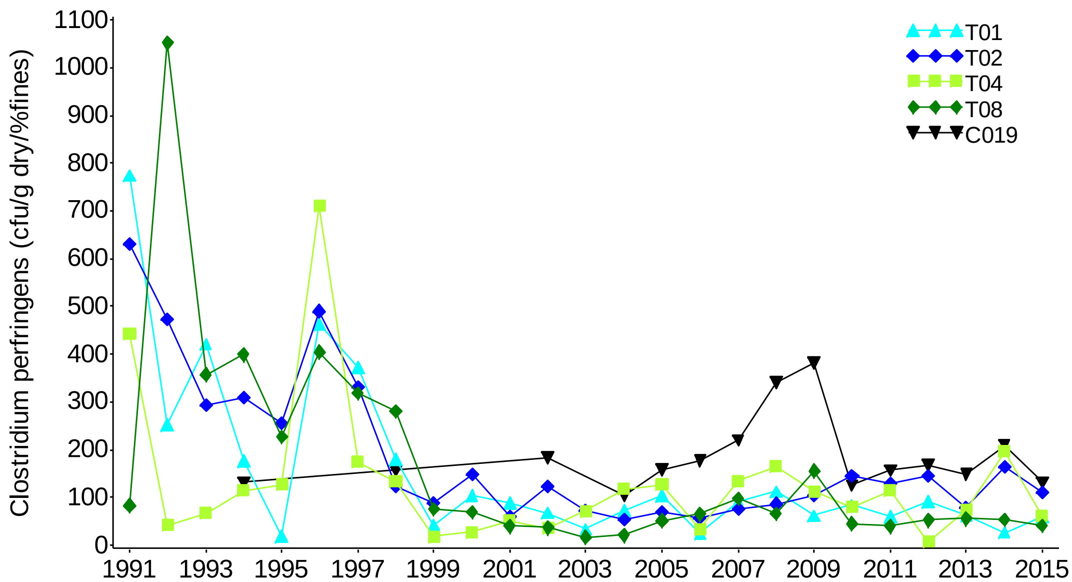

Figure 4-12. Mean concentrations of *Clostridium perfringens* spores at selected harbor stations, 1991–2015.

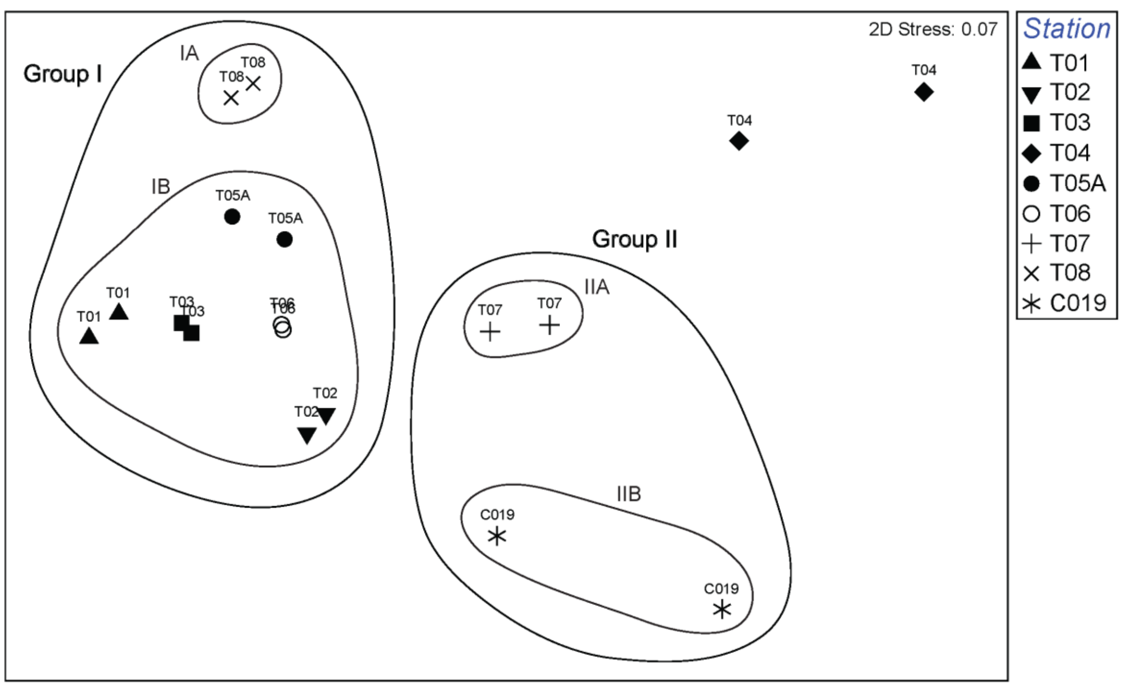

Figure 4-13. Ordination plot of 2015 Boston Harbor infauna samples. Group I comprises stations from the outer harbor; Group II includes Station C019 in the inner harbor and Station T07 in Quincy Bay. The assemblage most different from others was found at Station T04, at the mouth of Savin Hill Cove, in Dorchester Bay.

Contingency Plan Thresholds

There were no seafloor Contingency Plan threshold exceedances in 2015 (Table 4-1). Values for Shannon-Wiener diversity and Pielou's evenness, both diversity measures that triggered exceedances in 2010–2014, remained high but were within the upper caution-level ranges (Figure 4-14). Two other community threshold parameters, total number of species per sample (species richness) and Fisher's log-series alpha, another diversity measure, were also within the caution-level ranges. There has been no indication, even when diversity levels exceeded the upper bounds of the caution-level thresholds, that environmental conditions had worsened or that there had been any effect of the outfall. Percent opportunists among the soft-bottom community remained far below caution and warning levels.

Table 4-1. Contingency Plan threshold values and 2015 results for seafloor monitoring.

Parameter	Baseline	Caution Level	Warning Level	2015 Results
Sediment parameters				
RPD depth	NA	<1.18 cm	None	5.51 cm
Benthic community parameters				
Species per sample	NA	<42.99 or >81.85	None	61.0
Fisher's log-series alpha	NA	<9.42 or >15.8	None	13.1
Shannon-Wiener diversity	NA	<3.37 or >3.99	None	3.93
Pielou's evenness	NA	<0.57 or >0.67	None	0.66
% opportunists	NA	>10%	>25%	0.39%

HMW = high molecular weight; LMW = low molecular weight
NA = not applicable; RPD = redox potential discontinuity

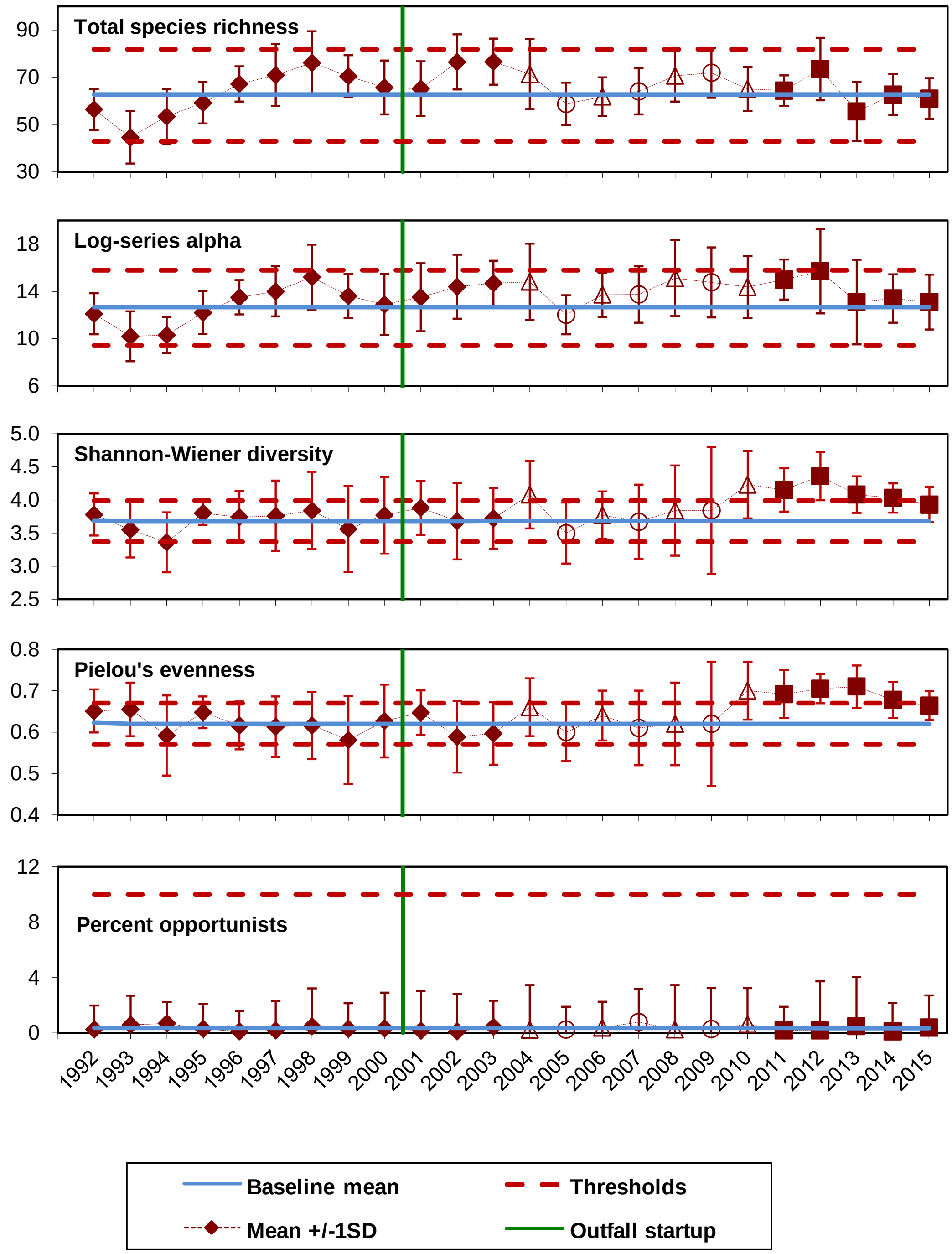

Figure 4-14. Annual community parameters with nearfield Contingency Plan thresholds. The varied symbols represent differences in the stations sampled over the years of the program. Results were tested against thresholds calculated for each sampling design, but only the current threshold values are shown. Except for the percent opportunists threshold, which is based on levels in Boston Harbor, thresholds have both upper and lower bounds to show potentially meaningful changes from the baseline. SD = standard deviation

5. Fish and Shellfish

Each year MWRA monitors the health of winter flounder from the Massachusetts Bay outfall site, Deer Island Flats in Boston Harbor, off Nantasket Beach just outside the harbor, and eastern Cape Cod Bay. Every three years, including 2015, monitoring includes chemistry measurements in flounder fillets and liver, lobster meat and hepatopancreas, and cage-deployed blue mussels. Lobsters are sampled from Deer Island Flats, the outfall site, and Cape Cod Bay. Mussels are deployed at two sites near the outfall, at Deer Island Light, and in Boston's inner harbor (Figure 5-1)

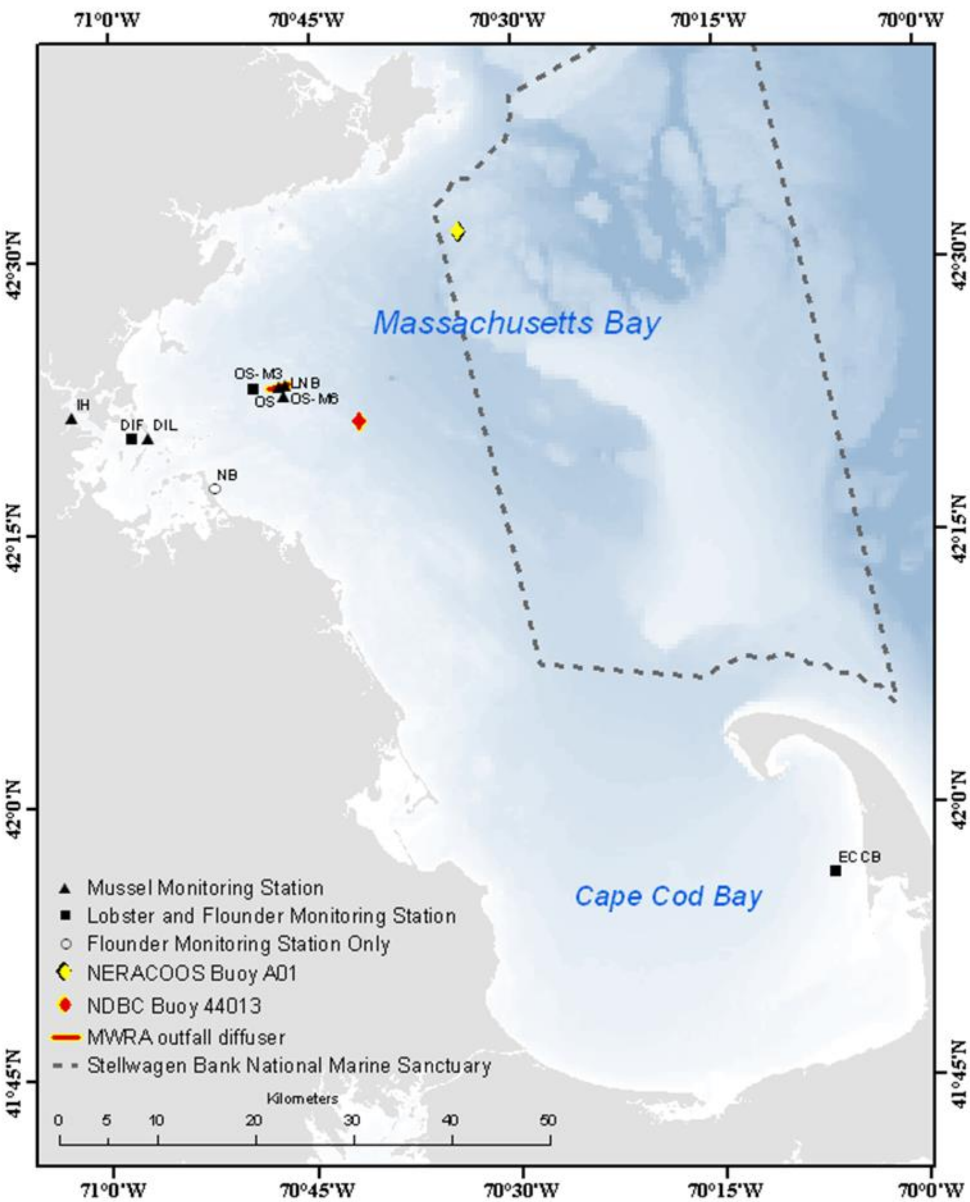

Figure 5-1. Fish-and-shellfish monitoring stations. Also shown are the two instrumented buoys, the MWRA outfall diffuser, and the boundaries of the Stellwagen Bank National Marine Sanctuary.

Flounder Health

Annual flounder monitoring focuses on the presence of early liver disease and liver neoplasia (tumors). Other indications of health are also documented. In April–May 2015, 50 sexually mature flounder were collected from Deer Island Flats, off Nantasket Beach, the outfall site, and eastern Cape Cod Bay (Moore et al. 2016). Catch per unit effort, which has varied through time, was highest at eastern Cape Cod Bay and the outfall site and lowest at Deer Island Flats and off Nantasket Beach. Abandoned fishing gear, sometimes referred to as "ghost gear," continued to interfere with catches, particularly in muddy depressions at the outfall and at Deer Island Flats.

Mean ages of fish ranged from 4.1 to 5.0 years across the sites, younger than samples from 2014, but well within the range for the monitoring program. Similar to 2014, lengths and weights were somewhat lower than typically observed but remained within historic ranges at all sites. As has been common throughout the duration of the monitoring program, the catches were dominated by females. (Additional information on flounder sex ratios is presented in Section 6, Special Studies.)

Measures of external condition, such as fin erosion and blind-side ulcers, also fell within historic ranges. Prevalence of fin erosion, a condition that can be indicative of elevated concentrations of ammonium and other pollutants, ranged from a low of 4% near the outfall to a high of 22% off Nantasket Beach.

Blind-side ulcers, which were first noted in 2003, were rare in 2015, ranging from a low of zero in eastern Cape Cod Bay to a high of 4% in fish from Deer Island Flats. There were elevated occurrences of ulcers in 2003–2006 and again in 2011. The pathology of the ulcers has been studied but is not well understood.

The incidence of centrotubular hydropic vacuolation (CHV), a mild condition associated with exposure to contaminants and a neoplasia precursor, remained lower than the baseline observations. Incidence of CHV at the outfall was about the same as in 2014 (Figure 5-2). Average severity of CHV (not shown) also remained lower than baseline levels. Fish from Deer Island Flats, near the former Boston Harbor outfall, showed an increase in CHV occurrence to 32%, but incidence remained lower than during the 1980s, when it was 75% or more.

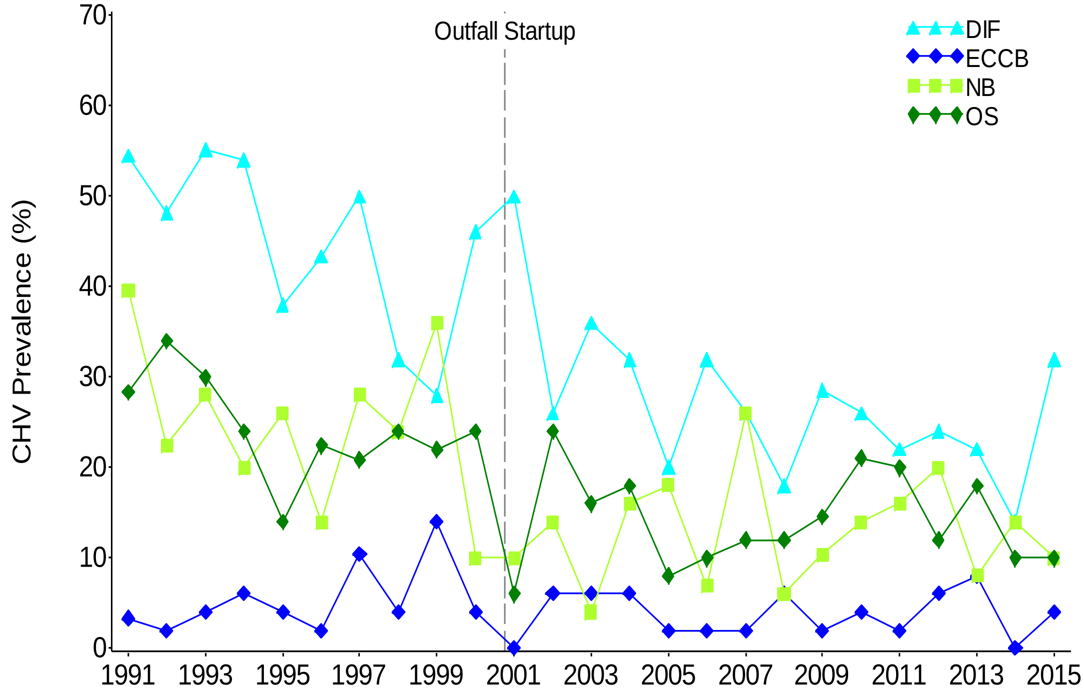

Figure 5-2. Annual prevalence of centrotubular hydropic vacuolation (CHV), 1991–2015. DIF = Deer Island Flats, ECCB = Eastern Cape Cod Bay, NB = Nantasket Beach, OS = Outfall Site

No liver tumors were observed in any fish from any site. Incidence of neoplasia has been rare throughout the area since MWRA monitoring started in 1991, although levels were higher in flounder taken from Boston Harbor for studies during the 1980s. Neoplasia has never been observed in a fish taken from the vicinity of the outfall.

Fish and Shellfish Chemistry

Samples for chemical analyses of winter flounder tissues were taken from the same April collections made for the health assessments. Samples of winter flounder fillet from each site were analyzed for PCBs, pesticides, and mercury. Liver samples from the same fish were analyzed for PCBs, pesticides, PAHs, and selected metals.

Lobsters were collected by local lobstermen in September and October, later than in other years. Samples of lobster meat from each site were analyzed for PCBs, pesticides, and mercury. Hepatopancreas (tomalley) samples from the same animals were analyzed for PCBs, pesticides, PAHs, and selected metals.

Over the years of the monitoring program, mussels have been collected in June from a reference location and deployed in cages for 45 and 60 days, ending in late August. Wild mussels were not available in 2015, so they were obtained from a commercial aquaculture facility in Blue Hill Bay, Maine. The commercial mussels had much thinner shells than the wild mussels deployed in the past and were apparently less hardy, as unusually low survival rates were observed, particularly at the inner harbor site. Survival rates were highest in the offshore deployments, including the outfall site. Reduced survival among the cage-deployed mussels limited the number of replicate samples that could be analyzed at some sites. There were, however, sufficient data to compare results across sites and years. Mussel tissues were analyzed for PCBs, pesticides, PAHs, mercury, and lead.

Overall, concentrations of banned organochlorine pesticides and PCBs remained low in all flounder fillet and liver, lobster meat and hepatopancreas, and deployed-mussel samples, with the highest concentrations found in samples from near Deer Island, the site of the former Boston Harbor outfall, and lowest in samples from Cape Cod Bay (Nestler et al. 2016). Slow declines in banned pesticides and PCBs continued across all samples types and locations and were particularly evident in samples taken near Deer Island (for example, Figures 5-3 and 5-4, which show total chlordane in flounder fillet and lobster meat). In fish and shellfish samples taken at the outfall site, concentrations of many organic compounds were the lowest measured throughout the duration of monitoring.

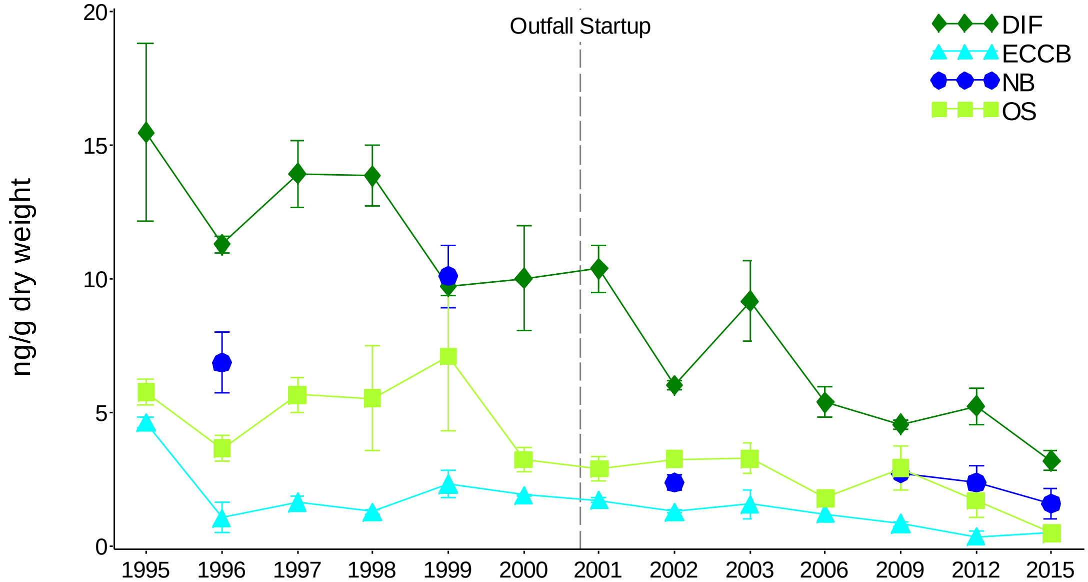

Figure 5-3. Total chlordane in flounder fillets, 1995–2015. Long-term declines in concentrations of banned organochlorine pesticides and PCBs were seen across sample types and locations. DIF = Deer Island Flats, ECCB = Eastern Cape Cod Bay, NB = Nantasket Beach, OS = Outfall Site

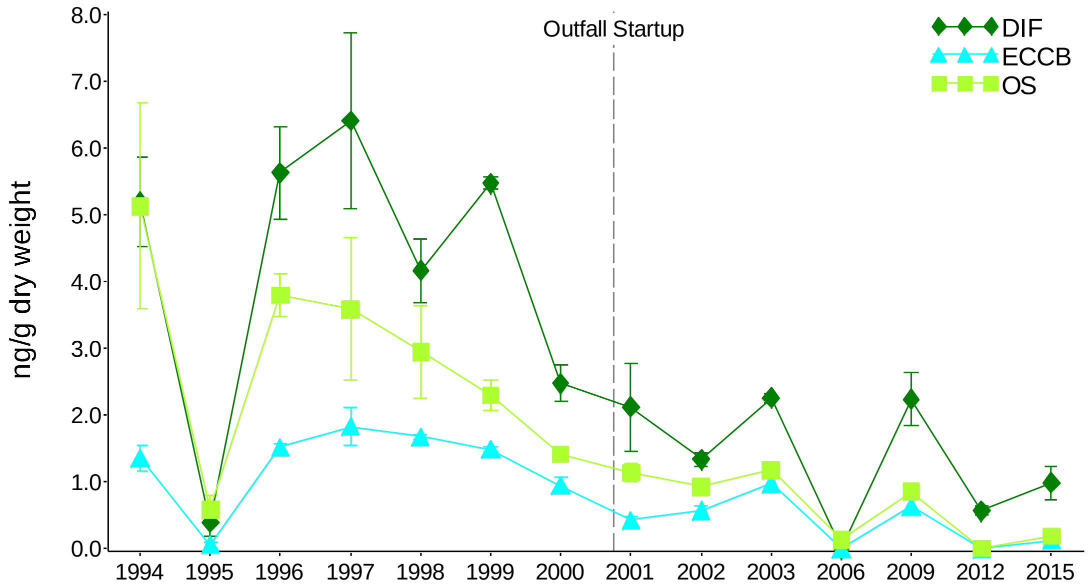

Figure 5-4. Total chlordane in lobster meat, 1994–2015. DIF = Deer Island Flats, ECCB = Eastern Cape Cod Bay, OS = Outfall Site

There has also been evidence of long-term declines in PAHs near Deer Island. Low molecular weight PAH concentrations were at or near monitoring-program lows in deployed mussels from all sites in 2015 (Figure 5-5). High molecular weight PAH concentrations (not shown) were slightly higher than those measured in 2012, but well below levels observed in the mid-1990s.

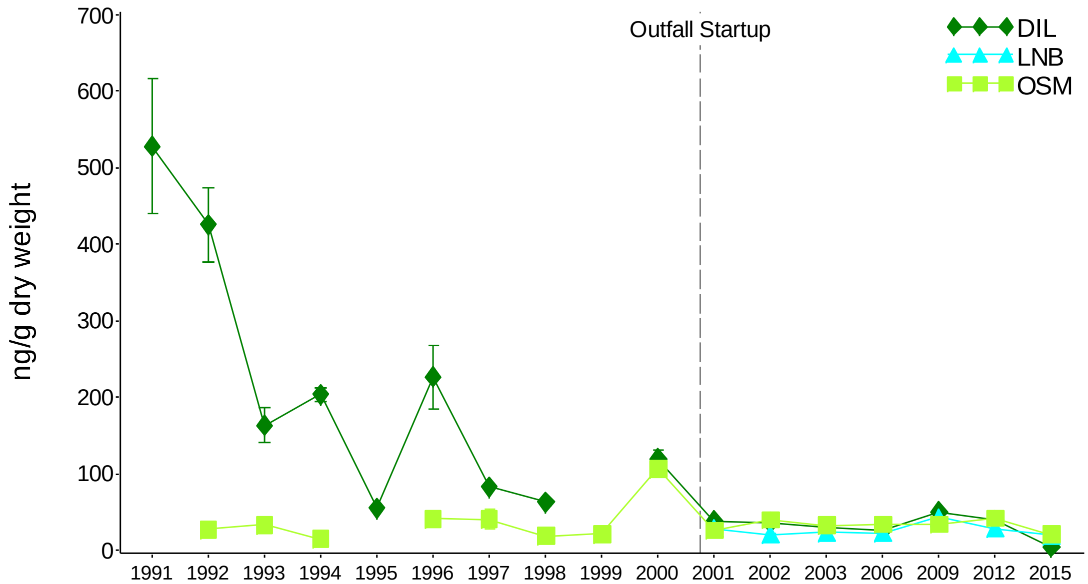

Figure 5-5. Low molecular weight PAHs in deployed mussels, 1991–2015. DIL = Deer Island Light, LNB = near the outfall, 1 kilometer south of the risers, OSM = Outfall Site

Unlike organic compounds, concentrations of metals in flounder, lobsters, and mussels have often been highest at the outfall site, even during the baseline period. Individual metals show varied temporal trends and sometimes no trend at all. Concentrations of silver, once considered a sewage indicator, have decreased in, for example, flounder livers from the outfall site (Figure 5-6), but concentrations of nickel (not shown) suggest a possible region-wide increase in concentrations. Overall, lead levels have declined throughout the region since the early 1990s, when pre-deployment mussels often had lead concentrations higher than post-deployment mussels from the outfall site (Figure 5-7).

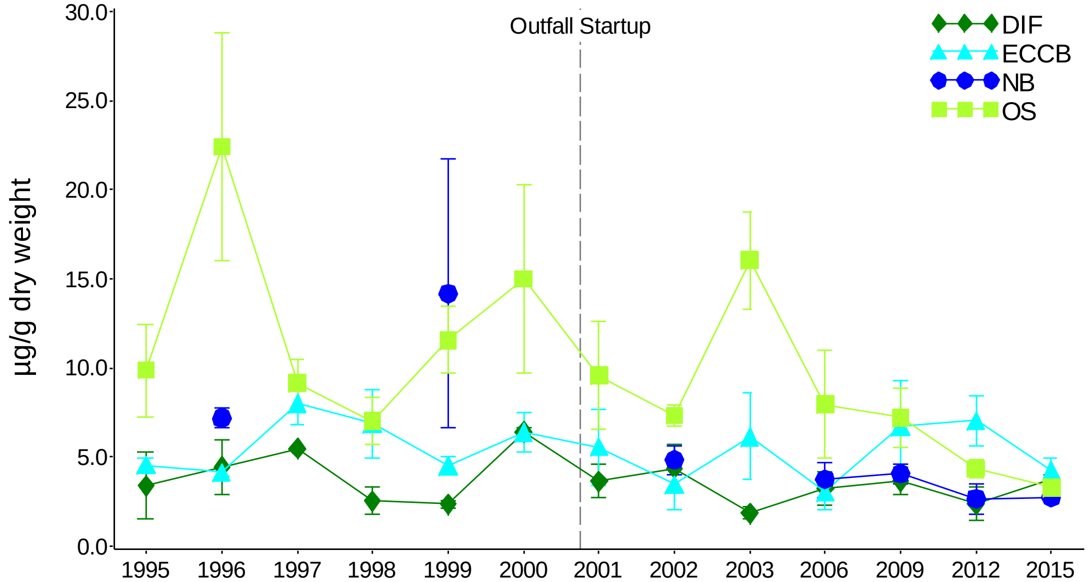

Figure 5-6. Silver in flounder livers, 1995–2015. DIF = Deer Island Flats, ECCB = Eastern Cape Cod Bay, NB = Nantasket Beach, OS = Outfall Site

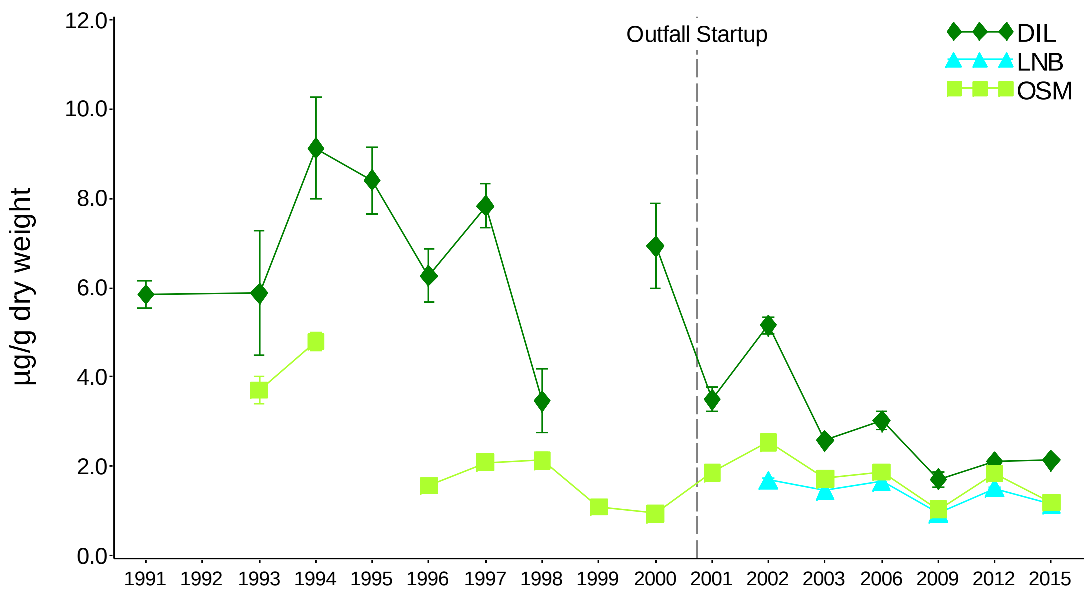

Figure 5-7. Lead in deployed mussels, 1991–2015. Gaps in data indicate years when concentrations in deployed mussels were lower than the pre-deployment controls. DIL = Deer Island Light, LNB = near the outfall, 1 kilometer south of the risers, OSM = Outfall Site

Contingency Plan Thresholds

There were no Contingency Plan threshold exceedances for fish and shellfish in 2015 (Table 5-1). Incidence of CHV, the most common indicator of liver disease in the winter flounder of the region, was 10% in fish taken from the vicinity of the outfall, lower than the 44.9% caution threshold and the 24.4% baseline average. Contaminant levels in flounder, lobster, and mussel tissues were also well below caution and warning thresholds.

Table 5-1. Contingency Plan threshold values and 2015 result for fish-and-shellfish monitoring.*

Parameter	Baseline	Caution Level	Warning Level	2015 Results
Flounder disease				
Liver disease (CHV)	24.4%	44.9%	None	10%
Flounder meat				
PCB	0.033 ppm	1 ppm wet weight	1.6 ppm wet weight	0.0153 ppm
Mercury	0.074 ppm	0.5 ppm wet weight	0.8 ppm wet weight	0.0694 ppm
Flounder meat, lipid normalized				
Chlordane	242 ppb	484 ppb	None	19 ppb
Dieldrin	63.7 ppb	127 ppb	None	0 ppb
DDT	775.9 ppb	1552 ppb	None	170 ppb
Lobster meat				
PCB	0.015 ppm	1 ppm wet weight	1.6 ppm wet weight	0.0121 ppm
Mercury	0.148 ppm	0.5 ppm wet weight	0.8 ppm wet weight	0.102 ppm
Lobster meat, lipid normalized				
Chlordane	75 ppb	150 ppb	None	2.3 ppb
Dieldrin	161 ppb	322 ppb	None	0 ppb
DDT	341.3 ppb	683 ppb	None	44.8 ppb
Mussel tissue				
PCB	0.011 ppm	1 ppm wet weight	1.6 ppm wet weight	0.00276 ppm
Lead	0.415 ppm	2 ppm wet weight	3 ppm wet weight	0.147 ppm
Mercury	0.019 ppm	0.5 ppm wet weight	0.8 ppm wet weight	0.00879 ppm
Mussel tissue, lipid normalized				
Chlordane	102.3 ppb	205 ppb	None	16.1 ppb
Dieldrin	25 ppb	50 ppb	None	0 ppb
DDT	241.7 ppb	483 ppb	None	26.3 ppb
PAH	1080 ppb	2160 ppb	None	1580 ppb

* Exceedances are values greater than (>) all thresholds.
CHV = centrotubular hydropic vacuolation

6. Special Studies

Besides monitoring the effluent and the water column, sea floor, and fish and shellfish in Massachusetts Bay and the surrounding area, MWRA conducts special studies in response to specific permit requirements, scientific questions, and public concerns. This year's overview focuses on eelgrass in Boston Harbor, bacterial water quality in Massachusetts Bay, winter flounder sex ratios, and ongoing monitoring by the Center for Coastal Studies in Cape Cod Bay.

Eelgrass in Boston Harbor

Historically, seagrasses, primarily eelgrass (*Zostera marina*), were prevalent in Boston Harbor, providing refuge and foraging habitat for marine animals, including commercial fish and shellfish. Over the past century, the health and extent of eelgrass beds declined, partly for reasons that affected sea grass beds globally and partly due to local changes in environmental conditions. Excess nutrients from sewage and fertilizers and other factors that lead to corresponding decreases in water clarity have been important factors in seagrass declines.

The change in nutrient regime in Boston Harbor provides some encouragement that excess nutrients no longer preclude re-establishment and maintenance of eelgrass beds. Once very high, about 800 kg per hectare per year, nitrogen loading to the harbor is now well below 150 kg per hectare per year (Figure 6-1). This value represents a maximum threshold thought to allow for eelgrass beds in southern New England (Latimer and Rego 2010).

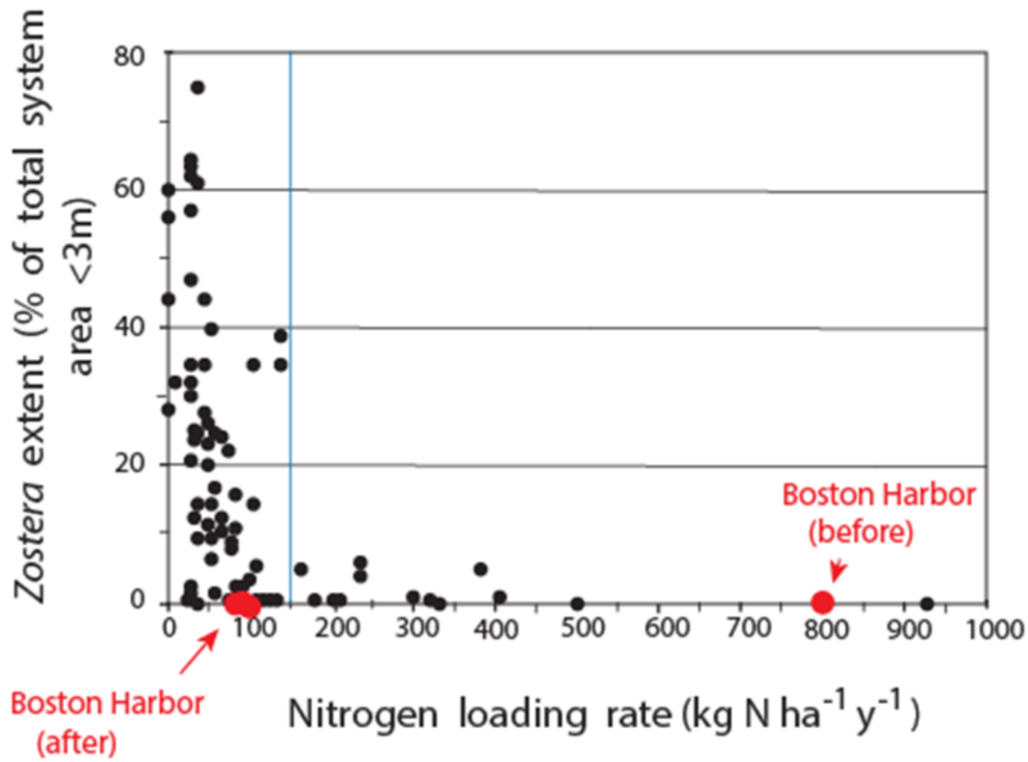

Figure 6-1. Percent eelgrass coverage vs. nitrogen loading in coastal systems compared to Boston Harbor before and after the Boston Harbor Project. The vertical blue line represents the 150 kg per hectare per year loading thought to allow for eelgrass beds in southern New England.

Since 2008, sediment-profile imagery in MWRA's in-house harbor-monitoring program has recorded eelgrass at Deer Island Flats, an area that some had thought was too degraded for colonization and restoration of seagrass beds. The MassDEP Eelgrass Mapping and Monitoring Program has documented eelgrass expansion in the north region of the harbor between 1995 and 2012 (Figure 6-2). This region once received the bulk of the harbor's elevated nitrogen inputs. Over the entire geographic extent of the harbor, however, eelgrass restoration remains a challenge. Other factors that affect turbidity may now be limiting seagrasses in the harbor.

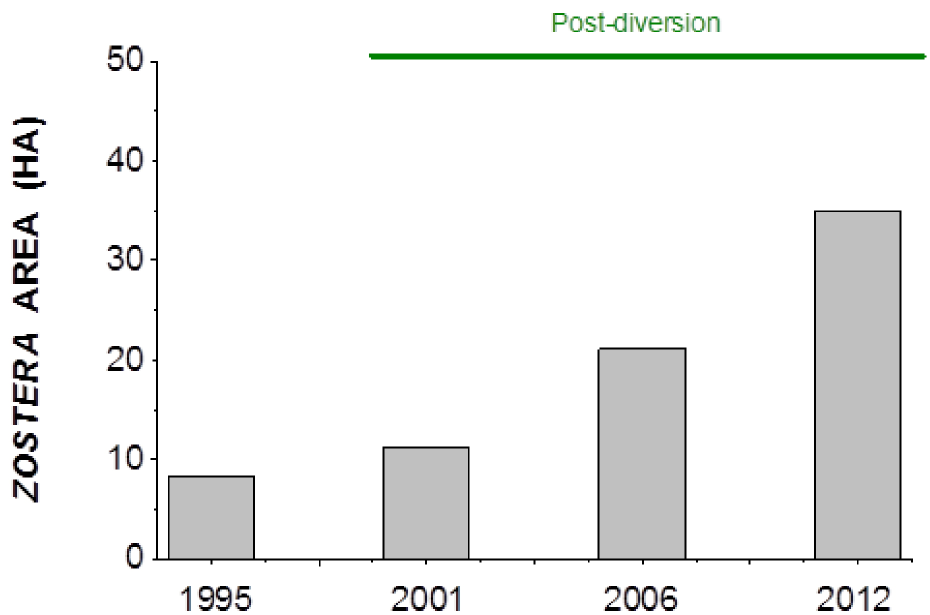

Figure 6-2. Eelgrass (*Zostera marina*) coverage in the north harbor, 1995–2012. (Data from MassDEP.)

Bacterial Water Quality in Boston Harbor and Massachusetts Bay

Before the Boston Harbor Project, bacterial pollution from untreated combined sewer overflows (CSOs), incompletely treated primary wastewater effluent, and daily discharge of digested sewage sludge (biosolids) resulted in widespread beach closures and violations of bacterial water-quality standards throughout the harbor. Degraded water quality from bacterial pollution was one of the main drivers behind the creation of MWRA and the court-ordered Boston Harbor Project.

Before 1991, wet-weather exceedances of water-quality standards were common and severe, with many parts of Boston Harbor exceeding the *Enterococcus* bacteria swimming standard (35 colonies/100 ml), sometimes by a factor of five or more (Figure 6-3, left). Since 2007, after the completion of DITP and most CSO projects, water quality in most of Boston Harbor and its tributaries meets the *Enterococcus* standard, even in wet weather (Figure 6-3, right). Remaining wet-weather *Enterococcus* exceedances occur in smaller areas and are less severe.

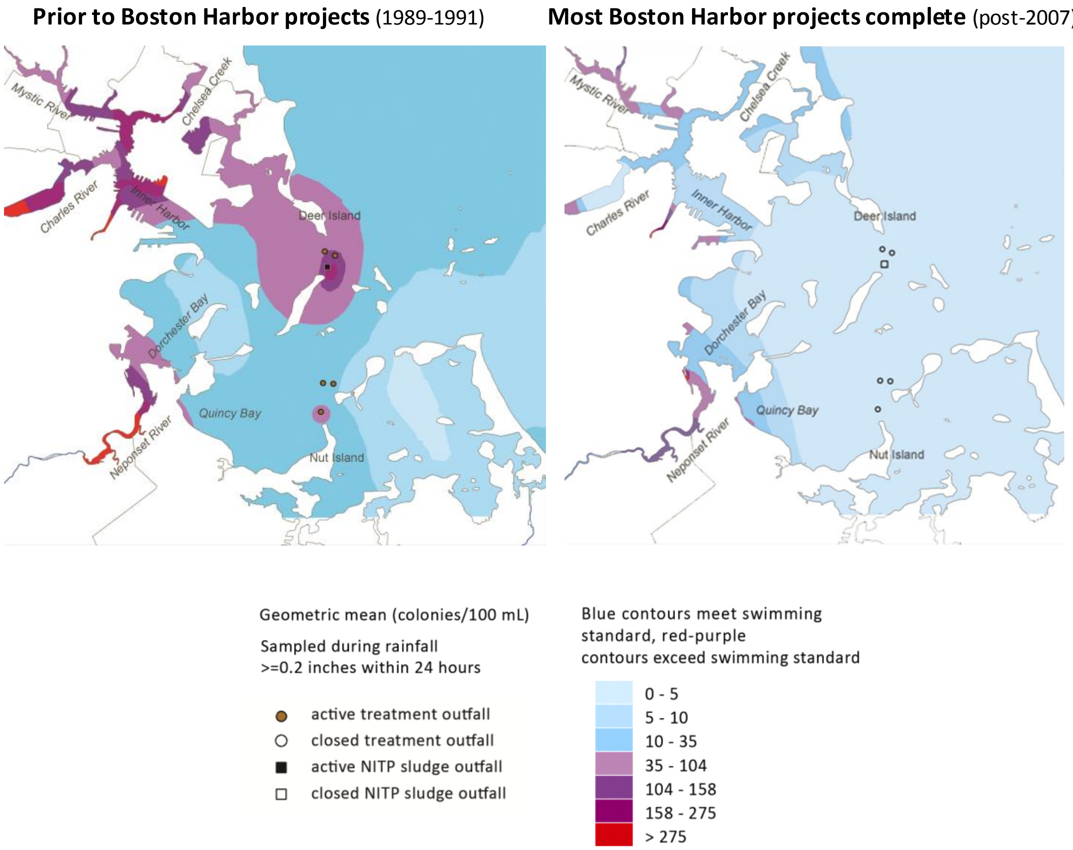

Figure 6-3. Bacterial water quality prior to the Boston Harbor Project and after completion of the treatment plant and most CSO projects.

The improvements in Boston Harbor have not been accompanied by any degradation to Massachusetts Bay. Since 1999, MWRA has monitored sewage-indicator bacteria (*Enterococcus* and fecal coliform bacteria) in the vicinity of the Massachusetts Bay outfall (Codiga et al. 2016). The surveys address permit conditions that the discharge meet the state water quality standard for primary-contact recreation and that it not adversely affect shellfishing resources.

Monitoring includes monthly surveys at 11 stations (Figure 6-4) and additional surveys of those same stations if triggered by a possibly adverse condition at DITP, such as an extended chlorination failure or a long period of blending primary-only treated effluent with effluent that has received full primary and secondary treatment.

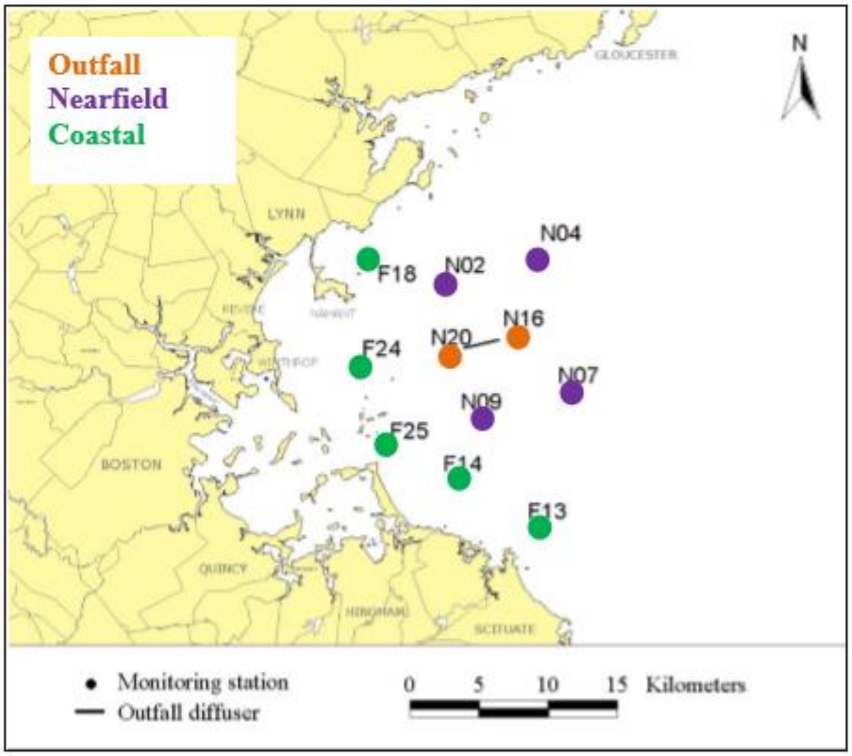

Figure 6-4. Stations monitored for sewage-indicator bacteria and the outfall diffuser.

Sampling and analysis assess water quality directly over the outfall, other locations in the outfall nearfield, and near the coastline, between the outfall and active shellfish beds. *Enterococcus* analyses determine whether waters near the outfall meet the standard for contact recreation (swimming). Fecal coliform bacteria counts determine whether waters meet the standard for shellfishing.

Results show that, annually, throughout the duration of monitoring, levels have remained well below the swimming standard, a geometric mean of 35 *Enterococcus* per 100 ml, at all areas (Figure 6-5). Similarly, fecal coliform bacteria counts have remained well below the standard for shellfishing, 14 fecal coliforms per 100 ml (Figure 6-6).

Of the more than 3,000 samples analyzed in 1999–2014 (the most recent year included in the analyses), the vast majority of samples had undetectable levels of sewage-indicator bacteria. Even beneath the pycnocline under stratified conditions, when dilution is minimized, 90% of the *Enterococcus* samples and 80% of the fecal coliform samples had undetectable levels of indicator bacteria. Further, sampling in response to adverse conditions detected only minor differences from the routine, monthly samples, and conditions at outfall stations were largely indistinguishable from nearfield and coastal stations. Even the highest measured concentrations of both indicators have been well below the standards. Overall results have demonstrated that water quality is sufficiently protected by treatment and disinfection at DITP.

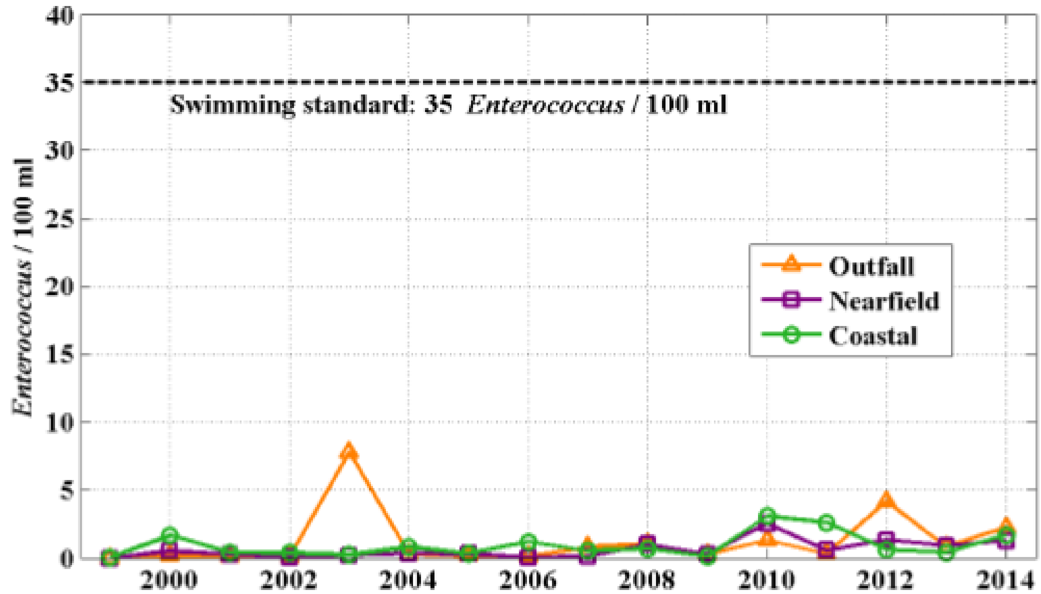

Figure 6-5. *Enterococcus*, 1999–2014, compared to the contact recreation standard of a geometric mean not exceeding 35 organisms/100 ml.

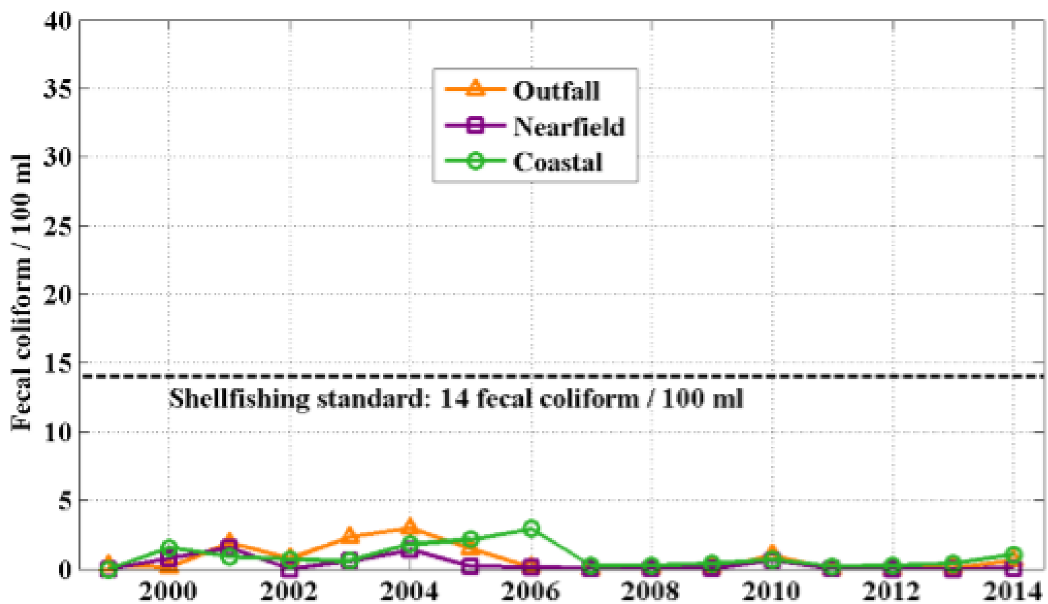

Figure 6-6. Fecal coliform bacteria, 1999–2014, compared to the shellfishing standard of a geometric mean not exceeding 14 organisms/100 ml.

Winter Flounder Sex Ratios

Throughout the duration of the monitoring program, winter flounder catches have been dominated by females. In most years, females have made up most of the catch at every sampling site, and in some years and sites, the samples have been almost 100% female (Figure 6-7).

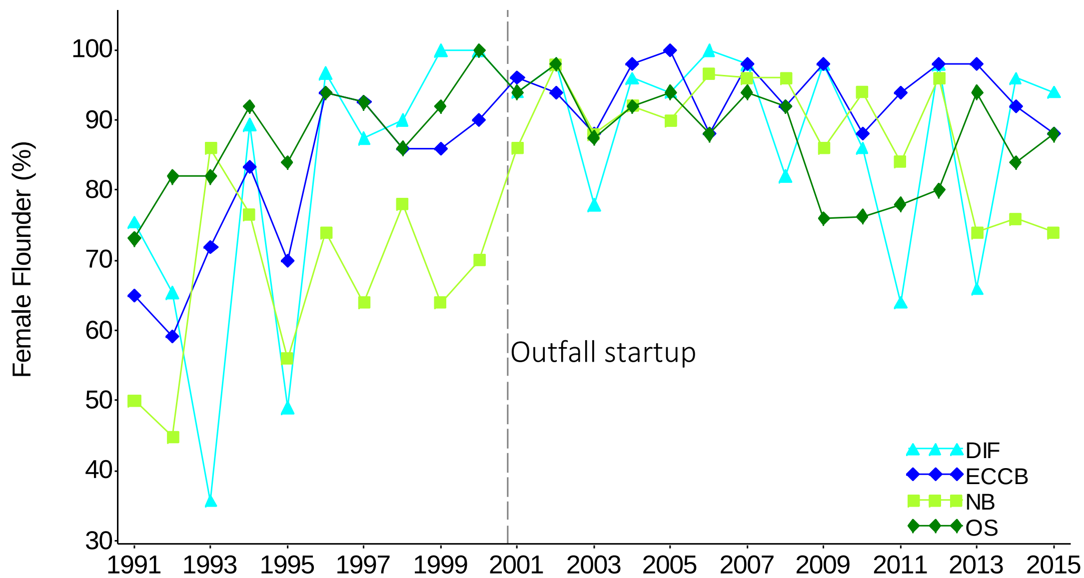

Figure 6-7. Proportion of catch made up of female flounder, 1991–2015. DIF=Deer Island Flats, ECCB=eastern Cape Cod Bay, NB=Nantasket Beach, OS=outfall site

In 2015, MWRA analyzed existing data from the monitoring program to determine whether there were detectable spatial or temporal trends (Moore et al. 2016). MWRA data were then compared with data from regional fisheries management agencies and other studies of winter flounder populations in New England and New Jersey.

The analysis of monitoring-program data found that overall, 83% of MWRA's total catch of winter flounder has been female. Regression analyses showed that catches were less skewed in the earlier years of monitoring, with the shifts towards greater percentages of females occurring during the 1990s. However, there was no consistent pattern in temporal shifts across sampling sites. For flounder caught near the outfall, the temporal shift has been slight, averaging 86% female in the early years of the monitoring program and 89% in more recent years, with a gradual increase in percent females during the 1990s and a gradual decline since 2000 (Figure 6-8). Fish caught in eastern Cape Cod Bay, the sampling site farthest from influence of MWRA's past discharges or current outfall have had the highest percentage of females and no discernable trend in the years since the Massachusetts Bay outfall began to discharge.

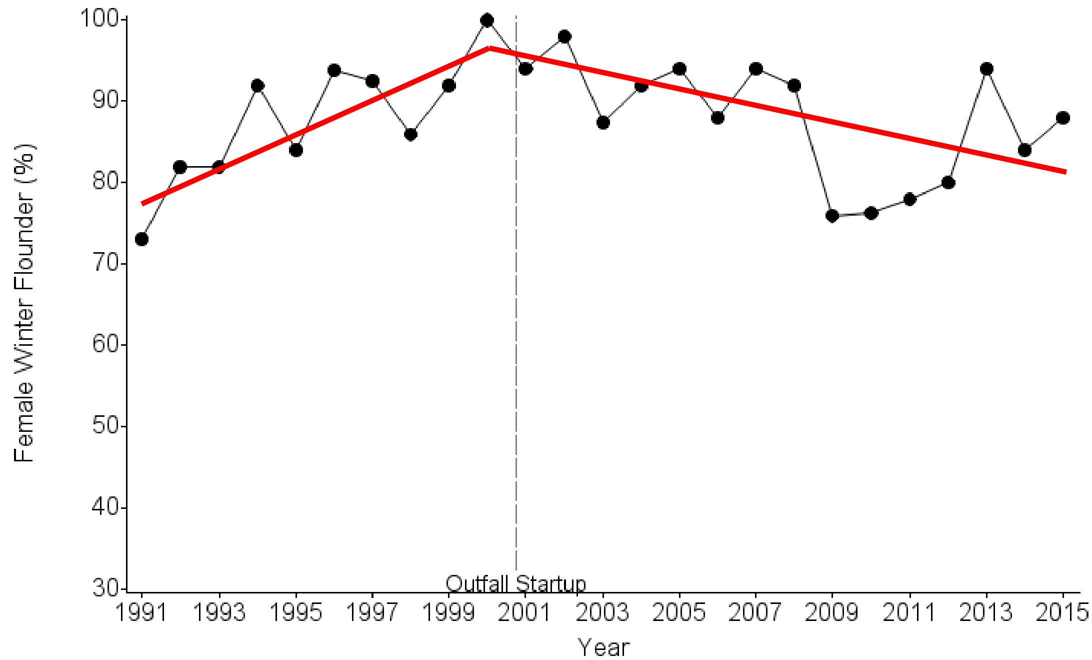

Figure 6-8. Percent female flounder taken from the vicinity of the outfall site, 1991–2015. The red line denotes the trends detected in time-series analysis.

The regional analyses compared MWRA data to information from coastal Maine and New Hampshire, Massachusetts, Rhode Island, Connecticut, and New Jersey and offshore on Georges Bank. None of the programs were specifically designed for analysis of sex ratios. Most of them targeted flounder with a greater size range than the larger, older fish targeted by MWRA to best examine the effects of longer exposure to chemical contaminants necessary for development of liver disease. The varying goals of the studies presented challenges in analyzing the results, as in general for winter flounder, percentage of females increases with length, particularly in the size range targeted by MWRA, longer than 30 cm total length. The comparisons confirmed that among the coastal populations, percent females increased with length between 30 and 40 cm (Figure 6-9), with about 83% total average percent females, the same as found by MWRA. Flounder from the offshore Georges Bank population did not show a skewed sex ratio.

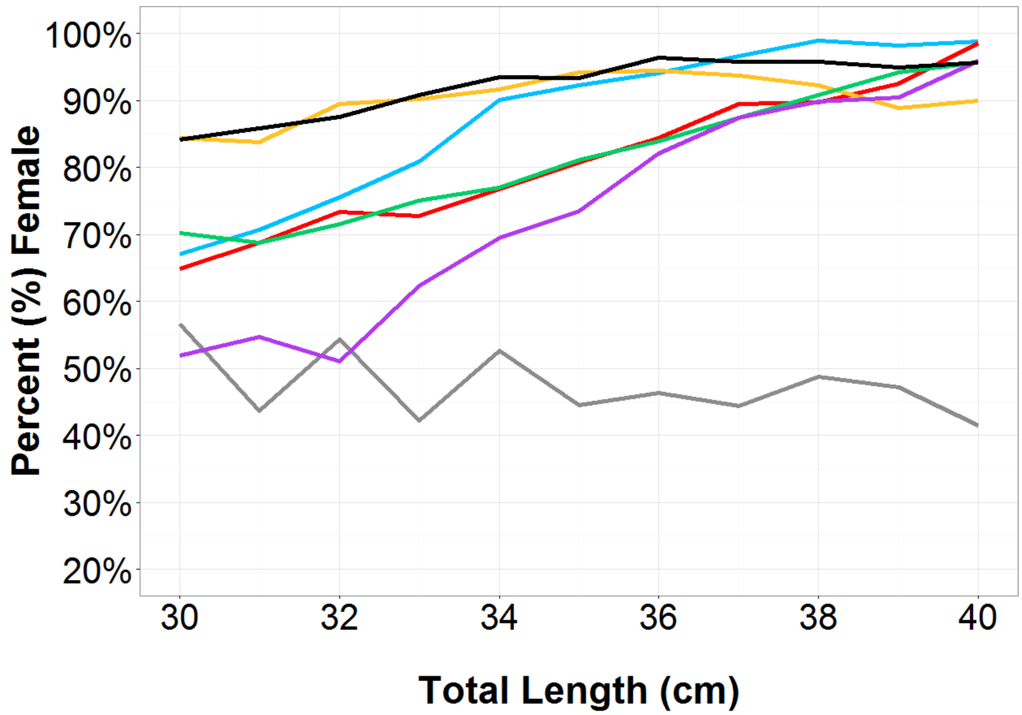

Figure 6-9. Sex ratios compared to total length of winter flounder in MWRA surveys, other northeast coastal surveys, and on offshore Georges Bank. Percent females increased with total length in all coastal surveys. Black = Rhode Island, Gold = Maine–New Hampshire, Blue = Connecticut, Green = MWRA, Red = Massachusetts, Purple = New Jersey, Gray = Georges Bank

Scientists have shown that sex ratios in fish may be linked to environmental factors, including temperature variations or exposure to chemicals that mimic endogenous hormones. However, the comparison of MWRA data with other data sets did not suggest any effect of temperature regimes or contaminant releases. The lack of female bias in the Georges Bank study is notable. However, temperature and contaminant inputs vary widely across the area included in the coastal studies. The consistently female-dominated collections of flounder in the size range targeted by MWRA, coupled with the lack of consistent temporal and spatial trends within the MWRA data set, suggests that there is no effect of the Massachusetts Bay outfall.

Cape Cod Bay Studies

The Center for Coastal Studies has conducted a monitoring program in Cape Cod Bay for many years, and since 2011, MWRA has collaborated on a portion of the program. The Center for Coastal Studies monitoring program includes MWRA water-column Station F29, on the southern boundary of Stellwagen Bank National Marine Sanctuary, MWRA Stations F01 and F02 in Cape Cod Bay and eight additional stations (Figure 6-10).

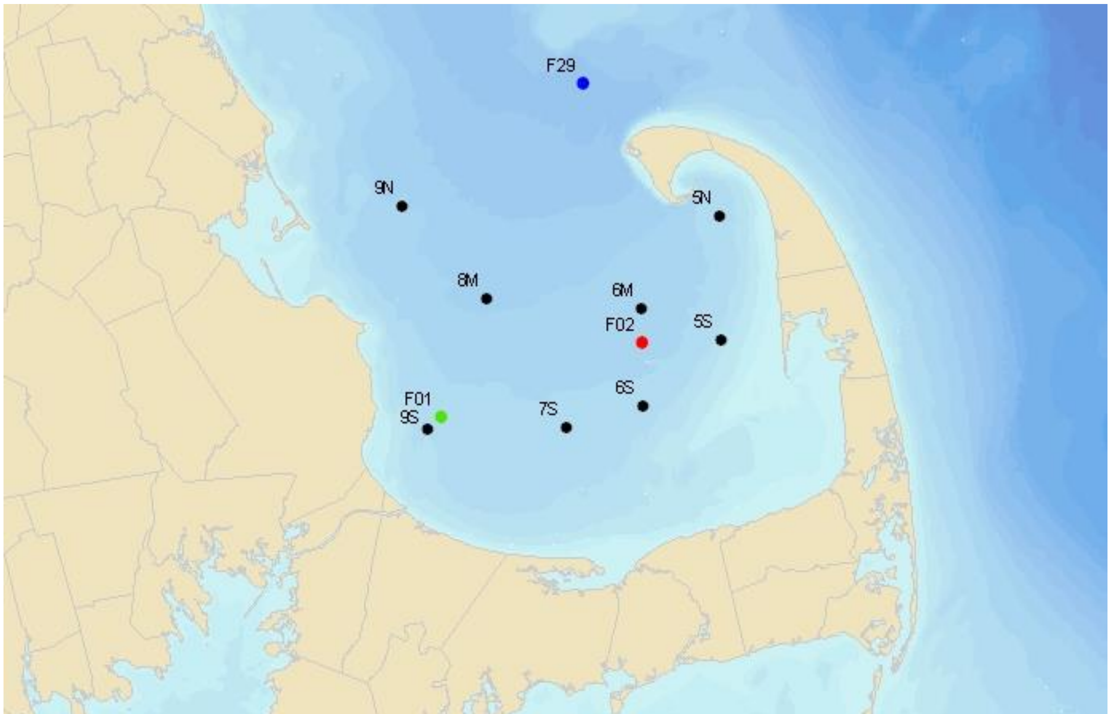

Figure 6-10. The Center for Coastal Studies monitors its own eight stations and three MWRA stations (F01, F02, and F29) in and near Cape Cod Bay. (Figure from the Center for Coastal Studies)

The Center for Coastal Studies also monitors North Atlantic right whales, with aerial surveys flown along a series of east-west tracks over Cape Cod Bay. The surveys record presence, dive times, and whale behaviors. Right whales typically occur in Cape Cod Bay during January through May, entering when nutrient and chlorophyll levels are high, and their large zooplankton food is abundant. Total annual whale sightings had been high in recent years, compared to the late 1990s and early 2000s (Figure 6-11). Sightings during 2015, however, were lower than in most recent years. The whales entered Cape Cod Bay later than usual and remained about two weeks longer than usual, so that high numbers remained until almost the very end of the season. In May, whales congregated in the western part of Cape Cod Bay, where they were visible from the shore (Figure 6-12).

There were 135 identified whales observed throughout the season, approximately one quarter of the known North Atlantic right whale population. While the number of identified right whales was much less than had been observed in 2007–2014, it was greater than the numbers observed in 1998–2006. The North Atlantic right whale remains protected under the U.S. Endangered Species and Marine Mammal Protection acts, with Massachusetts and Cape Cod bays considered to be key habitat for the western North Atlantic population.

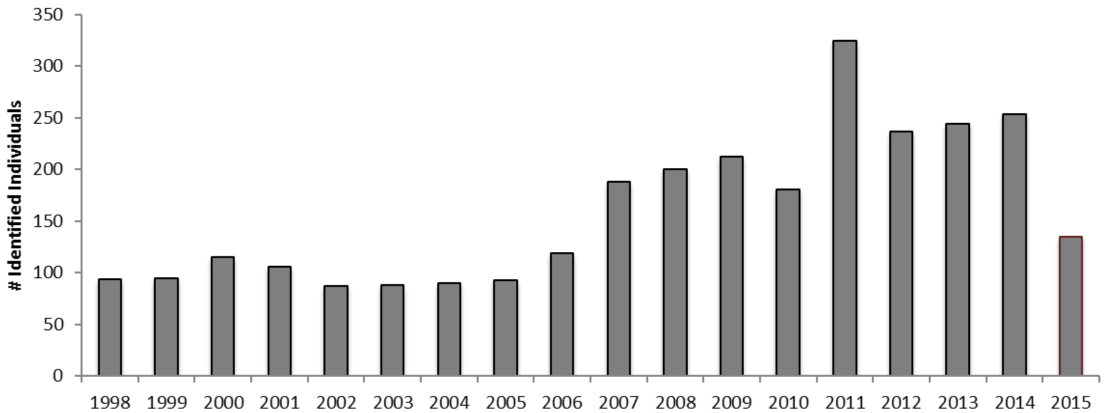

Figure 6-11. Right whale sightings in Cape Cod Bay, 1998–2015. (Figure from the Center for Coastal Studies.)

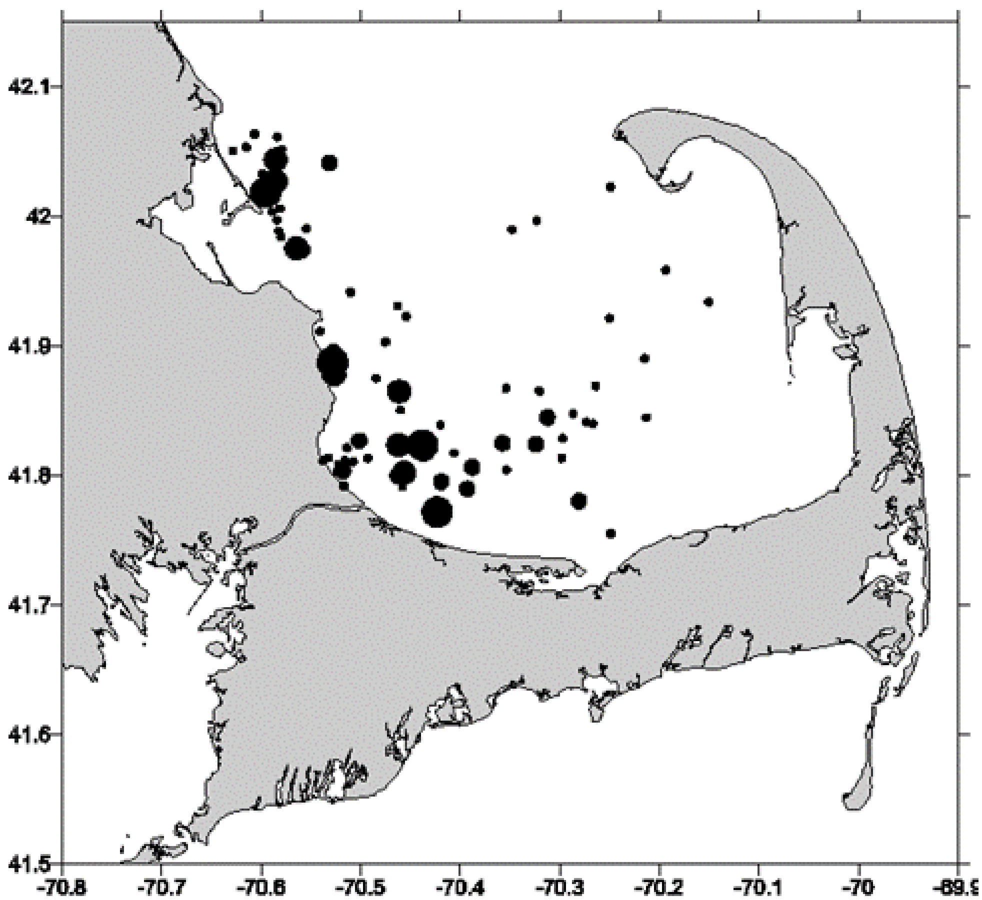

Figure 6-12. Whale sightings in Cape Cod Bay in May 2015. (Figure from the Center for Coastal Studies.)

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List of Acronyms

cBOD	Carbonaceous biochemical oxygen demand
CHV	Centrotubular hydropic vacuolation
CSO	Combined sewer overflow
DDT	Dichlorodiphenyltrichloroethane
DIF	Deer Island Flats
DIN	Dissolved inorganic nitrogen
DITP	Deer Island Treatment Plant
DO	Dissolved oxygen
ECCB	Eastern Cape Cod Bay
EPA	U.S. Environmental Protection Agency
FF	Farfield
HMW	High molecular weight
IAAC	Inter-Agency Advisory Committee
IPUE	Individuals per unit effort
LC50	50% mortality concentration
LMW	Low molecular weight
MassDEP	Massachusetts Department of Environmental Protection
MODIS	Moderate Resolution Imaging Spectroradiometer
MWRA	Massachusetts Water Resources Authority
NA	Not analyzed/not applicable
NACWA	National Association of Clean Water Agencies
NB	Nantasket Beach
NERACOOS	Northeastern Regional Association of Coastal Ocean Observing Systems
NF	Nearfield
NDBC	National Data Buoy Center
NOEC	No observed effects concentration
NPDES	National Pollutant Discharge Elimination System
OMSAP	Outfall Monitoring Science Advisory Panel
OS	Outfall site
PAH	Polycyclic aromatic hydrocarbon
PCB	Polychlorinated biphenyl
PIAC	Public Interest Advisory Committee
PSP	Paralytic shellfish poisoning
RPD	Redox potential discontinuity
SPI	Sediment-profile imaging

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