2005 outfall monitoring overview

Massachusetts Water Resources Authority

Environmental Quality Department

Report ENQUAD 2006-18

Citation:
Werme C, Hunt CD. 2006. **2005 outfall monitoring overview**. Boston: Massachusetts Water Resources Authority. Report ENQUAD 2006-18. 105p.

2005
Outfall Monitoring Overview

submitted to

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October 30, 2006

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Summary

In September 2005, the Massachusetts Water Resources Authority (MWRA) marked five years of effluent discharge from the Massachusetts Bay outfall. During the year, the Deer Island Treatment Plant continued to operate as designed, and there were no unexpected effects on the ecosystems of Massachusetts and Cape Cod bays. Total loads of many parameters measured within the effluent, including solids and metals, remain low.

After nine years of baseline monitoring and five years of discharge monitoring, the MWRA has been able to answer many of the questions that were posed when the program began (Table 1). As expected, monitoring has been able to detect minimal environmental responses in the immediate vicinity of the outfall. However, overall conditions within the bays have not changed from the baseline as a result of the offshore outfall.

There were three Contingency Plan exceedances during the year (Table 2). One of four monthly toxicity tests, the sea urchin chronic fertilization test, did not meet the Contingency Plan warning threshold for a sample collected on September 15. Effluent from the sample did meet the requirements of other toxicity tests, all other permit requirements were met, and there were no operational upsets that would have caused any violations of permit conditions.

As in 2002 through 2004, summer concentrations of the nuisance algal species *Phaeocystis pouchetii* exceeded the caution level. The wide geographical extent of the blooms suggest that regional processes, rather than the outfall, have been responsible for the increasing frequency of *Phaeocystis* blooms.

In May and June 2005, the largest large bloom of toxic dinoflagellates in the genus *Alexandrium* since 1972 occurred, triggering an exceedance of the caution threshold. The bloom originated in Maine and extended south of Martha's Vineyard. Concentrations of cells were orders of magnitude higher than in previous years. The MWRA outfall is not suspected to be a factor in the size or extent of this bloom.

While conditions in Massachusetts and Cape Cod bays have not changed from the baseline, MWRA has documented significant improvements in Boston Harbor. Concentrations of nutrients responsible for eutrophic conditions in the water column, chlorophyll levels, and pathogen-indicator bacteria level have decreased, while dissolved oxygen concentrations have increased. Concentrations of many PAHs, PCBs, pesticides, and some metals in the surface sediments have declined by 20 to 75%, and improvements in the benthic communities have been observed at some stations.

As in other years, no effects of the outfall on the Stellwagen Bank National Marine Sanctuary have been detected. Plume tracking, water column, and sea floor studies suggested that no effects of the outfall on the sanctuary were likely, and none have been measured.

Table 1. Summary of monitoring questions and status as of the end of 2005

Monitoring Question	Status
Do effluent pathogens exceed the permit limits?	Pathogenic viruses detectable in the final effluent but at very low numbers: secondary treatment and disinfection effectively remove pathogens.
Does acute or chronic toxicity of effluent exceed the permit limit?	General compliance with permit limits.
Do effluent contaminant concentrations exceed permit limits?	Compliance with permit limits. Discharges of priority pollutants well below SEIS predictions and in most cases meet receiving water quality criteria even before dilution.
Do conventional pollutants in the effluent exceed permit limits?	General compliance: discharges of solids and BOD have decreased by 80% compared to the old treatment plant.
What are the concentrations of contaminants in the influent and effluent and their associated variability?	High removal by treatment system with consistently low concentrations since secondary treatment brought on line.
Do levels of contaminants in water outside the mixing zone exceed water quality standards?	Water quality standards not exceeded, confirmed by plume studies conducted in 2001 and ongoing effluent monitoring.
Are pathogens transported to shellfish beds at levels that might affect shellfish consumer health?	Dilution is sufficient for pathogens to reach background concentrations before reaching shellfish beds, confirmed by plume studies conducted in 2001. Indicator bacteria surveys in Massachusetts Bay did not detect appreciable levels of indicator bacteria in the region of the outfall.
Are pathogens transported to beaches at levels that might affect swimmer health?	Dilution is sufficient for pathogens to reach background concentrations before reaching beaches, confirmed by plume studies conducted in 2001. Pathogen and indicator bacteria sampling in Massachusetts Bay did not detect appreciable levels of indicator bacteria in the region of the outfall.
Has the clarity and/or color of the water around the outfall changed?	Although clarity and color have not changed, there are occasional observations of tiny bits of grease, similar to samples collected at the treatment plant.
Has the amount of floatable debris around the outfall changed?	Floatable debris of concern is rare in the effluent. Signs of effluent can occasionally be detected in the field.
Are the model estimates of short-term (less than 1 day) effluent dilution and transport accurate?	Model estimates accurate, confirmed by plume studies conducted in 2001.
What are the nearfield and farfield water circulation patterns?	Flow is controlled by general circulation in the Gulf of Maine, affected by tides and local wind. Bottom currents around the outfall can flow in any direction with no mean flow.
What is the farfield fate of dissolved, conservative, or long-lived effluent constituents?	Changes in farfield concentrations of salinity and dissolved components not detected within tens of meters of outfall and not observed in farfield water or sediments.
Have nutrient concentrations changed in the water near the outfall; have they changed at farfield stations in Massachusetts Bay or Cape Cod Bay, and, if so, are they correlated with changes in the nearfield?	Changes consistent with model predictions. The effluent signature is clearly observed in the vicinity or the outfall but is diluted over a few days and 10s of kilometers.
Do the concentrations (or percent saturation) of dissolved oxygen in the water column meet the state water quality standards?	Conditions unchanged from background.

Monitoring Question	Status
Have the concentrations (or percent saturation) of dissolved oxygen in the vicinity of the outfall or at selected farfield stations in Massachusetts Bay or Cape Cod Bay changed relative to pre-discharge baseline or a reference area? If so, can changes be correlated with effluent or ambient water nutrient concentrations, or can farfield changes be correlated with nearfield changes?	Conditions not changed from background.
Has the phytoplankton biomass changed in the vicinity of the outfall or at selected farfield stations in Massachusetts Bay or Cape Cod Bay, and, if so, can these changes be correlated with effluent or ambient water nutrient concentrations, or can farfield changes be correlated with nearfield changes?	No substantial change detected.
Have the phytoplankton production rates changed in the vicinity of the outfall or at selected farfield stations, and, if so, can these changes be correlated with effluent or ambient water nutrient concentrations, or can farfield changes be correlated with nearfield changes?	Timing of the fall blooms in the nearfield appears to be different, but this change may not be associated with the discharge. Productivity patterns in Boston Harbor may be changing, as the area transitions from eutrophic conditions to a more typical coastal regime.
Has the abundance of nuisance or noxious phytoplankton changed in the vicinity of the outfall?	Frequency of *Phaeocystis* blooms has increased, but the phenomenon is regional in nature. The large *Alexandrium* bloom in 2005 was also regional and has not been attributed to the outfall.
Has the species composition of phytoplankton or zooplankton changed in the vicinity of the outfall or at selected farfield stations in Massachusetts Bay or Cape Cod Bay? If so, can these changes be correlated with effluent of ambient water nutrient concentrations, or can farfield changes be correlated with nearfield changes?	No change detected.
What is the level of sewage contamination and its spatial distribution in Massachusetts and Cape Cod bays sediments before discharge through the new outfall?	Effects of historic inputs from Boston Harbor and other sources detected.
Has the level of sewage contamination or its spatial distribution in Massachusetts and Cape Cod bays sediments changed after discharge through the new outfall?	Effluent signal detected as *Clostridium perfringens* spores, the most sensitive sewage tracer, within a few kilometers of the outfall.
Has the concentration of contaminants in sediments changed?	No general increase in contaminants. Effluent signal can be detected as silver, a sensitive sewage tracer, in sediment traps and as *Clostridium perfringens* spores in sediments within 2 km of the diffuser.
Has the soft-bottom community changed?	All observed changes appear to result from natural cycles/
Have the sediments become more anoxic; that is, has the thickness of the sediment oxic layer decreased?	No increase in total organic carbon or change in sediment RPD detected.
Are any benthic community changes correlated with changes in levels of toxic contaminants (or sewage tracers) in sediments?	No change detected.
Has the hard-bottom community changed?	No substantial changes detected. Decreases in coralline algae detected at some stations; not yet known whether these changes are related to the outfall.

Monitoring Question	Status
How do the sediment oxygen demand, the flux of nutrients from the sediment to the water column, and denitrification influence the levels of oxygen and nitrogen in the water near the outfall?	Described by baseline monitoring; conditions do not suggest adverse changes have resulted from moving outfall offshore.
Have the rates of these processes changed?	No changes over 5 years.
Has the level of contaminants in the tissues of fish and shellfish around the outfall changed since discharge began?	No in flounder or lobster contaminant body burdens. Detectable increases in PAHs and chlordane in mussels deployed at the outfall. Mercury concentrations in flounder tissue have been elevated.
Do the levels of contaminants in the edible tissue of fish and shellfish around the outfall represent a risk to human health?	No changes that would pose a threat to human health. Regional patterns have persisted since the baseline period, and there appears to be a general long-term downward trend for most contaminant levels.
Are the contaminant levels in fish and shellfish different between the outfall, Boston Harbor, and a reference site?	Differences documented during baseline monitoring. Regional patterns have persisted since the diversion.
Has the incidence of disease and/or abnormalities in fish or shellfish changed?	Blind-side skin lesions found on flounder from western Massachusetts Bay. Appear to be seasonal manifestations, and their cause has not been attributed to the outfall. Long-term downward trend in liver disease.

Table 2. Summary of contingency plan thresholds and exceedances as of 2005. (NA = not applicable, ✓ = no exceedance, **C** *= caution level exceedance,* **W** *= warning level exceedance)*

Location/ Parameter Type	Parameter	2000	2001	2002	2003	2004	2005
Effluent							
	pH	**W**	✓	✓	✓	✓	✓
	Fecal coliform bacteria, monthly	✓	✓	✓	✓	✓	✓
	Fecal coliform bacteria, weekly	✓	✓	✓	✓	✓	✓
	Fecal coliform bacteria, daily	✓	**W**	✓	✓	**W**	✓
	Fecal coliform bacteria, 3 consecutive days	✓	✓	✓	✓	✓	✓
	Chlorine residual, daily	**W**	✓	✓	✓	✓	✓
	Chlorine residual, monthly	✓	✓	✓	✓	✓	✓
	Total suspended solids, weekly	✓	✓	**W**	✓	✓	✓
	Total suspended solids, monthly	✓	✓	**W**	✓	✓	✓
	cBOD, weekly	✓	✓	✓	✓	✓	✓
	cBOD, monthly	✓	✓	✓	✓	✓	✓
	Acute toxicity, mysid shrimp	✓	✓	✓	✓	✓	✓
	Acute toxicity, fish	✓	✓	✓	✓	✓	✓
	Chronic toxicity, fish	✓	**W**	✓	✓	✓	✓
	Chronic toxicity, sea urchin	✓	**W**	✓	✓	✓	**W**
	PCBs	✓	✓	✓	✓	✓	✓
	Plant performance	✓	✓	✓	✓	✓	✓
	Flow	NA	✓	✓	✓	✓	✓
	Total nitrogen load	NA	✓	✓	✓	✓	✓
	Floatables	NA	NA	NA	NA	NA	NA
	Oil and grease	✓	✓	✓	✓	✓	✓

Location/ Parameter Type	Parameter	2000	2001	2002	2003	2004	2005
Water Column							
Nearfield bottom water	Dissolved oxygen concentration	C	✓	✓	✓	✓	✓
	Dissolved oxygen saturation	C	✓	✓	✓	✓	✓
Stellwagen Basin bottom water	Dissolved oxygen concentration	✓	✓	✓	✓	✓	✓
	Dissolved oxygen saturation	✓	✓	✓	✓	✓	✓
Nearfield bottom water	Dissolved oxygen depletion rate (June-October)	NA	✓	✓	✓	✓	✓
Nearfield chlorophyll	Annual	NA	✓	✓	✓	✓	✓
	Winter/spring	NA	✓	✓	✓	✓	✓
	Summer	NA	✓	✓	✓	✓	✓
	Autumn	C	✓	✓	✓	✓	✓
Nearfield nuisance algae *Phaeocystis pouchetii*	Winter/spring	NA	✓	✓	✓	C	✓
	Summer	NA	✓	C	C	C	C
	Autumn	✓	✓	✓	✓	✓	✓
Nearfield nuisance algae *Pseudonitzchia*	Winter/spring	NA	✓	✓	✓	✓	✓
	Summer	NA	✓	✓	✓	✓	✓
	Autumn	✓	✓	✓	✓	✓	✓
Nearfield nuisance algae *Alexandrium fundyense*	Any sample	✓	✓	✓	✓	✓	C
Farfield shellfish	PSP toxin extent	✓	✓	✓	✓	✓	✓
Plume	Initial dilution	NA	✓	Completed	Completed	Completed	Completed

Location/ Parameter Type	Parameter	2000	2001	2002	2003	2004	2005
Sea Floor							
Nearfield sediment contaminants	Acenaphthene	NA	✓	✓	NA	NA	✓
	Acenaphylene	NA	✓	✓	NA	NA	✓
	Anthracene	NA	✓	✓	NA	NA	✓
	Benzo(a)anthracene	NA	✓	✓	NA	NA	✓
	Benzo(a)pyrene	NA	✓	✓	NA	NA	✓
	Cadmium	NA	✓	✓	NA	NA	✓
	Chromium	NA	✓	✓	NA	NA	✓
	Chrysene	NA	✓	✓	NA	NA	✓
	Copper	NA	✓	✓	NA	NA	✓
	Dibenzo(a,h)anthracene	NA	✓	✓	NA	NA	✓
	Fluoranthene	NA	✓	✓	NA	NA	✓
	Fluorene	NA	✓	✓	NA	NA	✓
	Lead	NA	✓	✓	NA	NA	✓
	Mercury	NA	✓	✓	NA	NA	✓
	Naphthalene	NA	✓	✓	NA	NA	✓
	Nickel	NA	✓	✓	NA	NA	✓
	p,p'-DDE	NA	✓	✓	NA	NA	✓
	Phenanthrene	NA	✓	✓	NA	NA	✓
	Pyrene	NA	✓	✓	NA	NA	✓
	Silver	NA	✓	✓	NA	NA	✓
	Total DDTs	NA	✓	✓	NA	NA	✓
	Total HMW PAH	NA	✓	✓	NA	NA	✓
	Total LMW PAH	NA	✓	✓	NA	NA	✓
	Total PAHs	NA	✓	✓	NA	NA	✓
	Total PCBs	NA	✓	✓	NA	NA	✓
	Zinc	NA	✓	✓	NA	NA	✓
Nearfield sediment	RPD depth	NA	✓	✓	✓	✓	✓
Nearfield benthic diversity	Species per sample	NA	✓	✓	✓	✓	✓
	Fisher's log-series alpha	NA	✓	✓	✓	✓	✓
	Shannon diversity	NA	✓	✓	✓	✓	✓
	Pielou's evenness	NA	✓	✓	✓	✓	✓
Nearfield species composition	Percent opportunists	NA	✓	✓	✓	✓	✓

Location/ Parameter Type	Parameter	2000	2001	2002	2003	2004	2005
Fish and Shellfish							
Nearfield flounder tissue	Total PCBs	NA	✓	✓	✓	NA	NA
	Mercury	NA	✓	✓	✓	✓	NA
	Chlordane	NA	✓	✓	✓	NA	NA
	Dieldrin	NA	✓	✓	✓	NA	NA
	Total DDTs	NA	✓	✓	✓	NA	NA
Nearfield flounder	Liver disease (CHV)	NA	✓	✓	✓	✓	✓
Nearfield lobster tissue	Total PCBs	NA	✓	✓	✓	NA	NA
	Mercury	NA	✓	✓	✓	NA	NA
	Chlordane	NA	✓	✓	✓	NA	NA
	Dieldrin	NA	✓	✓	✓	NA	NA
	Total DDTs	NA	✓	✓	✓	NA	NA
Nearfield mussel tissue	Total PCBs	NA	✓	✓	✓	NA	NA
	Lead	NA	✓	✓	✓	NA	NA
	Mercury	NA	✓	✓	✓	NA	NA
	Chlordane	NA	C	C	✓	NA	NA
	Dieldrin	NA	✓	✓	✓	NA	NA
	Total DDTs	NA	✓	✓	✓	NA	NA
	Total PAHs	NA	C	C	C	NA	NA

1. Introduction

Background

For more than 20 years, the Massachusetts Water Resources Authority (MWRA) has worked to minimize the effects of wastewater discharge on the marine environment. MWRA was created by an act of the Massachusetts State Legislature in December 1984 and in 1985 embarked upon what has become known as the Boston Harbor Project. Before then, the Boston metropolitan area discharged both sewage sludge and inadequately treated sewage effluent into the confined waters of Boston Harbor, from outfalls located at Deer Island in the northern part of the harbor and Nut Island, in southern Quincy Bay. MWRA ended discharge of municipal sludge into Boston Harbor in 1991, when sludge from both treatment plants began to be barged to a processing plant in Quincy and made into fertilizer. Steps to minimize effects of effluent discharge have included:

- **Source reduction** to prevent pollutants from entering the waste stream.
- **Improved treatment** before discharge.
- **Better dilution** once the effluent enters the marine environment.

Source reduction has included projects to lessen household hazardous waste disposal and minimize mercury discharges from hospitals and dentists. An industrial pretreatment/pollution prevention program ensures that toxic contaminants are removed before they reach the sewer system. In addition, best management practices are employed at sewer facilities to mitigate accidental discharge of pollutants.

Improved treatment was implemented in a series of steps carried out during 1995-2001. In 1995, a new primary treatment plant at Deer Island was brought on line, and disinfection facilities were completed. (Primary treatment is a physical treatment process, which involves removal of solids through settling followed by disinfection.) Batteries of secondary treatment (which includes bacterial decomposition as well as settling followed by disinfection) went on line in 1997, 1998, and 2001. Also during 1998, discharge from the Nut Island Treatment Plant into Quincy Bay ceased, and all wastewater was conveyed to Deer Island for treatment, ending effluent discharge to the southern part of the harbor.

Efforts to improve treatment continued in 2005. MWRA initiated studies aimed at maximizing flow through the secondary treatment systems, achieving significant results by the end of the year. In April 2005 a tunnel connection opened between the Deer Island Treatment Plant and the Fore River Pelletizing Facility, where sludge is processed into fertilizer. Prior to opening the tunnel, sludge was centrifuged at Deer Island and barged to Fore River. The liquid removed by the centrifuge, known as centrate, was then sporadically added back at the head of the plant. With the opening of the tunnel, sludge is centrifuged at Fore River, and the centrate is returned to Deer Island by tunnel, resulting in a more stable treatment process.

Better dilution was achieved in 2000, by diverting the effluent discharge from Boston Harbor to the new 9.5-mile-long outfall and diffuser system, located offshore in Massachusetts Bay (Figure 1-1).

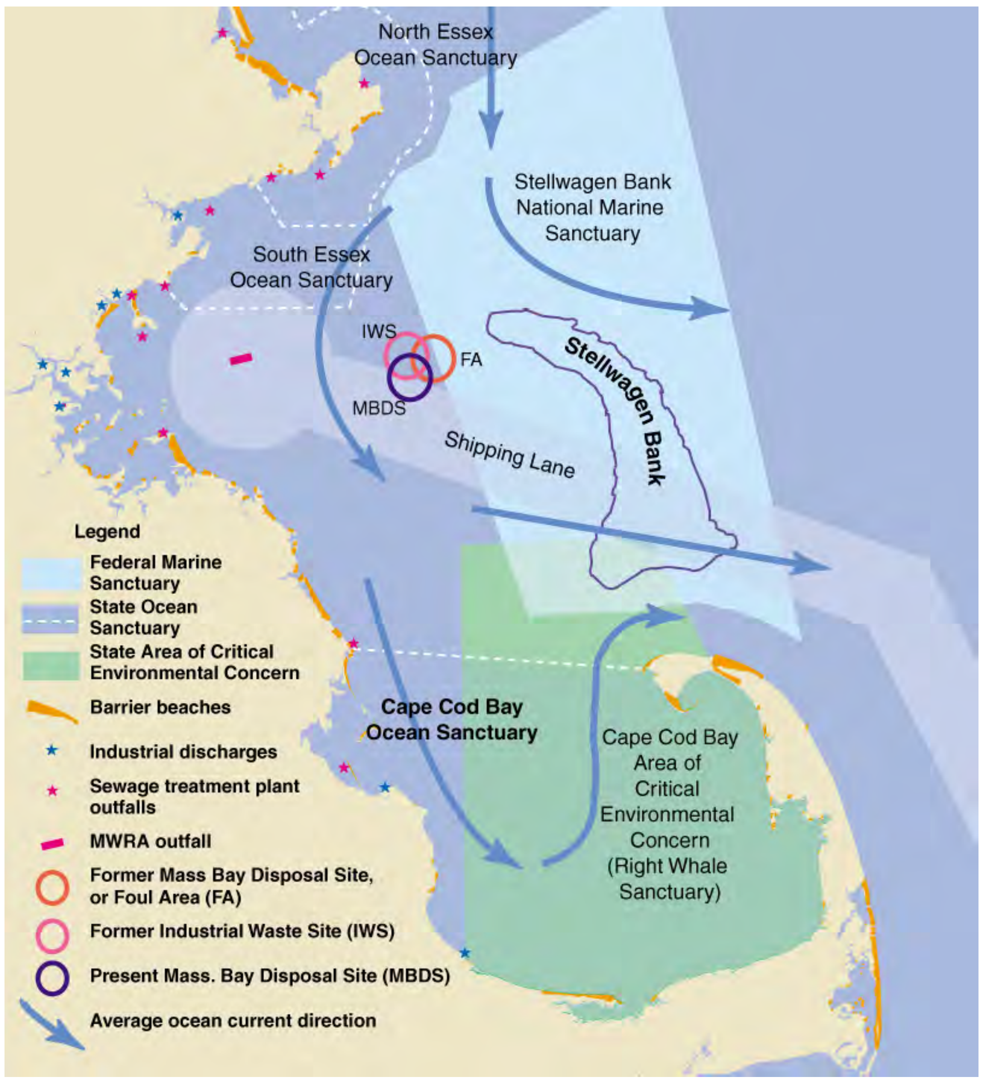

Figure 1-1. Map of Massachusetts and Cape Cod bays

The outfall site was selected because it had a water depth and current patterns that would promote effective dilution, it was the least likely of the alternative sites to affect sensitive resources, and it was feasible to construct an outfall tunnel to the location.

The outfall tunnel is bored through bedrock and has a diffuser system made up of 53 risers, each with five or six open ports, along its final 1.25 miles. Discharge from the diffuser heads is at the sea floor, at water depths of about 100 feet. Initial dilution at the outfall is about five times that of the Boston Harbor outfall, which was shallower, in 50 feet of water. The offshore location of the outfall ensures that effluent will not reach beaches or shellfish beds within a tidal cycle, even if currents are shoreward.

For many of the components of MWRA's work, there was little or no argument that the project benefited the marine environment and the people of the region. Moving the effluent outfall from the harbor to Massachusetts Bay did raise some concerns, which were expressed as general, continuing questions:

- Is it safe to eat fish and shellfish?
- Are natural/living resources protected?
- Is it safe to swim?
- Are aesthetics being maintained?

These concerns were recognized by MWRA and by the permit for the outfall issued jointly by the U.S. Environmental Protection Agency (EPA) and the Massachusetts Department of Environmental Protection (MADEP).

Outfall Permit

The permit issued by EPA and MADEP under the National Pollutant Discharge Elimination System (NPDES) became effective on August 9, 2000 and continued until August 9, 2005. (Since expiration, MWRA continues to operate under the conditions of the permit until a new one is issued.) It limits discharges of pollutants and requires reporting on the treatment plant operation and maintenance. The permit requires MWRA to continue its ongoing pollution prevention program and to employ best management practices aimed at preventing accidental discharge of pollutants to the sewer system.

The permit requires MWRA to monitor the effluent and the ambient receiving waters for compliance with permit limits and in accordance with a monitoring plan (MWRA 1991, 1997a, 2004) developed in response to the EPA Supplemental Environmental Impact Statement (SEIS) prepared as part of the outfall-siting process (EPA 1988). It requires that MWRA implement a Contingency Plan (MWRA 1997b, 2001), which identifies relevant environmental quality parameters and thresholds that, if exceeded, would require a response.

In 1998, in anticipation of the permit, EPA and MADEP established an independent panel of scientists to review monitoring data and provide advice on key scientific issues related to the permit. This panel, the Outfall Monitoring Science Advisory Panel (OMSAP, Table 1-1), conducts peer reviews of monitoring reports, evaluates the data, and advises EPA and MADEP on scientific implications. OMSAP also provides advice concerning any proposed modifications to the monitoring or contingency plans.

OMSAP may form specialized focus groups when specific technical issues require expanded depth or breadth of expertise. Two standing sub-committees also advise OMSAP. The Public Interest Advisory Committee (PIAC) represents local, non-governmental organizations and environmental groups and advises OMSAP on values and uses of the harbor and the bays. The Inter-agency Advisory Committee (IAAC) represents state and federal agencies and provides OMSAP with advice concerning environmental regulations.

Table 1-1. Rosters of panel and committee members

<table>
<tr><td colspan="2">OMSAP as of December 2005

Andrew Solow, Woods Hole Oceanographic Institution (chair)
Robert Beardsley, Woods Hole Oceanographic Institution
Norbert Jaworski, retired
Robert Kenney, University of Rhode Island
Scott Nixon, University of Rhode Island
Judy Pederson, MIT Sea Grant
Michael Shiaris, University of Massachusetts, Boston
James Shine, Harvard School of Public Health
Juanita Urban-Rich, University of Massachusetts, Boston

Catherine Coniaris Vakalopoulos,
MA Department of Environmental Protection (OMSAP staff)</td></tr>
<tr><td>IAAC as of December 2005

MA Coastal Zone Management
Todd Callaghan
Jan Smith (alternate)
MA Department of Environmental Protection
Catherine Coniaris Vakalopoulos
MA Division of Marine Fisheries
Jack Schwartz
National Marine Fisheries Service
David Dow
Stellwagen Bank National Marine Sanctuary
Ben Haskell
US Army Corps of Engineers
Thomas Fredette
US Environmental Protection Agency
Matthew Liebman
US Geological Survey
Michael Bothner</td><td>PIAC as of December 2005

Patty Foley (chair, representative of Save the Harbor/Save the Bay)
Association for the Preservation of Cape Cod
Maggie Geist
Tara Nye (alternate)
Bays Legal Fund
Wayne Bergeron
The Boston Harbor Association
Vivian Li
Cape Cod Commission
John Lipman
Steve Tucker (alternate)
Center for Coastal Studies
Peter Borrelli
Conservation Law Foundation
Priscilla Brooks
New England Aquarium
Marianne Farrington
Massachusetts Audubon Society
Robert Buchsbaum
MWRA Advisory Board
Joseph Favaloro
Safer Waters in Massachusetts
Salvatore Genovese
Polly Bradley (alternate)
Save the Harbor/Save the Bay
Bruce Berman (alternate)
Wastewater Advisory Committee
Edward Bretschneider</td></tr>
</table>

Monitoring Program

EPA and MADEP require monitoring to ensure compliance with the permit, to assess whether the outfall has effects beyond the area identified in the SEIS as acceptable, and to collect data useful for outfall management. In anticipation of these requirements, MWRA began some studies during 1989-1991 and implemented a broad baseline-monitoring program in 1992. Outfall ambient monitoring plans were originally developed and refined under the direction of an Outfall Monitoring Task Force (OMTF), made up of scientists, regulators, and environmental advocacy groups (MWRA 1991, 1997a). (The OMTF was disbanded upon creation of OMSAP.) Because the first years of monitoring following diversion of effluent to the bay found no unexpected changes to the system, changes to the monitoring program were approved by EPA and MADEP, and a new plan (MWRA 2004) was implemented in the 2004 monitoring year.

The outfall ambient monitoring plan expands the general questions of public concern by translating them into possible "environmental responses," which are more specific questions directly related to the outfall (Table 1-2). To answer those questions, the monitoring program focuses on critical constituents of treatment plant effluent, such as nutrients, organic material, toxic contaminants, pathogens, and solids. Presence and potential effects of these constituents are evaluated within the context of four environmental measurement areas: effluent, water column, sea floor, and fish and shellfish (Table 1-3).

The basic program is augmented by special studies, which are conducted in response to specific permit requirements, scientific questions, and environmental concerns. The monitoring program is designed to compare environmental quality of the Massachusetts Bay system, including Boston Harbor and Cape Cod Bay, before and after the outfall location moved from the harbor to the bay.

Table 1-2. Public concerns and environmental responses presented in the monitoring plan (MWRA 1991)

Public Concern: Is it safe to eat fish and shellfish? ▪ Will toxic chemicals accumulate in the edible tissues of fish and shellfish, and thereby contribute to human health problems? ▪ Will pathogens in the effluent be transported to shellfishing areas where they could accumulate in the edible tissues of shellfish and contribute to human health problems?
Public Concern: Are natural/living resources protected? ▪ Will nutrient enrichment in the water column contribute to an increase in primary production? ▪ Will enrichment of organic matter contribute to an increase in benthic respiration and nutrient flux to the water column? ▪ Will increased water-column and benthic respiration contribute to depressed oxygen levels in the water? ▪ Will increased water-column and benthic respiration contribute to depressed oxygen levels in the sediment? ▪ Will nutrient enrichment in the water column contribute to changes in plankton community structure? (Such changes could include stimulation of nuisance or noxious algal blooms and could affect fisheries.) ▪ Will benthic enrichment contribute to changes in community structure of soft-bottom and hard-bottom macrofauna, possibly also affecting fisheries? ▪ Will the water column near the diffuser mixing zone have elevated levels of some contaminants? ▪ Will contaminants affect some size classes or species of plankton and thereby contribute to changes in community structure and/or the marine food web? ▪ Will finfish and shellfish that live near or migrate by the diffuser be exposed to elevated levels of some contaminants, potentially contributing to adverse health in some populations? ▪ Will the benthos near the outfall mixing zone and in depositional areas farther away accumulate some contaminants? ▪ Will benthic macrofauna near the outfall mixing zone be exposed to some contaminants, potentially contributing to changes in community structure?
Public Concern: Is it safe to swim? ▪ Will pathogens in the effluent be transported to waters near swimming beaches, contributing to human health problems?
Public Concern: Are aesthetics being maintained? ▪ Will changes in water clarity and/or color result from the direct input of effluent particles or other colored constituents, or indirectly through nutrient stimulation of nuisance plankton species? ▪ Will the loading of floatable debris increase, contributing to visible degradation?

Table 1-3. Monitoring program objectives and analyses

Task	Objective	Analyses
Effluent		
Effluent sampling	Characterize wastewater discharge from Deer Island Treatment Plant	Flow Organic material (cBOD) Solids pH Bacterial indicators Total residual chlorine Toxicity Nutrients Toxic contaminants Floatables
Water Column		
Nearfield surveys	Collect water quality data near outfall location	Temperature Salinity Dissolved oxygen Nutrients Solids Chlorophyll Water clarity Photosynthesis Respiration Phytoplankton Zooplankton
Farfield surveys	Collect water quality data throughout Massachusetts and Cape Cod bays	
Moorings (GoMOOS and USGS)	GoMOOS near Cape Ann and USGS near outfall provide continuous oceanographic data	Currents Temperature Salinity Water clarity Chlorophyll
Remote sensing	Provides oceanographic data on a regional scale through satellite imagery	Surface temperature Chlorophyll
Sea Floor		
Soft-bottom studies	Evaluate sediment quality and benthos in Boston Harbor and Massachusetts Bay	Sediment chemistry Sediment profile imagery Community composition
Hard-bottom studies	Characterize marine benthic communities in rock and cobble areas	Topography Substrate Community composition
Fish and Shellfish		
Winter flounder	Determine contaminant body burden and population health	Tissue contaminant concentrations Physical abnormalities, including liver histopathology
American lobster	Determine contaminant body burden	Tissue contaminant concentrations Physical abnormalities
Blue mussel	Evaluate biological condition and potential contaminant bioaccumulation	Tissue contaminant concentrations

Baseline monitoring was initially planned to last for a minimum of three years, as the outfall was originally planned for completion in 1995. Delays in construction allowed a relatively long period for baseline studies. Consequently, MWRA was able to document greater natural variability and develop a better understanding of the system than would have been possible in a briefer baseline period. MWRA was also able to evaluate the environmental response in Boston Harbor to other facilities improvements (*e.g.*, Leo *et al.* 1995, Pawlowski *et al.* 1996, Rex and Connor 1997, Rex 2000, Rex *et al.* 2002, Taylor 2002, 2003, 2004, 2006). The extended period also meant that the discharge to Massachusetts Bay, when it did begin, had the benefit of nearly complete implementation of secondary treatment.

The monitoring plan is a "living document." That is, every effort is made to incorporate new scientific information and improved understanding resulting from the monitoring program into appropriate continued measurements. MWRA's NPDES permit allows an annual list of proposed changes to the monitoring plan.

Contingency Plan

The MWRA Contingency Plan (MWRA 1997b, 2001) describes how, if monitoring results indicate a possible environmental problem, MWRA and the regulatory agencies will respond to determine the cause of the problem and to specify the corrective actions that should be taken if the problem appears to be related to the discharge. The Contingency Plan identifies parameters that represent environmentally significant components of the effluent or the ecosystem and that, if specific threshold levels are exceeded, indicate a potential for environmental risk (Table 1-4). The plan provides a process for evaluating parameters that exceed thresholds and formulating appropriate responses.

Table 1-4. Contingency Plan threshold parameters

Measurement Area	Parameter
Effluent	pH Fecal coliform bacteria Residual chlorine Total suspended solids Biochemical oxygen demand Toxicity PCBs Plant performance Flow Total nitrogen load Floatables Oil and grease
Water Column	Dissolved oxygen concentration and saturation Dissolved oxygen depletion rate Chlorophyll Nuisance and noxious algae Effluent dilution
Sea Floor	Sediment contaminants Redox potential discontinuity depth Benthic community structure
Fish and Shellfish	PCBs, mercury, chlordanes, dieldrin, and DDTs in mussels and flounder and lobster tissue Lead in mussels Liver disease in flounder

Threshold values, the measurements selected as indicators of the need for action, are based on permit limits, state water quality standards, and expert opinion. To alert MWRA to any changes, some parameters have more conservative “caution” as well as “warning” thresholds. Exceeding caution or warning thresholds could indicate a need for increased attention or study. If a caution threshold is exceeded, MWRA, with guidance from OMSAP and the regulatory agencies, may expand the monitoring to track effluent quality and environmental conditions. The data are examined to determine whether it is likely that an unacceptable effect resulting from the outfall has occurred.

Exceeding warning levels could, in some circumstances, indicate a need for a response to avoid potential adverse environmental effects. If a threshold is exceeded at a warning level, the response includes early notification of EPA and MADEP and, if the outfall has contributed to adverse environmental effects, the quick development of a response plan. Response plans include a schedule for implementing actions, such as making adjustments in plant operations or undertaking an engineering feasibility study regarding specific potential corrective activities.

Every effort is made to incorporate new scientific information and improved understanding resulting from the monitoring program into appropriate thresholds. A process for modifying the Contingency Plan is set forth in MWRA's NPDES permit, and Revision 1 was approved during 2001.

Data Management

The monitoring program has generated extensive data sets. Data quality is maintained through program-wide quality assurance and quality control procedures. After validation, data from field surveys and laboratory analyses are loaded into a centralized project database. Data handling procedures are automated to the maximum extent possible to reduce errors, ensure comparability, and minimize reporting time. Data that are outside the expected ranges are flagged for review. Data reported by the laboratory as suspect (for example, because the sample bottle was cracked in transit) are marked as such and not used in interpretation or threshold calculations, although they are retained in the database and included in raw data reports. Any corrections are documented. Each data report notes any special data quality considerations associated with the data set.

As monitoring results become available, they are compared with Contingency Plan thresholds. Computer programs calculate each threshold parameter value from the data, compare it to the threshold, and notify the project staff if any caution or warning levels are exceeded.

Reporting

MWRA's NPDES permit requires regular reports on effluent quality and extensive reporting on the monitoring program. A variety of reports are submitted to OMSAP for review (Table 1-5). Changes to the monitoring program or the Contingency Plan must be reviewed by regulators and published in the *Environmental Monitor*. Data that exceed Contingency Plan thresholds and corrective actions must also be reported. Data that exceed thresholds must be reported within five days after the results become available, and MWRA must make all reasonable efforts to report all data on thresholds within 90 days of each sampling event.

Reports are posted on MWRA's web site (www.mwra.com), with copies placed in repository libraries in Boston and on Cape Cod. OMSAP also holds public workshops where outfall monitoring results are presented.

Table 1-5. Monitoring reports submitted to OMSAP

Report	Description/Objectives
Outfall Monitoring Plan Phase I—Baseline Studies (MWRA 1991) Phase II—Discharge Ambient Monitoring (MWRA 1997a, 2004)	Discusses goals, strategy, and design of baseline and discharge monitoring programs.
Contingency Plan (MWRA 1997b, 2001)	Describes development of threshold parameters and values and MWRA's planned contingency measures.
Program Area Synthesis Reports	Summarize, interpret, and explain annual results for effluent, water column, benthos, and fish and shellfish monitoring areas.
Special Studies Reports	Discuss, analyze, and cross-synthesize data related to specific issues in Massachusetts and Cape Cod bays.
Outfall Monitoring Overviews	Summarize monitoring data and include information relevant to the contingency plan.

Outfall Monitoring Overview

Among the many reports that MWRA completes, this report, the outfall monitoring overview, has been prepared for most baseline-monitoring years and for each year that the permit has been in place (Gayla *et al.* 1996, 1997a, 1997b, Werme and Hunt 2000a, 2000b, 2001, 2002, 2003, 2004, 2005). The report includes a scientific summary for the year of monitoring. Overviews for 1995-1999 included only baseline information. With the outfall operational, subsequent reports have included information relevant to the Contingency Plan, such as threshold exceedances, responses, and corrective actions. When data suggest that monitoring activities, parameters, or thresholds should be changed, the report summarizes those recommendations.

This year's outfall monitoring overview, the eleventh completed, presents monitoring program results for effluent and field data for 2005, marking five years of post-discharge monitoring. It compares all results to Contingency Plan thresholds. The overview also includes sections on special studies, Boston Harbor, and the Stellwagen Bank National Marine Sanctuary.

2. Effluent

Background

Pollution Prevention and Wastewater Treatment

Ensuring that the final effluent is clean is the most important element in MWRA's strategy to improve the environmental quality of Boston Harbor without degrading Massachusetts and Cape Cod bays. MWRA ensures clean effluent through a vigorous pretreatment program and by maintaining and operating the treatment plant well.

The MWRA Toxic Reduction and Control (TRAC) program sets and enforces limits on the types and amounts of pollutants that industries can discharge into the sewer system and works with industries to encourage voluntary reductions in their use of toxic chemicals. TRAC has also implemented programs to reduce mercury from dental facilities and to educate the public about proper disposal of hazardous wastes. A booklet, *A Healthy Environment Starts at Home* (available at www.mwra.com), identifies household products that could be hazardous and recommends alternatives.

Secondary treatment further reduces the concentrations of contaminants of concern, except for nutrients. The Deer Island Treatment Plant removes approximately 85-90% of the suspended solids and biochemical oxygen demand (BOD), 50-90% of the toxic chemicals, and about 20% of the nitrogen from the influent.

To prevent accidental discharge of pollutants and mitigate effects should an accident occur, MWRA has implemented best management practice plans at the treatment plant, its headworks facilities, the combined sewer overflow facilities, its pumping stations, and the sludge-to-fertilizer plant. The plans include daily visual inspections and immediate corrective actions. Effectiveness of best management practices is assessed by non-facility staff.

Environmental Concerns

Sewage effluent contains a variety of contaminants that can, at too high levels, affect the marine environment, public health, and aesthetics. The MWRA permit sets limits on these contaminants so as to ensure that these attributes will be protected. Several specific questions in the MWRA ambient monitoring plan respond to public concerns and possible environmental responses by addressing whether the effluent is meeting permit limits (Table 2-1). Other questions require the use of effluent data in conjunction with plume studies, which were completed in 2001, and water-column monitoring (see Section 3, Water Column).

Table 2-1. Monitoring questions related to the effluent

Is it safe to eat fish and shellfish? *Will pathogens in the effluent be transported to shellfishing areas where they could accumulate in the edible tissues of shellfish and contribute to human health problems?* ▪ Do effluent pathogens exceed the permit limit? ▪ Are pathogens transported to shellfish beds at levels that might affect shellfish consumer health?
Are natural/living resources protected? *Will the water column near the diffuser-mixing zone have elevated levels of some contaminants?* ▪ Do effluent contaminant concentrations exceed permit limits? ▪ What are the concentrations of contaminants and characteristic tracers of sewage in the influent and effluent and their associated variability? *Will finfish and shellfish that live near or migrate by the diffuser be exposed to elevated levels of some contaminants, potentially contributing to adverse health in some populations?* ▪ Does acute or chronic toxicity of effluent exceed permit limits? ▪ Do levels of contaminants in water outside the mixing zone exceed state water quality standards?
Is it safe to swim? *Will pathogens in the effluent be transported to waters near swimming beaches, contributing to human health problems?* ▪ Do effluent pathogens exceed the permit limit? ▪ Are pathogens transported to beaches at levels that might affect swimmer health?
Are aesthetics being maintained? *Will changes in water clarity and/or color result from the direct input of effluent particles or other colored constituents, or indirectly through nutrient stimulation of nuisance plankton species?* *Will the loading of floatable debris increase, contributing to visible degradation?* ▪ Do conventional pollutants in the effluent exceed permit limits? ▪ Has the clarity and/or color of the water around the outfall changed? ▪ Has the amount of floatable debris around the outfall changed?

The effluent constituents of greatest concern include pathogens, toxic contaminants, organic material, solid material, nutrients, oil and grease, and "floatables," including plastic and other debris. The MWRA permit also sets limits for chlorine and pH:

- **Pathogens**, including bacteria, viruses, and protozoa, are found in human and animal waste and can cause disease. Human exposure to water-borne pathogens can occur through consumption of contaminated shellfish or through ingestion or physical contact while swimming.
- **Toxic contaminants** include heavy metals, such as copper and lead, polychlorinated biphenyls (PCBs), pesticides, polycyclic aromatic hydrocarbons (PAHs), and petroleum hydrocarbons. Toxic contaminants can lower survival and reproduction rates of marine organisms. Some toxic contaminants can accumulate in

marine life, potentially affecting human health through seafood consumption.

- **Organic material**, a major constituent of sewage, consumes oxygen as it decays. Even under natural conditions, oxygen levels decline in bottom waters during the late summer, so any effluent component that might further decrease oxygen levels is a concern. Too much organic material could also disrupt animal communities on the sea floor.
- **Suspended solids**, small particles in the water column, decrease water clarity and consequently affect growth and productivity of algae and other marine plants. Excess suspended solids also detract from people's aesthetic perception of the environment.
- In marine waters, nitrogen is the limiting **nutrient** that controls growth of algae and other aquatic plants. Excess nitrogen can be detrimental, leading to eutrophication and low levels of dissolved oxygen, excess turbidity, and nuisance algal blooms. Nutrients, particularly dissolved forms, are the only components of sewage entering the treatment plant that are not substantially reduced by secondary treatment.
- **Oil and grease** slicks and floating debris known as **floatables** pose aesthetic concerns. Plastic debris can also be harmful to marine life, as plastic bags are sometimes mistaken for food and clog the digestive systems of turtles and marine mammals. Plastic and other debris can also entangle animals and cause them to drown.
- Sewage effluent is disinfected by addition of a form of **chlorine**, sodium hypochlorite, which is the active ingredient in bleach. While sodium hypochlorite is effective in destroying pathogens, at high enough concentrations, it is harmful to marine life. Consequently, MWRA dechlorinates the effluent with sodium bisulfite before discharge.
- Seawater is noted for its buffering capacity, that is, its ability to neutralize acids and bases. However, state water quality standards dictate that effluent discharges not change the **pH** of the ambient seawater more than 0.5 standard units on a scale of 1 to 14. Consequently, the outfall permit sets both upper and lower values for pH of the effluent.

Monitoring Design

Effluent monitoring measures the concentrations of constituents of the effluent and variability in those concentrations to assess compliance with NPDES permit limits, which are based on state and federal water quality standards and criteria and on ambient conditions. Effluent monitoring also provides measurements of mass loads of effluent constituents, so that fate, transport, and risk of contaminants can be assessed.

The permit includes numeric limits (Table 2-2) for suspended solids, fecal coliform bacteria, pH, chlorine, PCBs, and carbonaceous biochemical oxygen demand (cBOD). In addition, state water quality standards establish limits for 158 pollutants, and the permit prohibits any discharge that would cause or contribute to exceeding any of those limits.

Table 2-2. Reporting requirements of the outfall permit

Parameter	Sample Type	Frequency	Limit
Permit-required monitoring			
Flow	Flow meter	Continuous	Report only
Flow dry day	Flow meter	Continuous	436 MGD annual average
cBOD	24-hr composite	1/day	40 mg/l weekly 25 mg/l monthly
TSS	24-hr composite	1/day	45 mg/l weekly 30 mg/l monthly
pH	Grab	1/day	Not <6 or >9
Fecal coliform bacteria	Grab	3/day	14,000 col/100ml
Total residual chlorine	Grab	3/day	631 µg/l daily 456 µg/l monthly
PCB, Aroclors	24-hr composite	1/month	0.045 ng/l
Toxicity LC50	24-hr composite	2/month	50%
Toxicity C-NOEC	24-hr composite	2/month	1.5%
Settleable solids	Grab	1/day	Report only
Chlorides (influent only)	Grab	1/day	
Mercury	24-hr composite	1/month	
Chlordane	24-hr composite	1/month	
4,4'–DDT	24-hr composite	1/month	
Dieldrin	24-hr composite	1/month	
Heptachlor	24-hr composite	1/month	
Ammonium-nitrogen	24-hr composite	1/month	
Total Kjeldahl nitrogen	24-hr composite	1/month	
Total nitrate	24-hr composite	1/month	
Total nitrite	24-hr composite	1/month	
Cyanide, total	Grab	1/month	
Copper, total	24-hr composite	1/month	
Total arsenic	24-hr composite	1/month	
Hexachlorobenzene	24-hr composite	1/month	
Aldrin	24-hr composite	1/month	
Heptachlor epoxide	24-hr composite	1/month	
Total PCBs	24-hr composite	1/month	
Volatile organic compounds	Grab	1/month	
Contingency Plan-required monitoring			
Oil and grease, as petroleum hydrocarbons	Grab	Weekly	Warning threshold/ 15 mg/l
Floatables	Continuous	Under development	
Plant performance	Ongoing		5 violations/year

The permit prohibits discharge of nutrients in amounts that would cause eutrophication. It requires MWRA to test the toxicity of the effluent as a whole on sensitive organisms and establishes limits based on the tests. Allowable concentrations of contaminants were based on the predicted dilution at the outfall and verified by field studies of outfall plumes in 2001.

Most parameters are measured in 24-hour composite samples, and some must meet daily, weekly, or monthly limits. Flow is measured continuously. Nutrient measurements include total nitrogen, ammonium, nitrate, and nitrite. Organic material is monitored by measuring the cBOD. Monitoring for toxic contaminants includes analyses for heavy metals of concern, chlorinated pesticides, PCBs, volatile organic compounds, PAHs, total residual chlorine, and cyanide. Toxicity is tested using whole effluent samples. Tests for acute toxicity include 48-hour survival of mysid shrimp (*Americamysis bahia*, formerly known as *Mysidopsis bahia*) and inland silverside fish (*Menidia beryllina*). Chronic toxicity is assessed through inland silverside growth-and-survival and sea urchin (*Arbacia punctulata*) one-hour-fertilization tests. Pathogen monitoring consists of enumeration of fecal coliform bacteria. Total suspended solids (TSS) and settleable solids are also measured.

The contingency plan also sets limits for overall plant performance, annual nitrogen load, floatables, and oil and grease. Floatables are measured; threshold limits are under development.

Beyond the requirements of ordinary discharge monitoring, the MWRA monitoring plan requires additional nutrient measurements and non-standard, low-detection methods to measure toxic contaminants (Table 2-3). These measurements are made to better interpret field-monitoring results.

The monitoring plan also calls for an evaluation of indicators of human pathogens. To date, MWRA has collected data on anthropogenic viruses, viral indicators, and *Enterococcus* bacteria in the influent and effluent.

Table 2-3. Monitoring plan parameters for effluent

Parameter	Sample Type	Frequency
Total Kjeldahl nitrogen	Composite	Weekly
Ammonium	Composite	Weekly
Nitrate	Composite	Weekly
Nitrite	Composite	Weekly
Total phosphorus	Composite	Weekly
Total phosphate	Composite	Weekly
Acid base neutrals	Composite	Bimonthly
Volatile organic compounds	Grab	Bimonthly
Cadmium	24-hour composite	Weekly
Copper	24-hour composite	Weekly
Chromium	24-hour composite	Weekly
Mercury	24-hour composite	Weekly
Lead	24-hour composite	Weekly
Molybdenum	24-hour composite	Weekly
Nickel	24-hour composite	Weekly
Silver	24-hour composite	Weekly
Zinc	24-hour composite	Weekly
17 chlorinated pesticides	24-hour composite	Weekly
Extended list of PAHs	24-hour composite	Weekly
20 PCB congeners	24-hour composite	Weekly

Results

Average daily flow to the Deer Island Treatment Plant in 2005 was higher than any year since 1996 (Figure 2-1). Approximately 93% of the flow received secondary treatment, with a higher degree of secondary treatment as the year progressed, a result of studies designed to maximize flow through secondary treatment.

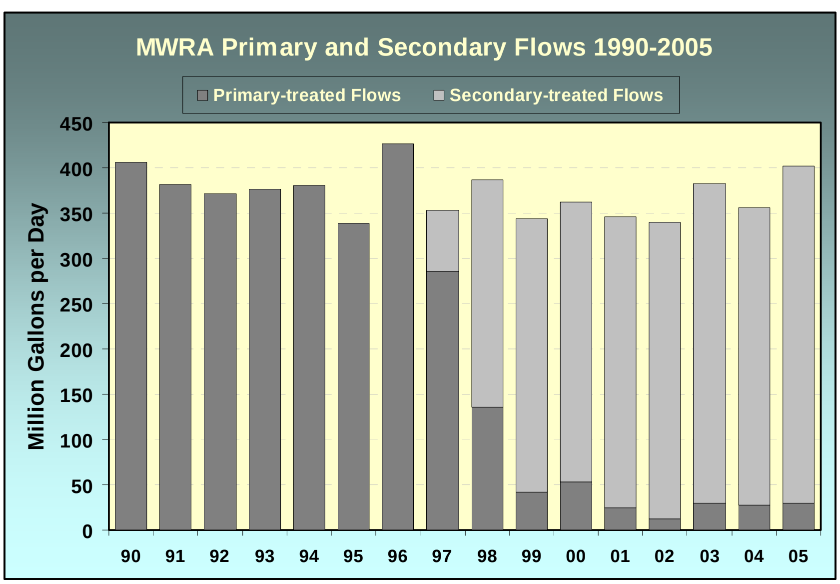

Figure 2-1. Annual effluent flows, 1990-2005

Solids discharges decreased slightly to the lowest level recorded in the monitoring program, while nitrogen discharges remained about the same as 2004 (Figure 2-2). Some metals loads were slightly lower (Figure 2-3, top). There was a decrease in load of total PAHs from 2.1 pounds per day in 2004 to 1.5 pounds per day in 2005 (not shown).

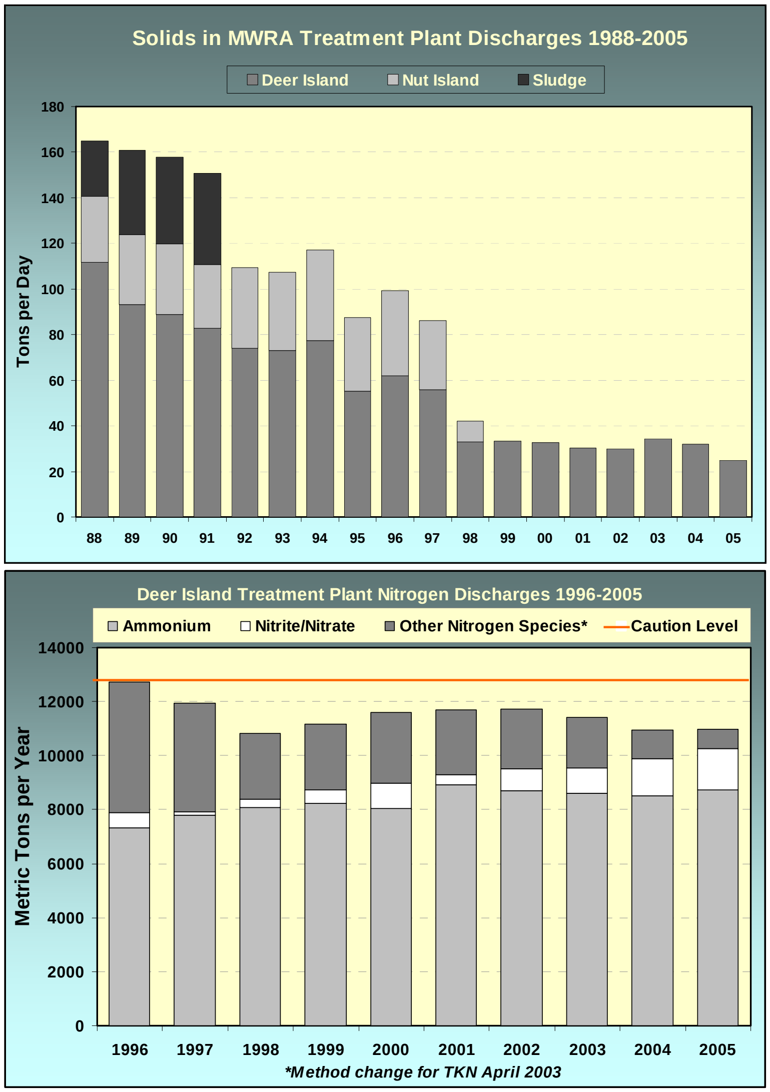

Figure 2-2. Annual solids (top) and nitrogen (bottom) discharges

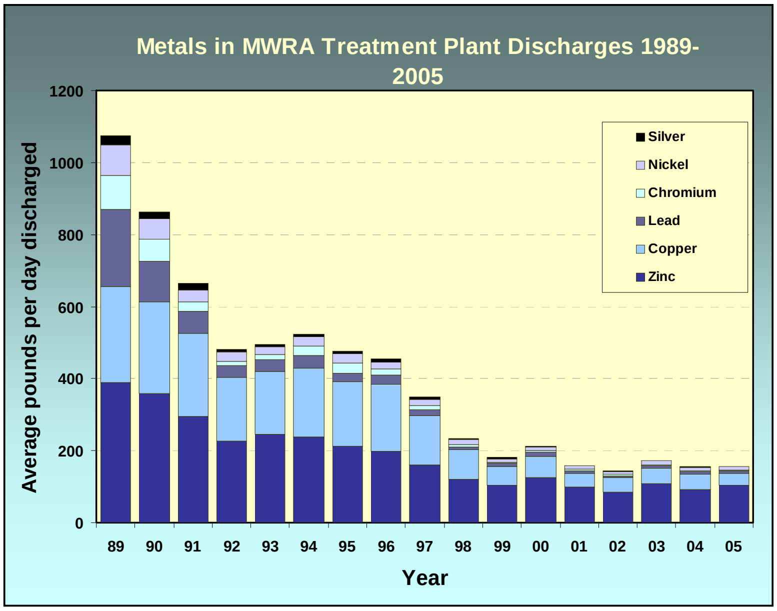

Figure 2-3. Annual metals discharges

Additional benefits can be expected from completion of the digested sludge pipeline that runs under the harbor from the Deer Island Treatment Plant to the Fore River sludge-to-fertilizer pelletizing plant. Prior to completion of the pipeline, sludge had to be thickened at Deer Island before being barged to the pelletizing plant. The nutrient-rich water remaining after thickening, called centrate, was added to the influent at irregular intervals. In addition, nutrient-rich centrate from the pelletizing plant was returned to Deer Island by barge and added to the influent in batches. Thus, the biological secondary process had to deal with relatively large fluctuations in nutrients. Since the pipeline was completed in 2005, liquid sludge is pumped to Fore River through the pipeline, and all centrifuging occurs at the pelletizing plant. The resulting centrate is returned to Deer Island via the tunnel as a more steady stream. This has had a stabilizing effect on the biological process and enabled more efficient operation.

Contingency Plan Thresholds

The Deer Island Treatment Plant had one permit violation during 2005 (Table 2-4). The Contingency Plan requires that four tests for effluent toxicity be conducted each month. One of the tests, the sea urchin chronic fertilization test, did not meet the Contingency Plan warning threshold for a sample collected on September 15. Effluent from the sample did meet the requirements of other toxicity tests, all other permit requirements were met, and there were no operational upsets that would have caused any violations of permit conditions.

MWRA is currently completing a special study of trace contaminants, including metals, pesticides, PCBs, and PAHs. Those results are presented in Section 6, Special Studies.

Table 2-4. Contingency Plan threshold values and 2005 results for effluent monitoring

Parameter	Caution Level	Warning Level	2005 Results
pH	None	<6 or >9	Not exceeded
Fecal coliform bacteria	None	14,000 fecal coliforms/100 ml (monthly 90th percentile, weekly geometric mean, maximum daily geometric mean, and minimum of 3 consecutive samples)	Not exceeded
Chlorine, residual	None	631 ug/l daily, 456 ug/l monthly	Not exceeded
Total 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
Toxicity	None	Acute: effluent LC50<50% for shrimp and fish Chronic: effluent NOEC for fish survival and growth and sea urchin fertilization <1.5% effluent	One exceedance of sea urchin fertilization test in September
PCBs	Aroclor=0.045 ng/l		Not exceeded
Plant performance	5 violations/year	Noncompliance >5% of the time	Not exceeded
Flow	None	Flow >436 for annual average of dry days	Not exceeded
Total nitrogen load	12,500 mtons/year	14,000 mtons/year	Not exceeded
Floatables			Threshold pending
Oil and grease	None	15 mg/l weekly	Not exceeded

3. Water Column

Background

Circulation and Water Properties

Circulation, water properties, and consequently, the biology of Massachusetts and Cape Cod bays are driven by the larger pattern of water flow in the Gulf of Maine (Figure 3-1) and by regional and local winds.

A coastal current flows southwestward along the Maine and New Hampshire coasts; it may enter the bays by Cape Ann to the north of Boston. This current drives an average counterclockwise circulation in Massachusetts Bay and (sometimes) Cape Cod Bay. Water flows back out of the bays to the north of Race Point at the tip of Cape Cod. Whether the coastal current enters the bays and whether it continues south into Cape Cod Bay depends on the strength of the current and the direction and speed of the wind. Because the coastal current is strongest during the spring period of high runoff from rivers and streams, the spring circulation pattern is more consistent than that of the summer and fall (Geyer *et al.* 1992, Jiang *et al.* 2006).

During the summer and fall, freshwater inflow is less, and so the wind and water density interact in a different, more complex way, with alternating periods of upwelling and downwelling in various locations, depending primarily on the wind direction and strength (Lermusiaux 2001). Water flow is variable, as the weather patterns change from week to week. Flow at any particular time depends on the wind speed and direction relative to the topography of the sea floor. At times, flow can "reverse," with flow northward along the coast. Transient gyres in Massachusetts and Cape Cod bays spin in either direction.

As in many coastal waters, during the winter the water is well-mixed from top to bottom, and nutrient levels are high. As light levels increase in the early spring, phytoplankton populations often begin a period of rapid growth known as a spring bloom. Contrary to popular wisdom, however, strong spring blooms do not occur every year. During the years in which they occur, spring blooms begin in the shallowest waters of Cape Cod Bay. Blooms in the deeper Massachusetts Bay waters follow two to three weeks later. Spring phytoplankton blooms are typically followed by an increase in zooplankton abundance. These zooplankton populations are food for many animals, including the endangered right whale.

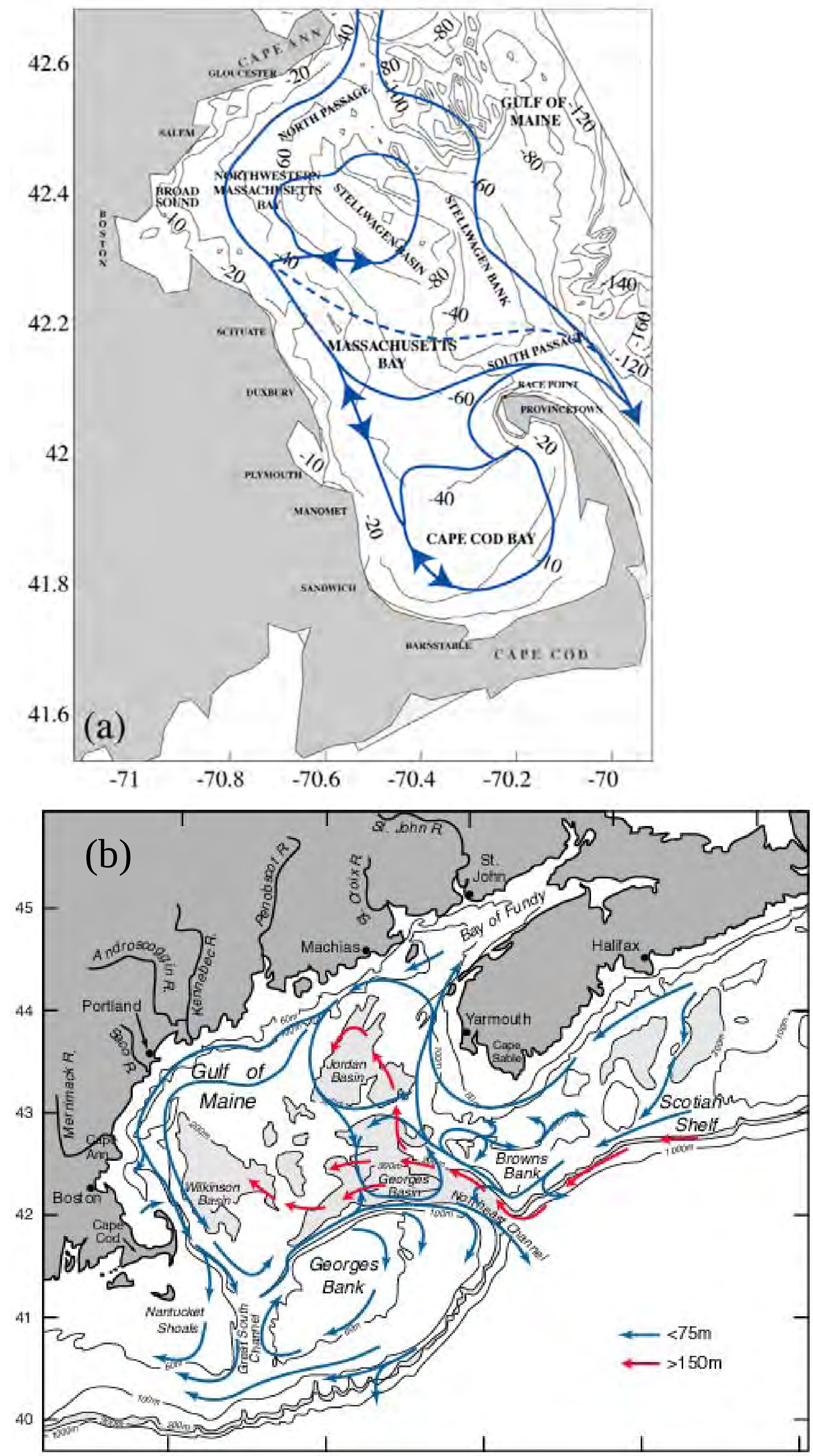

Figure 3-1. (a) General circulation within Massachusetts Bay. Reprinted from Journal of Marine Systems, Vol. 29, Author: PFJ Lermusiaux, "Evolving the subspace of the three-dimensional multiscale ocean variability: Massachusetts Bay", pp 385-422 © 2001 with permission from Elsevier. (b) General circulation within the Gulf of Maine (from Beardsley et al. 1997).

Later in the spring, the surface waters warm, and the water column stratifies. Inputs of freshwater from rivers contribute to the stratification, with lighter, less saline water remaining at the surface. Stratification effectively separates the surface and bottom waters, preventing replenishment of nutrients to the surface and oxygen to the bottom. Phytoplankton in the surface waters deplete the available nutrients and then undergo senescence, sinking through the pycnocline to the bottom. While oxygen levels remain high in the surface waters throughout the year, levels fall in the bottom waters, as bottom-dwelling animals respire, and bacteria use up oxygen as the phytoplankton decompose. Bottom-water oxygen levels are typically lowest during the late summer or early fall.

Cooling surface waters and strong winds during the autumn months promote mixing of the water column. Oxygen is replenished in the bottom waters, and nutrients brought to the surface can stimulate a fall phytoplankton bloom. Similar to the spring, varying meteorological and oceanographic conditions greatly influence the timing, magnitude, and spatial extents of the blooms, and fall blooms do not always occur. When they do occur, the fall blooms typically end in the early winter, when declining light levels limit photosynthesis. Plankton die and decay, replenishing nutrients in the water column.

Environmental Concerns

Water-column monitoring questions focus on the possible effects of nutrients, organic matter, pathogens, and floatable debris from wastewater on the water quality of Massachusetts Bay (MWRA 1991, Table 3-1). Due to source reduction and treatment, toxic contaminants discharged in the MWRA effluent are so low in concentrations that it is impractical to measure them in the water column. Because organic material, pathogens, and floatables are effectively removed by treatment at the Deer Island plant, but nutrients are not, nutrient issues cause the greatest concern.

The monitoring program looks extensively at possible effects of discharging nutrient-rich effluent into Massachusetts Bay. One concern is that excess nutrients, particularly nitrogen, could over-stimulate algal blooms, which would be followed by low levels of dissolved oxygen in the bottom waters when the phytoplankton organisms die, sink, and decompose. Another concern is that changes in the relative levels of nutrients could stimulate growth of undesirable algae. Three nuisance or noxious species or species groups are of particular concern: the dinoflagellate *Alexandrium fundyense* (*A. fundyense* and *A. tamarense* are now considered to be varieties of the same species), the diatom *Pseudo-nitzschia multiseries*, and the colonial flagellate *Phaeocystis pouchetii*. *Alexandrium fundyense* blooms are known in New England as red tides.

Table 3-1. Monitoring questions related to the water column

Is it safe to eat fish and shellfish? *Will pathogens in the effluent be transported to shellfishing areas where they could accumulate in the edible tissues of shellfish and contribute to human health problems?* ▪ Are pathogens transported to shellfish beds at levels that might affect shellfish consumer health?
Are natural/living resources protected? *Will nutrient enrichment in the water column contribute to an increase in primary production?* *Will nutrient enrichment in the water column contribute to changes in plankton community structure?* ▪ Have nutrient concentrations changed in the water near the outfall; have they changed at farfield stations in Massachusetts Bay or Cape Cod Bay, and, if so, are they correlated with changes in the nearfield? ▪ Has the phytoplankton biomass changed in the vicinity of the outfall or at selected farfield stations in Massachusetts Bay or Cape Cod Bay, and, if so, can changes be correlated with effluent or ambient water nutrient concentrations, or can farfield changes be correlated with nearfield changes? ▪ Have the phytoplankton production rates changed in the vicinity of the outfall or at selected farfield stations, and, if so, can these changes be correlated with effluent or ambient water nutrient concentrations, or can farfield changes be correlated with nearfield changes? ▪ Has the abundance of nuisance or noxious phytoplankton species changed in the vicinity of the outfall? ▪ Has the species composition of phytoplankton or zooplankton changed in the vicinity of the outfall or at selected farfield stations in Massachusetts Bay or Cape Cod Bay? If so, can these changes be correlated with effluent or ambient water nutrient concentrations, or can farfield changes be correlated with nearfield changes? *Will increased water-column and benthic respiration contribute to depressed oxygen levels in the water?* ▪ Do the concentrations (or percent saturation) of dissolved oxygen in the vicinity of the outfall and at selected farfield stations meet the state water quality standard? ▪ Have the concentrations (or percent saturation) of dissolved oxygen in the vicinity of the outfall or at selected farfield stations in Massachusetts Bay or Cape Cod Bay changed relative to pre-discharge baseline or a reference area? If so, can changes correlated with effluent or ambient water nutrient concentrations, or can farfield changes be correlated with nearfield changes?
Is it safe to swim? *Will pathogens in the effluent be transported to waters near swimming beaches, contributing to human health problems?* ▪ Are pathogens transported to beaches at levels that might affect swimmer health?
Are aesthetics being maintained? *Will changes in water clarity and/or color result from the direct input of effluent particles or other colored constituents, or indirectly through nutrient stimulation of nuisance plankton species?* *Will the loading of floatable debris increase, contributing to visible degradation?* ▪ Has the clarity and/or color of the water around the outfall changed? ▪ Has the amount of floatable debris around the outfall changed?
Information on transport and fate necessary to answer all the questions ▪ Are model estimates of short-term (less than 1 day) effluent dilution and transport accurate? ▪ What are the nearfield and farfield water circulation patterns? ▪ What is the farfield fate of dissolved, conservative, or long-lived effluent constituents?

They produce a toxin, which when sufficiently concentrated, causes paralytic shellfish poisoning (PSP), a condition that can be fatal to marine mammals, fish, and humans. At high concentrations (more than 1 million cells per liter), some diatoms in the genus *Pseudo-nitzschia* may produce sufficient quantities of toxic domoic acid to cause a condition known as amnesic shellfish poisoning, which is marked by gastrointestinal and neurological symptoms, including dementia. *Phaeocystis pouchetii* is not toxic, but individual cells can aggregate in gelatinous colonies that may be aesthetically displeasing or provide poor food for zooplankton.

Dissolved oxygen concentrations in bottom waters naturally decrease during the stratified period as part of the natural seasonal pattern. If discharged nutrients were to stimulate large phytoplankton blooms, the conditions could lead to lower levels of dissolved oxygen when the cells sink to the bottom and decay.

Because of the concern that lowered levels of dissolved oxygen could affect animals in the vicinity of the outfall, it was important during the baseline-monitoring period to develop an understanding of the natural fluctuations of oxygen levels within the system. Modeling and measurements showed that the typical periods of low oxygen in bottom waters correlate with warmer and saltier bottom waters. Ongoing monitoring assesses potential diversions from the natural conditions.

Monitoring Design

Water-column monitoring includes assessments of water quality, phytoplankton, and zooplankton in Massachusetts and Cape Cod bays. Regular monitoring includes four components: nearfield surveys, farfield surveys, continuous recording, and remote sensing (Table 3-2). Plume-tracking studies, conducted in 2001, qualitatively verified the expected dilution at the outfall and confirmed predictions that bacteria and toxic contaminant concentrations in the discharged effluent are very low.

Table 3-2. Components of water-column monitoring

Task	Objective
Nearfield surveys	Collect water quality data near the outfall
Farfield surveys	Collect water quality data throughout Massachusetts and Cape Cod bays
Moorings (GoMOOS and USGS)	GoMOOS near Cape Ann and USGS near outfall provide continuous oceanographic data near outfall location
Remote sensing	Provides oceanographic data on a regional scale through satellite imagery

Nearfield surveys provide vertical and horizontal profiles of physical, chemical, and biological characteristics of the water column in the area around the outfall where some effects of the effluent are expected and have been observed. Farfield surveys assess differences across the bays and seasonal changes over a large area. Several farfield stations mark the boundary of the monitoring area and are in or near the Stellwagen Bank National Marine Sanctuary. Two of those stations denote the "northern boundary," representing water entering Massachusetts Bay from the Gulf of Maine. Other stations are in Boston Harbor, coastal and offshore regions, and in Cape Cod Bay (Figure 3-2). Twelve surveys of seven nearfield stations and six surveys of 25 farfield stations were conducted in 2005, with two additional stations sampled in February and April.

Parameters measured are listed in Tables 3-3 and 3-4. Parameters measured in the water column include dissolved inorganic and organic nutrients, particulate forms of nutrients, chlorophyll, total suspended solids, dissolved oxygen, productivity, respiration, phytoplankton abundance and species composition, and zooplankton abundance and species composition. Nutrients measured include the major forms of nitrogen, phosphorus, and silica. The measurements focus on the dissolved inorganic forms, which are most readily used by phytoplankton. The surveys also include observations and net tows in the outfall area to assess the presence of floatable debris.

The continuous recording components of the program, the U.S. Geological Survey (USGS) and Gulf of Maine Ocean Observing System (GoMOOS) moorings, capture temporal variations in water quality between nearfield surveys. Remote sensing by satellite captures spatial variations in water quality on a larger, regional scale.

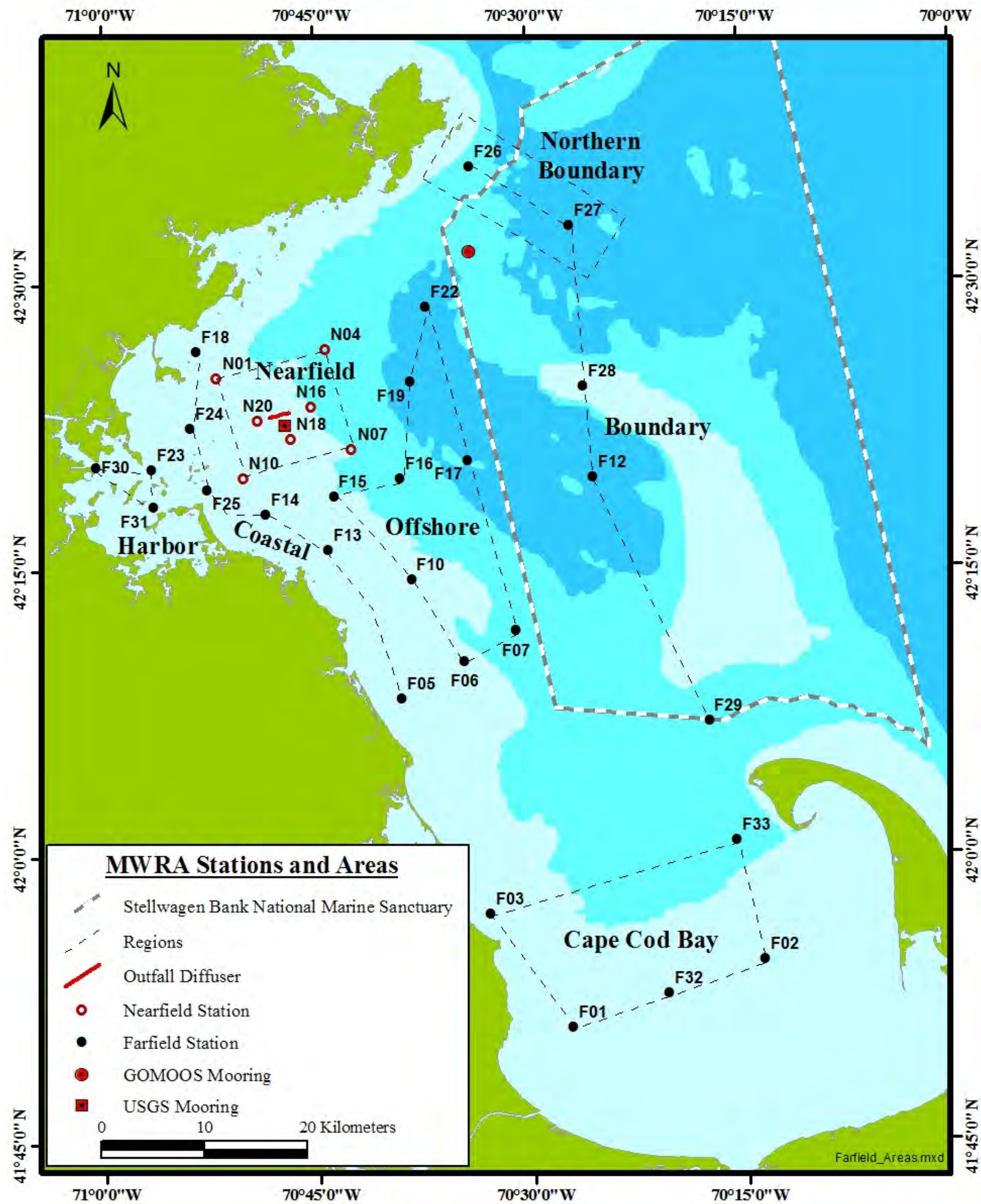

Figure 3-2. Water-column sampling stations and regions

Table 3-3. Nearfield water-column monitoring parameters

Parameter	Measurement details
Temperature Salinity Dissolved oxygen Chlorophyll fluorescence Transmissometry Irradiance Depth of sensors	In-situ sensor measurements Boat surveys of seven stations Every half meter depth
Ammonium Nitrate Nitrite Phosphate Silicate	Inorganic nutrients sampling Seven stations Five depths
Dissolved inorganic carbon Dissolved nitrogen Dissolved phosphorus Particulate carbon Particulate nitrogen Particulate phosphorus Particulate biogenic silica Total suspended solids	Additional nutrients sampling Seven stations Three depths
Primary productivity Respiration Phytoplankton Zooplankton	Rates and plankton sampling Two stations Variable depths
Floatables	Net tows

Table 3-4. Farfield water-column monitoring parameters

Parameter	Measurement details
Temperature Salinity Dissolved oxygen Chlorophyll fluorescence Transmissometry Irradiance Depth of sensors	In-situ sensor measurements Boat surveys of 25 stations Every half meter depth
Ammonium Nitrate Nitrite Phosphate Silicate	Inorganic nutrients sampling 23 stations at five depths Two shallow stations at three depths
Dissolved inorganic carbon Dissolved nitrogen Dissolved phosphorus Particulate carbon Particulate nitrogen Particulate phosphorus Particulate biogenic silica Total suspended solids Phytoplankton Zooplankton	Additional nutrients and plankton sampling Ten stations Variable depths
Primary productivity	Rates sampling One station Five depths
Respiration	Rates sampling Two stations Three depths

Results

Physical Conditions

The Massachusetts Bay region was wetter in 2005 than in many other years, particularly during the late spring and late fall. There were three significant storms during April through June and unusually wet conditions in October (Libby *et al.* 2006a). Flow of the Merrimack River in the late spring was the greatest measured throughout the duration of the monitoring program, a direct result of the storms and also the result of accelerated melting of a deeper-than-average winter snowpack. Similarly, flow through the Charles River was higher than average (Figures 3-3, 3-4).

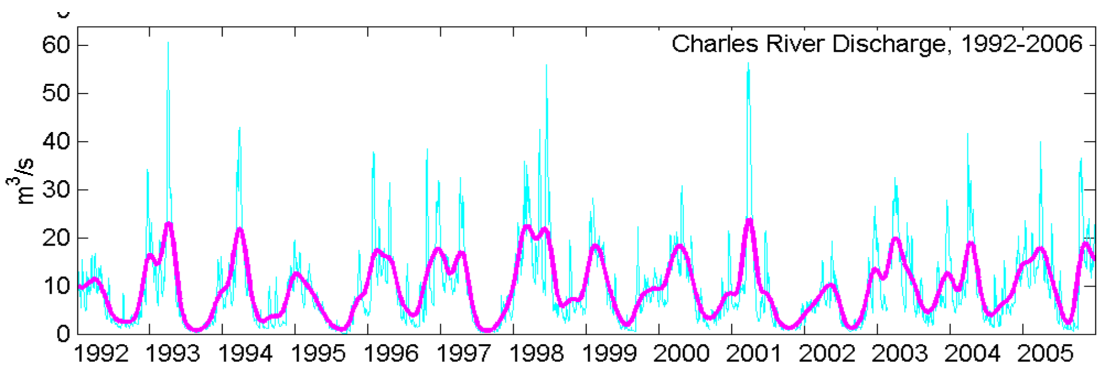

Figure 3-3. Charles River discharge, 1992-early 2006 (data from a gauge at Waltham and 3-month moving average)

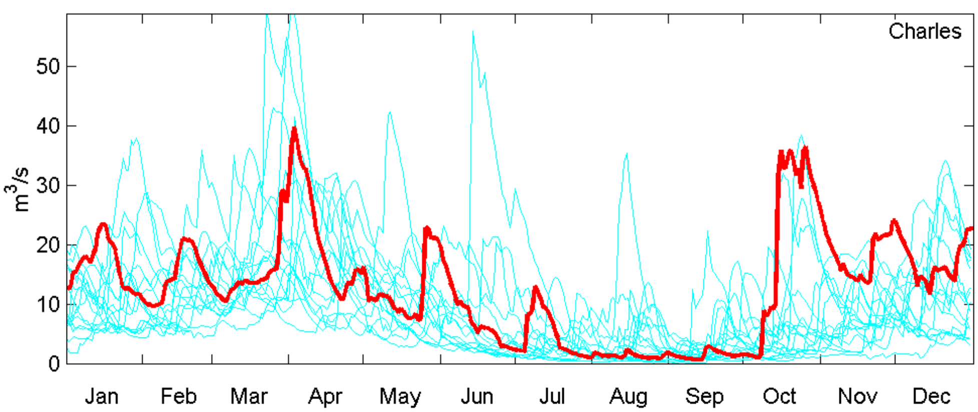

Figure 3-4. 2005 Charles River discharge compared to observations since 1992

May 2005 was particularly unusual. In most years, May is a transitional period between winter downwelling and summer upwelling conditions. In 2005, two large storms with winds from the northeast resulted in continued downwelling and wave heights greater than five meters, the roughest May conditions observed throughout the monitoring program.

Figure 3-5 shows annual surface and bottom water temperatures in the outfall nearfield since 1992. In 2005, winter air and water temperatures were average, but May was unusually cold, another consequence of the storms from the northeast. The May near-surface water temperature near the outfall was the coldest measured during the monitoring program (Figure 3-6). At the same time, bottom temperatures warmed, as the warmer surface waters mixed into the bottom waters during the storms. Usually, stratified conditions are established by May, but the storms broke down the stratification. Similarly, a late October storm broke down the summer stratified conditions, warming the bottom waters and cooling the surface waters. This breakdown of stratified conditions usually occurs later in the season.

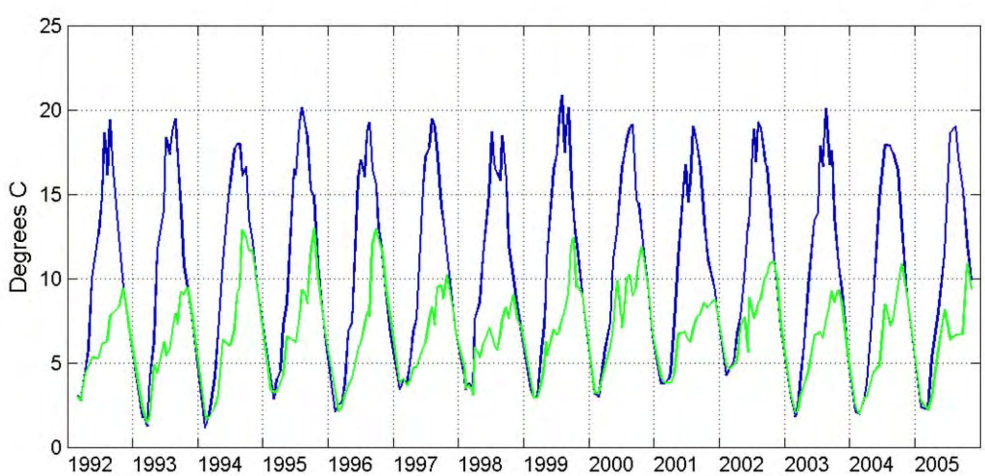

Figure 3-5. Nearfield surface and bottom water temperature (Surface measurements are the upper line.)

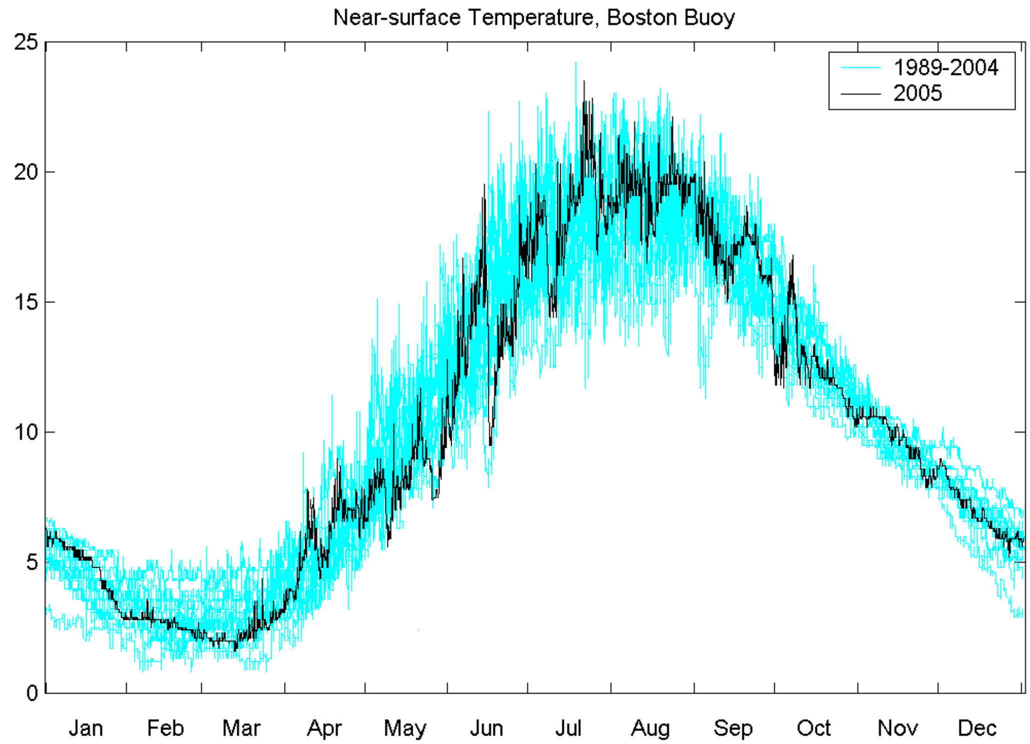

Figure 3-6. Hourly near-surface temperature for 2005 superimposed on the data from 1989-2004

In response to the runoff from the spring storms, salinities reached low levels, particularly in the bottom waters (Figure 3-7). Spring bottom-water salinities were among the lowest measured for the monitoring program.

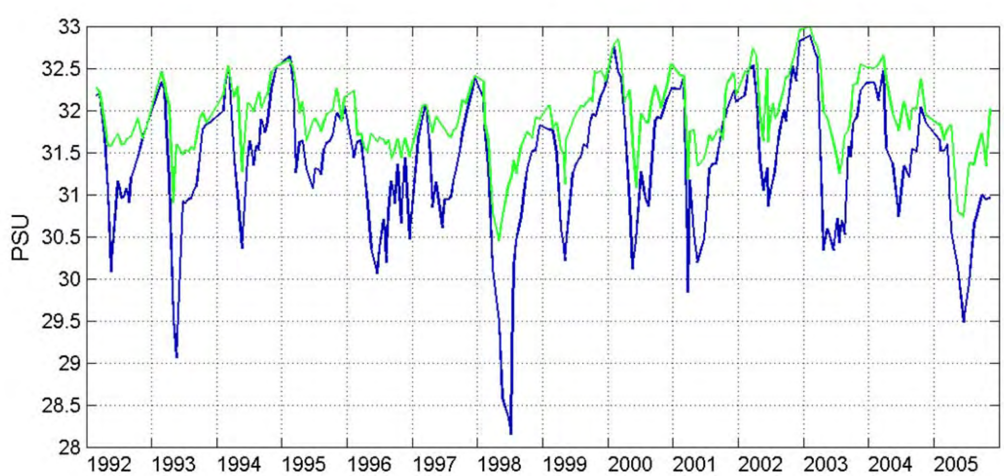

Figure 3-7. Nearfield surface and bottom water salinity (Surface measurements are the lower line.)

Water Quality

As in every year since the Massachusetts Bay outfall began operation, water quality measurements in 2005 continued to confirm predictions that it would be possible to detect localized effects of the discharge for some parameters, but that there would be no adverse effects on the farfield (Libby *et al.* 2006a). Trends in water quality parameters, including nutrients, phytoplankton biomass, and dissolved oxygen were generally similar to previous years. However, there were some differences in the timing and magnitude of events.

Ammonium is the form of nitrogen most readily taken up by phytoplankton, and localized, elevated concentrations have been observed in the nearfield since the outfall began operation (Figure 3-8). These elevated levels had been anticipated, because a large portion of the dissolved inorganic nitrogen in treated effluent is ammonium.

In 2005, there was some difference from the anticipated pattern. As expected, nearfield ammonium concentrations in early February were higher than the baseline range. However, by late February, concentrations dropped to less than the baseline mean, the result of nutrient uptake during the spring phytoplankton bloom. In mid May, concentrations of ammonium in the nearfield were 0.3 µM below the baseline range. Consequently, the annual average concentration of ammonium in the nearfield was the lowest measured since outfall diversion and not significantly different from the baseline period (Figure 3-9). These low levels were probably due to dilution caused by the stormy conditions that were prevalent during the year. The concentrations of ammonium in Boston Harbor, which had dropped dramatically following effluent diversion to Massachusetts Bay, remained low. Ammonium concentrations in the other regions were the lowest measured in nearly ten years.

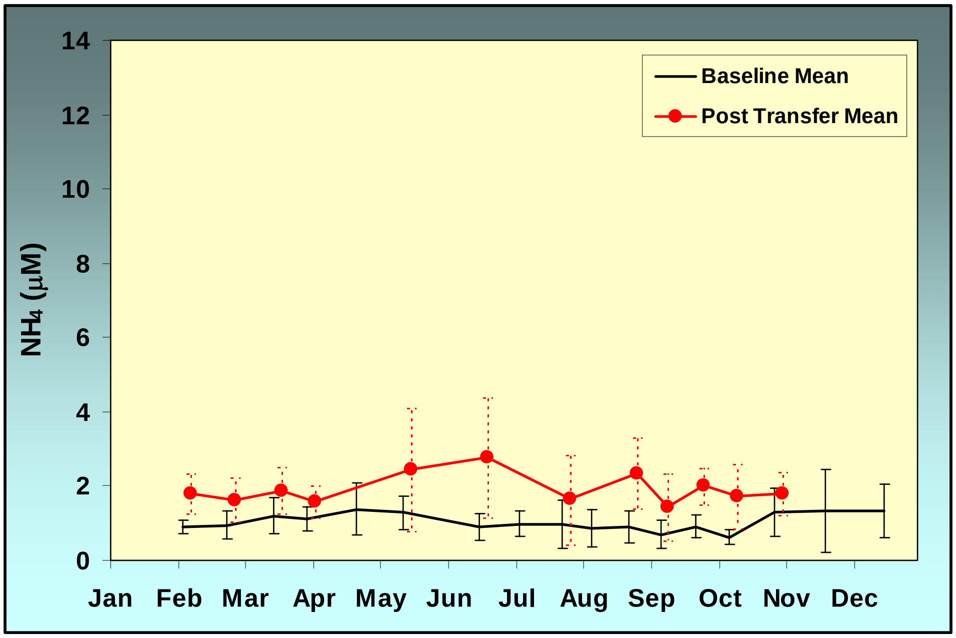

Figure 3-8. Post-transfer nearfield ammonium concentrations compared to baseline (Error bars represent one standard deviation.)

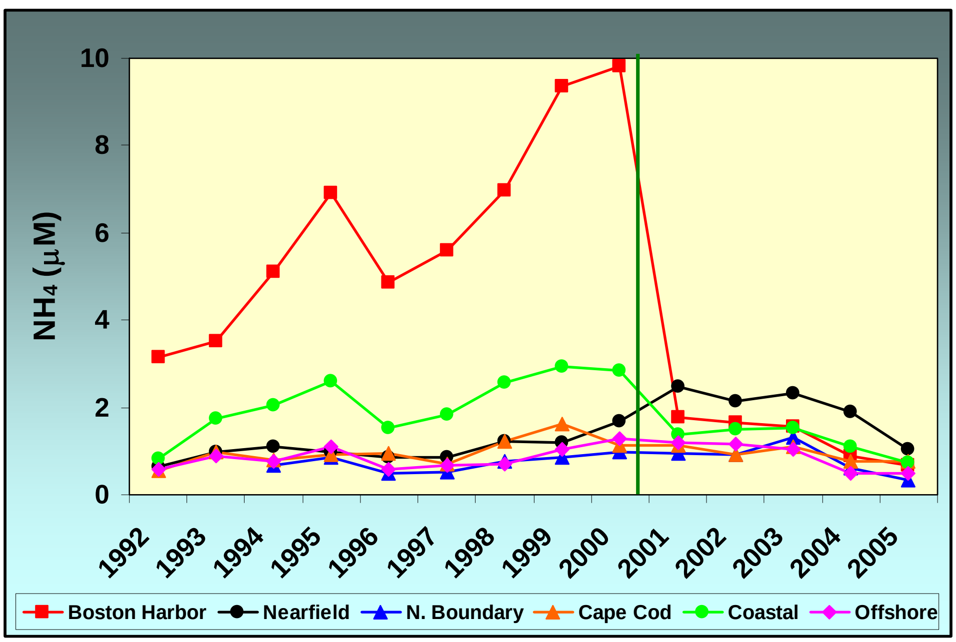

Figure 3-9. Annual mean ammonium concentrations in Massachusetts Bay regions

Concentrations of nitrate, another form of nitrogen readily used by phytoplankton and present in the effluent, continued to fall within the baseline range for most surveys and showed the same seasonal pattern as seen in baseline monitoring (Figure 3-10), and there have been no changes in the variable regional pattern (Figure 3-11). Nitrate concentrations in the nearfield were slightly elevated above the baseline range during one fall survey, as stratification broke down during the earlier-than-usual October storm, and nutrients from the bottom waters mixed throughout the water column.

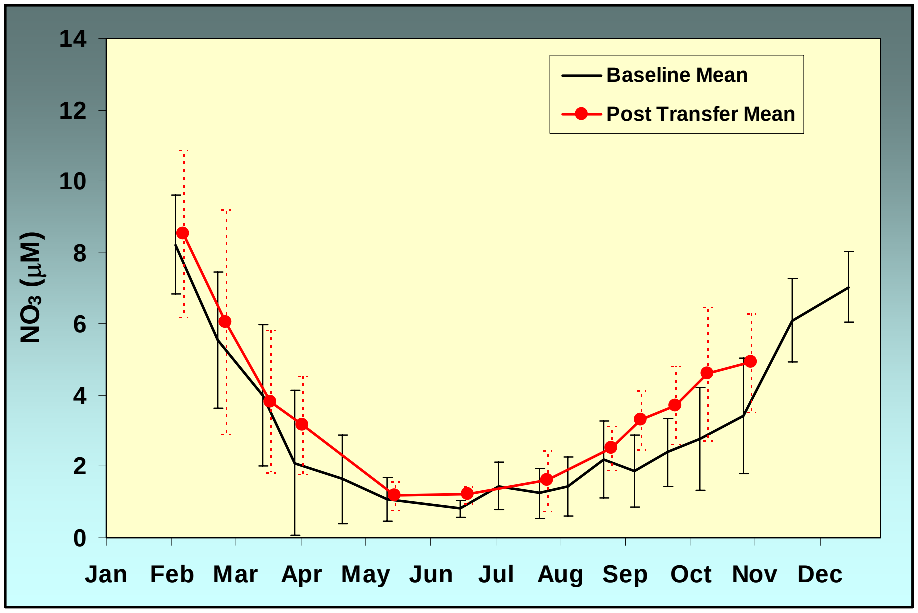

Figure 3-10. Post-transfer nearfield nitrate concentrations compared to baseline (Error bars represent one standard deviation.)

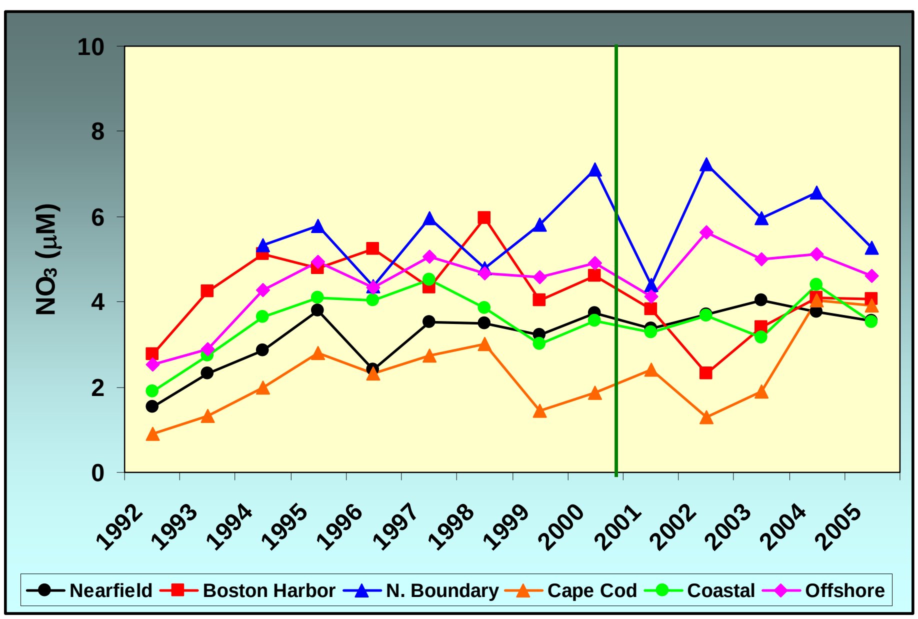

Figure 3-11. Annual mean nitrate concentrations in Massachusetts Bay regions

Phytoplankton biomass, as measured by chlorophyll and particulate organic carbon, showed similar trends as in previous years. Chlorophyll (mg per square meter) has shown no systematic response to nutrient enrichment of the outfall (Figure 3-12), although the data are marked by large variability in timing and magnitude of spring and fall peaks. Concentrations during the winter and spring of 2005 were in the upper end of the baseline range, and concentrations in the late spring and summer were close to the baseline mean. The annual average was at the low end of the baseline range, reflecting a lack of a fall bloom in 2005. Nearfield concentrations of particulate organic matter generally followed the baseline means and trends.

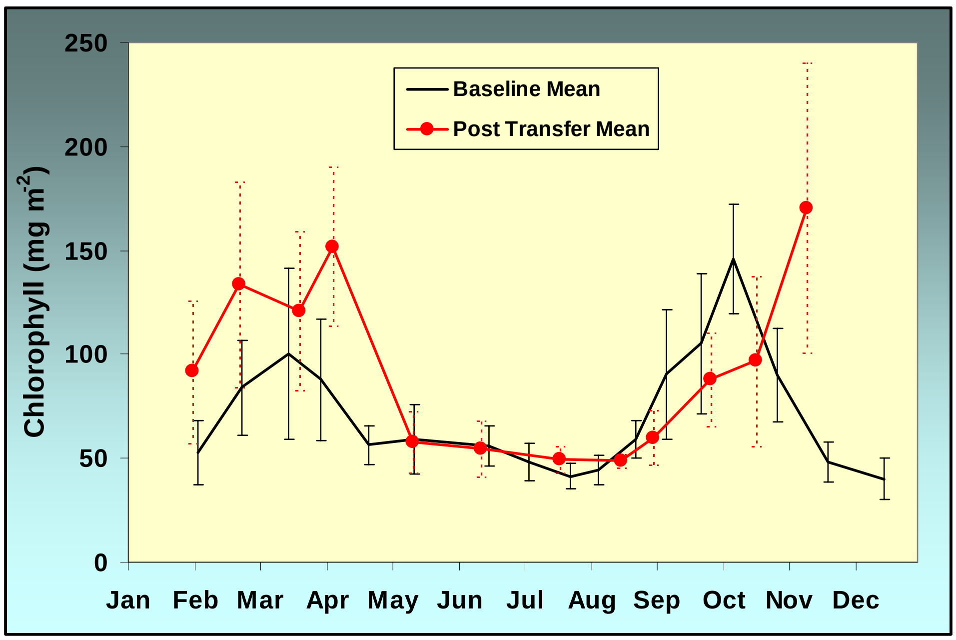

Figure 3-12. Post-transfer nearfield chlorophyll compared to baseline (Error bars represent one standard deviation.)

Measurements of concentrations (Figure 3-13) and percent saturation (not shown) of dissolved oxygen in the bottom waters have shown no response to nutrient enrichment or addition of organic matter from the outfall. As in other post-baseline years, the seasonal cycle of higher concentrations during the winter and spring and lower concentrations in the summer and fall, returning to higher concentrations following a fall overturn continued. Like 2004, near-bottom oxygen concentrations in the fall were higher than average, a result of strong mixing during the October storm.

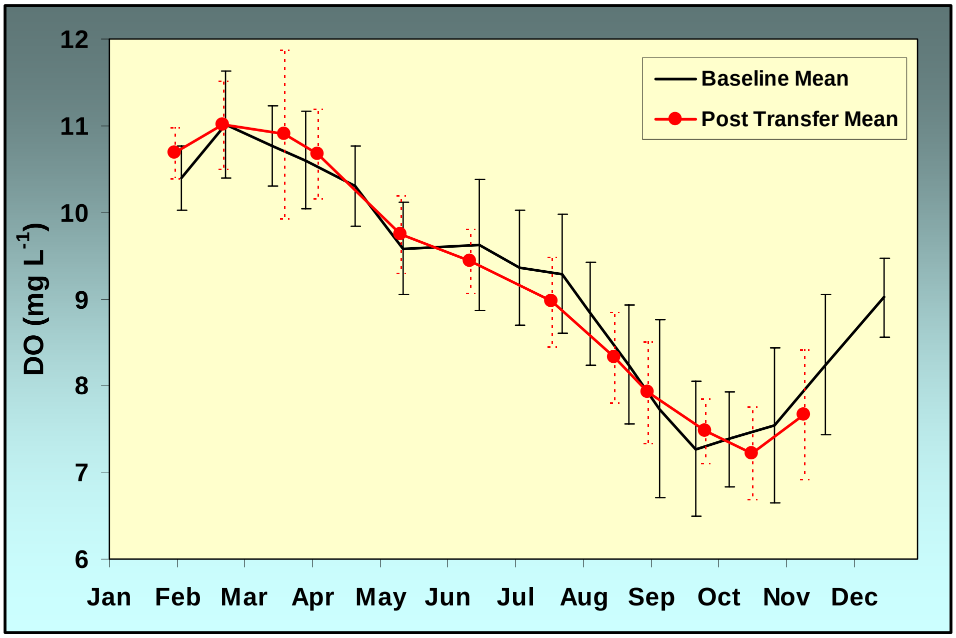

Figure 3-13. Post-transfer nearfield dissolved oxygen concentrations compared to baseline (Error bars represent one standard deviation.)

Phytoplankton Communities

Seasonal abundance of phytoplankton in the post-outfall diversion years has remained similar to the baseline mean for most survey dates (Libby *et al.* 2006a; Figure 3-14), and the taxonomic composition of the phytoplankton community has been relatively consistent. The year was marked, however, by an April bloom of the nuisance species *Phaeocystis pouchetii* and by a major May and June bloom of toxic dinoflagellates in the genus *Alexandrium*, producing the largest red tide in New England since 1972.

The usual species assemblage in Massachusetts Bay includes small microflagellates and cryptomonads, which are numerically dominant throughout the year, peaking in abundance during the warm summer months. Diatoms are usually abundant during the winter, spring, and fall. In some years, there are major blooms of a single species, such as *Asterionellopsis glacialis* in the fall or *Phaeocystis pouchetii* in the spring. The blooms tend to occur on broad regional scales, and the reasons they occur are not well understood.

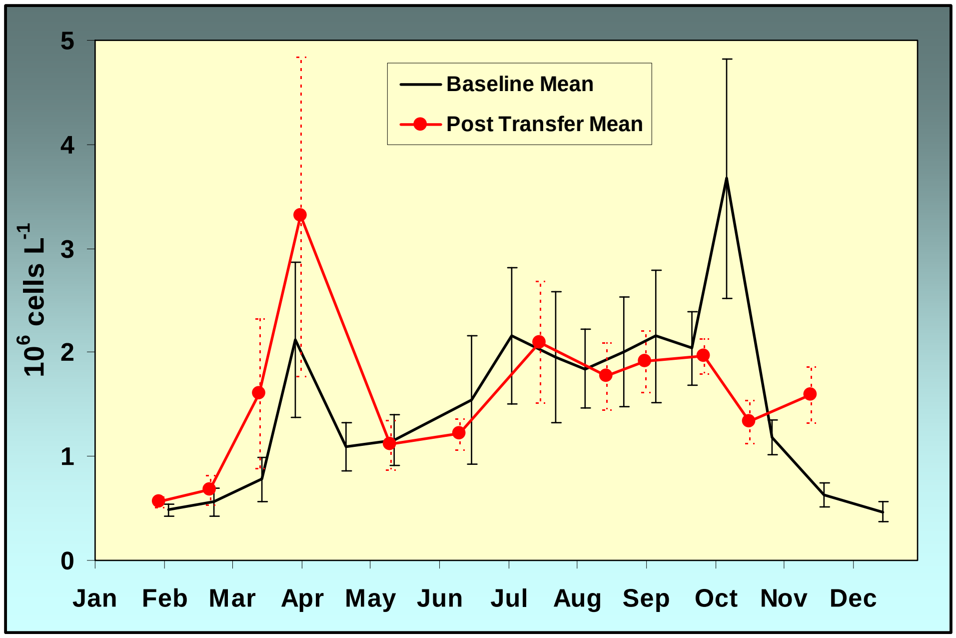

Figure 3-14. Post-transfer nearfield phytoplankton abundance compared to baseline (Error bars represent one standard deviation.)

The most pronounced change in the phytoplankton community over the course of the monitoring program has been an increase in the frequency of *Phaeocystis pouchetii* blooms (Figure 3-15). During the baseline period, there were spring *Phaeocystis* blooms approximately every three years, in 1992, 1994 (only recorded in the farfield), 1997, and 2000. Since the outfall began operation, the blooms have occurred annually and have increased in duration. In earlier years, *Phaeocystis* blooms occurred primarily in late March and April. Since 2002, they have begun earlier in March persisted until early May.

Reasons for the increases in occurrence and duration remain unknown. Because the *Phaeocystis* blooms occurred over such a broad geographic area, it is unlikely that the outfall is a cause. The blooms have occurred well beyond the boundaries of Massachusetts and Cape Cod bays, and there have been no obvious spatial associations with the outfall. A detailed discussion of the blooms will be presented in a review of issues related to nutrients in the region, currently in preparation.

In May and June, a large bloom of toxic dinoflagellates in the genus *Alexandrium* occurred (Figure 3-16), the largest since 1972. The bloom extended from Maine to south of Cape Cod and Martha's Vineyard. Concentrations of cells were orders-of-magnitude higher than in previous years. It is now understood that a high abundance of *Alexandrium* cysts in the western Gulf of Maine sediments was the main cause of the bloom. Wind conditions, particularly the northeast storms that occurred in May, accelerated flow along the coast and into Massachusetts Bay, contributing to the timing of the bloom, however even without the northeast winds, a major red tide would have occurred. The bloom is discussed further in Section 6, Special Studies.

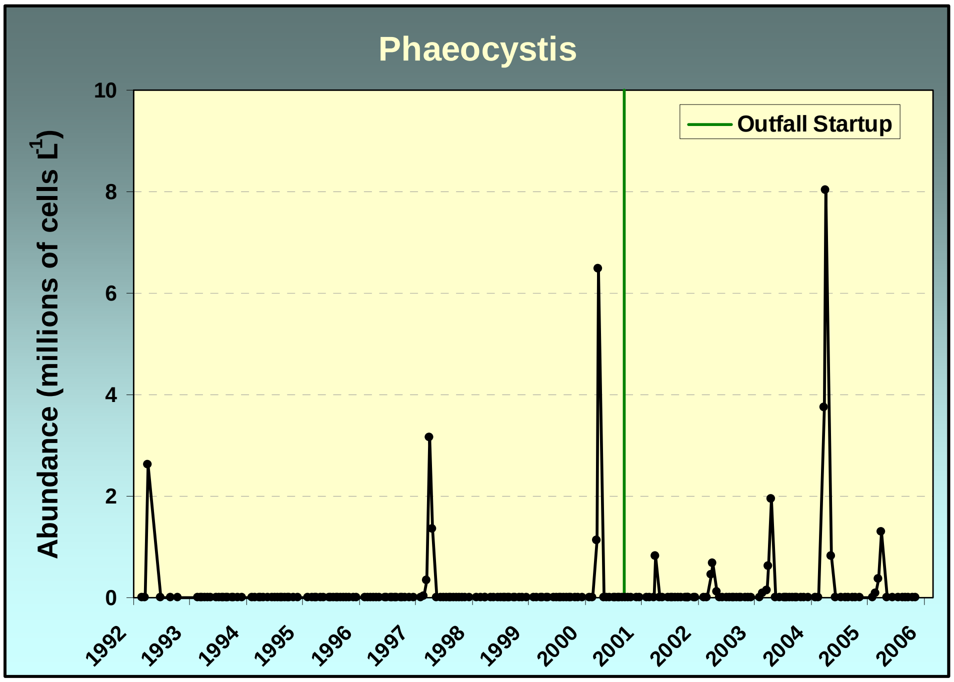

Figure 3-15. Abundance of Phaeocystis pouchetii *in the nearfield, 1992-2005*

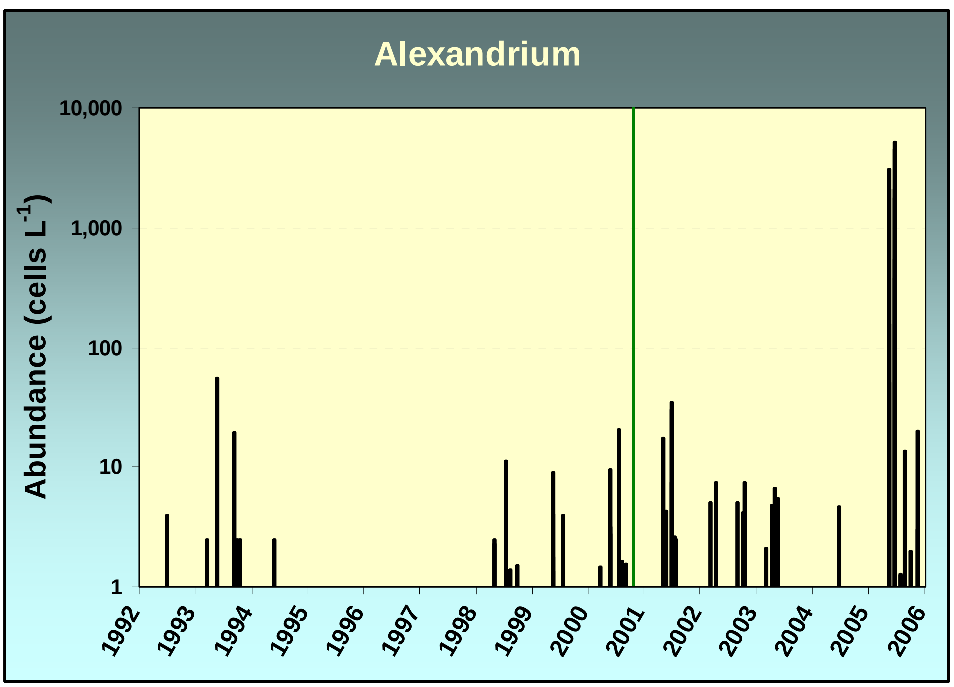

Figure 3-16. Abundance of Alexandrium *species in the nearfield, 1992-2005*

Zooplankton Communities

The structure of the zooplankton community in 2005 was similar to many earlier years and continued to show no effects of the outfall (Libby *et al.* 2006a). Abundance was dominated by copepod nauplii and copepodites and adults of the small copepods *Oithona similis* and *Pseudocalanus* spp. Other, less dominant, copepods typically include *Calanus finmarchicus*, *Paracalanus parvus*, *Centropages typicus*, and *C. hamatus*. The planktonic early life stages of bivalves, gastropods, barnacles, and polychaetes occur in sporadic pulses.

There has, however, been a measurable decrease in total zooplankton abundance during 2001 through 2005 in comparison to the baseline period (Figure 3-17). Total abundance has been lower during the late spring and early summer and during the fall.

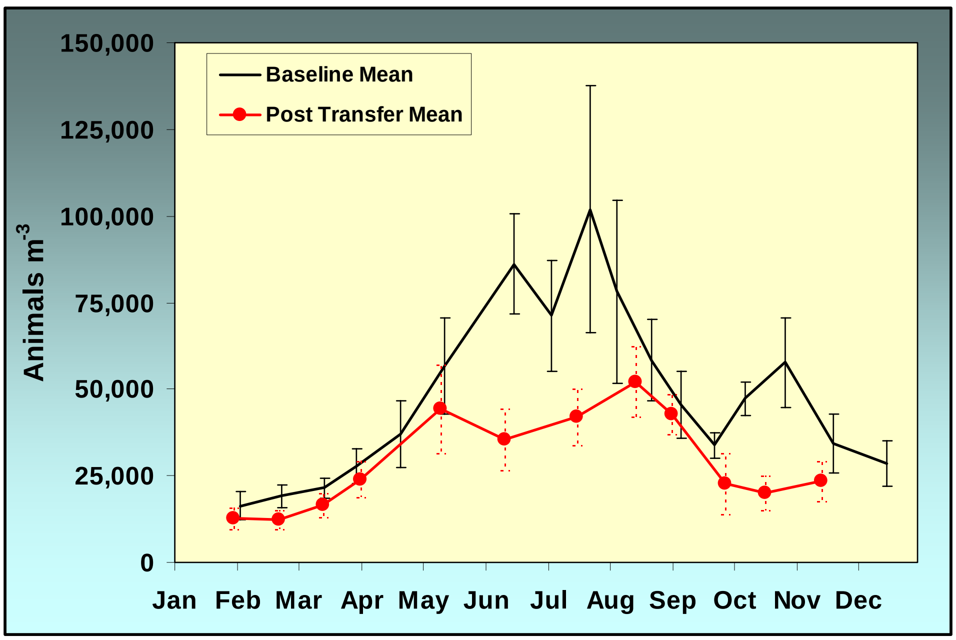

Figure 3-17. Post-transfer nearfield zooplankton abundance compared to baseline (Error bars represent one standard deviation.)

Similar decreases have been observed across Massachusetts Bay, including the northern boundary to the Gulf of Maine, the offshore, and the coastal stations, but not in the shallower, more inshore waters of Boston Harbor or Cape Cod Bay (Figure 3-18). This difference is not surprising: circulation modeling has found that Cape Cod Bay is generally isolated from Massachusetts Bay during the summer stratified season (Geyer *et al.* 1992, Lermusiaux 2001, Jiang *et al.* 2006).

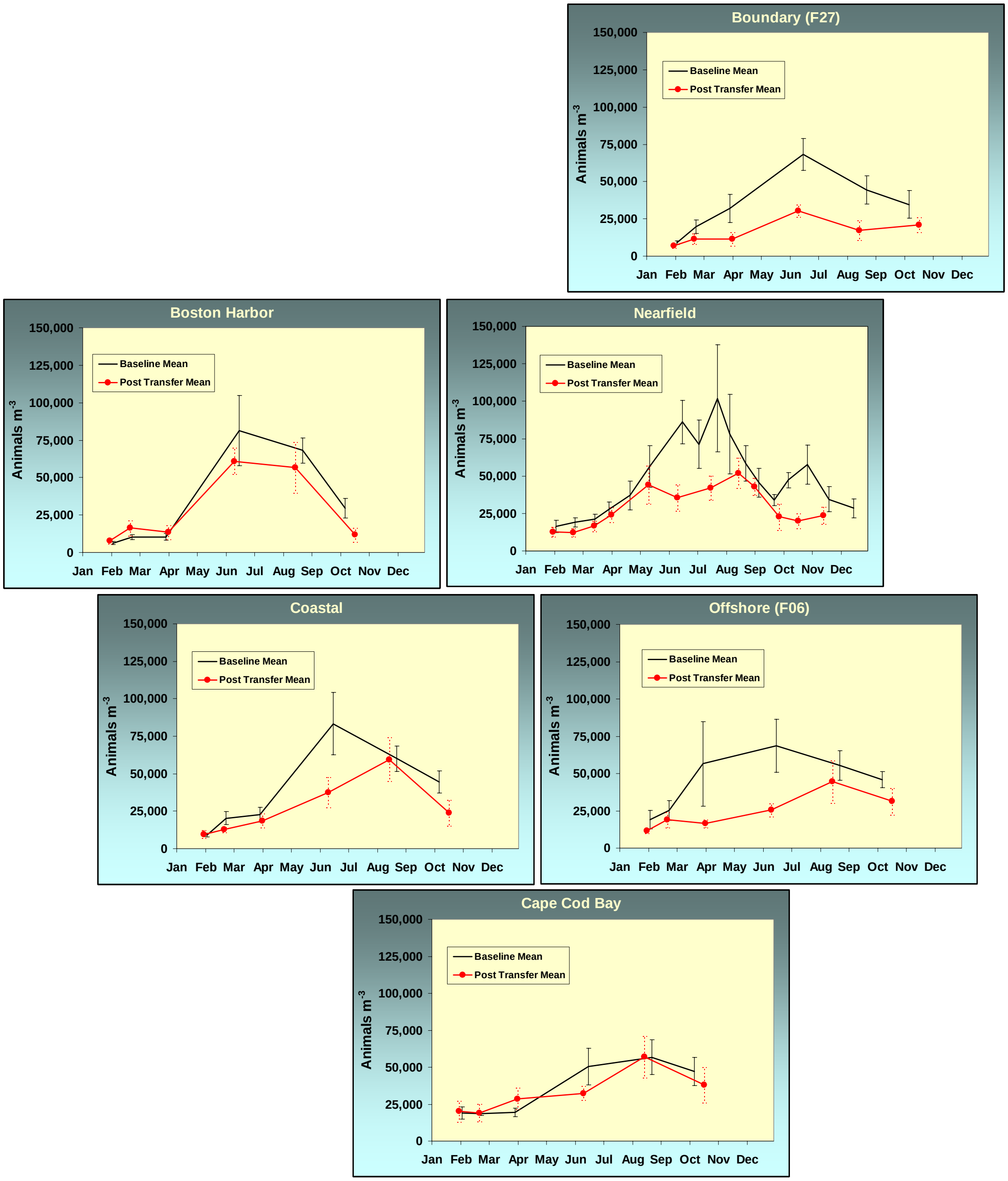

Figure 3-18. Total zooplankton abundance by region. The placement of the individual figures approximates their geographic positions; for example, the Boundary station is farthest to the north and east, and the Cape Cod Bay stations are farthest to the south.

Analysis of nearfield data has suggested that the low mean abundance during the late spring and summer can be attributed to low abundance of the small, dominant, *Oithona similis*; abundance of other species, such as the larger *Calanus finmarchicus*, a forage species for right whales, has remained at or above the baseline mean. The decline may be due to normal, large variability, but may also be a response to the consecutive *Phaeocystis pouchetii* blooms that have occurred throughout Massachusetts Bay. Some investigators have suggested that *Phaeocystis* is unpalatable to certain animals, such as right whales, but the effects on various zooplankton species are poorly understood. Regression analysis indicates that there is decreased abundance of *Oithona* but increased abundance of *Calanus finmarchicus* with increases in *Phaeocystis* abundance.

The mean decrease in total zooplankton abundance during the fall months may have resulted from the lack of substantial fall phytoplankton blooms, and in some years, may also be a response to late summer and fall blooms of the ctenophore *Mnemiopsis leidyi*, a zooplankton predator, which first appeared in the region in October 2000. Subsequent *Mnemiopsis* blooms, when they have occurred, have spanned geographically large areas, beginning in August and persisting until November.

Contingency Plan Thresholds

Threshold parameters for water-column monitoring include minimum dissolved oxygen concentrations and percent saturation in nearfield and Stellwagen Bank bottom waters, dissolved oxygen depletion rate in nearfield bottom waters, chlorophyll levels, abundance of nuisance algal species, geographic extent of PSP toxin, and initial dilution.

There were two exceedances of thresholds in 2005—the summer *Phaeocystis* threshold and the *Alexandrium* threshold. The summer *Phaeocystis* threshold has been exceeded each year since 2001, due to the extended duration of the blooms that have occurred in recent years and to the extremely low summer threshold. The *Alexandrium* threshold of 100 cells per liter was exceeded during the red tide, with more than 10,000 cells per liter measured during a regular nearfield survey and more than 36,000 cells per liter being measured during a rapid-response *Alexandrium* full (AF) survey undertaken in response to the bloom. The threshold for PSP toxin extent was not exceeded, because the spatio-temporal pattern of the red tide was consistent with past blooms, beginning in the north and progressing to the south. All other monitoring results were within ranges that met the thresholds.

Table 3-5. Contingency plan threshold values and 2005 results for water-column monitoring

Location/ Parameter	Specific Parameter	Baseline	Caution Level	Warning Level	2005 Results
Bottom water nearfield	Dissolved oxygen concentration	Background 5th percentile 5.75 mg/l	Lower than 6.5 mg/l for any survey (June-October) unless background conditions are lower	Lower than 6.0 mg/l for any survey (June-October) unless background conditions are lower	Lowest survey mean = 7.98 mg/l
	Dissolved oxygen percent saturation	Background 5th percentile 64.3%	Lower than 80% for any survey (June-October) unless background conditions are lower	Lower than 75% for any survey (June-October) unless background conditions are lower	Lowest survey mean = 80.7%
Bottom water Stellwagen Basin	Dissolved oxygen concentration	Background 5th percentile 6.2 mg/l	6.5 mg/l for any survey (June-October) unless background conditions lower	Lower than 6.0 mg/l for any survey (June-October) unless background conditions are lower	Lowest survey mean = 7.6 mg/l
	Dissolved oxygen percent saturation	Background 5th percentile 66.3%	Lower than 80% for any survey (June-October) unless background conditions	Lower than 75% for any survey (June-October) unless background conditions are lower	Lowest survey mean = 76.5%
Bottom water nearfield	DO depletion rate (June-October)	0.024 mg/l/d	0.037 mg/l/d	0.049 mg/l/d	0.013 mg/l/d
Chlorophyll nearfield	Annual	79 mg/m^2	118 mg/m^2	158 mg/m^2	79.22 mg/m^2
	Winter/spring	62 mgml^2	238 mg/m^2	None	133 mg/m^2
	Summer	51 mg/m^2	93 mg/m^2	None	61.2 mg/m^2
	Autumn	97 mg/m^2	212 mg/m^2	None	43 mg/m^2
Nuisance algae nearfield *Phaeocystis pouchetii*	Winter/spring	468,000 cells/l	2,020,000 cells/l	None	438,481 cells/l
	Summer	72 cells/l	357 cells/l	None	517 cells/l, caution exceedance
	Autumn	317 cells/l	2,540 cells/l	None	0 cells/l
Nuisance algae nearfield *Pseudo-nitzschia*	Winter/spring	6,200 cells/l	21,000 cells/l	None	147 cells/l
	Summer	14,600 cells/l	43,100 cells/l	None	3,317 cells/l
	Autumn	9,940 cells/l	24,700 cells/l	None	45 cells/l
Nuisance algae nearfield *Alexandrium fundyense*	Any nearfield sample	Baseline maximum = 163 cells/l	100 cells/l	None	10,919 cells/l (NF surveys); 36,830 (AF surveys), caution exceedance
Farfield	PSP toxin extent	Not applicable	New incidence	None	Closures from Maine to south of Cape Cod

4. Sea Floor

Background

Bottom Characteristics and Sediment Transport

The sea floor of Massachusetts and Cape Cod bays was originally shaped by the glaciers, which sculpted the bottom and deposited debris, forming knolls, banks, and other features. Within Massachusetts Bay, the sea floor ranges from mud in depositional basins to coarse sand, gravel, and bedrock on topographic highs. The area around the outfall is marked by underwater drumlins, which are elongated hills about 10 meters high, with crests covered by gravel and boulders. Long-term sinks for fine-grained sediments include Boston Harbor, Cape Cod Bay, and Stellwagen Basin.

Long-term monitoring and modeling have confirmed that sediment transport in the region occurs primarily during storms (Butman *et al.* 2005). Typically, waves during storms with winds from the northeast resuspend sediments, which are transported by shallow currents from western Massachusetts Bay toward Cape Cod Bay and by deeper currents to Stellwagen Basin. Cape Cod Bay is partially sheltered from large waves by the arm of Cape Cod, and storm waves are rarely large enough to resuspend sediments in Stellwagen Basin, which is the deepest feature in the region. Tidal currents, wind-driven currents, and currents associated with spring runoff are insufficient to resuspend sediments.

Environmental Concerns

Within Boston Harbor, studies of the sediments have documented recovery following the cessation of sludge and effluent discharges and other improvements (see Section 7, Boston Harbor Studies). Conversely, relocating the outfall raised concerns about potential effects on the offshore sea floor. Concern has focused on three mechanisms of potential disruption to the animal communities living on the seafloor: eutrophication and related low levels of dissolved oxygen, accumulation of toxic contaminants in depositional areas, and smothering (Table 4-1).

Table 4-1. Monitoring questions related to the sea floor

Are natural/living resources protected?

Will benthic enrichment contribute to changes in community structure of soft-bottom and hard-bottom macrofauna, possibly affecting fisheries?
Will benthic macrofauna near the outfall mixing zone be exposed to some contaminants, potentially contributing to changes in the community?
Will the benthos near the outfall mixing zone and in depositional areas farther away accumulate some contaminants?

- What is the level of sewage contamination and its spatial distribution in Massachusetts and Cape Cod bays sediments before discharge through the new outfall?
- Has the level of sewage contamination or its spatial distribution in Massachusetts or Cape Cod bays sediments changed after discharge through the new outfall?
- Have the concentrations of contaminants in sediments changed?
- Has the soft-bottom community changed?
- Are any benthic community changes correlated with changes in levels of toxic contaminants (or sewage tracers) in sediments?
- Has the hard-bottomed community changed?

Will increased water-column and benthic respiration contribute to depressed oxygen levels in the sediment?

- Have the sediments become more anoxic; that is, has the thickness of the sediment oxic layer decreased?

If transfer of the nutrient loads to offshore were to cause eutrophication, the depressed levels of dissolved oxygen that were also a concern in water-column monitoring could adversely affect bottom-dwelling animals. An increase in the amounts of particles and organic matter to the bottom could disrupt normal benthic community structure in the vicinity of the discharge. Although source control and treatment plant performance are designed to keep effluent contaminant concentrations too low to affect the sediments, the location of the outfall in an area of sediment transport caused concern about accumulation of toxic contaminants in Cape Cod Bay and Stellwagen Basin. Similarly, concentrations of particulate matter were expected to be low, but there remained some concern that bottom communities near the outfall could be affected by deposition.

Monitoring Design

Sea-floor monitoring includes several components: measurements of sediment characteristics, sewage effluent tracers, and contaminant concentrations in sediments; sediment-profile imaging to provide a rapid assessment of benthic communities and sediment quality; studies of nearfield and farfield soft-bottom communities (sampling sites in Figures 4-1 and 4-2); and study of hard-bottom communities (sampling sites in Figure 4-3).

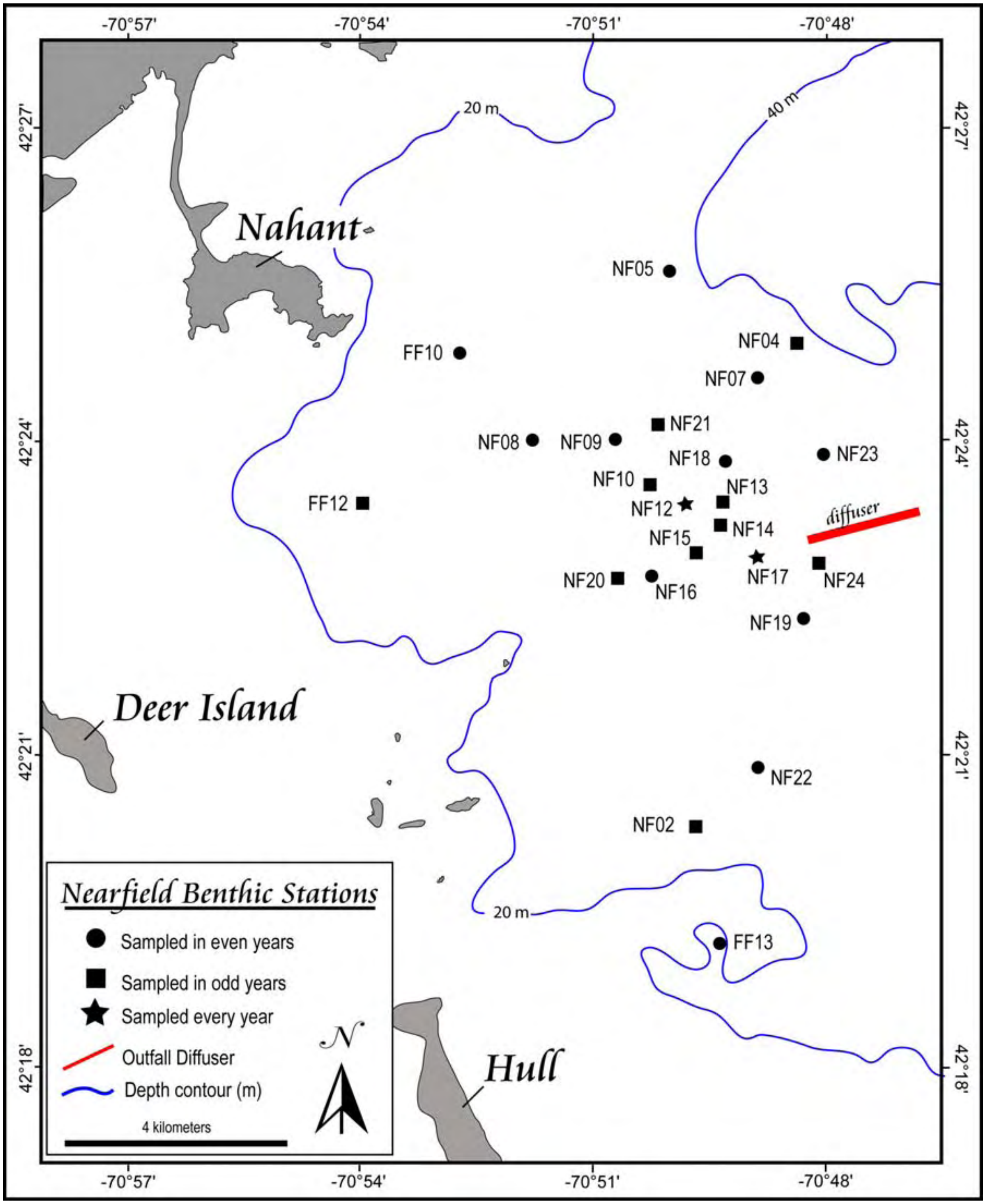

Figure 4-1. Locations of nearfield soft-bottom stations

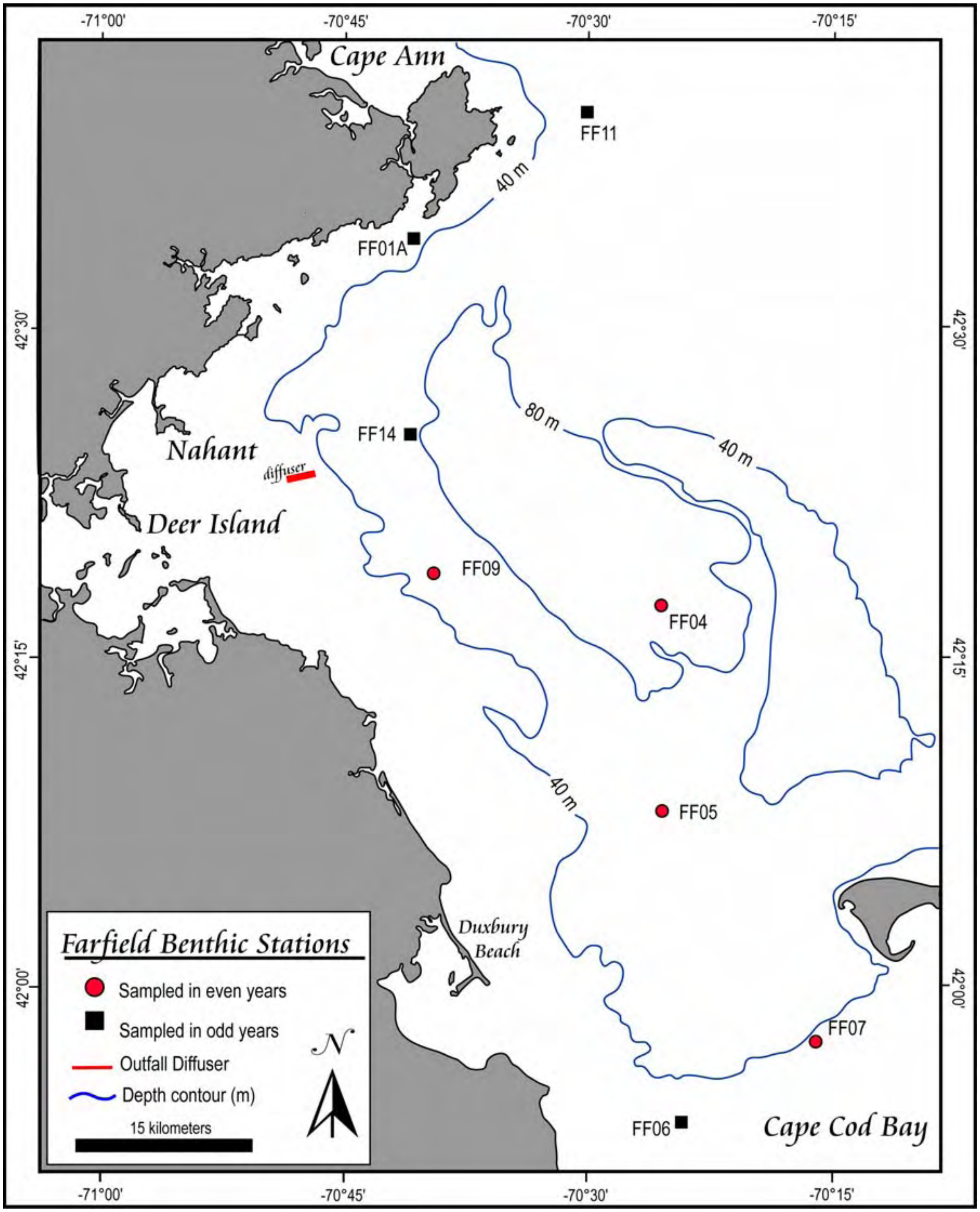

Figure 4-2. Locations of farfield soft-bottom stations

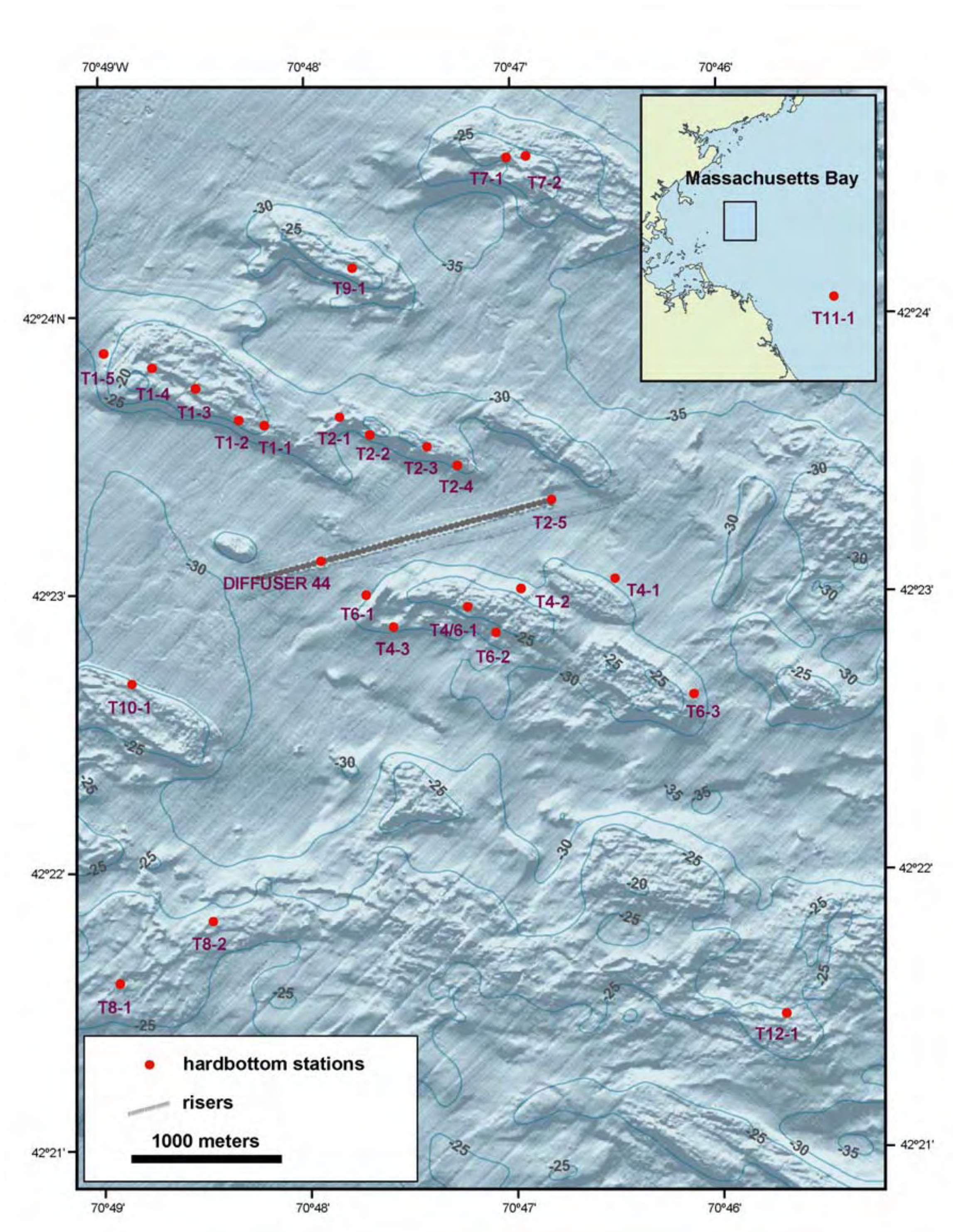

Figure 4-3. Locations of hard-bottom stations

Measurements of sediment characteristics, tracers, and contaminants include analyses of grain size, total organic carbon (TOC), *Clostridium perfringens* spores, PAHs, PCBs, chlorinated pesticides, and metals. Sediment-contaminant monitoring has been complemented by special studies, primarily in association with USGS (Bothner and Butman 2005). The USGS program is discussed in Section 6, Special Studies.

Sediment-profile image monitoring is conducted each August to give area-wide assessments of sediment quality and benthic community status. The sediment-profile images provide more rapid assessments of benthic habitat conditions than is possible from traditional faunal analyses. A system called “Quick Look,” which uses digital video cameras along with film, provides an even faster assessment. A real-time narration of the videotape describes the substrate and estimates depth to which oxygen penetrates, known as the oxidation-reduction (redox) potential discontinuity (RPD). Later, complete analyses of films provide information on prism penetration, surface relief, apparent color RPD depth, sediment grain size, sediment layering, fauna and structures, and successional stage of the soft-bottom animal communities.

Monitoring the soft-bottom benthic infauna also includes annual surveys conducted in August. Samples are collected with a 0.04-m^2 Young-Van Veen benthic grab, sieved on 300-µm mesh, and fixed in formalin in the field, then transferred to alcohol and stained with Rose Bengal in the laboratory. Animals are sorted, identified, and counted.

Most pollutant-effect monitoring studies of benthic communities, including the MWRA monitoring program, focus on the soft-bottom areas with finer-grained sediments, but such depositional areas are few in the vicinity of the outfall. Therefore, MWRA also conducts video and photographic surveys of the hard-bottom habitats found on the tops and flanks of drumlins in western Massachusetts Bay. Video and still photographs are taken at a series of stations or waypoints, including diffuser head #44 of the outfall (which was not opened) and diffuser head #2. These annual surveys are conducted in June. Photographs are examined for substrate type (top or flank of the drumlin, with relief defined by presence of boulders and cobbles), amount of sediment drape (the degree to which a layer of fine material covers the hard surface), and biota (taxa identified to species or species groups and counted).

Beginning in 2003 and 2004, the existing 23 nearfield and 8 farfield soft-bottom stations were split into two subgroups. This division was made randomly after accounting for regional representation and level of replication, with two stations (NF12 and NF17, which are also sampled by

USGS) being included in both groups. The program includes the following:

- Sediment characteristics and tracers, such as TOC, sediment grain size, and *Clostridium perfringens* spore counts, are sampled in one subset in alternate years, such that each station is sampled at least once every two years.
- Chemical constituents, including PAHs, PCBs, pesticides, and metals, are measured annually at the two stations included in both groups and once every three years at stations being sampled for other parameters, with sampling occurring in 2005.
- Sediment-profile images for the measurement of RPD depth continue to be taken at all 23 nearfield stations each year.
- Benthic infauna is studied at the same stations as are sampled for sediment characteristics. Species composition and abundance are assessed for all stations sampled.
- Hard-bottom monitoring continues as previously, except that two stations were discontinued and two stations were added in 2003.

Results

Sediment Characteristics, Tracers, and Contaminants

Baseline sampling at nearfield stations found that the area around the outfall was composed of heterogeneous sediments that had received historic inputs of contaminants from Boston Harbor, the atmosphere, and other sources. In the nearfield, contaminant concentrations have been correlated with grain size, with the muddier stations having more organic carbon and higher concentrations of contaminants.

Sampling and analysis for chemical constituents in 2005 was the most comprehensive since 2002. At several stations in 2005, sediments were coarser than they had been in prior years, presumably a result of the spring northeast storms. Concentrations of total organic carbon at some nearfield and farfield stations were among the lowest measured in the monitoring program. For many contaminants, including PCBs, DDT, aluminum, chromium, iron, nickel, and silver, the concentrations were low in comparison to other years since the outfall began operation. The decrease in concentrations of PCBs and DDT may reflect changes in analytic methods as well as the expected slow declines since PCBs and DDT were banned in the 1970s and 1980s. Decreases in concentrations of aluminum, chromium, iron, and nickel reflect the coarsening of the sediments. There was clear evidence of the discharge in concentrations of the sewage tracer *Clostridium perfringens* spores at stations located within two kilometers of the outfall, but no widespread detectable accumulation of any contaminant. Concentrations of *Clostridium perfringens* spores were lower than baseline levels at stations located between the mouth of Boston Harbor and the outfall and at farfield stations.

Sediment-Profile Imaging

Sediment-profile imaging measurements in 2005 showed no changes from the baseline to the post-baseline period (Maciolek *et al.* 2006; Figure 4-4). The mean RPD depth prior to outfall startup was 2.3 cm, while the post-diversion mean is 2.4 cm. No relationship between RPD depth and outfall operation has been detected, and no regional trends have appeared during the years that the outfall has been operating.

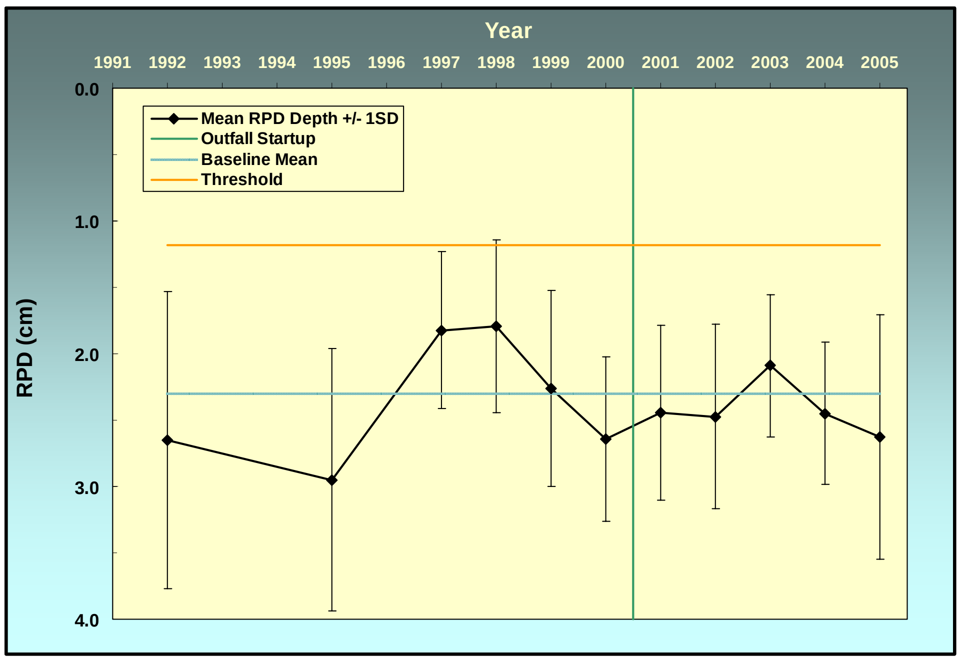

Figure 4-4. Apparent color RPD for all data from nearfield stations

Some sediment-profile images showed evidence of increased physical processes, probably a result of the 2005 storms. Sediments were coarser, and there were fewer biological structures, such as worm tubes. These effects were more obvious in Boston Harbor, where amphipod mats, which had predominated, were no longer evident. The changes in Boston Harbor sediments are discussed further in Section 7, Boston Harbor Studies.

Soft-bottom Communities

The soft-bottom communities have also shown no response to the outfall (Maciolek *et al.* 2006). During the baseline period, multivariate analyses indicated that sediment grain size was the dominant factor in structuring the benthic communities. In the nearfield, stations with fine sediments have been dominated by polychaete worms, such as *Prionospio steenstrupi*, *Spio limicola*, *Mediomastus californiensis*, and *Aricidea catherinae*. Sandier stations have been inhabited by the sand dollar *Echinarachnius parma*, polychaetes *Exogenes hebes, E. verugera, Spiophanes bombyx*, and *Owenia fusiformis*, and the amphipod *Crassicorophium crassicorne*.

The benthic communities of the farfield have differed from those in the nearfield, as the farfield stations span a greater depth range, are geographically widespread, and generally have finer sediments than those in the nearfield. Polychaete worms, including *Eucone incolor, Aricidea quadrilobata*, and *Levinsenia gracilus*, have predominated at most stations. *Prionospio steenstrupi* has also been common at some of the farfield stations. Another polychaete, *Cossura longicirrata*, has dominated at a station in Cape Cod Bay.

The nine years of baseline monitoring provided a broad base for understanding the potential responses of the benthic communities to the discharge. During the baseline period, some stations were severely affected by winter storms, while other, deeper stations exhibited more stability over time. The years of post-discharge-transfer monitoring have detected some statistical differences in community parameters, such as increased numbers and dominance of some species at some stations. These changes are considered to be natural fluctuations rather than patterns that can be related to the discharge.

In 2005, mean total abundance fell in both the nearfield (Figure 4-5, top) and the farfield (not shown). Species richness, measured as total number of species per sample and an index, log-series alpha, also declined (Figure 4-5, middle and bottom). These changes largely appear to result from natural cycles.

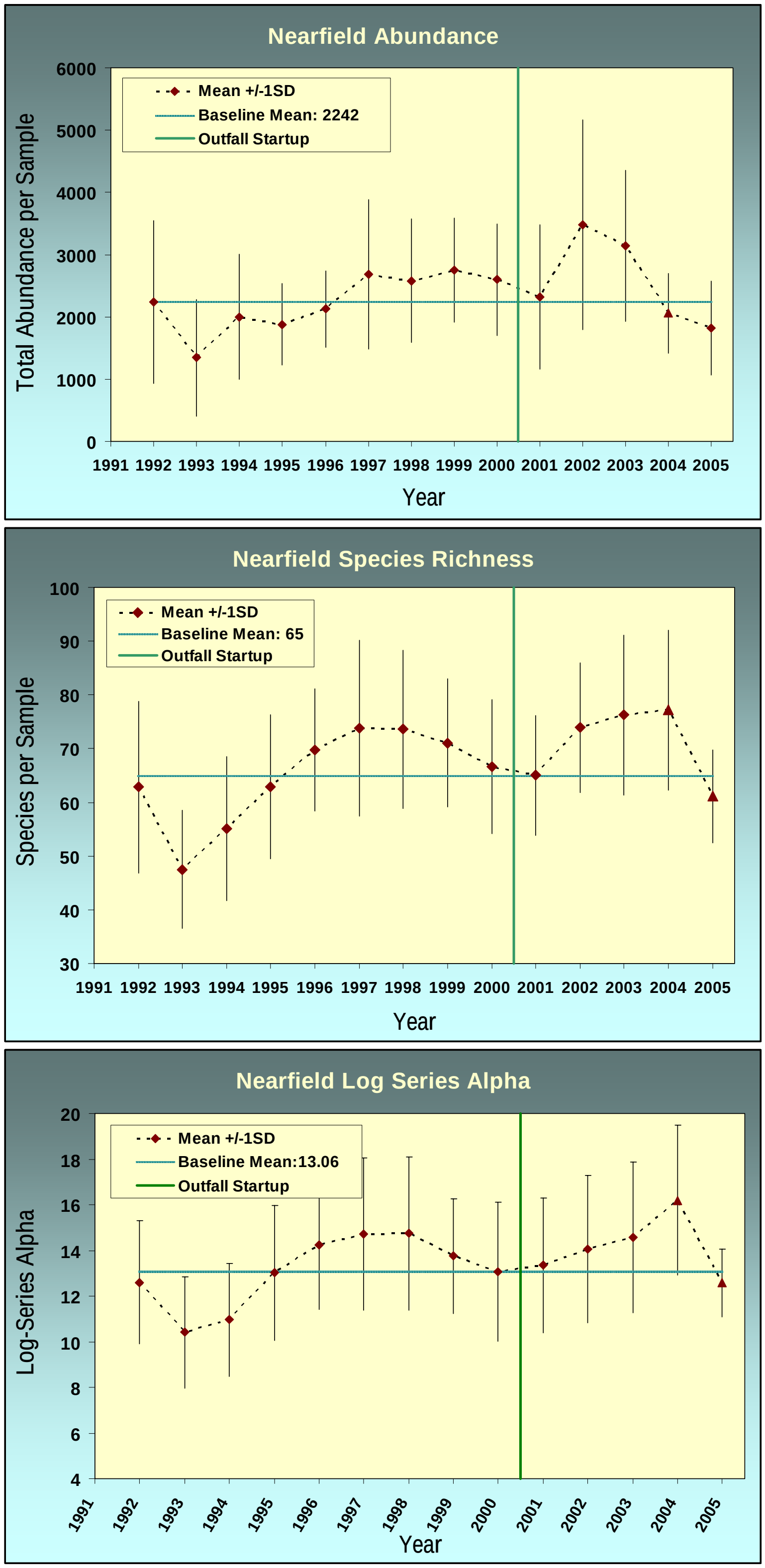

Figure 4-5. Community parameters in the nearfield, 1992-2005: Top: abundance per sample, Middle: species richness (number species per sample), Bottom: species richness (log-series alpha)

Hard-bottom Communities

Rocky environments in the vicinity of MWRA's outfall support communities of algae and invertebrates similar to those found throughout northern New England. Near the outfall, these environments and the communities they support are stable from year to year but vary over relatively short distances, on the scale of tens of meters. The habitat ranges from large boulders to cobbles to gravel pavements.

Some changes in the hard-bottom communities have been detected since the outfall began operation, but they have been modest, and it is difficult to attribute them to outfall operation (Maciolek *et al.* 2006). Other changes have occurred throughout the course of the monitoring program, beginning prior to the outfall start-up. For example, there has been a slight decrease in the number of upright algae at many stations, but these decreases began in the 1990s before the outfall went on-line, and the trend appears to be reversing. Other species, such as *Cancer* crabs, also appear to exhibit cycles of abundance. There have been steady increases in the number of cod throughout the duration of the program (Figure 4-6).

Figure 4-6. Cod and flounder in a 2005 transect

There have been increases in the amount of sediment drape and concurrent decreases in the percent cover of coralline algae at some stations, including the northernmost reference sites. In 2005, the decline in coralline algae was more pronounced and extended to additional sites that did not show any increase in sediment drape. Degree of coralline algae cover was hypothesized as a possible indicator of outfall effects. The geographic patterns observed in the declines, which include stations distant from the outfall, do not suggest that the outfall has been responsible.

Contingency Plan Thresholds

No Contingency Plan thresholds for sea-floor monitoring were exceeded in 2005 (Table 4-2). RPD depth was deeper than the baseline mean, soft-bottom community parameters were within normal ranges, and the percent of the soft-bottom community composed of opportunistic species remained low.

Table 4-2. Contingency Plan threshold values and 2005 results for sea-floor monitoring

Location	Parameter	Caution Level	Warning Level	2005 Results
Sediment toxic contaminants, nearfield	Acenaphthene	None	500 ppb dry	17.72 ppb dry
	Acenaphylene	None	640 ppb dry	26.88 ppb dry
	Anthracene	None	1100 ppb dry	92.24 ppb dry
	Benzo(a)anthracene	None	1600 ppb dry	250.4 ppb dry
	Benzo(a)pyrene	None	1600 ppb dry	245.39 ppb dry
	Cadmium	None	9.6 ppm dry	0.14 ppm dry
	Chromium	None	370 ppm dry	49.08 ppm dry
	Chrysene	None	2800 ppb dry	221.39 ppb dry
	Copper	None	270 ppm dry	18.39 ppm dry
	Dibenzo(a,h)anthracene	None	260 ppb dry	29.36 ppb dry
	Fluoranthene	None	5100 ppb dry	424.17 ppb dry
	Fluorene	None	540 ppb dry	28.26 ppb dry
	Lead	None	218 ppm dry	42.21 ppm dry
	Mercury	None	0.71 ppm dry	0.21 ppm dry
	Naphthalene	None	2100 ppb dry	31.3 ppb dry
	Nickel	None	51.6 ppb dry	7.09 ppb dry
	p,p'-DDE	None	27 ppm dry	0.48 ppm dry
	Phenanthrene	None	1500 ppb dry	238.73 ppb dry
	Pyrene	None	2600 ppb dry	383.94 ppb dry
	Silver	None	3.7 ppm dry	0.23 ppm dry
	Total DDTs	None	46.1 ppb dry	1.01 ppb dry
	Total HMW PAH	None	9600 ppb dry	3223.98 ppb dry
	Total LMW PAH	None	3160 ppb dry	961.31 ppb dry
	Total PAHs	None	44792 ppb dry	4185.29 ppb dry
	Total PCBs	None	180 ppb dry	6.88 ppb dry
	Zinc	None	410 ppm dry	59.26 ppm dry
Sediments, nearfield	RPD depth	1.18 cm	None	2.6 cm
Odd years, Benthic diversity, nearfield	Species per sample	<46.52 or >79.95	None	58.75
	Fisher's log-series alpha	<9.95 or >15.17	None	12.03
	Shannon diversity	<3.30 or >3.91	None	3.5
	Pielou's evenness	<0.56 or >0.66	None	0.6
Benthic opportunists	% opportunists	>10%	>25%	0.24%

5. Fish and Shellfish

Background

MWRA monitors fish and shellfish because of concerns for public health and because some fish and shellfish species are good indicators of effects of pollutants on overall marine health (Table 5-1). The fish and shellfish industry is an important part of the regional identity and economy of Massachusetts. There were concerns that the discharge of sewage effluent into the relatively clean waters of Massachusetts Bay could result in chemical contamination of the fisheries and that contaminants could cause direct damage to the fishery stocks.

Table 5-1. Monitoring questions related to fish and shellfish

Is it safe to eat fish and shellfish? *Will toxic chemicals accumulate in the edible tissues of fish and shellfish, and thereby contribute to human health problems?* ▪ Has the level of contaminants in the tissues of fish and shellfish around the outfall changed since discharge began? ▪ Do the levels of contaminants in the edible tissue of fish and shellfish around the outfall represent a risk to human health? ▪ Are the contaminant levels in fish and shellfish different between outfall, Boston Harbor, and a reference site?
Are natural/living resources protected? *Will fish and shellfish that live near or migrate by the diffuser be exposed to elevated levels of some contaminants, potentially contributing to adverse health in some populations?* ▪ Has the level of contaminants in the tissues of fish and shellfish around the outfall changed since discharge began? ▪ Are the contaminant levels in fish and shellfish different between the outfall, Boston Harbor, and a reference site? ▪ Are the contaminant levels in fish and shellfish different between outfall, Boston Harbor, and a reference site? ▪ Has the incidence of disease and/or abnormalities in fish or shellfish changed?

Because many toxic contaminants adhere to particles, which settle, animals that live on the bottom, in contact with sediments, and animals that eat bottom-dwelling organisms are most likely to be affected. Exposure to contaminated sediments could result in fin erosion, disease, or other, subtler, abnormalities in flounder, lobster, or other bottom-dwelling animals. Shellfish that feed by filtering suspended matter from large volumes of water are also potential bioaccumulators of toxic contaminants. Consumption of filter-feeding animals by predators could result in transferring contaminants up the food chain and ultimately to humans.

Monitoring Design

The monitoring program focuses on three indicator species: winter flounder (*Pseudopleuronectes americanus*), lobster (*Homarus americanus*), and blue mussel (*Mytilus edulis*). Winter flounder and lobster are important resource species in the region. The blue mussel is also a fishery species and is a common biomonitoring organism.

Like all flatfish, winter flounder live and feed on the bottom, often lying partially buried in the sediments. Consequently, flounder can be exposed to contaminants directly, through contact with the sediments, or indirectly, by ingesting contaminated prey. Flounder livers are examined to quantify disease, including three types of vacuolation (centrotubular, tubular, and focal, representing increasing severity), microphage aggregation, biliary duct proliferation, and neoplasia or tumors. Neoplasia and vacuolation have been associated with chronic exposure to contaminants. Chemical analyses of winter flounder tissues are also made to determine tissue burden and to evaluate whether contaminant burdens approach human health consumption limits. Chemical analyses (Table 5-2) of composite samples of fillets and livers include PCBs, pesticides, mercury, and lipids. Liver samples are also analyzed for PAHs, lead, silver, cadmium, chromium, copper, nickel, and zinc.

Lobsters live on a variety of surfaces within the region, including mud, sand, gravel, and rock outcrops. Commercial lobstermen collect lobsters for the monitoring program. Chemical analyses are performed on composite samples. Meat (from the tail and claw) and hepatopancreas are analyzed for lipids, PCBs, pesticides, and mercury. Hepatopancreas samples are also analyzed for PAHs, lead, silver, cadmium, chromium, copper, nickel, and zinc.

Like other filter feeders, blue mussels process large volumes of water and can concentrate toxic metals and organic compounds in their tissues. Mussels can be readily maintained in fixed cages, so they are convenient monitoring tools. Mussels are collected from clean reference sites (which have included Rockport, Gloucester, and Sandwich, Massachusetts, and Stover's Point, Maine). They are placed in cages and deployed in replicate arrays. After a minimum deployment of 40 days or a preferred deployment of 60 days, chemical analyses are performed on composite samples of mussel tissue. Tissues are analyzed for PCBs, pesticides, PAHs, lipids, mercury, and lead.

Table 5-2. Chemical analyses of fish and shellfish

Parameter	Measurement details
Flounder fillet	
Mercury PCBs Chlorinated pesticides Lipids	Three composites of fillets from five flounder
Flounder liver	
Trace metals PAHs PCBs Chlorinated pesticides Lipids	Three composites of livers from five flounder
Lobster meat	
Mercury PCBs Chlorinated pesticides Lipids	Three composites of meat from five lobsters
Lobster hepatopancreas	
Trace metals PAHs PCBs Chlorinated pesticides Lipids	Three composites of hepatopancreas from five lobsters
Mussel	
Mercury Lead PAHs PCBs Chlorinated pesticides Lipids	Six composites of soft tissue from ten mussels

Flounder and lobster are sampled from Deer Island Flats, the outfall site, and eastern Cape Cod Bay. Flounder are also taken near Nantasket Beach and Broad Sound. (No fish were collected at Broad Sound in 2005.) Flounder and lobster are examined for external lesions. Since 2004, histology analyses for flounder are made every year; chemical analyses for lobsters and flounder are completed every third year. Mussels are deployed every three years at five locations: at the edge of the mixing zone, one kilometer south of the diffuser line, in Cape Cod Bay, at at Deer Island Light, and in the Inner Harbor.

In 2005, only winter flounder were studied. Fifty sexually mature (at least three years old) winter flounder were taken from each of the four sampling sites during May. Each of the fish was examined for physical characteristics. All fish were used for histological and age analyses. As part of an ongoing investigation of external ulcers that have been observed on the blind sides of winter flounder since 2003, additional surveys were also conducted in the January and March.

Results

As in previous years, the mild centrotubular hydropic vacuolation (CHV) was the most common form of vacuolation noted in histological analyses (Moore 2006). Incidence of CHV was low, less than 20%, at all sites and less than five when the percentage was corrected for age (Figure 5-1). No neoplasia was observed in any fish from any site.

Ulcer prevalence followed the same spatial and temporal pattern that had been observed in previous years. The syndrome appears in the early spring and apparently diminishes by the early summer. The etiology remains unknown.

MWRA has also noted that a biogeographic assessment of Stellwagen Bank, currently being conducted by NOAA, will report an increase in kidney disease in flounder from the area near Deer Island in 2004 as compared to fish collected in the same area in the 1980s. No similar disease was seen in fish collected near the outfall, and there was no consistent indication that incidence of the disease was correlated with chemical exposure. MWRA will evaluate these data as they become available.

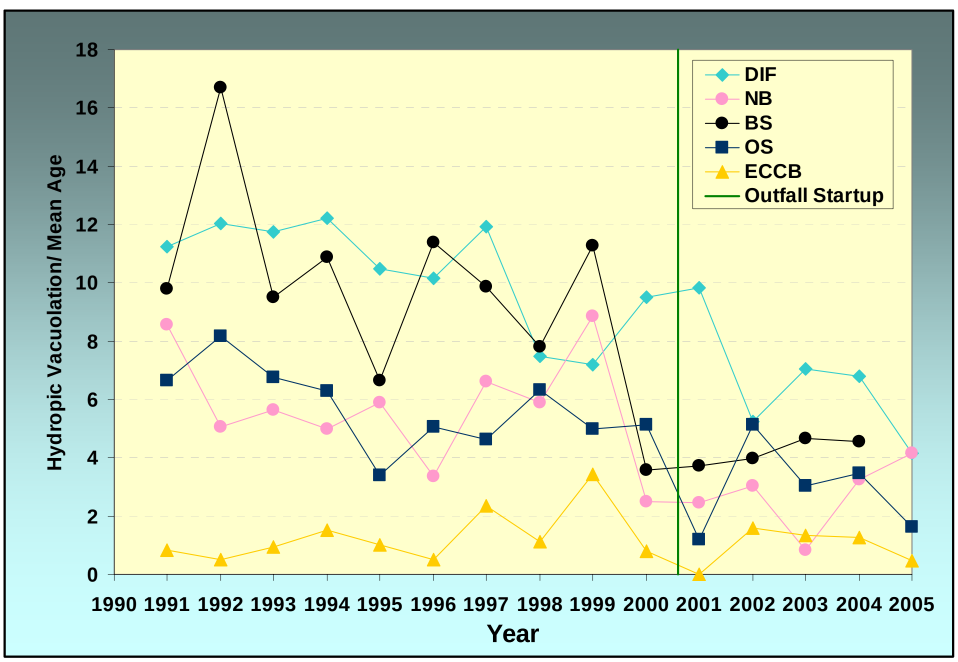

Figure 5-1. Prevalence of centrotubular hydropic vacuolation (CHV), corrected for age. (DIF = Deer Island Flats, OS = Outfall Site, ECCB = Eastern Cape Cod Bay, NB = Nantasket Beach, and BS = Broad Sound)

Contingency Plan Thresholds

Threshold parameters for fish and shellfish include levels of toxic contaminants in flounder, lobster, and mussels and liver disease in flounder; during 2005, only liver disease in flounder was tested (Table 5-3). Some thresholds are based on U.S. Food and Drug Administration (FDA) limits for maximum concentrations of specific contaminants in edible portions of food. Others are based on the baseline monitoring. Liver disease in flounder, measured as the percentage of fish exhibiting CHV, remained well below the baseline mean as well as caution and warning thresholds.

Table 5-3. Contingency Plan threshold values and 2005 results for fish and shellfish monitoring

Parameter Type/ Location	Parameter	Baseline	Caution Level	Warning Level	2005 Results
Flounder Nearfield	Liver disease (CHV)	24.4%	44.9%	None	8%

6. Special Studies

Background

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. During 2005, special studies included detailed analysis of the effluent, studies of nutrient flux at the sediment-water interface, marine mammal observations, water-quality modeling, studies related to the *Alexandrium* bloom or red tide, completion of a review of issues related to toxic contaminants, and completion of a summary report by USGS.

Effluent Analysis

The MWRA monitoring plan requires intensive monitoring of toxic contaminants in the final effluent in the Deer Island Treatment Plant, with lower detection limits than are usually required for NPDES permit monitoring. These specialized methods have allowed MWRA to detect relatively subtle changes in concentrations of contaminants in the effluent. Analysis of samples collected during the first five years of discharge to Massachusetts Bay have shown that none of the contaminants, with a possible exception of PCBs, have been present in concentrations that would result in exceeding water quality standards after 70:1 initial dilution, the dilution expected under near worst-case conditions of maximum effluent flow and strong stratification of the receiving waters (Tables 6-1, 6-2).

PCBs have not been detected in the effluent as Aroclor mixtures, the only PCB measurement for which the permit has set limits. However, a few congeners have been detected at low levels, with a median concentration of 1.4 nanograms per liter (parts per trillion). At an initial dilution of 70:1, these levels would translate to a concentration of 0.02 nanograms per liter in the receiving water, lower than but close to the current EPA recommended national water quality criterion of 0.064 nanograms per liter (EPA 2004). Interpretation of these PCB results is difficult, as there are no comparable data from the ambient water.

Table 6-1. Metals in final effluent from Deer Island Treatment Plant

Metal	Method*	Samples	Non-Detects	Detects (%)	Range (µg/L)	Median (µg/L)	Upper 95% Percentile (µg/L)	Lowest EPA Water Quality Criterion (µg/L)*
Aluminum	ICP	352	118	234 (66%)	24 – 860	78	191	None
Antimony	ICP	121	121	0 (0%)	<15 - <25			5.6 (HHC)
Arsenic	GFAA	124	120	6 (5%)	<0.8 – 1.2	<0.8		0.018 (HHC)
Beryllium	ICP	121	121	0 (0%)	<0.5			None
Boron	ICP	121	57	64 (53%)	<250 – 432	252	369	None
Cadmium	GFAA	417	56	361 (86%)	<0.03 – 0.39	0.089	0.198	8.8 (CCC)
Chromium	GFAA	417	51	366 (88%)	<0.70 – 8.1	1.0	1.96	50 (CCC) as Cr^{+6}
Copper	GFAA	161	1	160(99%)	<1 – 25	8.4	14.9	3.1 (CCC)
	ICP	458	142	316 (69%)	5.6 – 39.6	11.3	21.4	3.1 (CCC)
	ICP/MS	56	0	56 (100%)	5.6 – 21	10.2	16.3	3.1 (CCC)
Iron	ICP	144	0	144 (100%)	120 – 1090	355	618	None
Lead	GFAA	421	374	47 (11%)	<2.4 – 14.8	<2.4	3.52	8.1 (CCC)
	ICP/MS	31	1	30 (97%)	0.33 – 4.2	1.3	3.1	8.1 (CCC)
Mercury	CVAA	418	57	361 (86%)	<0.01 – 0.22	0.018	0.051	0.94 (CCC)
	CVAF	54	0	54 (100%)	0.0048 – 0.062	0.018	0.062	0.94 (CCC)
Molybdenum	GFAA	310	0	310 (100%)	2.1 – 28	7.2	13.8	None
Nickel	GFAA	421	1	429 (100%)	<0.7 – 7.3	2.9	4.9	8.2 (CCC)
Selenium	GFAA	121	121	0 (0%)	<0.9			71 (CCC)
Silver	GFAA	413	8	405 (98%)	<0.09 – 4.2	0.34	0.72	1.9 (CMC)
Thallium	GFAA	121	121	0 (0%)	<1			0.24 (HHC)
Zinc	ICP	428	0	428 (100%)	12 – 99	27.2	49.7	81 (CCC)

* See List of Acronyms on page 103; criteria from EPA 2004, based on salt water or human health criteria

Table 6-2. Pesticides, PAHs, and PCBs in final effluent from Deer Island Treatment Plant

Compound	Samples	Non-Detects	Detects (%)	Range (ng/L)	Median (ng/L)	Upper 95% Percentile (ng/L)	Lowest EPA Water Quality Criterion (ng/L)*
Total Chlordane	522	32	490 (94%)	0.24 – 58	2.25	8.25	0.80 (HHC) for Chlordane only
Alpha-Chlordane (SIM only)	221	0	221 (100%)	0.34 – 7.9	1.04	3.7	
Total DDT	510	77	443 (87%)	0.17 – 13	0.78	2.54	0.22 (HHC)
4,4'-DDE (SIM only)	199	0	199 (100%)	0.12 – 3.1	0.56	1.35	
4,4'-DDT (SIM only)	220	188	32 (14%)	0.17 – 11	0.40	1.47	
Gamma-BHC (Lindane)	638	386	252 (39%)	0.36 – 37	0.84	4.44	160 (CMC)
Gamma-BHC (Lindane) (SIM only)	221	175	46 (21%)	<0.5 – 37	0.51	4.54	160 (CMC)
Hexachlorobenzene (HCB)	638	495	143 (22%)	0.04 – 0.76	0.09	0.23	0.28 (HHC)
Hexachlorobenzene (HCB) (SIM only)	221	85	136 (62%)	0.04 – 0.63	0.09	0.17	0.28 (HHC)
Total PCB (SIM only)	268	0	268 (100%)	0.19 – 17.8	2.07	5.02	0.064 (HHC)
Chrysene	431	22	409 (95%)	3.18 – 334	13.5	52	3.8 (HHC)
Fluorene	431	74	357 (83%)	1.11 – 105	5.93	28	1,100,000 (HHC)
Total NOAA PAH	300	2	298 (99%)	10.8 – 3515	234	903	N/A

* See List of Acronyms on page 103; criteria from EPA 2004, based on salt water or human health criteria

Because flow from the treatment plant has been lower and the removal efficiencies of the treatment plant have been greater than had been projected during planning for the outfall, MWRA has recently updated loading estimates (Delaney and Hall 2006; Table 6-3). Estimates of annual loadings from the Deer Island Treatment Plant were first made for the EPA Supplemental Environmental Impact Statement (SEIS) prepared as part of the outfall-siting process (EPA 1988). Those estimates were based on presumed influent concentrations, which were based on the available analytical techniques at the time, many of which resulted in data that were "below detection limits." With better analytical detection limits, those estimates would have been less. Contaminant concentrations have also declined, in part because of MWRA's aggressive source reduction program, and also because changing technologies have reduced some contaminant concerns (*e.g.*, digital cameras have decreased the use of silver in photography). Sung and Higgins (1998) also projected loadings, based on limited early results from the treatment plant. The new estimates correspond to the average flow of 359 million gallons per day and 93% secondary effluent that have been observed over the first five years of outfall operation.

Table 6-3. Annual loading estimates (kilograms per year)

Parameter	**Projected (SEIS 1988)**	**Projected (Sung and Higgins 1998)**	**Mean Loading 2000-2005 (Delaney and Hall 2006)**
Cadmium	697	21	55
Chromium	3,517	490	648
Copper	11,945	14,000	6,588
Lead	4,961	2,400	850
Mercury	216	50	12
Molybdenum		6,800	3,743
Nickel	8,926	2,400	1,534
Silver	299	620	207
Zinc		14,000	16,318
Total PCB	50	4.8	0.91
Total PAH		1,400*	112+
Total DDT		0.67	0.46
4,4'-DDT (only)	28		0.37
Total Chlordanes		0.48	0.86
Heptachlor (only)	10		0.20

Marine Biological Laboratory scientists collect sediment samples to measure nutrient flux.

Nutrient Flux

One concern about the outfall was that increased loads of organic matter might enhance benthic respiration and nutrient fluxes between the sediments and the water column in the nearfield. The resulting higher rates of benthic respiration or sediment oxygen demand might lead to lower levels of oxygen in both the sediments and the water column. The monitoring plan required a special study to measure the organic matter loads, sediment oxygen demand, denitrification, and the flux of nutrients in the vicinity of the outfall to assess the importance of these processes (Table 6-4). Comparable studies take place in Boston Harbor.

Table 6-4. Monitoring questions related to nutrient flux

Are natural/living resources protected? *How do the sediment oxygen demand, the flux of nutrients from the sediment to the water column, and denitrification influence the levels of oxygen and nitrogen in the water near the outfall?* *Have the rates of these processes changed?* ▪ Will increased water-column and benthic respiration contribute to depressed oxygen levels in the water? ▪ Will increased water-column and benthic respiration contribute to depressed oxygen levels in the sediment? ▪ Will enrichment of organic matter contribute to an increase in benthic respiration and nutrient flux to the water column?

In 2005, monitoring of three sites in the nearfield and one site in Stellwagen Basin continued to show little or no indication of any effect of the outfall discharge (Tucker *et al.* 2006). Rather, the overriding influence on benthic nutrient cycling was the effect of the May northeast storms and the late October storm. Total organic carbon levels were lower than usual, probably because of scouring of surface sediments during the storms. Inventories of surface pigments also decreased, and rates of sediment oxygen demand and dissolved inorganic nitrogen flux were low. Phosphate fluxes were nearly undetectable.

Studies also continued at the four Boston Harbor stations, where the storms were also the major events affecting the benthos. Physical disturbance scoured the sediments and flushed porewaters, preventing formation of the *Ampelisca* amphipod mats, which had been important to the biogeochemistry of the harbor. (See Section 7, Boston Harbor Studies, for additional discussion of the *Ampelisca* tube mats.) Sediment oxygen demand and nutrient fluxes were the lowest observed in the monitoring program. The large variability between stations and years that existed early in the monitoring program has largely disappeared.

Prior to the outfall diversion, Boston Harbor had high rates of sediment oxygen demand compared to those in other coastal systems (Figure 6-1). During the post-diversion years, the rates in the harbor have progressively declined to levels lower than many estuaries, while the rates in Massachusetts Bay have not increased. The improvements in Boston Harbor with corresponding lack of change in Massachusetts Bay is one measure of the success of the Boston Harbor clean-up.

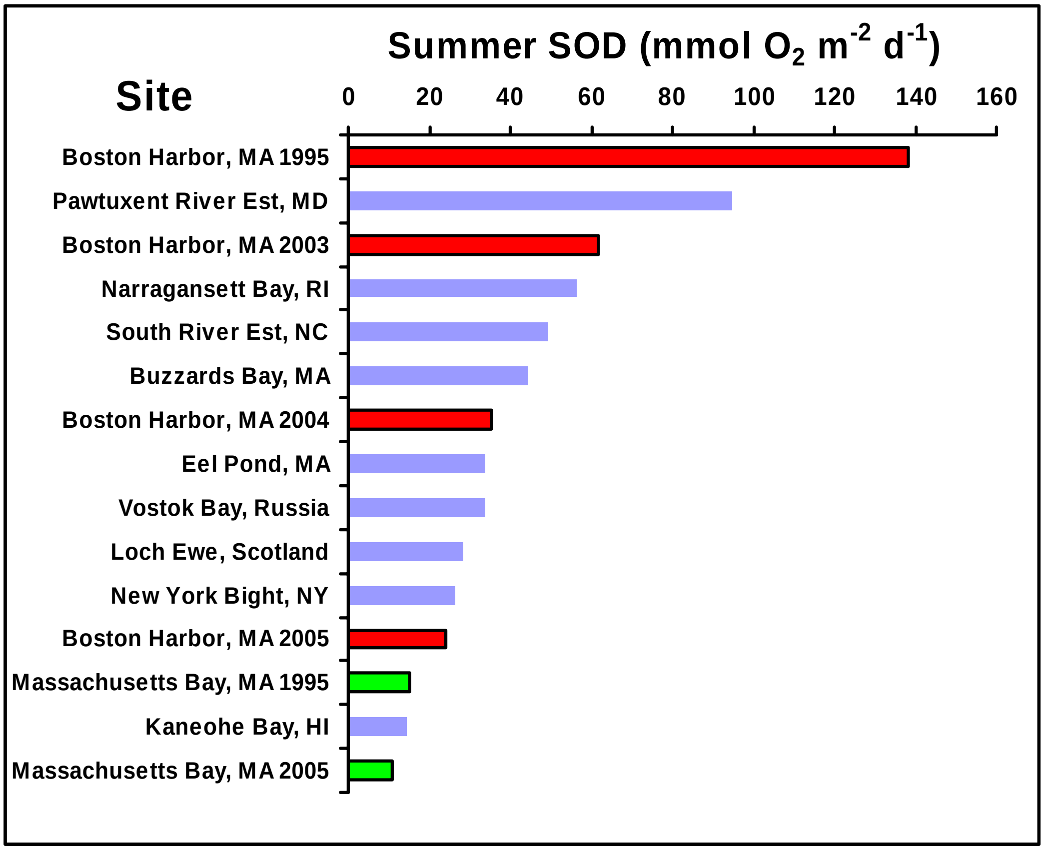

Figure 6-1. Sediment oxygen demand in Boston Harbor and the nearfield of Massachusetts Bay during pre- and post-diversion periods compared to other coastal ecosystems. Data for Boston Harbor and Massachusetts Bay are July-October averages; data for the other systems are summer rates from Nixon 1981

Marine Mammal Observations

Several endangered or threatened species of whales and turtles visit Massachusetts and Cape Cod bays, including the right, humpback, finback, sei, and blue whales. The minke whale, harbor porpoise, gray seal, harbor seal, and several species of dolphins, which are not endangered but are protected, also occur.

Since 1995, MWRA has included endangered species observers on monitoring surveys. In 2005, observers were included on twelve nearfield water quality surveys and three farfield surveys (Short and Michelin 2006). Besides providing observational data, the presence of trained marine mammal observers addresses a request by the National Marine Fisheries Service (NMFS) that MWRA take active steps to minimize the chances of a collision of one of its survey vessels with a right whale.

The surveys are not designed to determine possible effects of the outfall on marine mammals, but do provide some general information. During the 2005 surveys, about 30 individual whales, about 20 harbor porpoise, one unidentified porpoise, and a small pod of Atlantic white-sided dolphins were directly observed by the trained observers and other members of the monitoring team. Whale sightings were concentrated within Massachusetts Bay. The total number of whales sighted was higher than in those seen in 2002 through 2004. Records of the Whale Center of New England (www.whalecenter.org) also indicated an increase from the sparse sightings they had reported in 2004. They reported numerous fin whales and a group of approximately about 15 humpback whales during the summer months. Sei whales and right whales were reported during late July and early August.

During April, there were numerous reports of a humpback whale within Boston Harbor (Figure 6-2). The whale appeared to be feeding on schooling smelt and herring.

Figure 6-2. Humpback whale sighted near the Deer Island Treatment Plant in April 2005

Model Results

MWRA has used numerical models to simulate and predict the physical and biological conditions in Massachusetts Bay. A hydrodynamic model was developed by USGS (Signell *et al*. 1996) and a water quality model, known as the Bays Eutrophication Model (BEM), was developed by

Hydroqual, Inc. (2000) for MWRA. Working now with the University of Massachusetts Boston, MWRA continues to maintain, enhance, and apply the models (Jiang and Zhou 2004a, 2004b, 2006a, 2006b).

In September 2005, MWRA and the modeling team met with OMSAP's Model Evaluation Group (MEG), to present recent results and discuss future directions for the modeling effort. It was the first time that the MEG had convened since 2002. Among other findings and recommendations, the MEG expressed overall satisfaction with the modeling efforts, finding that the level of agreement between model results and observations seemed reasonable and typical. A list of questions, comments, and recommendations concerning future modeling efforts, improvements to model validity and presentation, and assessment measures was developed. These recommendations will be used by the permitting agencies to determine what, if any, continued modeling requirements will be included in MWRA's new NPDES permit. (The existing permit expired in 2005; the conditions of that permit continue until a new one is issued.)

2005 *Alexandrium* Bloom

During May-July 2005, an extensive bloom of *Alexandrium fundyense* (and *Alexandrium tamarense*, which scientists consider to be a variant of the same species) occurred along the coast of southern New England, eventually closing shellfish beds from central Maine to Massachusetts and resulting in the closure of 40,000 km^2 of offshore federal waters (Figure 6-3). *Alexandrium* is one of the nuisance algae of concern in water column monitoring, because it produces a toxin that can build up in shellfish to levels that can cause paralytic shellfish poisoning (PSP) in birds, marine mammals, and humans that eat the affected shellfish. *Alexandrium* blooms, known as red tides, have sporadically caused shellfish bed closures in Massachusetts Bay since 1972, when a strong bloom was first observed. PSP toxicity was not observed in Massachusetts Bay from 1994 to 2004.

The 2005 bloom was exceptional in several ways: high toxin levels were measured farther south than ever before in New England; levels of toxicity in many locations were higher than previously observed at those stations; for some locations, toxicity was above quarantine levels (levels high enough to close the shellfish beds) for the first time; and cell concentrations far exceeded those observed in the coastal waters of southern New England in the past.

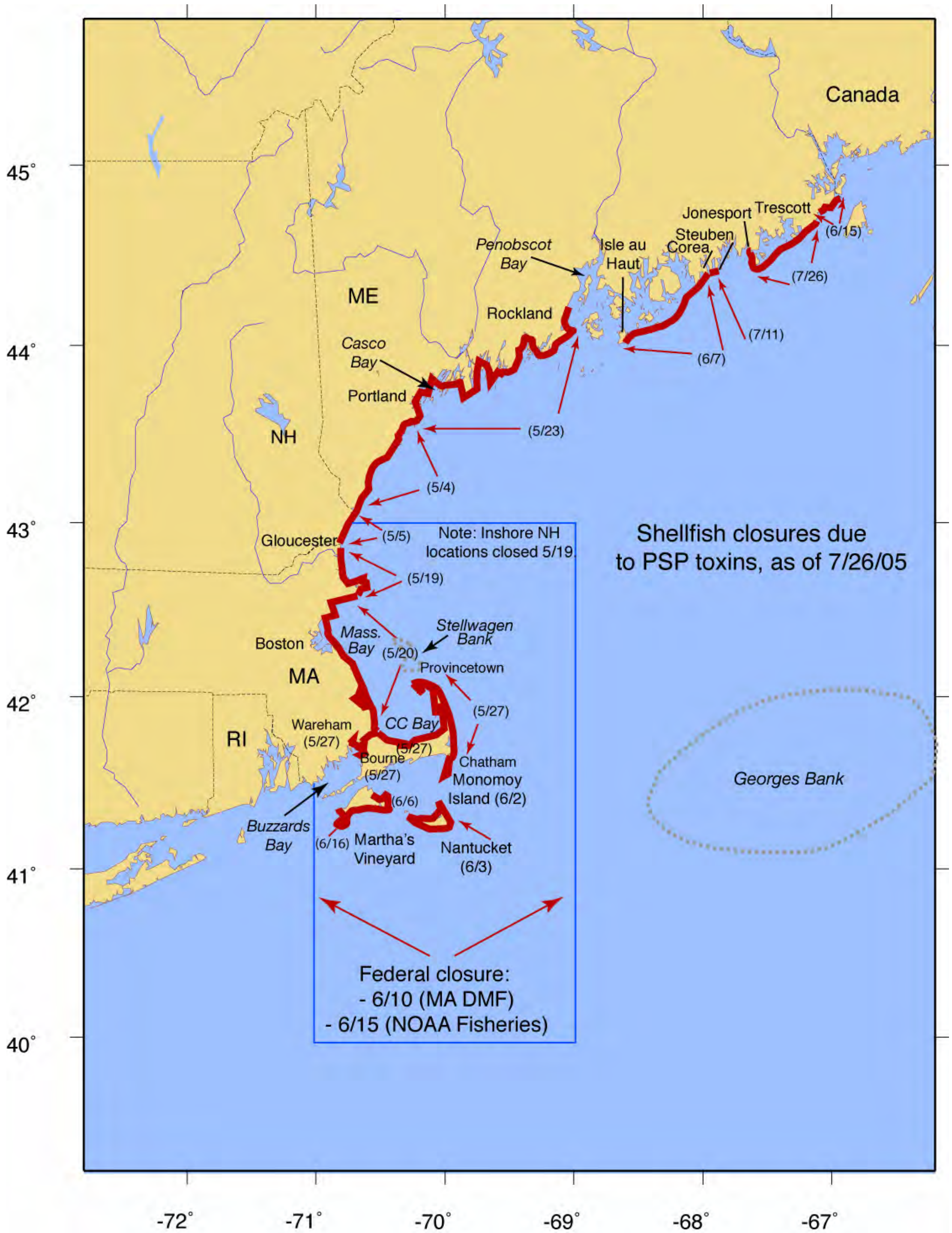

Figure 6-3. Geographic extent of shellfish bed closures in July 2005; initial dates of closure at each station shown in parentheses (figure courtesy of Don Anderson, Woods Hole Oceanographic Institution)

MWRA participated in a region-wide collaborative monitoring effort intended to help understand the scale and duration and to evaluate the causes of this unprecedented red tide. The monitoring showed that a large spring bloom developed in the coastal waters of Maine, where there were known *Alexandrium* cyst seedbeds. This bloom moved south with stronger-than-usual coastal currents, a result of high spring runoff from large rivers in Maine, and was transported into Massachusetts and Cape Cod bays and to waters south of the Cape by the two strong northeast storms that occurred in May.

The causes and effects of the bloom have continued to be evaluated. OMSAP held a meeting to review the bloom in August 2005, and in April 2006, MIT Sea Grant convened a symposium on the bloom. The high abundance of newly deposited cysts in the western Gulf of Maine is now thought to be the main cause of the bloom. A major concern was that the 2005 event could result in formation of similar seedbeds in Massachusetts Bay or further south in Nantucket Sound. That concern has not been realized, as sampling after the bloom found that cysts were only sparse in Massachusetts sediments. Dense seedbeds have persisted in the western Gulf of Maine.

The MWRA outfall is not suspected to be a factor in the region-wide size or extent of this bloom. Localized effects of the outfall were possible but have not been measured; there is no indication of any stimulation or prolongation of the bloom in the area of the outfall.

MWRA has developed a standing survey plan for monitoring *Alexandrium* (Libby 2006) to respond quickly to rapidly developing red tides. The survey plan is designed to supplement regular outfall monitoring. It provides a stepwise approach, with triggers that determine the appropriate level of response.

Toxic Contaminants Review

During 2005, MWRA prepared a review of issues associated with toxic contaminants in Boston Harbor and Massachusetts Bay (Hunt *et al.* 2006). The report made several findings:

- Contaminants in Boston Harbor and Massachusetts Bay have a historical legacy dating from the Civil War and subsequent industrial development that peaked in the post World War II era, but contaminant levels are decreasing in response to regulatory actions.
- MWRA actions to reduce sources and improve treatment have significantly reduced loading to the system. Current annual loads are significantly less than those that had been projected during the 1980s.

- MWRA and regulatory actions have substantially reduced contaminant levels in surface sediments in Boston Harbor, while only minimally affecting sediments in Massachusetts Bay.
- There has been decreased incidence of tumors in flounder and lowered contaminant levels in fish and shellfish for some contaminants. Levels of mercury and silver in flounder and lobster taken near the outfall have increased but are still low.
- Processes related to contaminant transport, fate, and bioavailability are becoming sufficiently understood to make judgments about future responses.
- Emerging contaminants of concern, such as endocrine-disrupter compounds and brominated flame retardants, are potentially important and should be understood in anticipation of possible regulatory actions over the next decade.
- The current knowledge base is sufficient to allow reduced monitoring but not to eliminate it.

USGS Studies

During 2005, the USGS completed a major review of the processes that influence transport and fate of contaminated sediments in Boston Harbor and Massachusetts Bay (Bothner and Butman 2005, available at http://pubs.usgs.gov/of/2005/1250/). USGS has conducted research in the region since the 1970s and expanded its program in 1989, with the beginnings of the Boston Harbor Project. Their focus is on several components related to sediment contamination and transport:

- **Sea-floor mapping.** Using sidescan sonar, high-resolution multibeam echosounding, seismic reflection profiling, sediment sampling, and bottom photographs and video, the USGS has developed fine-resolution maps of the region (Butman *et al.* 2004; Figure 6-4). The maps can be used to locate sediment types, define depositional regions, and study the effects of human activities, such as waste disposal and bottom trawls.
- **Currents and sediment-transport measurements and modeling.** USGS has made almost continuous measurements of temperature, salinity, currents, pressure, light transmission, and bottom characteristics from arrays of moored instruments. The measurements have been complemented by major modeling efforts. For example, USGS has used computer models (Signell and Butman 1992, Signell *et al.* 2000) to study flushing of Boston Harbor, provide input to a bay-wide water-quality model, and predict the dilution of effluent discharged from the outfall. Recently, USGS has coupled the circulation model with a sediment-transport model to examine the effects of storms on the transport of sediments in Massachusetts Bay.

- **Geochemical measurements and database.** Sediment samples collected three times per year near the outfall have been used to determine temporal trends in concentrations of metals and spores of the sewage tracer bacterium *Clostridium perfringens*. USGS has also sampled sediments from Boston Harbor and throughout Massachusetts Bay and has conducted special studies of geochemical processes. The work has highlighted the importance of erosion and resuspension of deeply buried particles as a continuing source of contamination to the region.

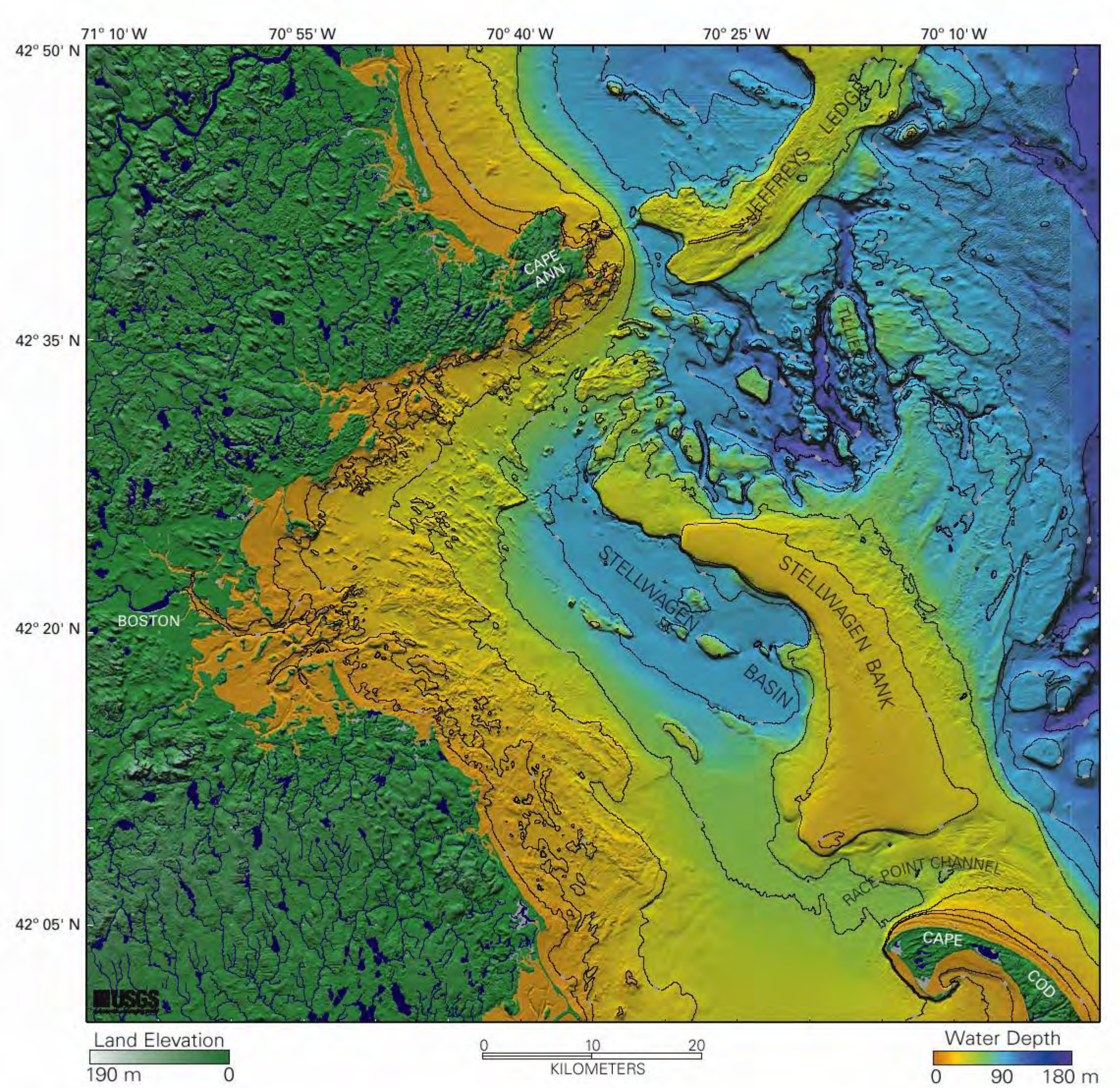

Figure 6-4. USGS map of the topography of Massachusetts Bay in shaded relief view, colored by water depth

USGS will continue to interpret and synthesize data and to refine and expand the application of sediment-transport modeling. Work is also underway to study the release of metals from the sediments to the overlying water and to evaluate the potential of using mollusk-shell growth rings as recorders of historic metals concentrations in the water column.

7. Boston Harbor Monitoring

Background

The goal of the Boston Harbor Project was to improve the quality of Boston Harbor without degrading Massachusetts Bay. This outfall monitoring overview generally focuses on Massachusetts Bay and the Contingency Plan thresholds that were established to ensure that there would be no unanticipated effects of the outfall. There has also been extensive monitoring in Boston Harbor; this section presents some of the results that were reported during 2005.

Wastewater Loads and Eutrophication

Large changes in the water quality of Boston Harbor have been observed through the duration of the Boston Harbor Project. Concentrations of the nutrients most responsible for eutrophication have declined, as have standing stocks of phytoplankton and concentrations of particulate organic mater. The harbor has shown increases in concentration of dissolved oxygen in bottom waters and lowered counts of pathogen-indicator bacteria (Taylor 2004, 2006).

Recently, MWRA has analyzed historical data to determine whether relationships exist among these observed changes and the decreases in the wastewater loadings to the harbor (Taylor 2005a, 2005b, 2006). The analysis has shown strong relationships between the annual loadings and the annual average concentrations of the dissolved and non-dissolved inorganic fractions of total nitrogen in the harbor water samples (Figure 7-1). During the first four years after the direct wastewater discharges to the harbor were ended, nitrogen concentrations were the lowest observed (these four years are indicated by the ellipses on the figure).

NITROGEN CONC. VS LOADINGS

TN conc = 15.07 + (0.010 x TN loadings), r^2 = 0.94, p = <0.01

DIN conc = 2.33 + (0.009 x DIN loadings), r^2 = 0.86, p = <0.01

Non-DIN conc = 12.82 + (0.011 x Non-DIN loadings), r^2 = 0.74, p = <0.01

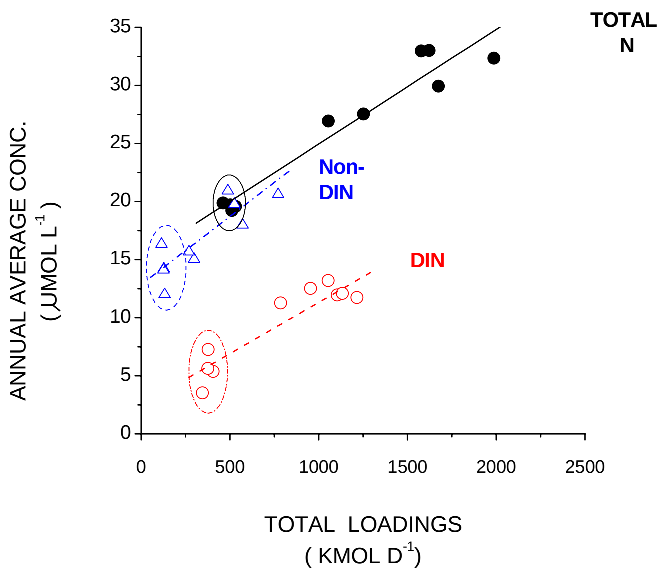

Figure 7-1. Relationships between total annual loads and nitrogen concentrations in the water column in Boston Harbor. Ellipses indicated years after MWRA treatment plant discharges to the harbor ended. TN=total nitrogen, DIN=dissolved inorganic nitrogen

For annual average concentrations of chlorophyll, a measure of phytoplankton biomass, the relationship was not quite as robust (Figure 7-2). This result is to be expected for a biological variable. During three of the four years after the direct treatment plant discharges to the harbor were ended, however, average chlorophyll concentrations were lower than in previous years.

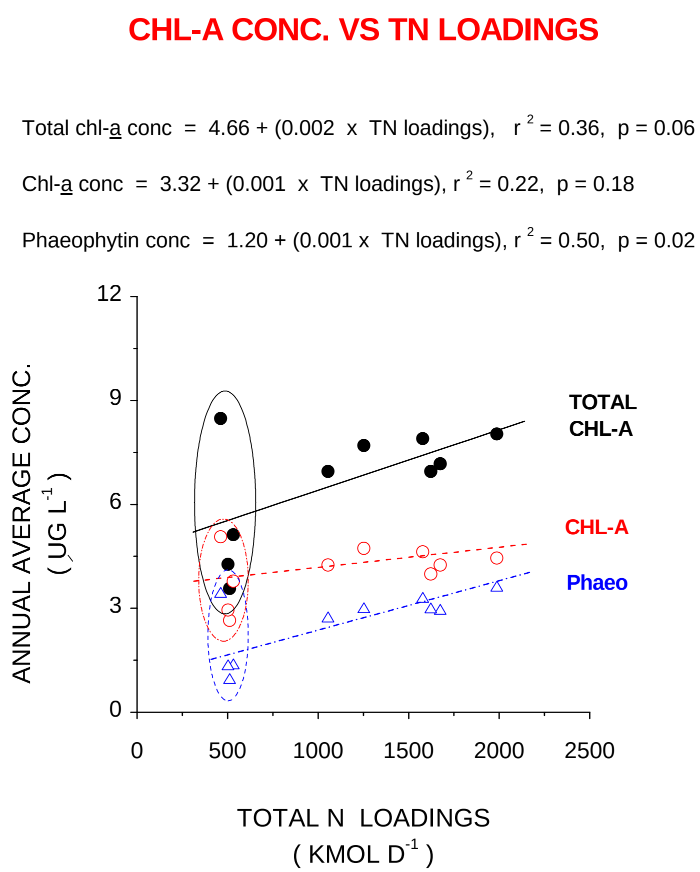

Figure 7-2. Relationships between total loads and chlorophyll. Ellipses indicate years after MWRA treatment plant discharges to the harbor ended. CHL-A=total chlorophyll a, "active" or acid-corrected chlorophyll a; Phaeo="degraded" chlorophyll or phaeophytin

Water Quality Monitoring: Tributary Rivers

MWRA monitors water quality at more than 50 stations in Boston Harbor and its major tributaries, the Charles, Mystic, and Neponset rivers. One major goal of the monitoring is to assess the effects of MWRA's combined sewer overflow (CSO) control plan (MWRA 1997c) on the waterbodies affected by CSOs. By the end of 2005, 63 CSOs remained active within Boston Harbor and its tributaries; 21 have been closed since the early 1990s. The annual volume of flow has decreased from more than three billion gallons per year in the late 1980s to about one half billion gallons per year (Figure 7-3).

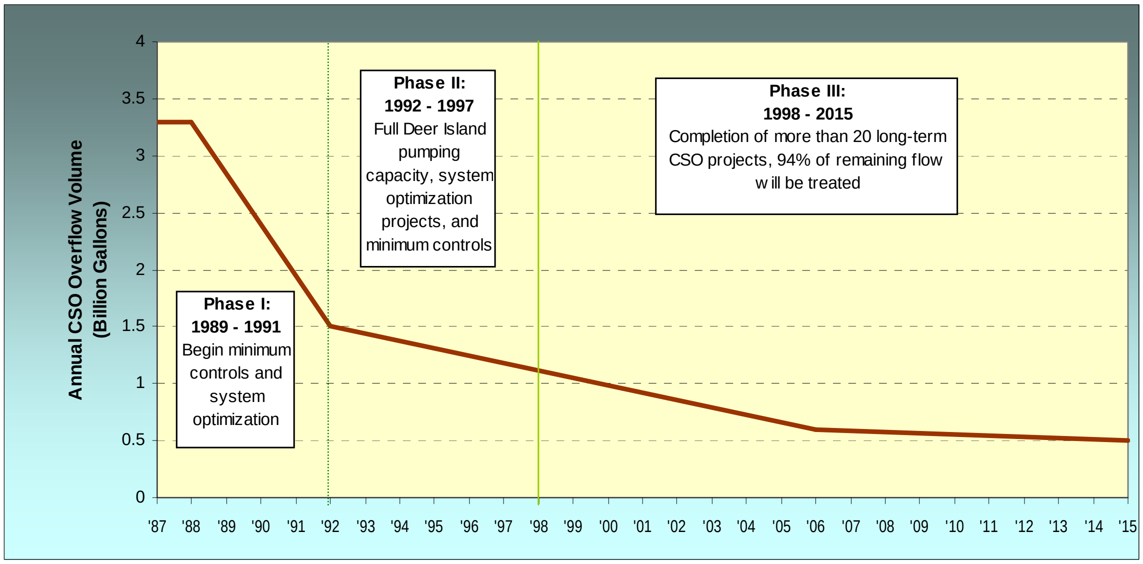

Figure 7-3. Impact of CSO control plan on system-wide CSOs

Monitoring is conducted year-round with the most intensive sampling occurring during the spring and summer. Testing focuses on bacteria and parameters related to eutrophication. A recent report (Coughlin 2006) summarized information from the Charles River, the Mystic River, and the major tributary to the Mystic River, Alewife Brook.

MWRA samples in the Charles River from the Watertown Dam downstream to the New Charles River Dam in Boston. Stations are located so that they bracket 12 CSO outfalls along the river in Cambridge and Boston. Contaminants also enter the river from upstream sources, a brook near Kenmore Square, and illicit connections to storm drains, many of which have been identified and eliminated. In general, water quality is poorest at upstream locations, improving as the river widens and slows. Dissolved oxygen concentrations follow the opposite pattern, worsening downstream, due to summer stratification. Seawater leaking through the Charles River locks contributes to the strong seasonal stratification and consequent low levels of dissolved oxygen in the bottom water.

There have been noticeable improvements in the Charles River since MWRA implemented the long-term CSO plan. Average bacteria counts during heavy rain, when the river is affected by contaminated stormwater and CSO, have decreased substantially; there have also been noticeable decreases during dry weather and light rain, when illicit connections and contaminated storm water have the largest effects because the CSOs typically only discharge in heavy rain (Figure 7-4).

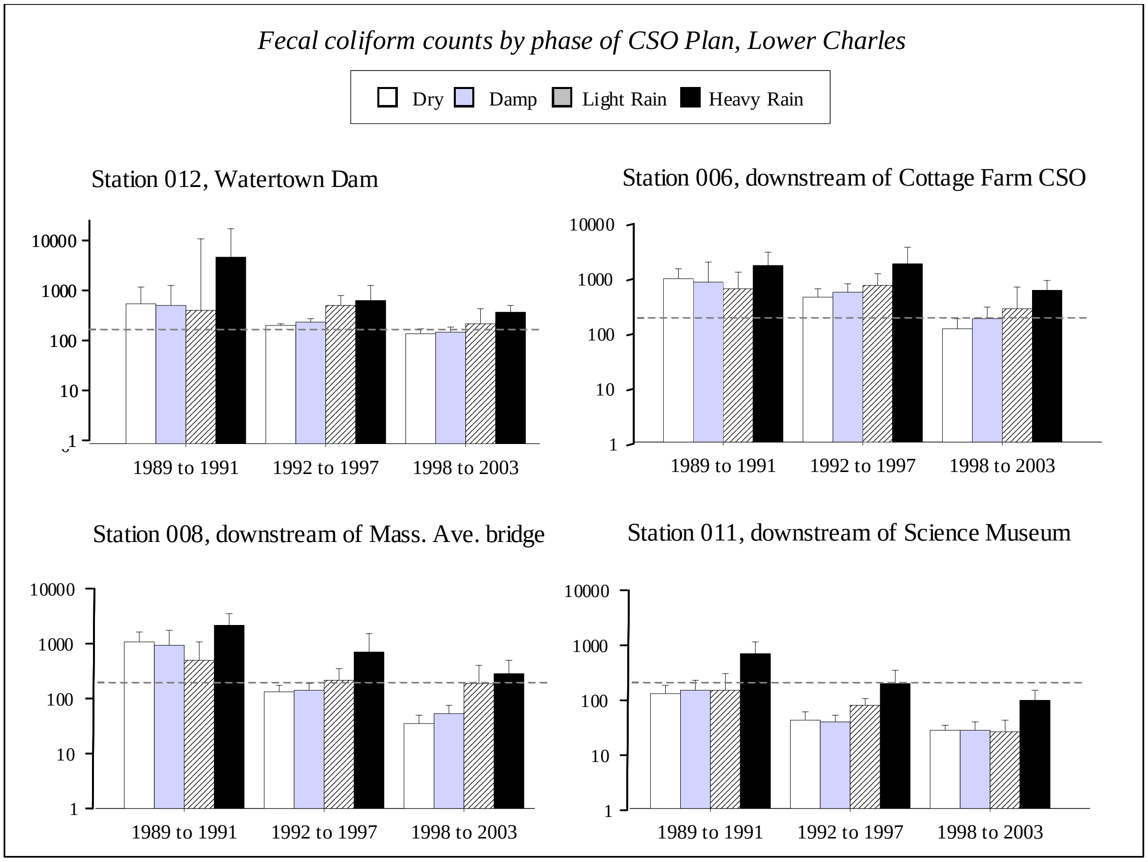

Figure 7-4. Average fecal coliform counts in different weather conditions and during phases of MWRA's CSO control plan at four locations in the lower Charles River. Dotted line indicates 200 fecal coliform/100 ml, the swimming standard. (Note log scale.)

The Mystic River and Alewife Brook are affected by nine CSOs and runoff from many storm drains in Cambridge and Somerville. Alewife Brook is the primary source of bacterial contamination to the lower Mystic River. Bacteria counts in Alewife Brook frequently fail to meet standards; water clarity and dissolved oxygen conditions are also poor. In the lower portions of the Mystic River, however, bacteria counts meet standards even during heavy rains, an improvement that has occurred since the 1990s.

Nutrients, especially phosphorus, affect the water quality of both the Charles and Mystic rivers, particularly in the lower reaches where dams prevent the free flow of water, the rivers broaden, and flow rates decrease. In the summer, high nutrient loads entering from upstream, combined with low flow, warm temperatures, and sunlight, contribute to excess levels of algae (measured as chlorophyll) in the downstream reaches of the rivers (Figures 7-5, 7-6).

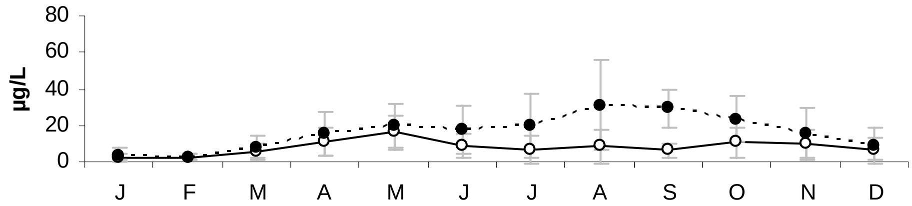

Figure 7-5. Average monthly Charles River chlorophyll levels at Watertown Dam (upstream, open circles) and Museum of Science stations (river mouth, black circles), 1998-2003. Summer chlorophyll levels in the downstream Charles are typically elevated above 25 µg/L, which indicates algal overgrowth.

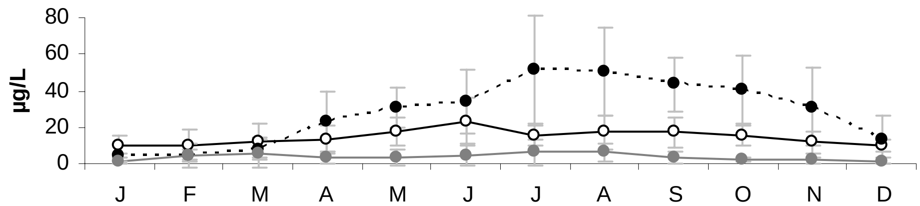

Figure 7-6. Average monthly Mystic River chlorophyll levels at (upstream at Alewife confluence, open circles) river mouth, (black circles) and inner harbor (gray circles), 1998-2003. Summer chlorophyll levels in the downstream Mystic River are typically extremely high, well above 25 µg/L, which indicates excessive algal growth.

Effects of Rain on Bacteria: Boston Harbor Beaches

MWRA monitors bacterial indicators not only in the tributaries to Boston Harbor, but also at harbor beaches (Figure 7-7). During the years of the Boston Harbor Project, flows of untreated water from CSOs have declined significantly, yet additional improvements remain to be made. Several CSO projects are underway, including a storage tunnel to collect combined sewage and stormwater that would otherwise discharge to South Boston beaches and elimination of other CSOs in Dorchester Bay by constructing separate sewers for stormwater and sewage. Beaches continue to be closed due to increased levels of indicator bacteria after rainstorms wash contaminated stormwater, sometimes combined with sewage, into the harbor.

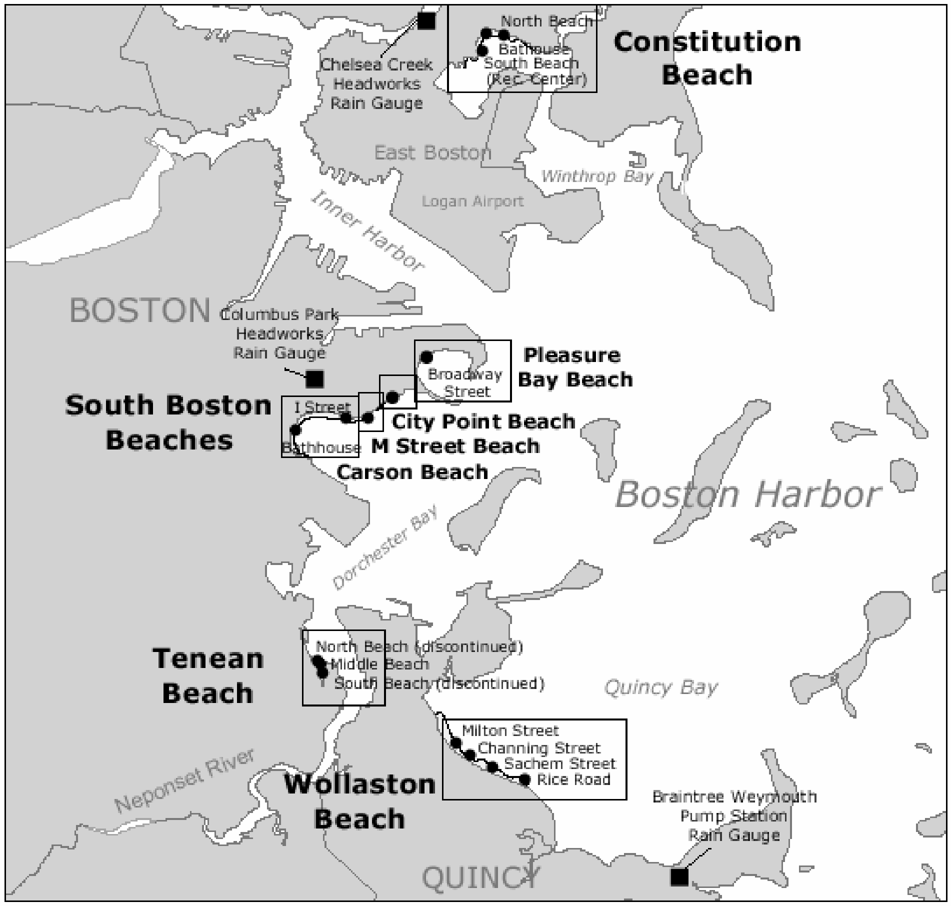

Figure 7-7. Boston Harbor beach monitoring stations

These continued improvements to the CSO system and elimination of sewage contamination of stormwater are the most important actions that communities and MWRA are taking to ensure that waters are safe for swimming and boating. Together with the Harvard School of Public Health, MWRA has also been developing better tools for assessing water conditions. Bacteria enumeration requires at least 24 hours, but rainfall can be known in real time. Therefore, a statistical tool called receiver operating characteristic (ROC) curve analysis has been used to quantify the relationships between rainfall and bacteria indicators (Morrison 2005, Morrison and Coughlin 2005) to more accurately assess beach conditions. ROC curves are generated from “true positive” and “false positive” rates, with the best indicators having high true positive and low false positive rates.

ROC curve analysis of rainfall and bacteria monitoring data collected from Boston Harbor beaches in 1996-2004 enabled the development of rainfall thresholds for posting swimmers’ advisories (Morrison and Coughlin 2005). Although no rainfall threshold produced an ideal result of 100% true positive and 0% false positive rates, rainfall was a superior predictor of beach water quality than the "previous day's" bacteria results. The thresholds are being used by the Department of Conservation and Recreation to "presumptively" post beaches after rainstorms rather than waiting a day for the bacteria data.

Similarly, MWRA has characterized the water quality of Alewife Brook and the Mystic River, which lie at the boundary of Cambridge, Somerville, and Arlington, and which continue to be affected by stormwater and by discharge through CSOs. Those studies found a strong relationship between antecedent rain and increased indicator bacteria levels.

ROC curve analysis indicated that the most downstream station in Alewife Brook provided the best indicator of bacteria levels following storms (Morrison 2005). At this station, 0.27 inches of rain occurring within three days prior to sampling predicted levels of the indicator bacteria *E. coli* high enough to exceed the boating standard 75% of the time. The study found that each sampling location responded to rainfall differently, so that the ability to use rainfall as a real-time indicator of bacteria levels varies by location.

Changes in the Sediments

At the onset of the Boston Harbor Project, portions of the harbor contained sediments with high levels of contamination. Some areas of the Inner Harbor were nearly devoid of life, although the Outer Harbor had areas with diverse, bottom-dwelling communities.

Sediment samples from Boston Harbor have been regularly collected for chemical analysis since 1991. Surface sediments have been analyzed for the sewage tracer bacterium *Clostridium perfringens* spores and for contaminants, including PCBs, pesticides, PAHs, linear alkyl benzenes, and metals. The data have shown significant decreases in concentrations of the bacteria tracer and of the chemical contaminants. In the early 1990s, concentrations of *Clostridium perfringens* spores were high and variable (Figure 7-8, see Figure 7-9 for station locations). There was a mean of about 3,500 colony-forming units for each percent dry fine-grained sediment (cfu/g dw/% fines), the standard measurement unit, in the Outer Harbor. By 1998, concentrations of *Clostridium perfringens* spores throughout the harbor had declined to about 170 cfu/g dw/% fines.

Similarly, concentrations of PAHs, PCBs, DDTs, mercury, cadmium, and silver in the surface sediments have declined by 20 to 75% since 1994, depending on the chemical and the location within the harbor. Concentrations of silver (a sewage tracer) in the Inner Harbor declined 50% between 1994 and 2002, possibly because of a decline in photographic processes that use silver as well as due to improved treatment. In Dorchester Bay, concentrations of the pesticide DDT and its breakdown products declined 71% during the same period. In contrast, concentrations of lead and copper have not changed substantially, suggesting that there are sources other than sewage.

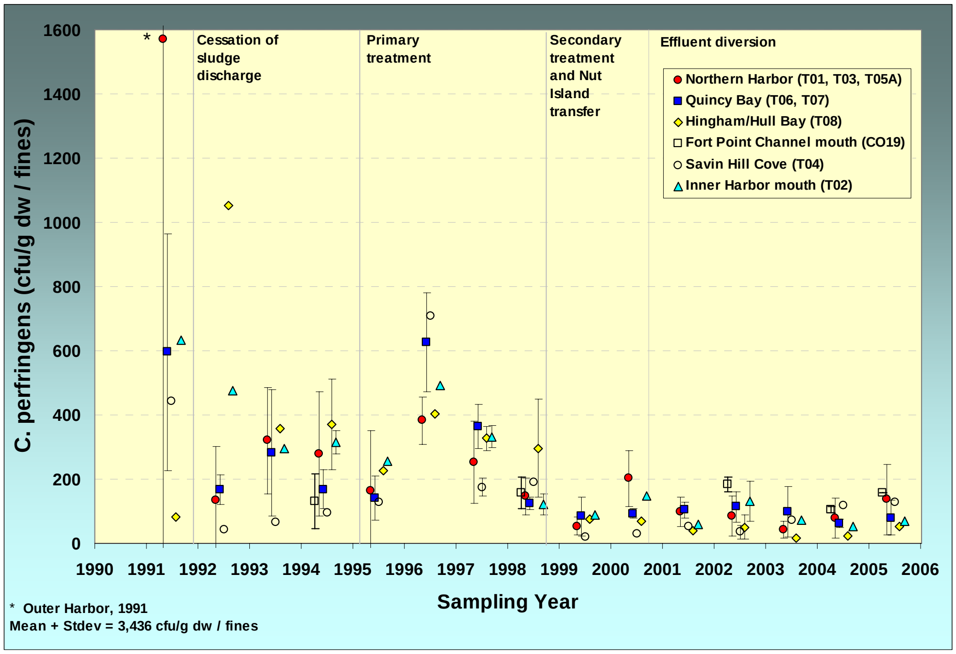

Figure 7-8. Yearly mean abundance of Clostridium perfringens *spores in Boston Harbor (Error bars represent one standard deviation.)*

Changes in the Benthic Community

In New England, the animals comprising a normal, nearshore, soft-sediment community include a variety of mollusks, arthropods, and worms. Areas of Boston Harbor that were affected by sewage had severely reduced numbers and types of animals, often dominated by pollution-tolerant worms. Changes in the bottom animal communities have been dramatic, as the communities responded to ending of sludge and effluent discharges and also to severe storms. These changes have been documented through collection and analysis of sediment grab samples, which have been collected during August of each year (from nine stations in recent years) within the harbor (Figure 7-9). Greater geographic coverage is achieved by taking sediment-profile images from 61 reconnaissance stations.

The changes in the bottom communities are not always evident from examining averages of standard community parameters. Since 1991, the total abundance of organisms has fluctuated (Figure 7-10, top). The species richness parameters, number of taxa and log-series alpha, increased when the Massachusetts Bay outfall went on line, but have since declined (Figure 7-10, middle and bottom). Dramatic improvements have been seen at some stations, such as Station T01 near Deer Island, where diversity is much higher, and Station T05A at the harbor mouth, which now supports many species that were previously found only in Massachusetts Bay.

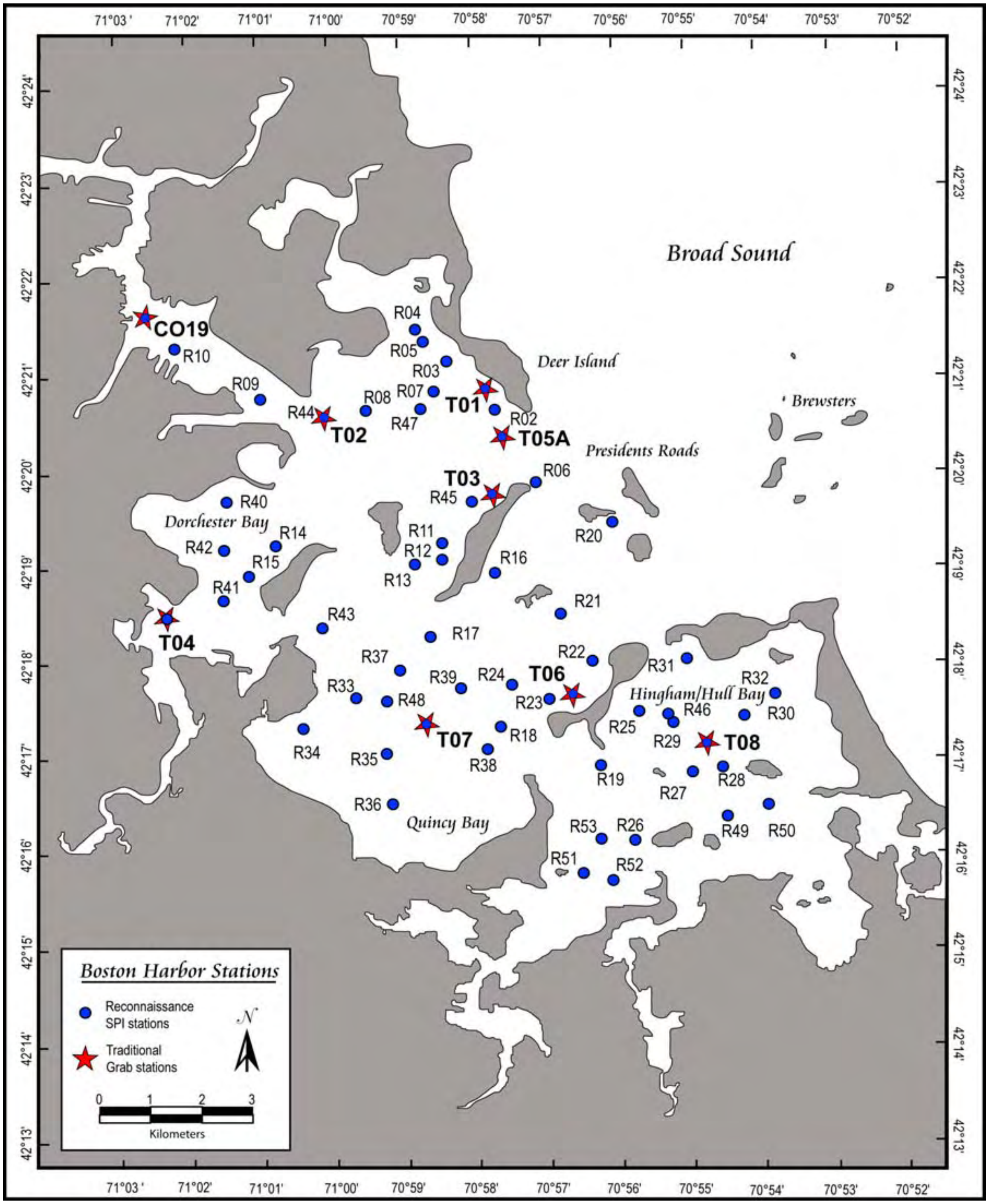

Figure 7-9. Locations of benthic stations within Boston Harbor

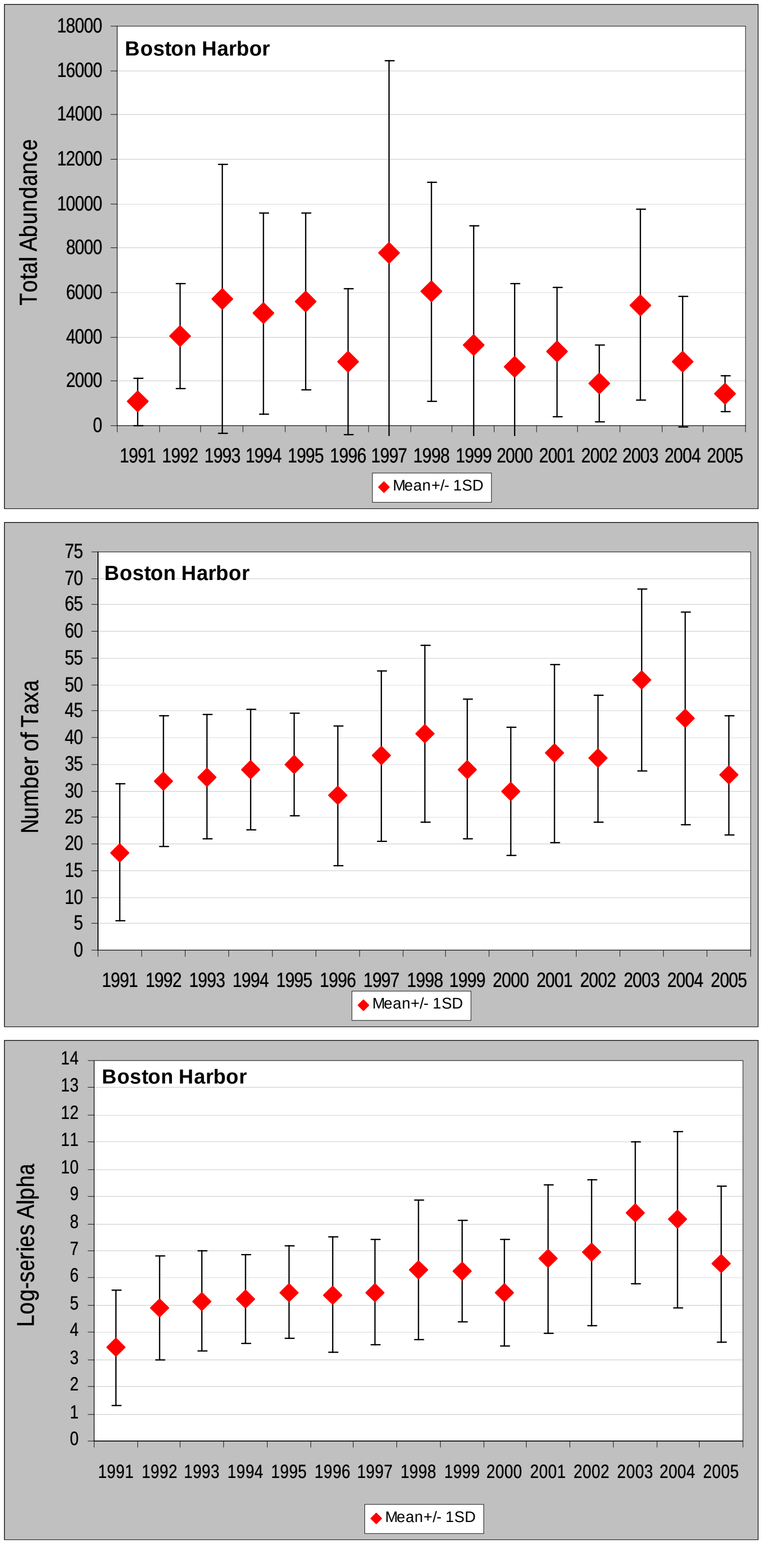

Figure 7-10. Benthic community parameters in Boston Harbor, 1991-2005. Parameters calculated from traditional grab stations: Top: abundance per sample, Middle: species richness (number species per sample), Bottom: species richness (log-series alpha)

The changes can also be demonstrated by examining the increase and subsequent decline in tube mats formed by the amphipods in the genus *Ampelisca*. In 1989 and 1990, MWRA found *Ampelisca* tube mats at only 24% of the stations sampled in the harbor. In October 1991, a major storm, immortalized as "The Perfect Storm," caused the highest storm surge in Boston Harbor in two decades, scouring soft (and contaminated) sediments from the sea floor. This scouring, coupled with the ending of sludge discharges to the harbor in December 1991, was followed by a surge in *Ampelisca*. By August 1992, more than 50% of stations in the harbor had tube mats.

Total number of *Ampelisca* increased through 1994 (Figure 7-11). The number of stations with mats increased through 1996, when more than 80% of the stations had tube mats. After the mid-1990s, the numbers of total *Ampelisca* appeared to be declining, only to increase again in 2003 and decrease in 2004. It was expected that these fluctuations would continue, that they were normal successional changes such as would be expected in the healthier, cleaner environment.

However, the severe storms that occurred in May 2005 interrupted the usual seasonal pattern of amphipod growth, and only 616 *Ampelisca* individuals were found in the harbor samples (compared to 73,112 in 2003). Existing mats had been broken apart and washed away. Changes in the surface sediments were observed in the sediment-profile images (Figure 7-12) and in the benthic grab samples. Scientists are unsure whether *Ampelisca* will ever return in high numbers or whether a new community will be established.

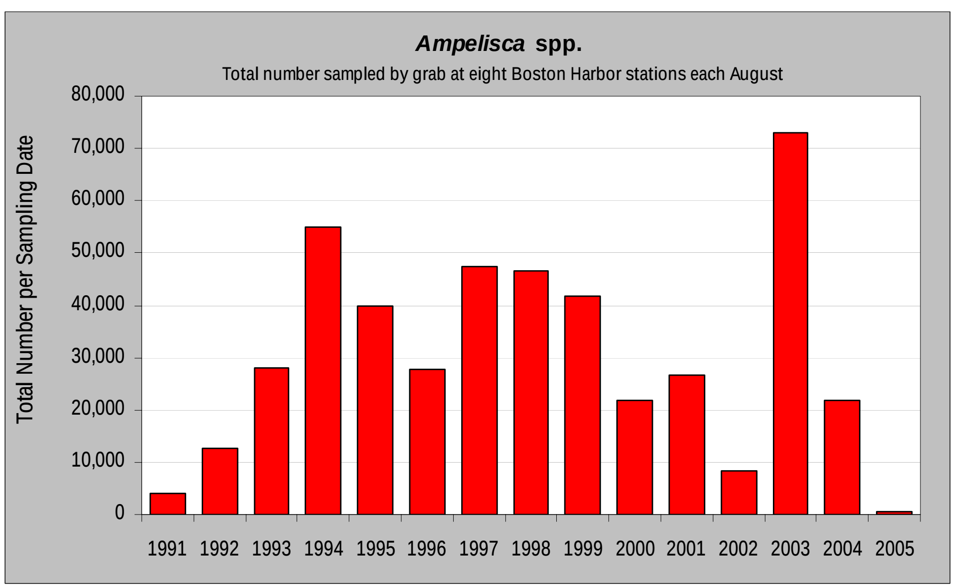

Figure 7-11. Total number of Ampelisca *per sample, 1991-2005*

Figure 7-12. Photographs from the same station (R28) in Hingham Harbor in 2004 (top) and 2005 (bottom). Note amphipod tube mats in 2004 photograph.

8. Stellwagen Bank National Marine Sanctuary

Background

The Gerry E. Studds Stellwagen Bank National Marine Sanctuary (SBNMS) comprises 842 square miles located at the boundary between Massachusetts Bay and the rest of the Gulf of Maine. Its landward boundaries lie approximately 25 miles east of Boston, three miles north of Provincetown, and three miles south of Gloucester. Stellwagen Basin, which is partially within the sanctuary, is the deepest part of Massachusetts Bay and a long-term sink for fine-grained sediments. Stellwagen Bank, a sand-and-gravel plateau, lies to the east of Stellwagen Basin and has water depths of about 65 feet. Tidal mixing of nutrients throughout the relatively shallow water column creates a rich habitat for marine life on Stellwagen Bank.

MWRA's discharge permit recognizes concerns about possible effects of the outfall on the sanctuary and requires an annual assessment of those possible effects.

Monitoring Design

MWRA's regular water-column and sea-floor monitoring efforts include stations within and near the sanctuary. Five water-column stations, including four within the sanctuary and one just outside its northern border, are considered "boundary" stations, because they mark the boundary between Massachusetts Bay and the rest of the Gulf of Maine. These stations are important to MWRA, not just because of their location within a marine sanctuary, but also because water-column processes within Massachusetts Bay are largely driven by the regional processes in the Gulf of Maine. Eight water-column stations located between the sanctuary and the coast are considered "offshore" stations by the MWRA program.

Since 2001, the sanctuary managers, in conjunction with MWRA's contractor Battelle, have conducted a monitoring program which added four stations to the August and October MWRA surveys (Figure 8-1). These sites were selected to provide a more comprehensive evaluation of water quality across the sanctuary. The program and results for 2005 are described in Libby *et al.* (2006b).

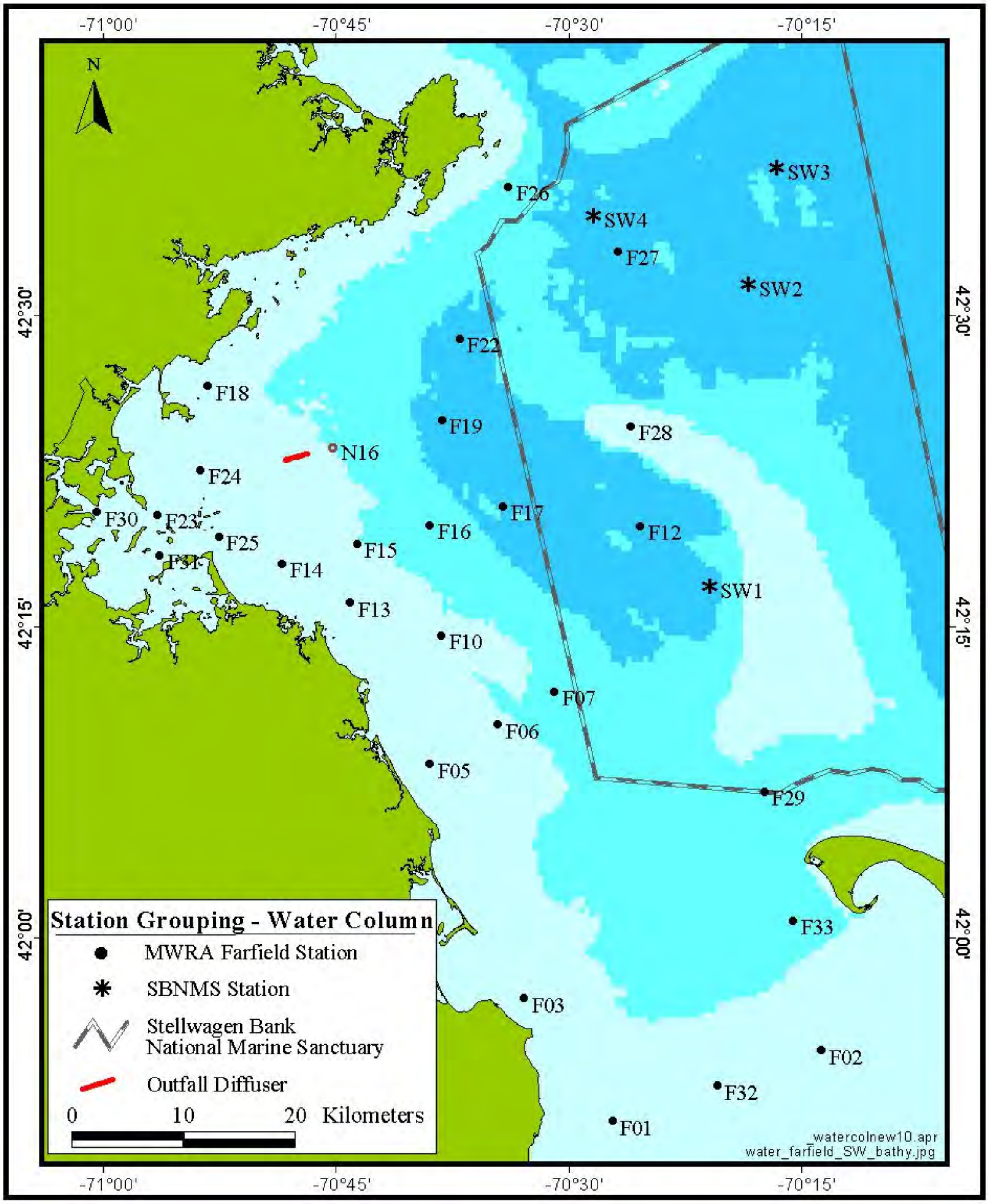

Figure 8-1. Water column stations, including the additional Stellwagen Bank National Marine Sanctuary (SBNMS) stations sampled in August and October 2001-2005; F32 and F33 sampled in February, March, and April; other stations sampled in February, March, April, June, August, and October

Two MWRA sea-floor stations are within the sanctuary, one at the southern boundary and one within Stellwagen Basin (FF04 and FF05, see Figure 4-2). A third sea-floor station (FF11) is just north of the sanctuary boundary and a fourth station (FF14) is located outside the sanctuary, but within Stellwagen Basin. These four stations are the deepest of those included in the MWRA monitoring program and have similar properties, with muddy sediments and moderate concentrations of total organic carbon. The station north of the sanctuary and the one within Stellwagen Basin are east or northeast of the outfall, outside the general circulation pattern that transports diluted effluent south and southeastward in Massachusetts Bay. From 1992 through 2003, these stations were sampled annually in August. Changes to the benthic monitoring program implemented in 2004 call for sampling approximately half the stations each year. Stations FF11 and FF14 were sampled in 2005.

Results

Water Column

Overall, water quality within the sanctuary was excellent during 2005. There was no indication of any effect of the MWRA outfall (Libby *et al.* 2006B). While ammonium concentrations rose in the nearfield following the outfall diversion, there has been no parallel annual increase in Stellwagen Bank or Cape Cod Bay (Figure 8-2, top). Nitrate concentrations (Figure 8-2, bottom) continue to show an upward trend in offshore Massachusetts Bay and in the nearfield, a regional phenomenon that predates the outfall diversion and is not well understood. Other measurements of nitrogen (Figure 8-3) and dissolved phosphate (not shown) also show these long-term trends. Concentrations of nitrate, dissolved inorganic nitrogen, and total dissolved nitrogen have consistently been higher in samples from the sanctuary than those measured at other stations. In contrast, concentrations of total nitrogen have been similar in all regions.

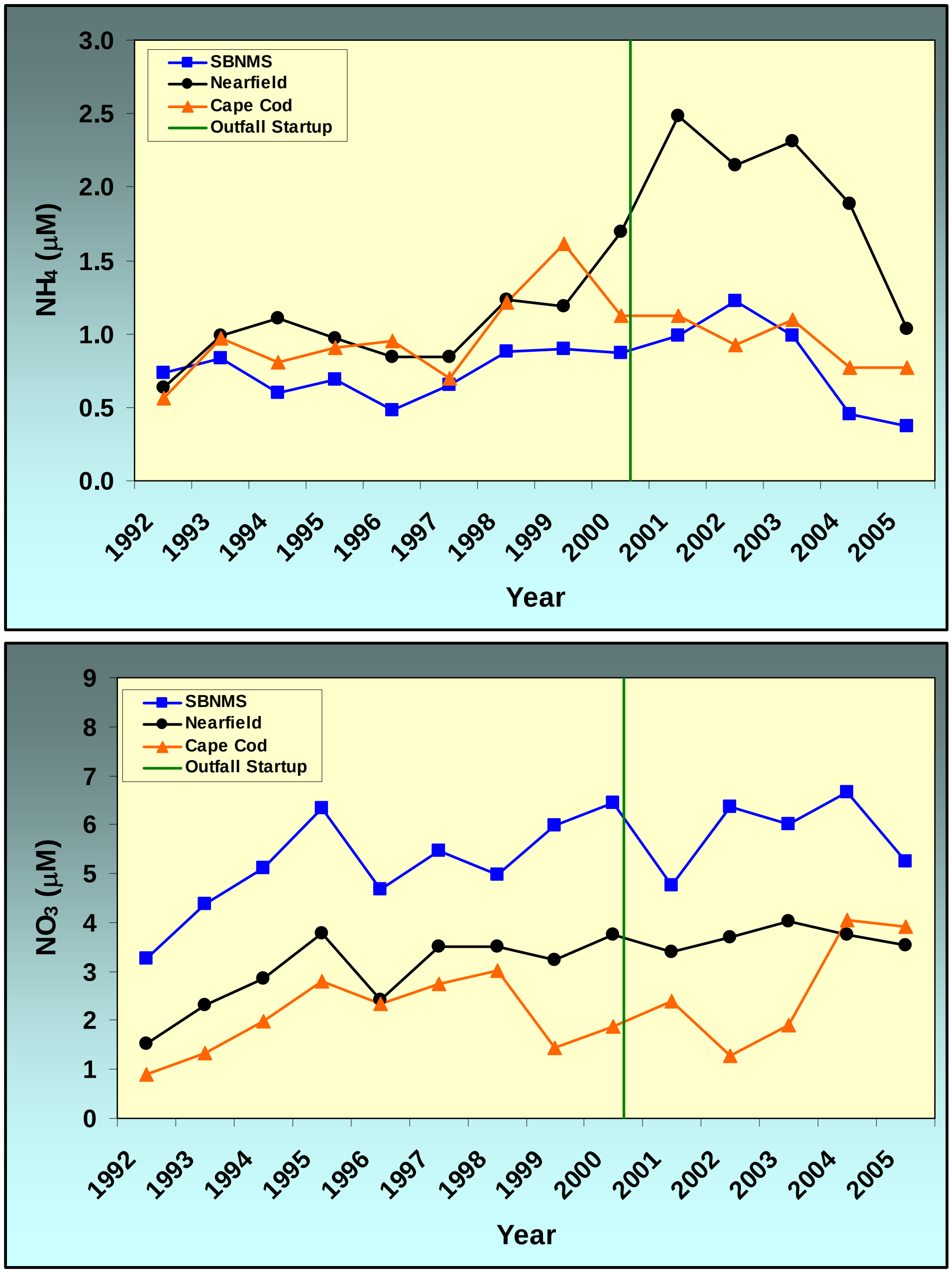

Figure 8-2. Annual mean ammonium (top) and nitrate (bottom) in the Stellwagen Bank National Marine Sanctuary, the nearfield, and Cape Cod Bay

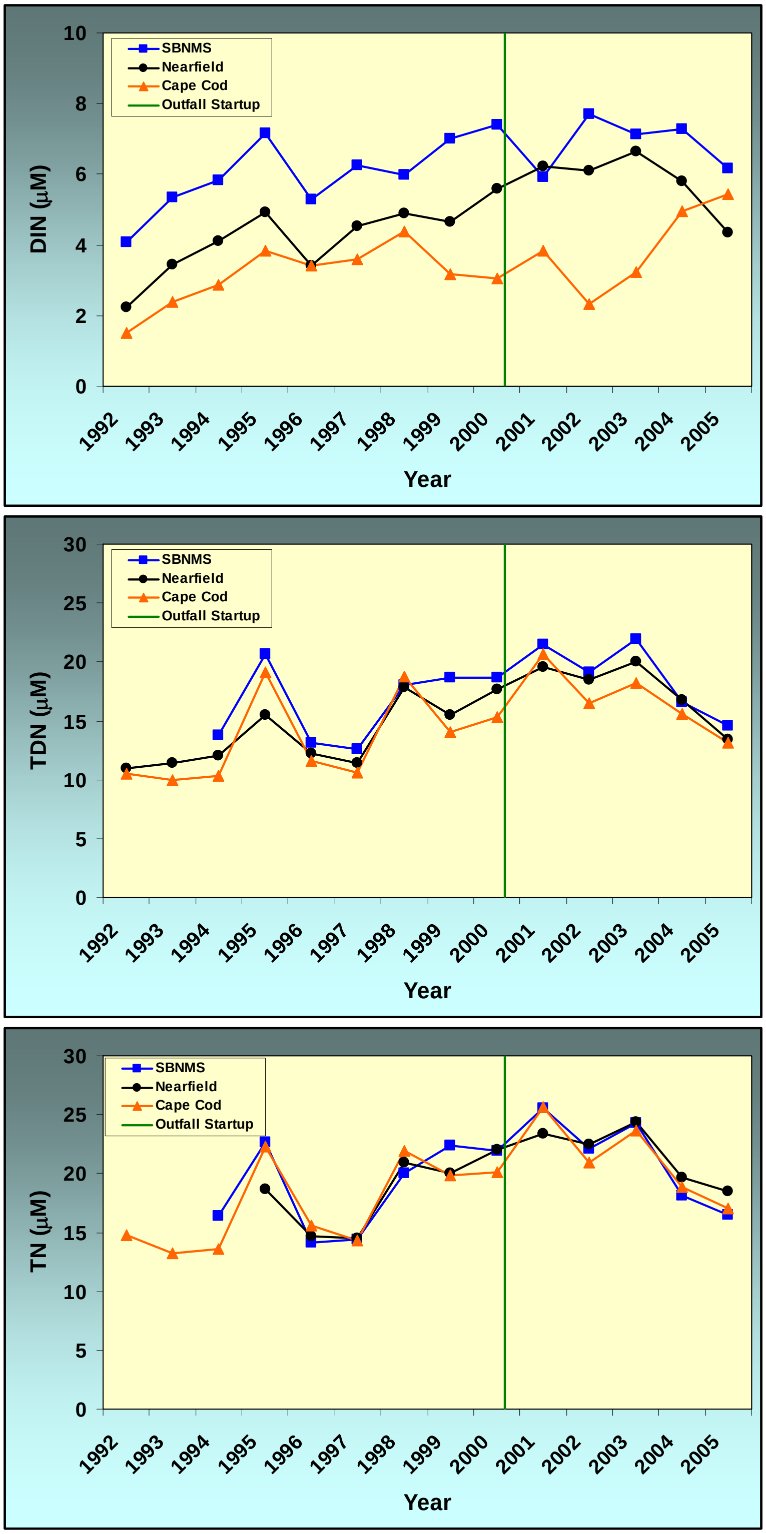

Figure 8-3. Top: Annual mean dissolved inorganic nitrogen (DIN); Middle: total dissolved nitrogen (TDN); Bottom: total nitrogen (TN) in Stellwagen Bank National Marine Sanctuary, the nearfield, and Cape Cod Bay

The five years of August and October sampling by the sanctuary have shown that within stations and depths, levels of nitrogen species, such as nitrite, are generally similar to one another, although there is some variation among stations and by year, as shown for nitrite (Figure 8-4). One feature that stands out is the lower concentrations of nitrite plus nitrate in the bottom waters of Station F28, which is located on Stellwagen Bank (Figure 8-5). This difference appears to reflect the station's shallow depth.

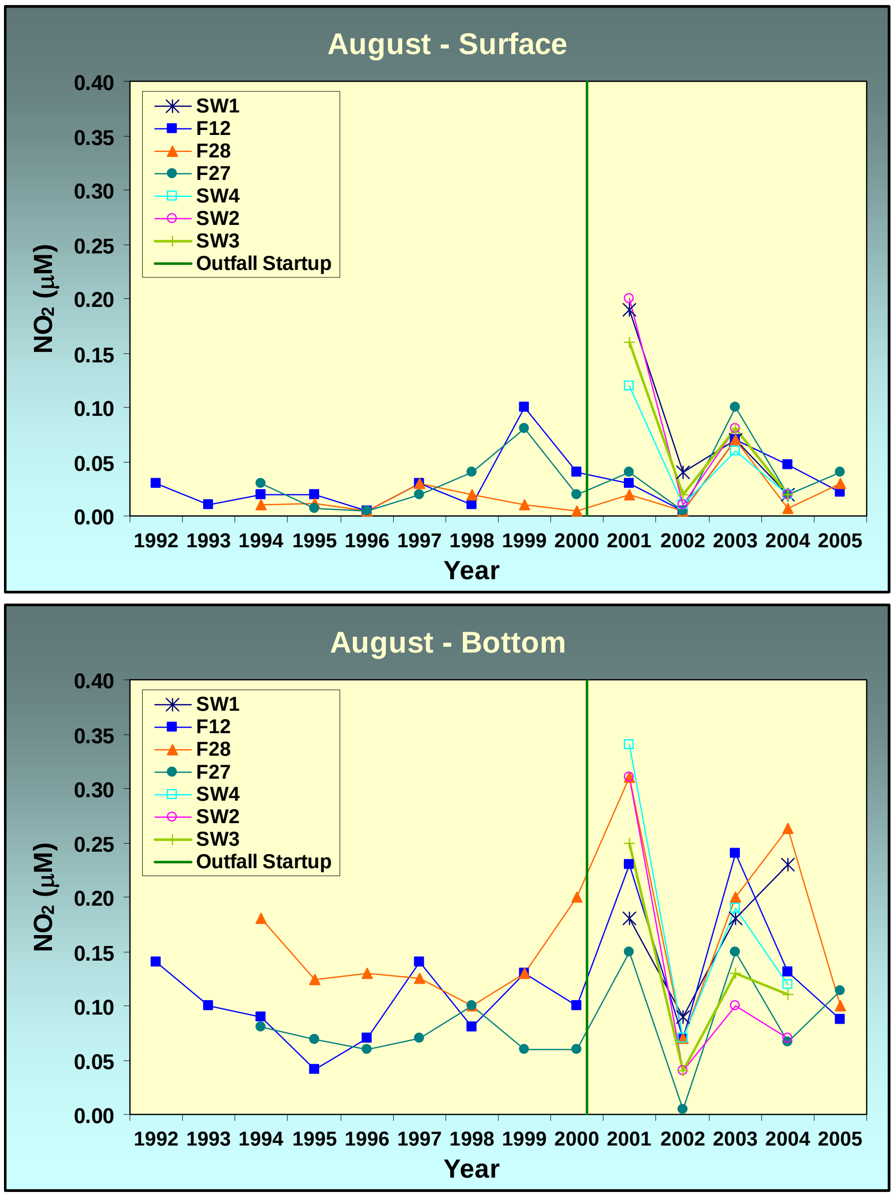

Figure 8-4. Nitrite in October surface (top) and bottom (bottom) waters at individual stations in Stellwagen Bank National Marine Sanctuary

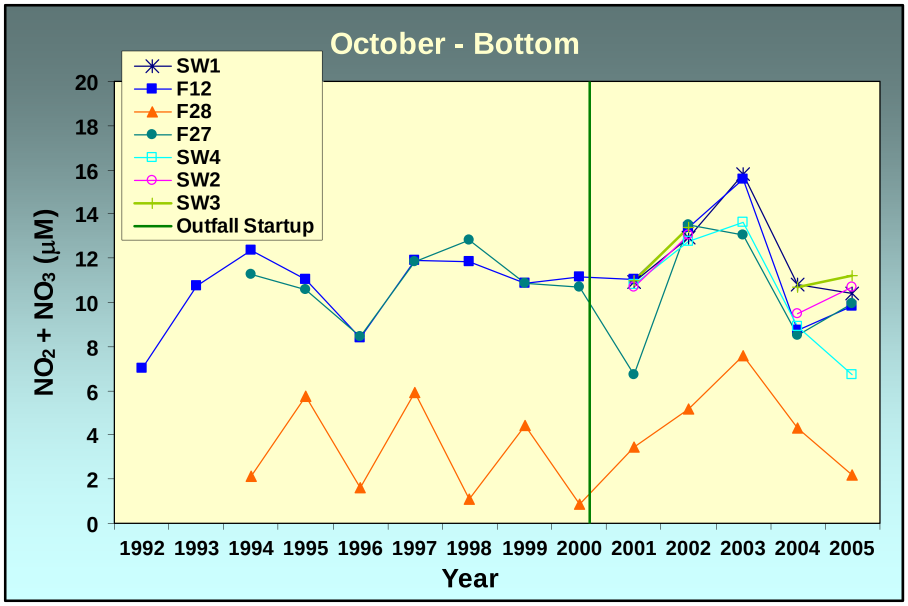

Figure 8-5. Total nitrite plus nitrate in bottom waters at individual stations in Stellwagen Bank National Marine Sanctuary

The mean annual chlorophyll levels have not changed in response to the outfall discharge (Figure 8-6). Annual chlorophyll levels were similar in the nearfield, Cape Cod Bay, and Stellwagen Bank.

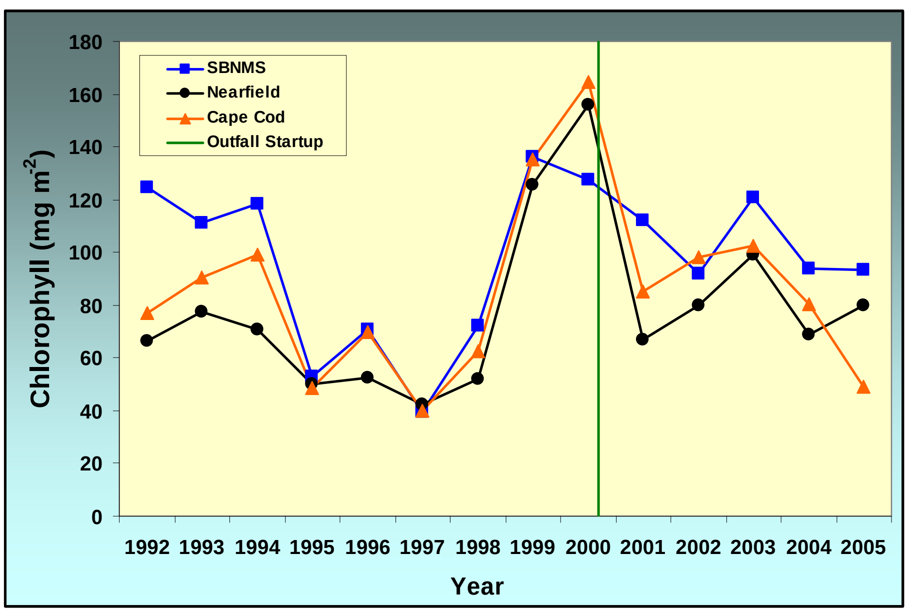

Figure 8-6. Annual mean chlorophyll in Stellwagen Bank National Marine Sanctuary and other regions

As in other years, the MWRA monitoring program documented a spring *Phaeocystis pouchetii* bloom throughout Massachusetts and Cape Cod bays (Libby *et al.* 2006a; disussed in Section 3, Water Column). The major *Alexandrium* bloom (discussed in Section 3, Water Column, and Section 6, Special Studies) occurred in May and June. By August, no evidence of the bloom remained within the waters of the sanctuary.

Concentrations of dissolved oxygen and percent saturation have not declined in the Stellwagen Basin or in the nearfield (data not shown). Rather than showing a decline, levels in 2005 were slightly high compared to the baseline years.

Sea Floor

No changes in concentrations of sewage tracers or sewage-related contaminants were observed in the sediment samples from stations within the sanctuary, and there were no changes in community parameters in 2005 (Maciolek *et al.* 2006).

The deep-water stations (see Figure 4-2) continued to support a distinct infaunal community with recognizable differences from communities in the nearfield and Cape Cod Bay. Benthic community parameters at individual stations showed no pattern of change following start-up of the outfall in 2000 (Figure 8-7). Overall, the numbers of individual organisms and species per sample have increased, paralleling results from throughout Massachusetts Bay. No consistent pattern has been found that relates to outfall operation.

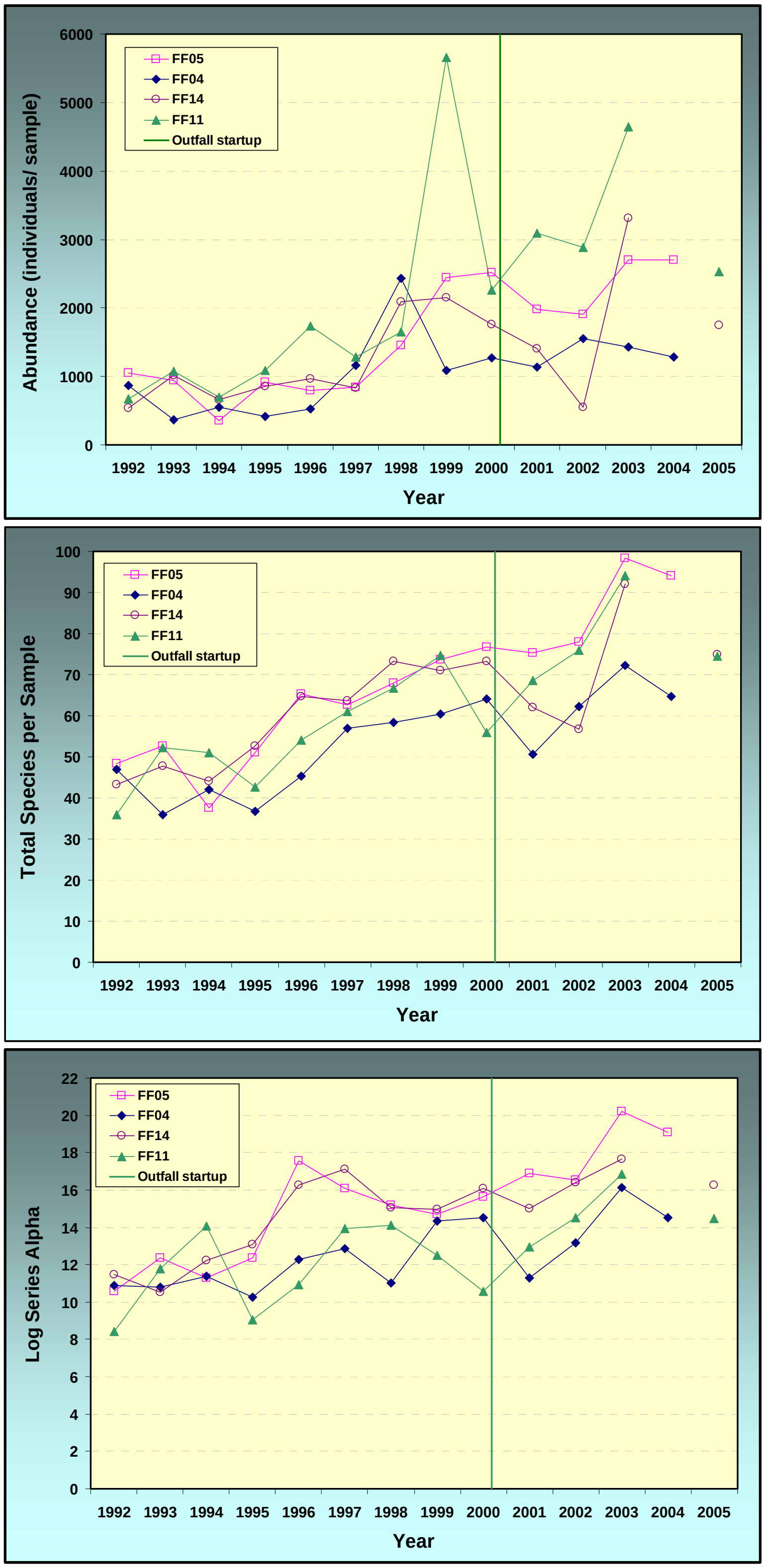

Figure 8-7. Benthic community parameters at stations in or near the Stellwagen Bank National Marine Sanctuary, 1992-2005

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List of Acronyms

AF	*Alexandrium fundyense* targeted survey
BEM	Bays Eutrophication Model
BOD	Biochemical oxygen demand
BS	Broad Sound
cBOD	Carbonaceous biochemical oxygen demand
CCB	Cape Cod Bay
CCC	Criterion continuous concentration
CHV	Centrotubular hydropic vacuolation
CMC	Criterion maximum concentration
C-NOEC	Chronic test, no observable effect concentration
CSO	Combined sewer overflow
DDE	Dichlorodiphenylethylene
DDT	Dichlorodiphenyltrichloroethane
DIF	Deer Island Flats
DIN	Dissolved inorganic nitrogen
DO	Dissolved oxygen
ECCB	Eastern Cape Cod Bay
EPA	U.S. Environmental Protection Agency
FDA	U.S. Food and Drug Administration
FA	Foul Area
FF	Farfield
GFAA	Graphite furnace atomic adsorption
GoMOOS	Gulf of Maine Ocean Observation System
HHC	Human health criterion
HMW	High molecular weight
IAAC	Inter-agency Advisory Committee
ICP	Inductively coupled plasma
ICP/MS	Inductively coupled plasma mass spectrometry
IWS	Industrial Waste Site
LC50	50% mortality concentration
LMW	Low molecular weight
MADEP	Massachusetts Department of Environmental Protection
MADMF	Massachusetts Division of Marine Fisheries
MBDS	Massachusetts Bay Disposal Site
MEG	Model Evaluation Group
MGD	Million gallons per day
MIT	Massachusetts Institute of Technology
MWRA	Massachusetts Water Resources Authority
NA	Not analyzed/not applicable
NB	Nantasket Beach
ND	Not detected
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NPS	Nonpoint source
NOEC	No observable effect concentration
NPDES	National Pollutant Discharge Elimination System

OMSAP	Outfall Monitoring Science Advisory Panel
OMTF	Outfall Monitoring Task Force
OS	Outfall site
PAH	Polycyclic aromatic hydrocarbon
PCB	Polychlorinated biphenyl
ppb	Parts per billion
ppm	Parts per million
PIAC	Public Interest Advisory Committee
RPD	Redox potential discontinuity
PSP	Paralytic shellfish poisoning
ROC	Receiver operating characteristic
SBNMS	Stellwagen Bank National Marine Sanctuary
SD	Standard deviation
SEIS	Supplemental Environmental Impact Statement
SIM	Selective ion monitoring
SOD	Sediment oxygen demand
SPI	Sediment-profile imaging
TCR	Total chlorine residual
TDN	Total dissolved nitrogen
TN	Total nitrogen
TOC	Total organic carbon
TRAC	Toxic Reduction and Control Program
TSS	Total suspended solids
USGS	U.S. Geological Survey

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