Outfall Benthic Monitoring Interpretive Report: 1992–2007 Results

Massachusetts Water Resources Authority

Environmental Quality Department
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Outfall benthic monitoring interpretive report: 1992–2007 results

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EXECUTIVE SUMMARY

The benthic surveys discussed in this report began in 1992 as part of the Benthic (Sea-Floor) Monitoring component of the MWRA Harbor and Outfall Monitoring (HOM) program. The benthic program has four major components, including the annual late-summer measurement of

- geochemical properties, contaminants, and sewage tracers in sediments
- the apparent redox potential layer in sediment profile images (SPI) taken in the nearfield
- benthic infaunal (soft-bottom) community structure
- hard-bottom community structure

In 2003, the MWRA received permission from the USEPA to modify the benthic sampling, including reduction in the number of stations sampled each year, as well as a reduction in the sediment chemistry parameters measured at each station. The nearfield and farfield stations were randomly binned into two subsets, to be sampled in alternate years. In August 2007, all of the SPI and hard-bottom stations were to be visited, whereas the soft-bottom benthos and sediment geochemical parameters were sampled at roughly half the number of stations that had been evaluated annually through 2003.

Contingency Plan Thresholds

The offshore outfall is regulated under a permit issued to MWRA by the United States Environmental Protection Agency (USEPA) and Massachusetts Department of Environmental Protection (DEP), under the National Pollutant Discharge Elimination System (NPDES). The permit stipulates that MWRA must monitor the outfall effluent and the ambient receiving waters to test for compliance with NPDES permit requirements; specifically, whether the impact of the discharge on the environment is within the bounds predicted by the SEIS (USEPA 1988), and whether any changes within the system exceed any of the Contingency Plan thresholds, including those for sediment redox depth, toxic contaminant concentrations, community structure, or abundance of opportunistic species (MWRA 2001).

The Contingency Plan (MWRA 2001) is an attachment to the MWRA's Discharge Permit. Warning level thresholds listed in the plan are based on effluent limits, observations from baseline monitoring, national water quality criteria, state standards, and, in some cases, best professional judgment. Contingency plan threshold values (Table 1) for benthic monitoring were originally based on averages calculated for the period 1992 through 2000, *i.e*., from the beginning of the monitoring program through September 2000, when diversion of highly treated effluent to the new outfall was initiated. Benthic community thresholds were adjusted to reflect the stations sampled in alternate years (Williams *et al.* 2005). No thresholds were exceeded in 2007.

Monitoring Questions

The benthic monitoring program was designed to address a series of questions (MWRA 2001) regarding sediment contamination and tracers, and the benthic communities:

- *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 and Cape Cod Bays sediments changed after discharge through the new outfall?*
- *Have the concentrations of contaminants in sediments changed?*
- *Have the sediments become more anoxic; that is, has the thickness of the sediment oxic layer decreased?*
- *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-bottom community changed?*

Table 1. Contingency plan thresholds established by MWRA for monitoring potential impacts of the offshore outfall. Benthic thresholds adjusted for stations collected in even- and odd-numbered years (Williams *et al.* 2005).

Location	Parameter	Caution Level	Warning Level
Sediment toxic contaminants, nearfield	Acenaphthene	None	500 ppb dry
	Acenaphylene	None	640 ppb dry
	Anthracene	None	1100 ppb dry
	Benz(a)pyrene	None	1600 ppb dry
	Benzo(a)pyrene	None	1600 ppb dry
	Cadmium	None	9.6 ppm dry
	Chromium	None	370 ppm dry
	Chrysene	None	2800 ppb dry
	Copper	None	270 ppm dry
	Dibenzo(a,h)anthracene	None	260 ppb dry
	Fluoranthene	None	5100 ppb dry
	Fluorene	None	540 ppb dry
	Lead	None	218 ppm dry
	Mercury	None	0.71 ppm dry
	Naphthalene	None	2100 ppb dry
	Nickel	None	51.6 ppb dry
	p,p’-DDE	None	27 ppm dry
	Phenanthrene	None	1500 ppb dry
	Pyrene	None	2600 ppb dry
	Silver	None	3.7 ppm dry
	Total DDTs	None	46.1 ppb dry
	Total HMWPAH	None	9600 ppb dry
	Total LMWPAH	None	3160 ppb dry
	Total PAH	None	44792 ppb dry
	Total PCBs	None	180 ppb dry
	Zinc	None	410 ppm dry
Sediments, nearfield	RPD depth	1.18 cm	None
Even Years Benthic diversity, nearfield	Species per sample	<48.41 or >82.00	None
	Fisher’s log-series *alpha*	<9.99 or >16.47	None
	Shannon diversity	<3.37 or >4.14	None
	Pielou’s evenness	<0.58 or >0.68	None
Odd Years Benthic diversity, nearfield	Species per sample	<46.52 or >79.95	None
	Fisher’s log-series *alpha*	<9.95 or >15.17	None
	Shannon diversity	<3.30 or >3.91	None
	Pielou’s evenness	<0.56 or >0.66	None
All Years Species composition, nearfield	Percent opportunists	10%	25%

Sediment Geochemistry and Sewage Tracer

- *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 and Cape Cod Bays sediments changed after discharge through the new outfall?*

Prior to effluent diversion, abundances of the sewage tracer *Clostridium perfringens* measured in surface sediments throughout Massachusetts and Cape Cod Bays ranged from 63 colony forming units per gram dry weight (cfu/g dry weight) to 24,100 cfu/g dry weight. In general, abundances were low throughout the bay, with slightly higher levels observed closer to Boston Harbor. Abundances generally decreased with distance from the harbor, with farfield sediments located far away from Boston Harbor (>20 km) having the lowest abundances (Figure 1).

Abundances of *C. perfringens* increased one year after effluent diversion at stations located within 2 km of the outfall (Figure 1). This pattern generally held through 2007, although abundances were unusually low in 2006 compared to other post-diversion years. A statistical data analysis confirmed this finding, which was within expectations. *Clostridium* abundances have decreased in the transition and farfield regions of Massachusetts and Cape Cod Bays since the mid- to late 1990s.

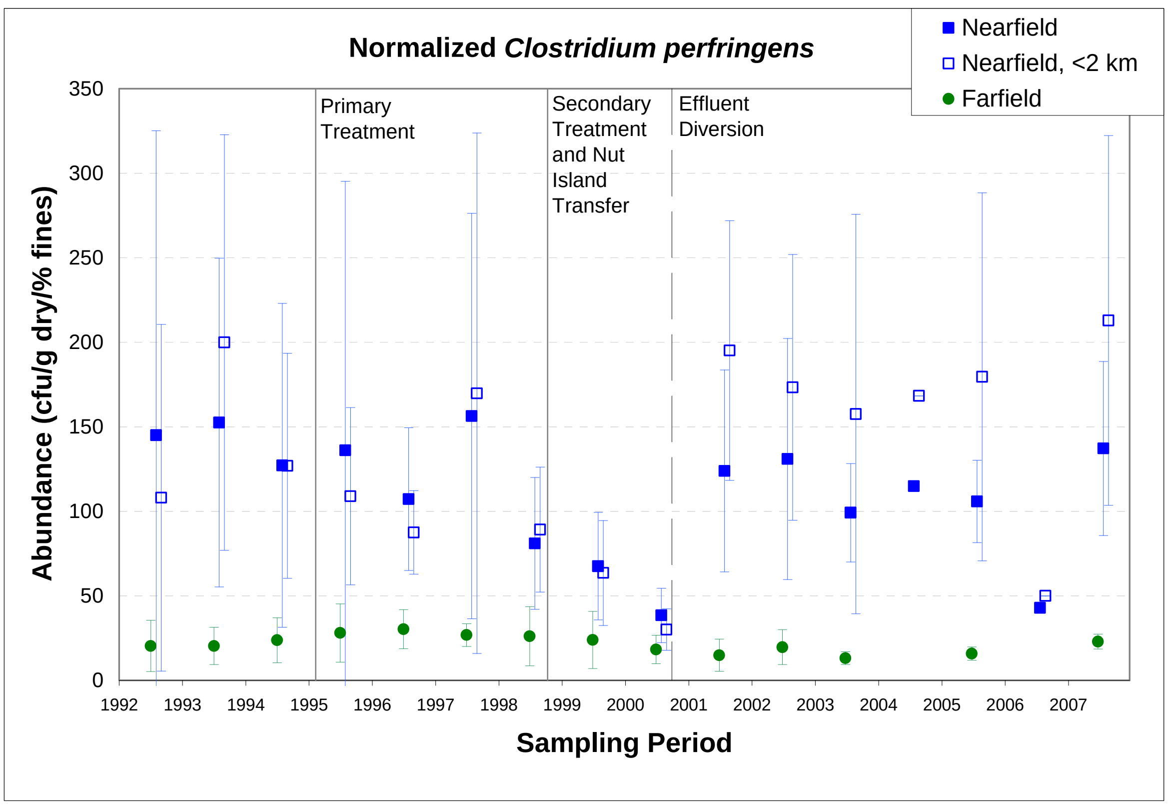

Figure 1. Yearly mean abundance of *Clostridium perfringens*, normalized to percent fines, in nearfield and farfield sediments, 1992 to 2007. The nearfield (filled square symbol) increase is largely associated with stations located within two kilometers of the outfall (open square symbol). Yearly mean abundance is the average of all stations and replicates for a given year, by region. Vertical bars represent one standard deviation.

Sediment Contaminants

♦ *Have the concentrations of contaminants in sediments changed?*

The long-term monitoring data (1992–2007) show that concentrations of anthropogenic contaminants in surface sediments at nearfield and farfield regions of Massachusetts and Cape Cod Bays are spatially and temporally variable and reflect differences in sediment characteristics, such as grain-size distributions and TOC content, rather than an outfall effect. For example, storm-induced impacts to the sediment bed following the May 2005 nor'easters likely contributed to a coarsening of sediment grain-size distributions and a corresponding decrease in 2005 in concentrations of aluminum, chromium, iron, and nickel, which are primarily crustal in nature.

Post-diversion mean concentrations of total PCB (Figure 2), total DDT, and total CHLOR decreased significantly (at the 95% level of confidence) at farfield regions of the Massachusetts and Cape Cod Bays compared to the baseline. Post-diversion mean concentrations of total DDT, total CHLOR, and total PEST also decreased significantly at the nearfield region of Massachusetts Bay. Decreases in total DDT and total PCB may be associated with the banning of these chemicals in the 1970s and 1980s, which in turn reduced inputs of these chemicals to the system. Decreases in total CHLOR and total PEST that occurred since the mid-1990s could be associated with remediation activities including source reduction actions and improvements to sewage treatment, which have reduced the loading of contaminants to coastal Massachusetts. Overall, sediment data to date indicate that post-diversion (2001–2007) concentrations of most anthropogenic contaminants have not changed substantively compared to the baseline (1992–2000).

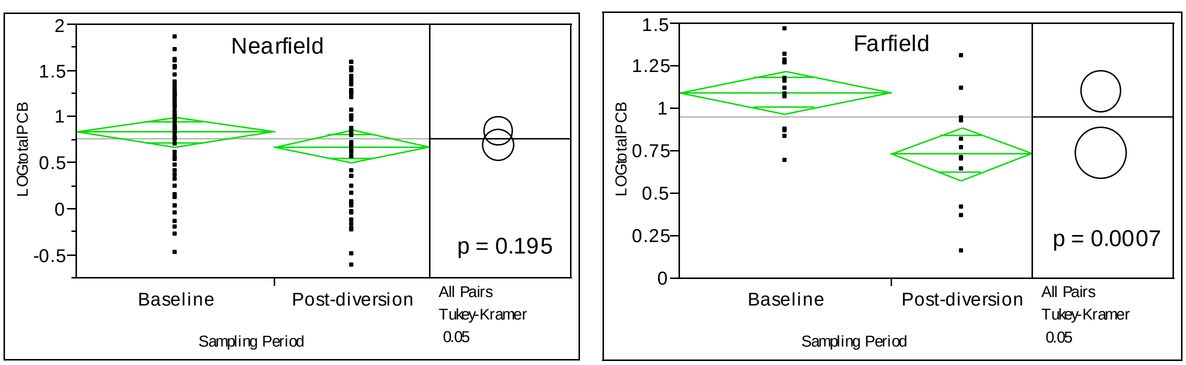

Figure 2. One-way analysis of total PCB (log normalized) by sampling period (baseline and post-diversion) in nearfield and farfield sediments, 1992– 2007. The means diamond illustrates the sample mean and 95% confidence. The line across each diamond represents the group mean. The vertical span of each diamond represents the 95% confidence interval for each group. Markers represent individual data points. The Tukey-Kramer comparison circles plot is a visual representation of group mean comparisons. Circles for means that are significantly different (at the 95% confidence level) either do not intersect or intersect slightly.

Sediment Redox Potential Layer

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

For assessing outfall effects, the critical trigger level for the apparent color Redox Potential Layer (RPD) layer depth would be a 50% reduction over the study area. Similarly, a 50% increase over the baseline depth would be noteworthy. In 2007, the average apparent color RPD was 3.4 cm, which was deeper than measured in 2006 (Figure 3), and significantly different from (deeper than) the baseline RPD of 2.3 cm. The difference in RPD depth between 2007 and baseline was a deepening of the RPD by an average of 1.1 cm or 46%; thus the threshold was not exceeded. In fact, the average RPD for 2007 was the high point of the range of annual RPDs, with 1997 and 1998 being the shallowest year at 1.8 cm.

In 2006, a comparison of baseline to discharge years indicated that the discharge years had significantly deeper RPD layers (baseline to discharge years multiplier 0.202, SE = 0.097, p = 0.038). The addition of the deeper RPD layer data from 2007 makes the discharge years even more different than baseline years. Based on the color and texture of sediments in the 2007 SPI images, it does not appear that the amount of deposited organic matter has changed relative to the operation of the outfall, post-diversion, or the baseline for the nearfield SPI stations.

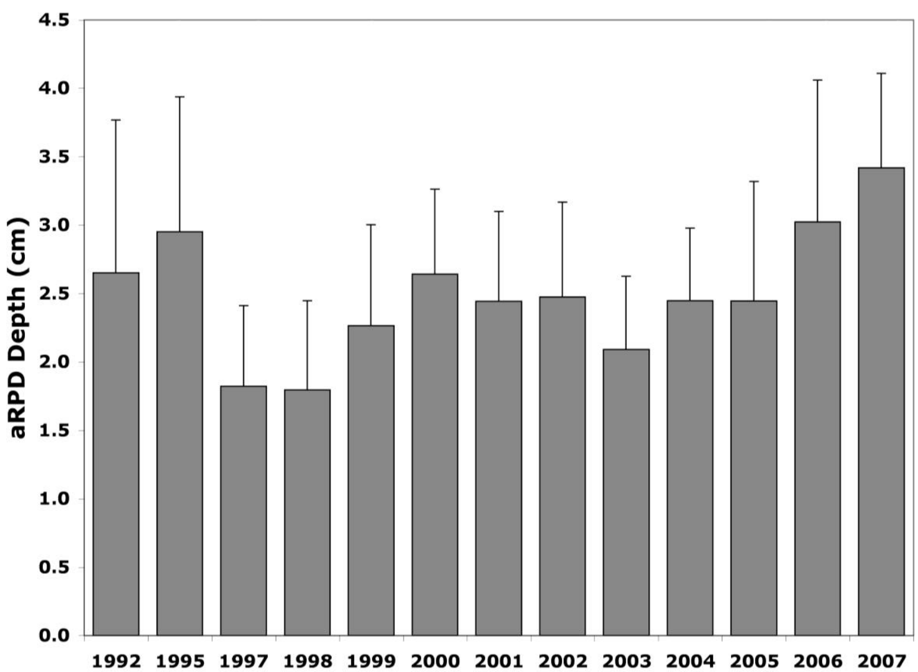

Figure 3. Apparent color RPD layer depth (cm) for the nine nearfield stations that had measured values for all years.

Soft-Bottom Benthic Infaunal Communities

- ♦ *Has the soft-bottom community changed?*

There have been clear temporal changes in the soft-bottom benthic infaunal community over the 16 years of the monitoring program, including changes in total infaunal density, species composition and richness, and, to a lesser extent, diversity. By 2002 infaunal abundance (per sample) had increased by roughly 60% over abundances recorded in the early years of the program, due primarily to increased abundances of only a few species, especially *Prionospio steenstrupi* (Figure 4), which replaced another spionid polychaete, *Spio limicola*, as the dominant at the medium- to fine-grained stations. Much of the decline in abundances seen in 2003–2007 was again due to the population fluctuation of the same species. Such fluctuations are characteristic of invertebrate species and cannot be construed as related to the operation of the outfall.

Some benthic community parameters have fluctuated in a sine-wave-like pattern, with increases followed by declines (Figure 5). Although mean Shannon diversity dropped below baseline in 2002, 2003, and 2005, it did not fall below the lower threshold level of 3.30 in any year. Diversity as measured by log-series *alpha* also fell below baseline in 2005, but not below the critical threshold level of 9.95 (Table 1). Parameters for this same set of stations were well above baseline in 2007, the current sampling year.

The high variability at some stations, which contrasts with the stability of other stations over time, suggests that several processes, biological as well as physical, operate in this system. Annual fluctuations in the population densities of several species, especially the dominant polychaetes at the finer-grained stations, and the occasional scouring of the bottom by storms both contribute to the overall invertebrate densities recorded from the benthic grab samples.

The larger patterns elucidated over time for the Massachusetts Bay stations have remained stable throughout the program. In similarity tests, the farfield stations have always differed from the nearfield, *e.g*., the Cape Cod Bay stations comprise a suite of species that gives them a unique signature. Nearfield stations FF10, FF12, and FF13 can be distinguished from the remaining nearfield stations, reflecting the transitional sediment texture at those stations; similarly, the nearfield sandy stations such as NF17 can be distinguished from nearfield fine-grained stations. These patterns have held whether the entire station set is sampled, or whether the 2004/2006 or 2005/2007 subsets are considered.

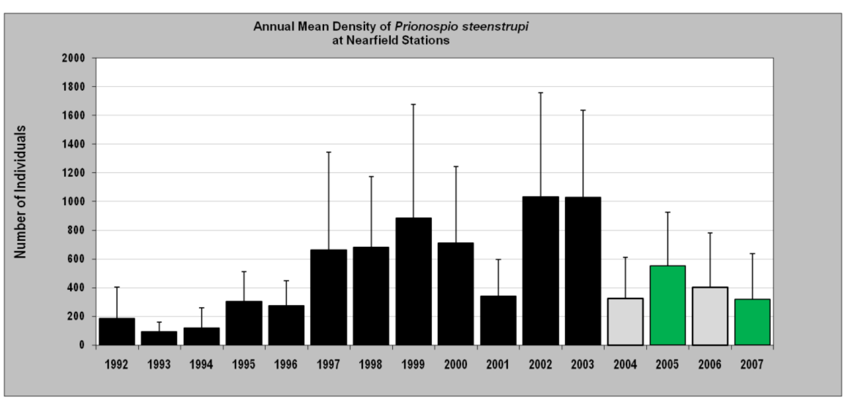

Figure 4. Annual mean density of *Prionospio steenstrupi* at nearfield stations. Two subsets of stations were sampled, one in 2004/2006 and the other in 2005/2007.

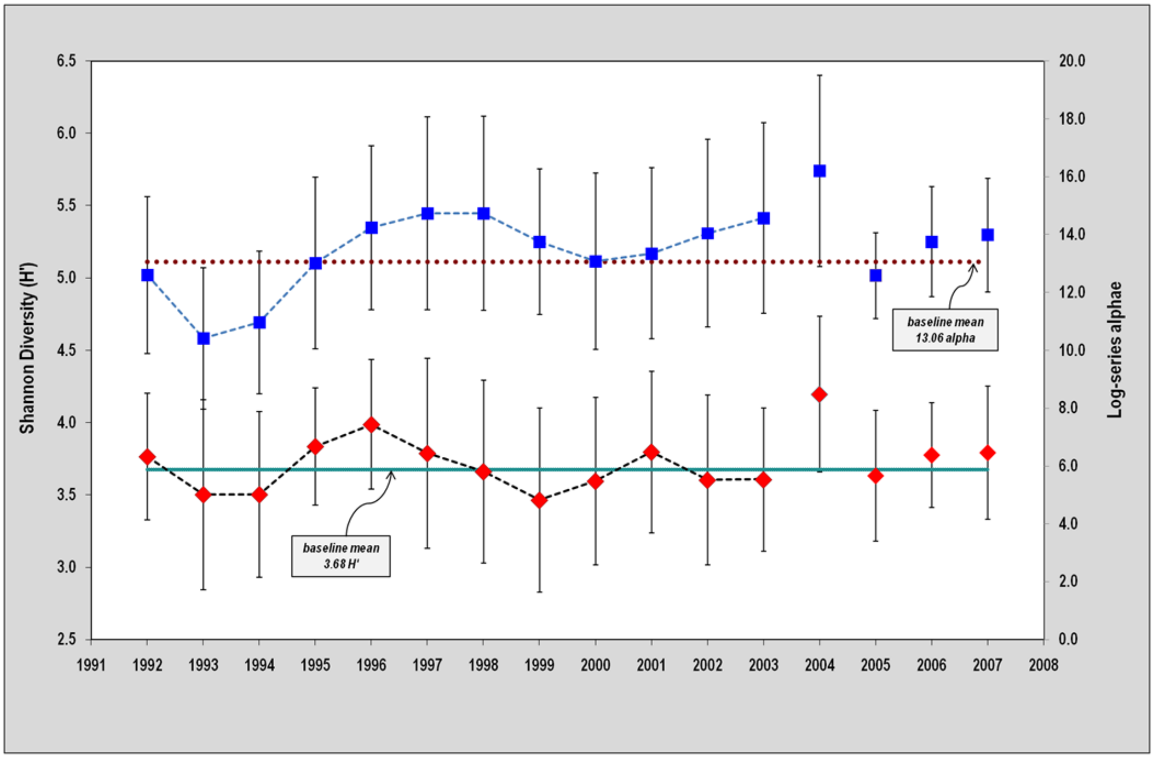

Figure 5. Annual mean diversity ± one standard deviation at nearfield stations. Shannon diversity (bottom curve) and Fisher's log-series *alpha* (top curve) are compared to the mean established during baseline years, prior to the activation of the offshore outfall in 2000. Different subsets of stations were sampled in 2004/2006 and 2005/2007.

- *Are any benthic community changes correlated with changes in levels of toxic contaminants (or sewage tracers) in sediments?*

Detailed investigation of individual stations has not suggested any localized outfall impact, even at stations within 2 km of the outfall (*e.g.*, NF17) where elevated levels of the sewage tracer *Clostridium perfringens* suggested a modest impact of the discharge in previous years. None of the species dominant at any of the stations are those considered to be opportunists responding to organic enrichment, which has, in fact, not been seen at the outfall sites.

Hard-Bottom Benthic Communities

- *Has the hard-bottom community changed?*

The hard-bottom benthic communities near the outfall remained relatively stable over the baseline period, and have not changed substantially with activation of the outfall in fall 2000. Major departures from baseline conditions have not occurred during the post-diversion years, however some modest changes have been observed, including decreases in the number of upright algae at some stations and increases in drape and decreases in percent cover of coralline algae at some stations (mainly drumlin top stations north of the outfall.

It is unlikely that the decrease in upright algae was attributable to diversion of the outfall, since abundances of upright algae were quite variable throughout the baseline period, reflecting both temporal and spatial heterogeneity. A general decline in the number of algae had started in the late 1990's and now appears to be reversing at a number of stations. The decline has been most pronounced at the northern reference stations and may, in part, reflect physical disturbance of the seafloor from an increase in anchoring activity of LNG tankers at these locations after 2001. Disturbance of the seafloor in the form of overturned boulders and areas of shell lag has been noted at T7-1 and T7-2 in the last several years (Figure 6).

The decrease in percent cover of coralline algae has been noticeable at five stations located north of the outfall in all seven post-diversion years. This decrease was particularly pronounced in 2005 and it extended to eight additional stations both north and south of the outfall. Mechanisms relating the decrease in coralline algae to outfall diversion are not clear, since the impact was noted further from the outfall rather than nearby. It is possible that some of the decreases in coralline algae observed at the northern reference stations are related to the physical disturbance of the seafloor observed at these stations, but it does not explain why coralline algae has declined at a number of other stations. It is possible that we are observing long-term changes in sedimentation patterns and hence coralline algae.

The first seven years of discharge monitoring, have shown modest changes that could be consistent with outfall impact at a subset of five stations, and some additional subtler changes at a number of other stations. However, two of the five stations in this subset may have been compromised by post 9/11 increases in the anchoring frequency of LNG tankers, causing physical disturbance of the seafloor at these sites. Lush epifaunal growth continues to thrive on the diffuser heads surveyed for this study and throughout many of the other stations visited (Figure 7). However, despite the fact that outfall impacts, if any, appear to be minimal at this time, changes in the hard-bottom communities could be chronic and/or cumulative, and may take a longer time to manifest themselves.

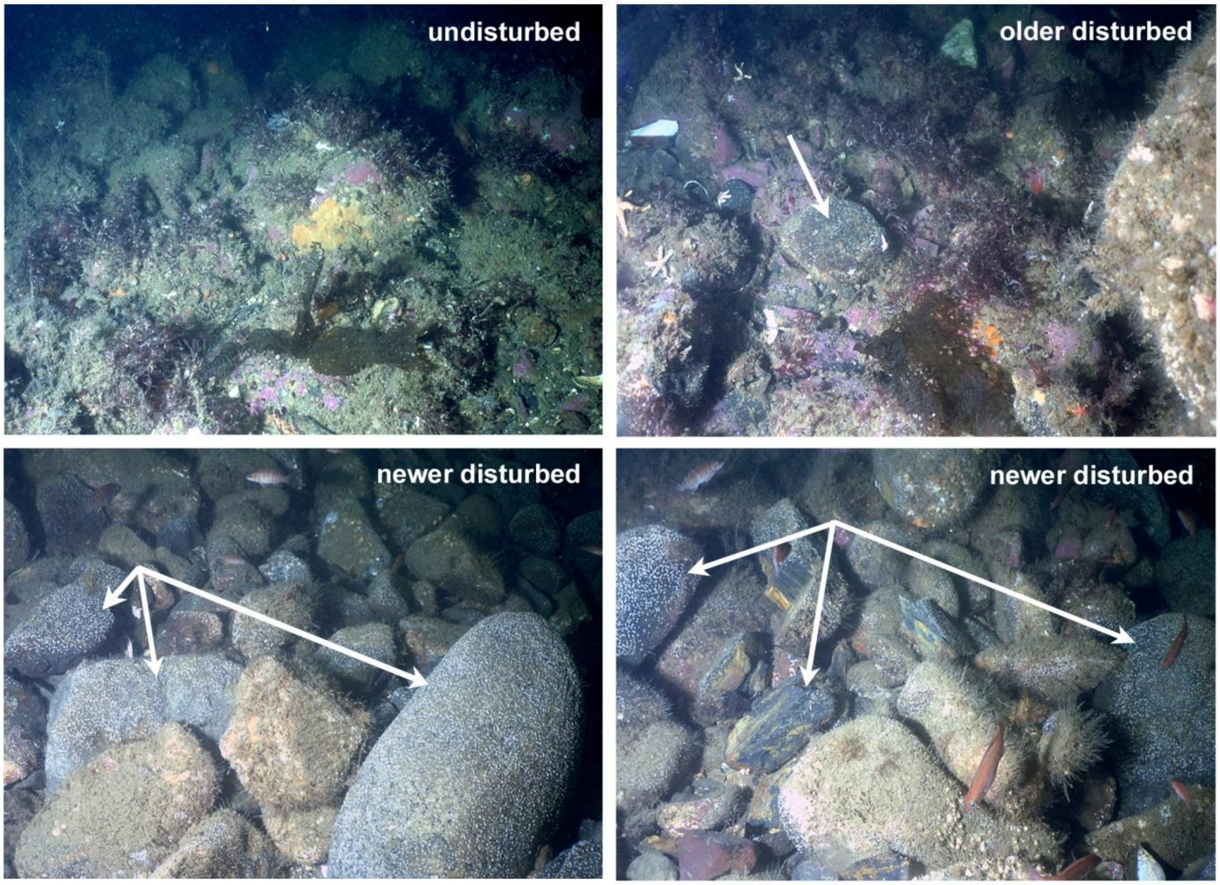

Figure 6. Photographs taken in 2007 of physical disturbance at northern reference station T7-1 possibly caused by the anchoring of LNG tankers. The undisturbed seafloor is characterized boulders encrusted with coralline algae, moderately-light to moderate drape, and upright algae. An older disturbed area has similar characteristics, but shows some evidence of physical disturbance such as bare rock surfaces. The newer disturbed areas are characterized by boulders that have been turned over exposing bare rock surfaces with little drape, and coralline algae on their lower surfaces. The newly settled barnacles (appear to be a spring set) indicate that the disturbance likely occurred in the winter or early spring. Examples of turned over rocks highlighted by arrows.

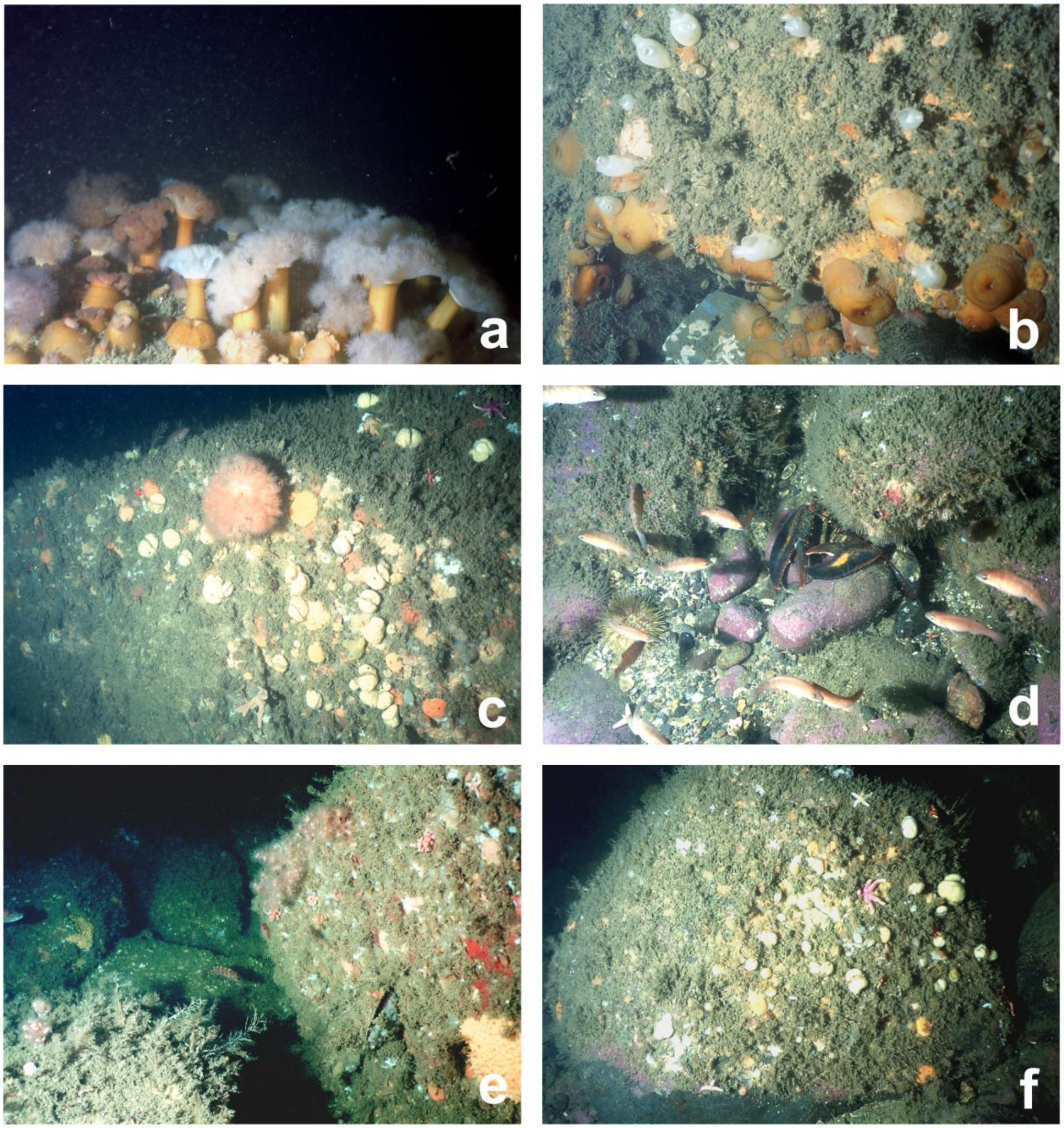

Figure 7. Photographs taken in 2007 of hard-bottom communities at two diffuser heads and selected hard-bottom stations. (a) The top of the active diffuser head #2 (T2-5) showing colonization by many frilled anemones *Metridium senile*. (b) The side of the inactive diffuser head (#44) showing colonization by sea peach tunicates *Halocynthia pyriformis* and frilled anemones *M. senile*. (c) A rock at T2-4 supporting numerous brachiopods *Terebratulina septentrionalis*, a *M. senile*, other encrusting organisms, and a few sea stars. (d) A lobster in its burrow at T4/6-1 with numerous cunner *Tautogolabrus adspersus*. (e) A boulder at southern reference station T10-1 with numerous soft red corals *Gersemia rubiformis*, a *Polymastia* sponge, the invasive tunicate *Botrylloides violaceus*, and other encrusting organisms. (f) A boulder at the northern reference station with numerous brachiopods, a variety of encrusting organisms, and sea stars.

1. INTRODUCTION

by Nancy J. Maciolek

1.1 Background

A burgeoning population and the impacts of industrialization throughout the first half of the twentieth century increasingly stressed Boston Harbor and Massachusetts Bay, as it did many urbanized coastal areas (Stolzenbach and Adams 1998). In response, federal legislation was passed in the early 1970s mandating that wastewater facilities be upgraded to secondary treatment, providing substantially greater removal of most chemical and domestic wastes. Further federal regulation of toxic chemicals and banning of contaminants, such as polychlorinated biphenyls (PCBs) and DDTs, in the 1970s and 1980s led to the continued reduction in toxic discharges over the past 30 years. Against this backdrop, the Massachusetts Water Resources Authority (MWRA) was created in 1985 with a mandate to implement both short-term and long-term remediation activities to decrease anthropogenic contamination discharge into the harbor.

Major improvements to the water and sediment quality in Boston Harbor began with the abatement of sludge discharge into the harbor in late 1991. Also, from 1991 to the start of outfall operation in 2000, a series of regional events transpired that influenced both Boston Harbor and the nearfield area. Climatologically, a severe storm passed over the region in October 1991, representing the highest bottom stress winter on record (Butman *et al*.2005). Freshwater flow was also elevated over long-term averages for much of the baseline period except for 1995, which was a low flow year (Taylor 2005).

In 1995, a new primary treatment facility at the Deer Island plant was brought online. In 1998, all wastewater was transferred to the Deer Island treatment plant and discharged off Deer Island at the mouth of the harbor. By this time, loadings from wastewater were reduced to about 4,000 mt C/yr from a high of about 11,400 mt C/yr. Secondary treatment was achieved in phases, with the final phase completed in 2000 and becoming fully operational in 2001.

In September 2000, the effluent from Deer Island was diverted to a new outfall approximately 15 km offshore, in 32 m water depth in Massachusetts Bay. All of these improvements—the improved effluent treatment, the complete cessation of sludge discharge to the harbor in 1991, and the transfer of wastewater discharge offshore—were implemented to improve the water quality in Boston Harbor and to increase effluent dilution with minimal impact on the environment of Massachusetts and Cape Cod Bays. Overall, the changes in wastewater discharge and improved treatment from 1995 to 2001 resulted in about a 90% decrease in loadings to Boston Harbor to about 1,200 mt C/yr. The operation of the offshore outfall diverted about 2,800 mt C/yr directly to the nearfield, which represents about 70% of the annual regional loadings (Taylor 2005, 2006). As a comparison to carbon fixed by primary production in the nearfield, which is about 400 g C/m^2/yr (Keller *et al.* 2001) or about 1 mt C per 2,500 m^2, the amount of carbon delivered to the nearfield via the outfall would be equal to the primary production in an area of about 7 km^2. This is a significant carbon input at scales of kilometers squared and might be expected to account for some changes in the study area.

The offshore outfall is regulated under a permit issued to MWRA by the United States Environmental Protection Agency (USEPA) and Massachusetts Department of Environmental Protection (DEP), under the National Pollutant Discharge Elimination System (NPDES). The permit stipulates that MWRA must monitor the outfall effluent and the ambient receiving waters to test for compliance with NPDES permit requirements; specifically, whether the impact of the discharge on the environment is within the bounds predicted by the SEIS (USEPA 1988), and whether any changes within the system exceed any of the

Contingency Plan thresholds, including those for sediment redox depth, toxic contaminant concentrations, community structure, or abundance of opportunistic species (MWRA 2001).

The Contingency Plan (MWRA 2001) is an attachment to the MWRA's Discharge Permit. Warning level thresholds listed in the plan are based on effluent limits, observations from baseline monitoring, national water quality criteria, state standards, and, in some cases, best professional judgment (Table 1-1). The Contingency Plan also details the process of how the MWRA would respond to any exceedances of the threshold values. Threshold values for benthic monitoring were originally based on averages calculated for the period 1992–2000, *i.e*., from the beginning of the monitoring program through September 2000, when diversion of highly treated effluent to the new outfall was initiated. In 2003, the MWRA received permission to redesign the sampling program, and the benthic community thresholds were adjusted to reflect the stations actually sampled in alternate years (Williams *et al.* 2005).

The studies included in the monitoring plan (MWRA 1991, 1997) are more extensive than necessary to calculate the Contingency Plan threshold values or to meet the NPDES permit requirements (MWRA 2003). Relocating the outfall raised concerns about potential effects of the discharge on the offshore benthic (bottom) environment. These concerns focused on three issues: eutrophication and related low levels of dissolved oxygen; accumulation of toxic contaminants in depositional areas; and smothering of animals by particulate matter. Extensive information collected over the baseline and post-diversion periods has allowed a more complete understanding of the bay system and has provided data to address the question of whether MWRA's discharge has contributed to any changes in the parameters of interest.

1.2 Design of the Benthic Monitoring Program

The benthic surveys discussed in this report began in 1992 as part of the benthic monitoring component of the MWRA Harbor and Outfall Monitoring (HOM) program (MWRA 1991). The benthic program has four major components, including the measurement of

- the apparent redox potential layer in sediment profile images (SPI)
- geochemical properties, contaminants, and sewage tracers in sediments
- benthic infaunal (soft-bottom) community structure
- hard-bottom community structure

Although SPI are taken only in the nearfield, the other three technical components are carried out at both nearfield (defined as being within 8 km of the outfall) and farfield locations.

Monitoring Questions. The benthic monitoring program was designed to address seven questions (MWRA 2001) regarding sediment contamination and tracers and benthic communities:

- *Have the concentrations of contaminants in sediments changed?*
- *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 and Cape Cod Bays sediments changed after discharge through the new outfall?*
- *Have the sediments become more anoxic; that is, has the thickness of the sediment oxic layer decreased?*
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All Years Species composition, nearfield	Percent opportunists	10%	25%

Achieving a good monitoring design for the nearfield was difficult because of the heterogeneity of habitats in the vicinity of the outfall. As a result, the sampling protocol was modified several times to find the best approach. Shifts in station design have presented some problems in comparing year-to-year trends because the 1993 nearfield design departed significantly from that of 1992 and 1994−2003. Nevertheless, the baseline data accrued from 1992−2000 are considered to be sufficient to assess long-term regional trends and to establish thresholds against which potential impacts from the effluent discharge can be measured.

In 2003, the MWRA began an intensive review of all elements of the monitoring program and the results to date, including the four components of the benthic monitoring. As part of the Nearfield Special Study, sediments around the outfall were sampled three times per year before and after outfall start-up to see if there would be rapid accumulation of contaminants there). In the first two years after the outfall came online, the concentrations of contaminants and sewage tracers in sediments changed only modestly and only in the immediate vicinity of the outfall, and no changes in any of the benthic community parameters that could be related to the outfall had been detected (Maciolek *et al*. 2004). MWRA therefore proposed to reduce sampling effort in several program areas; the proposed changes were reviewed and ultimately approved by the USEPA and the MADEP. A revised sampling plan was released in March 2004 (MWRA 2004).

Until 2003, 23 nearfield and 8 farfield stations were sampled (either replicated or as single-sample stations) for benthic infauna and chemical contaminants; SPI was taken at 23 locations in the nearfield, and the hard-bottom communities photographed using ROV-mounted cameras at 23 waypoints in both nearfield and farfield areas. Under the revised plan, the frequency of sampling for infaunal benthos and chemical constituents was reduced by at least 50 percent. The revised plan included the following adjustments (Table 1-2):

- SPI is taken at all 23 nearfield stations
- Infaunal stations were randomly split into two subsets that are sampled in alternate years, with the result that all stations will be sampled every two years. Stations were binned by region and level of replication before the random selection (MWRA 2003).
- Sediment characteristics/tracers, including total organic carbon (TOC), sediment grain size, and *Clostridium perfringens* spore counts in the 0–2-cm depth fraction are sampled annually at each of the stations sampled for infauna
- Chemical constituents, *i.e*., PAHs, PCBs, pesticides, and metals, are sampled at a variable number of stations, depending on the year
- Stations NF12 and NF17 are sampled annually for all parameters
- Every three years, starting in 2005, all stations sampled for infauna are sampled for all chemical constituents
- The only modification to the hard-bottom sampling was to drop two locations and add two new ones. The details of this station placement are discussed in Chapters 2 and 6 of this report.

The sewage tracer and organic carbon data, and sediment trap data from a companion US Geological Survey (USGS) study, are evaluated to ensure that there are no sudden changes in sediment chemistry over the next few years. If the sediments are still not accumulating contaminants, and effluent toxic contaminant concentrations remain low, the MWRA might propose to further reduce chemistry sampling.

Table 1-2. Revised benthic station sampling and replication (from MWRA 2004).

Station Group	Stations	Year sampled	Replication: biology	Replication: metals and organic contaminants	Replication: TOC/grain size
Core (2 stations to be sampled every year)	NF12, NF17	2004–2007	3	2	2
Even years replicated nearfield (2 stations)	FF10, FF13	2004, 2006	3	0	2
Even years unreplicated nearfield (9 stations)	NF05, NF07, NF08, NF09, NF16, NF18, NF19, NF22, NF23	2004, 2006	1	0	1
Even years farfield (4 stations)	FF04, FF05, FF07, FF09	2004, 2006	3	0	2
Odd years replicated nearfield (2 stations)	FF12, NF24	2005, 2007	3	2	2
Odd years unreplicated nearfield (8 stations)	NF02, NF04, NF10, NF13, NF14, NF15, NF20, NF21	2005, 2007	1	1	1
Odd years farfield (4 stations)	FF01A, FF06, FF11, FF14	2005, 2007	3	2	2

2. 2007 FIELD OPERATIONS

by Stacy A. Doner

2.1 Sampling Design

2.1.1 Soft Bottom

***Sediment Samples*—**Benthic monitoring surveys are conducted each year in August. The nearfield station array was designed to provide detailed spatial coverage of the infaunal communities inhabiting depositional sediments within about 8 km of the diffuser (Figure 2-1). Farfield stations, located more than 8 km from the diffuser, serve primarily as reference areas for the nearfield; these stations are located throughout Massachusetts and Cape Cod Bays (Figure 2-2). Target locations for all soft-sediment stations are given in Table 2-1. The actual station data for each biology and chemistry grab sample, along with a brief description of each, are in Appendix A1. In 2007, sediment grab samples were collected at 12 nearfield and 4 farfield stations (the odd-year subset of stations).

***Sediment Profile Images*—**The Sediment Profile Image (SPI) survey is conducted in August of each year at all 23 nearfield stations (Figure 2-1). The SPI survey allows a rapid comparison of benthic conditions to the triggering threshold for depth of the apparent color RPD layer. SPI can also be integrated with the quantitative results from the infaunal and sediment chemistry analyses to aid in assessing outfall effects. Sediment profile imagery, currently using digital photography, permits a faster evaluation of the benthos than can be made by traditional infaunal analyses. The target locations for SPI stations are the same as those of the nearfield grab stations (Table 2-1). In 2007, sediment profile images were taken at all 23 nearfield stations. Specific locations of all sediment profile images collected in 2007 are listed in Appendix A2.

2.1.2 Hard Bottom

Because of the relative sparseness of depositional habitats in the vicinity of the diffusers and adjacent nearfield, a photographic study of hard-bottom habitats is conducted each June. The hard-bottom ROV (remotely operated vehicle) survey of the outfall area is designed to provide semi-quantitative data about the hard-bottom community and its responses to the operation of the outfall. Video and 35-mm photographic images were collected at 17 waypoints distributed along six transects and six additional waypoints (T9-1, T10-1, T11-1, T12-1, Diffuser #2 and Diffuser #44) (Figure 2-3). Target locations for hard-bottom survey waypoints are listed in Table 2-2. Station data taken at the arrival of each station is given in Appendix A-3.

2.2 Field Program Results

2.2.1 Vessel and Navigation

The soft-bottom and SPI surveys in 2007 were conducted on Battelle's research vessel, the R/V *Aquamonitor.* The hard-bottom survey was performed using the F/V *Barbara L. Peters*, owned by Mr. Frank Mirachi and contracted through C.R. Environmental. Vessel positioning was accomplished with the Battelle Oceans Sampling Systems (BOSS) Navigation system, which consists of a Northstar differential global positioning system (DGPS) interfaced to an on-board computer. Data are recorded and reduced using NAVSAM© data acquisition software. The GPS receiver has six dedicated channels and is capable of locking onto six satellites at once. The system is calibrated with coordinates obtained from USGS navigation charts at the beginning and end of each survey day.

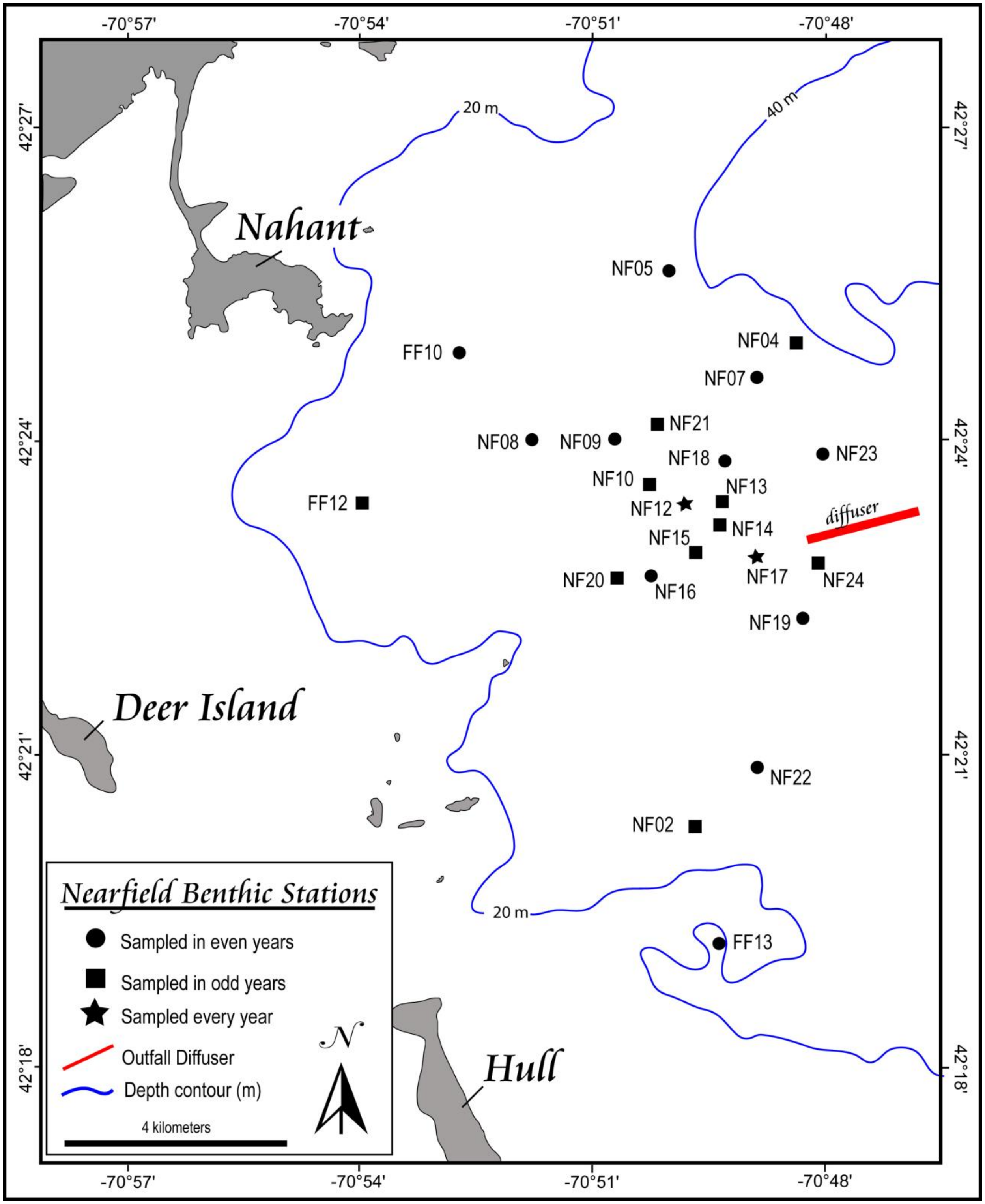

Figure 2-1. Locations of nearfield benthic stations sampled in August 2007. All stations were sampled by SPI and those denoted by square and star symbols were sampled by grab.

Table 2-1. Target locations for outfall survey grab and SPI stations.

Station	Latitude	Longitude	Depth (m)
Nearfield Stations			
FF10 [1]	42°24.84′N	70°52.72′W	28.7
FF12 [1,2]	42°23.40′N	70°53.98′W	23.5
FF13 [1]	42°19.19′N	70°49.38′W	20.7
NF02 [1,2]	42°20.31′N	70°49.69′W	26
NF04 [1,2]	42°24.93′N	70°48.39′W	34
NF05 [1]	42°25.62′N	70°50.03′W	36
NF07 [1]	42°24.60′N	70°48.89′W	32
NF08 [1]	42°24.00′N	70°51.81′W	28
NF09 [1]	42°23.99′N	70°50.69′W	29
NF10 [1,2]	42°23.57′N	70°50.29′W	32.9
NF12 [1, 2]	42°23.40′N	70°49.83′W	34.9
NF13 [1,2]	42°23.40′N	70°49.35′W	33.8
NF14 [1,2]	42°23.20′N	70°49.36′W	34.1
NF15 [1,2]	42°22.93′N	70°49.67′W	32.7
NF16 [1]	42°22.70′N	70°50.26′W	31.1
NF17 [1, 2]	42°22.88′N	70°48.89′W	30.6
NF18 [1]	42°23.80′N	70°49.31′W	33.3
NF19 [1]	42°22.30′N	70°48.30′W	33.2
NF20 [1,2]	42°22.69′N	70°50.69′W	28.9
NF21 [1,2]	42°24.16′N	70°50.19′W	30
NF22 [1]	42°20.87′N	70°48.90′W	30
NF23 [1]	42°23.86′N	70°48.10′W	36
NF24 [1,2]	42°22.83′N	70°48.10′W	37
Farfield Stations			
FF01A [2]	42°33.84′N	70°40.55′W	35
FF04 [3]	42°17.30′N	70°25.50′W	90
FF05 [3]	42°08.00′N	70°25.35′W	65
FF06 [2]	41°53.90′N	70°24.20′W	35
FF07	41°57.50′N	70°16.00′W	39
FF09	42°18.75′N	70°39.40′W	50
FF11 [2]	42°39.50′N	70°30.00′W	88.4
FF14 [2]	42°25.00′N	70°39.29′W	73.3

[1]Stations sampled by SPI in 2007 (all NF stations)
[2]Stations sampled by grab in 2007 (12 NF and 4 FF stations)
[3]Farfield stations in the Stellwagen Marine Sanctuary were not sampled in 2007

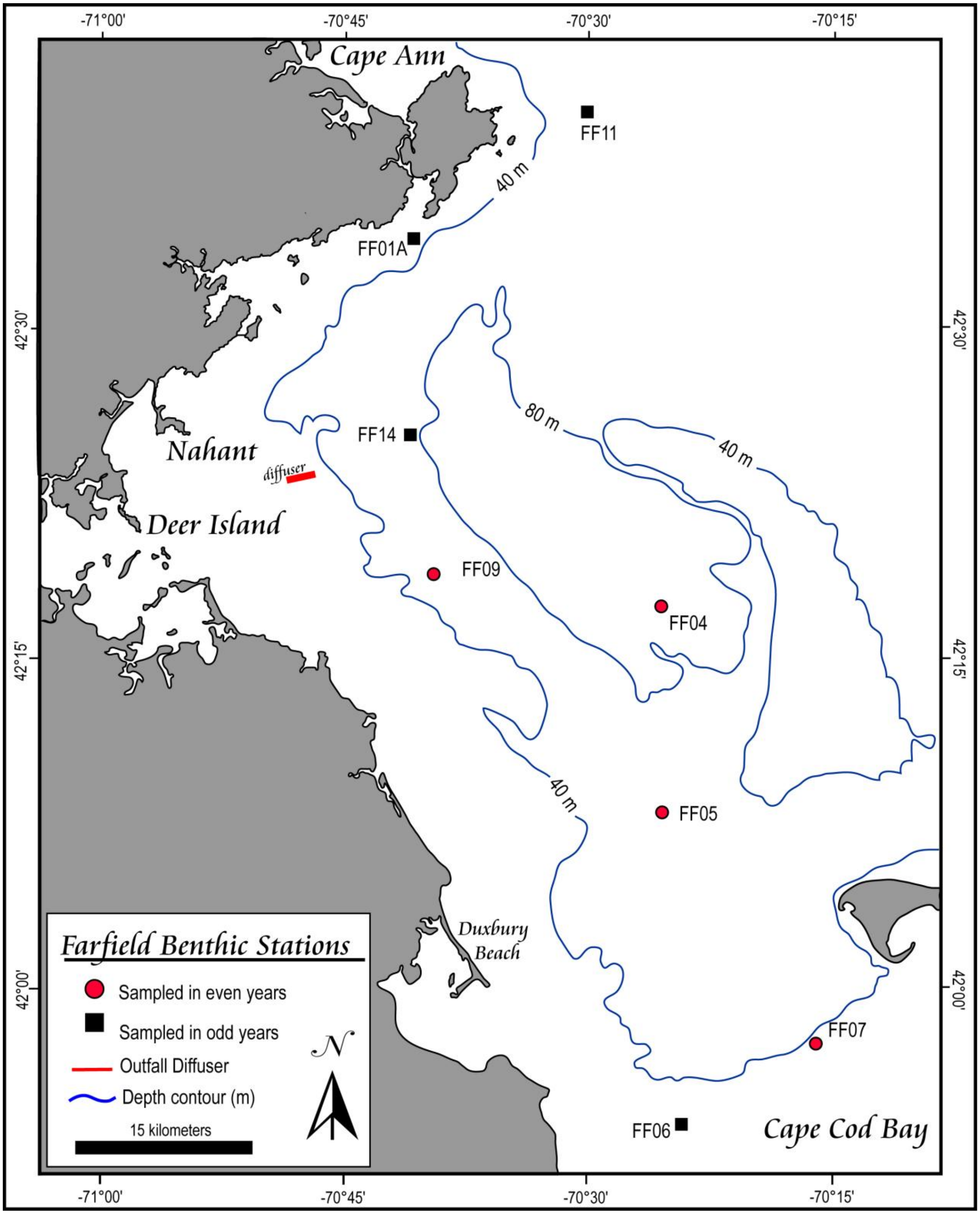

Figure 2-2. Locations of farfield grab stations sampled in August 2007 (indicated by black squares).

Table 2-2. Target locations for hard-bottom survey waypoints.

Transect	Waypoint/ Station	Latitude	Longitude	Depth (m)
T1	1	42°23.606'N	70°48.201'W	25
T1	2	42°23.625'N	70°48.324'W	24
T1	3	42°23.741'N	70°48.532'W	22
T1	4	42°23.815'N	70°48.743'W	20
T1	5	42°23.869'N	70°48.978'W	27
T2	1	42°23.634'N	70°47.833'W	26
T2	2	42°23.570'N	70°47.688'W	27
T2	3	42°23.525'N	70°47.410'W	26
T2	4	42°23.457'N	70°47.265'W	32
T2	5 (Diffuser #2)	42°23.331'N	70°46.807'W	34
T4	2	42°23.012'N	70°46.960'W	29
T4/6	1	42°22.948'N	70°47.220'W	23
T6	1	42°22.993'N	70°47.712'W	30
T6	2	42°22.855'N	70°47.082'W	27
T7	1	42°24.565'N	70°47.015'W	23
T7	2	42°24.570'N	70°46.920'W	24
T8	1	42°21.602'N	70°48.920'W	23
T8	2	42°21.823'N	70°48.465'W	23
T9	1	42°24.170'N	70°47.768'W	24
T10	1	42°22.680'N	70°48.852'W	26
T11	1	42°14.405'N	70°34.373'W	36
T12	1	42°21.477'N	70°45.688'W	29
	Diffuser # 44	42°23.116'N	70°47.931'W	33

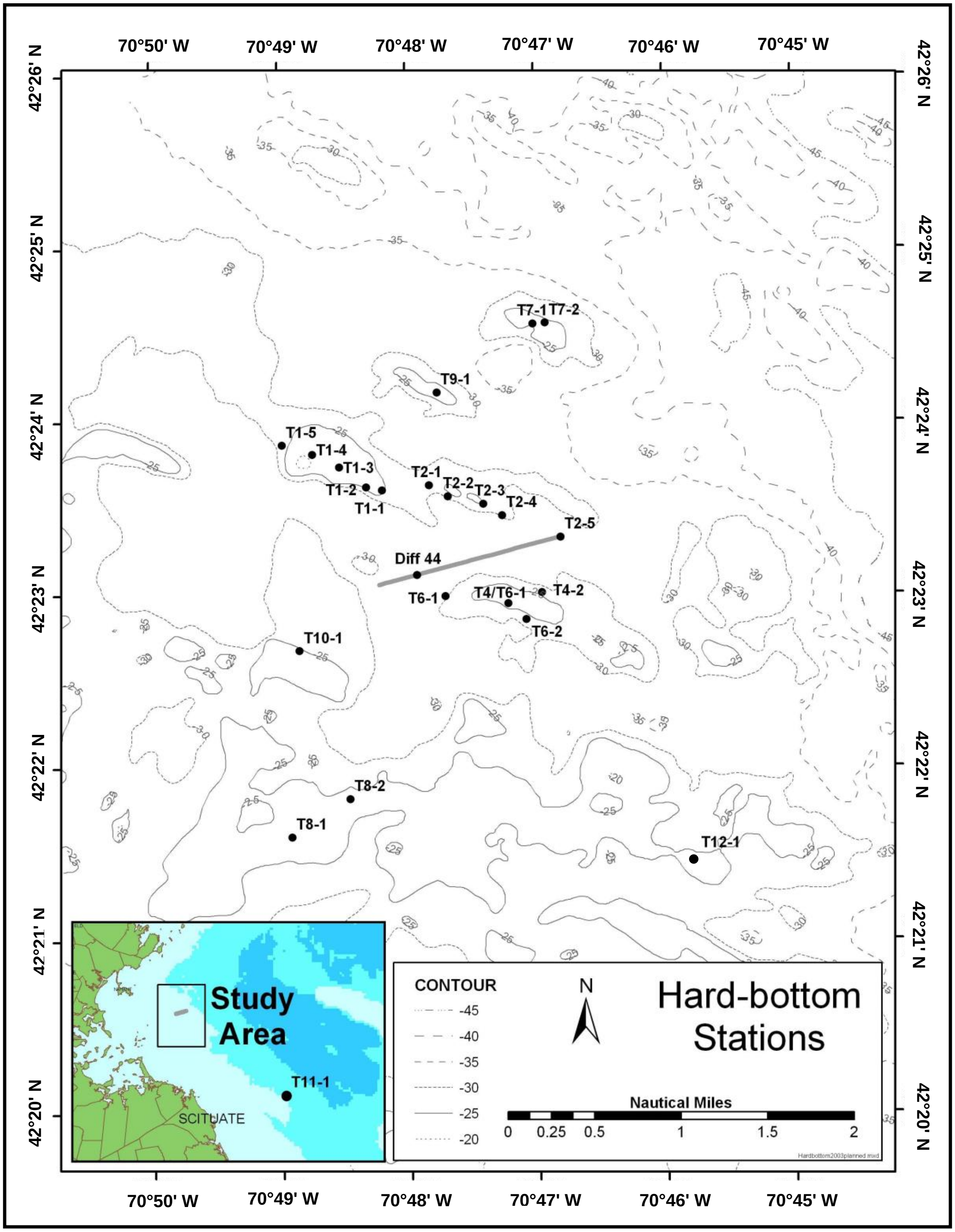

Figure 2-3. Hard-bottom stations sampled in June 2007.

At each sampling station, the vessel is positioned as close to target coordinates as possible. The NAVSAM© navigation and sampling software collects and stores navigation data, time, and station depth every 2 seconds throughout the sampling event, and assigns a unique designation to each sample when the sampling instrument hits bottom. The display on the BOSS computer screen is set to show a radius of 30 m around the target station coordinates (six 5-m rings) for all MWRA benthic surveys. A station radius of up to 30 m is considered acceptable for benthic sampling for this program.

2.2.2 Grab Sampling

Dr. Pamela Neubert was the Chief Scientist for collection of soft-sediment grab samples. In 2007, three sampling protocols were used for the 16 stations sampled during the Nearfield/Farfield Benthic Survey BN071/BF071.

- At two nearfield stations (NF24 and FF12) and the four farfield stations (FF01A, FF06, FF11, and FF14), three replicate samples for infaunal analysis and two replicate samples for chemical analysis of sedimentary parameters were collected.
- At two nearfield stations (NF12 and NF17), three replicate samples for infaunal analysis and two replicate samples for chemical analysis of metals and organics in addition to sedimentary parameters were collected.
- At eight nearfield stations (NF02, NF04, NF10, NF13, NF14, NF15, NF20, and NF21), one sample for infaunal analysis and one sample for chemical analysis of sedimentary parameters were collected.

Samples for the sedimentary parameters, which include total organic carbon, sediment grain size, and *Clostridium perfringens* were collected from all 16 stations. Samples for metals and organics analyses were collected only from stations NF12 and NF17. Numbers of samples collected are summarized in Table 2-3. At all stations, samples were collected with modified van Veen grab samplers; specifically, a 0.04-m^2 grab for infaunal samples and a 0.1-m^2 Kynar-coated grab for chemistry samples.

Infaunal samples were sieved onboard with filtered seawater over a 300-μm-mesh sieve and fixed in 10% buffered formalin. For chemistry samples, the top 2 cm of the sediment in the grab was removed by using a Kynar-coated scoop and homogenized in a clean glass bowl before being distributed to appropriate storage containers. The TOC, metals, and organics samples were frozen, whereas the *C. perfringens* and grain size samples were placed on ice in coolers.

Table 2-3. Benthic samples collected in 2007.

Survey Type	Survey ID	2007 Date(s)	Samples Collected									
			Inf	TOC	GS	Cp	Org	TM	SPI	35	V	DVD
Nearfield Benthic	BN071	30 July–2 Aug	20	16	16	16	4	4				
Farfield Benthic	BF071	30 July–2 Aug	12	8	8	8						
SPI	BR071	27–29 Aug							75			
Hard-bottom	BH071	18–22 June								~730	~440	14

Key: Inf: Infauna; TOC: total organic carbon; GS: grain size; Cp: *Clostridium perfringens*; Org: organic contaminants; TM: trace metals; SPI: individual sediment profile images; 35: 35-mm slides; V: minutes of video; DVD: digital video discs.

2.2.3 Sediment Profile Imagery (SPI)

Dr. Pamela Neubert was Chief Scientist and Dr. Robert Diaz was Senior Scientist for the 2007 SPI Survey (BR071). The digital camera used for this survey captured a 5.2-megapixel image that produced a 14.1-megabyte RGB image that was then recorded to either an IBM 1-gigabyte microdrive or solid state memory cards. The digital camera was also equipped with a video-feed used to send images to the surface via cable so that prism penetration could be monitored in real time. The camera frame also supported a video-plan camera mounted to view the seabed surface. These images were also relayed to the surface via the video cable permitting the camera operator to see the seafloor and to know exactly when the camera had reached the bottom. The camera operator then switched to the digital still camera and, while viewing the prism penetration, chose exactly when to record sediment profile images. A series of 2-4 photographs was taken each time the camera was on the bottom, generally within the first 12 seconds after contact.

At each station, the camera was lowered to the seafloor three to five times to ensure that at least three replicate images suitable for analysis were obtained (Table 2-3; Appendix A2-2). It was necessary to take a fourth replicate image at only four nearfield stations and five drops were necessary at a single station (NF16). The video signal showing the surface of the seafloor was recorded on mini-DVD digital videotape for later review. The date, time, station, water depth, photo number and estimated camera penetration were recorded in a field log, with each touch down of the camera also marked as an event by NAVSAM©.

The microdrive was capable of recording more images than could be collected during a day of sampling and the system was very conservative on energy consumption. It was not necessary to take test shots on deck because loss of battery power to the strobe or camera would have been noticed immediately if the video cable failed to relay any images. Consequently, the camera housing did not have to be opened during this survey, except at the end of each day when images were downloaded from the microdrive to the laptop computer. This digital capability allowed a review of the collected images within 20 min of downloading; all images were then copied to a compact disc (CD) for archiving.

2.2.4 Hard-Bottom Sampling

Dr. Pamela Neubert was Chief Scientist and Dr. Barbara Hecker was Senior Scientist for the 2007 Hard-bottom Nearfield Survey (BH071) during which 22 of the 23 target waypoints were visited (Table 2-2; Appendix A-3). The final waypoint, T12, was not obtained due to weather and complications with camera and strobe malfunctions. An Outland Technology "Outland 1000" ROV equipped with a UWC-360D, low-light, dual camera on 360° tilt was deployed from the survey vessel to obtain the necessary video, DVD, and photographic images. The video camera recorded in color (480 line, 0.01 lux). A Nikon mini-camera mounted to the ROV frame collected 35-mm images. The ROV was guided as close to the bottom as possible so that the clarity of the video and photographs was maximized. At least 20 minutes of video footage per waypoint were recorded along a randomly selected heading (Table 2-3). Along each route, still photographs were taken as selected by Dr. Hecker, until an entire roll of 35-mm film) was expended.

The date, time, and ROV depth were recorded on the videotapes and appeared on the video monitor during the recording. The beginning and end of each video tape, the start of each roll of film, and the capture of each 35-mm image were recorded as separate events on the NAVSAM© system. The time displayed on the video monitor (and recorded on the tape) was synchronized with the NAVSAM© clock. When a still photograph was taken, the event and frame-identifying observations (made by Dr. Hecker) were recorded on the videotape. The NAVSAM© produced barcode labels for the videotapes (attached to the videotape cartridge) and photographic film (attached to the ENSR survey logbook). All film was developed onboard to monitor camera performance, then mounted and labeled upon return to ENSR. Additionally, each 35-mm slide was digitized and copied onto a compact disc (CD) for archival. Digital Video Discs (DVDs) were also produced as the ROV was filming the hard-bottom stations.

3. 2007 CHEMISTRY

by Deirdre T. Dahlen and Carlton D. Hunt

3.1 Status of the Bay

A recent review on toxic contaminant issues in Boston Harbor and Massachusetts and Cape Cod Bays (Hunt *et al.* 2006) documents that the remediation activities, including source reduction actions and improvements to sewage treatment, have contributed to major improvements to the water and sediment quality in Boston Harbor. Notably, these improvements have resulted in reductions in contaminant loadings and a five-fold decrease in effluent solids discharge (Hunt *et al.* 2006). Since many contaminants readily bind onto solid particles, the magnitude of the solids reduction is mirrored for most chemicals of concern in the MWRA effluent. Improvements to other MWRA facilities have also resulted in smaller contaminant loadings from the MWRA waste collection system.

Consistent with predictions made in the Supplemental Environmental Impact Statement (SEIS) for the Massachusetts Bay outfall (EPA 1988), major findings from the benthic monitoring program (Hunt *et al.* 2006 and Maciolek *et al.* 2005, 2006, 2007) show that contaminant-related impacts have not been detected in the regional coastal environment from the diversion of effluent into Massachusetts Bay in September 2000. In contrast, some influence of the Bay outfall discharge on nearby sediments has been found, but has not caused substantive local or regional changes in the quality of the environment nor has the discharge acutely impacted marine life in the vicinity of the outfall and Bay at large.

This chapter presents the 2007 sediment chemistry data and incorporates these data into the understanding of the Massachusetts and Cape Cod Bay system. Monitoring year 2007 represents the seventh year following effluent diversion to Massachusetts Bay. Results from the 2007 monitoring are evaluated in the context of the larger monitoring period (1992–2006), the conclusions reached in Hunt *et al.* (2006) and Maciolek *et al.* (2005, 2006, and 2007), and with respect to severe weather events.

3.2 Methods

Massachusetts Bay benthic investigations have been conducted by MWRA annually in August since 1992. Surface (top 2 cm) sediment samples were generally collected at 23 nearfield and 8 farfield stations located throughout Massachusetts and Cape Cod Bays. Consistent with recent revisions to the monitoring program (MWRA 2004), a reduced set of stations has been sampled beginning in 2003 for anthropogenic[1] contaminants, and beginning in 2004 for sediment grain-size distribution, total organic carbon (TOC) content, and *Clostridium perfringens* as described in Section 1.3. Monitoring year 2007 represents an 'odd' sampling year under the revised program, with approximately half of the nearfield and farfield stations sampled for sediment grain size, TOC, and *C. perfringens*, and two nearfield stations (NF12 and NF17) sampled (in duplicate) for anthropogenic contaminants (Figures 2-1 and 2-2). Sediment chemistry data evaluated in this report from the 1992–2007 monitoring period are limited to stations sampled during odd sampling years to ensure consistency in the evaluations. Stations used in the evaluations include

[1] Anthropogenic analytes are generated or enriched in the environment by human activity. They are functionally defined in this analysis as polycyclic aromatic hydrocarbons (PAH), polychlorinated biphenyls (PCB), pesticides, and *C. perfringens*. In addition, they include the metals aluminum, cadmium, chromium, copper, iron, lead, mercury, nickel, silver, and zinc. All of these can be enriched by anthropogenic activities. However, aluminum and iron are crustal metals that do not typically intensify unless there is a nearby metallurgical industry (*e.g.*, steel mill or aluminum smelter). Normally, aluminum and iron can be used as reference values for comparing the metal composition of samples collected at different locations.

nearfield stations FF12, NF02, NF04, NF10, NF12, NF13, NF14, NF15, NF17, NF20, NF21, and NF24 and farfield stations FF01A, FF06, FF11, and FF14.

Surface sediment samples collected in 2007 were analyzed according to methods outlined in the project Quality Assurance Project Plan (Prasse *et al.* 2007). The testing procedures are summarized in Sections 3.2.1 and 3.2.2. Section 3.2.3 describes how the data were evaluated to characterize the sediments and assess changes in sediment quality that may have resulted from diversion of effluent discharge to the Massachusetts Bay outfall.

3.2.1 Grain Size, Total Organic Carbon, and *Clostridium perfringens*

Grain Size—Samples were analyzed for grain-size distribution by a sequence of wet- and dry-sieving methodologies following Prasse *et al.* (2007) and Folk (1974). Data were presented as weight percent by size class. In addition, the gravel:sand:silt:clay ratio and a numerical approximation of mean particle size and standard deviation were calculated. Grain-size analyses were performed by Applied Marine Sciences, Inc., of League City, Texas.

Total Organic Carbon (TOC)—Samples were analyzed for TOC by using a DC-190 analyzer following Prasse *et al.* (2007). Data were presented as percent dry weight. TOC analyses were performed by the Department of Laboratory Services (DLS), MWRA.

***Clostridium perfringens*—**Sediment extraction methods for determination of *C. perfringens* spores followed Prasse *et al.* (2007) and are based on Emerson and Cabelli (1982), as modified by Saad (1992). Data are reported as colony-forming units per gram (cfu/g) dry weight of sediment. This analysis was performed by BAL Laboratory, Cranston, Rhode Island.

3.2.2 Anthropogenic Contaminants

Sediment samples were analyzed for a suite of anthropogenic contaminants including PAH, PCBs, pesticides, and metals following procedures referenced in Prasse *et al.* (2007). PAH, PCB, and pesticide analyses were conducted by using gas chromatography with mass spectrometry detection. Aluminum, chromium, copper, iron, and zinc were analyzed by using flame atomic absorption; cadmium, nickel, lead, and silver were analyzed by using graphite furnace atomic absorption; and mercury was analyzed by using cold vapor atomic absorption. Anthropogenic contaminant analyses were performed by the DLS, MWRA.

3.2.3 Data Analyses

Methods used to analyze the sediment data are summarized here, and described in detail in Appendix B1. Microsoft® Excel 2003 and JMP (The Statistical Discovery Software, a business unit of SAS Institute, Inc.) were used to analyze the sediment chemistry data from system-wide and station-specific perspectives. Station mean values were used in all data analyses. Graphical representations of the results were presented as ternary plots, box plots, histograms, range, and variability gage plots. The total concentration for each contaminant class studied (see Appendix B1) was used in the data evaluations (*i.e.*, total PAH, total PCB, total DDT, total pesticides [total PEST], and total chlordanes [total CHLOR]). When an individual analyte was not detected, a value of zero (0) was used in the summation. Linear alkyl benzene (LAB) data were not evaluated here because sediments have not been analyzed for these chemicals since 2004; the most recent evaluation of LAB sediment data was presented in Maciolek *et al.* (2006).

Abundances of the sewage tracer *C. perfringens* were normalized to percent fines because the distribution of *C. perfringens* has been found to vary with the proportion of fine-grained material in the sediments

(Parmenter and Bothner, 1993), and normalization provides a more conservative means of evaluating the data for trends.

Sediment data were evaluated statistically by using the Tukey-Kramer means comparisons and Pearson pair-wise correlation analyses. Prior to statistical evaluations, the sediment data were checked for normality with the Shapiro-Wilk test, and the data used in the statistical tests were log-transformed, where appropriate. Tukey-Kramer was used to test system-wide and station-specific differences in group means between the baseline (1992–2000) and post-diversion (2001–2007) periods. The Pearson pair-wise correlation analyses were used to evaluate potential effects of effluent diversion on the relationships between sediment variables at nearfield and farfield locations. Sediment data from 1999 and 2000 were used in the correlation analysis to represent the baseline because this sampling period represents the conditions after most of the improvements to wastewater treatment were complete (*i.e.*, primary and secondary treatment, Taylor 2005) and provide two years of data before effluent diversion to the new outfall. The Pearson product-moment correlation coefficient (r) measures the degree to which two variables have a linear relationship if the variables have normal distributions. Values near 1 indicate that the two variables have a strong positive correlation, values near -1 indicate that the two variables have a strong negative correlation, and values near 0 indicate that the two variables are unrelated. Strong correlation coefficients do not necessarily indicate a direct dependence of the variables.

Nearfield and farfield sediment data were also compared to Sediment Quality Guidelines (SQG) (Long *et al*. 1995) to evaluate whether changes in sediment quality have occurred in the system since the early 1990s or between baseline (1992–2000) and post-diversion (2001–2007) periods. For this analysis, station mean values were compared with published marine effects range-low (ER-L) and effects range-median (ER-M) concentrations (Long *et al*. 1995) for 26 chemicals (13 PAHs, 5 pesticides/PCBs, and 8 metals). The number of sediment stations with chemical data used in the evaluation ranged from 2 to 16 depending on the monitoring year (*e.g*., two stations sampled in 2003, 2004, 2006, and 2007; 16 stations sampled in 1994, 1995, 1999, 2001, 2002, and 2005; no data available for 1996–1998). The total number of ER-L and ER-M exceedances for each year was summed by station and by chemical.

3.3 Results and Discussion

This section describes findings from the evaluation of sediment chemistry data collected from the 1992 to 2007 monitoring period at regional stations sampled during odd years under the revised monitoring program. Sediment data for 2007 (16 stations sampled for grain size, TOC, and *C. perfringens* and 2 stations sampled for anthropogenic contaminants) are discussed in context of the larger monitoring period (1992–2006), with respect to severe weather events, and in context of the conclusions reached in Hunt *et al.* (2006) and Maciolek *et al.* (2005, 2006, and 2007). System-wide and station-specific sediment data are also discussed with focus on how the post-diversion data (2001–2007) compare to the baseline data (1992–2000). All sediment results are discussed in terms of dry weight.

3.3.1 Sediment Grain Size and Total Organic Carbon

Grain-size distributions for the 16 stations sampled in 2007 were generally within the range of values measured over the larger monitoring period (1992–2006) (Figure 3-1). TOC content for the 16 stations sampled in 2007 was frequently among the lowest measured during the monitoring program, especially at nearfield stations (Figure 3-2). Storm-induced impacts to the sediment bed, such as a winnowing of fines resulting in a coarsening of grain size, were not evident in the 2007 data.

Long-term data (1992–2007) reveal that monitoring stations include a series of locations throughout Massachusetts and Cape Cod Bays that have heterogeneous sediments. Surface sediments sampled at nearfield stations located within 2 km of the offshore outfall were, with the exception of NF24, consistently coarse-grained (grain-size distributions cluster close to the gravel+sand axis in the ternary plot shown in Figure 3-1; median value[2] for nearfield sediments within 2 km of outfall is 91% gravel+sand) with low concentrations of organic carbon (median value is 0.37% TOC). Sediment at station NF24 contained higher percentages of silt and clay (Figure 3-1, median value for NF24 is 52% fines) and organic carbon (Figure 3-2, median value is 1.1% TOC). Although grain-size distributions were more variable from year to year at station NF24, sediments appear to be coarser during the post-diversion period than the baseline (post-diversion grain-size distributions for NF24 cluster closer to the gravel+sand axis in the ternary plot shown in Figure 3-1 compared to the baseline data).

Surface sediments sampled at nearfield stations located more than 2 km from the outfall had a wide range of grain-size distributions (Figure 3-1) and TOC content (Figure 3-2). Surface sediments were coarse-grained with low TOC content (*e.g.*, NF04) to fine-grained with higher TOC content (*e.g.*, NF12). Surface sediments sampled at the transition area were coarse-grained (Figure 3-1, median value is 71% gravel+sand) with low TOC content (Figure 3-2, median value is 0.53%). Excluding station FF01A, surface sediments sampled at the farfield regions of Massachusetts and Cape Cod Bays were generally fine-grained (median value for farfield is 70% fines) with higher concentrations of organic carbon (median value is 1.3% TOC). Station FF01A was comprised of coarse-grained sediments (Figure 3-1, median value is 81% gravel+sand) with lower organic carbon (Figure 3-2, median value is 0.39% TOC).

System-wide, substantive changes in grain-size distributions and TOC content were difficult to discern because of the high variability among the data over the monitoring period (1992–2007). At a given station, significant differences were observed between sampling periods for grain-size distributions but not TOC (see Appendix B2 for output from the Tukey-Kramer statistical tests). Small changes[3] in sand content were detectable as statistically significant in homogeneous (less variable grain-size) sediments at stations NF17 and FF12 whereas more substantial changes[4] were detectable as significant in heterogeneous (more variable grain-size) sediments at stations NF12 and NF24 (see comparison circle plots in Appendix B2). For example, a coarsening of grain-size was observed at station NF24, evident by a significant increase (at the 95% level of confidence, $p = 0.039$) in sand content between the baseline and post-diversion mean values (Appendix B2). In contrast, sediments were less coarse and more fine-grained following effluent diversion at stations NF12, NF17, FF12, and FF14. Post-diversion mean values decreased significantly compared to the baseline mean values for gravel content at station FF14 ($p = 0.012$) and for sand content at stations FF12 ($p = 0.026$), NF12 ($p = 0.006$), and NF17 ($p = 0.026$) (Appendix B2). A coincident and significant increase in silt content was observed at stations NF12 ($p = 0.019$) and NF17 ($p = 0.035$), whereas clay content increased at stations FF12 ($p = 0.036$) and FF14 ($p = 0.044$) (Appendix B2). The observed changes in grain-size distributions do not appear to be outfall related, as there were no clear trends (*e.g.*, increasing fines and TOC) observed at stations located near or far from the outfall. For example, among the stations located near the outfall, sediments coarsened at station NF24, were more fine-grained at station NF17, and were unchanged (no significant difference) at NF13, NF14 and NF15. Changes in grain-size distributions are more likely associated with natural fluctuations in the bay, which are expected in a dynamic system influenced by physical forces such as severe weather events.

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[2] Median values for station or group (transition area; <2 km from outfall; >2 km from outfall; farfield) are based on data from the entire monitoring period (1992–2007).
[3] Small changes in sand content between sampling periods at NF17 (decreased from a mean of 98.3% in baseline to 97.3% during post-diversion monitoring) and FF12 (decreased from a mean of 69.7% in baseline to 64.8% during post-diversion monitoring).
[4] More substantial changes in sand content between sampling periods at NF12 (decreased from a mean of 29.8% in baseline to 19.5% during post-diversion monitoring) and NF24 (increased from a mean of 36.1% in baseline to 55.7% during post-diversion monitoring).

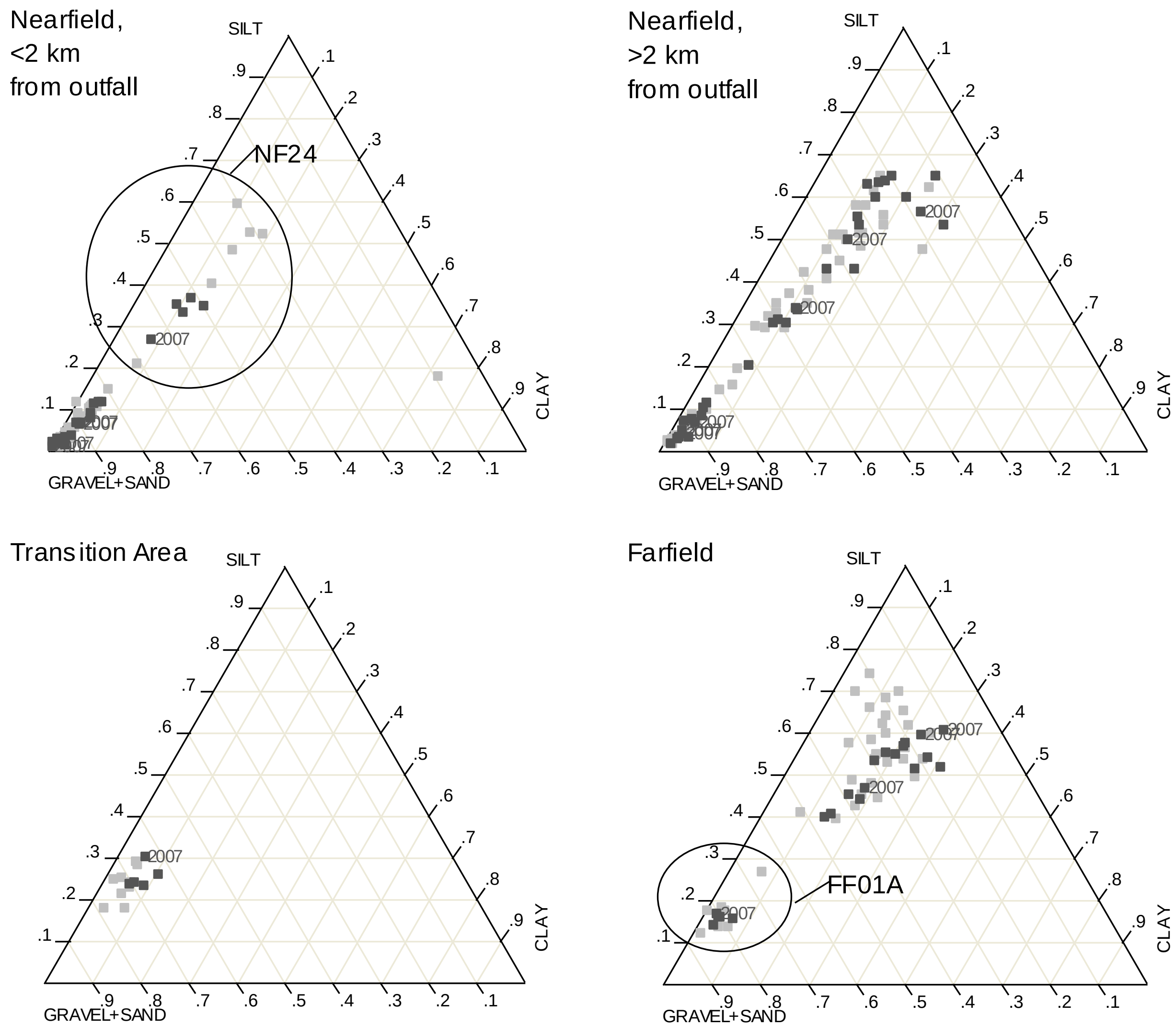


Figure 3-1. The distribution of percentages gravel+sand, silt, and clay at nearfield and farfield stations during baseline (1992–2000, gray filled squares) and post-diversion (2001–2007, black filled squares; 2007 data labeled) periods. Nearfield data are grouped according to three distance categories: <2 km from the outfall, > 2 km from the outfall, and the transition area between Boston Harbor and the outfall.

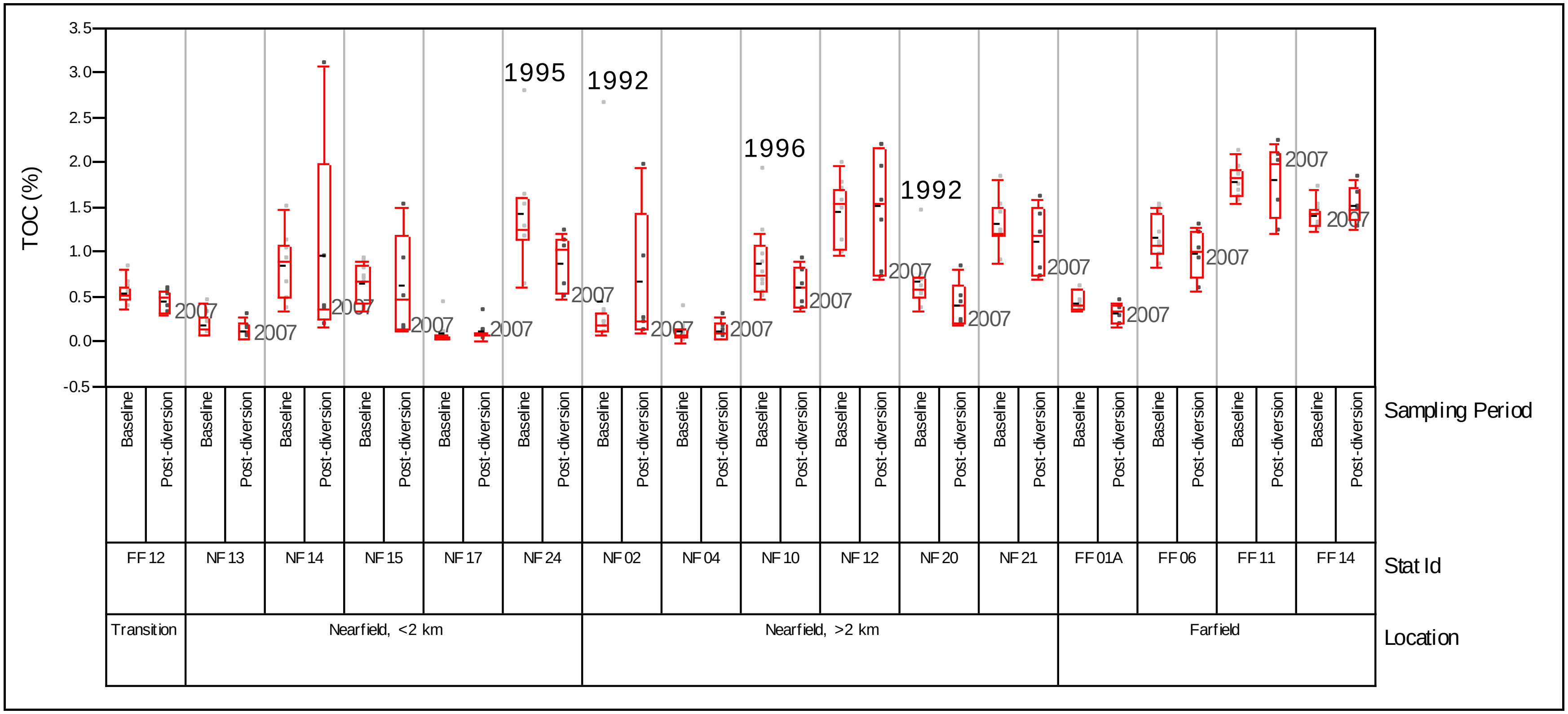


Figure 3-2. Distribution of TOC in nearfield and farfield sediments during baseline (1992–2000) and post-diversion (2001–2007; 2007 data labeled) sampling periods. Nearfield data are grouped according to three distance categories: transition area located between Boston Harbor and the outfall, <2 km from the outfall, and > 2 km from the outfall. The ends of the box represent the 25th and 75th quartiles, the line across the middle represents the median value, and the dashed line across the middle represents the mean value. The vertical lines are "whiskers" that extend from the ends of the box to the outermost data point that falls within the distances computed (a distance of 1.5 X the interquartile range, difference between 25th and 75th quartiles). Data points above or below the whiskers represent possible outliers.

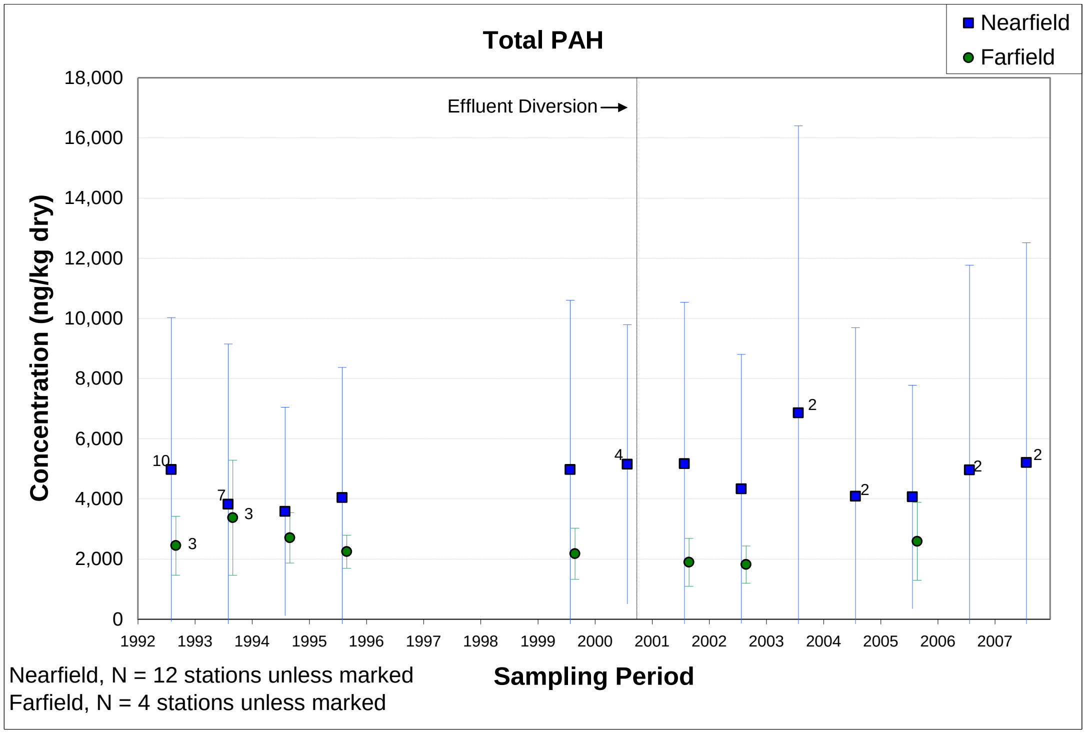
3.3.2 Anthropogenic Contaminants

Concentrations of anthropogenic contaminants in sediment at the two stations (NF12 and NF17) sampled in 2007 were generally within the ranges of values measured over the larger monitoring period (1992–2006). Long-term monitoring data (1992–2007) show that contaminant concentrations in surface sediments in Massachusetts and Cape Cod Bays are highly variable, which often reflects differences in sediment grain-size characteristics and TOC (representative contaminants, total PAH and copper, are shown in Figures 3-3 and 3-4; all data are in Appendix B3). A chemometric assessment of the 1992–2002 sediment data (Maciolek *et al.* 2003) confirmed that the primary factor associated with the variance in the chemical data was sand content (*i.e*., high percent sand was inversely correlated with chemical concentrations which presumably reflected the dilution of organic and inorganic analytes with sand), and that secondary factors were associated with anthropogenic analytes and fine particles. Physical forces, such as severe weather events, that can impact the sediment bed can also indirectly influence chemical concentrations. For example, the observed decrease in concentrations of crustal metals, including aluminum, chromium, iron, and nickel, in nearfield and farfield sediments in 2005 (Appendix B3, Figures B3-6, B3-8, B3-10, and B3-13) was attributed to the May 2005 nor'easters that caused winnowing of the sediments (Maciolek *et al.* 2006). Local storms did not appear to affect sediments and chemical concentrations in 2007.

While nearfield sediments are typically coarser and contain lower organic carbon content compared to farfield sediments, annual mean concentrations of some anthropogenic contaminants (*i.e*., total PCB, total PAH, silver, mercury, lead, and copper) are higher in nearfield sediments compared to farfield sediments (total PAH and copper shown in Figures 3-3 and 3-4; all data in Appendix B3). The higher contaminant concentrations likely reflect the proximity of nearfield sediments to the historic leading source of contamination, Boston Harbor. Annual mean concentrations of crustal metals aluminum, iron, nickel, and zinc were slightly higher in farfield sediments than in nearfield sediments (Appendix B3). These findings were consistent with the chemometric assessment, which showed that most farfield sediments contained high silt and clay without a large anthropogenic chemical content (Maciolek *et al.* 2003). The chemometric assessment also showed that anthropogenic contaminant concentrations appear to decrease over time (based on the evaluation of 1992–2002 sediment data), suggesting that inputs to nearfield sediments associated with the historical discharges of untreated or inadequately treated sewage from Boston Harbor have decreased (Maciolek *et al.* 2003). A statistical analysis of the long-term monitoring data (1992–2007) confirmed that the post-diversion mean concentrations of total DDT, total CHLOR, and total PEST decreased significantly (at the 95% level of confidence, p values range from <0.0001 to 0.023) compared to the baseline mean value at the nearfield region of Massachusetts Bay (Appendix B2). Significant decreases in post-diversion mean concentrations of total DDT, total CHLOR, and total PCB were also observed at the farfield regions of Massachusetts and Cape Cod Bays (p values range from 0.001 to 0.026, Appendix B2). The observed decreases in total DDT and total PCB concentrations are likely associated with reduced inputs resulting from the banning of these chemicals in the 1970s and 1980s and the gradual winnowing of the chemicals from the sediment. The observed decreases in total CHLOR and total PEST occurred in the mid-1990s (Appendix B3, Figures B3-4 and B3-5), and could be associated with remediation activities, including source reduction actions and improvements to sewage treatment, which have reduced the loading of contaminants to coastal Massachusetts.

A station-specific evaluation of the sediment data showed that most of the post-diversion data were within the general range of data for samples collected during the baseline period (total PAH and copper shown in Figures 3-3 and 3-4, all data in Appendix B3). Localized increases and/or decreases in post-diversion data at one or more stations have been observed in the MWRA program (Maciolek *et al.* 2006). Briefly, substantive increases above the baseline range were observed for total DDT at NF21 (2001), copper at NF14 (2001), and lead at NF15 (2002). Contaminant concentrations returned to baseline in subsequent sampling events and the localized increases were attributed to analytical interferences, random spikes, or unknown contamination (Maciolek *et al.* 2006). Small but widespread increases above the baseline range were observed for aluminum in 2002. The aluminum increase was probably associated with small changes in grain-size distributions, rather than due to a chemical factor. Aluminum concentrations returned to baseline in later surveys, but localized increases were observed again in 2007 at stations NF12 and NF17. Widespread decreases below the baseline range were observed for nickel in 2005; the widespread decrease was attributed to storm-induced effects to the sediment bed from the May 2005 nor'easters (Maciolek *et al.* 2006).

Although drawing definitive conclusions is confounded by the large intra- and inter-annual variability observed in the data, overall the system response seven years since outfall startup suggests that diversion of treated effluent discharge to the Massachusetts Bay outfall has not caused widespread or systematic increases in anthropogenic contaminants of environmental concern to the Bay system.



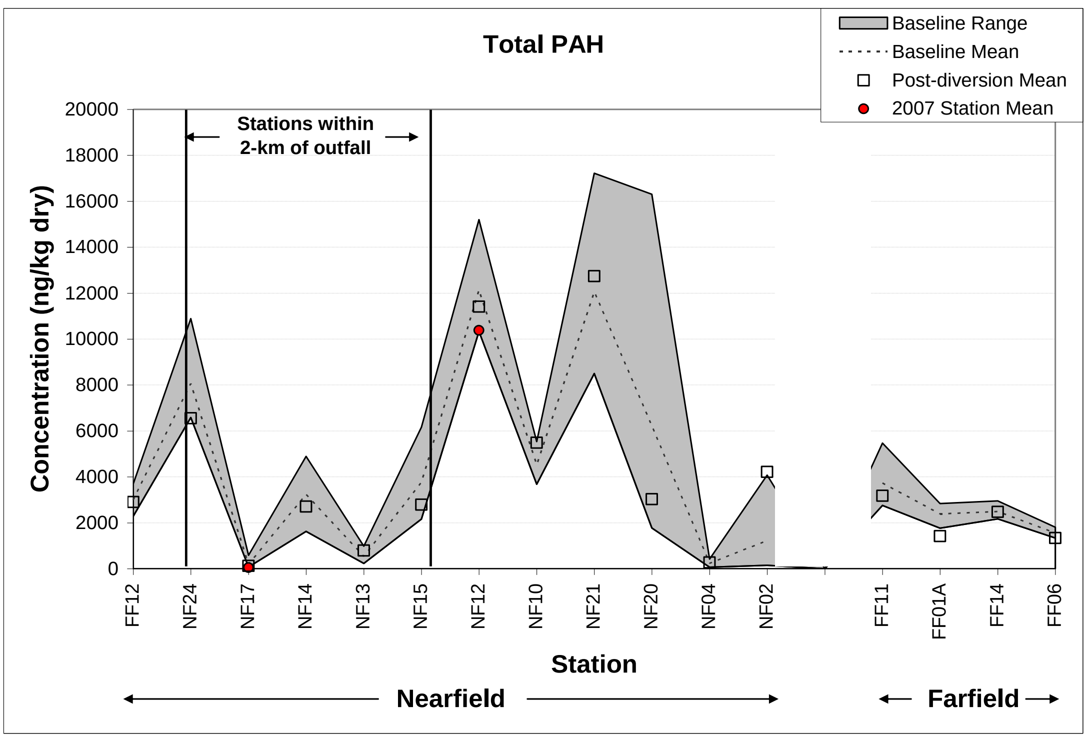


Figure 3-3. Temporal (top) and spatial (bottom) trends in total PAH in the nearfield and farfield regions of Massachusetts and Cape Cod Bays, 1992 to 2007. Temporal trends (top) are illustrated using the yearly mean abundance (i.e., the average of all stations and replicates for a given year, by region); vertical bars represent one standard deviation. Spatial trends (bottom) are illustrated using range plots, where the range of values during baseline (1992–2000) is represented by the grey band, the baseline mean is the dashed line within the gray band, and post-diversion data are represented by symbols.

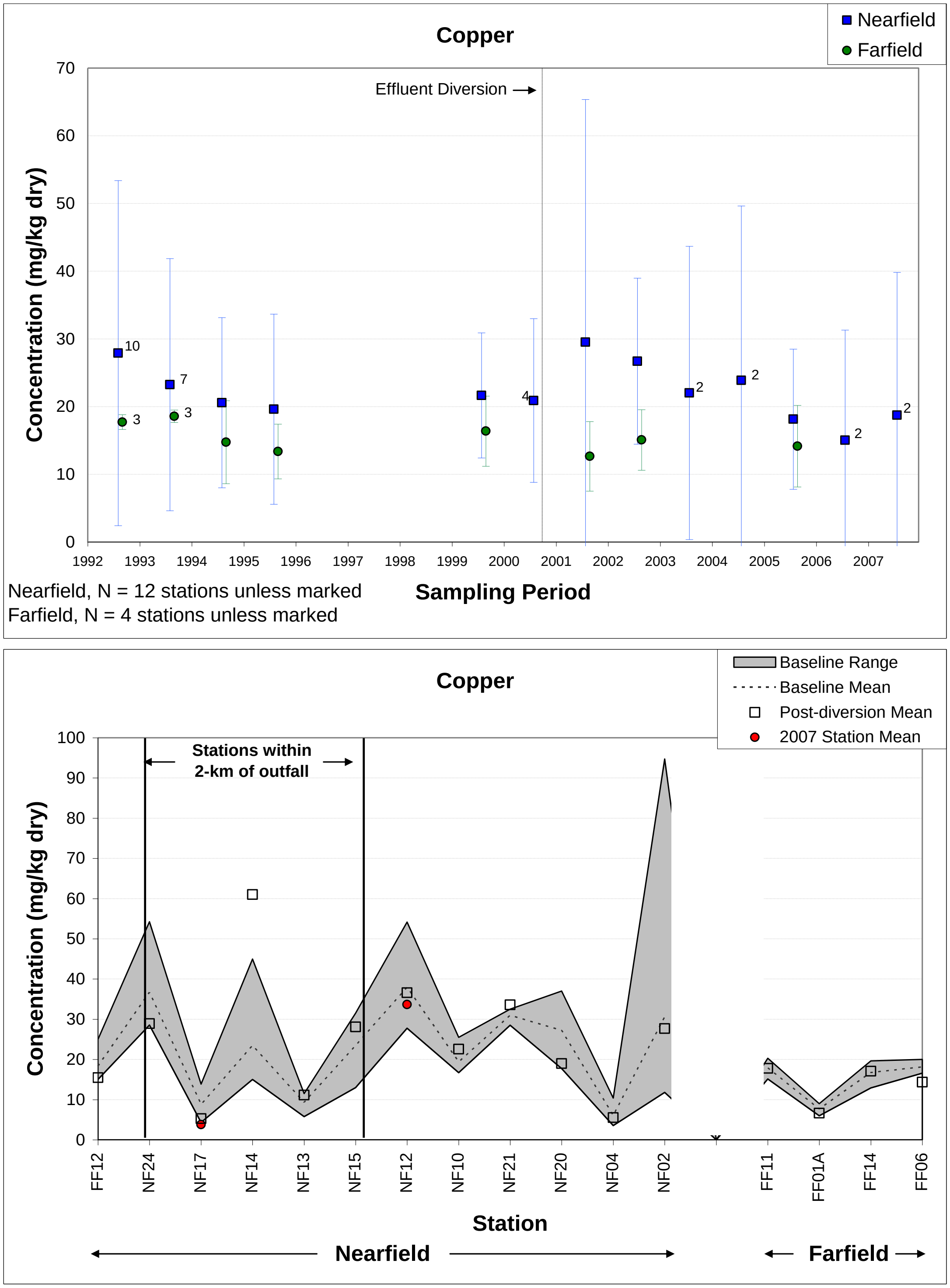


Figure 3-4. Temporal (top) and spatial (bottom) trends in Copper in the nearfield and farfield regions of Massachusetts and Cape Cod Bays, 1992–2007. Temporal trends (top) are illustrated using the yearly mean abundance (i.e., the average of all stations and replicates for a given year, by region); vertical bars represent one standard deviation. Spatial trends (bottom) are illustrated using range plots, where the range of values during baseline (1992–2000) is represented by the grey band, the baseline mean is the dashed line within the gray band, and post-diversion data are represented by symbols.

3.3.3 Sewage Tracer *Clostridium perfringens*

The 2005 Toxics Issue Review (Hunt *et al.* 2006) indicated that understanding the response of sewage tracers in sediments to the Boston Harbor cleanup effort provides a means of evaluating how the system reacted when the intensity of sewage sources was reduced in the 1990s. One of the most commonly used tracers of sewage-derived sources in marine systems is *Clostridium perfringens*, an anaerobic bacterium common to the intestinal tract of mammals (Emerson and Cabelli 1982).

From a system-wide perspective, *C. perfringens* abundances were generally higher and more variable in the nearfield region of Massachusetts Bay than in the farfield (Figure 3-5). Abundances decreased with increasing distance from Boston Harbor, and the lowest abundances (<50 cfu/g dw/% fines) were measured at farfield stations located more than 20 km from Deer Island Light (Figures 3-5 and 3-6). Annual mean abundances of *C. perfringens* decreased in the late 1990s at nearfield locations (Figure 3-5), likely from the Boston Harbor cleanup efforts (*e.g.*, secondary treatment) which resulted in a reduction in wastewater solids discharge to the system (Hunt *et al.* 2006). Nearfield abundances increased one year after effluent diversion (*i.e.*, 2001) compared to 2000 pre-diversion values (Figures 3-5 and 3-6). This pattern generally held through 2007, although abundances were unusually low in 2006 compared to other post-diversion years (Figure 3-5). While the 2006 decrease was also evident in the even-year station set (n = 11), an obvious explanation for the decrease (*e.g.*, sampling or analytical method issue, cleaner effluent, or physical processes) is not evident. Sampling and analysis methods used in 2006 were comparable to previous years, nor were any issues that could have compromised sample integrity documented. It is also unlikely that a cleaner effluent was discharged in 2006 compared to 2005 or 2007. Sufficient data are not available to assess the impact of physical processes, such as biological processes or sediment layering that could have preferentially diluted the abundances of *C. perfringens* in 2006. Finally, the 2006 decrease does not appear to be an artifact of the reduced monitoring program, as stations NF12 and NF17, which are sampled every year (not just during odd or even years) responded similarly in 2006 (decrease) and 2007 (increase).

The nearfield-wide post-diversion increase in *C. perfringens* abundances is attributed, in large part, to increased abundances at stations located within 2 km of the outfall (Figures 3-5 and 3-6). A statistical analysis confirmed that the post-diversion increase in the nearby sediments is significant (p = 042, Appendix B2). These findings are consistent with conclusions drawn from the USGS sediment trap program (Bothner and Butman 2005), which showed statistically higher *C. perfringens* abundances in post-diversion samples collected about 1 km south of the outfall. The USGS sediment trap data and the MWRA data provide complementary evidence regarding the strength of the outfall signature in Massachusetts Bay and increase the confidence in the ability of the monitoring program to document the transport and fate of the effluent-related contaminants discharged in Massachusetts Bay. Sediment core data (surface 0-0.5 cm interval) from the same USGS study, however, showed no significant change in *C. perfringens* abundances following effluent diversion. According to Bothner and Butman (2005), the sediment traps may be a more sensitive method for identifying outfall-related chemical changes than analysis of surficial bottom sediments which are continuously mixed and diluted with older sediment of different composition. The ability of the MWRA's monitoring to detect this change in surficial sediments could be attributed to the spatially replicated sampling design, and documents the importance of the sampling design when evaluating the impact of a relatively clean discharge on coastal sediments with a history of modest levels of contamination.

The statistical analysis also showed that the post-diversion mean abundances of the sewage tracer *C. perfringens* (log transformed) decreased significantly (at the 95% level of confidence), compared to baseline, at the transition ($p = 0.003$) and farfield ($p = 0.003$) regions of Massachusetts and Cape Cod Bays (Appendix B2). Clearly the long-term monitoring data for *C. perfringens* illustrates the major improvements in sewage treatment implemented by the MWRA over the last decade.

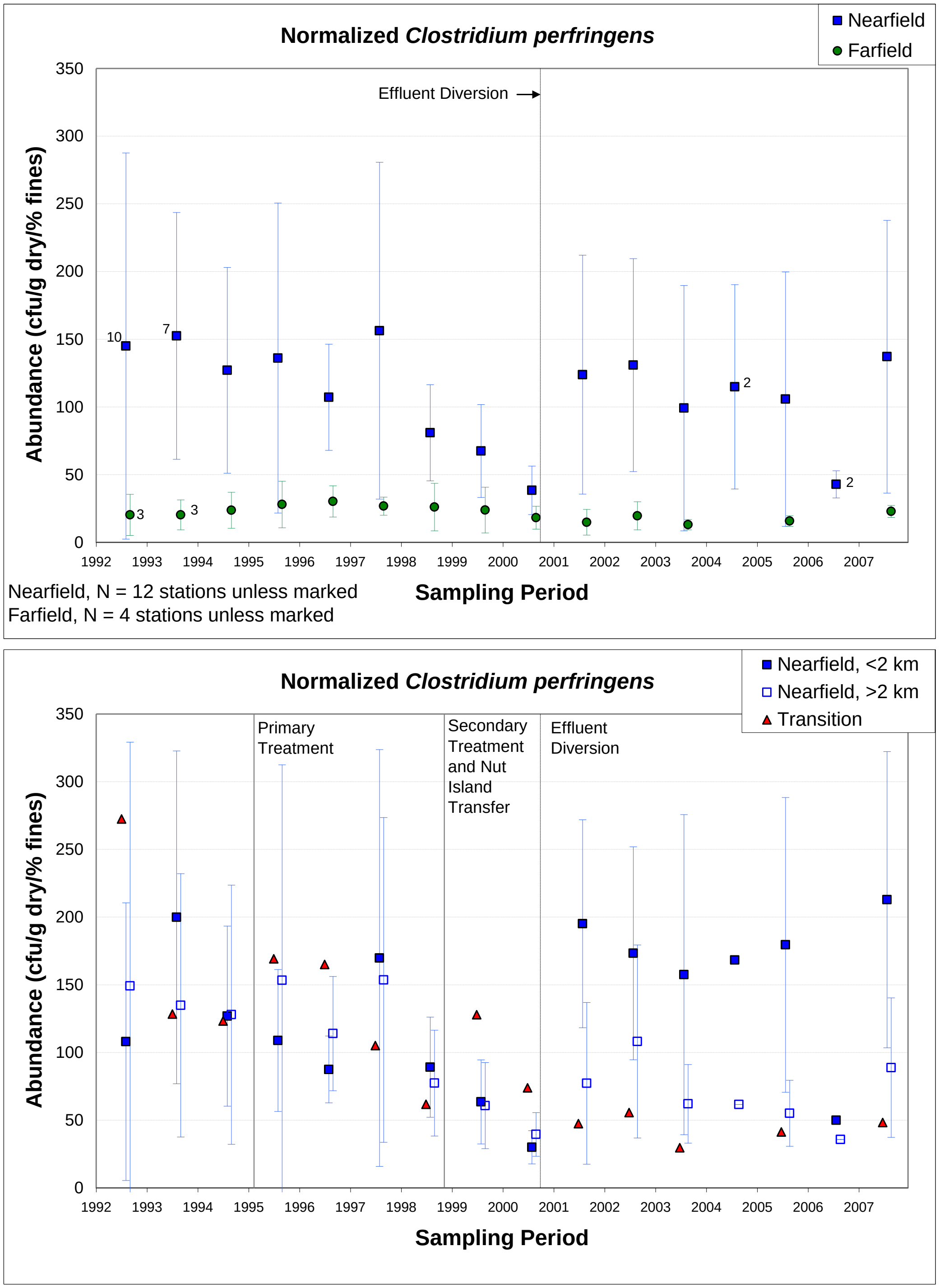


Figure 3-5. Yearly mean abundance of *Clostridium perfringens*, normalized to percent fines, in nearfield and farfield sediments, 1992 to 2007. The top plot illustrates the nearfield and farfield data following effluent diversion in 2000. The bottom plot shows that the nearfield increase is largely associated with stations located within two kilometers of the outfall, relative to the other nearfield and transition area stations. Yearly mean abundance is the average of all stations and replicates for a given year, by region. Vertical bars represent one standard deviation.

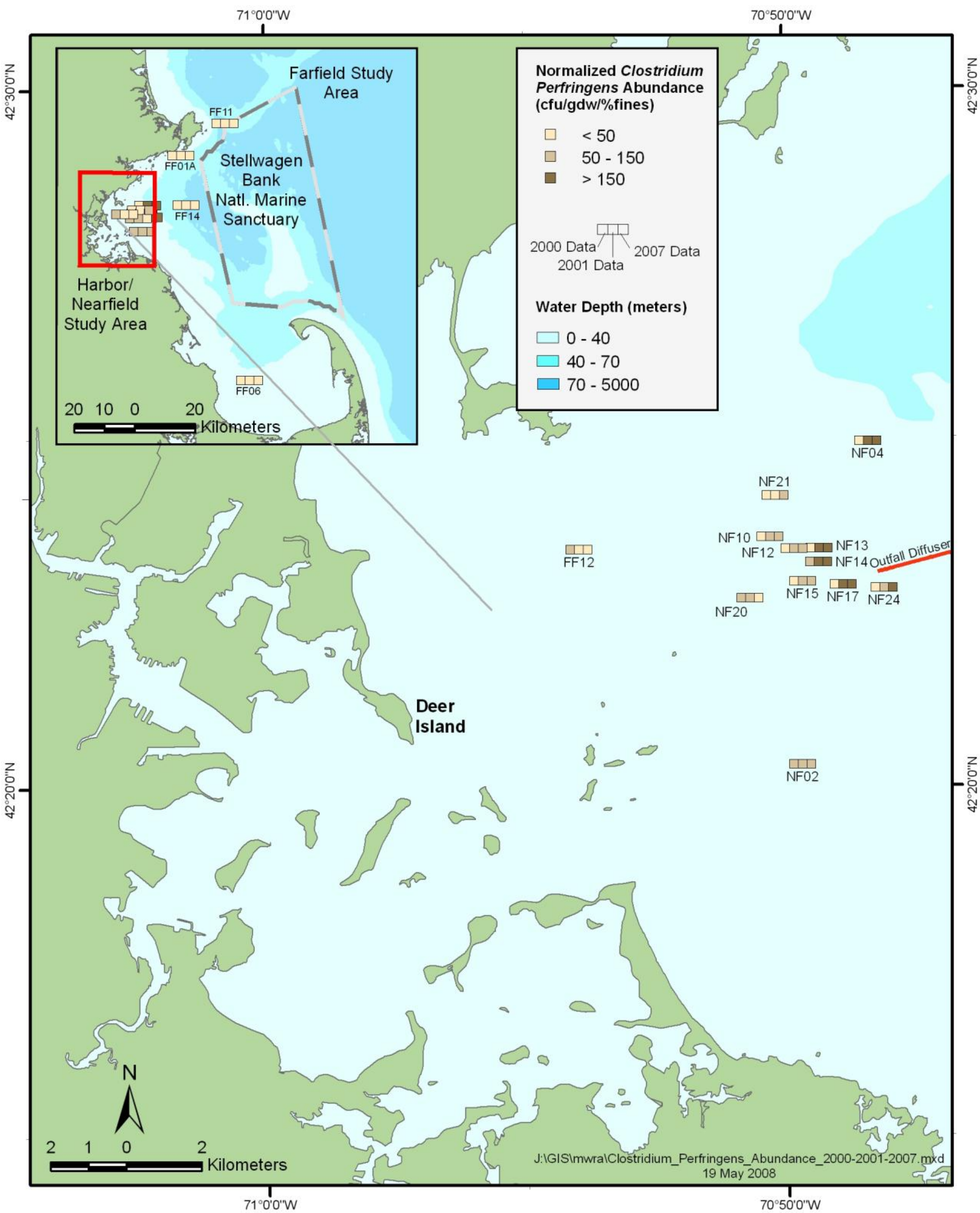


Figure 3-6. Pre-diversion (2000) and post-diversion (2001, 2007) station mean abundances of *Clostridium perfringens*, normalized to percent fines, as a function of distance from Deer Island Light at the entrance to Boston Harbor.

3.3.4 Sediment Correlations

Many anthropogenic contaminants measured in nearfield and farfield sediments during the 1999–2007 monitoring period correlated well with sediment grain size and organic carbon content. Contaminants were positively correlated with percent fines (or negatively correlated with sand content, consistent with chemometric assessment, which showed that the primary factor associated with the variance in the data was sand content) and TOC. These findings indicate that fine-grained sediments with higher organic carbon content characteristic of depositional environments generally contain higher contaminant concentrations, and coarse-grained sediments with lower organic carbon content typically contain lower contaminant concentrations. Results from the correlation analysis are provided in Appendix B4.

The correlation between percent fines and TOC yielded *r* values ranging from 0.84 to 0.92 (Appendix B4), which indicates that about 70% to 80% of the variation in the grain size and TOC data (at nearfield and farfield locations) is related. The correlation (*r*) between the sewage tracer *C. perfringens* and percent fines or TOC ranged from 0.68 to 0.90 (Appendix B4), which indicates that approximately 46% to 80% of the variation in the data is related. The correlations between anthropogenic analytes and percent fines or TOC were also moderate to moderately strong, with *r* values typically 0.5 or higher, indicating that 25% or more of the variation in the data is related.

There are some subtle differences in the correlations among sediment variables between nearfield and farfield regions during the 1999–2007 monitoring period. For example, many organic contaminants (*i.e.*, total DDT, total PAH, total PCB, and total PEST) have slightly stronger correlations with percent fines and TOC at nearfield locations compared to farfield locations (Figure 3-7). Metals as a group did not consistently have stronger correlations with percent fines and TOC at a given region of the bay. Rather, aluminum, cadmium, mercury, and silver typically have stronger correlations at nearfield locations, whereas chromium, iron, and lead typically have stronger correlations at farfield locations (Figure 3-7).

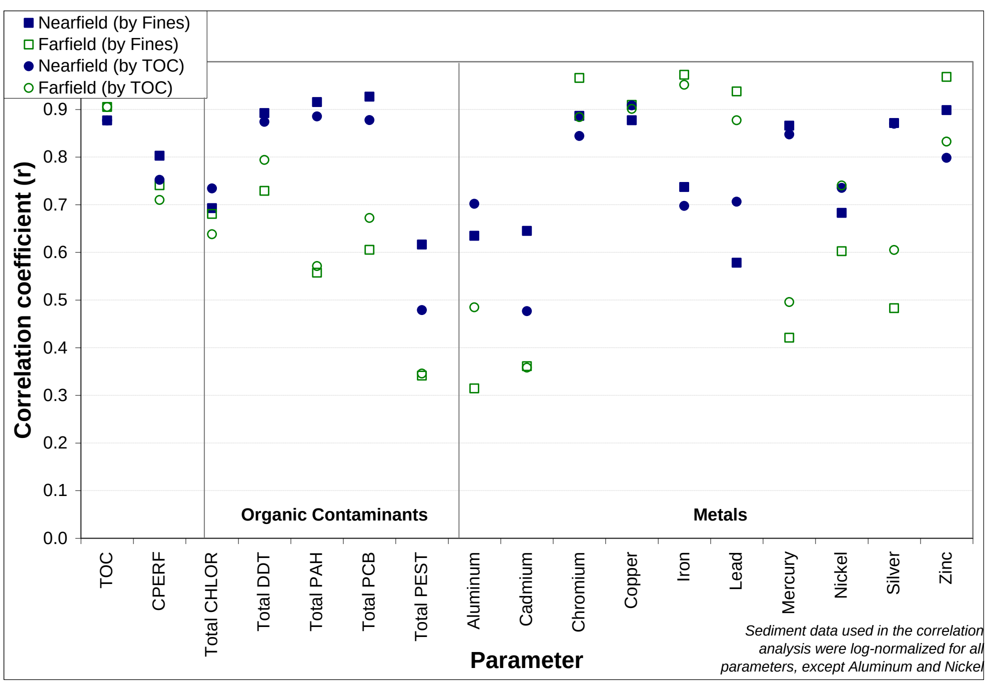


Figure 3-7. Pearson pair-wise correlation coefficient (r) values among sediment variables and percent fines (square symbols) or TOC (circle symbols) at nearfield and farfield locations, 1999 to 2007.

Comparison of the correlations among sediment variables between the baseline and post-diversion monitoring periods did not reveal an outfall impact. Rather, the correlations among most sediment variables were comparable (*i.e.*, *r* values within 30% RPD and similar *p* values) between sampling periods, especially at nearfield locations (Appendix B4, Table B4-2). Substantive changes in the correlations among sediment variables occurred more frequently at the farfield (Appendix B4, Table B4-3), which could be an artifact of limited data available for analysis (n < 12) and the lower contaminant concentrations typical of farfield sediments.

The correlation analysis also showed that the proximity to the primary historic source of contaminants, Boston Harbor, influenced the contaminant concentrations in nearfield and farfield sediments. Nearfield sediments that had grain-size distributions similar to farfield sediments generally had higher concentrations of many anthropogenic contaminants compared to farfield values, especially for organic contaminants (total PAH shown in Figure 3-8; all data in Appendix B4). Anthropogenic concentrations present at levels above the underlying farfield signature are indicative of proximity to local sources (*e.g.*, Boston Harbor, Salem Harbor), as evidenced by a higher slope value from the regression analysis for nearfield data compared with farfield data (total PAH shown in Figure 3-8; all data in Appendix B4). Anthropogenic concentrations at farfield locations are primarily influenced by widely distributed sources (*e.g.*, atmospheric input, distant rivers). The chemometric assessment (conducted in 2002 using 1992–2002 data) supported this and showed that the composition of sediments at farfield sampling sites may reflect regional inputs that are distinct from Boston Harbor (Maciolek *et al*. 2003).

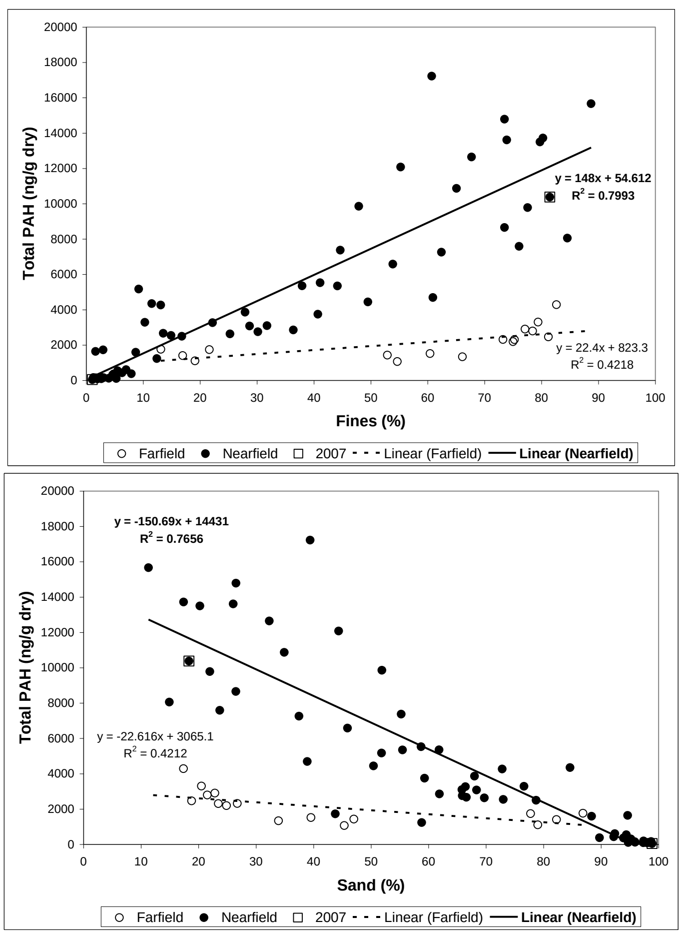


Figure 3-8. Correlation between total PAH and percent fines (top) or percent sand (bottom) in nearfield and farfield sediments, 1999–2007.

3.3.5 Sediment Quality

Complete sediment quality assessments are complex and can incorporate any of several measurement approaches, including biological characteristics, toxicological data, chemical data, and combinations of these attributes. The only long-term information on sediment quality in Massachusetts and Cape Cod Bays is the chemical and benthic infauna community data collected by MWRA. The benthic infauna data have not revealed broad scale infaunal community impairment from outfall diversion (Chapter 5, this report). Sediment data for 26 chemicals were compared against SQGs (Long *et al.* 1995) to evaluate potential changes or trends in sediment quality over the course of the monitoring period (1992–2007). The number of sediment stations with chemical data used in the evaluation ranged from 2 to 16 depending on the monitoring year (*e.g.*, two stations sampled in 2003, 2004, 2006, and 2007; 16 stations sampled in 1994, 1995, 1999, 2001, 2002, and 2005; no data available for 1996–1998). Results are summarized below; complete details are provided in Appendix B5.

The number of chemicals with concentrations above the SQGs, at any given station and monitoring year, ranged from 0 to 24 out of a maximum of 26 potential SQG exceedances. The number of SQG exceedances appears to be influenced by proximity to the historic source of contaminants (Boston Harbor) and differences in bulk sediment characteristics (grain size and TOC). For example, nearfield sediments typically have more SQG exceedances than farfield sediments (Figure 3-9). Further, sediments with higher percentages of fines (silt+clay) and TOC content typically have more SQG exceedances than coarse-grained sediments with low TOC content (Figure 3-9). For example, nearfield stations NF12, NF21, and NF24 had the highest number of SQG exceedances and the highest median values for percent fines and TOC content during the 1992–2007 monitoring period.

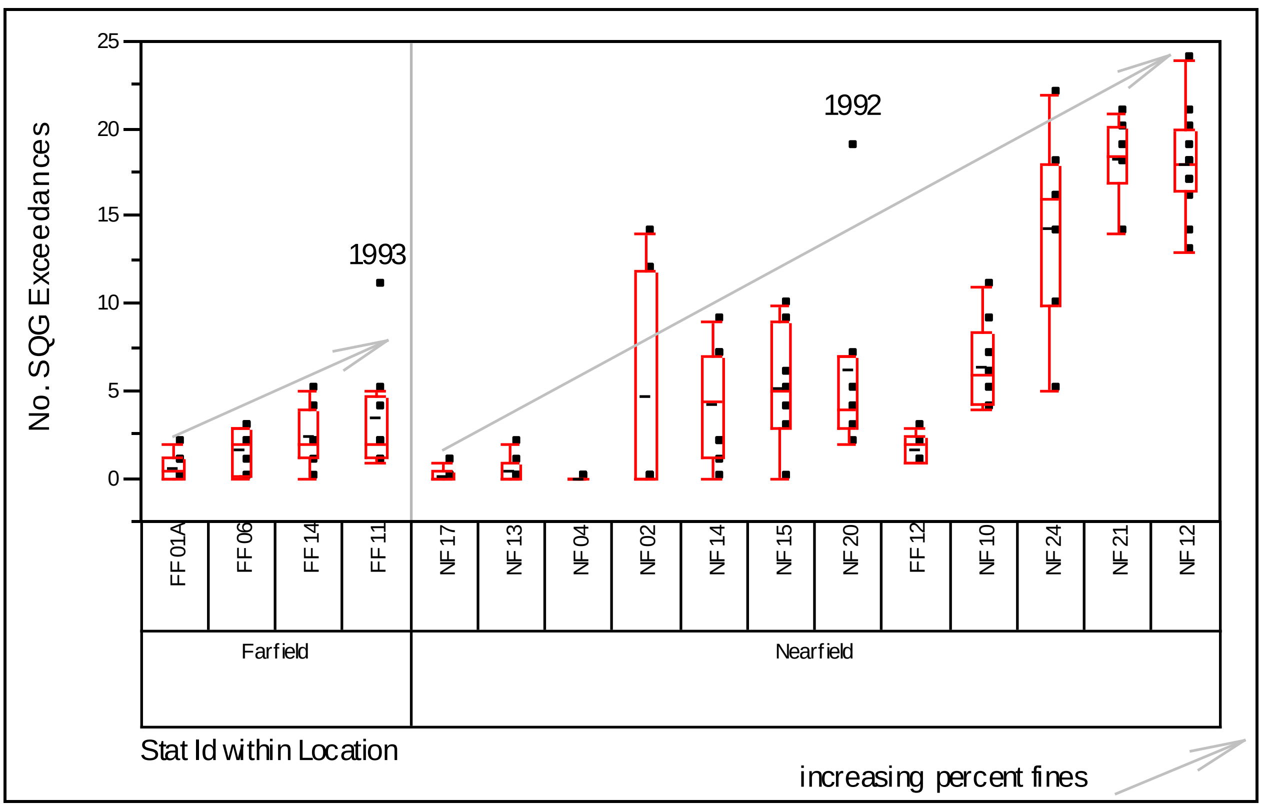


Figure 3-9. Distribution of SQG exceedances at farfield and nearfield stations during the 1992 to 2007 monitoring period. Within each region, stations are sorted by increasing percent fines.

Most SQG exceedances were attributed to chemicals with concentrations above the ER-L. Chemical concentrations above the ER-M occurred rarely, and primarily during the early 1990s. Many chemicals contributed to the overall number of SQG exceedances; however, fluorene, mercury, and acenaphthene were among the most frequent chemicals to exceed the SQGs (Appendix B5, Tables B5-1 through B5-3). Concentrations of cadmium were below the SQGs at all stations and during all sampling events.

There were no significant changes in the number of SQG exceedances between the baseline and post-diversion periods at the nearfield region of Massachusetts Bay (Figure 3-10, Appendix B2). While station NF24 has not been sampled annually (data available for 1994–1995, 1999–2002, and 2005), the number of SQG exceedances appears to decrease over time (Appendix B5). The decrease may be associated with a coarsening of grain size at this station between the baseline and post-diversion periods (Figure 3-1). A significant decrease (at the 95% confidence level, $p = 0.035$, Appendix B2) in the number of SQG exceedances was observed at the farfield regions of Massachusetts and Cape Cod Bays between the baseline and post-diversion periods (the decrease is significant even if FF11 in 1993, an apparent outlier as shown in Figure 3-10, is excluded). The farfield decrease is largely attributed to station FF11, located at Cape Ann. The number of SQG exceedances has decreased at station FF11 since the mid-1990s, which likely reflects remediation activities including source reduction actions and improvements to sewage treatment that have reduced contaminant loadings to the system. Overall, the comparison of baseline and post-diversion data to SQGs for 26 chemicals suggests that sediment quality in Massachusetts and Cape Cod Bays has not been dramatically or adversely impacted as a result of effluent diversion to the bay.

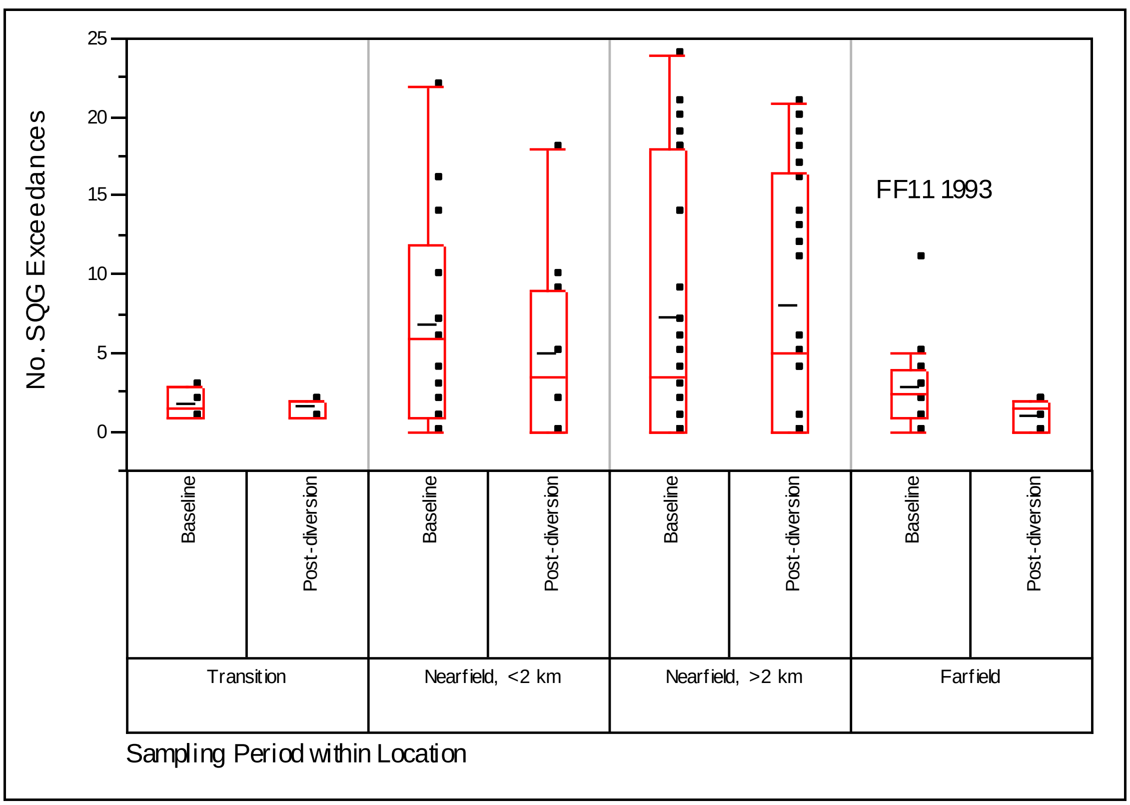


Figure 3-10. Distribution of SQG exceedances at nearfield and farfield regions of Massachusetts and Cape Cod Bays between the baseline (1992–2000) and post-diversion (2001–2007) periods. Nearfield data are grouped according to three distance categories: the transition area located between Boston Harbor and the outfall; <2 km from the outfall, and > 2 km from the outfall.

3.4 Monitoring Questions

Relocation of the MWRA outfall to Massachusetts Bay raised environmental concerns regarding potential effects of the diverted discharge on the sea floor. These concerns focused on three issues: eutrophication and related low levels of dissolved oxygen, accumulation of toxic contaminants in depositional areas, and smothering of animals by particulate matter (MWRA 1991, 1997). This section focuses on the second issue, accumulation of potentially toxic contaminants. Sediment monitoring conducted under the Benthic (Sea Floor) Monitoring component of the MWRA HOM program was designed to address specific monitoring questions.

- *Have the concentrations of contaminants in sediment changed?*

The long-term monitoring data (1992–2007) show that concentrations of anthropogenic contaminants in surface sediments at nearfield and farfield regions of Massachusetts and Cape Cod Bays are spatially and temporally variable and reflect differences in sediment characteristics, such as grain-size distributions and TOC content, rather than an outfall effect. For example, storm-induced impacts to the sediment bed following the May 2005 nor'easters likely contributed to a coarsening of sediment grain-size distributions and a corresponding decrease in 2005 in concentrations of aluminum, chromium, iron, and nickel, which are primarily crustal in nature.

Post-diversion mean concentrations of total DDT, total CHLOR, and total PCB decreased significantly (at the 95% level of confidence) at farfield regions of the Massachusetts and Cape Cod Bays compared to the baseline. Post-diversion mean concentrations of total DDT, total CHLOR, and total PEST also decreased significantly at nearfield region of Massachusetts Bay. Decreases in total DDT and total PCB may be associated with the banning of these chemicals in the 1970s and 1980s, which in turn reduced inputs of these chemicals to the system. Decreases in total CHLOR and total PEST that occurred since the mid-1990s could be associated with remediation activities including source reduction actions and improvements to sewage treatment, which have reduced the loading of contaminants to coastal Massachusetts. Overall, sediment data to date indicate that post-diversion (2001–2007) concentrations of most anthropogenic contaminants have not changed substantively compared to the baseline (1992–2000).

- *What is the level of sewage contamination and its spatial distribution in Massachusetts and Cape Cod Bays sediments before discharge through the new outfall?*

Clostridium perfringens abundances (not normalized to percent fines) measured in surface sediments throughout Massachusetts and Cape Cod Bays ranged[5] from 63 cfu/g dry weight (NF17 in 2000) to 24,100 cfu/g dry weight (NF21 in 1997) prior to diversion. In general, *Clostridium* abundances were low throughout the bay, with slightly higher levels observed closer to Boston Harbor. Abundances generally decreased with distance from the harbor, with farfield sediments located far away from Boston Harbor (>20 km) having the lowest *C. perfringens* abundances.

- *Has the level of sewage contamination or its spatial distribution in Massachusetts and Cape Cod Bays sediments changed after discharge through the new outfall?*

Abundances of *C. perfringens* increased one year after effluent diversion at stations located within 2 km of the outfall. This pattern generally held through 2007, although abundances were unusually low in 2006 compared to other post-diversion years. An explanation for the low abundances in 2006 is not evident. A

[5] Range of *C. perfringens* abundances based on 'odd' sampling year stations, station mean values.

statistical analysis confirmed the post-diversion increase in *C. perfringens* abundances (log-transformed) at nearby sediments is significant.

The post-diversion mean abundances of *C. perfringens* (log-transformed) decreased significantly compared to the baseline means in the transition and farfield regions of Massachusetts and Cape Cod Bays. Most anthropogenic contaminant data did not show this response.

3.4.1 Conclusions

Consistent with predictions of the SEIS for the Massachusetts Bay outfall (EPA 1988), the transfer of the MWRA effluent discharge into Massachusetts Bay has not resulted in a general widespread increase of anthropogenic contaminants in the sediment, nor in specific depositional areas. Moreover, comparison of the long-term monitoring data to SQGs for 26 chemicals suggests that the effluent has not caused substantive changes in the quality of the environment near to or far from the outfall location. There was a clear signature of effluent discharge on nearby sediments following effluent diversion, whereas post-diversion mean abundances of *C. perfringens* decreased significantly in the transition area and farfield compared to the baseline mean values. The *C. perfringens* data clearly trace the major improvements to sewage treatment implemented by the MWRA, which have dramatically reduced the loading of contaminants under their control to coastal Massachusetts.

4. 2007 SEDIMENT PROFILE IMAGING

by Robert J. Diaz

4.1 Status of the Bay

The MWRA offshore outfall is located about 13 to 15 km off Boston Harbor along the inner edge of Massachusetts Bay in an area of complex and variable seafloor morphology and sediment texture that changes over a multitude of scales from a few kilometers to tens of meters (Butman *et al.* 2004). The area encompassing the outfall was designated as the nearfield (see Chapter 2 this report; Figure 4-1). Starting in 1992, Sediment Profile Images (SPI) were collected at a set of unconsolidated sediment stations to gather baseline data on benthic habitat conditions for infaunal communities and the depth of the apparent color redox potential discontinuity (RPD) layer as described in the MWRA's Contingency Plan (MWRA 2001). Multibeam mapping of the nearfield allowed for the analysis of the complex topography and how it may relate to benthic habitat quality. Ten of the nearfield stations were located in a relatively flat topographic feature, which included the outfall, and areas west and south of the outfall at depths of 30–35 m (Figure 2-1, Figure 4-1). Another 13 stations were scattered around the outfall, primarily to the west. The baseline included six annual August collections from 1992 to 2000. In September 2000, the offshore outfall went into operation, thus annual August data collected from 2001 to 2006 represent post-diversion conditions in the nearfield.

For assessing outfall effects, the MWRA (1997) set a 50% reduction in the apparent color RPD layer depth over the study area as a critical trigger level since the RPD is an integrated measure of biogeochemical processes in surface sediments. The dynamics of the RPD layer are related principally to the interaction of physical and biological processes that structured surface sediments and infaunal communities. Over the baseline period the grand mean RPD depth was 2.3 cm (SE = 0.35). The mean annual RPD layer depth varied from a low of 1.8 cm (SE = 0.13 to 0.14) in 1997 and 1998 to a high of 3.0 cm (SE = 0.22) in 1995. In 1997, due to technical problems, sampling occurred in both August and October, which may have contributed to shallower RPD layers since the RPD layer becomes seasonally shallower in the fall. The deepest mean RPD layer depth was 3.4 cm in 2007 (Figure 4-2).

The two biggest increases in the depth of the RPD layer between successive samplings was 0.5 cm from 1998 to 1999 and 0.6 cm from 2005 to 2006. The 1998 to 1999 deepening appeared to be associated with an increase in the levels of biogenic activity following the 1998 low-storm-frequency winter (Butman *et al*. 2008) that allowed for the preservation of biogenic structures. The increased occurrence of Stage II communities in 1998 and 1999, and Stage III in 1999 (Figure 4-3), was a key factor in the deepening of the RPD. It appeared that successional Stage I pioneering communities dominated the nearfield stations from the start of SPI sampling in 1992 through 1997. Starting in 1998, it appeared that intermediate successional Stage II communities dominated to the end of the baseline period in 2000 and into 2004. In 2005 and 2006 the RPD layer depth increased and there were indications that both pioneering Stage I and equilibrium Stage III communities had increased relative to Stage II (Figure 4-3). Most of the biogenic activity was related to burrowing organisms that created feeding mounds and pits in the sediment surface, and to small tube-building worms.

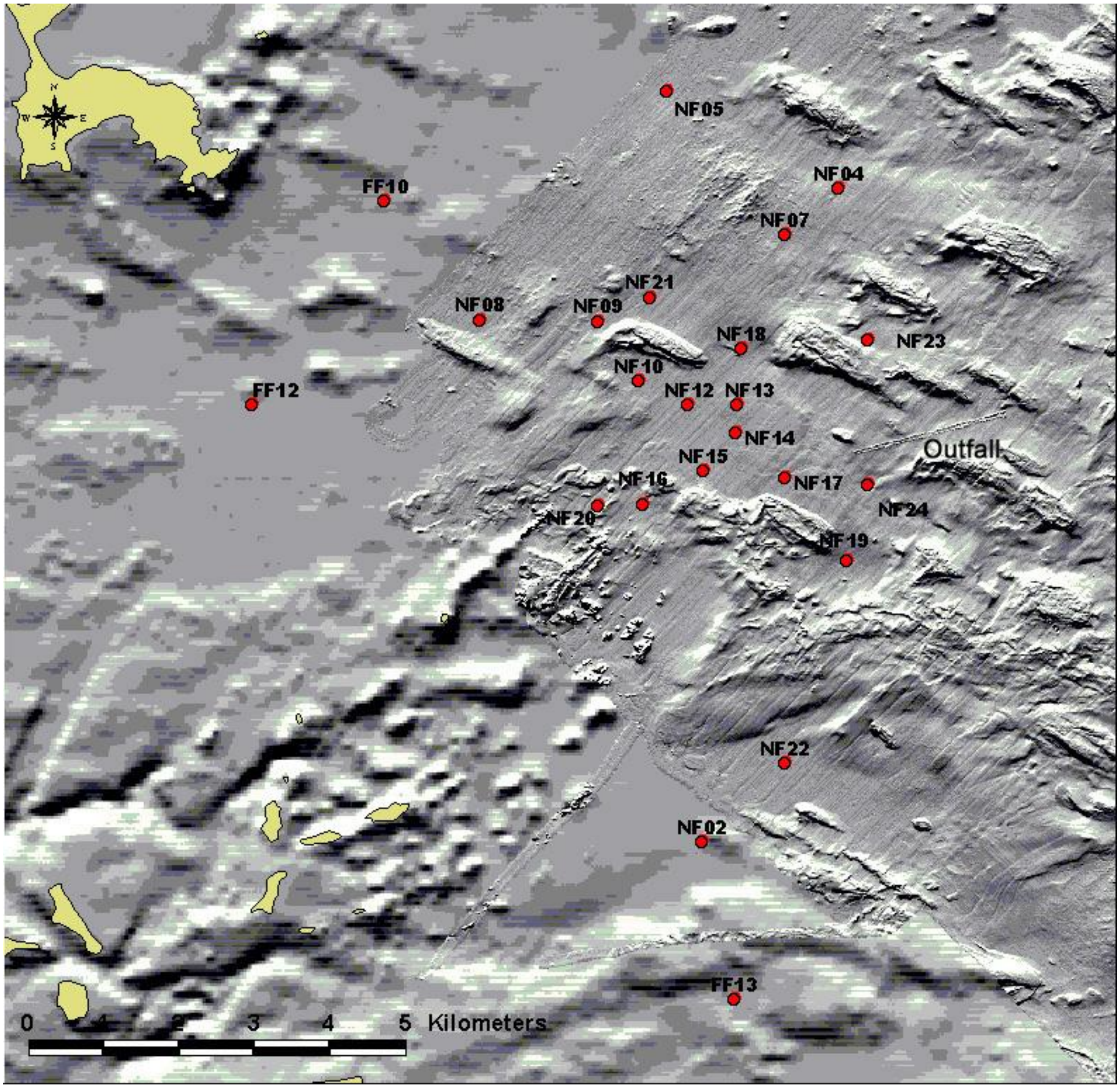


Figure 4-1. Locations of nearfield stations overlaid on multibeam bathymetry of Butman *et al.* (2004).

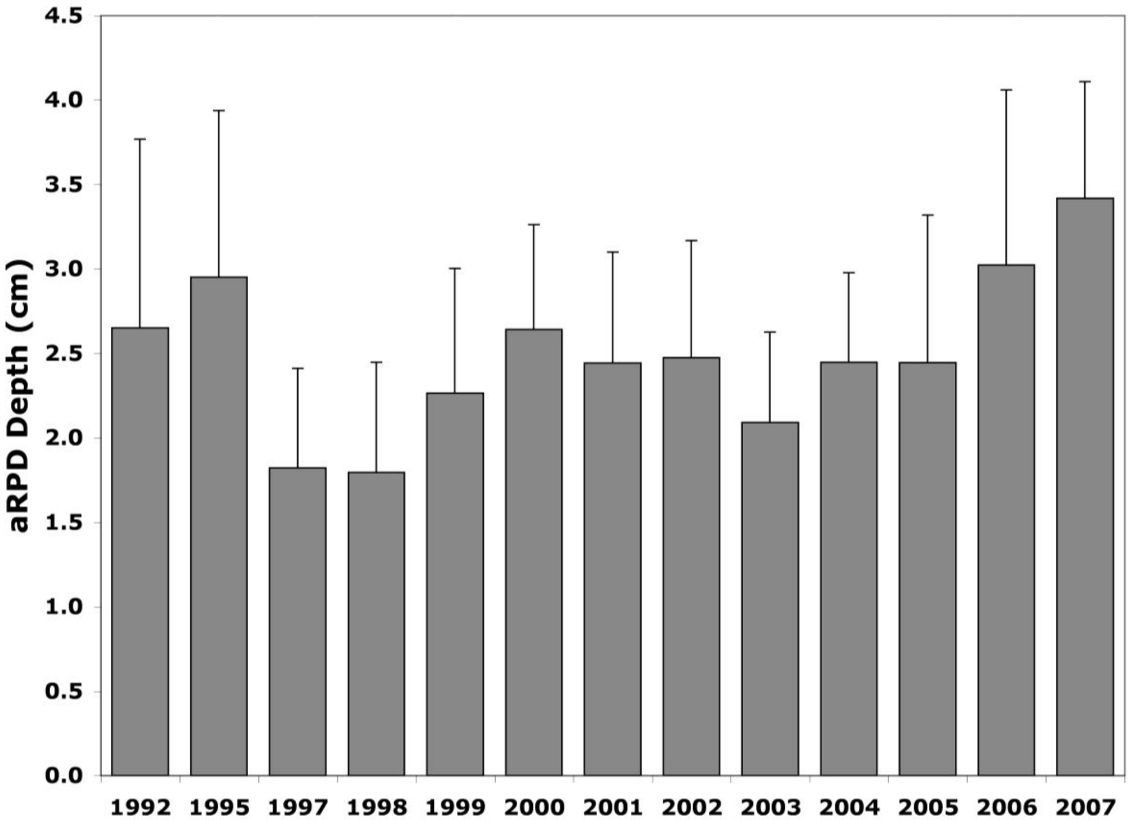


Figure 4-2. Apparent color RPD layer depth (cm) averaged by year for all data from nearfield stations.

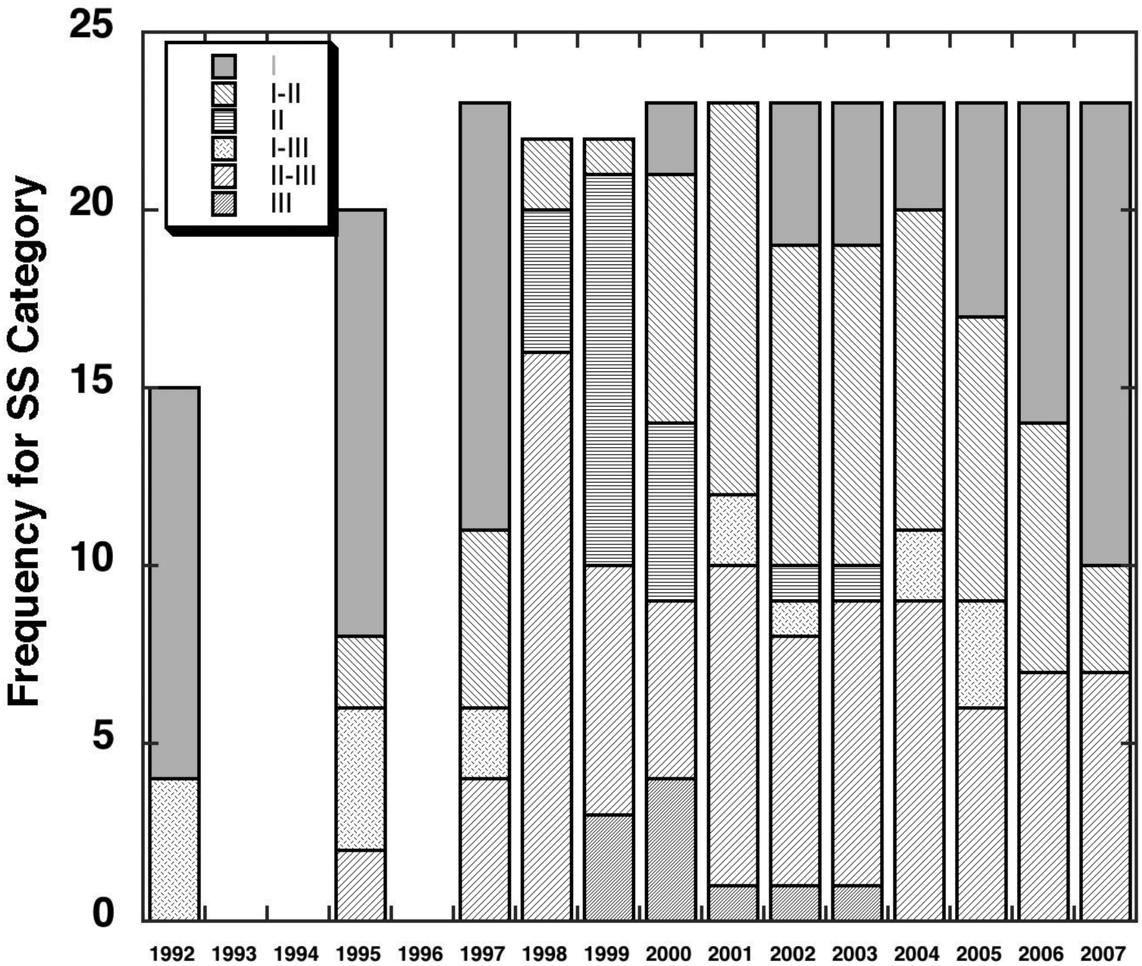


Figure 4-3. Estimated successional stage from nearfield SPI for all years.

Factors responsible for the depth of the RPD layer in the nearfield appeared to be acting at regional scales with yearly patterns in RPD depth reasonably consistent across stations. From 1997 (*i.e.*, the start of annual sampling) to 2006, nine stations had measurable RPD layer depths for all years with a general concordance between these stations and time (Figure 4-4). There was a significant deepening trend in RPD from 1997 to 2000 throughout the nearfield area. This trend occurred among the four stations within the topographic feature that contains the outfall and the five stations in other topographic features surrounding the outfall (Figures 4-1 and 4-4). The increase in RPD layer depth in 2007 resulted in a post-diversion increase in RPD layer depth; the general deepening trend can be seen in the nine stations that had measured RPD layers for all year (Figure 4-3).

The Organism Sediment Index (OSI), a measure of benthic habitat condition, indicated that infaunal communities at 30% of the nearfield stations might have been stressed for three or more years during the baseline period. This assessment is based on applying the interpretation of OSI developed by Rhoads and Germano (1986) for inshore estuarine habitats, where an OSI <6 would be indicative of stressed conditions. The likely stressors in the nearfield were the physical processes shaping the dynamic sedimentary environment rather than water or sediment quality, since both water and sediment quality were consistently found to be good (see Chapter 3 this report, Libby *et al.* 2003, Tucker *et al.* 2005). In the long term, the annual OSI oscillated around a baseline grand mean of 6.6 (SD = 0.81), with the greatest departure in 1997 likely due to the shift in sampling dates from August to October. When stations were grouped by topographic feature (the flat area that contains the outfall that may be more prone to sedimentation versus other areas to the north, west, and east, see Figure 4-1) and only stations with measured OSI values for all years were considered, there was a significant increase in OSI through time for the baseline years (Figure 4-5, Maciolek *et al.* 2007). This increase was related to the deepening RPD layers and advancing estimated successional stages, the two factors used in OSI calculation. Post-diversion, from 2001 to 2007, there were no significant trends in OSI. This correspondence between defined topographic areas and OSI through time for the baseline period indicated that factors affecting OSI were acting at broader regional scales. For example, much of the increase in OSI during the baseline period may have been related to relief from storm-generated bottom stress. The winter of 1997 was stormy with lower OSI values while the winter of 1998 was calm and had correspondingly high levels of biogenic activity with increasing OSI values.

In the post-diversion period, the OSI exhibited no significant trends even in 2005, which was the stormiest year on record (Butman *et al.* 2008). However, the increase in pioneering Stage I fauna in 2005 through 2007 would be consistent with increased stress to the benthos, with the two likely sources in 2005 being outfall operation and severe storm activity. Relative to outfall operation, there was a localized increase in abundances of *Clostridium* spores (normalized to percent fines) in the nearfield from 2001 to 2005 compared to 2000 pre-diversion values. Spore abundances decreased sharply in 2006, however, which points to either (1) a cleaner effluent was discharged or (2) physical processes related to storm activity mixed spores into the sediments or dispersed them (Maciolek *et al.* 2007). Examination of sediment TOC also points to physical processes as controlling factors in the nearfield. TOC did not increase post-diversion, when normalized to percent fines. Sediment grain-size also became coarser (reduction in fines) following the 2005 storms (Maciolek *et al.* 2007). In 2007 SPI, estimated grain-size was finer than in 2006, indicating that physical and biological processes are in better balance.

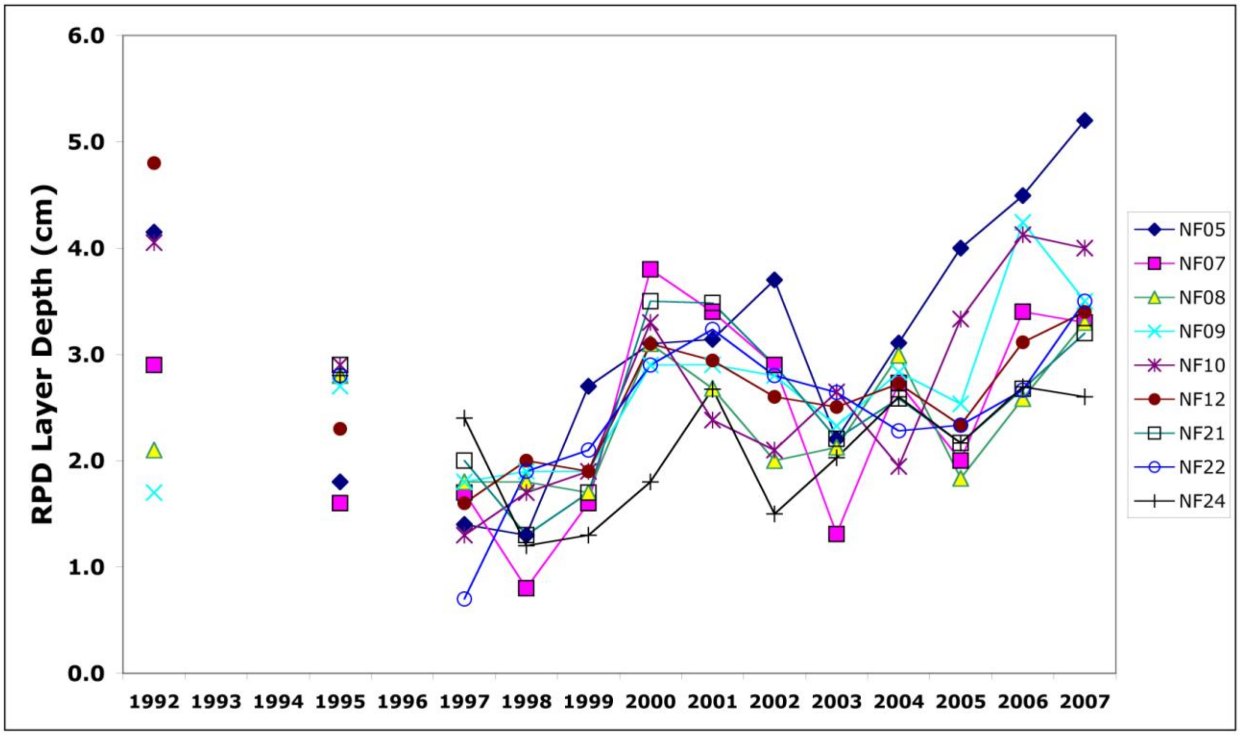


Figure 4-4. Apparent color RPD layer depth (cm) for the nine nearfield stations that had measured values for all years.

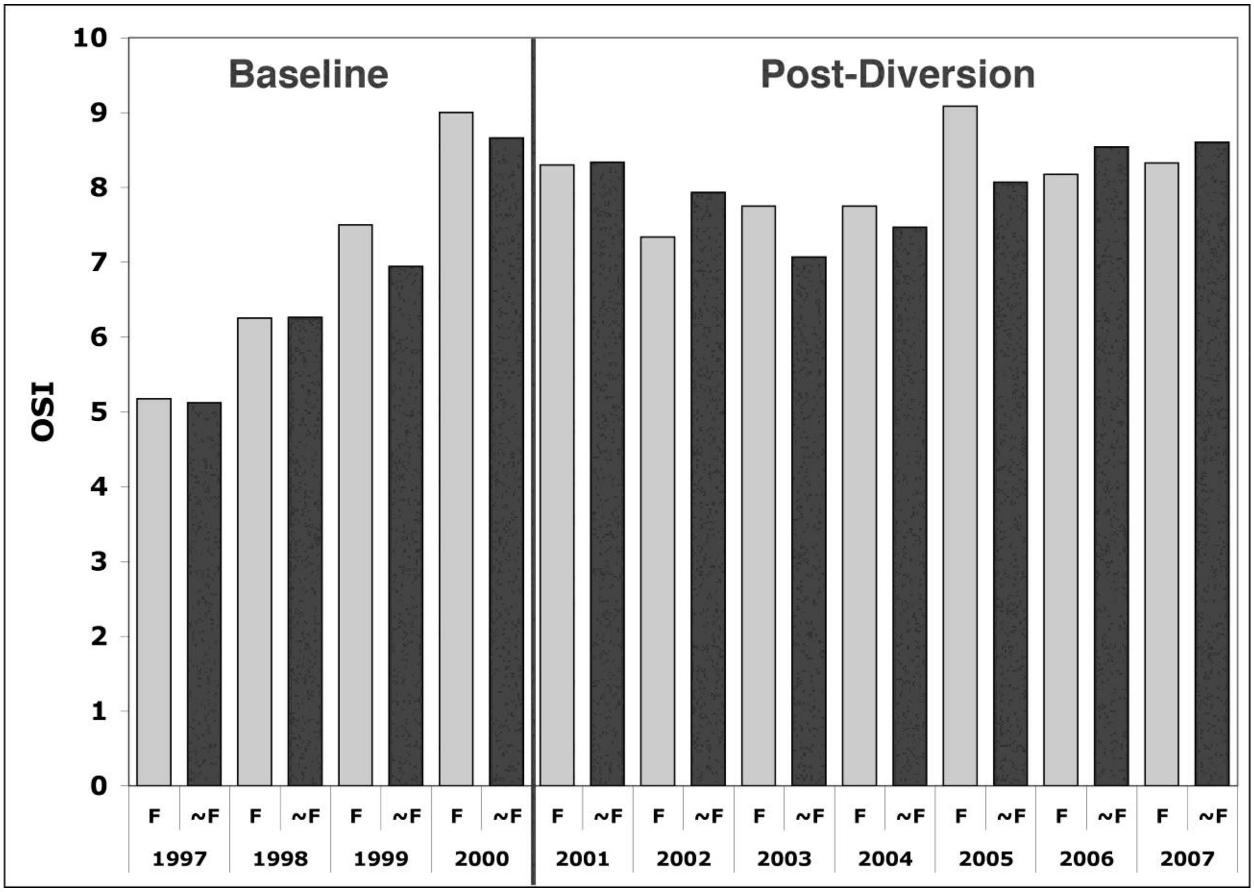


Figure 4-5. Average Organism Sediment Index (OSI) summarized by year and topographic features for stations with measured values in all years. The relatively flat topographic area within which the outfall is located is F (see Figure 4-1), other areas around the outfall are ~F.

4.2 Methods

4.2.1 Image Analysis

The digital SPI images were analyzed by using Adobe Photoshop®. Data from each image were sequentially saved to a spreadsheet file for later analysis. Details of how these parameters were estimated can be found in Diaz and Schaffner (1988) and Rhoads and Germano (1986). Table 4-1 summarizes the parameters measured. Video of surface sediments in front of the prism were recorded onto digital videotape and still frames were extracted using Final Cut Pro® software. Still frame images were sharpened and the histograms equalized with Adobe Photoshop®.

4.2.2 Statistical Analysis

Analysis of variance (ANOVA) and analysis of covariance were also used to test for differences between and within areas for quantitative parameters. Normality was checked with the Shapiro-Wilk test and homogeneity of variance with Bartlett's test. If variance was not homogeneous, Welch analysis of variance, which allows standard deviations to be unequal, was used in testing for mean differences (Zar 1999). Tukey's LSD test was used for multiple mean comparisons. All statistical tests were conducted using SAS® (SAS Institute, Inc.).

4.3 Results and Discussion

4.3.1 Summary of 2007 SPI Data

Physical Processes and Sediments—Sediment grain size in 2007 continued to be heterogeneous and ranged from pebble to fine-sand-silt-clay (Figures 4-6 and 4-7, Table 4-2) with about half of the stations (11 of 23) having maximum grain sizes as coarse as or coarser than gravel, which is similar to the previous three years (Maciolek *et al.* 2007). From 2005 to 2007 the sediments appeared coarser compared to 1999, 2000, 2003, and 2004. Part of the year-to-year variation in grain-size within some stations can be attributed to small-scale patchiness of sediments within the 30-m radius station target, but the storminess of 2005 appeared to be a major factor in the coarsening of nearfield sediments. Sediment grain-size analysis also confirmed a coarsening of sediments in 2005 and 2006 (Maciolek *et al.* 2007). Prism penetration was variable and related to grain-size. Penetration was shallowest (1.4 cm) at Station FF13, which was fine-sandy-silt with gravel and pebbles, and deepest (14.6 cm) at Station NF12, which had fine-sand-silt-clay (Figure 4-6 and Table 4-3). SPI grain-size estimates indicated that the fines (silt and clay) increased slightly in 2007 at a number of stations compared with previous years. The coarsening of sediments in 2006 that was still apparent in 2007 despite the slightly finer sediments was likely still related to bottom disturbance from 2005 storms, which were associated with the second highest bottom stress winter on record (Butman *et al.* 2008). However, bioturbation by benthic fauna appeared to be reworking surface sediments as grain-size layering observed at six stations in 2006 was not evident in 2007 images (Table 4-3). In 2007, sediment layering was observed only at station NF07, which did not appear layered in 2006.

Table 4-1. Parameters measured from Sediment Profile Images.

Parameter	Units	Method	Description
Sediment Grain Size	Modal phi interval	V	An estimate of sediment types present. Determined from comparison of image to images of known grain size
Prism Penetration	cm	CA	A geotechnical estimate of sediment compaction. Average of maximum and minimum distance from sediment surface to bottom of prism window
Sediment Surface Relief	cm	CA	An estimate of small-scale bed roughness. Maximum depth of penetration minus minimum
Apparent Reduction-oxidation Potential Discontinuity Depth (from color change in sediment)	cm	CA	Estimate of depth to which sediments appear to be oxidized. Area of aerobic sediment divided by width of digitized image
Thickness of Sediment Layers	cm	CA	Measure thickness above original sediment surface
Methane/Nitrogen Gas Voids	Number	V	Count
Epifaunal Occurrence	Number	V	Count, identify
Tube Density	Number /cm^2	V	Count
Tube Type			
Burrow Structures	—	V	Identify
Pelletal Layer	cm	V	Measure thickness, area
Bacterial Mats	—	V	Determine presence and color
Infaunal Occurrence	Number	V	Count, identify
Feeding Voids	Number	V	Count, measure thickness, area
Apparent Successional Stage	—	V,CA	Estimated based on all of the above parameters
Organism Sediment Index	—	CA	Derived from RPD, successional stage, gas voids (Rhoads and Germano 1986)

V: Visual measurement or estimate

CA: Computer analysis

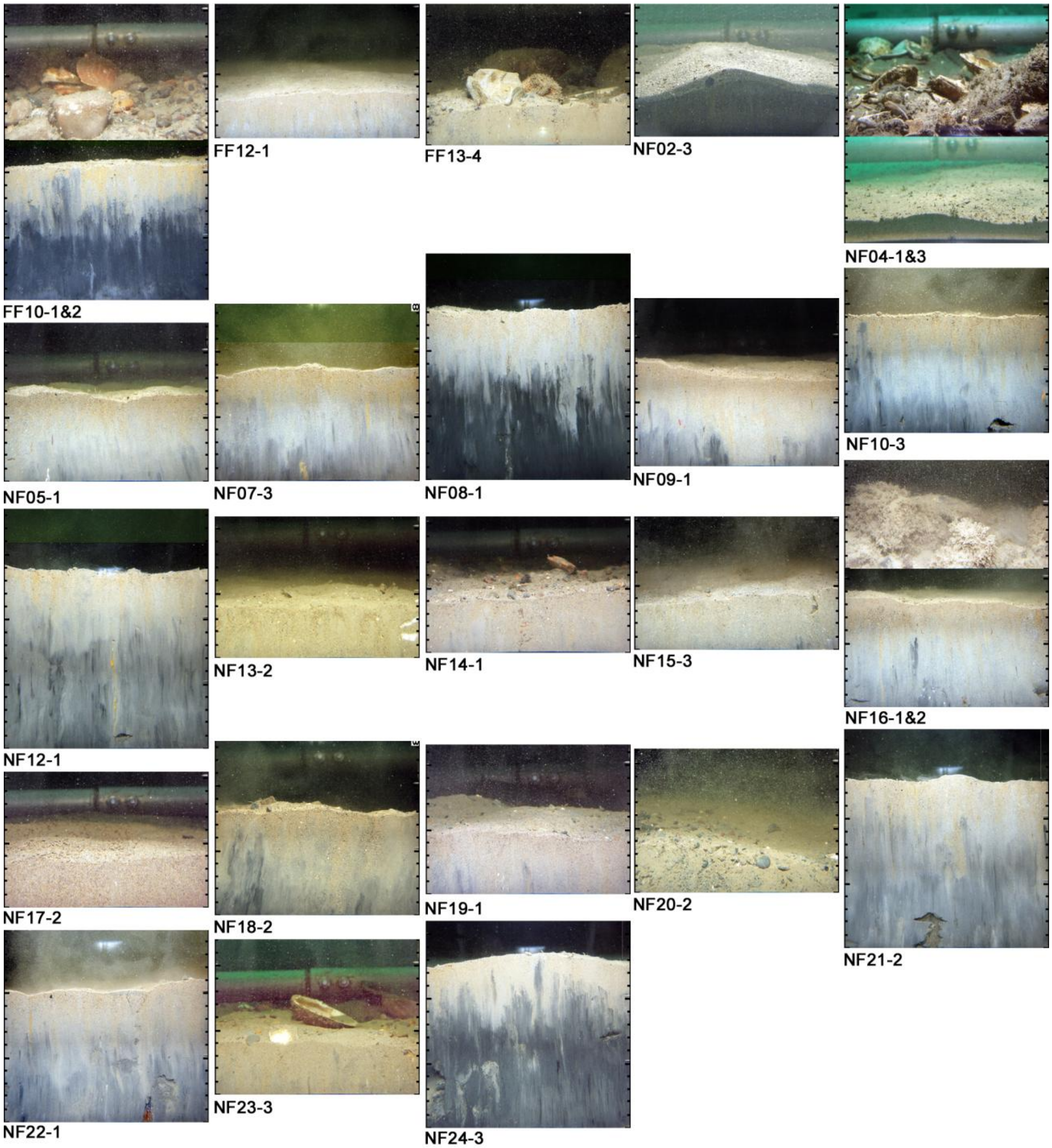


Figure 4-6. Example SPI for 2007 nearfield stations. Number following station is replicate image number. Image color was enhanced to emphasize the difference between oxic and anaerobic sediments. Scale around the edge of each image is in cm.

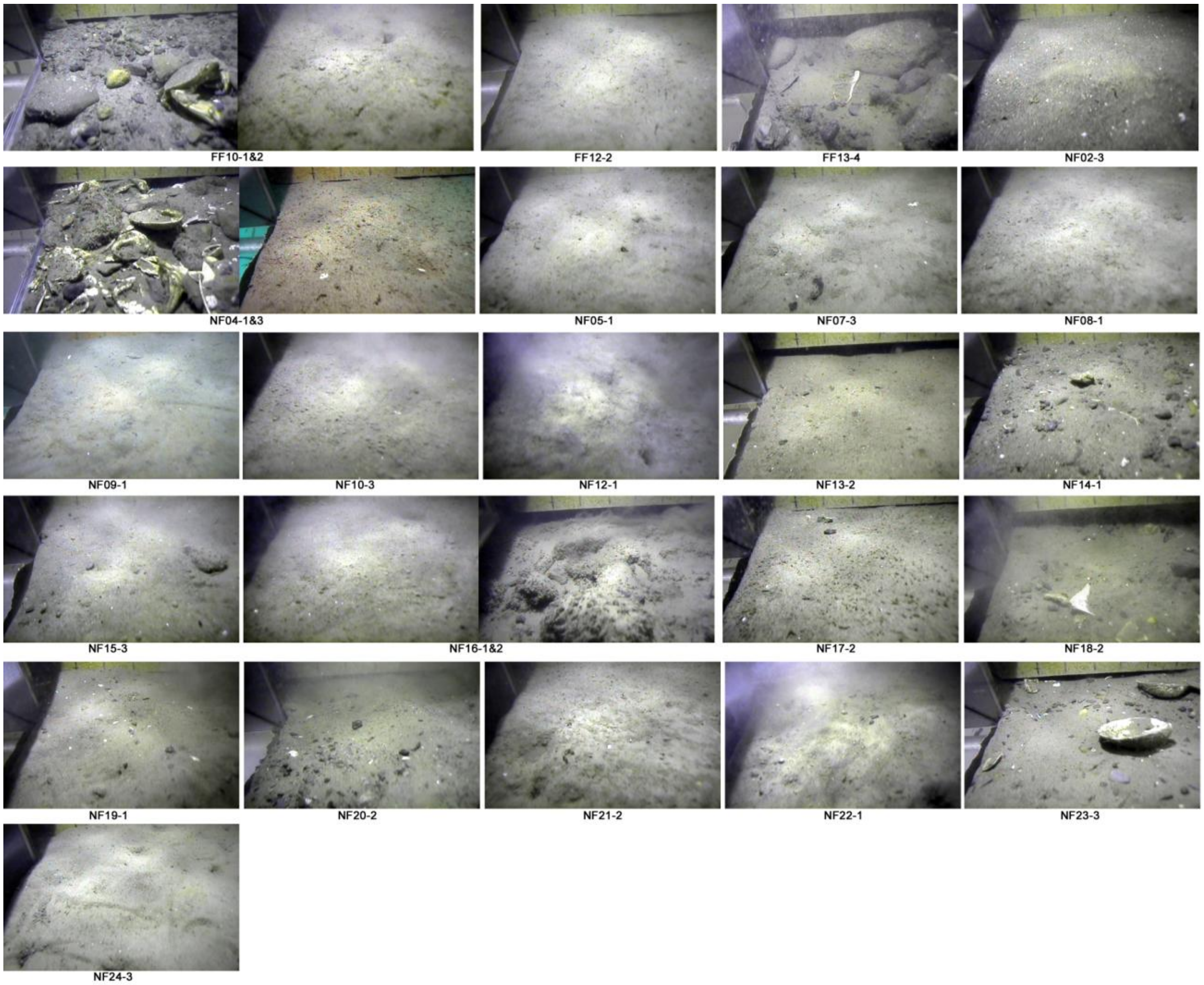


Figure 4-7. Example sediment surfaces for 2007 nearfield stations. Images were extracted from videotape, contrast enhanced, and edge sharpened. Number following station is replicate image number.

Table 4-2. Summary of SPI parameters for nearfield stations, August 2007. Data from all replicates were averaged for quantitative parameters and the median was used for categorical parameters.

STA	PEN[1] (cm)	SR[2] (cm)	RPD[3] (cm)	Modal Grain Size	Max Grain Size	Surface Process	Amphi. Tubes	Worm Tubes	INF[4]	BUR[5]	Oxic Voids	SS[6]	OSI[7]
FF10	6.5	0.8	2.1	FSSI to FSGRPB	PB	BIO/PHY	NONE	MANY	4.0	3.5	1.0	I	IND**
FF12	2.8	1.2	>2.8*	FS	FS	BIO/PHY	NONE	SOME	1.3	2.3	0.0	I-II	IND
FF13	1.4	1.1	>2.9	FSSIGRPB	CB	PHY	NONE	SOME	0.0	0.0	0.0	I	IND
NF02	2.2	1.2	>3.4	FS to CB	Wood	PHY	NONE	SOME	0.0	0.0	0.0	I	7.0
NF04	2.6	1.4	>3.6	FSMS	MS	PHY	NONE	MANY	0.0	0.0	0.0	I	7.0
NF05	7.2	0.7	5.2	FSSI	FS	BIO/PHY	NONE	SOME	4.0	3.3	0.7	II-III	9.3
NF07	8.4	0.9	3.3	FSSI/CL?	FS	BIO/PHY	NONE	SOME	1.7	2.3	0.3	I-II	7.7
NF08	13.3	0.8	3.3	FSSICL	FS	BIO/PHY	NONE	SOME	4.7	2.7	1.0	II-III	8.3
NF09	7.1	1.1	3.5	FSSI	FS	BIO/PHY	NONE	MANY	3.0	2.7	1.3	II-III	9.0
NF10	8.6	0.8	4.0	FSSICL	FS	BIO/PHY	NONE	SOME	4.0	4.3	1.0	II-III	9.0
NF12	14.6	0.7	3.4	FSSICL	FS	BIO/PHY	NONE	SOME	4.7	2.3	2.3	II-III	9.3
NF13	3.1	0.5	>3.1	FSMS	MS	PHY	NONE	SOME	0.0	0.0	0.0	I	7.0
NF14	3.6	2.0	3.6	FSSIGRPB	PB	PHY	NONE	MANY	0.7	0.0	0.0	I	7.0
NF15	4.2	1.3	>4.2	FSSI to FSSIGR	PB	PHY	NONE	SOME	0.0	0.0	0.0	I	7.0
NF16	2.7	0.3	3.0	FSSI to PBCB	CB	PHY	NONE	MANY	5.0	4.0	2.0	I	9.0
NF17	2.8	1.0	>2.8	FSMS	MS	PHY	NONE	SOME	0.0	0.0	0.0	I	7.0
NF18	6.4	0.8	3.4	FSSIGRPB	PB	PHY	NONE	SOME	2.7	0.0	0.0	I	6.0
NF19	3.7	1.2	>3.7	FSSI	PB	PHY	NONE	MANY	0.0	0.3	0.0	I	7.0
NF20	3.1	1.5	>3.1	FSSIGR	PB	PHY	NONE	SOME	0.7	0.3	0.0	I	IND
NF21	12.9	0.7	3.2	FSSICL	FS	BIO/PHY	FEW	MANY	6.0	4.0	2.3	II-III	9.0
NF22	11.8	0.9	3.5	FSSICL	FS	BIO/PHY	NONE	MANY	5.3	2.3	2.7	II-III	8.7
NF23	4.8	0.6	>4.8	FSMSGRPB	PB	PHY	NONE	SOME	0.0	0.0	0.0	I-II	7.7
NF24	10.6	1.1	2.6	FSSICL	GR	BIO/PHY	NONE	MANY	5.0	2.3	0.7	I	6.0

IND = Indeterminate ** > = Actual values are deeper than prism penetration.

Table 4-3. Range of sediment grain size at nearfield SPI stations for all sampled years.

	Baseline						Post-Diversion						
Sta	**1992**	**1995**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**
FF10	VFS	.	PB to VFS	VFS	CB to SIFS	PB to GR	CB to FS	PB to FSSICL	VFS	FSSICL	PB to FSSI	FS to FSGRPB	FSSI to FSGRPB
FF12	.	.	VFS	FS	FS	VFS	VFS	VFS	VFS	VFS	VFS	FSGR	FS
FF13	.	.	SIFS	SIFS	CB to FSSI	CB to SI	FSSI	CB to FSGR	CB to FSSI	FSSI	CB to PB	CLPB to CBPB	FSSIGR PB
NF02	VFS	PB to CS	SIFS	PB to GR	CB to FSSI	CB to MSCS	FSSI	FSSI	FSMS/FSSI	FSSICL	SIFS	FS/FSSI to FSPB	FS to Wood
NF04	FS	FS	PB to VFS	FS	GR to FS	FS	PB to FSMS	PB to FS	FS	FS	FSMS	FS/FSMS to FSMSPB	FSMS
NF05	FS	VFS	VFS	VFS	FS/SICL	FS/SICL	FSSICL	FSSICL	FSSICL	FSSICL	FS/FSSI	FS/FSSI to FSSI	FSSI
NF07	VFS	VFS	VFS	VFS	SIFS	SIFS/CL	FSSICL	FSSICL	FSSICL	FSSICL	PB to FSSICL	FSSICL	FSSI/CL ?
NF08	VFS	SIFS	VFS	VFS	SIFS	SIFS	SIFS	FSSICL	SIFS	FSSICL	FSSICL	FSSICL	FSSICL
NF09	VFS	VFS	VFS	VFS	FSSI	FSSI	FSSICL	FSSI	FSSICL	FSSICL	FSSICL	FSSICL	FSSI
NF10	VFS	VFS	VFS	VFS	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
NF12	VFS	SI	SIFS	SIFS	FSSICL	FSSICL	FSSICL	FSSI	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
NF13	FS	PB to VFS	PB to FS	PB to SIFS	FSMS	PB to FSMS	GR to FSMS	PB to FSMS	PB to FSMS	FSMSGRPB	FSMSG R	FSMSGRPB	FSMS
NF14	FS	PB to VFS	PB to VFS	PB to VFS	PB to SIFS	PB to FSSICL	PB to FSSI	PB to FSSI	PB to FSSIGR	FSMSSIGRP B	PB to FSMSSI	FSSIGRPB	FSSIGR PB
NF15	FS	PB to VFS	PB to VFS	GR to FS	PB to FSSI	PB to FSSI	PB to FSSI	GR to VFS	PB to FSSIGR	FSMSSIGRP B	PB to FSMSSI	FSSIGRPB	FSSI to FSSIGR
NF16	VFS	SIFS	VFS	SIFS	FSSICL	PB to FSSI	CB to FSSICL	FSSICL	CBPB	PB to FSSICL	PB to SICL	FSSI/SICL to FSSIGRPB	FSSI to PBCB
NF17	FS	CS to FS	FS	FS	GR to FSMS	PB to FSMS	FSMS	FSMS	FSMS	FSMS	FSMS	FSMS	FSMS
NF18	VFS	PB to VFS	GR to VFS	GR to VFS	PB to SIFS	FSSICL	PB to FSSICL	PB to FSSICL	PB to FSSIGR	FSSIGRPB to FSMS	PB to FSSI	FSSI to FSSIGRPB	FSSIGR PB
NF19	.	PB to VFS	GR to VFS	FSSICL	FSSICL	CB to FSSICL	GR to FSSI	VFS	CB to FSSI	FSSIGRPB	PB to FSSI	FS/FSSI to FSPB	FSSI
NF20	VFS	PB to VFS	CB to FSMS	GR to SICL	PB to SIFS	PB to SIFS	PB to FSSI	FSSI	CB to FSSIGR	FSSIGRPB	PB to FSSI	FSSIGRPB	FSSIGR
NF21	.	SIFS	VFS	SIFS	SIFS	SIFS	SIFS	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
NF22	.	SIFS	SIFS	SIFS	SIFS	SIFS	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
NF23	.	CS to VFS	FS	FS	PB to FSSICL	GR to FSMS	PB to FSMS	GR to FSMS	PB to FSMS	FSMSGRPB	PB to FSMS	FSMSGRPB	FSMSG RPB
NF24	.	SI	SIFS	FSSICL	PB to FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICLGR	FSSICL

CB = Cobble GR = Gravel PB = Pebble CS = Coarse-sand CL = Clay MS = Medium-sand FS = Fine-sand VFS = Very-fine-sand SI = Silt

Apparent color RPD Depth—About half the stations had apparent color RPD layer depths deeper than the prism penetration for all replicates (Table 4-2). For these stations, prism penetration was then assumed to be a conservative minimum estimate of the RPD layer depth and was included in the calculation of the average RPD layer depth for 2007. At stations FF10, NF14, and NF16, one or two of the three replicate images had RPD layers that were deeper than the prism penetration. RPD layer depths in 2007 continued the deepening trend that appeared to start in 2003 (Figures 4-2 and 4-4). In 2007, the average apparent color RPD layer depth ranged from 2.1 cm (FF10) to 5.5 cm (NF05), with a grand mean of 3.4 cm (SD = 0.67 cm) for all 23 stations. For the stations with measured RPD layer depths, the average was 3.5 cm (0.62 cm). A Welch ANOVA, which tests for equality of mean while allowing the standard deviations to be unequal (a problem when sample sizes are unequal, 123 for baseline years vs. 23 for 2007), found that there was a significant increase in the depth of the apparent color RPD layer depth between baseline years and 2007 ($F = 44.3$, $p = <0.001$). The fact that in 2007 the RPD was deeper than baseline would indicate that the RPD threshold was not exceeded. The difference between 2007 and the baseline was a deepening of the RPD by an average of 1.1 cm or 46%.

Biogenic Activity—Biogenic structures and organism activity observed in SPI for 2007 appeared to be higher than for both 2005 and 2006, and about the same as in 2004, the last year with similar levels of biogenic structures. For example, while tubes were observed at all 23 stations, their overall density was lower in 2005 and 2006 with five and four stations with many tubes (>24 tubes/image), respectively. In 2007, 11 stations had many tubes (Table 4-2). Most of the tubes were small (<1 mm diameter) polychaete tubes, likely spionids, which are the most abundant small tube-building infauna at nearfield stations (Chapter 5). Only station NF20 had larger amphipod-like tubes. The increased number of biogenic structures would be consistent with recovery from physical stress imposed on the community from the 2005 storm events. In 2007, 11 of the 23 stations appeared structured by a combination of biological and physical processes (*e.g.*, NF09), up from eight stations in 2006. At the other 13 stations (*e.g*., FF13), physical processes dominated. No station was classified as having a biologically structured sediment surface in 2007 (Table 4-2).

The number of subsurface biogenic structures, primarily burrows and oxic voids, and free-burrowing infaunal worms were not significantly different between 2006 and 2007, but mean structures per image all trended up, a reversal from 2005. The number of worms in 2007, 2.3 (SE = 0.65) worms per image, was still significantly lower than during the last three years of the baseline period, the only years with worms per image data (Welch ANOVA, $F = 59.4$, $p = 0.010$). The last three years of the baseline period averaged 3.9 (SE = 0.40) worms per image.

Successional Stage and Organism Sediment Index—The distribution of estimated successional stages of the infaunal communities in 2007 was skewed towards pioneering (Stage I) at 56% and a combination of pioneering and intermediate (Stage I to II) at 13%, relative to a combination of intermediate and equilibrium stages (Stage II to III) at 30% of stations (Figure 4-3). Stations with successional Stage I designation had little indication of biogenic activity other than small worm tubes on the sediment surface and tended to have coarser-grained sediments (Table 4-2). Stage II and III successional designations were made based on the degree of biogenic sediment reworking and presence of larger fauna. Pioneering Stage I classification increased in 2007 for the fourth time, the other times being 2002, 2005, and 2006. Over the 15-year period of sampling the nearfield, the largest shift in successional stage occurred during the baseline period between 1997 and 1998 when the number of stations with Stage I classification declined and stations with Stage II to III increased (Figure 4-3). Prior to 1998, the Stage I classification accounted for over half of all stations. From 1998 to 2006 Stage II and III classifications dominated. It appears that Stage I fauna, or what appear to be Stage I species, dominate the nearfield stations. Overall, trends in estimated successional stage for the nearfield corresponded closely to those within Boston Harbor (Maciolek *et al.* 2006). This correspondence may reflect some broad regional response to a combination of nutrient reduction, shifting location of loading points, and climatic events.

In 2006, the mean Organism Sediment Index (OSI) was 7.8 (SE = 0.26) for the 19 stations with calculated values, which was statistically higher than the baseline grand mean of 6.4 (SE = 0.15) (Welsh ANOVA, F = 22.8, p = <0.001). Rhoads and Germano (1986) developed the OSI for assessing benthic conditions of inshore estuarine and coastal embayments in the northeast and found that OSI values <6 were associated with benthic communities under some form of stress, either from organic loading or physical processes, while higher values of the OSI were associated with well-developed communities. Based on this interpretation of the OSI, the nearfield SPI stations were, on average, not stressed. However, caution must be applied when the OSI is used as a means of assessing benthic conditions in a different environment. Diaz *et al.* (2003) found that for Chesapeake Bay OSI values of <3 were associated with stressed benthic communities based on comparison with the benthic index of biotic integrity (BIBI, Weisberg *et al.*, 1997). In 2007, two stations had OSI values <6 (NF18 and NF24). At these stations the stressor appeared to be physical processes with no sign of stress from organic loading.

4.3.2 Comparison of Pre-and Post-Diversion Results

If the outfall were considered a point source of stress to the nearfield, then local outfall effects would be modified by local topography and currents, which would influence erosion/deposition events and transport of materials from the outfall, and with distance from the outfall. To test this hypothesis Maciolek *et al.* (2007) constructed a series of GEE models considering topography (flat area where outfall was located vs. other areas, see Figure 4-1), pre- and post-baseline period, and distance from the outfall with SPI, infaunal community, and sediment data. Overall, their analysis failed to identify many significant differences. At the community structure level, none of the infaunal parameters was different between baseline and post-diversion periods, or between topographic features, or distance from outfall. For sediment parameters, *Clostridium perfringens* spores and TOC, both normalized to percent fines, decreased with distance from the outfall; however, there were no significant relationships with baseline/post-diversion or topographic features, likely due to high between-year variation. For SPI parameters, infauna per image, oxic and anaerobic voids per image all declined post-diversion, while RPD layer depth increased post-diversion (Maciolek *et al*. 2007).

Benthic habitat conditions in 2007, as determined by SPI, continued to be heterogeneous with no large changes in the sedimentary environment relative to baseline vs. post-diversion years. Coarsening of sediments in 2005 and 2006 pointed to the possible influence of storms as a major structuring factor for nearfield benthic habitats. Elevated biogenic activity (tubes, burrows, infauna, and oxic voids all trending up) in 2007 may have facilitated the accumulation of fines, leading to more balance between physical and biological processes. In 2005, sediment grain-size analysis did indicate that sediments at seven nearfield stations were coarser relative to 2004, possibly related to bottom stress from winter storms that were the strongest on record for the Boston area (Maciolek *et al.* 2007, Butman *et al*. 2008). Overall, modal grain-size estimated from SPI in 2005 for all 23 stations (mean 4.1, SE 0.4 Phi) tended to be coarser than 2004 (mean 4.4, SE 0.3 Phi), with 2006 (mean 3.8, SE 0.4 Phi) being almost as coarse as the sediment in 1992 (mean 3.6, SE 0.1 Phi), which was the second most stormy year on record (Butman *et al.* 2008). SPI grain-size estimates for 2007 averaged 4.1 Phi (SE 0.2 Phi). Thus, it appears that particularly stormy years can influence surficial sediments at a broad regional scale within the nearfield for at least several years. Sediment grain-size heterogeneity is a characteristic of most nearfield stations and is related to regional geomorphology (Butman *et al.* 2004). The predominance of coarse-grained sediments also reflected the importance of physical processes in structuring benthic habitats. In 2005 and 2006, it appeared that physical processes predominated over biological processes in structuring surface sediments with biogenic structures on the sediment surface and organism activity within the sediment appearing to be lower relative to 2004 and less than the last three years of the baseline period, which marked the high point for biogenic activity and coincided with a period of low winter storm activity.

Based on SPI, there did not appear to be much change between the baseline and post-diversion periods in the sediment color or fabric at a station, which would indicate there has not been an accumulation of organic matter in surface sediments of the nearfield stations since the start of outfall operation. If TOC of sediments was increasing, the color of anaerobic sediments would shift from lighter gray to darker gray (Fenchel 1969). Sediment flux measurements and TOC trends support the SPI conclusions that organic material for the post-diversion years have remained low, indicating there has been little change in sediment quality since start of outfall operation (Chapter 3 and Tucker *et al*. 2006.).

The OSI, an index of benthic habitat conditions, has trended upward from 2004 with a grand average of 7.4 (SE 0.4) in 2005, 7.6 (SE 0.3) in 2006, and 7.8 (SE 0.26) in 2007 (Figure 4-5). This increase in OSI appears counter to the increase in physical stress the bottom received over the winter of 2004–2005 (Butman *et al*. 2008); however, it was the surficial sediments with small surface- and near-surface-dwelling infauna, mostly pioneering successional Stage I fauna, that were disrupted by the higher bottom stress. These pioneering species were able to recolonize the area after the disturbance and they still appear to be dominant in 2007. Deeper dwelling fauna responsible for much of the subsurface biogenic activity appeared less affected, with the number of burrows and oxic voids trending up in 2007. This, combined with deeper RPD layer depths, led to higher OSI values even with the increased predominance of physical processes. This positive response of the OSI to increased physical stress in coastal habitats points to the problems of using an index based on a muddy estuarine paradigm for assessing habitat conditions in open coastal systems. In contrast, the increasing trend in OSI that started in 1998 was in response to increased importance of biological processes in structuring surface sediments throughout the nearfield. For example, in 1999 nine stations and in 2001 four stations had dense mats of what appeared to be polychaete tubes (>50,000 tubes per m^2), but tube mats have not been observed since 2002. Also, the medium-size twisted tube that was widespread at nearfield stations in 2001 and 2002 did not occur in 2007. While biogenic activity at the sediment surface appeared to be elevated in 2007 compared with 2006, it was lower compared with the last portion of the baseline period. The level of subsurface biogenic activity, however, was more consistent between years and periods.

4.3.3 Spatial and Temporal Patterns

Within the nearfield, variation through time appeared to be related to both regional trends and small-scale—on the order of 10s of m—spatial variation (Maciolek *et al.* 2006). For example, based on the modal grain size estimated from SPI for 1997 to 2006, Maciolek *et al.* (2007) divided stations into two groups based on temporal trends. Group A included six coarser stations with Group B containing the other 17 stations that tended to be finer grained (examples in Figures 4-8 to 4-11). From 1999 to 2006, median Phi was significantly lower for Group A stations. Differences in modal grain-size between Groups A and B tended to increase from 2003 to 2006, primarily because Group A coarsened relative to Group B. Modal grain-size for Group B stations exhibited no pattern and little change over this period (Maciolek *et al*. 2007). The coarsening of grain-size in 2006 for Group A is consistent with the higher bottom stress in 2005 from winter storms (Butman *et al*. 2008). The only sedimentary parameter spatially related to the outfall was *Clostridium* spores normalized to percent fines, which increased at Group A stations the first two years after outfall operation (2001 and 2002). In subsequent years the groups were not significantly different. Percent TOC normalized to percent fines was not significantly different between groups for any year, which indicates outfall operation is not affecting organic carbon distribution over the nearfield (Maciolek *et al.* 2007).

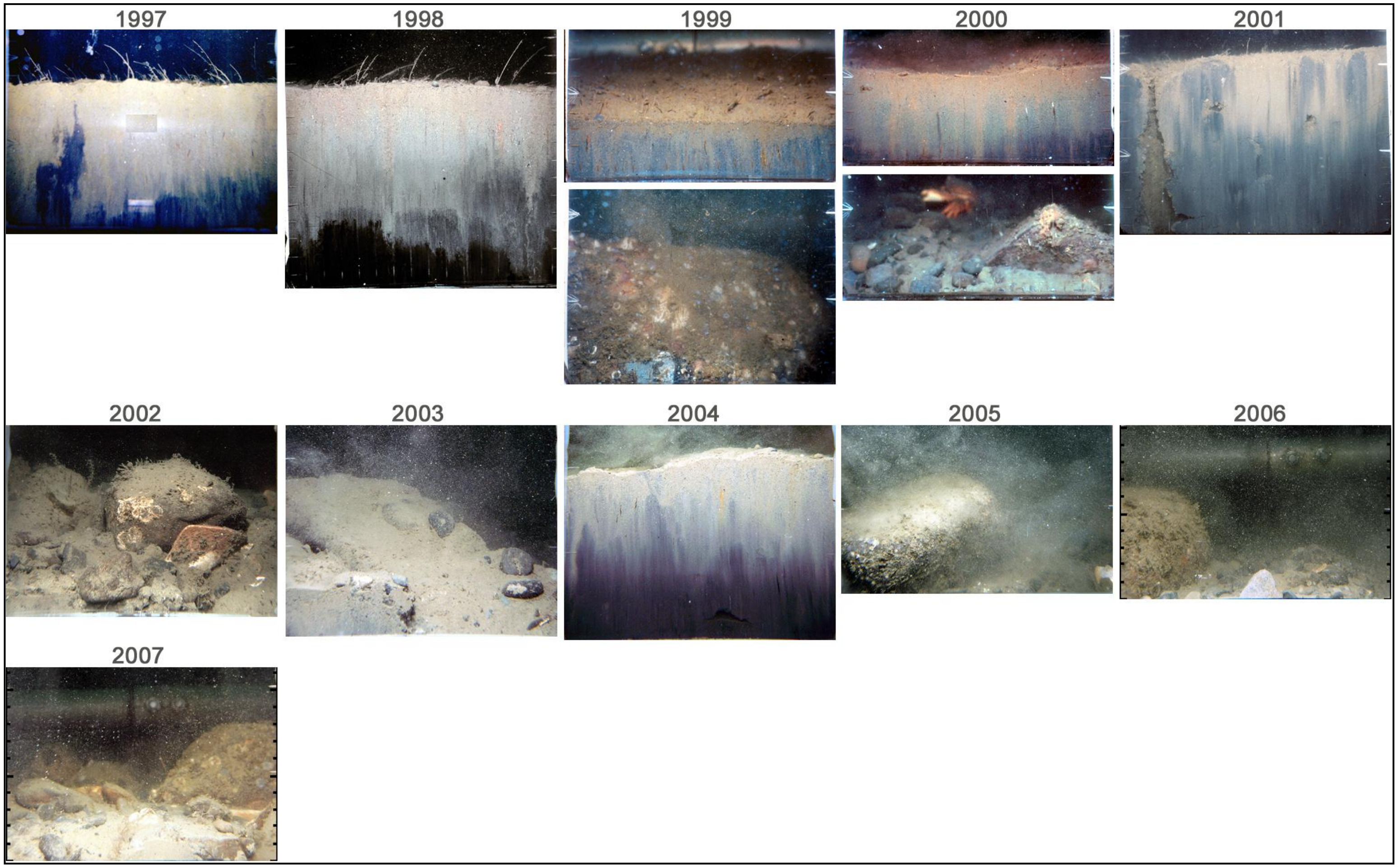


Figure 4-8. Example of heterogeneous, coarser sediment group station (FF13) for all years sampled. All images are about 15 cm wide. Image color was enhanced to emphasize the difference between oxic and anaerobic sediments.

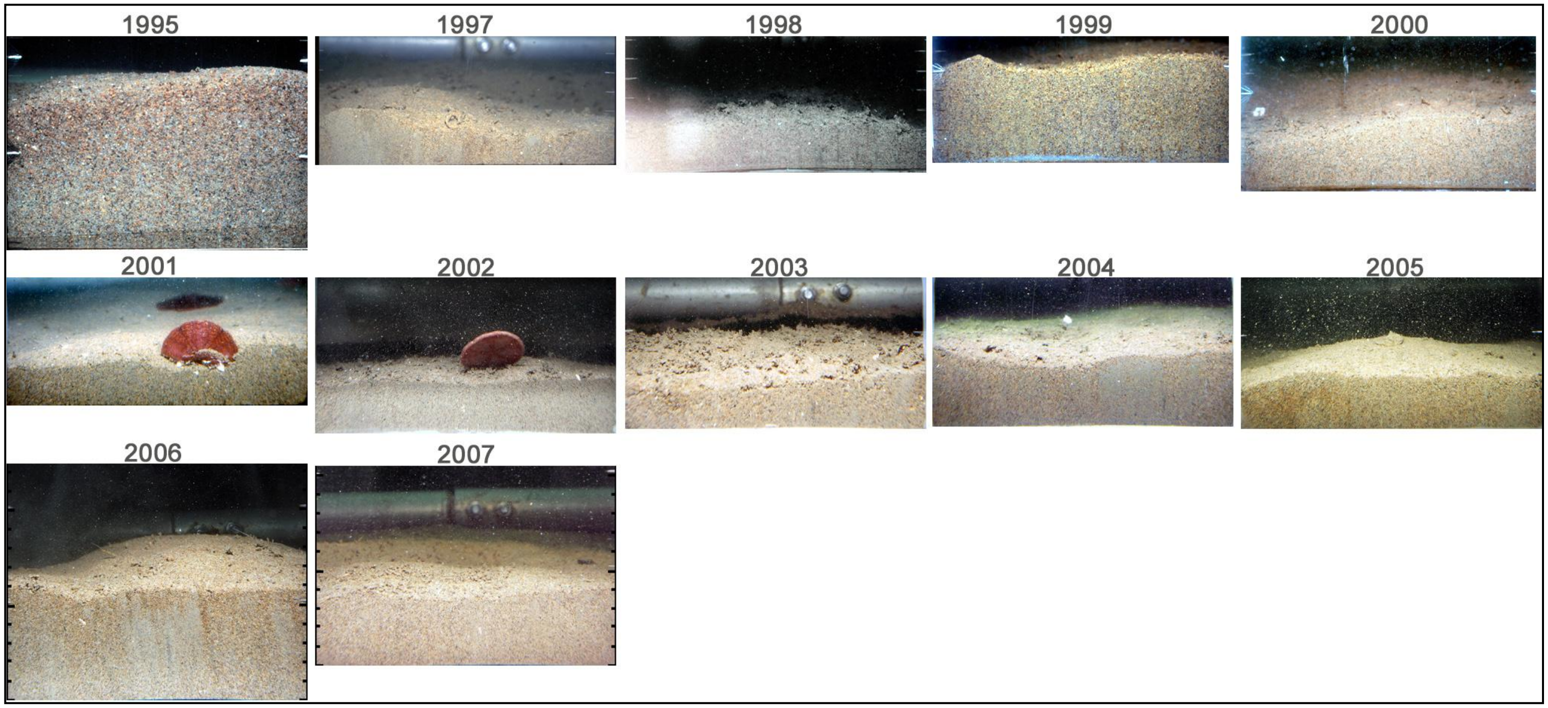


Figure 4-9. Example of homogeneous, coarser sediment group station (NF17) for all years sampled. All images are about 15 cm wide. Image color was enhanced to emphasize the difference between oxic and anaerobic sediments.

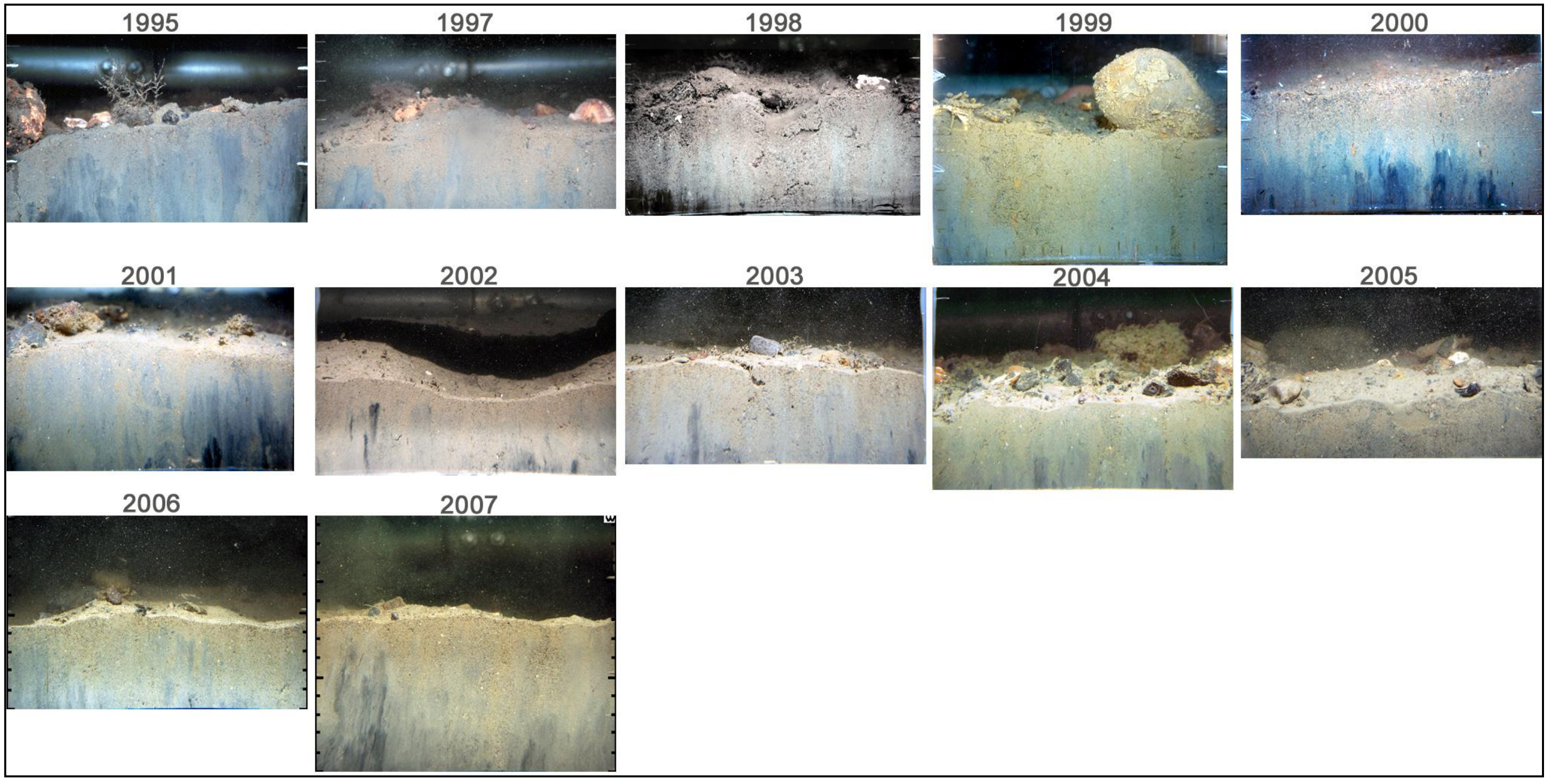


Figure 4-10. Example of heterogeneous, finer sediment group station (NF18) for all years sampled. All images are about 15 cm wide. Image color was enhanced to emphasize the difference between oxic and anaerobic sediments.

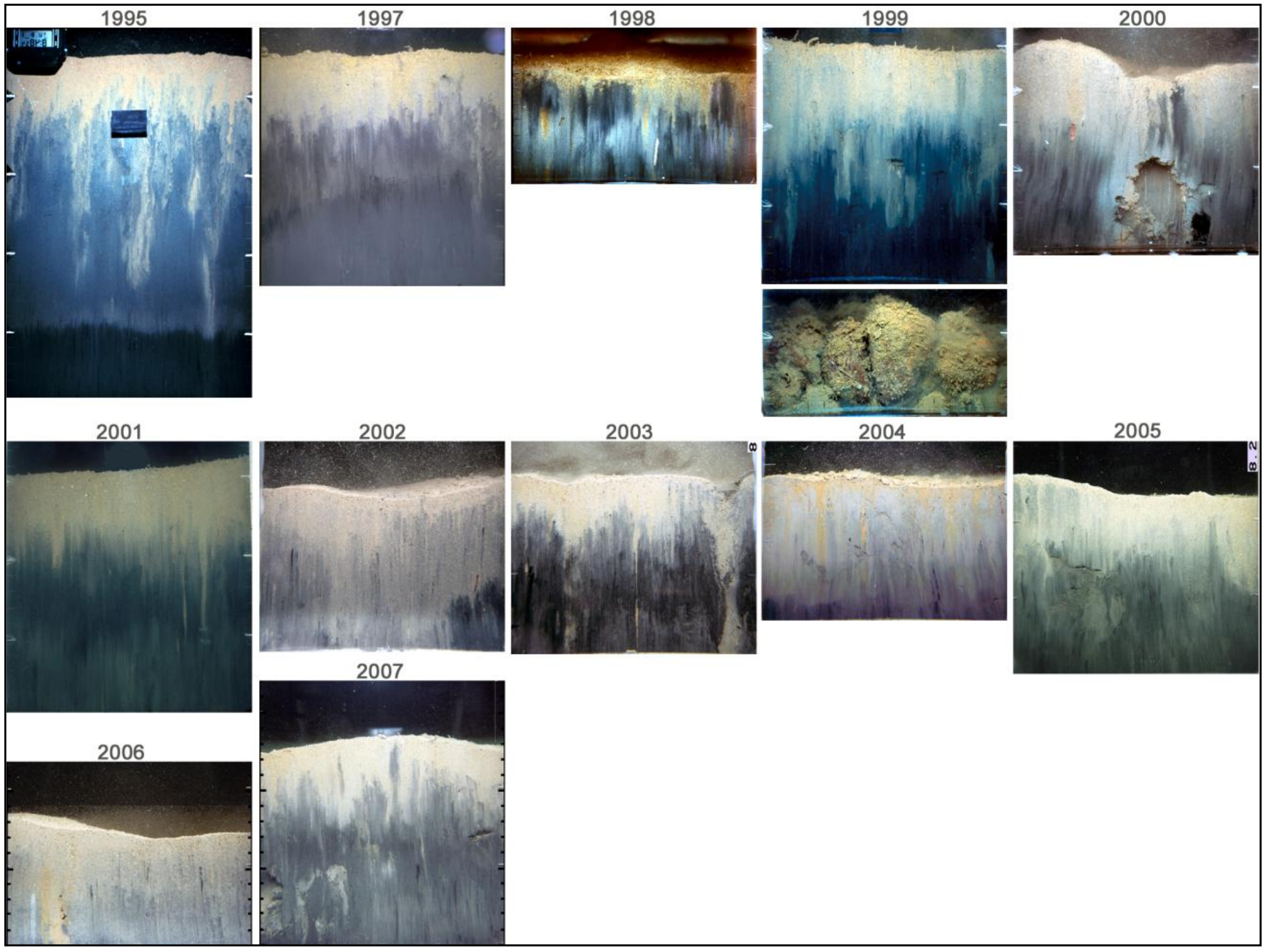


Figure 4-11. Example of homogeneous, finer sediment group station (NF24) for all years sampled. All images are about 15 cm wide. Image color was enhanced to emphasize the difference between oxic and anaerobic sediments.

4.4 Monitoring Question

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

For assessing outfall effects, the MWRA (1997) set a 50% reduction in the apparent color RPD layer depth over the study area as a critical trigger level. Similarly, a 50% increase in apparent color RPD over the baseline would be noteworthy. The average apparent color RPD for 2007 of 3.4 cm (SD = 0.67 cm) was significantly different from the baseline RPD of 2.3 cm ($F = 8.65$, $p = 0.007$). The fact that in 2007 the RPD was deeper than baseline would indicate that the RPD threshold was not exceeded. The difference between 2007 and the baseline was a deepening of the RPD by an average of 1.1 cm or 46%. The average RPD for 2007 was the high point of the range of annual RPDs, with 1997 and 1998 being the shallowest year at 1.8 cm (Figure 4-2).

In 2006, Maciolek *et al.* (2007) compared baseline to discharge years and found the discharge years had significantly deeper RPD layers (baseline to discharge years multiplier 0.202, $SE = 0.097$, $p = 0.038$). The addition of the deeper RPD layer data from 2007 would make the discharge years even more different than baseline years. Based on the color and texture of sediments in the 2007 SPI images, it does not appear that the amount of deposited organic matter has changed relative to the operation of the outfall, post-diversion, or the baseline for the nearfield SPI stations. TOC was also not different between baseline and post-diversion years (Chapter 3).

5. 2006 SOFT-BOTTOM BENTHIC INFAUNAL COMMUNITIES

by Nancy J. Maciolek and *Woollcott K. Smith*

5.1 Status of the Bay

5.1.1 Monitoring Program

The MWRA has studied the soft-bottom benthos of Massachusetts Bay for several years as part of the program to locate an outfall system nine miles off Deer Island. Stations have been sampled annually since August 1992. The area near the diffuser array, where potential impacts might occur, is primarily hard-bottom with few areas of soft sediments, resulting in the necessity of positioning benthic stations according to sediment type, rather than randomly. This constraint has resulted in the majority of the 23 nearfield stations being positioned to the north and west of the diffuser array (see Figure 2-1). Six of these stations (NF12, NF17, NF24, FF10, FF12, FF13) are sampled in triplicate, and single samples are collected from the remaining 17 stations. Eight farfield stations, also sampled in triplicate, represent an area far enough from the outfall that they are not expected to be impacted by the discharge. These farfield stations are located in a wide geographical area, from near Cape Ann in the north to Cape Cod Bay in the south. Two of the stations (FF04 and FF05) are located within the Stellwagen Basin National Marine Sanctuary, and two stations (FF06 and FF07) are within Cape Cod Bay.

Only minor repositioning of stations has occurred since the inception of the program (*i.e.*, station FF01 was replaced with FF01A). Three stations (FF10, FF12, and FF13) originally considered as farfield stations were reclassified as nearfield beginning in 1996, although the station designations were not changed. Other changes in the sampling program, which occurred primarily during the early years (1992–1994), are discussed in the annual reports to the MWRA (*e.g.*, Blake *et al.* 1998). In 2003, the MWRA reviewed and revised the monitoring program, and with the concurrence of the EPA, has rescaled the sampling effort. Beginning in 2004, only half the stations were sampled for benthos and sediment parameters TOC and grain size. In 2007, the subset of stations sampled was the same as that sampled in 2005 *i.e.*, four of the eight farfield and 12 of the 23 nearfield stations (see Chapter 1 Introduction and Chapter 2 Field Operations, this report).

5.1.2 Benthic Communities

During the baseline period (1992–2000), multivariate analyses of the infauna data suggested that sediment grain size was the dominant factor in structuring the benthic communities. The nearfield stations fall into one of two major sediment regimes: fine sediments characterized by the polychaete annelids *Prionospio steenstrupi*, *Spio limicola*, *Mediomastus californiensis*, and *Aricidea catherinae*; and sandy sediments (primarily NF13, NF17, and NF23) characterized by the syllid polychaetes *Exogone hebes* and *E. verugera* and the amphipods *Crassicorophium crassicorne* and *Unciola* spp. In addition to the influence of habitat heterogeneity, the nearfield area, in water depths of 27–35 m, is often affected by strong winter storms (*e.g.*, Bothner 2001, Butman *et al.* 2008), which cause episodes of sediment resuspension that potentially impact the benthic communities (Hilbig and Blake 2000, Kropp *et al.* 2002).

The fauna that characterizes the farfield differs from that seen in the nearfield. The farfield stations span a greater depth range (33–89 m) and are geographically widespread, with sediment types that are generally finer than those seen in the nearfield. Polychaete worms (*e.g., Euchone incolor, Aricidea quadrilobata,* and *Levinsenia gracilis*) are the predominant organisms at most of the stations, although *P. steenstrupi* is common at some of the stations. A different species of polychaete, *Cossura longocirrata*, is dominant at station FF06 in Cape Cod Bay, along with *Euchone incolor*, which typically indicates the presence of the deep-burrowing holothurian *Molpadia oolitica* (Rhoads and Young 1971).

Samples collected in 2001–2007, after the outfall went online, have not indicated any discernable impact of the discharge on the infauna (Maciolek *et al.* 2005, 2006, 2007). The few statistical differences detected in the benthic community parameters, such as increased numbers of certain species and increased dominance by certain species at one or two of the nearfield stations, were considered to be natural fluctuations in the populations and not related to the outfall discharge.

5.2 Methods

5.2.1 Laboratory Analyses

Sediment grab samples were rinsed with filtered seawater over 300-µm-mesh screens and transferred to 70–80% ethanol for sorting and storage. To facilitate the sorting process, all samples were stained in a saturated, alcoholic solution of Rose Bengal at least overnight, but no longer than 48 h. After rinsing with clean alcohol, all organisms, including anterior fragments, were removed and sorted to major taxonomic categories such as polychaetes, arthropods, and mollusks. Organisms were then identified to the lowest practical taxonomic category, usually species. Voucher specimens of each newly reported species were added to the MWRA reference collection.

5.2.2 Data Analyses

Preliminary Data Treatment—Appendix C1 contains detailed information on how various taxa were treated prior to statistical analysis. For example, some taxa were merged before the analyses were performed so that the data are consistent throughout the several years of the program. Another 173 taxa are juvenile or categories that represent more than one species, and are therefore not included in calculations of diversity. These modifications were generally similar to those performed in previous years; one difference for the 2007 data was that *Pholoe minuta*, *P. tecta*, and *P*. spp. were not merged prior to analyses.

Calculations of abundance included all infaunal taxa occurring in each sample, whether identified to species level or not, but did not include epifaunal or colonial organisms. Calculations based on species (number of species, dominance, diversity, evenness, similarity, and principle components analysis) included only those taxa identified to species level, or those treated as such. A list of all taxa identified during the Outfall Monitoring Program (1992–2007) is contained in Appendix C2.

Statistical Analysis—Initial inspection of the benthic data included production of summaries of species densities by sample, tables of species dominance, and tabulation of numbers of species and numbers of individuals per sample. Data were inspected for any obvious faunal shifts or species changes between stations. Following these preliminary inspections of the data, a series of community parameters was calculated along with multivariate statistics to assess community patterns and structure. Changes in infaunal community structure that are suspected to be due to the outfall can be assessed by comparing community structure differences between the nearfield and farfield through time, and evaluating changes in community structure before and after the outfall went online in September 2000.

Multivariate similarity and clustering programs used for this report are included in COMPAH96, originally written by Dr. Donald Boesch and now available from Dr. Eugene Gallagher at the University of Massachusetts, Boston (http://www.es.umb.edu/edgwebp.htm). Patterns in benthic communities were analyzed by similarity analysis using CNESS (chord-normalized expected species shared), which was developed by Gallagher (Trueblood *et al.* 1994) and is related to Grassle and Smith's (1976) NESS (normalized expected species shared). CNESS and NESS can be made more or less sensitive to rare species in the community; these algorithms were developed primarily for use with deep-sea data, in which no single species usually accounts for more than 4–10% of the individuals. CNESS is calculated from the expected species shared (ESS) between two random draws of *m* individuals from two samples. For this project, the optimal value of *m* was determined to be 15. For comparison, the Bray-Curtis similarity measure was also used, based on a fourth-root transformation of the data (performed in order to diminish the impact of numerically dominant species). Both similarity matrices were clustered using group average sorting and dendrograms were plotted. Results of these analyses were inspected for patterns among and between the different seasons.

PRIMER v.6 (Clarke and Gorley 2006) was used to calculate several diversity indices, including Shannon's H′ (base 2), Pielou's evenness value J′, Sanders-Hurlbert rarefaction, and Fisher's log-series *alpha*. Magurran (1988) classifies diversity indices into three categories: (1) species richness indices (*e.g.*, rarefaction); (2) species abundance indices (*e.*g., log-series *alpha*), and (3) indices based on the proportional abundances of species (*e.g*., Shannon index). The Shannon index, which is based on information theory, has been popular with marine ecologists for many years, but this index assumes that individuals are randomly sampled from an infinitely large population and that all species are present in the sample (Pielou 1975, Magurran 1988): neither assumption correctly describes the environmental samples collected in most marine benthic programs. Fisher's log-series model of species abundance (Fisher *et al.* 1943) has been widely used, particularly by entomologists and botanists (Magurran 1988). Taylor's (1978) studies of the properties of this index found that it was the best index for discriminating among subtly different sites, and May (1975) demonstrated that Sanders-Hurlbert rarefaction curves are often identical to those produced under the assumption that the distribution of individuals among species follows a log-series distribution. Hubble (2001) considers *alpha* the fundamental biodiversity parameter and promoted the use of this index for studies of diversity in all environments.

Principal Components Analysis of Hypergeometric Probabilities (PCA-H) was also applied to the benthic data. PCA-H is an ordination method for visualizing CNESS distances among samples (see Trueblood *et al.* 1994 for details). The PCA-H method produces a metric scaling of the samples in multi-dimensional space, as well as two types of plots based on Gabriel (1971). The Euclidean distance biplot, presented in this report, provides a two-dimensional projection of the major sources of CNESS variation. The species that contribute to the CNESS variation can be determined using matrix methods adapted from Greenacre's correspondence analysis (Greenacre 1984). These species are plotted as vectors in the Euclidean distance biplot. PCA-H was performed using MATLAB as an operating platform and additional programs written by Dr. E.D. Gallagher.

Negative Binomial Model. All models described and analyzed in this report start with the following basic log-linear model for mean abundance or concentration, μ_{ij}, at station *i* in year *j* with sediment property, x_{ij}.

$$\log\left(\mu_{ij}\right) = \mu + \alpha_{si} + \alpha_{yj} + \beta_1 x_{ij},$$

where α_{si} denotes the fixed effect associated with station *i* and α_{yj} denotes the fixed effect associated with station year *j*. In most cases we have used percent fine grains as the covariate variable that adjusts for sediment type.

The indicator variable $I_D(y)$ denotes the diversion event,

$$I_D(y) = \begin{cases} 1 & if \;\; y \geq 2001 \\ 0 & if \;\; y < 2001 \end{cases}$$

and the indicator variable $I_N(station)$ denotes the nearfield station,

$$I_5(\text{station}) = \begin{cases} 1 & \text{if station is less than 5 km from outfall.} \\ 0 & \text{otherwise.} \end{cases}$$

and

$$I_{2.5}(\text{station}) = \begin{cases} 1 & \text{if station is less than 2.5 km from outfall.} \\ 0 & \text{otherwise.} \end{cases}$$

A linear model that includes the diversion-by-nearfield factor can be written as

$$\begin{aligned} \log\left(\mu_{ij}\right) = \mu + \alpha_{si} + \alpha_{yj} + \beta_1 x_{ij} + \alpha_{5D} I_5(station_i) I_D(y_j) \\ + \alpha_{2.5D} I_{2.5}(station_i) I_D(y_j) \end{aligned} \qquad (0.1)$$

where α_{5D} and $\alpha_{2.5D}$ are the fixed effect interaction terms associated with the zones after the diversion event. The goal is to estimate "relative differences between these zones that are associated with the divergence event,"

$$\text{Relative change associated within 5 km after 2000} = e^{\alpha_{5D}}$$

$$\text{Relative change associated within 2.5 km after 2000} = e^{\alpha_{2.5D}}$$

Note that for stations within 2.5 km of the diffuser these effects are nested and multiplicative. For these stations, the change relative to stations greater than 5 km from the diffuser is $e^{\alpha_{5D}} e^{\alpha_{2.5D}}$.

This analysis estimates the relative change and the degree of statistical uncertainty associated with the relative change.

When response variable of interest, Y_{ij}, can be modeled as a continuous positive variable, the most applicable and straightforward model is the lognormal model, that is, $\log\left(Y_{ij}\right)$ is approximately normally distributed with mean $\log\left(\mu_{ij}\right)$ given by equation (0.1) with a standard deviation of σ . Under the lognormal model we have that

$$E[Y_{ij} \mid \mu_{ij}, \sigma] = \mu_{ij} \exp\left(\sigma^2/2\right) \text{ and } Var(Y_{ij}) = \mu_{ij}^{\,2}\left(\exp\left(\sigma^2\right) - 1\right).$$

Note that under this model the variance is proportional to the square of the expected response. Also, μ_{ij} denotes the geometric mean and $\mu_{ij} \exp\left(\sigma^2/2\right)$ denotes the arithmetic mean.

The above model needs to be modified when the dependent variable is a count of a relatively rare indicator species. When some counts are zero or near zero, the distribution of the discrete response variable can be modeled as negative binomial distribution with mean μ_{ij} given by equation (0.1) and the dispersion parameter $1/\theta$.

$$\Pr(Y_{ij} = k \mid \mu_{ij},\, \theta) = \frac{\Gamma\left(k+\theta\right)\mu_{ij}^{k}\,\theta^{\theta}}{\Gamma\left(\theta\right) k!(\theta + \mu_{ij})^{\,\theta+k}} \quad .$$

Under the negative binomial model we have that

$$E\left[Y_{ij} \mid \mu_{ij}, \theta\right] = \mu_{ij} \text{ and } \mathrm{Var}\left[Y_{ij} \mid \mu_{ij}, \theta\right] = \mu_{ij} + \frac{\mu_{ij}^2}{\theta} \quad . \tag{0.2}$$

Note that under the negative binomial model the variance is proportional to the mean squared plus an additional term, μ_{ij}, which accounts for the Poisson variation in the counts.

A maximum likelihood method implemented in the Splus library, MASS, was used to estimate the model parameters for this model and to test the null hypothesis $H_0 : \alpha_{5D} = 0$ and $H_0 : \alpha_{2..5D} = 0$ Similar negative binomial regression procedures are available in SAS, STATA and other statistical software systems.

Poisson-lognormal Model. The negative binomial model, used for the species abundance data above, is a mixture of the Poisson distribution with a gamma distribution. The negative binomial model is mathematically elegant, computationally convenient, and widely used. However, a more natural model is the Poisson lognormal, this is the exact analogue to the loglinear model used for the continuous variables. For the Poisson lognormal mixture model the probability is written

$$\Pr(Y_{ij} = k \mid \mu_{ij}, \sigma) = \int_0^\infty \frac{\lambda^k \exp(-\lambda)}{k!} \frac{1}{\sqrt{2\pi}\ \lambda} \exp\left(-\frac{1}{2}\left(\frac{\log(\lambda) - \log(\mu_{ij})}{\sigma} \right)^2 \right) d\lambda$$

where μ_{ij} is given by the log-linear model in equation (0.1)

Using this model, sophisticated numerical integration methods, and a new application the classical EM algorithm one can obtain maximum likelihood estimates and tests of significance. In general the model fits are close to the model fits for the negative binomial model. However, the negative binomial procedure tends to underestimate the true population variability, and thus the computed p-values are smaller than expected. Since the Poisson-lognormal procedure is not yet in the literature, we have used the generic negative binomial model. We have indicated with a footnote the p-values that are significant under the negative binomial model, but not under the Poisson-lognormal model. In general we can say the very small p-values are highly dependent on the distribution assumption in the analysis. In this case the change of mixing distributions from a gamma to a lognormal.

5.3 Results and Discussion

5.3.1 Species Composition of 2007 Samples

Species Composition—A list of all species collected as part of the Outfall Monitoring Program is included in Appendix C2. Five taxa were newly reported from the 2007 samples, which comprised 234 valid species. Two of these, a polynoid polychaete, *Gattyana nutti* Pettibone, 1955 and a bivalve, *Macoma calcarea* (Gmelin, 1791), were new to the MWRA database. Two species of amphipod, *Crassicorophium bonnelli* (Milne Edwards, 1830) and *Ericthonius brasiliensis* (Dana, 18530), and the crab *Cancer irroratus* Say, 1817, were new to the Massachusetts Bay species list, but had been previously identified in Boston Harbor.

The number of valid taxa in the Massachusetts Bay database, which includes both nearfield and farfield samples, and also includes all of the stations sampled in the program, now stands at 467 species. Over the course of the program, 365 and 306 species have been found at the subset of nearfield and farfield stations sampled in 2007, respectively.

5.3.2 Benthic Community Analysis for 2007: Nearfield

Several benthic community parameters, including the number of organisms and species in each sample, and the calculated measures of diversity (Shannon H′) and evenness (Pielou's J′), and Fisher's log-series *alpha*, were calculated for each sample. All nearfield samples collected prior to the outfall becoming operational in September 2000 were used to determine a baseline average value for each parameter. Baseline values were not recalculated after the stations were divided into subsets to be sampled on a rotating basis because the subsets, which were chosen randomly, are considered to be reflective of the original range of values (MWRA 2003).

Baseline values and the mean value for each parameter for each year from beginning in 1992 are plotted below. Results by sample are given in Appendix C3, Table C3-1, and community parameters for individual stations are plotted in the figures in Appendix C3.The means for all parameters except abundance were slightly higher than those recorded for the same subset of stations in 2005.

Density—The highest mean infaunal density per nearfield sample was recorded in 2002 (3,476 organisms per sample), and was only slightly lower in 2003 (3,138 organisms per sample). Since then, mean abundance has declined to well below the baseline value (Figure 5-1). The 2007 mean was 1,545.2 ± 588.8 SD organisms per sample, the third lowest recorded in the program, with only 1993 and 2006 being slightly lower (Figure 5-1, Maciolek *et al.* 2007). Mean density in 2007 was about 15 percent lower compared with the same stations in 2005. Maciolek *et al.* (2003) considered the high variability at some stations, which contrasted with the stability of other stations over time, and suggested that several processes, biological as well as physical, were operating in this system. Annual fluctuations in the population densities of several species and the occasional scouring of the bottom by storms both contribute to the overall invertebrate densities recorded from the benthic grab samples. The next few sampling years should indicate if the trend of declining mean abundance will be reversed, in keeping with a 10–15-year cycle.

Inspection of the abundance data for individual nearfield stations (Appendix C3, Table C3-1, Figure C3-1) revealed that total densities increased at six of the 12 nearfield stations (NF02, NF12, NF14, NF15, NF17, and NF20) and decreased at the remaining six stations (NF04, NF10, NF13, NF21, NF 24, and FF12). *(Note: Values for NF12 and NF17 are compared with values for 2006, since those stations are sampled every year.)*

At the six stations where densities had decreased, the decline ranged from 10.8 percent at NF24 to 65.6 percent at NF10. Increases ranged from 3.8 percent at NF14 to 71.3 percent at NF17. The lowest abundances were found at NF04 (772 organisms per sample) and NF10 (895 organisms per sample), and the highest at NF15 and FF12 (2,319 and 2,360 organisms per sample, respectively).

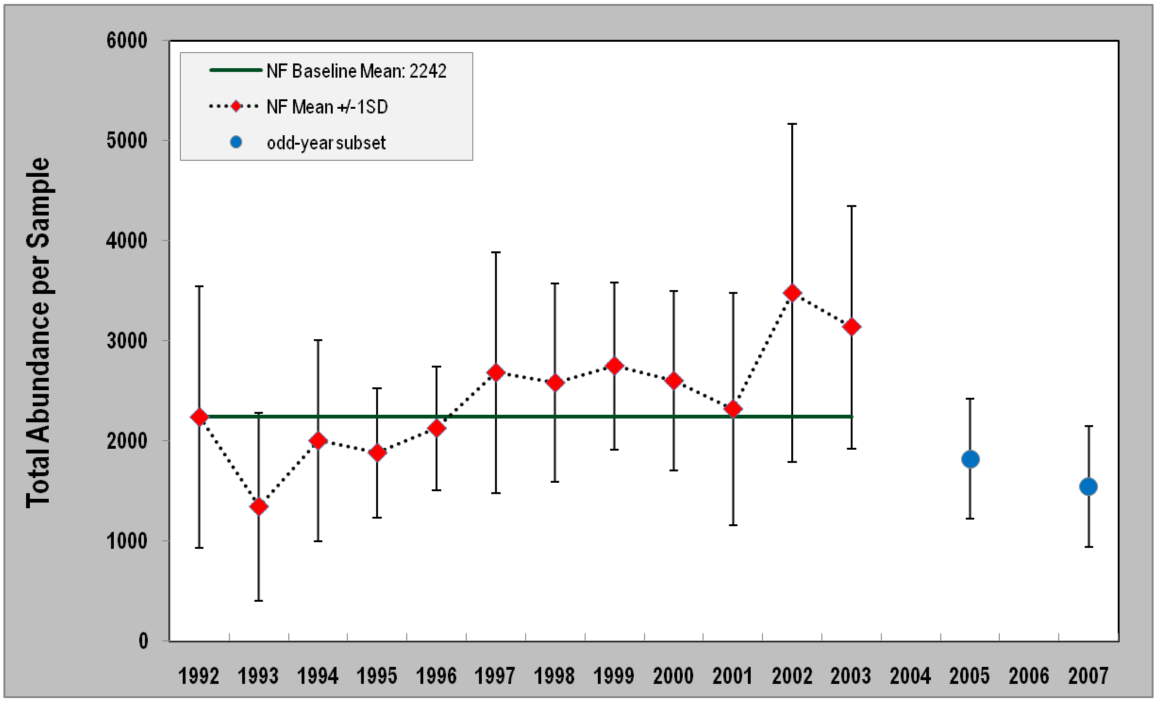


Figure 5-1. Mean abundance per sample for nearfield stations. The baseline mean is based on all NF stations, whereas the means for 2005 and 2007 are based on a subset of 12 stations.

Species Richness—In 2007, 189 species were recorded from the 20 nearfield samples, with a mean of 64.3 species per sample (Figure 5-2A); this result is slightly higher than species richness in 2005, when a mean of 61.1 species per sample was recorded for the same set of nearfield stations (Maciolek *et al.* 2006). The average number of species per nearfield sample increased from 2001 through 2004, when it was well above the baseline average of 65, but decreased in 2005 (Figure 5-2A).

In 2007, species richness was the same at NF13 and decreased at four stations (NF19, NF 14, NF17, and NF21). The decrease was small at NF14 and NF17 (a loss of 3.0 and 1.3 species, respectively); the largest decline in species richness was at NF21, where a loss of 23 species representing a 31.1 percent decrease was recorded. Increased species richness of 8.8 to 24.5 percent was noted at the remaining stations, with the largest increase at NF02 (24.5 percent, 13 species) (Appendix C3, Figure C3-2).

Diversity and Evenness**—**In 2007, all three measures indicated a small, insignificant increase in diversity compared with the same stations in 2005 (Figure 5-2B–D).

As in 2005, the means of both Shannon diversity (H′ = 3.79) and Pielou's evenness (J′ =0.63) were comparable to the baseline means (H′ = 3.68; J′ = 0.62) (Figure 5-2B,C; Appendix C3, Figures C3-3 and C3-4). Shannon diversity values at individual stations remained the same or increased at nine of the 12 stations, with minimal changes at NF04 (from 3.92 to 3.97), NF20 (3.71 in both 2005 and 2007), and NF21 (from4.21 to 4.28) and slightly larger increases at NF02, NF10, NF12, NF13, NF24, and FF12; the largest increase occurred at NF02 (from 2.94 to 4.00, or 36.2 percent) (Appendix C3, Figure C3-3). Small declines in H′ occurred at NF14 and NF15

With the exception of 2006, H′ has declined at NF17 every year since reaching a high of 4.29 in 2002; in 2006, H′ increased to 3.7, but declined again in 2007 to 2.75, the lowest value seen at that stations with the exception of 1994 (Appendix C3, Figure C3-3).

Mean evenness in 2007 was 0.63, a small increase from the mean (0.61) measured for the same station set in 2005. Most individual stations had increased evenness values compared with those measured the last time each station was sampled. The largest changes were seen at NF17 (a decrease from 0.65 in 2006 to 0.49 in 2007) and NF02 (an increase from 0.51 in 2005 to 0.66 in 2007) (Appendix C3, Figure C3-4).

The diversity measure log-series *alpha* was higher in 2007 (13.98) than for the same station set in 2005 (12.6) (Figure 5-2D, Appendix C3, Figure C3-5), but lower than recorded for the alternate station set in 2004, when the program high of 16.2 was reached (Maciolek *et al*. 2005)

When individual stations were considered (Appendix C3, Figure C3-5), *alpha* was higher at eight stations and lower at four in 2007 compared with the previous sampling year. The largest increase was at NF13, where *alpha* increased from 10.57 in 2005 to 17.1 in 2007. Declines were seen at NF12, NF14, NF20, and NF21, with the largest decline at NF 20, where alpha was 12.77 in 205 and 10.3 in 2007. Compared to the Shannon index, which is based on information theory and makes assumptions that are not met by the present samples (see Methods section 5.2.2 above), log-series *alpha*, which is based on species numbers and abundances, appears to provide a better discrimination among subtly different sites and thus is more reliable in reflecting the actual environmental trend.

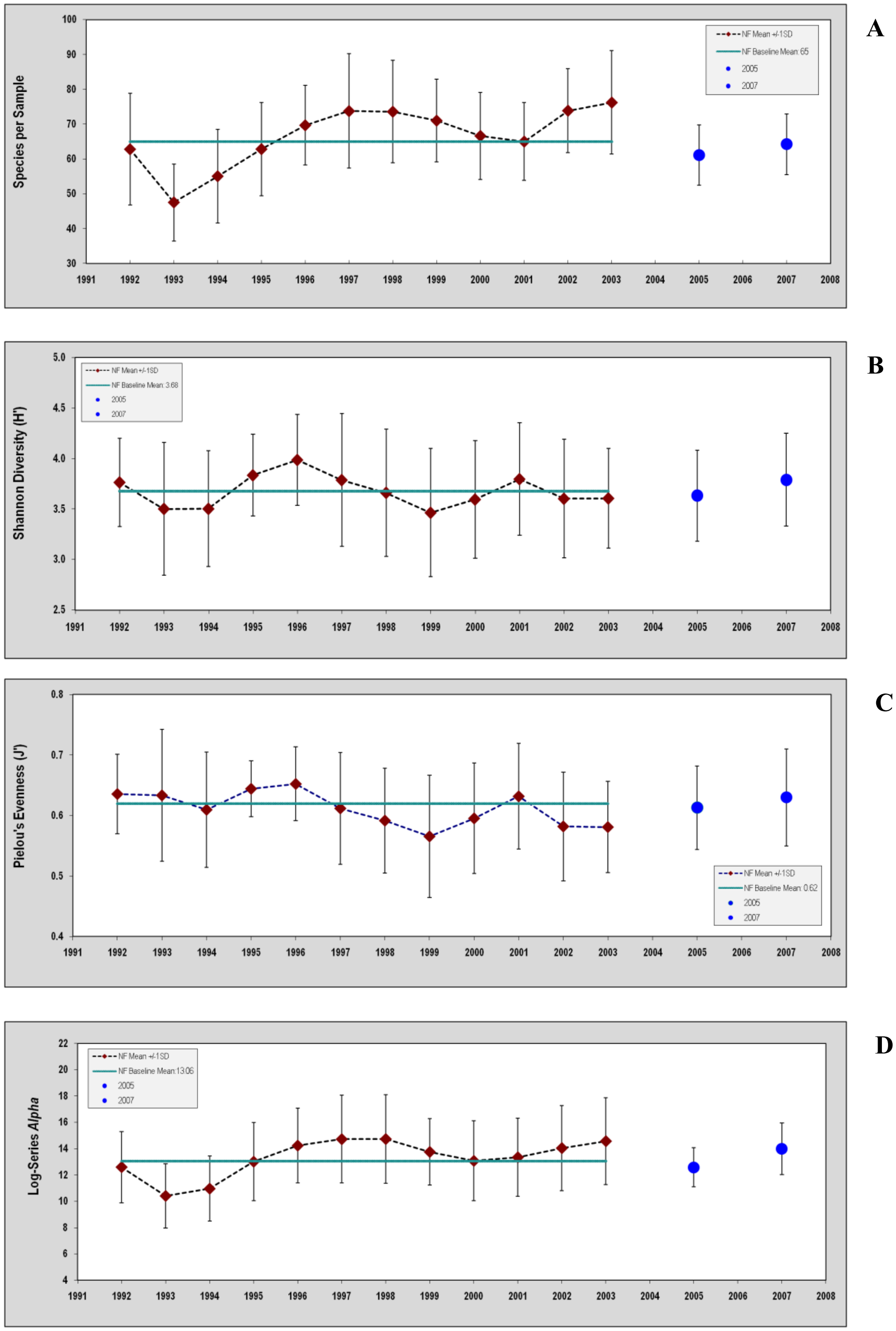


Figure 5-2. (A) Number of species per sample, (B) Shannon diversity, (C) evenness, and (D) log-series alpha at nearfield stations from 1992–2007.

***Dominant Species*—**Dominant species at each nearfield station are listed in Appendix C4, along with the percent contribution of each to the total community, based on total individuals in the sample and those that were identified to species. In the latter case, the percentage is usually just a few tenths of a point less than when calculated for total individuals. The dominant species at the nearfield stations have been consistent over the past several years, although changes in their absolute numbers, and numerical rank in the samples, have changed from year to year.

The spionid polychaete *Prionospio steenstrupi* has been the numerical dominant in Massachusetts Bay for the past several years, and is found in all sediment types, which range from 5 to 70 % fines (see Chapter 3), found at the nearfield stations. In spite of reduced densities beginning in 2004, *P. steenstrupi* remained the numerical dominant at six of the 13 nearfield stations sampled that year (Maciolek *et al.* 2005) and was the numerical dominant at nine of the 12 nearfield stations sampled in 2005 (Maciolek *et al.* 2006). In 2007, at the same subset of stations, *P. steenstrupi* accounted for 20.1 percent of all infaunal organisms collected, compared to 32.6 percent in 2005, and was the numerical dominant at only four of the 12 nearfield stations, where it accounted for 26–43 percent of the organisms at any individual station (Appendix C4) . It was also second to *Aricidea catherinae* at one additional station (NF14), where it accounted for 23.5% of the organisms. At the sandy station NF17, where *P. steenstrupi* had been the fourth most abundant species for the past two years, it dropped to eleventh place in 2007. Although sediments at NF17 were slightly coarser in 2007 compared with recent years (Chapter 3, this report), the increase in percent sand from 97.5 in 2006 to 98.9 in 2007 does not seem to be great enough to be the only factor responsible for the decline in importance of *P. steenstrupi* at this station, especially in light of the fact that *P. steenstrupi* was the numerical dominant at NF02 in both 2005 and 2007, when sediments were 23.7 and 92.9 % sand, respectively.

Maciolek *et al.* (2006) discussed a faunal shift at NF02 between 2003 and 2005, and suggested that this change most likely associated with the change in sediment composition at this site: sediments at NF02 were coarse (<10% silt-plus-clay) in all years except 1992, 2002, and 2005, when 77%, 61% , and 76% silt-plus-clay, respectively, were measured. In 2005, 76% fine sediments were again recorded at this station . A large faunal change appeared to be associated with the shift from 77% silt+clay in 1992 to 3% in 1993, and between 2003 and 2005, but there was little indication of a faunal change that might have been associated with the change in grain size between 2001 and 2002. In 2007, when sediments were once again coarse (92.9% sand), the dominant species *P. steenstrupi* and *Mediomastus californiensis* retained numerical dominance, while others, such as *Pholoe tecta*, which ranked second and *Nephtys cornuta*, which ranked seventh in 2005, dropped in importance to fourteenth and fifteenth place, respectively. In contrast to *P. steenstrupi*, which can alternate between surface deposit feeding and filtering food particles from the water column, *P. tecta* and *N. cornuta* are restricted to bottom feeding, perhaps as omnivores or selective deposit feeders. In addition to a lag time associated with changes in sediment composition, the flexibility of some species such as *P. steenstrupi* in terms of feeding behavior most likely accounts for its success in a wide variety of sediment types. In addition, in 2007 *Capitella capitata* complex accounted for 7.8% of the organisms at NF02; the increase in coarser sediments at this station might have resulted in the increase in this species, which responds to disturbed areas.

Other polychaete species, including *Mediomastus californiensis*, *Levinsenia gracilis*, and *Tharyx acutus*, were also among the numerical dominants at many nearfield stations, particularly those with the finest sediments (*e.g.*, NF10, NF12, NF20, and NF21). Maciolek *et al*. (2007) noted that the polychaete *Ninoe nigripes* had become increasingly more abundant over the past several years, whereas *L. gracilis* and *M. californiensis* have maintained their numerical rank in the nearfield communities for the past several years. However, *N. nigripes* was about as common in 2007 as it had been at the same subset of stations in 2005, increasing in numerical rank only at NF20 and NF21 while at other stations retaining a rank similar to that recorded in 2005.

A different suite of species is found at the coarsest-grained station NF17, where percent fines are only about 2% of the sediments. At this station, which is sampled every year, the ascidian *Molgula manhattensis* has ranked either first or second for several years. In 2007, the amphipod *Crassicorophium crassicorne* was the numerical dominant, and the polychaetes *Phyllodoce mucosa*, *Exogone hebes*, and *Chaetozone anasimus* were subdominants (Appendix C4). Although these sandy communities have been fairly consistent throughout the course of the monitoring program, some changes have been observed, *e.g.*, *P. mucosa* has not previously been among the top numerical dominants at this station. Others that have been common, such as *Spiophanes bombyx*, dropped in importance in 2007 compared with previous sampling years. NF13, also a coarse-sediment station with about 6% fines, has a faunal composition that includes components of both NF17 and the finer-grained stations: species such as *Exogone hebes*, *S. bombyx*, and *M. manhattensis* are among the top dominants, but *Aricidea catherinae*, *Tharyx acutus*, and *P. steenstrupi* are also common (Appendix C).

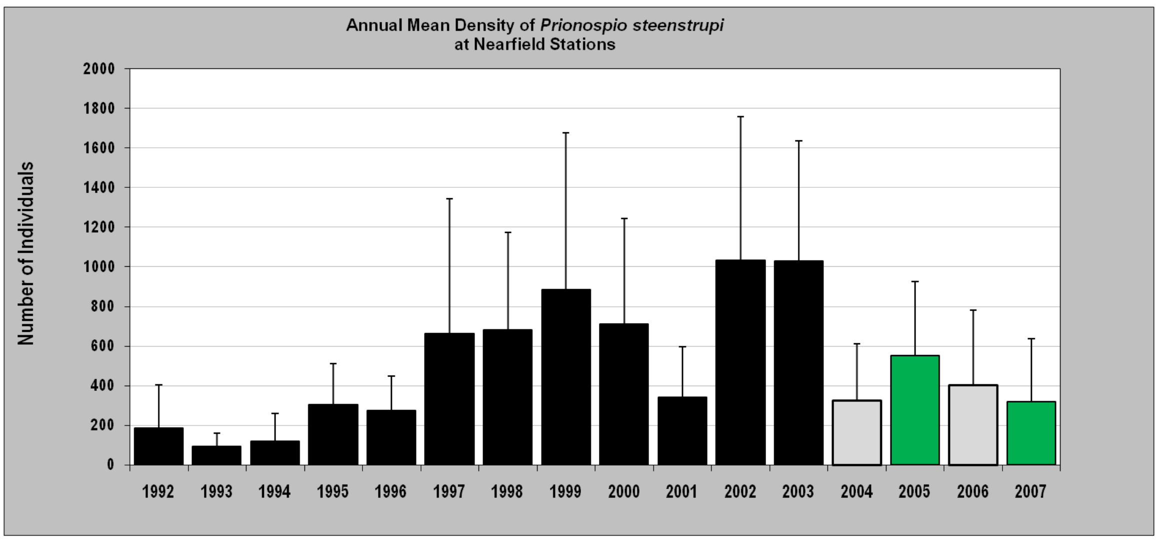


Figure 5-3. Annual mean density of *Prionospio steenstrupi* at nearfield stations. Two subsets of stations were sampled, one in 2004/2006 and the other in 2005/2007.

5.3.3 Benthic Community Analysis for 2007: Farfield

Benthic community parameters, including the number of organisms and species in each sample, and the calculated measures of diversity (Shannon H′) and evenness (Pielou's J′)and Fisher's log-series *alpha*, are examined annually. All farfield samples collected prior to the outfall becoming operational in September 2000 were used to determine a baseline average value for each parameter; these values were not recalculated after the stations were divided into subsets to be sampled on a rotating basis because the subsets, which were chosen randomly, are considered to be reflective of the original range of values (MWRA 2003).

Baseline values and the mean value for each parameter for each sampling year from beginning in 1992 are plotted below. Results by sample are given in Appendix C3, Table C3-1, and community parameters for individual stations are plotted in the figures in Appendix C3.

The farfield stations are located within a large geographic area, and consequently occupy a variety of habitats (Figure 2-2, Table 2-1), making it difficult to generalize over the area. FF11 is the northernmost station, off Cape Ann, and at 88 m water depth, is also the deepest station. FF01A is located inshore and to the south of FF11 in 35 m. FF14 is to the east of the diffuser array, in 73 m. FF06 is in Cape Cod Bay in about 35 m (see Table 2-1).

Density—Mean density at the farfield stations in 2007 was slightly lower than recorded in 2005, although mean densities in both 2005 and 2007 had declined compared to the program high recorded in 2003 (Figure 5-4). The 2007 mean of 2080 ± 744.7 organisms per sample was well above the baseline average of 1615 organisms per sample. Mean abundance increased slightly at FF01A and FF06 and declined at FF11 and FF14 compared with 2005 values (Figure 5-5, Table C-1), when these stations were last sampled. The change was most pronounced at FF14, where 2003 values had been particularly high and the 2005 and 2007 values were similar to those recorded in 1998–2001. At FF14, the numerical dominant, *Spio limicola*, which had been present in roughly equal abundances in 2003 and 2005, declined by an order of magnitude in 2007 to 89.0 ± 15.4 SD individuals per sample and was replaced as the numerical dominant by *Anobothrus gracilis*, which had a mean abundance of 127.0 ± 82.4 SD.

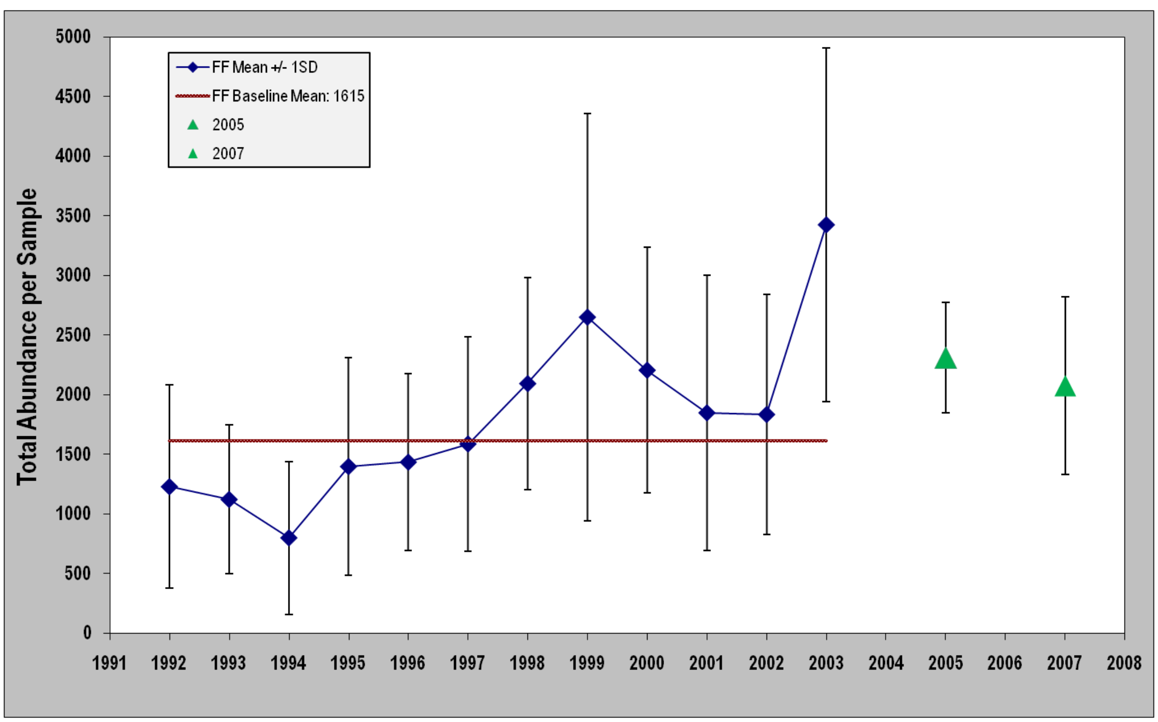


Figure 5-4. Mean abundance per sample for farfield stations sampled in 2007.

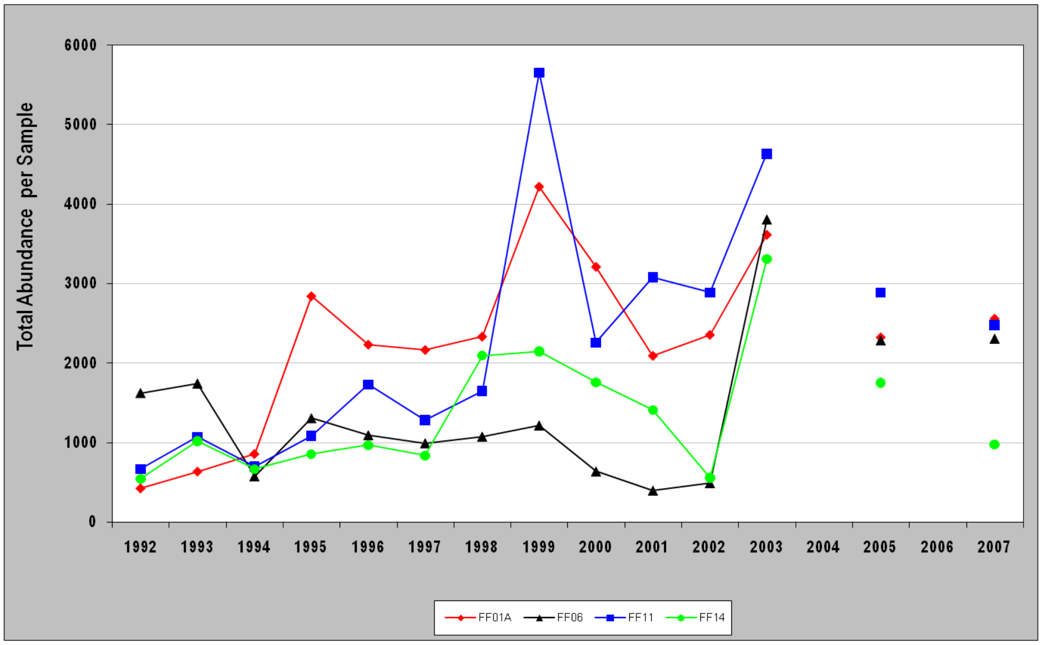


Figure 5-5. Annual mean abundance at each farfield station.

Species Richness—In 2007, 184 species were identified from the 12 farfield samples taken at four locations, with an average of 76.7±10.2 species per sample and a range from 62.3 species at FF11 to 87.0 species at FF01A (Figure 5-6A). In 2005, 172 species were recorded from these stations, with an average of 73.1 species per sample (69.7 at FF06 to 75.0 at FF14) (Maciolek *et al*. 2006). The mean number of species per sample increased at three of the four farfield stations, FF01A, F06, and FF14 (Figure 5-7A, Appendix C3), and decreased only at FF11, with the overall mean remaining well above the baseline value of 61 species.

Diversity and Evenness—Compared with mean values obtained for 2005, Shannon diversity, evenness, and log-series alpha increased at the farfield stations in 2007, although, as in previous years, the pattern of change differed among stations. Rarefaction curves (Figure C3-5 in Appendix C3) indicate that FF14 is the most diverse farfield station and FF11 the least.

Mean Shannon diversity (H′) was 4.16, an increase over the 3.79 value recorded in 2005 and due primarily to increased diversity at FF01A and FF14 (Figure 5-6B). At FF01A, Shannon diversity increased from 2.98 in 2005 to 3.81 in 2007, and at FF14, from 4.08 to 5.09 (Figure 5-7B, Appendix C3). Declines at the other two stations were trivial compared with these increases.

Mean Pielou's evenness (J′) (0.66) was also higher in 2007 compared with the 2005 mean value of 0.61, and higher than the baseline value of 0.64 (Figure 5-6C). Evenness at FF06 had been particularly low (0.47) in 2003; however, the results for 2005 and 2007 were similar to those seen in the majority of sampling years (Figure 5-7C).

Mean log-series *alpha* increased from 14.65 in 2005 to 16.44 in 2007, well above the baseline mean of 13.4 (Figure 5-6D). These four stations had a mean *alpha* value of 16.35 when sampled in 2003 (Maciolek *et al.* 2006). *Alpha* increased at three of the four farfield stations, the exception being FF11, where *alpha* declined from 13.84 in 2005 to 11.84 in 2007 (Figure 5-7D, Appendix C3).

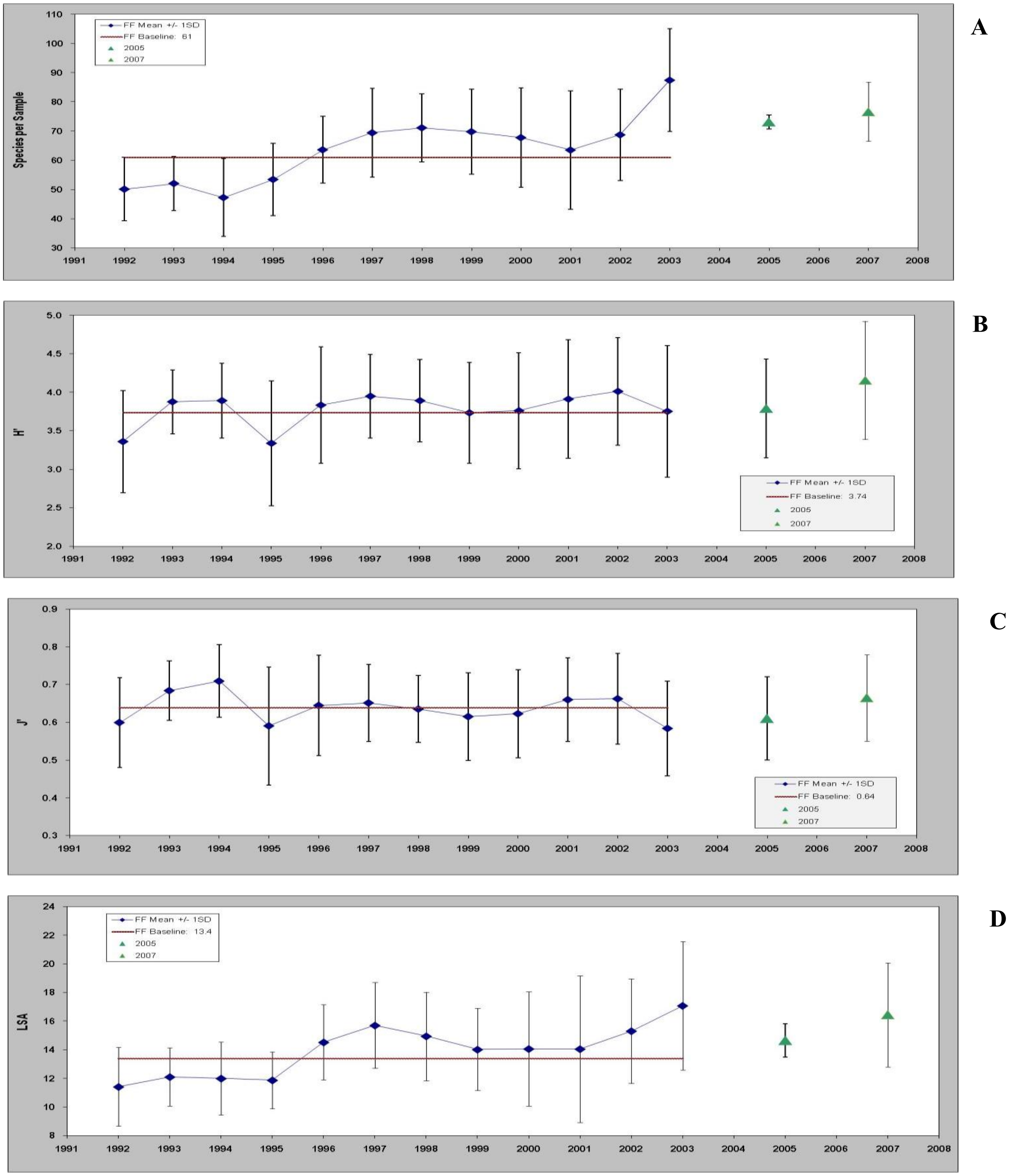


Figure 5-6. Annual mean parameters for farfield benthic infaunal stations. (A) Mean number of species per sample, (B) Mean Shannon diversity, (C) Mean evenness, and (D) Mean log-series *alpha* at farfield stations from 1992–2007.

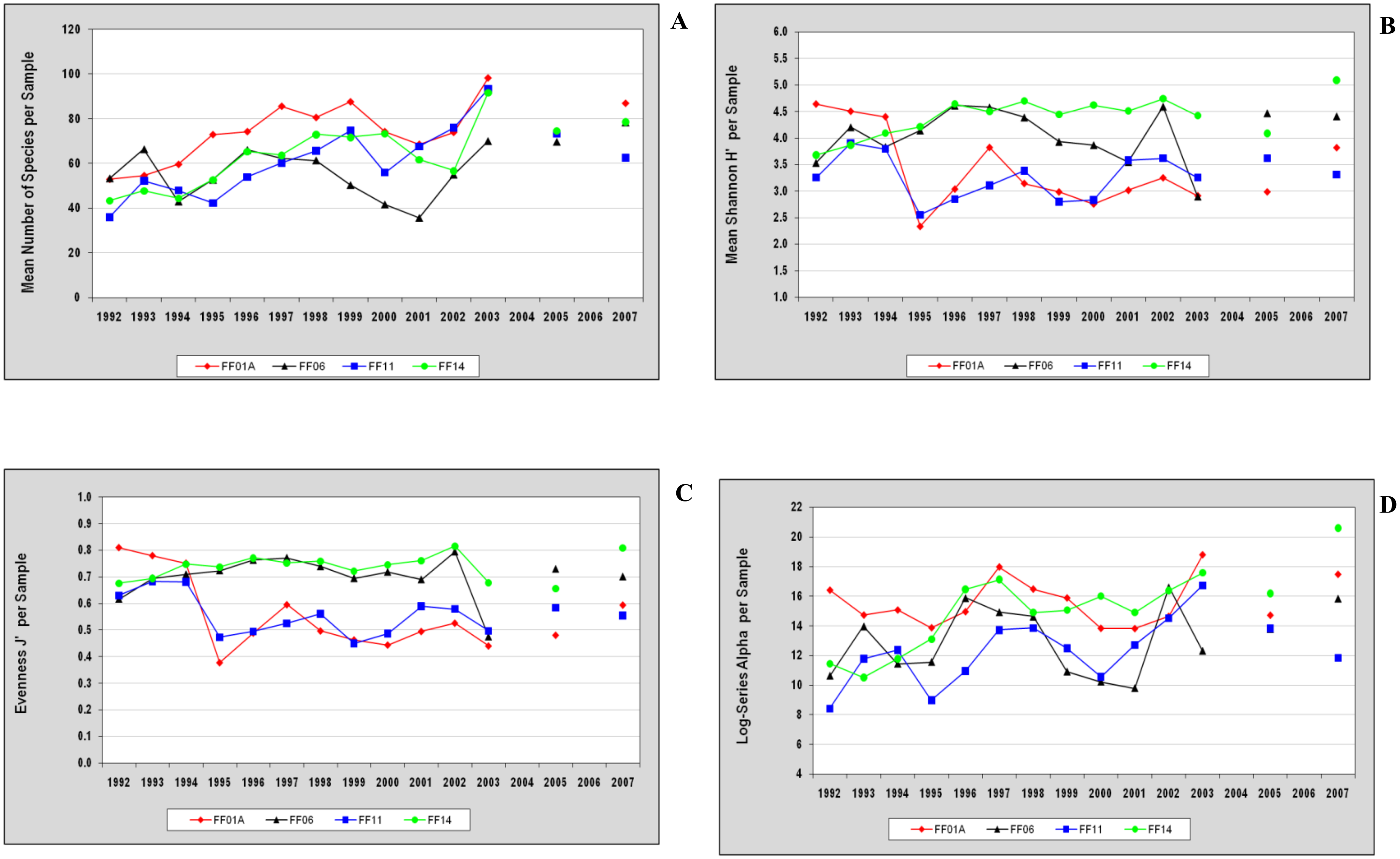


Figure 5-7. Annual parameters for individual farfield benthic infaunal stations sampled in 2007. (A) Mean number of species per sample, (B) Mean Shannon diversity, (C) Mean evenness, and (D) Mean log-series *alpha*.

Dominant Species—Dominant species at each farfield station are listed in Appendix C4, along with the percent contribution of each to the total community based on both total individuals in the sample and those that were identified to species. In the latter case, the percentage is usually just a few tenths of a point less than when calculated for total individuals. The population fluctuations of four of the dominant species are shown in Figure 5-8. The species composition at FF01A and FF11 has remained fairly stable over the past several years, whereas greater changes have been seen at FF06 and to a lesser extent, at FF14.

- FF01A—*Prionospio steenstrupi* has been the numerical dominant for the last several years, and, in 2005, accounted for over 58% of the organisms collected at that station even though overall densities were reduced. In 2007, this species was once again the numerical dominant, although accounting for only 36.5% of the total fauna. As in 2003 and 2005,the bivalve *Nucula delphinodonta* and the polychaetes *Tharyx acutus*, *Levinsenia gracilis*, *Aricidea catherinae*, and *Mediomastus californiensis* were among the ten most numerous species, as was *Monticellina baptisteae.*

- At FF06, in Cape Cod Bay, the top three numerical dominants were *Euchone incolor*, *Tharyx acutus,* and *Cossura longocirrata*. Prior to 2003, *Euchone incolor* was rarely encountered at this station, but was the numerical dominant in 2003 and 2005; this species is associated with the mounds made by the deep-burrowing holothurian *Molpadia oolitica*. Similarly, *P. steenstrupi* and *Spio limicola* occurred only in low numbers for several years, but in 2005 were the second and fourth most numerous species. In 2007, both species declined in abundance; *P. steenstrupi* was replaced by *T. acutus* as the second most numerous species. *Cossura longocirrata,* a species generally associated with fine sediments, held a similar ranking (third) in 2005.

- FF11—*Prionospio steenstrupi* continued to be the numerical dominant at this station as for the past several years. In 2007, this species accounted for over 43% of the infauna, an increase over the 34% reported for 2005 (Maciolek *et al.* 2006). Other numerical dominants at this station have remained stable for the past several years; these species include the polychaetes *Aricidea quadrilobata, S. limicola, Anobothrus gracilis, L. gracilis, E. incolor,* and *Chaetozone anasimus* (formerly *C. setosa* mb), and the oligochaete *Tubificoides apectinatus*.

- At FF14, the numerical dominant, *Spio limicola*, which had been present in roughly equal abundances in 2003 and 2005 and the numerical dominant since 2002, declined by an order of magnitude in 2007 to 89.0 ± 15.4 SD individuals per sample and was replaced as the numerical dominant by *Anobothrus gracilis*, which had a mean abundance of 127.0 ± 82.4 SD. Other species common in 2007 included Nemertea sp. 12, *Aricidea quadrilobata*, and *Mediomastus californiensis,* all of which displaced the dominant species recorded in 2005; these prior dominants continued to be present in the samples, although at lower abundances.

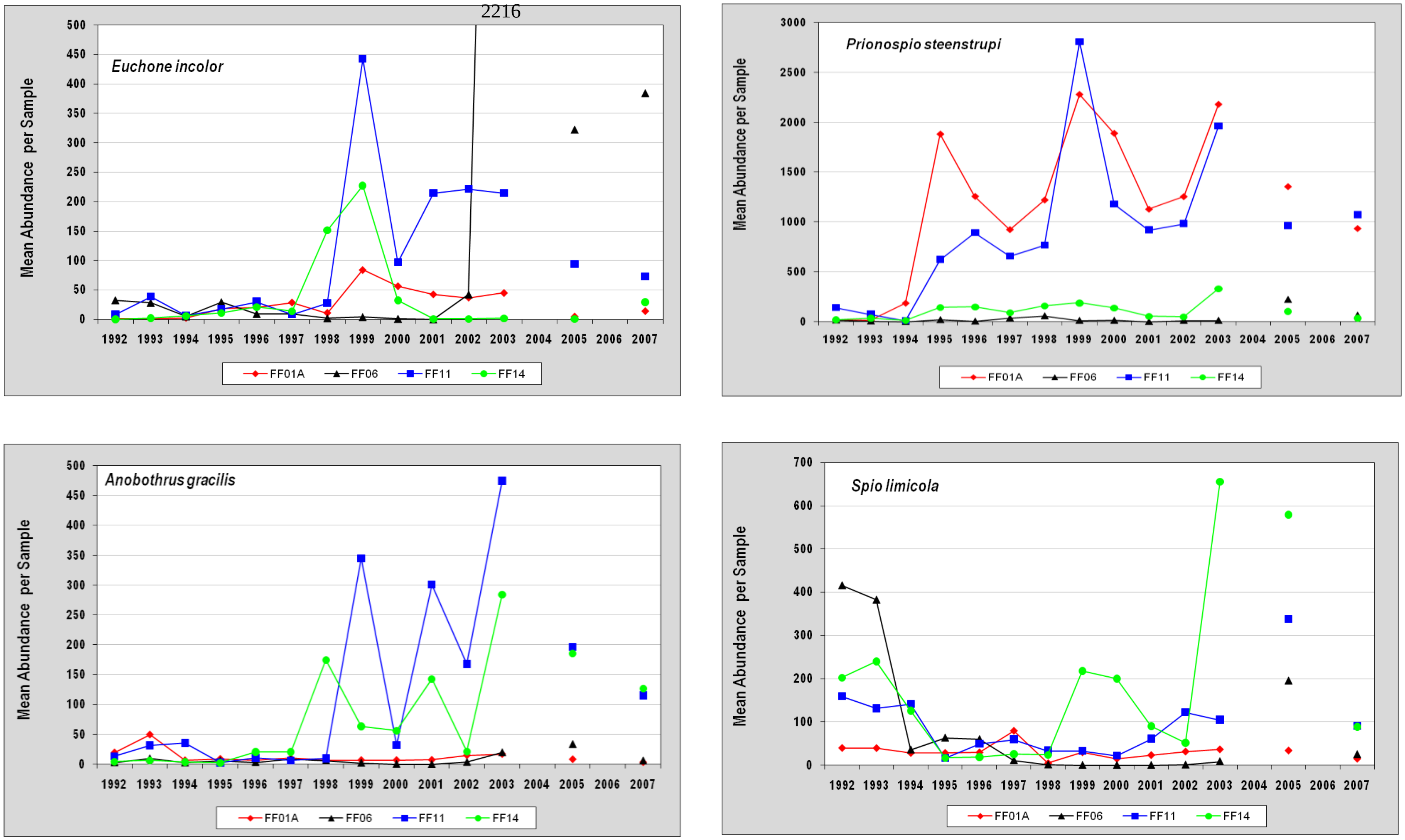


Figure 5-8. Mean density per 0.04-m^2 sample of species common at the 2007 farfield stations.

5.3.4 Multivariate Analysis of 2007 Samples

***Similarity Analysis*—**A similarity (or resemblance) analysis of the samples taken in 2007 was carried out using both the CNESS (*m*=15) and Bray-Curtis algorithms (Figure 5-9). The results of each were similar both to the other and to the same analysis carried out on the 2005 data (Maciolek *et al*., 2006). The level of similarity among stations appears lower for the 2007 samples than seen in 2005 for the same subset of stations (Maciolek *et al.* 2006). As in previous years, where replicates were taken at a station, those replicates were always more similar to samples from the same station than to samples from another station.

At the fairly low (1.0) level of similarity in CNESS, the samples formed four major groups or clusters: (1) a mix of nearfield stations, the northernmost station FF01A and Cape Cod Bay station FF06, together representing a wide range of sediment types, (2) fine-grained farfield stations FF11 and FF14, (3) nearfield sandy stations NF04 and NF13, and (4) coarse-grained NF17 (Figure 5-9, top). At the more similar 0.78 level, group 1 comprises five smaller groups (labeled a–e in the diagram), three of which represent single stations: the nearfield station NF02 and two farfield stations, FF01A and FF06.

In 2005, the sample from NF02 differed from other nearfield stations due to >100 individuals of *Pholoe minuta/tecta*/spp. in the sample. In 2007, the sediment had coarsened at this station (see Chapter 3, this report) and while only 13 individuals of *Pholoe* were recorded, the 112 specimens of *Capitella capitata* complex were an order of magnitude greater than recorded in other samples and most likely accounted for the low level of similarity with other nearfield stations.

The Bray-Curtis analysis of these data (after a fourth-root transformation to decrease the influence of species with high abundances) resulted in a pattern nearly identical with that from CNESS (Figure 5-9, bottom). In this analysis, the Cape Cod Bay station FF06 clustered with FF11 and FF14, as it did in 2005 with both this algorithm and CNESS (Maciolek *et al.* 2006); the only other difference was that NF 20 clustered with NF14 and NF15, rather forming an outlier to a group comprising those two stations and NF24.

***PCA-H analysis*—** The PCA-H analysis based on the CNESS similarities separated the cluster groups discussed above along several multidimensional axes, with axis 1 and axis 2 together accounting for 50% of the total variation (Figure 5-10). The CNESS cluster groups are indicated in this two-dimensional presentation: groups 1a–e and especially group 2 separate along axis 2, and group 3 (NF04 and NF13) and group 4 (NF17) separate along axis 1. These two axes most likely represent a combined sediment grain size vs. depth (or region) gradient; however, these factors are not clearly assignable to either axis. With CNESS (*m*=15), 37 of the 232 species recorded in 2005 accounted for 90% of the variation in the community structure, and contributed at least 1% to the PCA-H axes (Table 5-1).

The species accounting for at least 2% of the CNESS variation, and therefore the ones responsible for the separation of the samples, are indicated for Axes 1 and 2 in the Gabriel Euclidean distance biplot (Figure 5-10) and are detailed for Axes 1–3 in Table 5-2. The majority of nearfield stations are structured by the surface-deposit- (and sometimes filter-) feeder *Prionospio steenstrupi*, and the subsurface deposit feeders *Mediomastus californiensis*, *Levinsenia gracilis*, *Monticellina baptisteae*, and *Tharyx acutus*. The sandy nearfield stations (NF17, NF13, and NF04) are characterized by the syllid polychaete *Exogone hebes* (an omnivore), the ascidian *Molgula manhattensis,* and the amphipod *Crassicorophium crassicorne*. The bivalve, *Ensis directus*, which was important in 2005, was not as important in 2007. At farfield stations FF11 and FF14, the important species comprise a suite of polychaetes including *Anobothrus gracilis, Spio limicola*, *Aricidea quadrilobata*, the oligochaete *Tubificoides apectinatus*, and a nemertean.

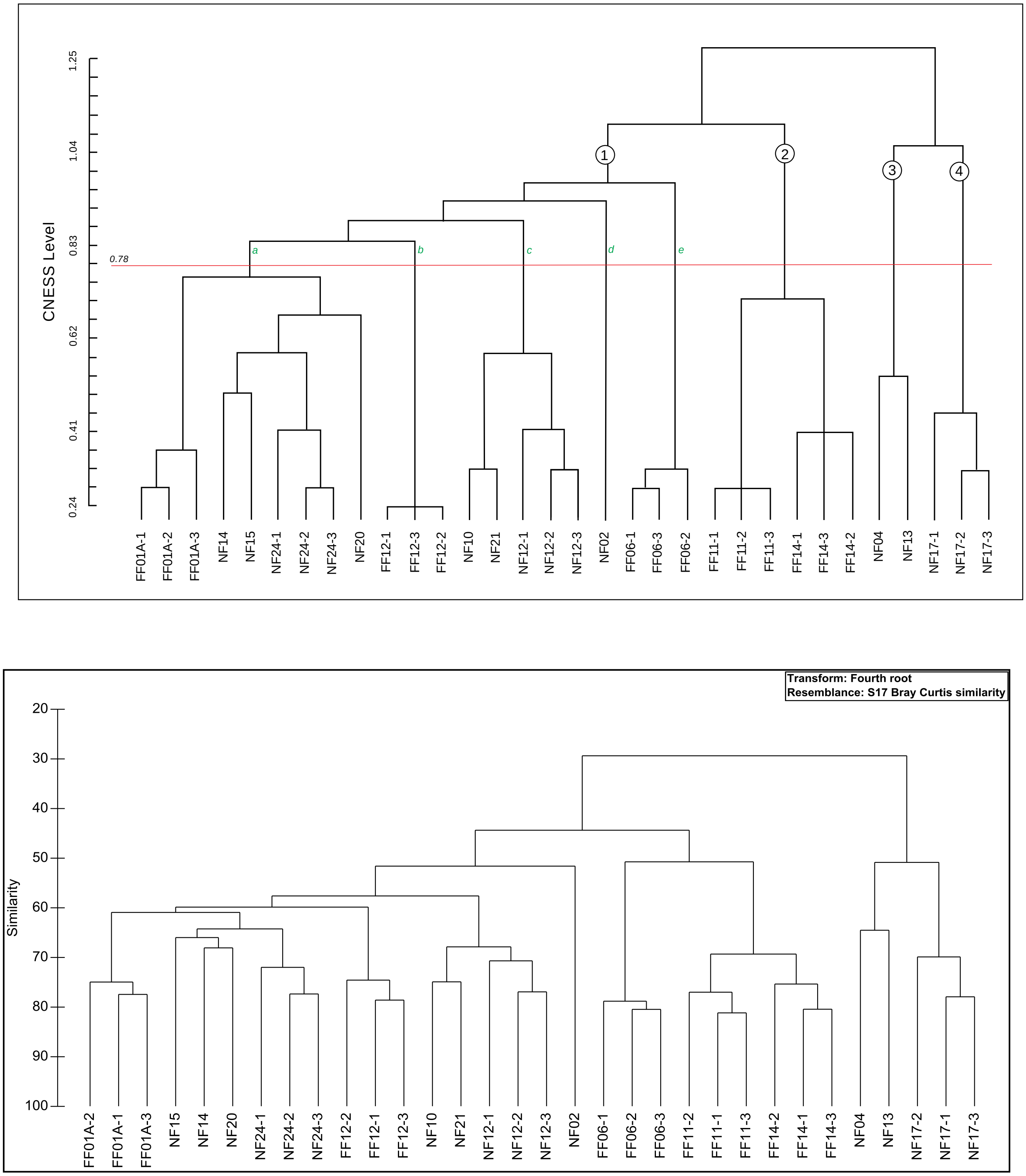


Figure 5-9. Relationship of 2007 samples based on (top) CNESS similarity (*m*=15) and group average clustering and (bottom) Bray-Curtis similarity after fourth-root transformation of the data and group average clustering.

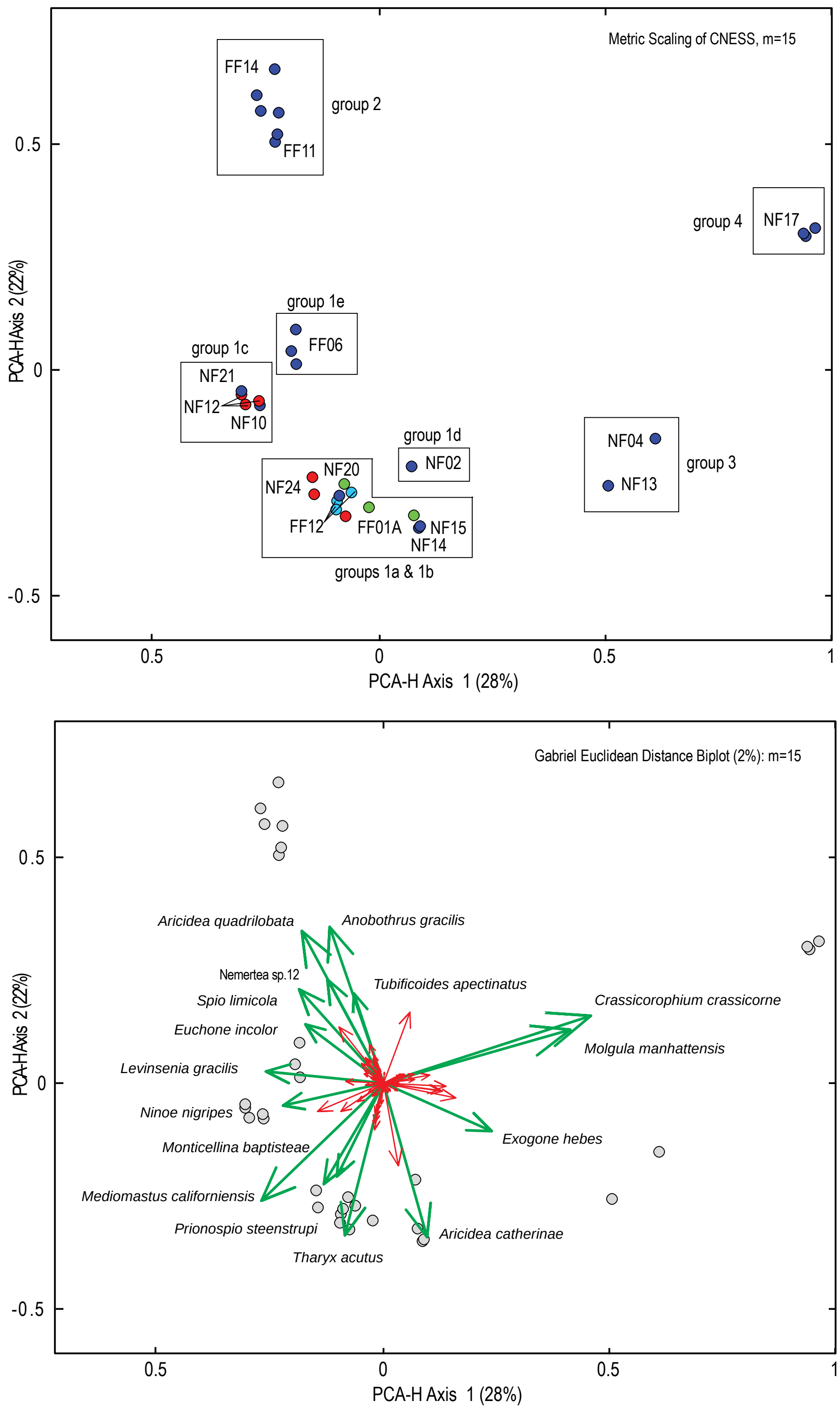


Figure 5-10. Metric scaling on PCA-H axes 1 and 2 of the 2007 benthic infaunal samples with CNESS cluster groups indicated (top) and the Euclidean distance biplot showing the species responsible for at least 2% of the variation (bottom).

Table 5-1. Contribution of the 33 species in the 2007 Massachusetts and Cape Cod Bay samples identified by PCA-H analysis as important in structuring the infaunal communities, and their loadings on each of the seven PCA-H axes.

PCA-H Rank	Species	Contr.	Total Contr.	Ax.1	Ax.2	Ax.3	Ax.4	Ax.5	Ax.6	Ax.7
1	*Crassicorophium crassicorne*	7	7	21	2	5	0	0	0	4
2	*Aricidea catherinae*	7	14	1	12	11	19	0	2	2
3	*Prionospio steenstrupi*	6	20	2	5	30	5	3	5	14
4	*Molgula manhattensis*	6	26	17	1	3	0	0	0	1
5	*Mediomastus californiensis*	5	31	7	7	5	0	1	4	2
6	*Aricidea quadrilobata*	5	36	3	11	3	3	3	2	3
7	*Tharyx acutus*	5	40	1	11	2	12	0	0	0
8	*Owenia fusiformis*	4	45	0	3	2	14	27	0	9
9	*Anobothrus gracilis*	4	49	1	12	5	0	1	1	3
10	*Exogone hebes*	4	52	6	1	1	1	3	0	19
11	*Nucula delphinodonta*	4	56	1	0	1	0	3	45	10
12	*Levinsenia gracilis*	3	59	7	0	4	1	1	0	3
13	*Spio limicola*	3	62	3	4	0	0	6	2	3
14	*Euchone incolor*	3	65	3	2	0	9	9	1	0
15	*Monticellina baptisteae*	2	67	1	4	2	3	0	4	1
16	Nemertea sp. 12	2	70	2	5	1	0	1	0	2
17	*Leitoscoloplos acutus*	2	72	2	0	5	3	3	2	1
18	*Cossura longocirrata*	2	74	1	2	0	10	9	0	0
19	*Ninoe nigripes*	2	77	5	0	5	0	2	0	0
20	*Tubificoides apectinatus*	2	78	0	4	3	0	1	0	0
21	*Ampharete acutifrons*	2	80	0	0	3	1	1	2	0
22	*Nephtys cornuta*	1	81	0	1	0	5	7	3	2
23	*Phyllodoce mucosa*	1	82	3	0	0	0	1	1	3
24	*Limnodriloides medioporus*	1	83	0	1	0	0	0	1	0
25	*Capitella capitata complex*	1	84	0	0	0	0	3	2	0
26	*Chaetozone anasimus*	1	85	0	2	0	0	0	0	0
27	*Scoletoma hebes*	1	86	0	0	0	3	4	1	1
28	*Monticellina dorsobranchialis*	1	87	0	1	0	2	1	0	1
29	*Spiophanes bombyx*	1	88	2	0	0	0	0	0	1
30	*Aglaophamus circinata*	1	88	2	0	0	0	0	1	0
31	*Cerastoderma pinnulatum*	1	89	1	0	0	0	0	0	0
32	*Ophelina acuminata*	1	90	0	0	0	0	1	1	0
33	*Parougia caeca*	1	90	1	0	1	0	0	0	1

Table 5-2. Contributions to PCA-H axes by species accounting for at least 2% of the CNESS variation among the infaunal samples collected in 2007 (see Figure 5-10).

Important species: Axis 1 vs. 2					
PCA-H Rank	**Species**	**Contr.**	**Total Contr.**	**Axis1**	**Axis2**
1	*Crassicorophium crassicorne*	13	13	21	2
2	*Molgula manhattensis*	10	23	17	1
3	*Mediomastus californiensis*	7	30	7	7
4	*Aricidea quadrilobata*	7	37	3	11
5	*Anobothrus gracilis*	6	43	1	12
6	*Aricidea catherinae*	6	49	1	12
7	*Tharyx acutus*	5	54	1	11
8	*Spio limicola*	4	58	3	4
9	*Levinsenia gracilis*	4	62	7	0
10	*Exogone hebes*	4	65	6	1
11	*Prionospio steenstrupi*	3	69	2	5
12	Nemertea sp. 12	3	72	2	5
13	*Ninoe nigripes*	3	75	5	0
14	*Monticellina baptisteae*	3	77	1	4
15	*Euchone incolor*	2	80	3	2
16	*Tubificoides apectinatus*	2	82	0	4
Important species: Axis 1 vs. 3					
PCA-H Rank	**Species**	**Contr.**	**Total Contr.**	**Axis 1**	**Axis 3**
1	*Crassicorophium crassicorne*	16	16	21	5
2	*Molgula manhattensis*	13	29	17	3
3	*Prionospio steenstrupi*	10	39	2	30
4	*Mediomastus californiensis*	7	46	7	5
5	*Levinsenia gracilis*	6	52	7	4
6	*Ninoe nigripes*	5	57	5	5
7	*Exogone hebes*	4	62	6	1
8	*Aricidea catherinae*	4	65	1	11
9	*Leitoscoloplos acutus*	3	69	2	5
10	*Aricidea quadrilobata*	3	72	3	3
11	*Spio limicola*	2	74	3	0
12	*Anobothrus gracilis*	2	76	1	5
13	*Euchone incolor*	2	79	3	0
Important species: Axis 2 vs. 3					
PCA-H Rank	**Species**	**Contr.**	**Total Contr.**	**Axis 2**	**Axis 3**
1	*Prionospio steenstrupi*	13	13	5	30
2	*Aricidea catherinae*	11	25	12	11
3	*Anobothrus gracilis*	10	34	12	5
4	*Aricidea quadrilobata*	8	43	11	3
5	*Tharyx acutus*	8	51	11	2
6	*Mediomastus californiensis*	6	57	7	5
7	*Nemertea sp. 12*	4	61	5	1
8	*Tubificoides apectinatus*	4	64	4	3
9	*Monticellina baptisteae*	3	68	4	2
10	*Crassicorophium crassicorne*	3	71	2	5
11	*Owenia fusiformis*	3	74	3	2
12	*Spio limicola*	3	77	4	0
13	*Leitoscoloplos acutus*	2	79	0	5
14	*Molgula manhattensis*	2	81	1	3

5.3.5 Multivariate Analysis of the 1992–2007 Nearfield Samples

As in previous years (Maciolek *et al*. 2004, 2006, 2007), the farfield stations continued to have low similarity to the nearfield stations; therefore, only the nearfield samples were examined in greater detail for any evidence of an impact from the outfall. In addition, given the high intra-station similarities detected in previous analyses, only replicate 1 was used for those stations where multiple replicates had been taken. Reducing the number of samples from 284 to 164 also resulted in 25 species being dropped, leaving a total of 340 species included in the similarity, cluster, and PCAH analyses.

Similarity and Cluster Analysis— Both the CNESS and Bray-Curtis algorithms were used and gave similar results; only the Bray-Curtis dendrograms are presented here. A multivariate analysis of 164 nearfield samples collected from the 2007 subset of stations between 1992 and 2007 indicated two major groups of samples with 33 percent similarity to each other (Figure 5-11). As seen previously with CNESS (Maciolek *et al*. 2006), and again this year, this major division separates the coarsest-grained stations from finer-grained ones.

The majority of samples in Group 1 (Appendix C5, Figure C5-1) are similar at levels of 50% or higher, with a small number of samples that have lower similarity to the rest of the cluster. Samples from NF02 were found in several separate clusters, including a highly dissimilar subgroup of two samples (1992 and 1993), a group of seven samples from 1997–2001 plus 2005 and 2007, and the remainder scattered in the largest group of nearfield samples. Sediments at NF02 have differed considerably over the course of the monitoring program: in three sampling years (1992, 2002, and 2005), sediments ranged from 60.9–77.2% fines (silt + clay); in all other years, sediments were coarse (2.9–10.6% fines). Even though the sediments differed substantially in 2005 and 2007, and the numerous individuals of *Pholoe minuta/tecta*/spp. that were evoked to explain the low similarity of 2005 to other samples (Maciolek *et al*. 2006) had disappeared from the station, these two NF02 samples were nearly 60% similar to each other in this analysis. Other samples with low similarity to the majority included samples from FF12 and NF20 in 1994, and NF1 samples from 1998, 1999, and 2002.

Group 2 (Appendix C5, Figure C5-2) includes samples from NF04, NF13, and NF17—the same grouping of stations that was seen for the annual 2007 samples and for the multiyear analyses based on samples collected through 2005 and 2006 (Maciolek *et al.* 2006, 2007). Of the 16 samples from NF17, all but two form a subcluster (labeled 2a in Figure 5-11) separate from the remaining samples in this major division; those two samples, from 1996 and 2002, are similar first to each other, and then to the group of samples from NF04 and NF13. Within the larger subcluster, samples from 2004–2007 tend to have a higher level of similarity (60–65%) to each other than to samples from other years; however, there are groupings of years such as 1998 with 2003, indicating that there is no clear separation of earlier monitoring years from later ones. Subcluster 2b includes 13 of the 14 samples from NF04 (all except 1997) and 12 of the 13 samples from NF13 (all except 1992), as well as four samples from NF14 (1994, 1997, 2000, and 2001). As with NF17, samples from more recent years (2003,2005, 2007) tend to form a unit of higher similarity within the subcluster.

Maciolek *et al.* (2006) discussed some of the differences in benthic community composition that resulted in the levels of similarity detected by a similar analysis of samples collected through 2005; changes in sediment composition due to physical processes, as well as natural population cycles of some of the dominant species, rather than an impact from the outfall discharge, appear to be responsible for the similarity patterns detected.

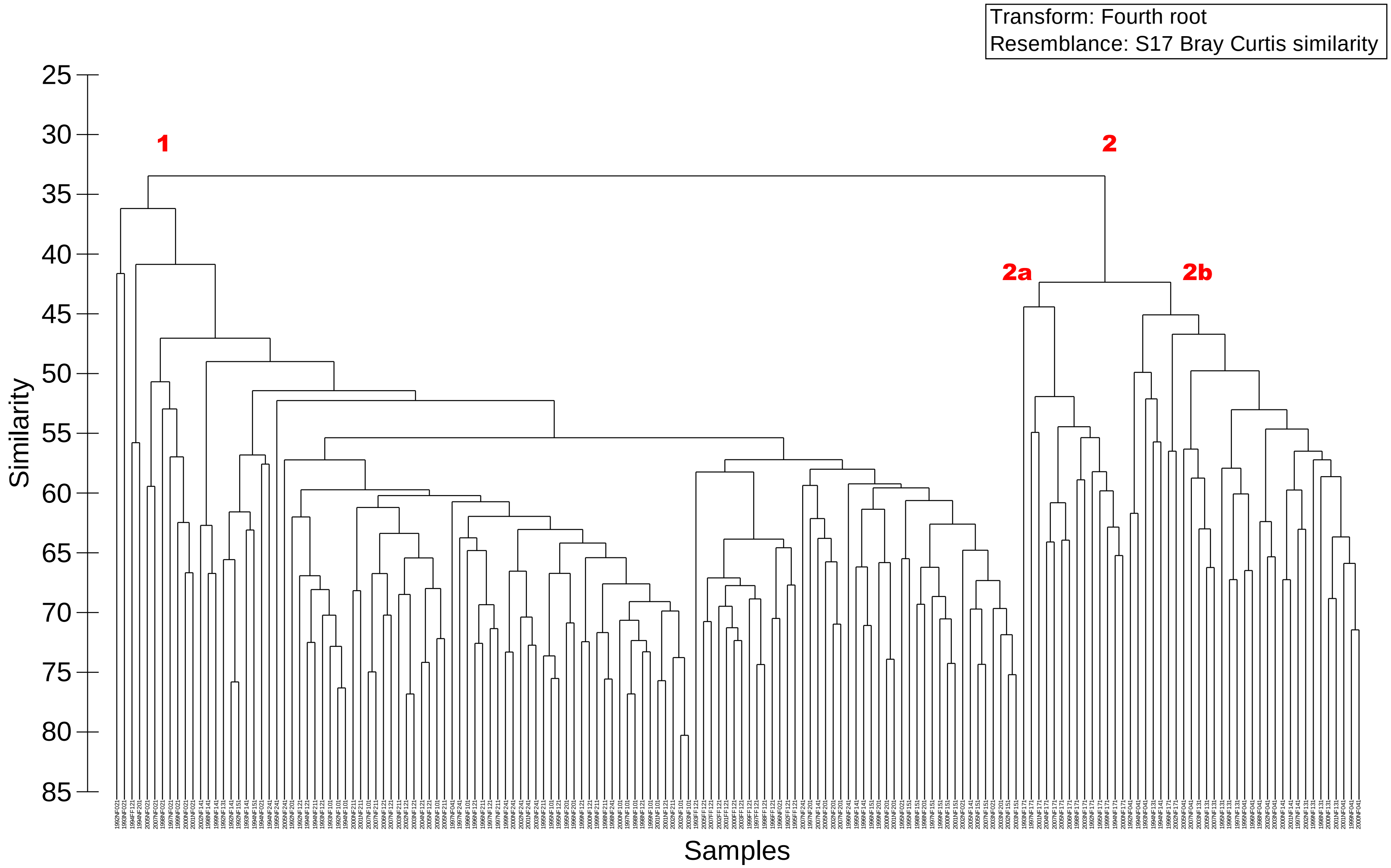


Figure 5-11. Cluster dendrogram of 164 nearfield samples collected 1992–2007, using the Bray-Curtis algorithm based on a fourth-root transformation of the data. See Appendix C5 for details of the two major groups.

PCAH Analysis—With CNESS (*m*=15), 41 of the 340 species in the subset of 164 samples accounted for 89% of the variation in community structure, and contributed at least 1% to the PCA-H axes (Table 5-3). These species are essentially the same as those identified as structuring the community in 2005, when all replicates of the nearfield stations were included (Maciolek *et al.* 2006): the addition of 2007 data to the sample set has not indicated any noteworthy differences in community structure.

Axes 1 and 2 of this multidimensional analysis accounted for 41% of the total CNESS variation. As seen in previous years, and other analyses presented in this report, the sandier station NF17 separated from the remaining samples along Axis 1 (Maciolek *et al.* 2006, 2007) (Figure 5-12). As in previous years, the majority of nearfield samples separated only along axis 2; in particular, FF12, which has a slightly different species composition, separated from the remaining nearfield stations along this axis, similar to the alignment seen for FF11 and FF13 in 2004 and 2006 (Maciolek *et al.* 2005, 2007).

Samples collected in 2007 are indicated by red star symbols (Figure 5-12, top); the remaining samples are not specifically identified, but correspond to results reported in detail in previous years (Maciolek *et al.* 2005, 2007). Axis 2 appears to have a temporal component, with samples from earlier years towards the top (positive values) of the diagram. Stations with intermediate positions most likely reflect a gradient of species composition and sediment texture. While the majority are found within the cloud of points associated with the majority of samples, some, such as NF04 and NF13 appear to be somewhat isolated from the other samples from those stations.

The species accounting for at least 2% of the CNESS variation of this dataset are indicated in the Gabriel Euclidean distance biplot (Figure 5-12, bottom) and detailed in Table 5-4. As seen for the 2005 (and 2006) samples, the majority of nearfield stations are structured by the spionid polychaetes *Spio limicola* and *Prionospio steenstrupi*, which were dominant in the early and more recent years of monitoring, respectively; these two small-bodied deposit- or filter-feeding species account for much of the separation of the nearfield samples along Axis 2. Other small deposit-feeding polychaetes, especially *Mediomastus californiensis,* and to a lesser extent, *Aricidea catherinae, Levinsenia gracilis*, *Ninoe nigripes*, and *Tharyx acutus* contribute 2–6% in structuring the communities.

The sandy nearfield stations (*e.g*., NF17) are influenced by a different suite of species including the polychaetes *Exogone hebes*, *Spiophanes bombyx*, *Polygordius jouinae*, the amphipod *Crassicorophium crassicorne,* and the ascidian *Molgula manhattensis*. The influence of particular species also carries a temporal component, with, for example, *Dipolydora socialis* being strongly influential in the early 1990s but not in later years.

Table 5-3. Contribution of the 41 species identified by PCA-H analysis as important in structuring the infaunal communities in the 164 Massachusetts Bay nearfield samples, and their loadings on each of seven PCA-H axes.

PCA-H Rank	Species	Contr.	Total Contr.	Ax.1	Ax.2	Ax.3	Ax.4	Ax.5	Ax.6	Ax.7
1	*Prionospio steenstrupi*	6	6	11	12	8	1	0	10	12
2	*Spio limicola*	6	13	7	31	1	4	0	3	4
3	*Exogone hebes*	6	19	10	1	22	2	0	7	1
4	*Mediomastus californiensis*	6	25	16	0	1	1	0	0	2
5	*Crassicorophium crassicorne*	5	29	11	0	4	1	2	0	2
6	*Aricidea catherinae*	5	34	2	2	13	30	10	2	15
7	*Tharyx acutus*	4	39	4	9	1	0	0	28	13
8	*Dipolydora socialis*	4	43	1	14	5	4	23	2	2
9	*Owenia fusiformis*	4	46	0	8	0	1	45	3	3
10	*Exogone verugera*	3	49	2	4	10	8	1	0	0
11	*Molgula manhattensis*	3	52	2	1	0	1	0	3	13
12	*Ninoe nigripes*	3	55	4	0	2	6	0	0	4
13	*Polygordius jouinae*	2	57	3	1	4	1	0	0	2
14	*Spiophanes bombyx*	2	59	2	3	4	2	1	6	0
15	*Marionina welchi*	2	61	2	0	1	7	1	0	2
16	*Aphelochaeta marioni*	2	64	1	3	0	0	0	1	6
17	*Monticellina baptisteae*	2	66	2	1	3	1	0	1	4
18	*Hiatella arctica*	2	68	0	0	0	7	0	12	0
19	*Levinsenia gracilis*	2	70	3	0	3	4	2	0	0
20	*Cerastoderma pinnulatum*	2	72	2	1	0	0	1	1	0
21	*Euchone incolor*	2	73	1	0	0	1	0	4	0
22	*Unciola inermis*	1	75	1	0	0	3	1	1	0
23	*Pseudunciola obliquua*	1	76	1	0	5	1	0	1	1
24	*Phyllodoce mucosa*	1	77	0	1	0	3	0	0	0
25	*Leitoscoloplos acutus*	1	78	1	0	1	0	0	0	0
26	*Ampharete acutifrons*	1	79	0	1	0	0	0	0	0
27	*Scoletoma hebes*	1	80	0	2	0	1	4	1	2
28	*Limnodriloides medioporus*	1	81	0	0	0	1	2	0	1
29	*Asabellides oculata*	1	81	0	0	1	1	0	1	0
30	*Phoronis architecta*	1	82	0	0	0	0	1	1	0
31	*Crenella decussata*	1	83	0	0	1	0	0	0	0
32	*Aglaophamus circinata*	1	84	1	0	0	0	0	0	0
33	*Protomedeia fasciata*	1	84	0	0	1	1	1	1	0
34	*Echinarachnius parma*	1	85	1	0	1	0	0	1	0
35	*Nucula delphinodonta*	1	86	0	0	0	0	0	2	0
36	*Dipolydora quadrilobata*	1	86	0	0	0	0	1	0	0
37	*Euclymene collaris*	1	87	1	0	0	0	0	0	0
38	*Maldane sarsi*	1	87	0	0	0	0	0	0	0
39	*Arctica islandica*	1	88	0	0	0	0	0	1	0
40	*Parougia caeca*	1	88	0	0	0	0	1	0	0
41	*Chaetozone anasimus*	1	89	0	0	0	0	0	1	1

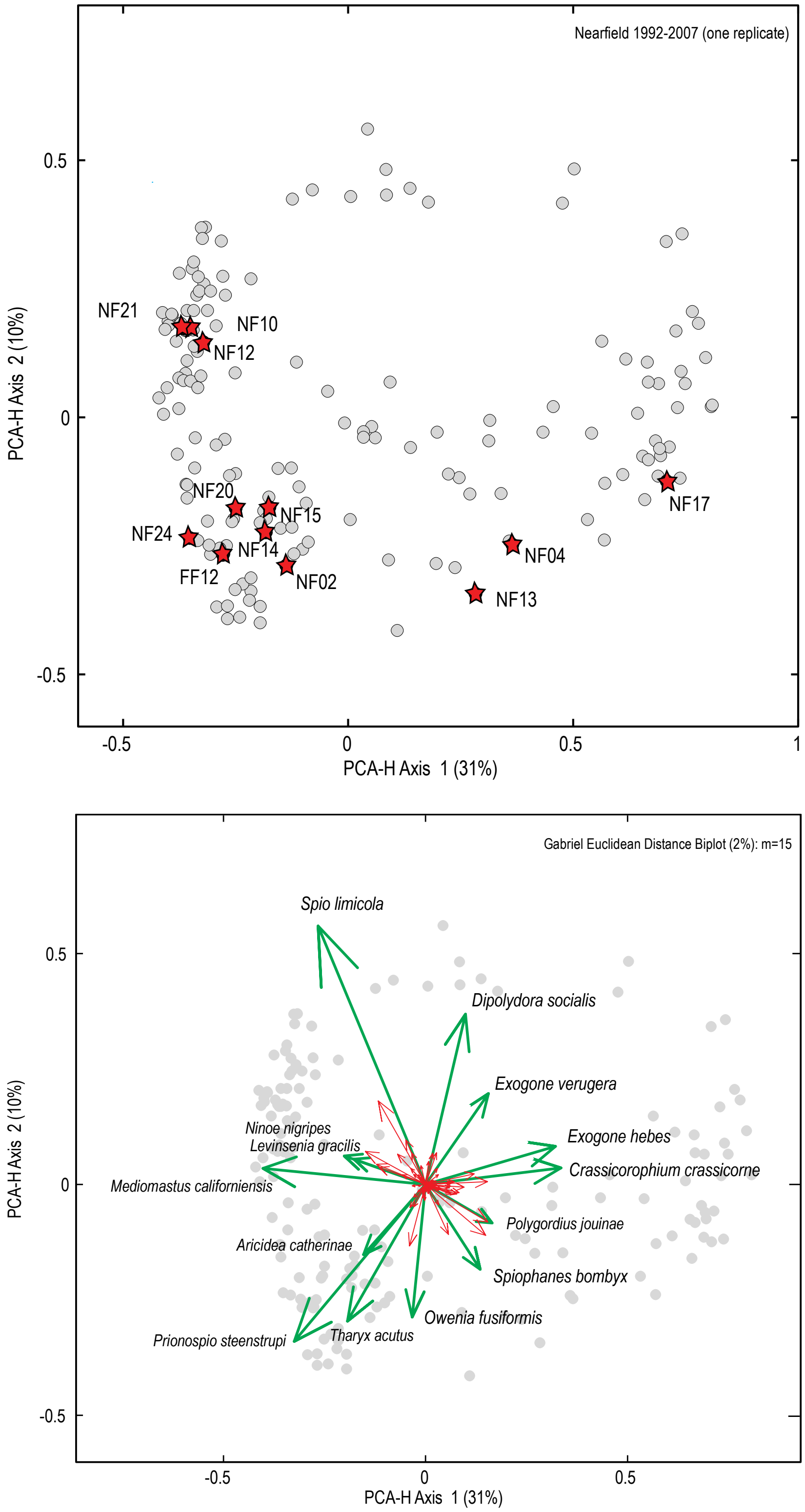


Figure 5-12. (top) Metric scaling on PCA-H axes 1 and 2 of 164 nearfield benthic infaunal samples collected 1992–2007, with the samples collected in 2007 labeled. (bottom) Euclidean distance biplot showing the species responsible for at least 2% of the CNESS (m= 15) variation.

Table 5-4. Contributions to PCA-H axes by species accounting for at least 2% of the CNESS variation among the infaunal samples collected from nearfield stations 1992–2007 (see Figure 5-12 for plot of axis 1 vs. axis 2).

Important species: Axis 1 vs. 2					
PCA-H Rank	**Species**	**Contr.**	**Total Contr.**	**Axis1**	**Axis2**
1	*Spio limicola*	13	13	7	31
2	*Mediomastus californiensis*	12	25	16	0
3	*Prionospio steenstrupi*	11	36	11	12
4	*Crassicorophium crassicorne*	9	45	11	0
5	*Exogone hebes*	8	53	10	1
6	*Tharyx acutus*	5	58	4	9
7	*Dipolydora socialis*	4	62	1	14
8	*Ninoe nigripes*	3	65	4	0
9	*Exogone verugera*	3	67	2	4
10	*Levinsenia gracilis*	2	70	3	0
11	*Aricidea catherinae*	2	72	2	2
12	*Polygordius jouinae*	2	74	3	1
13	*Spiophanes bombyx*	2	77	2	3
14	*Owenia fusiformis*	2	79	0	8
PCA-H Rank					
1	*Mediomastus californiensis*	13	13	16	1
2	*Exogone hebes*	12	26	10	22
3	*Prionospio steenstrupi*	10	36	11	8
4	*Crassicorophium crassicorne*	10	46	11	4
5	*Spio limicola*	6	52	7	1
6	*Aricidea catherinae*	4	56	2	13
7	*Exogone verugera*	4	60	2	10
8	*Ninoe nigripes*	4	63	4	2
9	*Tharyx acutus*	3	67	4	1
10	*Levinsenia gracilis*	3	70	3	3
11	*Polygordius jouinae*	3	73	3	4
12	*Monticellina baptisteae*	2	75	2	3
13	*Spiophanes bombyx*	2	77	2	4
14	*Marionina welchi*	2	79	2	1
15	*Cerastoderma pinnulatum*	2	81	2	0
PCA-H Rank					
1	*Spio limicola*	19	19	31	1
2	*Dipolydora socialis*	10	29	14	5
3	*Prionospio steenstrupi*	10	39	12	8
4	*Exogone hebes*	9	48	1	22
5	*Exogone verugera*	7	55	4	10
6	*Aricidea catherinae*	7	62	2	13
7	*Tharyx acutus*	6	67	9	1
8	*Owenia fusiformis*	5	72	8	0
9	*Spiophanes bombyx*	4	76	3	4
10	*Aphelochaeta marioni*	2	78	3	0

5.3.6 Statistical Analysis

The basic goal of this analysis was to assess differences in benthic stations after the diversion event in September 2000. Clearly there are differences between stations, years, and sediment types that are not related to the diversion event. A model that accounts for all these sources of variation first can then estimate more efficiently the change associated with the diversion. For this analysis all nearfield stations were divided into three zones: from 10 km to 5 km, from 5 km to 2.5 km, and less than 2.5 km. This stratification divides the stations into roughly equal groups with no stations near the boundaries of the three groups. The stratification partitions the stations in the following way: the 10–5 km stratum includes two stations, FF12 and NF02; the 5–2.5 km stratum includes four stations, NF04, NF10, NF20, and NF21; and the < 2.5 km stratum includes six stations, NF12, NF13, NF14, NF15, NF17, and NF24.

The mean species abundances and other variables, including species richness and total abundance, were plotted separately by zone on a log scale (Figures 5-13–5-14, Appendices C6 and C7). The vertical line indicates the date when the effluent was first diverted to the offshore diffuser. The log scale is used for the response variable. On the log scale, zero abundance at a station cannot be plotted, therefore zero values are not shown on these plots and can be thought of as lying just below the plotted area

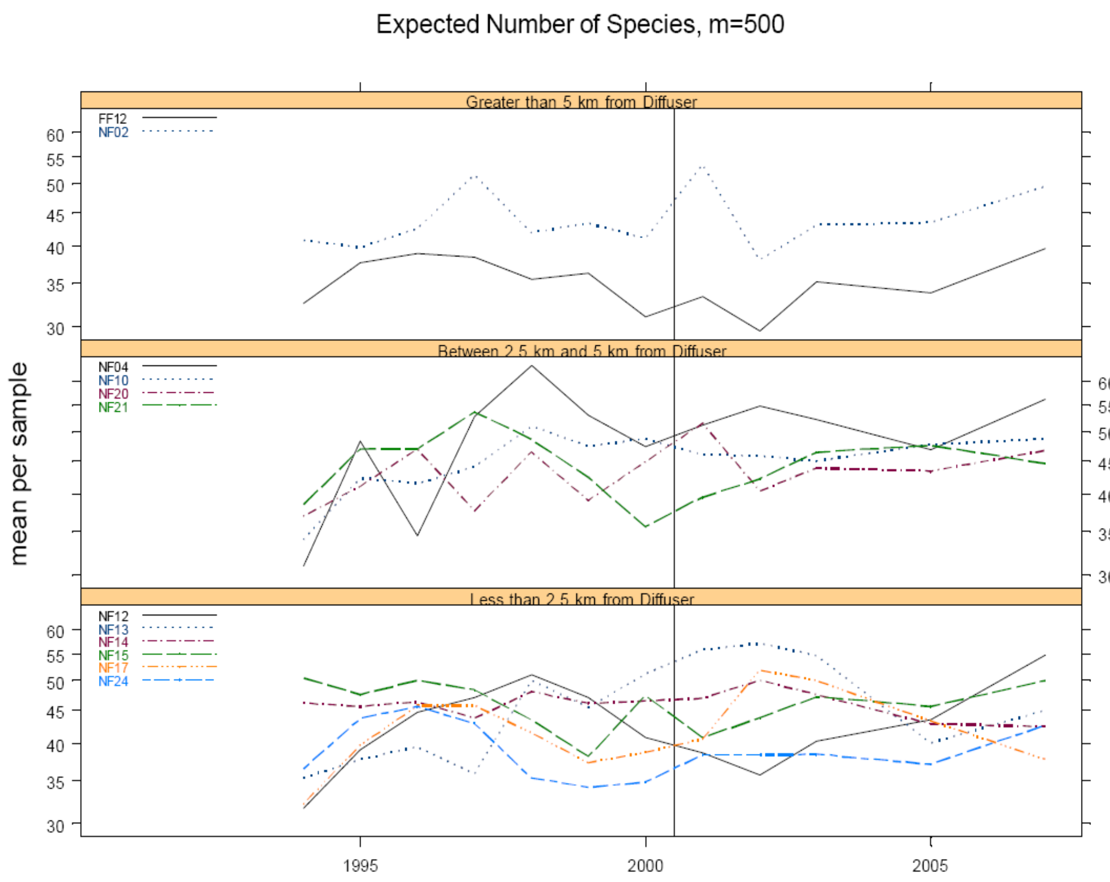


Figure 5-13. Log plots of expected number of species for a subsample of size *m* = 500.

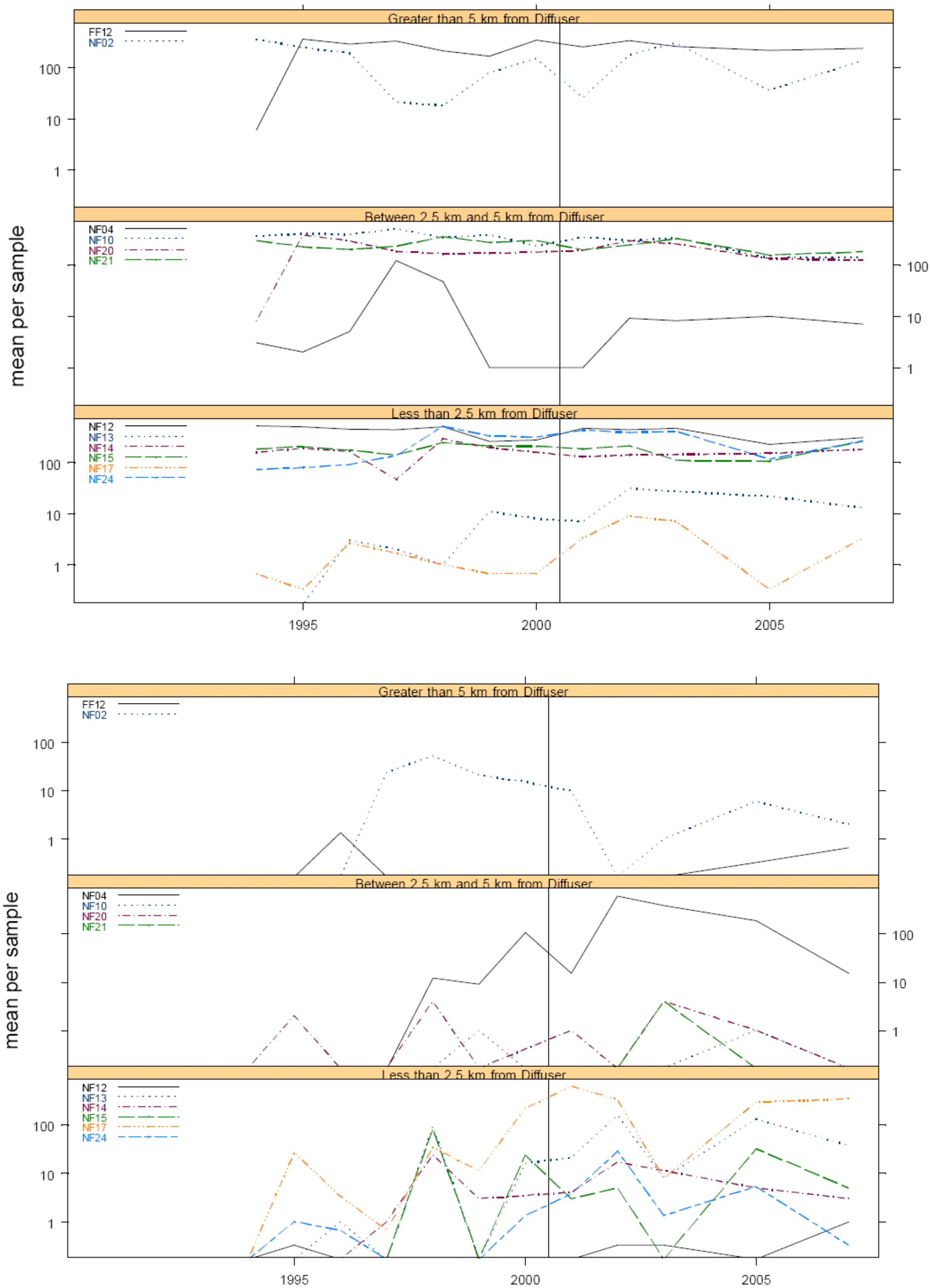


Figure 5-14. Log plots of *Mediomastus ambiseta* (top) and *Molgu1a manhattensis* (bottom) at the nearfield stations. Plots of additional species are presented in Appendix C5.

It is clear from the plots for nearly all species that stations have differing mean abundances and that species abundance varies between years. Indeed, a large proportion of the variation in the data can be explained with this simple log-linear year and station effect model. The question answered by the analysis in the tables below is: how much of the remaining variation in the data is associated with the diversion? To model this effect, we included a parameter for the relative increase (decrease) in abundances in stations less than 5 km from the diffuser after September 2000. An additional parameter, change in abundance at stations less than 2.5 km from the diffuser relative to all nearfield stations, was also included. These two relative differences summarize the general changes in the species abundance patterns after the fall of 2000.

A total of 21 species abundances were analyzed using this method (Appendix C5). In this situation, where multiple hypotheses are tested, one needs to adjust for multiple testing. A definition of statistical error that is natural for this kind of question is the false discovery rate (FDR, Benjamini and Hochberg 1995). This error rate is defined for each single null hypothesis—say, that a single species abundance does not change in the nearfield after the fall 2000 diversion. The false discovery rate is the conditional probability that a single null hypothesis is true, given that null hypothesis has been rejected by the FDR procedure. In many areas of modern biotechnology, where many compounds or species are tested at once, this false discovery rate is the logical error rate to use. For the results presented here, we have implemented the Benjamini and Hochberg procedure at a false discovery rate of $\alpha = 0.05$. In the procedure we compare

$$p - value_i < \frac{i}{m}\alpha,$$

where $p - value_i$ is the i-th smallest $p - value$ and m is the number of comparisons.

One then rejects all null hypotheses below the highest p-value that satisfies the above condition. Bold values in the table indicate which p-values satisfy the above decision rule at the $\alpha = 0.05$ level.

Only the parts of the model estimation that are related to the estimation of the zone-by-diversion sub-model are discussed here. For the continuous variables reported in Table 5-5, the only important association is an estimated 1.10 and 1.08 relative increase in *Clostridium* in the within-5-km and within-2.5-km zones respectively. That is, there was an estimated combined relative increase in the near zone of approximately 19% after the diversion. Approximately 59% of the variance was explained by the complete model, which included year, station, and fine sediment as explanatory variables. However, only 14.6% of the variation was explained by the zone-by-diversion sub-model. Thus, this environmental survey was able to detect a post-outfall 19% relative increase in *Clostridium* at the stations closest to the outfall, even though this increase accounted for only a small percent of the total natural variation in the data. As expected, TOC was strongly associated with percent silt in the sediment, but not with zone-by-diversion effects. None of the infaunal parameters (total abundance, species richness, Fisher's *alpha*, Shannon's H' and expected species) were significant.

Table 5-5. Results of the model of six selected continuous variables for the infauna stations.

	Zone-by-Diversion Effect				Log (Silt) Covariate		R-squared	
	Within 5 km		Within 2.5 km					
	multiplier	P-value	multiplier	P-value	coefficient	P-value	Complete Model	Diversion by Zone Submodel
Clostridium	1.100	**0.002**	1.082	**0.000**	-0.031	0.290	0.590	0.146
TOC	1.040	0.702	1.039	0.603	0.874	**0.000**	0.906	0.001
Species Richness	1.021	0.552	1.011	0.657	-0.012	0.730	0.593	0.003
Fisher's Alpha	1.028	0.433	1.010	0.704	0.045	0.189	0.548	0.005
H'	1.035	0.284	0.989	0.649	0.015	0.626	0.363	0.006
Expected Species, *m*=500	1.047	0.137	0.989	0.632	0.049	0.103	0.496	0.010

The analysis of the individual species abundance data is reported in Table 5-6. Pseudo R^2 denotes the proportion of variation in the count data explained by the model. The natural measure of total variation is the chi-squared rather than the total sum of squares. In all significance tests, the false discovery criterion outlined above was used, with a FDR of α=0.05. Since 21 simultaneous tests are conducted for each effect, the p-value needed for a statistically significant effect is relatively small.

Only two species exhibited significant effects, either within 2.5 km or within 5 km of the diffuser. In the zone closest to the diffuser, the polychaete *Mediomastus californiensis* showed a significant zone-by-diversion effect. This nested effect compares stations in the 2.5-km stratum with stations in the 2.5–5 km stratum. This increase of 55% was not statistically significant under the Poisson-lognormal model (see the discussion in the methods section).

The within-5-km effect was significant for only the tunicate *Molgula manhattensis*. This effect compares the two stations in the >5-km stratum with all stations that are <5 km from the diffuser. Note that for this species the within-2.5-km effect is small, insignificant, and in the opposite direction. Thus, this may indicate a secular trend not reflected in the two farfield stations in the analysis.

It is important to note that the statistical analyses conducted here cannot prove that outfall discharge has impacted the abundance of these taxa. All it can do is identify taxa whose patterns of abundances changed between baseline and discharge monitoring, in a manner consistent with a hypothesized outfall effect. Even in the best designed environmental impact studies this limitation on causal inference exists. This issue is discussed in detail in the reviews of Smith (2002) and Beyers (1998).

It is also important to note that none of the significant zone-by-diversion terms explained more than 2.0 percent of the variability in species abundances in these models, confirming the sensitivity of the analysis and the statistical power afforded by MWRA's monitoring design.

The fact that significant zone-by-diversion effects were observed only for two species, and explain only a small percentage of the variability in their abundances, is consistent with the compositional and multivariant analyses shown in section 5.3.5. Those analyses document broad consistency in community composition at nearfield stations through time, with no evidence for a shift in community composition following outfall startup in September 2000.

Table 5-6. Results of the statistical analysis of species abundances at the nearfield infaunal stations.

	Zone by Diversion Effect							Pseudo R-squared	
	Within 5 km		Within 2.5 km		Log(Silt) Covariate			Proportion Chi-squared	
Species	multiplier	P-value	multiplier	P-value	coefficient	P-value	Negative Binomial Theta	Complete Model	Diversion by Zone Submodel
Aphelochaeta marioni	1.726	0.013	1.349	0.162	-0.265	0.068	1.085	0.705	0.015
Aricidea catherinae	1.114	0.152	1.560	0.047	-0.258	0.107	1.017	0.435	0.020
Crassicorophium crassicorne	0.486	0.313	1.409	0.367	-0.740	0.202	0.707	0.851	0.002
Dipolydora socialis	1.711	0.465	0.639	0.208	-0.552	0.210	0.483	0.479	0.007
Euchone incolor	0.741	0.322	1.209	0.268	-0.080	0.973	1.743	0.739	0.004
Exogone hebes	0.694	0.051	0.989	0.942	-0.321	0.362	2.148	0.810	0.005
Exogone verugera	0.773	0.303	0.893	0.460	-0.383	0.222	1.982	0.801	0.002
Hiatella arctica	1.305	0.982	0.678	0.154	0.157	0.716	0.884	0.665	0.004
Leitoscoloplos acutus	0.862	0.912	1.390	0.025	-0.034	0.705	2.497	0.762	0.007
Levinsenia gracilis	0.928	0.972	1.160	0.215	0.085	0.619	3.626	0.826	0.001
Mediomastus californiensis	0.835	0.655	1.545	**0.001**[a]	-0.148	0.259	2.511	0.754	0.017
Molgula manhattensis	6.354	**0.000**	0.927	0.844	0.275	0.487	0.609	0.771	0.026
Monticellina baptisteae	0.904	0.751	1.066	0.387	-0.135	0.459	1.149	0.662	-0.001
Ninoe nigripes	0.692	0.120	0.987	0.948	-0.584	0.114	1.135	0.581	0.006
Owenia fusiformis	1.806	0.331	0.629	0.159	0.175	0.933	0.569	0.702	0.006
Phyllodoce mucosa	1.316	0.383	0.844	0.272	-0.617	**0.002**	1.952	0.632	0.004
Polygordius jouinae	1.277	0.986	0.682	0.052	-0.665	0.005	2.059	0.841	0.004
Prionospio steenstrupi	0.907	0.560	1.412	0.018	-0.422	0.009	1.869	0.690	0.011
Spio limicola	0.912	0.691	1.435	0.106	-0.296	0.260	0.904	0.664	0.006
Spiophanes bombyx	1.593	0.011	1.027	0.858	-0.421	0.007	2.428	0.801	0.008
Tharyx acutus	1.556	0.033	1.180	0.379	-0.565	**0.002**	1.132	0.552	0.014

[a] p-value = 0.016 under Poisson-lognormal model, see text

5.4 Monitoring Questions

- *Has the soft-bottom community changed?*

There have been clear temporal changes in the soft-bottom benthic infaunal community over the 16 years of the monitoring program, including changes in total infaunal density, species composition and richness, and, to a lesser extent, diversity. By 2002 infaunal abundance (per sample) had increased by roughly 60% over abundances recorded in the early years of the program, due primarily to increased abundances of only a few species, especially *Prionospio steenstrupi*, which replaced another spionid polychaete, *Spio limicola*, as the dominant at the medium- to fine-grained stations. Much of the decline in abundances seen in 2003–2007 was again due to the population fluctuation of the same species. Such fluctuations are characteristic of invertebrate species and cannot be construed as related to the operation of the outfall.

Some benthic community parameters have fluctuated in a sine-wave-like pattern, with increases followed by declines. Although mean Shannon diversity dropped below baseline in 2002, 2003, and 2005, it did not fall below the lower threshold level of 3.30 in any year. Diversity as measured by log-series *alpha* also fell below baseline in 2005, but not below the critical threshold level of 9.95 (Table 1). Parameters for this same set of stations were well above baseline in 2007, the current sampling year.

The high variability at some stations, which contrasts with the stability of other stations over time, suggests that several processes, biological as well as physical, operate in this system. Annual fluctuations in the population densities of several species, especially the dominant polychaetes at the finer-grained stations, and the occasional scouring of the bottom by storms both contribute to the overall invertebrate densities recorded from the benthic grab samples.

The larger patterns elucidated over time for the Massachusetts Bay stations have remained stable throughout the program. In similarity tests, the farfield stations have always differed from the nearfield, *e.g.*, the Cape Cod Bay stations comprise a suite of species that gives them a unique signature. Nearfield stations FF10, FF12, and FF13 can be distinguished from the remaining nearfield stations, reflecting the transitional sediment texture at those stations; similarly, the nearfield sandy stations such as NF17 can be distinguished from nearfield fine-grained stations. These patterns have held whether the entire station set is sampled, or whether the 2004/2006 or 2005/2007 subsets are considered.

- *Are any benthic community changes correlated with changes in levels of toxic contaminants (or sewage tracers) in sediments?*

Detailed investigation of individual stations has not suggested any localized outfall impact, even at stations within 2 km of the outfall (*e.g.*, NF17) where elevated levels of the sewage tracer *Clostridium perfringens* had suggested a modest impact of the discharge in previous years (Chapter 3, this report). None of the species dominant at any of the stations are those considered to be opportunists responding to organic enrichment, which has, in fact, not been seen at the outfall sites.

6. 2007 HARD-BOTTOM BENTHIC HABITATS AND FAUNA

by Barbara Hecker

6.1 Status of the Nearfield Hard-Bottom Environment

Hard-bottom communities inhabiting drumlins in the vicinity of the outfall have been surveyed annually for the last 14 years. These benthic communities have been surveyed utilizing a remotely operated vehicle (ROV) to photograph the seafloor habitats and their inhabitants. The first seven years of surveys (1994 to 2000) provided a baseline database that allowed characterization of the habitats and communities on the drumlins, as well as insight into their spatial and temporal variability (Kropp *et al*. 2002 and others). During the baseline period, the sampling design changed from videotaping a series of transects near the outfall in 1994 (Coats *et al*. 1995), to surveying discrete stations (waypoints) on the drumlins immediately north and south of the outfall, and at several reference sites on drumlins further away (since 1995). The emphasis on data products also has changed from reliance mainly on videotape (1995) to more emphasis on still photographs (1996 to 2007). The video images cover a much broader area and are mainly useful for assessing habitat relief and variability and enumeration of rare, larger mobile fauna, while the still photographs offer much higher resolution for identification and enumeration of most of the fauna.

Images collected during the baseline period indicate that the nearfield hard-bottom habitats are spatially quite variable and the benthic communities inhabiting them are temporally quite stable. The seafloor on the top of drumlins usually consists of a mix of boulders and cobbles, with habitat relief ranging from moderately high to high in areas dominated by larger boulders to moderate to low in areas consisting of a mix of cobbles and occasional boulders. Sediment drape on the top of drumlins varies from light to moderate at most locations and moderately heavy to heavy at a few locations. The seafloor on the flanks of drumlins is frequently variable, and usually consists of a cobble pavement interspersed to varying degrees with patches of sand, gravel, and boulders. Habitat relief on the flanks ranges from low to moderate, depending on how many boulders are present. Sediment drape in the flank areas usually ranges from moderate to heavy. The tops of the drumlins generally tend to be more spatially homogeneous than either the edges of the tops or the flanks of the drumlins, which tend to be more spatially heterogeneous. As a result, small lateral shifts in position near the edges of the drumlin tops or on the flanks frequently result in substantially different habitat characteristics, and hence different communities.

Algae usually dominate benthic communities on the tops of drumlins, while invertebrates (mostly encrusting or attached forms) become increasingly dominant on the flanks of the drumlins. Both encrusting coralline algae and several species of upright algae are quite common throughout the hard-bottom areas near the outfall. Coralline algae usually dominate in areas with light to moderately light sediment drape, while upright algae frequently dominate in areas with moderate sediment drape. Coralline algae is the most abundant and widely distributed taxon encountered in the hard-bottom areas. Its' areal coverage and distribution remained quite stable during the entire baseline period. The percent cover of coralline algae appears to be related to the amount of sediment drape, with cover being highest in areas with light drape and lowest in areas with moderately heavy-to-heavy drape. This pattern may reflect susceptibility of the encrusting growth form of coralline algae to smothering by fine particles. In contrast, the abundance and distribution of upright algae appear to be related to habitat relief. These algae are patchily distributed and are only found in appreciable abundances in areas of moderate to high relief. Areas supporting numerous upright algae also tend to have moderate sediment drape, with the holdfasts of the algae appearing to trap sediment.

The benthic communities inhabiting the hard-bottom areas were quite stable during the baseline period, with the structure of the benthic communities remaining relatively unchanged between 1995 and 2000. Occasional year-to-year shifts in cluster designation of specific sites frequently reflected spatial habitat heterogeneity rather than temporal changes in the biotic communities. Upright algae dominated the communities inhabiting the northern reference sites, and several other sites on the top of drumlins on either side of the outfall. In contrast, coralline algae dominated the communities at the two southernmost reference sites, as well as at some drumlin top and flank sites on either side of the outfall. Another southern reference site, located southwest of the outfall, represents a relatively extreme habitat characterized by very large boulders with heavy sediment drape. This area supports few algae, but is inhabited by numerous invertebrates, including a red soft coral *Gersemia rubiformis* which is not found at any of the other sites. Several sites on the flanks of the drumlin located just south of the outfall are relatively depauperate when compared to the other sites. The diffuser heads of the outfall have been colonized by a luxuriant community of frilled sea anemones, *Metridium senile*, sea-peach tunicates, *Halocynthia pyriformis*, and northern sea stars, *Asterias vulgaris*.

The nearfield hard-bottom communities observed during the first five discharge surveys were remarkably similar to those observed during the baseline period (Maciolek *et al.* 2004, 2005, 2006a, b and 2007). Several modest differences between the pre- and post discharge periods have been noted. The most consistent difference has been a slight increase in sediment drape and a concurrent decrease in percent cover of coralline algae at five stations north of the outfall during the discharge years. A more widespread (11 stations) and more pronounced decrease in percent cover of coralline algae was observed in 2005. The decreases in coralline algae observed in 2005 were not accompanied by concurrent increases in sediment drape. A trend of decreased abundances of upright algae was also noted during the post discharge years, and was particularly pronounced in 2003. The decrease in upright algae has been particularly pronounced at the northern reference stations and appears to be related to physical disturbance of the seafloor at these sites.

The data discussed in this chapter were collected during the seventh discharge survey of the hard-bottom communities conducted during late June 2007. This chapter presents the results of the 2007 survey and compares these results to pre-discharge baseline conditions and to the previous discharge conditions. Twenty-two of the 23 waypoints were successfully surveyed during 2007, including an actively discharging diffuser head at the eastern end of the outfall.

6.2 Methods

An Outland Technology "Outland 1000" remotely operated vehicle (ROV) equipped with video and still cameras was deployed at each station. The ROV was operated at slow speeds close to the seafloor to optimize visual clarity of the images. Video images were collected to provide broad large-scale coverage, while still photographs (slides) were collected to provide high-resolution images used for semi-quantitative assessment of habitat characteristics and biota.

Both video footage and still photographs were obtained at each of 22 waypoints (Table 6-1, see Figure 2-3). One of the southern reference stations (T12-1) was not surveyed in 2007 due to strong winds, and at an additional three stations (T1-2, T9-1, and T11-1) the boat was dragged approximately 100 m off station during the survey of that station. Photographic coverage ranged from 19 to 24 minutes of video footage and 29 to 33 usable still photographs (35-mm slides) at each waypoint. A total of 693 still photographs was taken and used in the following data analysis. Additionally, 461 minutes of video were also viewed and analyzed.

6.2.1 Visual Analysis

Each 35-mm slide was projected and analyzed for sea-floor characteristics (*i.e.*, substratum type and size class, and amount of sediment drape) and biota. Sediment drape refers to the visible layer of detrital material that drapes many of the rock surfaces in the hard-bottom areas. This material likely consists of a combination of phytodetritus, zooplankton fecal material, fine-grained resuspended sediments, biogenic tubes, and possibly effluent particles. The amount of sediment draped on the rock surfaces was assessed as relative thickness and amount of surface area covered, ranging from clean when the entire rock surface was visible to heavy when none of the rock surface was visible. Examples of several of the sediment drape categories can be seen in Figure 6-1. To facilitate comparisons among stations and years, mean sediment drape values were calculated using the following numerical assignments:

Sediment Drape Category	Numerical value
clean to very light	0
light	1
moderately light	2
moderate	3
moderately heavy	4
heavy	5

Most recognizable taxa were counted and recorded. Several very abundant taxa (for which accurate counts were impossible to obtain) were assessed as percent cover or relative abundance. The abundance of encrusting coralline algae was assessed as rough estimates of percent cover. Several other taxa, a filamentous red alga (identified at *Ptilota serrata*), colonial hydroids, and small barnacles and/or spirorbid polychaetes, that were frequently too abundant to count reliably were assessed as relative abundance. The following categories were used to assess abundances of taxa that were not counted on the still photographs:

Category	Percent cover	Numerical value assigned for analysis
rare	1-5	1
few	6-10	2
common	11-30	5
	31-50	10
abundant	51-70	15
	71-90	20
	>90	25

Organisms were identified to the lowest practical taxonomic level, about half of them to species, with the aid of pictorial keys of the local flora and fauna (Martinez and Harlow 1994, Weiss 1995) and web searches. Many of the encrusting taxa have not been identified to species. Most of these have been assigned to descriptive categories (e.g., “orange-tan encrusting”); however, each of these descriptive categories possibly includes several species. Additionally, some species might be split between two similar descriptive categories (e.g., “orange encrusting” and “orange lumpy encrusting”), as a result of morphological variability or differences in viewing angles and lighting. Because of high relief in many of the habitats surveyed, all reported abundances are extremely conservative. In many areas, only a portion of available surface area is visible; thus, actual faunal abundances in these areas are undoubtedly much higher than the counts indicate. A summary of the 2007 slide analysis is included in Appendix D1.

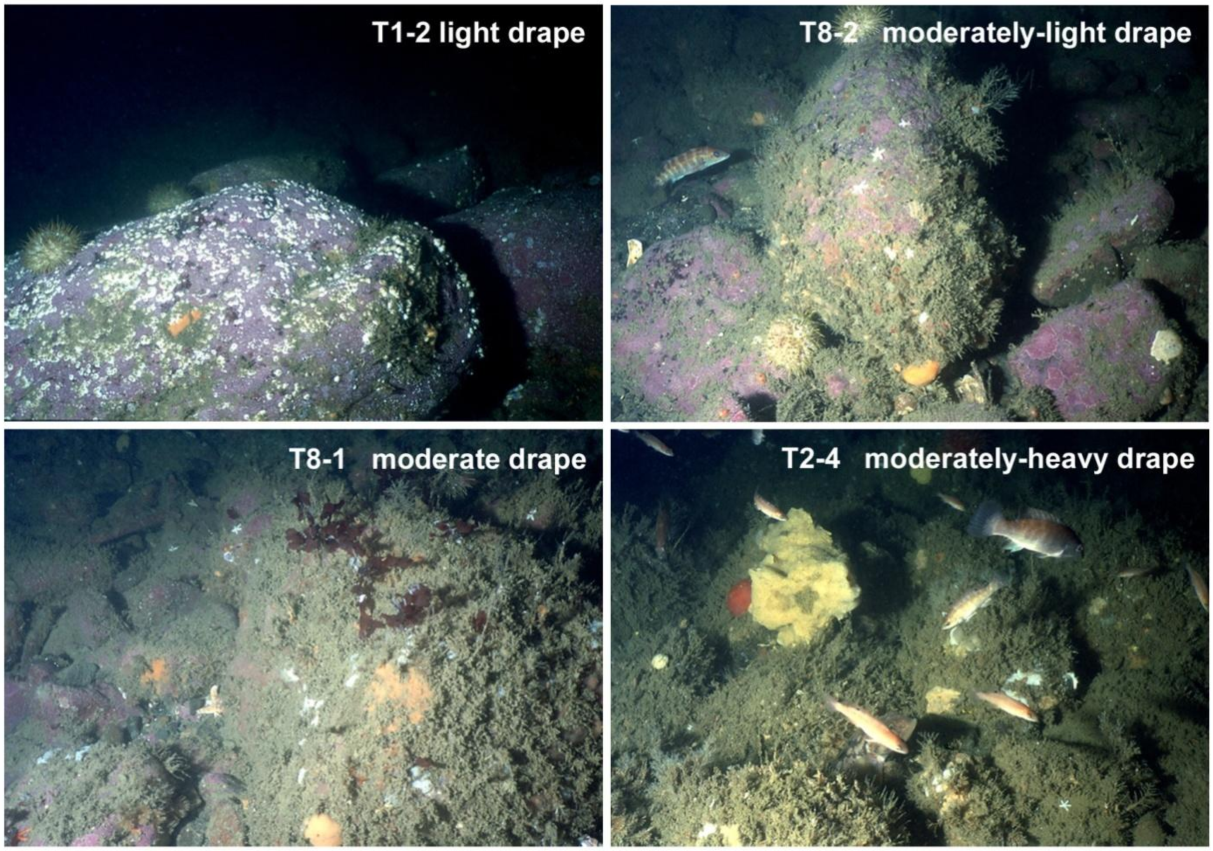


Figure 6-1. Photographs taken in 2007 that are representative of sediment drape categories. Light drape is the presence of a dusting or small patches of sediment leaving the rock surfaces clearly visible. Moderately light drape is the presence of larger patches of sediment, yet still leaving most of the rock surfaces visible. Moderate drape is the presence of drape on much of the rock surfaces with only small patches showing through. Moderately heavy drape is most of the rock surface covered by a substantial amount of drape.

Changes in taxonomic designations that have occurred during the years of this survey are summarized in Maciolek *et al*. 2006. Briefly, coralline algae is a taxon composed of at least five species of pink crustose algae that cannot be differentiated from each other on photographs. Additionally, red filamentous algae previously designated as *Asparagopsis hamifera* were subsequently identified as *Ptilota serrata*. Hydroids on or near the diffuser heads previously referred to as *Campanularia* sp. are *Tubularia* sp. A sponge previously referred to as *Halichondria panecia* (crumb of bread sponge), is a species of papillate sponge that belongs to the genus *Polymastia*. This species, *Polymastia* sp. A, is a circular yellow sponge on hard substrate. Another *Polymastia* sponge, *Polymastia* sp. B, is an irregular whitish sponge whose basal cushion is partially buried in sediment. This sponge was previously referred to as a siphon sponge.

The video images (in DVD format) were viewed to provide additional information about uniformity of the habitat at each of the sites. Notes on habitat relief, substrate size classes, and relative amount of sediment drape were recorded. Rare, large, and clearly identifiable organisms were enumerated. With the exception of the cunner *Tautogolabrus adspersus* (which was frequently very abundant), all fish were enumerated. Counts of abundant motile organisms (namely cunner), cryptic organisms (such as mussels), and all encrusting organisms were not attempted because of the large amount of time accurate counts would require and the general lack of resolution of the video footage. These organisms were assessed in terms of the range of relative abundances mentioned above. A summary of the 2007 video analysis is included in Appendix D2.

6.2.2 Data analysis

Data for all slides taken at each waypoint were pooled. Comparisons among waypoints were facilitated by normalizing species counts to mean number of individuals per slide to account for differences in the number of slides collected at each site. Hydroids, small barnacles, and/or spirorbids were omitted from the data analysis because they consisted of several species, could not be accurately assessed, and it was impossible to tell if they were alive. General taxonomic categories (*i.e*., fish, sponge, etc.) were included in estimates of total faunal abundances, but were omitted from the community analysis. For community analysis of the 2007 data, only taxa with an abundance of ten or more individuals in the data set were retained. This resulted in 50 of the original 81 taxa being retained for community analysis. Community analysis of the entire data set (years 1996 to 2007) used only taxa that were present with an absolute abundance of at least 50 individuals. Additionally, some taxa were excluded if they had not been consistently identified over the years. This resulted in 56 of the original 114 taxa being used for community analysis of the entire data set.

Community analyses were run using the software package PRIMER v.6 (Clarke and Gorley 2006). Two complementary multivariate pattern recognition techniques, hierarchical classification and non-metric multidimensional scaling (NMDS), were used to examine species similarities among stations obtained from data collected from the still photographs. Both analyses started with pair-wise comparisons of the species composition of stations using the Bray-Curtis similarity coefficient. Prior to analysis the data were square-root transformed to lessen the impact of numerically dominant species. This coefficient was chosen because it relies on the relative proportion that each species contributes to the faunal composition, and as a result is less sensitive to differences in sampling effort among locations than other coefficients. For hierarchical classification, the pairwise station similarities were used to form groupings of stations (clusters) with similar species composition. With this technique stations with similar species composition cluster closely together, while those with dissimilar species composition cluster further apart. Group-average linkage was used as the clustering algorithm, as this strategy has the advantage of being relatively conservative in clustering intensity, while avoiding excessive chaining. However, the clustering attempts to group stations into discrete clusters and does not adequately depict the finer inter-relationships among stations. NMDS was utilized to further examine inter-relationships among the stations and years. This technique "maps" samples by rank order of their species dissimilarities, and plots species with similar species composition close together and dissimilar species composition further apart.

Habitat relief was determined only from the video images. A general habitat relief category was assigned for each station following a review of the video images collected at that station. This category was based on a subjective assessment of overall relief of the habitats encountered at that station. Low-relief areas usually consisted of a pavement of cobbles and gravel with few if any smaller boulders. Moderately low-relief areas usually consisted of cobbles with occasional patches of smaller boulders. Moderate-relief areas usually consisted of an equal mix of cobbles and boulders. Moderately high-relief areas consisted of numerous medium to large boulders interrupted by smaller areas of cobbles. High-relief areas usually consisted almost entirely of large boulders with cobbles nestled at their bases. Mean habitat relief was determined by assigning the following values for each relief category, low=1, moderately low=2, moderate=3, moderately high=4, and high=5, and averaging these values over the years.

6.3 Results and Discussion

Habitat characterizations and dominant taxa that were determined separately from video images and still photographs were similar, indicating that the still photographs were representative of the areas surveyed. Differences between the two types of coverage were mainly related to a higher occurrence of some sparsely distributed larger taxa observed in the greater geographic coverage afforded by the videotapes, and the higher occurrence of encrusting and/or smaller taxa afforded by the superior resolution of the still photographs. Additionally, larger mobile organisms that actively avoid the ROV, like the cod *Gadus morhua*, were less likely to be seen in the still photographs.

6.3.1 Distribution of Habitat Types

The seafloor on the tops of the drumlins consisted of a mix of glacial erratics in the boulder and cobble size categories. The seafloor on the drumlin immediately north of the outfall mainly consisted of areas of moderate to moderately high relief characterized by numerous boulders interspersed with cobbles. Two areas on the flank of this drumlin had a moderately low relief seafloor characterized by cobbles with occasional boulders (T1-1 and T1-5). The seafloor on the top of the drumlin located south of the outfall (T4/6-1) had a moderate relief mix of boulders and cobbles. The three flank areas on the southern drumlin consisted of one low relief area of mostly cobbles and gravel (T6-1), and two areas of mixed substrates resulting in moderately low relief (T6-2 and T4-2). The seafloor at the three northern reference sites (T7-1, T7-2, and T9-1) consisted of a mix of boulders and cobbles, resulting in moderate habitat relief. The seafloor at the southern reference sites ranged from moderately low to high relief. One southern reference site consisted primarily of cobbles with occasional boulders (T8-1) resulting in moderately low relief, while the other southern reference site (T8-2) had more boulders resulting in moderate relief. The remaining southern reference site (T10-1) consisted mainly of large boulders, which resulted in a high relief habitat. The seafloor at the farfield reference site near Scituate (T11-1) consisted of a cobble pavement overlain with a few large boulders, which resulted in a moderately low relief habitat.

The tops of drumlins had varying amounts of sediment drape, ranging from a light to moderately light drape at T8-2 and T1-4 to a moderately heavy drape at T10-1. Drape at most of the drumlin top areas ranged from moderately light to moderate. In contrast, drape at drumlin flank areas frequently ranged from moderate to moderately heavy. Two of the three southern reference sites had moderately light drape (T8-1 and T8-2), while the remaining one had moderately heavy drape (T10-1). In contrast, two of the three northern reference sites had moderate drape (T7-1 and T7-2), while the remaining site (T9-1) had slightly less drape. Sediment drape was moderate to moderately heavy at most of the flank sites.

Habitat relief and sediment drape frequently were quite variable within many of the sites surveyed. Most moderate to high relief areas also contained numerous small patches of lower relief cobbles and gravel, and some of the low relief areas contained occasional islands of higher relief boulders. Additionally, in areas of moderate to heavy sediment drape, occasional bare rock surfaces neighbored heavily draped ones.

Two diffuser heads were also visited during the 2007 survey, one that was actively discharging effluent (T2-5, Diffuser #2) and one that had not been activated (Diffuser #44). The seafloor in the vicinity of both diffusers consisted of angular rocks in the small boulder size category. This resulted in a high relief island (the diffuser head) surrounded by a moderate relief field of boulders. Sediment drape was moderately heavy at both diffuser heads.

A large area of physical disturbance to the seafloor was observed at northern reference station T7-1 (Figure 6-2). Numerous large boulders had been turned over, as evidenced by exposed bare rock surfaces and coralline algae being on bottom rather than top and/or side surfaces. This area also had less drape than surrounding undisturbed areas. Additionally, the bare rock surfaces had been colonized by numerous small barnacles, most likely the settlement of an early spring set of nauplii larvae. The disturbed area definitely appeared to be caused by some type of mechanical disturbance to the seafloor. Clear evidence of physical disturbance to the seafloor at the northern reference stations was first observed in 2006 (Maciolek *et al.* 2007). We hypothesized that the most likely cause of the disturbance would be from the anchoring activity of LNG (Liquefied Natural Gas) tankers. Since 9/11/2001, the year following the diffuser going online, LNG tankers have frequently been seen anchoring in the vicinity of the northern reference stations. During several of the surveys the field team could not occupy T7-1 or T7-2 until after a tanker vacated the area. The finding of a large disturbed area in 2007 lends further support for the theory that increased anchoring activity at the northern reference locations may be compromising the usefulness of these stations as unaffected reference sites.

6.3.2 Distribution and Abundance of Epibenthic Biota

Eighty-four taxa were seen during the visual analyses of the 2007 nearfield hard-bottom survey still photographs and videotapes (Table 6-2). Eighty-two of these taxa were seen on the still photographs and fifty-three were seen on the video footage. Taxonomic counts or estimates of abundances from the still photographs included 4,457 algae, 32,646 invertebrates, and 1,157 fish (Table 6-3). Coralline algae was the most abundant alga taxon observed during the survey, with an estimated abundance of 3,216 individuals. Two other algae commonly seen were dulse (*Palmaria palmata*) and a red filamentous alga *Ptilota serrata*, with abundances of 1,060 and 166 individuals, respectively. The least abundant alga encountered was the shotgun kelp, *Agarum cribosum* (15 individuals).

The five most abundant invertebrates observed on the slides were the frilled anemone *Metridium senile* (3,488 individuals), the northern sea star *Asterias vulgaris* (3,166 juveniles and 593 adults), barnacles *Balanus* sp. (3,240 individuals), the northern white-crust tunicate *Didemnum albidum* (2,879 individuals), and the brachiopod *Terebratulina septentrionalis* (2,173 individuals). Other abundant invertebrates observed on the still photographs were a small branching bryozoan ?*Crisia* spp. (1,683 individuals), an unidentified orange/tan sponge (1,554 individuals), unidentified encrusting bryozoans (1,548 individuals), an unidentified orange sponge (1,255 individuals), the blood sea star *Henricia sanguinolenta* (1,154 individuals), a white sponge encrusting brachiopod shells (1,010 individuals), and the horse mussel *Modiolus modiolus* (969 individuals). Additionally, the drumlin habitats were also inhabited by numerous other sponges and encrusting organisms. The most abundant fish observed in the still photographs was the cunner *Tautogolabrus adspersus* (1,101 individuals). Other fish observed were cod *Gadus morhua* (21 individuals), rock gunnel *Pholis gunnellus* (16 individuals), winter flounder *Pseudopleuronectes americanus* (8 individuals), sculpin *Myoxocephalus* spp. (4 individuals), ocean pout *Macrozoarces americanus* (4 individuals), and the sea raven *Hemitripterus americanus* (2 individuals).

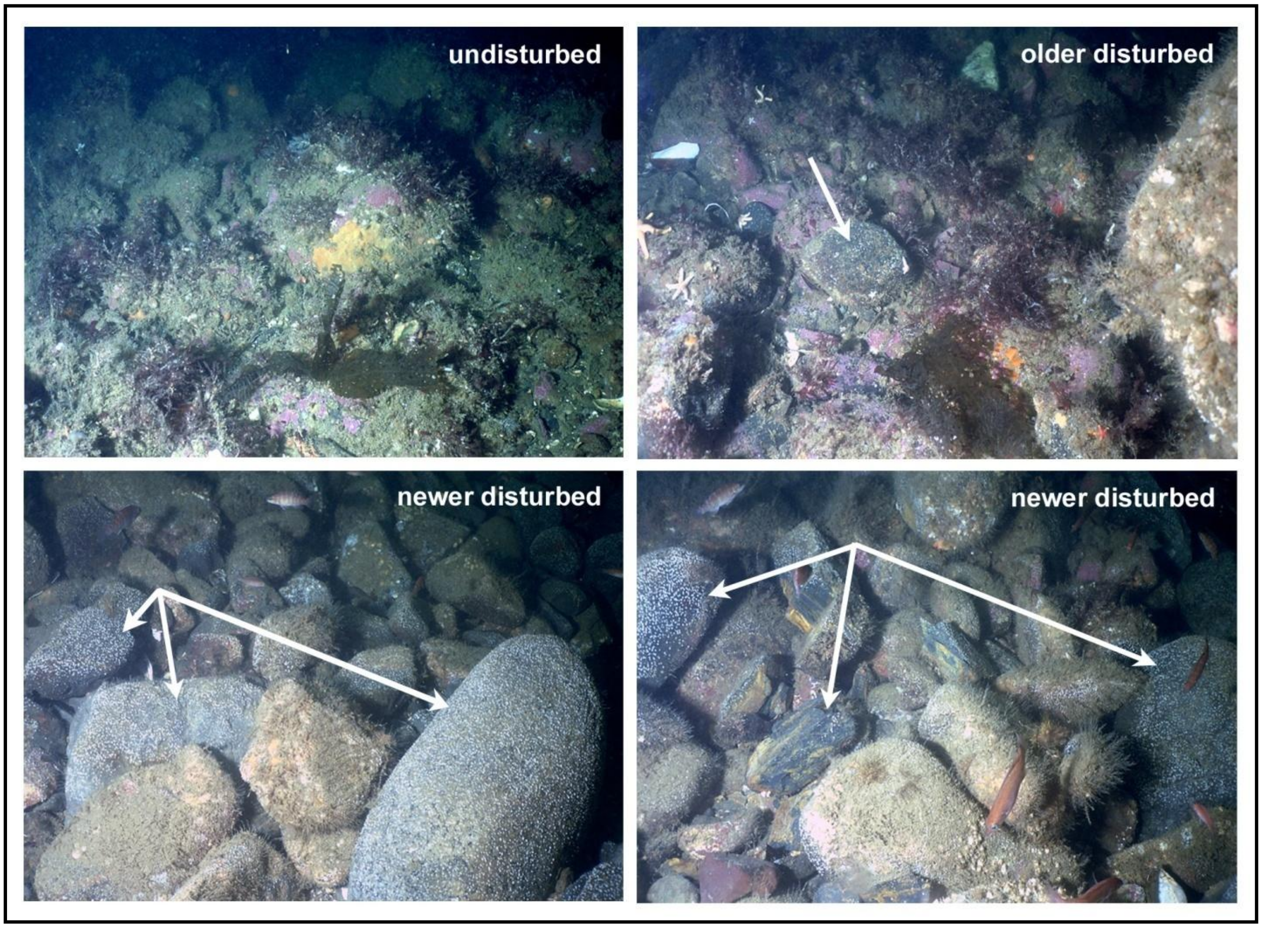


Figure 6-2. Photographs of physical disturbance taken in 2007 at northern reference station T7-1 possibly caused by the anchoring of LNG tankers. The undisturbed seafloor is characterized boulders encrusted with coralline algae, moderately-light to moderate drape, and upright algae. An older disturbed area has similar characteristics, but shows some evidence of physical disturbance such as bare rock surfaces. The newer disturbed areas are characterized by boulders that have been turned over exposing bare rock surfaces, little drape, and coralline algae on their lower surfaces. The newly settled barnacles (appear to be a spring set) indicate that the disturbance likely occurred in the winter or early spring. Examples of turned over rocks highlighted by arrows. The boulders range in size from approximately 30 to 150 cm in length, suggesting that substantial force is required to turn them over.

Table 6-1. Photographic coverage at locations surveyed during the 2007 nearfield hard-bottom survey.

Station	Location on drumlin	Depth (m)	Video (min)	Stills (# frames)
T01-1	Flank	30	22	32
T01-2	Top	28	19	30
T01-3	Top	26	19	30
T01-4	Top	27	20	32
T01-5	Flank	31	19	32
T02-1	Flank	30	20	31
T02-2	Flank	34	19	31
T02-3	Flank	31	23	33
T02-4	Flank	34	22	32
T04-2	Flank	34	23	32
T04/T06-1	Top	27	21	31
T06-1	Flank	34	20	31
T06-2	Flank	32	23	32
Northern reference				
T07-1	Top	28	21	32
T07-2	Top	28	21	32
T09-1	Top	27	19	33
Southern reference				
T08-1	Top	28	21	31
T08-2	Top	26	24	32
T10-1	Top	27	24	30
T12-1	Top	*	*	*
Farfield reference				
T11-1		36	21	32
Diffusers				
T02-5	Diffuser #2	36	20	29
Diffuser 44	Diffuser #44	36	20	33

* not surveyed in 2007

Table 6-2. Taxa observed during the 2007 nearfield hard-bottom survey.

	Name	Common name
	Algae	
	Coralline algae	pink encrusting algae
	Ptilota serrata	filamentous red algae
	Palmaria palmata	dulse
	Agarum cribosum	shotgun kelp
	Invertebrates	
	Sponges	
	general sponge	
*	*Aplysilla sulphurea*	sponge (yellow encrust)
	Haliclona oculata	finger sponge
	Haliclona spp. (encrusting)	sponge
	Melonanchora elliptica	warty sponge
	Polymastia sp. A	encrusting yellow sponge
	Phakellia spp.	chalice sponge
	Suberites spp.	fig sponge (globular)
*	cream encrusting	sponge
*	filamentous white encrusting	sponge
*	gold encrusting	sponge
*	orange/tan encrusting	sponge
*	orange encrusting	sponge
*	pink fuzzy encrusting	sponge
*	rust-cream encrusting	sponge
	thick cream with projections	sponge
	white divided	sponge on brachiopod
*	white translucent	sponge
	yellowish-cream encrusting	sponge
*	general encrusting	
*	globular translucent	
	Cnidarians	
	general hydroids	
	Obelia geniculata	hydroid
	Tubularia sp.	hydroid
	general anemone	
	Metridium senile	frilly anemone
	Urticina felina	northern red anemone
	Cerianthus borealis	northern cerianthid
	Gersemia rubiformis	red soft coral
*	*Alcyonium digitatum*	dead man's fingers
*	*Astrangia danae*	northern stony coral
	Mollusks	
*	general gastropod	
	Tonicella marmorea	mottled red chiton
*	*Crepidula plana*	flat slipper limpet
	Buccinum undatum	waved whelk
*	*Neptunea decemcostata*	ten-ridged whelk
*	general nudibranch	
	Modiolus modiolus	horse mussel
	Placopecten magellanicus	sea scallop
*	*Arctica islandica*	ocean quahog
	Crustaceans	
*	*Balanus* spp.	acorn barnacle
	Homarus americanus	lobster
	Cancer spp.	Jonah or rock crab
*	hermit crab	
	Echinoderms	
	Strongylocentrotus droebachiensis	green sea urchin
	small white starfish	juvenile Asterias
	Asterias vulgaris	northern sea star
	Crossaster papposus	spiny sunstar
	Henricia sanguinolenta	blood star
**	*Porania insignis*	badge star
	Pteraster militaria	winged sea star
	Solaster endeca	smooth sunstar
	Ophiopholis aculeata	daisy brittle star
	Psolus fabricii	scarlet holothurian
*	burrowing holothurian	
	Tunicates	
*	general tunicate	
	Aplidium spp.	sea pork tunicate
*	*Boltenia echinata*	cactus tunicate
	Boltenia ovifera	stalked tunicate
	Botrylloides violaceus	Pacific tunicate
*	*Ciona intestinalis*	sea vase tunicate
*	*Dendrodoa carnea*	drop of blood tunicate
*	*Didemnum albidum*	northern white crust tunicate
	Halocynthia pyriformis	sea peach tunicate
	Bryozoans	
*	general bryozoan	
*	?*Crisia* spp.	bryozoan
*	red crust bryozoan	bryozoan
	Miscellaneous	
	Myxicola infundibulum	slime worm
	spirorbids	
	Terebratulina septentrionalis	northern lamp shell
	Fish	
	general fish	
	Dogfish	
	Gadus morhua	cod
	Hemitripterus americanus	sea raven
	Macrozoarces americanus	ocean pout
	Myoxocephalus spp.	sculpin
	Pholis gunnellus	rock gunnel
	Pseudopleuronectes americanus	winter flounder
**	*Sebastes fasciatus*	rosefish
	Tautogolabrus adspersus	cunner

* seen only on still photographs
** seen only on video

Table 6-3. Taxa seen in still photographs taken during the 2007 nearfield hard-bottom survey, arranged in order of abundance.

Taxon	Count	Taxon	Count
Algae			
Coralline algae	3216*	*Cancer* spp.	51
Palmaria palmata	1060	thick cream with projections	42
Ptilota serrata	166*	general anemone	26
Agarum cribosum	15	*Urticina felina*	26
Total algae	**4457**	cream encrusting sponge	25
		Homarus americanus	15
Invertebrates		*Haliclona oculata*	13
Metridium senile	3488	*Tonicella marmorea*	12
Balanus spp.	3240	*Melonanchora elliptica*	11
small white starfish	3166	*Obelia geniculata*	7
Didemnum albidum	2879	*Placopecten magellanicus*	7
Terebratulina septentrionalis	2173	general tunicate	7
?*Crisia* spp.	1683	filamentous white encrusting sponge	6
orange/tan encrusting sponge	1554	*Cerianthus borealis*	6
general bryozoan	1548	*Buccinum undatum*	6
orange encrusting sponge	1255	*Pteraster militaria*	5
globular translucent	1200	*Haliclona* spp. (encrusting)	4
Henricia sanguinolenta	1154	*Phakellia* spp.	3
white divided sponge	1010	*Alcyonium digitatum*	3
Modiolus modiolus	969	hermit crab	3
Dendrodoa carnea	932	*Boltenia ovifera*	3
Halocynthia pyriformis	874	rust-cream encrusting sponge	2
Asterias vulgaris	593	*Astrangia danae*	2
general encrusting	485	general gastropod	2
Polymastia sp. A	446	*Crossaster papposus*	2
white translucent sponge	421	*Ciona intestinalis*	2
pink fuzzy encrusting sponge	397	*Neptunea decemcostata*	1
Crepidula plana	330	general nudibranch	1
Aplidium spp.	285	*Solaster endeca*	1
Boltenia echinata	244	burrowing holothurian	1
Tubularia sp.	220	hydroid	**
general sponge	217	spirorbids	**
Aplysilla sulphurea	187	**Total invertebrates**	**32646**
Gersemia rubiformis	173		
red crust bryozoan	172	**Fish**	
Myxicola infundibulum	164	*Tautogolabrus adspersus*	1101
Suberites spp.	132	*Gadus morhua*	21
Botrylloides violaceus	122	*Pholis gunnellus*	16
gold encrusting sponge	119	*Pseudopleuronectes americanus*	8
Strongylocentrotus droebachiensis	116	*Myoxocephalus* spp.	4
Psolus fabricii	116	*Macrozoarces americanus*	4
Ophiopholis aculeata	114	*Hemitripterus americanus*	2
yellowish-cream encrusting sponge	109	general fish	1
Arctica islandica	64	**Total fish**	**1157**

* estimated ** not counted

Coralline algae was one of the most widely distributed taxa encountered during the survey. This encrusting alga was seen at 20 of the 22 waypoints surveyed in 2007, being absent from the two diffuser sites. Mean areal coverage of coralline algae ranged from 54.8% cover at T8-2 to <0.1% cover at T10-1. Figure 6-3 shows the relationships between depth, sediment drape, percent cover of coralline algae, and topography. The strongest relationship was observed between percent cover of coralline algae and degree of sediment drape. Corallines were most abundant in areas that had moderately light sediment drape on the rock surfaces and least abundant in areas that had moderately heavy sediment cover. Amount of sediment drape did not show a strong relationship with either depth or topography. Additionally, percent cover of coralline algae was variable and showed a weak general trend of higher cover at shallower depths. In contrast to the wide distribution of coralline algae, the two most abundant upright algae, *Palmaria palmata* and *Ptilota serrata* had much more restricted distributions, with *P. palmata* being common at only eight of the sites (two of the northern reference sites (T7-1 and T7-2), five sites on a drumlin immediately north of the outfall (T1-1, T1-2, T1-3, T1-4, and T2-3), and one of the southern reference sites (T8-1)) and *P. serrata* being common at only the one of the northernmost reference sites (T7-1) and a site on top of the drumlin north of the outfall (T1-3). These upright algae were common in areas characterized by moderate to moderately high relief and moderate sediment drape. The reduced percent cover of coralline algae in areas supporting high abundances of upright algae may be related to fine particles being trapped by the holdfasts of the upright algae and blanketing the rock surfaces. In areas with heterogeneous substrate characteristics, *P. serrata* and *P. palmata* frequently dominated on the tops of boulders, whereas corallines dominated on the cobbles and smaller boulders in between.

Several of the commonly seen invertebrates also had wide distributional patterns. Juvenile and adult northern sea stars *Asterias vulgaris* were found at all of the sites surveyed. Juvenile *Asterias* were most abundant on large boulders on top of the drumlins, while adult *Asterias* were most abundant in areas of lesser relief. The blood sea star *Henricia sanguinolenta* was observed at 21 of the 22 sites. This species was most abundant on larger boulders. The northern white crust tunicate *Didemnum albidum* was also widely distributed, being found at all 22 sites and abundant at 15 of them. This encrusting species was most abundant in areas with larger boulders and light to moderate sediment drape. The horse mussel *Modiolus modiolus* was also very widely distributed, being found at all sites but the diffuser heads. This mussel was most abundant on the top of drumlins at the reference sites, where they were observed nestled among cobbles and at the bases of boulders. Because of the mussel's cryptic nature of being nestled in among rocks, being encrusted by organisms and being draped with sediment or partially buried, the observed abundances are very conservative. The number of mussels is underestimated even more in areas of high relief, because the bases of larger boulders were rarely visible in the images. The sea peach tunicate *Halocynthia pyriformis* was found at 19 sites but was only found in high abundances on the head of the inactive diffuser (Diffuser #44). With the exception of the diffuser heads, this species was usually only seen on the sides of larger boulders.

Three additional species were also primarily restricted to large boulders. The brachiopod *Terebratulina septentrionalis* was found at 17 of the sites, but was only seen in high abundances at six of them (T2-3, T2-4, T4-2, T7-1, T9-1, and T11-1). This species was largely restricted to the sides of large boulders, where it is partially protected from sediment loading, which could clog the brachiopod's filtering apparatus. The frilled anemone *Metridium senile* was another species that was markedly more abundant on large boulders. This anemone was found at 9 sites, but was common to abundant at only the two diffuser heads. *Metridium senile* was exceptionally abundant on the head of the active diffuser (Diffuser #2) where it almost completely covered the surface. Additionally, it occluded the closed ports on the diffuser head and extended down onto the riprap at its base. This anemone was much less abundant on the head of the inactive diffuser (Diffuser #44). *Metridium* is generally quite abundant on most of the active diffuser heads. One species with a very restricted distribution was the red soft coral *Gersemia rubiformis*, which was seen at only one of the sites, where it inhabited the tops of large boulders found at T10-1.

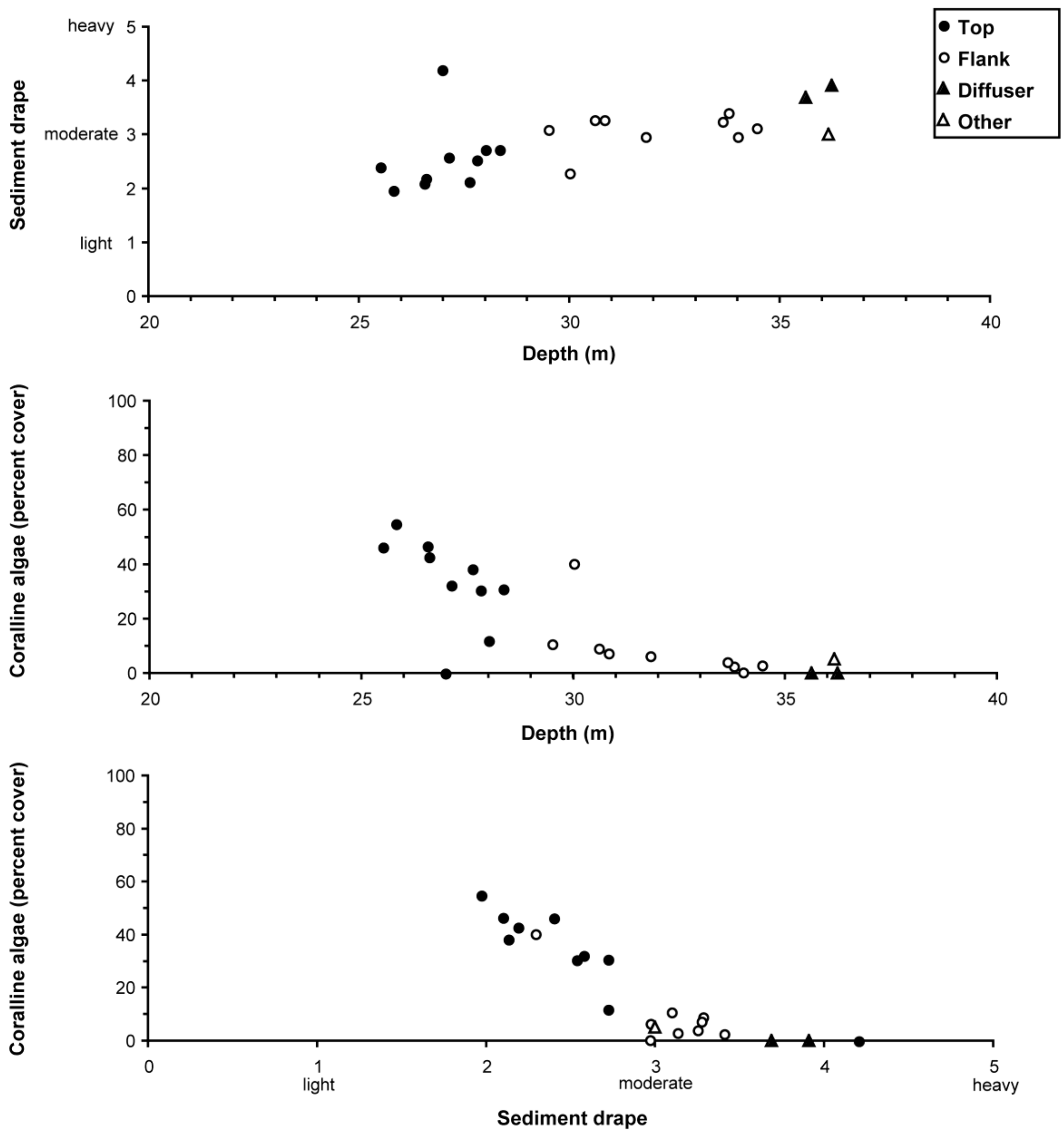


Figure 6-3. Depth, sediment drape, and percent cover of coralline algae of the sites from the 2007 nearfield hard-bottom survey.

Encrusting invertebrate taxa generally were most abundant in moderate to high relief areas that had light to moderate sediment drape on the rock surfaces. This is not surprising because most juveniles of attached taxa require sediment-free surfaces for settlement. Additionally, clean rock surfaces are indicative of strong currents that could provide adequate food supplies for suspension-feeding organisms. Boulders and large cobbles also provide a physically more stable environment than smaller cobbles as they are more resistant to mechanical disturbance.

The green sea urchin *Strongylocentrotus droebachiensis* was relatively widely distributed, being found at 11 sites, but it was commonly observed at only one of these sites (T2-1). The red holothurian *Psolus fabricii* also was widely distributed. This holothurian was found at 18 sites, but was commonly observed at only six of them (T1-3, T2-1, T2-3, T4/6-1, T9-1, and T8-2). Reasons for its high abundance in some areas, and not in others, were not readily apparent.

Several taxa that have been "newly" designated or recognized in recent years were also seen. All four of the invertebrate taxa newly recognized in 2006, two sponges unique to the farfield reference station T11-1, a clear attached globular organism with opaque matter at it's center, and the northern stony coral *Astrangia danae*, were seen in 2007. One taxon that was "newly" designated in 2005, the invasive tunicate *Botrylloides violaceus*, was found at 11 sites and was commonly observed at three of them (T2-4, T10-1, and T11-1). A total of 122 colonies were identified as *B. violaceus* this year, compared to 146 and 80 colonies observed in 2005 and 2006, respectively. Only one individual of another taxa "newly" encountered in 2005, a large unidentified holothurian found only at T11-1, was observed this year. Two species that were newly observed in 2004 on rocks that had previously been heavily colonized by barnacles, a frilly white encrusting sponge? (possibly a nudibranch egg case) and a dark grey translucent material (tentatively identified as *Diplosoma listerianum*), were not seen in 2007.

The fish fauna was dominated by the cunner *Tautogolabrus adspersus*, which was observed all 22 waypoints. This fish was most abundant in moderate to high relief areas, where it tended to congregate among large boulders (T1-3, T2-1, T2-3, T2-4, T7-1, and Diffuser #44). In areas of heterogeneous or low relief, *T. adspersus* was usually seen only in the immediate vicinity of boulders. Six other fish species, cod (*Gadus morhua*), rock gunnel (*Pholis gunnellus*), winter flounder (*Pseudopleuronectes americanus*), sculpin (*Myoxocephalus* spp.), ocean pout (*Macrozoarces americanus*), and sea raven (*Hemitripterus americanus*), also were seen on the still photographs. The sculpin and flounder were usually seen in flat low-relief areas, while cod and ocean pout were only seen around boulders.

6.3.3 Community Structure

Classification analysis of the 22 waypoints and 47 taxa defined one large grouping of stations loosely joined to a small group of the two diffuser stations (Figure 6-4). The large grouping of stations further subdivided into two more cohesive clusters of stations and two solitary stations at a faunal similarity level of 65%. The clustering structure reflected a combination of topography, habitat characteristics, and geographic proximity. The first cluster consisted mainly of drumlin top stations, including both northern and southern reference stations, while the second cluster consisted mainly of drumlin flank stations. These two clusters further subdivided into several more cohesive groups of stations at a faunal similarity of 75%. Neighboring waypoints with similar habitat characteristics tended to cluster together (T7-1 and T7-2; T1-2, T1-3, and T1-4; T8-1 and T8-2). Habitat characteristics and the range of abundance of dominant taxa for each of the cluster groups are presented in (Table 6-4). Biotic differences among the hard-bottom stations generally reflected shifts in the relative proportion of only a few dominant taxa.

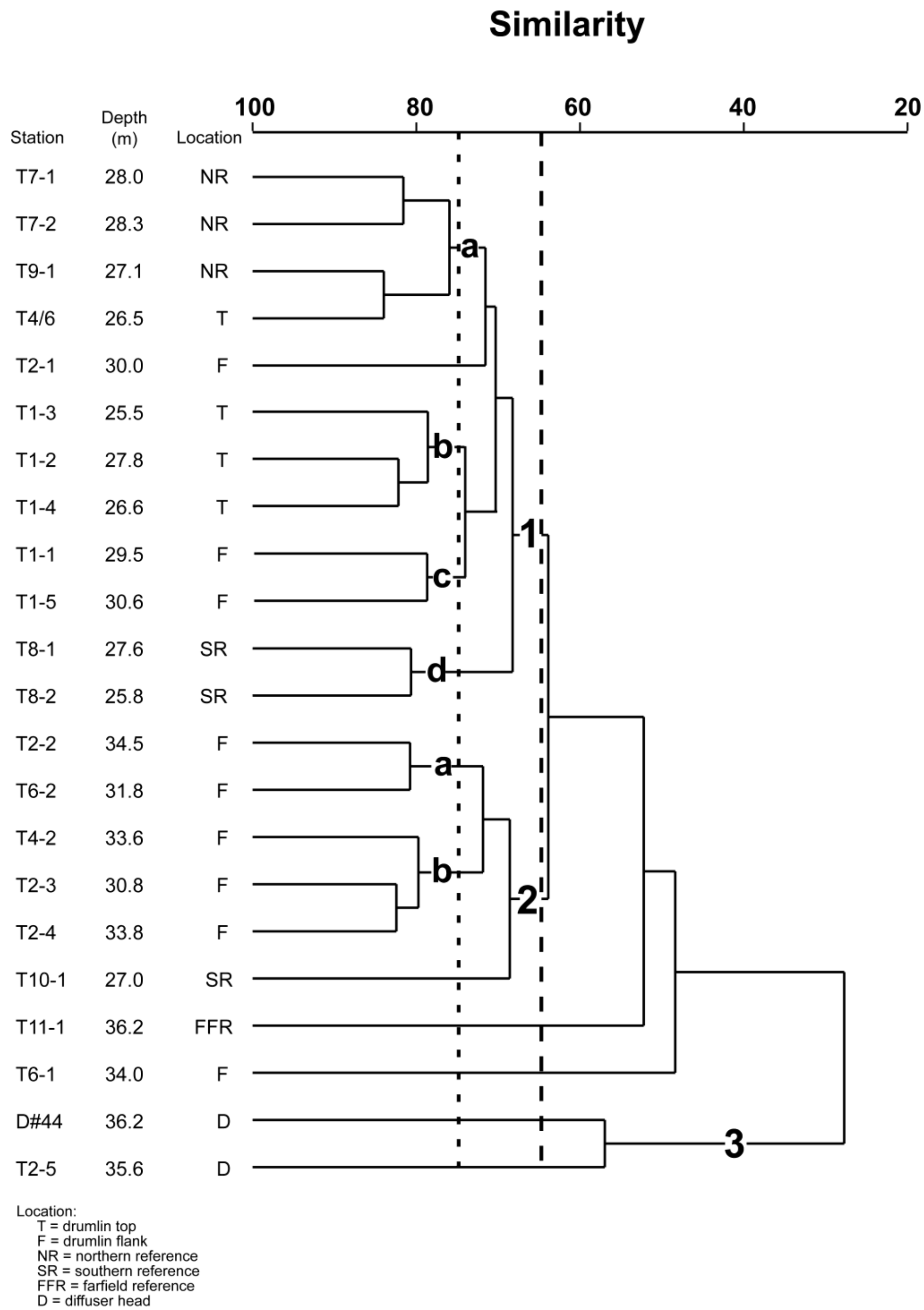


Figure 6-4. Cluster analysis of data collected from still photographs taken during the 2007 nearfield hard-bottom survey.

Table 6-4. Habitat characteristics and range of abundance (number per slide) of selected taxa in clusters defined by classification analysis. Numbers in bold highlight major differences among clusters and subgroups.

Cluster	1					2			T11-1	T6-1	3
	a	T2-1	b	c	d	a	b	T10-1			
Depth (m)	27-28	30	25-28	30-31	26-28	34-35	31-34	27	36	34	36
Substrate[1]	b+c	c+b	b+c	c+b	mx+b	c+mx	mix	b+c	cp+ob	cp+g	d+rr
Relief[2]	M	M	M-MH	LM	LM-M	L-M	LM-MH	H	LM	L	M
Drape[3]	lm-m	lm	lm-m	m	lm	m	m	mh	m	m	m-mh
Coralline algae (percent)	**12.0-46.6**	**40.3**	**30.5-46.3**	**9.1-10.8**	**38.2-54.8**	3.1-6.5	2.6-7.3	>0.1	5.2	0.5	-
Coralline algae (numerical)	**3.00-10.97**	**9.23**	**6.87-11.17**	2.25-2.84	**8.77-13.13**	1.00-1.91	0.97-2.18	0.03	1.28	0.42	-
Palmaria palmata	0.58-6.88	0.26	**2.93-6.87**	0.22-1.81	0.28-2.81	-	0.03-3.24	0.20	-	-	-
Ptilota serrata	0.00-2.69	-	0.00-1.47	-	-	-	-	-	-	-	-
juvenile Asterias	**5.58-8.06**	2.42	**6.23-11.59**	**4.25-4.66**	**6.00-8.55**	1.34-1.58	2.06-4.63	0.77	1.06	**4.81**	0.34-1.12
Modiolus modiolus	1.61-3.06	1.26	0.56-1.40	0.66-0.69	**2.94-3.66**	1.03-1.65	0.84-1.48	0.73	2.00	0.23	-
Didemnum albidum	2.64-4.29	1.58	**3.53-7.40**	**5.91-6.38**	1.53-3.16	**4.91-5.48**	**4.53-7.55**	3.87	0.25	**4.06**	0.76-1.30
orange/tan encrusting sponge	1.78-2.88	**3.00**	1.10-2.53	**2.19-4.97**	1.65-1.84	**2.65-2.88**	**2.55-3.81**	1.07	**4.28**	1.03	-
orange encrusting sponge	0.65-3.25	**2.55**	1.00-2.03	**2.22-2.50**	0.68-2.06	1.34-1.65	**2.13-3.97**	1.60	2.31	0.03	-
Henricia sanguinolenta	0.13-1.03	**2.48**	0.27-1.13	0.44-0.59	0.58-0.81	**1.52-2.50**	0.00-1.00	0.27	0.53	0.90	0.07-0.58
Asterias vulgaris	1.33-2.72	**5.00**	1.25-1.67	1.44-2.44	1.00-1.03	0.81-1.61	1.25-2.21	2.80	0.56	0.32	0.17-0.67
Balanus spp.	0.32-21.91	**41.74**	1.56-8.70	0.00-2.81	0.06-1.41	0.90-11.03	0.13-0.94	-	0.03	-	0.00-0.21
Terebratulina septentrionalis	2.00-5.45	0.13	0.00-0.03	0.09-0.09	-	0.63-1.26	**9.97-19.63**	2.77	**9.13**	-	0.03-0.03
Gersemia rubiformis	-	-	-	-	-	-	-	**5.77**	-	-	-
Ophiopholis aculeata	-	-	-	-	-	-	-	-	**3.56**	-	-
yellowish-cream encrusting sponge	-	-	-	-	-	-	-	-	**3.41**	-	-
Metridium senile	0.00-0.16	0.35	0.00-0.07	-	-	-	0.00-0.09	0.03	0.06	-	**21.42-95.03**
Halocynthia pyriformis	0.33-3.31	0.42	0.03-0.27	0.09-0.16	0.00-0.16	0.19-0.34	0.58-2.38	0.53	0.25	-	**0.00-14.12**
Tautogolabrus adspersus	**1.15-2.69**	**2.68**	**1.63-3.50**	0.81-1.19	0.26-0.44	0.38-0.87	0.78-3.33	**1.80**	0.16	0.06	**1.72-3.39**
Species	37-45	41	29-37	37-39	33-35	40-41	42-45	37	47	28	18-24
Algae	**8.45-13.00**	**9.48**	**9.87-19.50**	2.47-4.66	**11.58-13.41**	1.00-1.94	1.06-5.42	0.23	1.28	0.42	-
Invertebrates	36.52-72.56	79.26	33.23-43.57	25.34-39.53	30.55-33.66	34.94-45.94	50.72-77.59	34.13	45.41	14.61	45.12-105.14
Fish	**1.15-2.75**	**2.68**	**1.63-3.60**	0.84-1.31	0.29-0.50	0.50-0.97	0.81-3.39	1.87	0.25	0.06	**1.93-3.67**

[1] b=boulder, c=cobble, g=gravel, m=mix of boulders, cobbles, and gravel, cp=cobble pavement, d=diffuser, rr=riprap
[2] L=low, LM=moderately low, M=moderate, MH=moderately high, H=high
[3] l=light, lm=moderately light, m=moderate, mh=moderately heavy, h=heavy

The first cluster (cluster 1) consisted mainly of drumlin top sites that grouped together at a faunal similarity of 68 percent. Coralline algae was one of the dominant components of the benthic community observed at each of the sites in this cluster. Additionally, all of the stations in this cluster supported some upright algae and many juvenile *Asterias* sp. Species richness was moderate to high at the stations in this cluster, ranging from 29 to 45 species. The subgroups within this cluster appeared to largely reflect geographic differences among the stations. The four stations in subgroup 1a, the three northern reference sites (T7-1, T7-2, and T9-1) and the drumlin top site south of the outfall (T4/6-1), clustered together at a faunal similarity of 76 percent. Substrate at these stations consisted of a moderate relief mix of boulders and cobbles, with moderately light to moderate sediment drape. These stations supported a modest to high percent cover of coralline algae (12.0 to 46.6% cover) and both dulse *Palmaria palmata* and filamentous red algae *Ptilota serrata*. A flank site (T2-1) that joined subgroup 1a had high percent cover of coralline algae (40.3% cover), but supported very few dulse and no filamentous red algae. This site differed from other stations in cluster 1 in that it was colonized by numerous barnacles. This site also supported many encrusting invertebrates, adult *Asterias*, and fish. The three stations in subgroup 1b, all located on top of the drumlin directly north of the outfall, clustered together at a faunal similarity of 79 percent. The seafloor at these drumlin top sites consisted of boulders interrupted by patches of cobbles, resulting in moderate to moderately high habitat relief. These stations supported moderately high percent cover of coralline algae (30.5 to 46.3% cover), as well as numerous *P. palmata* and a few red filamentous algae. The two flank sites in subgroup 1c were also located on the drumlin north of the outfall and clustered together at a similarity of 79 percent. The seafloor at these sites consisted mainly of cobbles interspersed by occasional boulders, resulting in moderately low relief habitat. These two sites supported moderately low percent cover of coralline algae (9.1-10.8% cover), a few dulse, numerous encrusting organisms and seastars, and few fish. The two sites in subgroup 1d, southern reference stations T8-1 and T8-2, clustered together at a faunal similarity of 81 percent. The seafloor at these stations consisted primarily of a cobble pavement interrupted by patches of boulders and gravel, resulting in a moderately low relief habitat at T8-1 and a slightly higher relief habitat at T8-2. These southern reference stations supported moderately high percent cover of coralline algae (38.2-54.8% cover), few dulse, many seastars and mussels, and few fish.

The second cluster (cluster 2) consisted mainly of drumlin flank stations (five flank and one top station) that grouped together at a faunal similarity of 69 percent. The stations in this cluster varied widely in terms of habitat characteristics, but they all supported relatively few algae. This cluster also further divided into two subgroups of stations and one outlier. The first subgroup (2a) consisted of two drumlin flank stations that clustered together at a faunal similarity of 81 percent. The seafloor at these sites consisted of a mix of cobbles, boulders, and gravel, overlain by a moderate sediment drape. Both of these sites supported numerous invertebrates and a relatively high number of species (40 and 41 species). The three flank stations in subgroup 2b clustered together at a similarity of 80 percent. The seafloor at these sites consisted of a mix of substrates, with habitat relief that ranged from moderately low to moderately high. All three of these sites supported numerous brachiopods (*Terebratulina septentrionalis*), many other invertebrates, and a high number of species (42-45 species). The high relief southern reference station T10-1 joined the other stations in cluster 2 at a faunal similarity of 69 percent. The seafloor at this station consisted of large boulders covered with a heavy sediment drape. This station supported very little coralline algae, a few dulse, and moderate numbers of invertebrates. This was the only station that was inhabited by the soft coral *Gersemia rubiformis*.

The two main clusters of stations joined together at a faunal similarity of 64 percent. Two stations individually joined this larger group of stations at lower levels of similarity. The first station, farfield southern reference station T11-1, joined the main group at a similarity of 52 percent. The seafloor at this station was a moderately low relief mix of cobbles interspersed with occasional large boulders and covered with a moderate sediment drape. This station supported moderate numbers of invertebrates, few algae, few fish, and a high number of species (47 species). Brachiopods dominated the faunal community at this station, where they were found on many of the boulders throughout the site. Yellowish-cream encrusting sponges, as well as daisy brittlestars *Ophiopholis aculeata*, were also commonly observed in this area. The final solitary station that joined the main group at a similarity of 48 percent was a deep flank station (T6-1). The seafloor at this station consisted of a low relief cobble pavement interrupted by occasional patches of gravel, covered by a moderate sediment drape. This station was relatively depauperate. It supported very few algae, few invertebrates, few fish, and relatively few species (28 species).

The two diffuser stations joined together at a faunal similarity of 57 percent (cluster 3). These sites each consisted of a diffuser head and the riprap immediately surrounding it. The fauna inhabiting these diffuser heads has not changed much since diversion of the outfall. Both of these stations supported no algae and moderately high numbers of fish (mainly cunner and cod). The head of the active diffuser (#2 at T2-5) was heavily colonized by frilled anemones (*Metridium senile*), where dense aggregations of anemones covered most of the exposed surfaces of the dome, as well as the indentations of the discharge ports (Figure 6-5a and b). In contrast, the head of the inactive diffuser (#44) was much more sparsely populated. This diffuser was colonized by far fewer *M. senile* and numerous sea peach tunicates *Halocynthia pyriformis* and (Figure 6-5c and d). Both diffuser stations supported relatively few species (18 and 24 species, respectively) compared to the hard-bottom drumlin sites (28 to 47 species).

Two-dimensional non-metric multidimensional scaling (NMDS) of the same data set is presented on Figure 6-6a. The 2d-NMDS analysis resulted in a stress level of 0.11, which means that the 2-d ordination space reflects the higher-dimensional relationship between the stations to a reasonable degree. The two stations that consisted of diffuser heads and the surrounding riprap (T2-5 and Diffuser #44) were omitted from the NMDS because their benthic communities differed substantially from the remaining stations, and hence constricted the ordination space of the remaining stations. Within this constraint, the 2D-NMDS results generally reflected the groupings defined by the cluster analysis, with sites within a cluster being closer together than sites from other clusters. The two solitary stations, T11-1 and T6-1, clearly separate out from the remaining stations. One anomaly was a slight overlap of the NMDS space occupied by the two main clusters, with the cluster 2 flank station T6-2 within the space of stations in cluster 1. However, this station did separated out from the space occupied by cluster 1 stations in the third dimension of the NMDS analysis. Figure 6-6b shows that much of the clustering structure and ordination reflects the percent cover of coralline algae found at each of the stations. Stations located on the top of drumlins (this includes the reference stations) generally have higher percent cover of coralline algae than stations located the flanks of drumlins. Flank station T2-1 clustered with the northern reference stations (subgroup 1a) largely because it supported a fairly high percent cover of coralline algae. The other flank stations in cluster 1 (T1-1 and T1-5) both occupy a distal position in the space occupied by stations in cluster 1. The unusual southern reference station T10-1 had only trace amounts of coralline algae and occupied a distal position in the space occupied by stations in cluster 2.

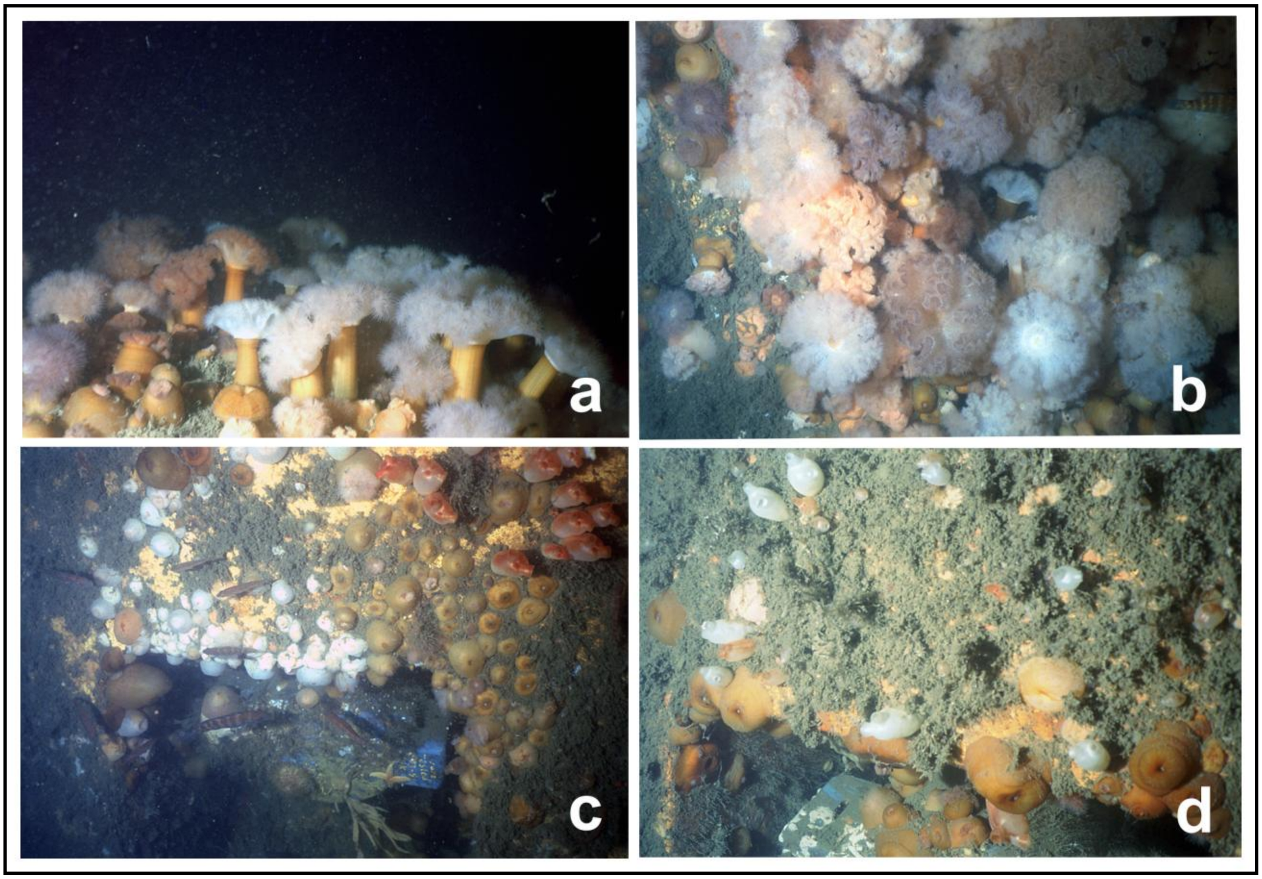


Figure 6-5. Photographs showing colonization of the diffuser heads. (a) The top (a) and side (b) of the active diffuser head #2 (T2-5) showing colonization by many frilled anemones *Metridium senile*. One side (c) of the inactive diffuser head (#44) showing colonization by numerous frilled anemones and a few sea peach tunicates *Halocynthia pyriformis*. (d) Another side of diffuser head #44 showing numerous sea peaches and frilled anemones.

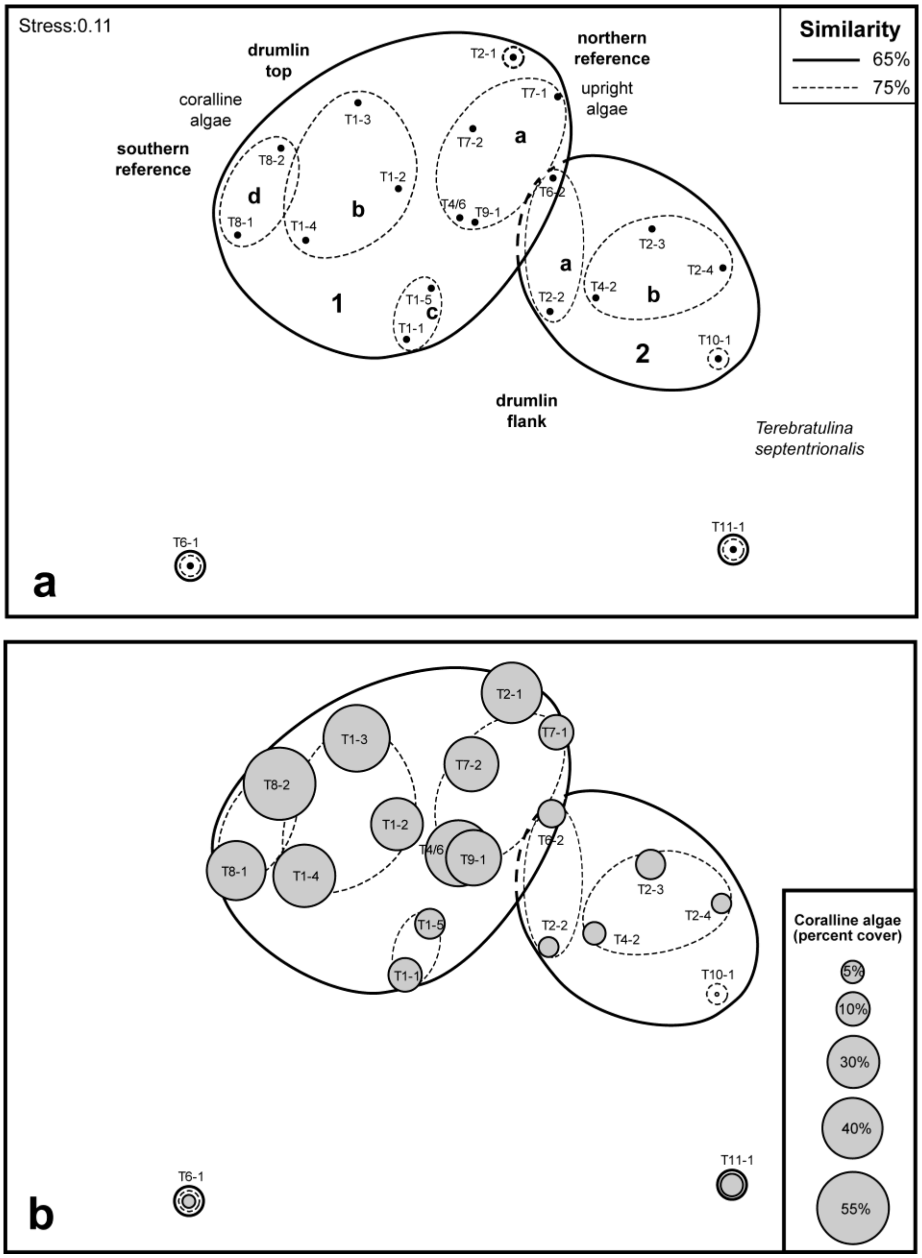


Figure 6-6. (a) Two-dimensional non-metric multidimensional scaling plot of the 2007 nearfield hard-bottom still photograph data, with cluster designations from hierarchical classification superimposed. (b) Percent cover of coralline algae at each station plotted in the 2D-NMDS space.

6.3.4 Comparison of Pre- and Post-Diversion Communities

The nearfield hard-bottom communities in the vicinity of the outfall have been surveyed annually for 14 years. Seven of the surveys occurred under pre-discharge “baseline” conditions, while the last seven surveys occurred under discharge conditions. The baseline surveys provided a substantial database that allowed characterization of the habitats and benthic communities found on the drumlins in the vicinity of the outfall. The sampling design and approach has evolved to maximize the probability of detecting potential impacts of outfall operations. The present design includes 13 sites near the outfall, 7 nearfield reference sites (3 north and 4 south of the outfall), one farfield reference site off Scituate, and an inactive and an active diffuser head. Additionally, the emphasis on data products also has evolved. Still photographs and video footage are both utilized to provide a detailed characterization of the seafloor and of the biota inhabiting the hard-bottom sites. The still photographs provide the high resolution required to provide detailed data on habitat characteristics (substrate size classes and amount of sediment drape), estimated percent cover of encrusting algae, estimated relative abundances of upright algae, and faunal composition of the benthic communities. In contrast, the much broader areal coverage provided by the video images has allowed assessment of habitat relief, spatial heterogeneity, and the occurrence of large, rare biota.

The hard-bottom habitats, though spatially quite variable, have shown consistent trends over time. At many of the waypoints, year-to-year variations in habitat characteristics tended to be relatively small. Habitat relief does not vary over time, but slightly different areas of the sites were surveyed each year, so varying relief at a site indicates habitat heterogeneity. Figure 6-7 shows the mean habitat relief observed during the 1996 to 2007 surveys. Location on the drumlins appeared to be a primary factor in determining habitat relief. The seafloor on the tops of drumlins usually consisted of a mix of boulders and cobbles. Habitat relief varied from moderate to high on drumlin tops dominated by boulders (T1-2, T1-3, T4/6-1, T7-1, T7-2, T9-1, T10-1, and T12-1) to moderate to moderately low on drumlin top areas that consisted of a mix of cobbles and boulders (T1-4, T8-1, and T8-2). The seafloor on the flanks of drumlins was quite variable, but usually consisted of a cobble pavement interspersed with patches of sand, gravel and occasional boulders. Habitat relief on the flanks ranged from low to moderately low on the drumlin south of the outfall (T4-1, T4-2, T4-3, T6-1, and T6-2) to moderately low to moderately high on the drumlin north of the outfall (T1-1, T1-5, T2-1, T2-2, T2-3, and T2-4). The variance shown by the error bar indicates that some sites are quite homogeneous (T1-3, T8-1, T10-1, T12-1, and the diffuser stations), while other sites tend to be more heterogeneous (T2-2, T4-2, T4/6-1, T6-2, T7-1, and T7-2).

Figure 6-8 shows the amount of sediment drape seen on the rock surfaces during the 1996 to 2007 surveys. Sediment drape was lightest on the shallowest part of the two drumlins adjacent to the outfall (T1-2, T1-3, T1-4 and T4/6-1), slightly more at the southernmost reference sites (T8-1, T8-2 and T12-1), and moderate to moderately heavy at the northern reference sites (T7-1, T7-2, and T9-1). Drape was also heavy on the flanks of the drumlins north and south of the outfall (T1-1, T2-2, T2-3, T2-4, T4-2, and T6-1). Drape was consistently heaviest at T10-1, the southern reference site west-southwest of the outfall. Additionally, sediment drape has consistently been higher at several of the stations north of the outfall (T1-2, T1-3, T1-4, T7-1, and T7-2) during the post-diversion years.

Encrusting coralline algae has historically been the most abundant and widely distributed taxon encountered during the hard-bottom surveys. Figure 6-9 shows the percent cover of coralline algae estimated from the slides taken during the 1996 to 2007 surveys. Coralline algae were generally most abundant on the top of drumlins on either side of the outfall (T1-3, T1-4, and T4/6-1) and least abundant on the flanks of the drumlins (T2-2, T2-4, T4-1, and T6-1). The percent cover of coralline algae was most variable near the edges of the tops of drumlins or on the flanks, where small lateral shifts in location frequently resulted in large differences in coralline algal cover. Percent cover of coralline algae was quite stable during the “baseline” period and remained stable at most of the stations during the first four years

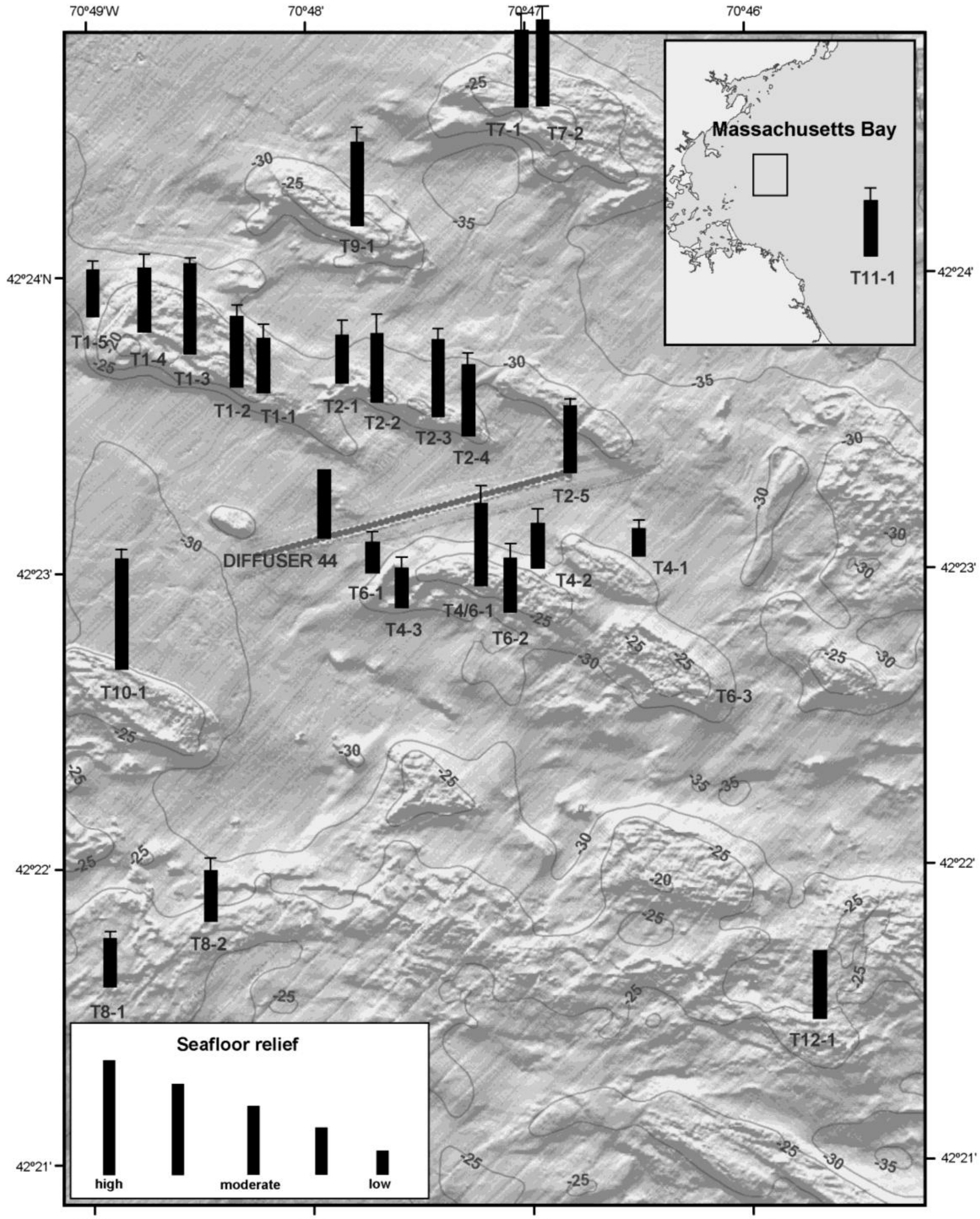


Figure 6-7. Habitat relief (mean values) determined from the 1996 to 2007 nearfield hard-bottom surveys. Error bars are one standard deviation To generate the relief bars habitat relief was coded as: low=1, moderately low=2, moderate=3, moderately high=4,and high=5.

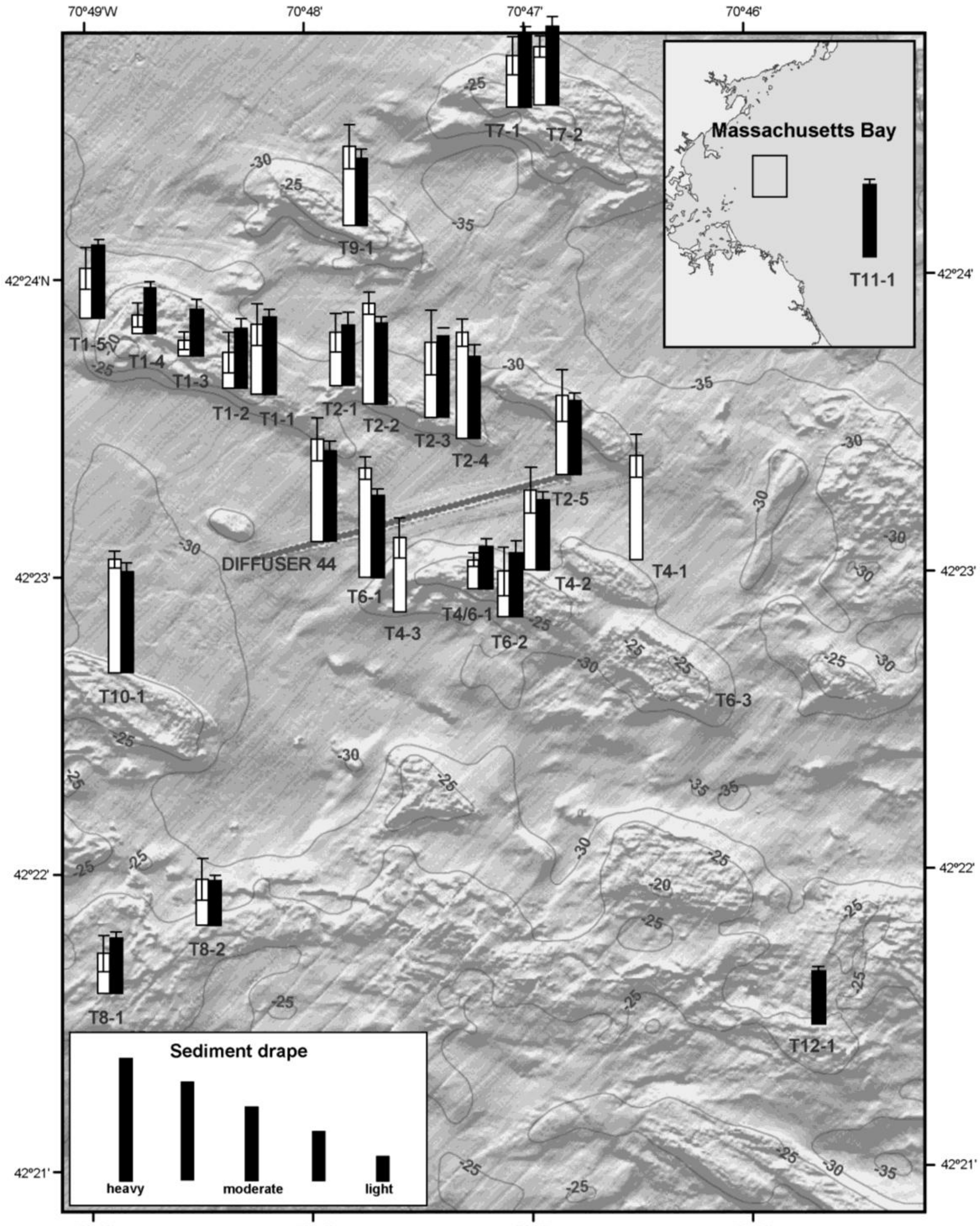


Figure 6-8. Sediment drape determined from 35-mm slides collected during the 1996 to 2007 nearfield hard-bottom surveys. White bars are mean pre-diversion values and black bars are mean post-diversion values. Error bars are one standard deviation.

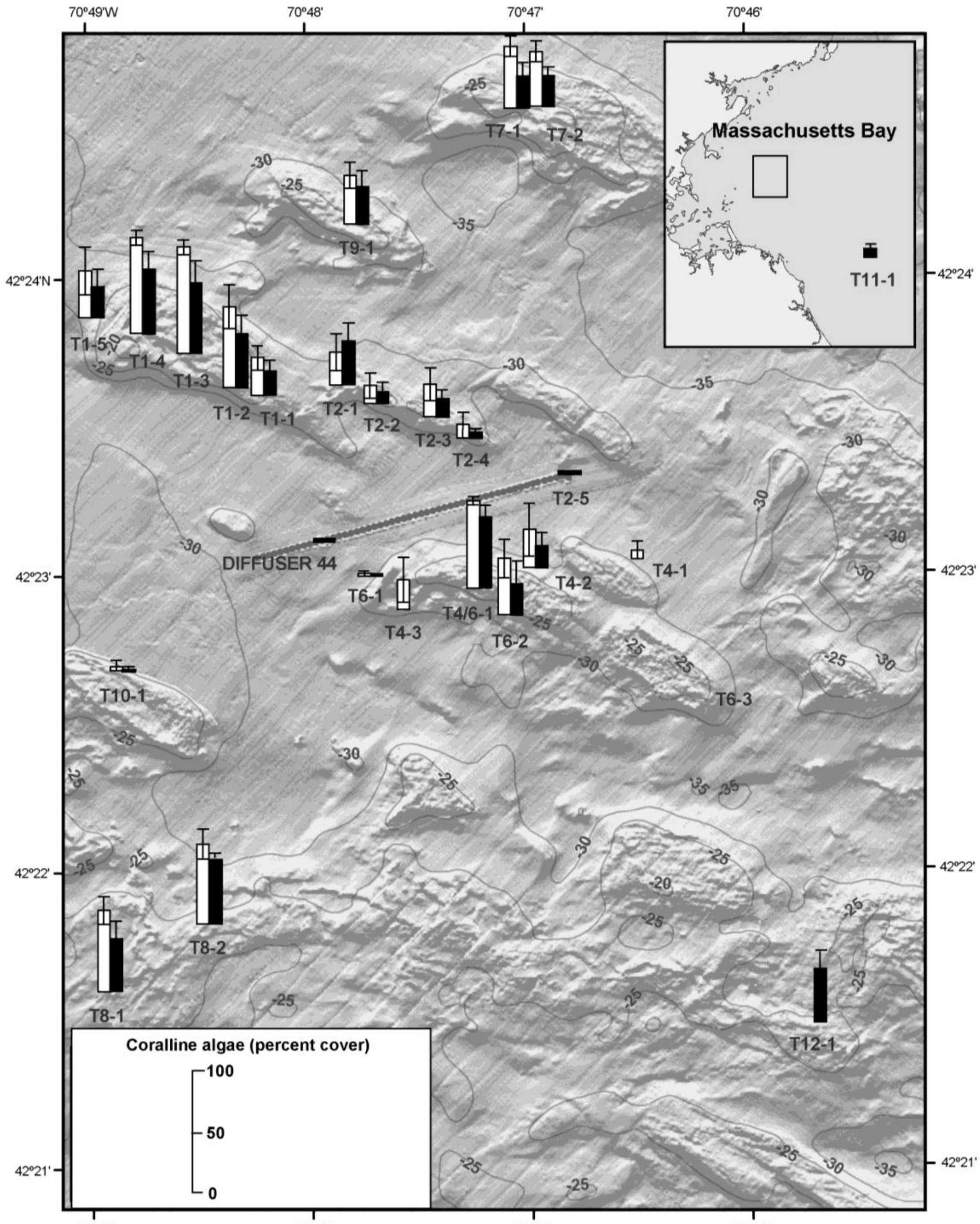


Figure 6-9. Percent cover of coralline algae determined from 35-mm slides collected during the 1996 to 2007 nearfield hard-bottom surveys. White bars are mean pre-diversion values and black bars are mean post-diversion values. Error bars are one standard deviation.

of the discharge period. The major exception to this occurred at five stations located north of the outfall (T1-2, T1-3, T1-4, T7-1, and T7-2), which consistently had less percent cover of coralline algae during each of the post-diversion years. Additionally, since 2005 the entire area has been experiencing a general decrease in percent cover of coralline algae.

This trend can be seen in greater detail in Table 6-5, which lists the estimated percent cover of coralline algae at each station for the 1996 to 2007 time period. The decrease in percent cover of coralline algae at the northern stations mentioned above was particularly pronounced after 2005. Additionally, concurrent decreases in percent cover of coralline algae have been observed at sites south of the outfall since 2005. Two stations that have not shown dramatic decreases in coralline algae are T2-1 located just north of the outfall, and T8-2 one of the southern reference stations. In contrast, another nearby southern reference station, T8-1, has shown a marked decrease in percent cover since 2005. A flank station T4-2 also had less percent cover of coralline algae during the last five post-diversion years. One additional station (T4/6-1) has shown a decrease in coralline algae during the last four years. Part of the variation at this station may reflect spatial variability within the site, since two excursions at this site in 2002 yielded widely different estimates in percent cover of coralline algae (50 versus 80% cover)

It is unlikely that light attenuation with depth is a limiting factor for coralline algae, within the range of depths covered during this survey (Sears and Cooper 1978; Vadas and Steneck 1988). However, in previous years of this study, percent cover of coralline algae has been found to be inversely related to sediment drape (Kropp *et al*. 2002, Maciolek *et al.* 2004). Percent cover is usually highest in areas that have little drape and lowest in areas that have moderate to heavy drape. This is not surprising, because the encrusting growth form of coralline algae would make them quite susceptible to smothering by fine particles.

Changes in percent cover of coralline algae and sediment drape at each of the stations over time can be seen on Figure 6-10. The widespread decreases in percent cover of coralline algae observed in the last three years can be seen at 13 of the stations. In the past, consistent post-diversion decreases in coralline algal cover were seen at only five stations (T1-2, T1-3, T1-4, T7-1, and T7-2) and were usually accompanied by increases in sediment drape. This does not appear to be the case since 2005, where only slight concurrent increases in sediment drape have been noted at only several stations. Reasons for the dramatic decrease in coralline algae starting in 2005 are not readily apparent. Reasons for the post-diversion increases in sediment drape and decreases in coralline cover at some locations and not at others are not readily apparent, but may be related to the discharge. Additionally, some of the decreases in percent cover of coralline algae noted at the northern reference stations may be related to increased physical disturbance of the seafloor observed at these locations. We speculate that an increase in anchoring activity of LNG tankers at these stations since 2001 may be responsible for the observed physical disturbances. Additional plots of this data, highlighting some of these trends can be found in Appendix D3.

In contrast to the wide distribution of coralline algae, the distributions of the three upright algae commonly inhabiting the drumlins, the filamentous red alga *Ptilota serrata,* the dulse *Palmaria palmata*, and the shotgun kelp *Agarum cribosum,* were quite restricted. Additionally, their abundances varied quite widely during both the pre- and post-diversion periods. Some of this variability appears to reflect patchiness in the small-scale (within station) spatial distributions of the upright algae. Dense stands of upright algae were frequently seen neighboring areas totally devoid of them. This spatial patchiness may reflect that upright algae were most abundant on the top of larger boulders in areas of moderate to high relief. However, much of the variability observed appears to reflect yearly changes in the abundance of upright algae, rather than changes related to outfall diversion.

Table 6-5. Estimated percent cover of coralline algae from 1996 to 2007. Large differences between pre- and post-diversion are highlighted by shading. Asterisks mark differences that appear to be related to shifts in position of the areas surveyed.

Station	Pre-diversion					Post-diversion						
	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
T1-1	33	42	37	26	16	15	34	28	25	18	10	11
T1-2	67	72	79	36*	79	47	61	67	27	44	32	31
T1-3	90	96	80	83	86	68	69	80	70	38	34	46
T1-4	85	83	82	70*	77	58	71	63	65	32	42	43
T1-5	67*	12	37	37	37	29	35	45	34	17	5	9
T2-1	46	33	9*	35	14	18	39	53	53	13	36	40
T2-2	5	13	33*	13	10	9	28	8	7	8	3	3
T2-3	26	41	39	21	8*	17	23	25	15	6	13	7
T2-4	7	26	18	4	<1	2	12	6	5	4	3	3
T4-1		15*	<1	-	11	1	2					
T4-2	41	53	9*	8*	47	37	28	12	22	11	10	4
T4-3	12	12	56*	25	16	19	41					
T4/6-1	72	67	77	72	71	73	64	66	57	48	54	47
T6-1	2	4	5	2	2	3	3	2	3	<1	<1	<1
T6-2	69*	55	45	29	36	42	56	23	32	14	7	6
Northern reference												
T7-1	65*	43	49	47	52	32	36	39	33	15	17	12
T7-2	52	54	45	36	36	24	28	30	27	8	23	31
T9-1		40	54	28	38	30	36	19	51	11	37	32
Southern reference												
T10-1		12	-	2	3	-	1	0	7	0	0	<1
T8-1		73	74	69	49	58	59	47	50	24	23	38
T8-2	81	75	65	51	58	48	56	59	58	46	52	55
T12-1								63	48	30	33	
Farfield reference												
T11-1								1	8	11	8	5
Diffuser												
Diff #44		-	<1		<1	<1	<1	<1	-	-	-	-
T2-5 (D#2)	<1	<1	<1			-	-	-	-	-	-	-

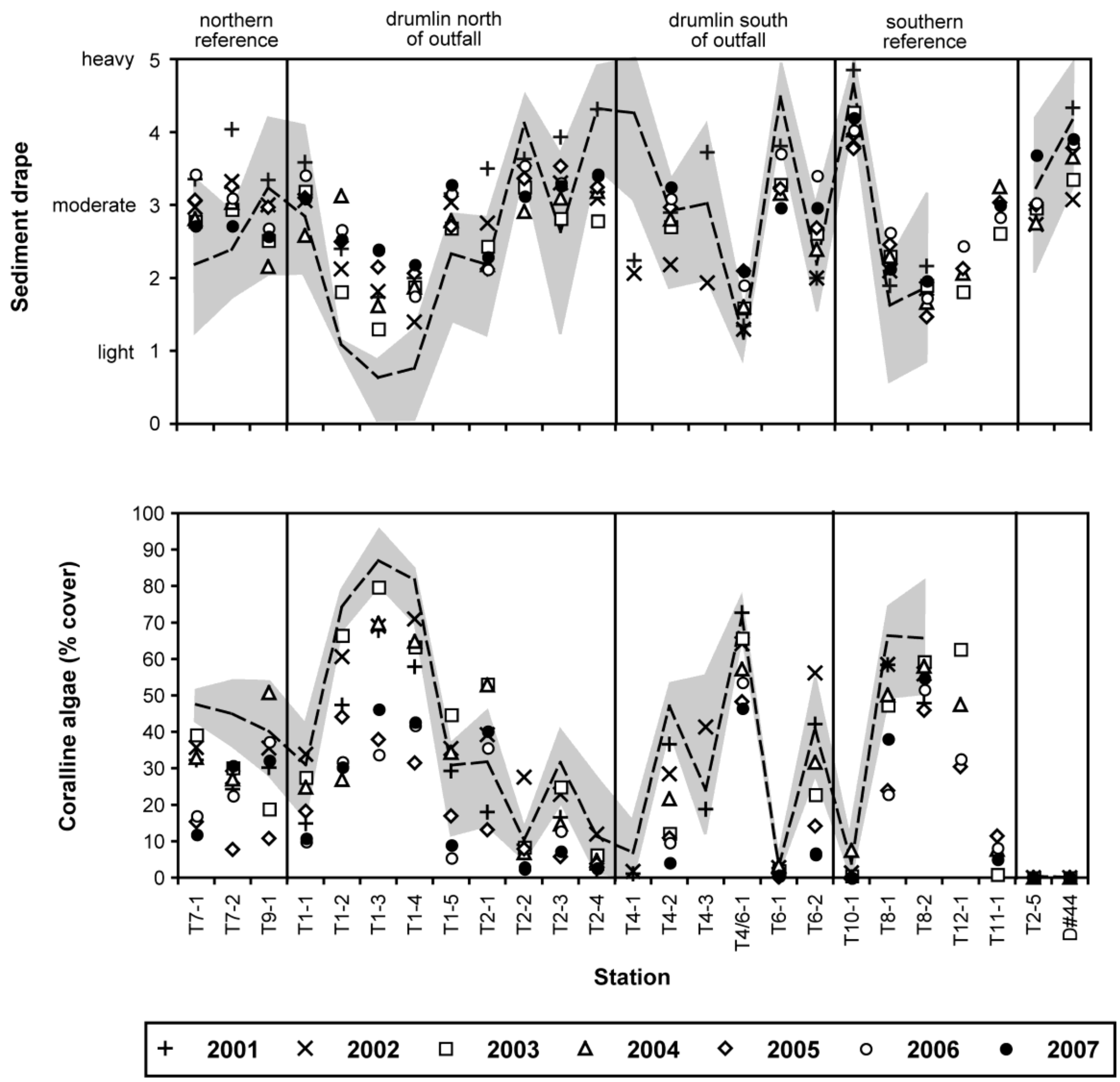


Figure 6-10. Sediment drape and percent cover of coralline algae at the nearfield hard-bottom sites determined from 35-mm slides taken during the 1996 to 2007 surveys. The dashed line shows the mean baseline value and the shaded area shows the range of baseline values.

Upright algae were generally most abundant at the northern reference stations (Figures 6-11 and 6-12). Both *P. palmata* and *P. serrata* were commonly observed at the three northern reference sites (T7-1, T7-2, and T9-1) and on the drumlin immediately north of the outfall (T1-1, T2-2, T2-3, and T2-4). *Palmaria palmata* was most abundant in 1997, decreased in 1998, slowly increased until 2001 or 2002, decreased in 2003, and has remained relatively steady for the last 4 years. On the drumlin immediately north of the outfall, dulse was present but variable at several stations until 2003, when it decreased at all of the stations. Since then it has been increasing again at several of the stations. Dulse has been largely absent from most of the southern stations, though it was abundant at two of them (T4/6-1 and T10-1) in 1997. This alga increased modestly in abundance at the southern reference stations in 2006 and 2007.
In contrast, *P. serrata* was most abundant in 1996 and 1998, and least abundant in 1997 (Figure 6-12). Additionally, the density of this filamentous red alga has declined since 1998 at many of the stations. This algae has never been common at any of the southern stations. In contrast, *Agarum cribosum* had the most restricted distribution of the upright algae, and was abundant only at the northern reference sites. This alga was most abundant at T7-2 where peak numbers were observed in 2000, then rapidly declined in 2001 and 2002, increased again between 2003 and 2006, and disappeared in 2007. The peak density of shotgun kelp in 2000 coincided with the appearance of numerous lacy bryozoans *Membranipora* sp. encrusting many of the kelp fronds. The dramatic decline in shotgun kelp after 2000 may be related to the appearance of this invasive bryozoan, rather than the start of outfall discharge. This algae has been increasing at another northern reference station T7-1 since 2003, and has disappeared at the remaining northern reference site T9-1 since 2002. There does appear to be a general trend of decreased abundances of upright algae over time, particularly since 2003. Again, part of this decrease may be related to the above mentioned physical disturbances noted at the northern reference stations.

One pronounced biotic change was noted in 2003, when dense aggregations of adult barnacles were observed at 13 of the 23 stations. This massive influx of barnacles appeared to reflect a large recruitment event that occurred in the fall of 2002 (Maciolek *et al*. 2004; Appendix D3). By 2004 most of these barnacles had died off because of overcrowding, leaving large surfaces of rocks covered with barnacle bases and valves. Rocks covered with barnacle debris were observed at 11 stations. Two species “newly” observed in 2004 were a frilly white encrusting sponge? and a grey translucent encrusting organism, were seen only on boulders that had previously been colonized by the barnacles. Both of these species were very sparse in 2005 and absent since then. Large numbers of barnacles were observed at three of the stations (T7-1, T2-1, and T6-2) in 2007.

The total number of species seen on the still photographs at each of the stations does not appear to have been impacted by diversion of the outfall (Figure 6-13). The number of species seen during the post-diversion period was well within the range of species seen pre-diversion at most of the stations. Additionally, the number of species observed at many of the stations was higher than in most of the previous years. However, part of this may reflect better species discrimination in recent years. Deep drumlin flank stations tended to support fewer species than drumlin top stations. The fewest species were generally seen at the two diffuser stations.

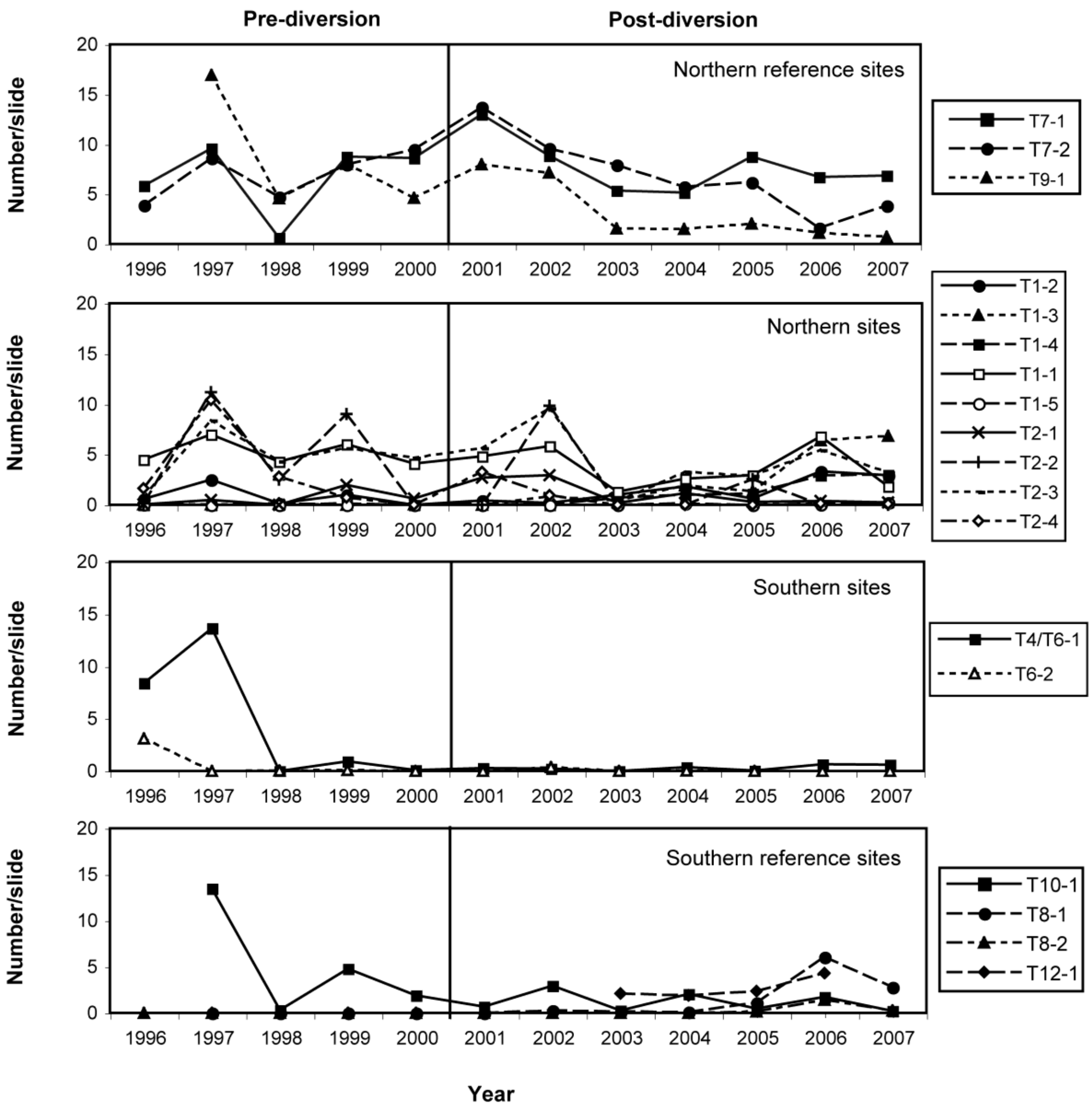


Figure 6-11. Abundance of dulse *Palmaria palmata* over time at the nearfield hard-bottom sites, as determined from 35-mm slides taken during the 1996 to 2007 surveys.

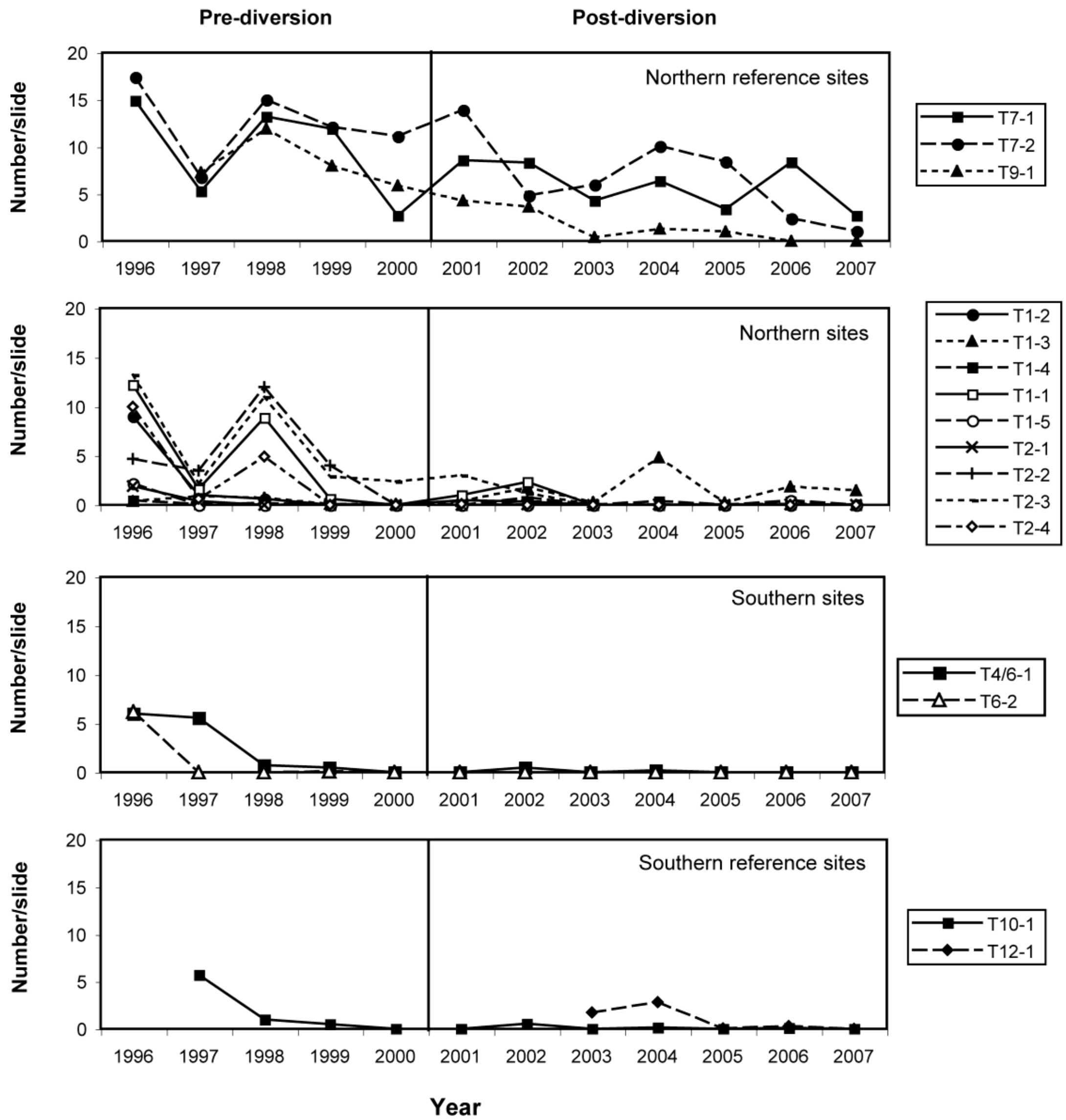


Figure 6-12. Abundance of the filamentous red alga *Ptilota serrata* over time at the nearfield hard-bottom sites, as determined from 35-mm slides taken during the 1996 to 2007 surveys.

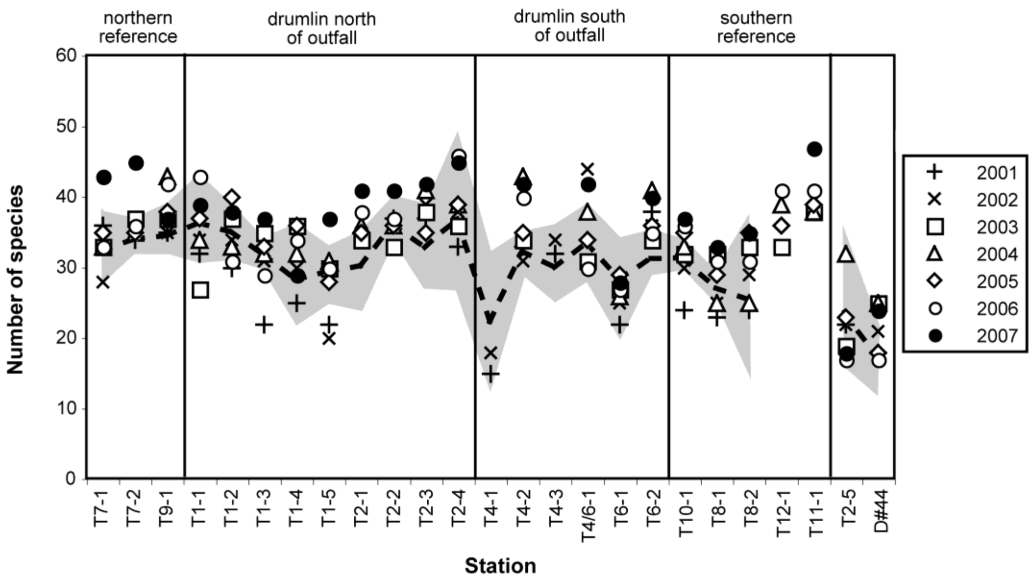


Figure 6-13. Total number of species seen on still photographs collected at the nearfield hard-bottom sites during the 1996 to 2007 surveys. The dashed line shows the mean baseline value and the shaded area shows the range of baseline values.

Figure 6-14 shows the results of hierarchical classification of data collected from still photographs taken during the 1996 to 2007 time period. The clustering structure appeared to be controlled by a combination of geographic location and topography, and to a lesser degree by time period. Several smaller groupings of stations also appeared to reflect yearly differences. The stations grouped into ten clusters of stations joined by one individual station. The overwhelming structuring factor appeared to be geographic location with neighboring stations frequently clustering together or different years of the same station clustering together. Examples of this can be seen in: cluster 1 which consisted largely of northern reference stations (T7-1, T7-2, and T9-1); the two largest groups in cluster 2 which consisted mainly of southern reference stations (T8-1 and T8-2) and nearfield drumlin top stations (T1-2, T1-3, T1-4, and T4/6-1), respectively; cluster 5 which consisted of southern reference station T10-1; cluster 9 which consisted of diffuser stations (T2-5 and D#44); and cluster 10 which consisted of a deep drumlin flank station (T4-1). Some cluster groups were comprised of both pre- and post-diversion years, while others consisted mainly of years from one diversion period. The first group in cluster 1 consisted of both pre- and post-diversion years, while the remaining groups in this cluster consisted entirely of pre-diversion years. The groups in cluster 2 consisted of both pre- and post-diversion years. In contrast, cluster 3 consisted almost exclusively of post-diversion years, with several of the groups consisting only of the last three years. The subtle grouping of stations by diversion period may reflect minor shifts in benthic communities due to outfall diversion, or it may merely reflect changes in benthic communities over time. It is interesting to note that the northern (first group in cluster 1) and southern reference stations (second group in cluster 2), and the nearfield drumlin top stations (fourth group in cluster 2) generally do not separate on the basis of diversion period, while some of the stations on the flanks of drumlins nearer the outfall do separate into pre- and post-diversion periods.

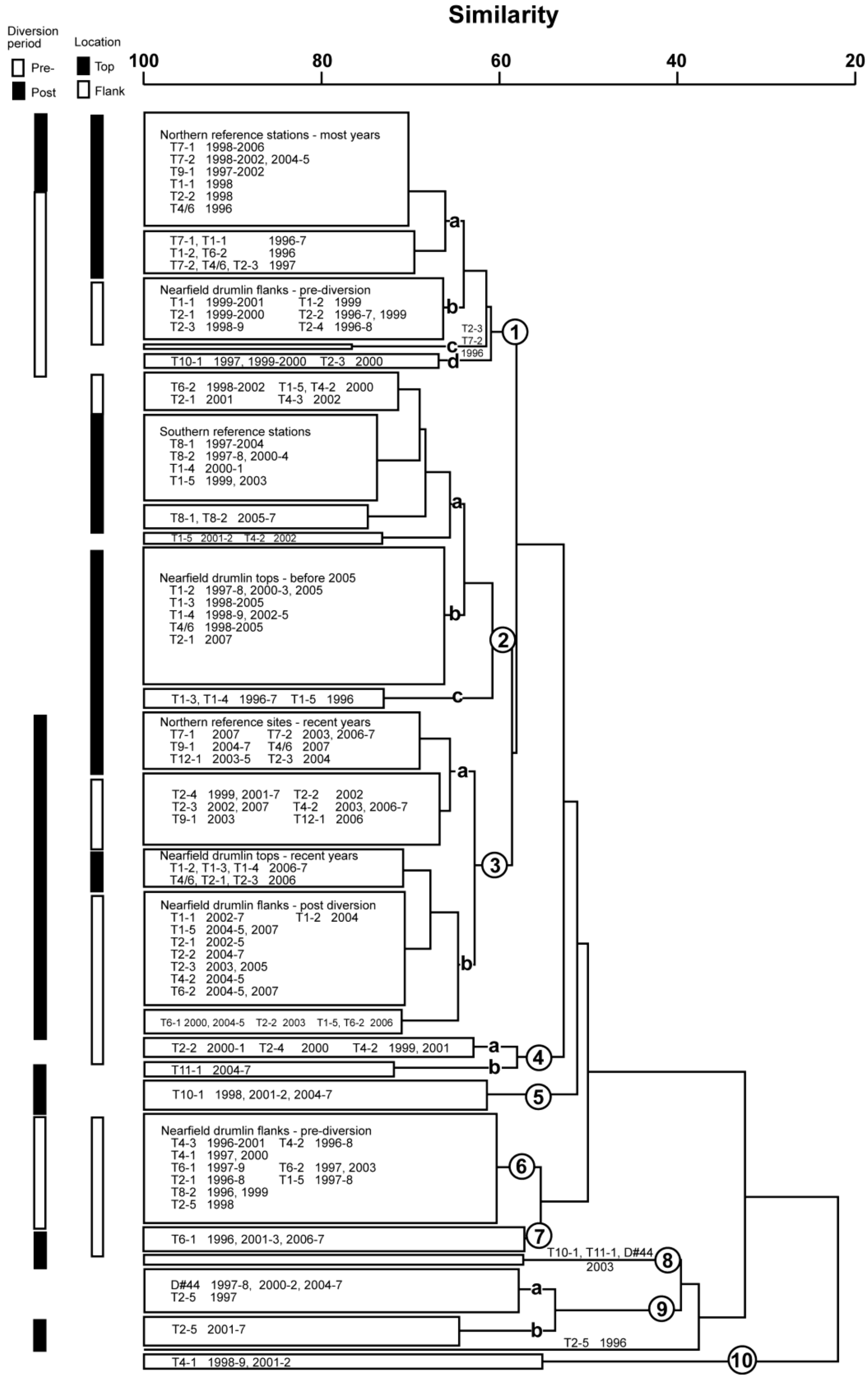


Figure 6-14. Summarized cluster analysis of data collected from still photographs taken during the 1996 to 2007 nearfield hard-bottom surveys. Location, topography, and diversion period are noted for cohesive clusters.

Table 6-6 shows the dominant species that control much of the clustering structure. Stations in the first two clusters (clusters 1 and 2) supported moderate to high numbers of coralline algae, while the remaining clusters (clusters 3 to 10) only supported few or none. These stations also supported many mussels. Areas in cluster 2 (mainly southern reference stations and drumlin top stations near the outfall) supported the most coralline algae, while those in cluster 1 (mostly northern reference stations) supported fewer coralline algae. Not surprisingly most of the stations in cluster 1 were the only stations that supported substantial numbers of upright algae (namely *Ptilota serrata* and *Palmaria palmata*). The stations in the remaining clusters all supported few if any upright algae. The stations in cluster 3 (recent years at varying locations) supported the relatively few coralline algae, but did support numerous invertebrates. The stations in cluster 3 also supported northern white crust tunicates (*Didemnum albidum*), while the stations in cluster 2 supported another tunicate (*Aplidium* sp.). Cluster 4 consisted of the farfield southern reference station T11-1 and some flank stations, which supported few coralline algae, many brachiopods (*Terebratulina septentrionalis*), as well as numerous encrusting taxa. Cluster 5 consisted of southern reference station T10-1, which supported only trace amounts of coralline algae, but numerous red soft corals *Gersemia rubiformis*, seastars, and fish (the cunner *Tautogolabrus adspersus*). The stations in cluster 6 consisted of drumlin flank stations that had relatively few coralline algae and no other distinctive taxa. Cluster 7 consisted of a flank station T6-1 that was quite depauperate. Cluster 8 consisted of three stations from 2003, when dense aggregations of adult barnacles (*Balanus* spp.) were encountered following a major settlement event in fall of 2002. Cluster 9 consisted of the two diffuser stations, with the active diffuser (T2-5) clustered separately from the inactive diffuser (D#44). The frilled anemone *Metridium senile* was the dominant inhabitant of the active diffuser head, while the sea peach tunicate *Halocynthia pyriformis* was the dominant inhabitant of the inactive diffuser head. Finally cluster 10, which consisted entirely of flank station T4-1 was generally quite depauperate during all the years that it was surveyed (it was dropped from the program in 2003) and supported relatively few taxa. This was the only station where the burrowing anemone *Cerianthus borealis* and the sea scallop *Placopecten magellanicus* were routinely encountered.

Figure 6-15 shows the NMDS analysis of the 1996 to 2007 data. The stations in clusters 8 (the 2003 barnacle settlement), 9 (diffuser stations), and 10 (depauperate flank station, T4-1) separated away from the main grouping of stations. Additionally, the one outlier to clusters 8 and 9 (T2-5 in 1996) also clustered separately from the main group. Clusters 5 (T10-1 with high relief and a relatively unique community), 6 (pre-diversion nearfield flank stations), and 7 (deeper, low relief flank station) also separated somewhat from the other clusters, with a little spatial overlap with adjacent clusters. In contrast, the remaining clusters (clusters 1 to 4) had a fair amount of spatial overlap in the NMDS space with neighboring clusters. The overlap of stations indicates that the two-dimensional NMDS does not provide a good solution for the data. This lack of a good fit to the data is also shown by the stress value of 0.17. The stress indicates the degree to which the data does not fit the solution provided by the NMDS space. Generally stress values below 0.1 provide good solutions with little chance of misinterpretation. Results with stress values between 0.1 and 0.2 are still useful but require more care in interpretation. The data was also run in a three-dimensional NMDS space, which provided a better solution with a stress value of 0.12. However, clear graphic representation of the stations in three dimensions was not feasible.

Several points illustrated by the NMDS analysis were notable. Different years at a station were frequently close in NMDS space, even if they were in different clusters. A good example of this can be seen at the boundary between clusters 6 and 7, where three years at station T6-1 were in cluster 6 yet were in close proximity to the cluster 7 space (mostly T6-1 from other years). Numerous other instances of this phenomenon were also noted. Another interesting observation was a subtle shift of points representing the post-diversion period toward the upper right of the NMDS space. This shift may reflect subtle long-term changes in fauna over time or it may reflect changes due to outfall diversion. This shift in NMDS space may represent the decrease in coralline algae observed over time, since stations with high percent cover of coralline algae (cluster 2c) were located toward the bottom left of the ordination space.

Table 6-6. Abundance (mean number per slide) of selected taxa in clusters defined by classification analysis of hard-bottom stations from 1996 to 2007. Numbers indicating major differences among clusters are highlighted by shading.

Cluster	1	2	3	4	5	6	7	8	9	10
Average similarity (percent)	66.3	66.69	65.94	63.53	66.16	63.28	66.14	59.47	60.43	59.66
Coralline algae	**6.97**	**13.62**	**4.41**	**2.31**	-	5.29	0.67	-	-	0.34
Palmaria palmata	**5.66**	-	1.14	-	1.00	-	-	-	-	-
Ptilota serrata	**5.34**	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-	-	-
juvenile *Asterias*	**3.65**	**4.33**	**4.80**	**2.28**	**2.72**	**2.13**	**2.16**	0.85	1.74	0.59
Modiolus modiolus	**2.82**	**3.28**	1.66	1.35	1.56	0.37	0.30	-	-	-
Aplidium spp.	0.76	**1.82**	0.86	-	-	0.59	0.59	-	-	-
Didemnum albidum	0.98	0.98	**4.33**	0.44	2.22	-	0.67	0.32	-	-
orange/tan encrusting sponge	1.12	1.12	**2.43**	**2.66**	0.98	1.12	0.90	**2.10**	-	-
orange encrusting sponge	0.86	0.69	**1.42**	**1.00**	0.98	0.22	-	-	-	-
Terebratulina septentrionalis	-	-	1.82	**5.43**	-	-	-	-	-	-
white divided sponge	-	-	-	**2.43**	-	-	-	-	-	-
Gersemia rubiformis	-	-	-	-	**4.80**	-	-	-	-	-
Asterias vulgaris	1.14	1.04	1.59	0.38	**2.79**	0.36	0.30	0.81	0.53	0.07
Polymastia sp. A	-	-	-	-	**1.19**	-	-	-	-	-
Dendrodoa carnea	0.61	0.94	0.88	-	-	0.16	-	-	-	-
Myxicola infundibulum	0.35	-	0.42	0.28	-	-	-	-	-	-
Strongylocentrotus droebachiensis	-	0.52	-	-	-	-	-	-	-	-
Psolus fabrici	-	0.45	-	-	-	-	-	-	-	-
Henricia sanguinolenta	-	-	1.08	0.66	-	0.41	0.83	-	0.90	0.35
Suberites spp.	-	-	-	0.66	-	0.18	-	-	-	-
Aplysilla sulphurea	-	-	-	0.40	0.45	-	-	-	-	-
Arctica islandica	-	-	-	-	-	-	0.29	-	-	-
Balanus spp.	-	-	-	-	-	0.74	-	**56.55**	-	-
Metridium senile	-	-	-	-	-	-	-	**5.02**	**32.26**	-
Halocynthia pyriformis	-	-	-	-	-	-	-	2.31	**5.11**	-
Placopecten magellanicus	-	-	-	-	-	-	-	-	-	**0.41**
Tautogolabrus adspersus	1.46	1.12	1.51	0.22	**3.42**	0.17	-	1.10	1.19	-

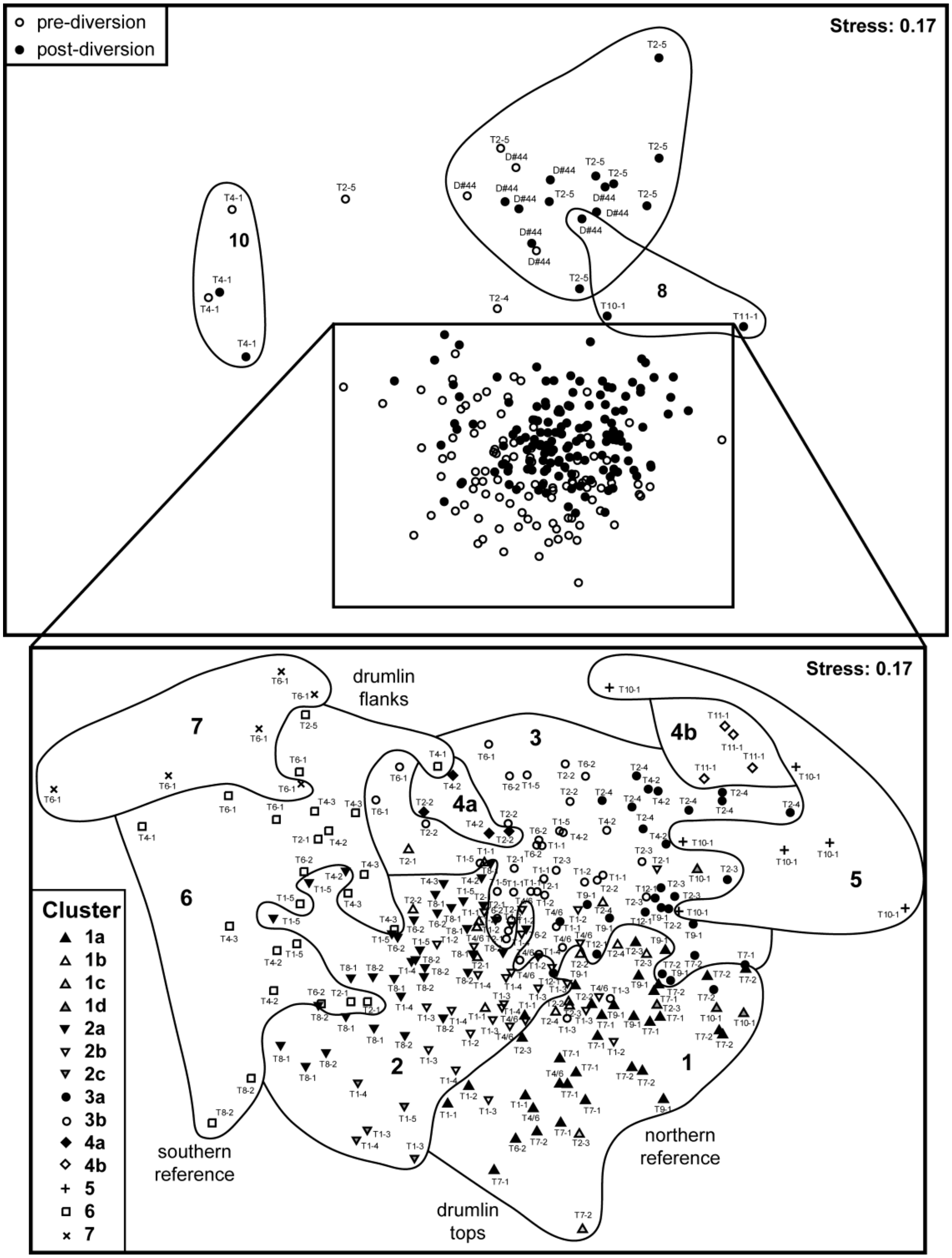


Figure 6-15. Non-metric multidimensional scaling plot of data collected from still photographs taken during the 1996 to 2007 nearfield hard-bottom surveys, with cluster designations from hierarchical classification superimposed.

The strong influence of geographic location and topography on the clustering structure can best be seen in Figure 6-16, which shows the station locations plotted in the NMDS space. Cluster 1 clearly consisted mainly of northern reference stations. Additionally, the few northern reference stations in cluster 3 were near the border between the two clusters. Cluster 2 consisted mainly of drumlin top stations and two of the southern reference stations (T8-1 and T8-2). Cluster 5 consisted exclusively of the high relief southern reference station T10-1. Additionally, the few years at station T10-1 that clustered with other stations were located near the NMDS space occupied by cluster 5. Clusters 3, 6 and 7 mainly consisted of drumlin flank stations, with most of the pre-diversion flank stations in clusters 6 and 7 and most of the post-diversion flank stations in cluster 3. Half of cluster 4 (4a) consisted of flank stations, while the other half (4b) consisted of farfield reference station T11-1.

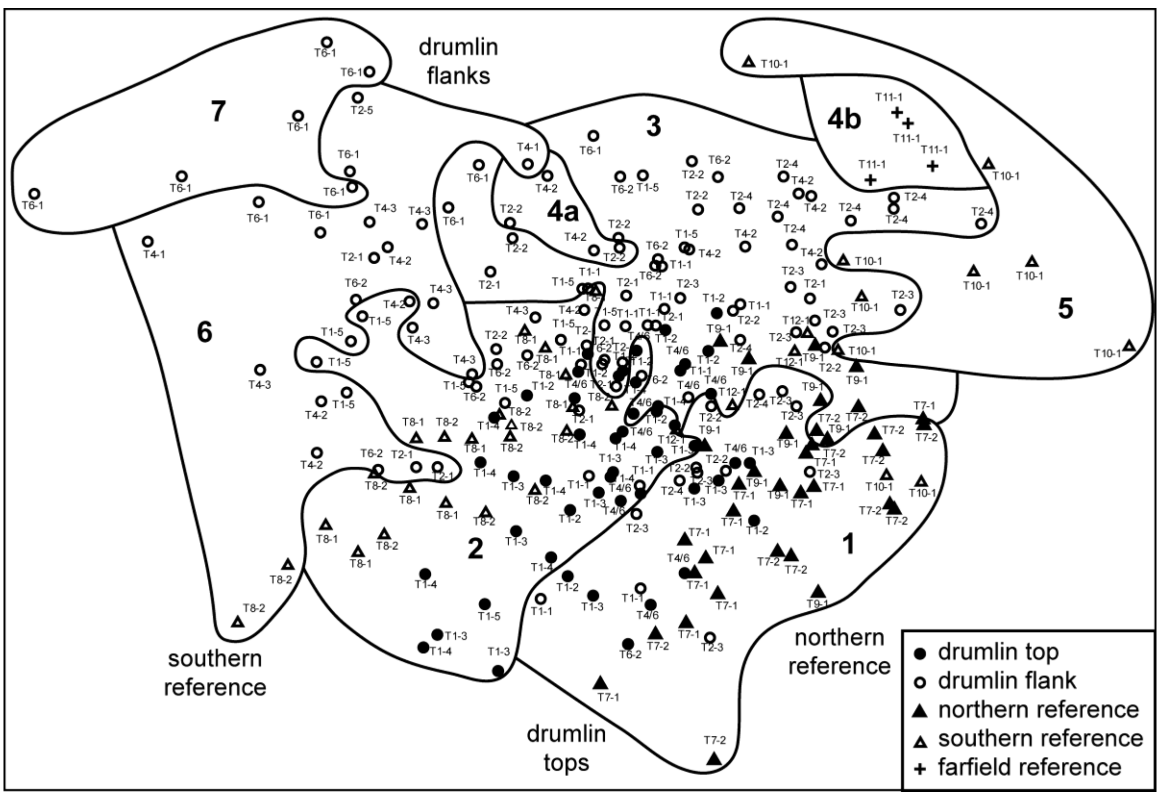


Figure 6-16. Station location plotted in non-metric multidimensional scaling space of data collected from still photographs taken during the 1996 to 2007 nearfield hard-bottom surveys, with space occupied by clusters defined from hierarchical classification superimposed.

The benthic communities inhabiting the hard-bottom areas have been relatively stable over the years, with many of the sites remaining unchanged from year to year. Figure 6-17 shows a map of the cluster designations of the hard-bottom stations over time. The benthic communities at both the northern (T7-1, T7-2, and T9-1) and southern (T8-1 and T8-2) reference stations have remained quite stable, with communities at the northern stations consistently dominated by upright algae and communities at the southern stations consistently dominated by coralline algae. The shift in cluster designation at the northern reference sites from cluster 1 to cluster 3 reflects the decrease in upright algae during the last five years at T9-1, and the last 2 years at T7-2. These changes may reflect the physical disturbances (possibly from LNG tanker anchorages) noted at the northern reference in recent years. The shallow drumlin top stations north (T1-2, T1-3, and T1-4) and south (T4/6-1) of the outfall have also remained relatively stable during both the pre- and post-diversion periods. Benthic communities at these stations have consistently been dominated by coralline algae, even though coralline algae has been decreasing over time (shifting from cluster 2 to cluster 3). The benthic communities inhabiting the flank stations appear to be slightly more variable over time. However, this may just partially reflect greater spatial heterogeneity in terms of habitat characteristics. Additionally, the close proximity of different years of these stations on the NMDS plot indicates that the benthic communities have not changed substantially over time. One flank station that has remained quite stable was T6-1, a low-relief deep station south of the outfall, which supports a relatively depauperate fauna. No consistent shifts in community structure could be detected when comparing the pre- and post-diversion periods.

The taxa inhabiting the diffuser heads of the outfall have remained stable over time and did not change when the outfall went on line. The diffuser heads continue to provide suitable substrate for many frilled anemones (*Metridium senile*) and sea peach tunicates (*Halocynthia pyriformis*). The different cluster designation of T2-5 in 1998 occurred because the diffuser head was not found that year and only the surrounding sediment and riprap were surveyed. The differing cluster designation of Diffuser #44 in 2003 reflected the large barnacle settlement event, where the entire top of the diffuser head was covered by barnacles. By 2004 the barnacles had all died and the community reverted to being dominated by sea peach tunicates. Additionally, the riprap in the immediate vicinity of the diffuser heads continues to be colonized by a variety of encrusting organisms.

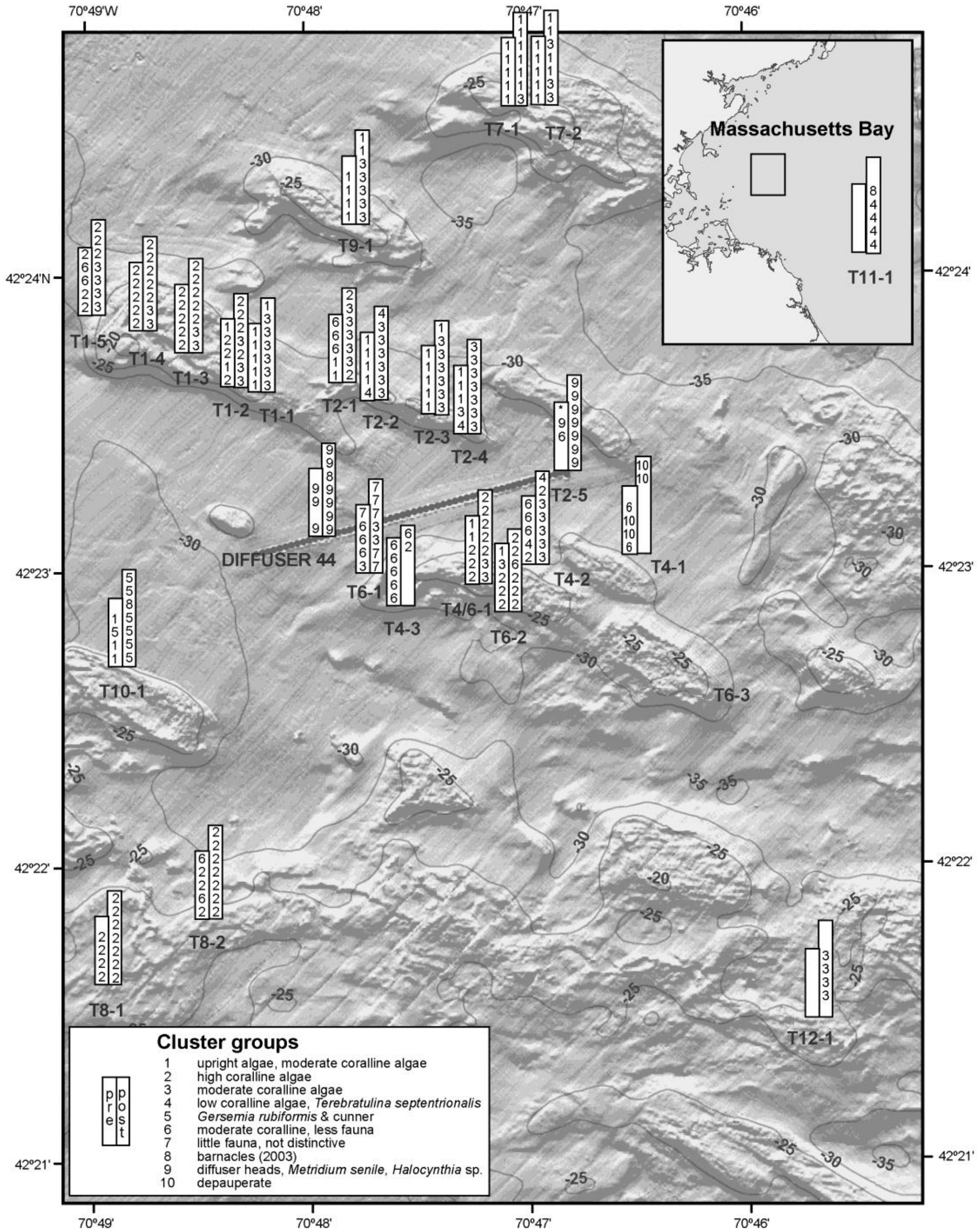


Figure 6-17. Benthic communities defined from classification of the 35-mm images taken during the 1996 to 2006 nearfield hard-bottom surveys. Bars show the successive years in the pre- and post-diversion periods. Asterisks indicate no cluster designation.

Table 6-7, which includes only stations sampled every year, highlights several trends that appear to reflect widespread temporal changes in the population structure of individual taxa that have been noted over the time course of the nearfield hard-bottom surveys. These changes do not appear to be related to the outfall discharge, since they started before the outfall went on line and have continued since that time. Abundances of the green sea urchin *Strongylocentrotus droebachiensis* appear to follow a cyclical pattern, declining from 0.83 individuals per photograph in 1996 to 0.25 individuals per photograph in 2000, then increasing slightly in 2001 and 2002 (0.31 and 0.37 individuals per photograph, respectively), and again decreasing between 2003 and 2007 (<0.21 individuals per photograph). Two other species, the crab *Cancer* sp. and the lobster *Homarus americanus*, increased until 2002 and 2003, respectively, and then started decreasing. In the still photographs, *Cancer* crabs increased from one to six individuals seen annually between 1996 and 1999, to 63 individuals seen in 2002, decreased in 2004 and 2005, and increased again in 2006 and 2007. A similar pattern was reflected in the video data, with 3 to 15 *Cancer* crabs observed annually between 1996 and 1999, increasing to 168 individuals in 2002, and decreasing again in 2004 to 2007. The video data for lobsters showed a similar trend, with the highest numbers of lobsters being seen in 2002, 2003, 2006, and 2007. With the exception of 2003, the number of cod observed during these surveys has steadily increased over time, with the highest number of cod observed during the post-diversion period. Prior to the outfall going on-line, no cod had been seen at the diffuser stations, yet in all post-diversion years cod have been seen in the vicinity of both the active (Diffuser #2 at T2-5) and inactive (Diffuser #44) heads. Interestingly, the codfish appear to be behaving differently at the outfall than at the other hard-bottom stations. At most of the stations codfish tend to shy away from the ROV, usually ducking behind large boulders, but at the diffuser sites they were much less hesitant and occasionally came right up to the vehicle. The presence of numerous cod in the vicinity of the outfall was particularly noticeable during a visual structural survey of the diffuser heads that was conducted in June of 2003, where the presence of codfish was frequently used as an indicator of proximity to an actively discharging diffuser head. Cod have also become much more wide-spread away from the outfall.

6.4 Monitoring Question

Has the hard-bottom community changed? (Question #30)

The hard-bottom benthic communities near the outfall remained relatively stable over the 1996 to 2000 baseline time period, and have not substantially changed with activation of the outfall in fall 2000. Major departures from baseline conditions have not occurred during the post-diversion years, however some modest changes have been observed. A decrease in the number of upright algae has been observed at many of the stations. However, it is unlikely that this decrease was attributable to diversion of the outfall, since the general decline had started in the late 1990’s and the number of upright algae appears to be increasing again at a number of stations. The decline has been quite pronounced at the northern reference stations and may reflect physical disturbance of the seafloor. A likely cause of the observed disturbance is an increase in anchoring intensity of LNG tankers at these locations after 2001. Disturbance of the seafloor in the form of overturned boulders and areas of shell lag has been noted at T7-1 and T7-2 in the last several years. Abundances of upright algae were found to be quite variable throughout the baseline period, reflecting temporal changes in abundance as well as spatial heterogeneity in habitat characteristics. Some of the variability has continued into the post-diversion period and may also reflect inherent cyclical changes.

Table 6-7. Number of individuals of selected species observed during the nearfield hard-bottom surveys, adjusted to include only stations that were surveyed in all 11 years (with the exception of two stations added after 1996).

	Pre-discharge					**Discharge**						
	1996*	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**
Video												
Minutes of video	438	487	439	422	444	448	495	469	454	466	419	440
Cancer spp. (rock crab)	6	3	4	15	92	123	168	144	115	67	81	108
Gadus morhua (cod)	-	6	12	22	11	41	53	10	52	64	59	40
Homarus americanus (lobster)	6	2	11	4	18	21	31	33	12	10	35	36
Still Photographs												
Number of photographs	534	622	635	551	635	583	672	661	675	664	666	661
Strongylocentrotus droebachiensis	444	339	282	299	157	180	249	90	113	82	145	116
Cancer spp. (rock crab)	4	1	4	6	14	44	63	47	16	22	56	49
Gadus morhua (cod)	-	-	2	3	-	9	12	-	3	17	5	19
Homarus americanus (lobster)	1	-	3	3	5	4	13	6	5	9	19	15

* did not include T9-1 and T10-1

Another discharge change that has been observed in the hard-bottom communities has been an increase in sediment drape, and a concurrent decrease in percent cover of coralline algae, at several sites on the top of the drumlin north of the outfall and at the two northernmost reference sites (Figure 6-18). The decrease in coralline algae has been noticeable in all six post-diversion years. Additionally, in 2005 this decrease was more pronounced and extended to eight additional stations, located both north and south of the outfall. The dramatic decreases first observed in 2005 were not accompanied by concurrent increases in sediment drape and have extended into 2007. The baseline data indicated that coralline algae was the most promising indicator species for detecting habitat degradation as a result of the outfall coming on line. It was the most predictable taxon encountered in terms of abundance, distributional pattern, and habitat requirements. Coralline algae was the least patchily distributed taxon, dominated in all areas that were shallower than 33 m and had little sediment drape, and was common in areas of both high and low relief. Mechanisms relating the decrease in coralline algae to outfall diversion are not as clear, since the impact was noted further from the outfall rather than nearby. It is quite possible that some of the decreases in coralline algae noted at the northern reference stations are related to physical disturbance of the seafloor at these stations. In contrast, the decreases in percent cover of coralline algae at the stations closer to the outfall may be related to the diversion, since no disturbance to the seafloor has been noted at these stations. However, it is also possible that we are observing long-term changes in sedimentation, and hence coralline algae, patterns. No similar decline of percent cover of coralline algae was observed at another location at 27 m in Massachusetts Bay in 2005 or 2006 (Hecker, personal observation).

The outfall might be expected to alter the amount of particulate material reaching the seafloor. A continued increase of sediment drape, and/or a continued decrease in the percent cover of coralline algae might be expected if the discharge from the outfall were causing accumulation of materials in the vicinity of the drumlins. Changes might also be expected in the depth distribution of coralline algae and upright algae if discharges from the outfall alter properties of the water column that affect light penetration. If water clarity is reduced it is expected that the lower depth limit of both coralline and upright algae would be reduced. Conversely, if water clarity were increased, then it is expected that high coralline algal coverage or upright algae could extend into some of the deeper areas. No noticeable changes in the depth distribution of coralline algae have been observed since discharge began. Additionally, the decline observed in the numbers of upright algae in recent years appears to be reversing.

The first seven years of discharge monitoring, have shown modest changes suggestive of outfall impact at a subset of five stations, and some additional subtler changes at a number of other stations. However, two of the five stations in this subset may have been compromised as "reference" stations by physical disturbance of the seafloor. The most likely cause of the observed physical disturbance at these sites would be post 2001 increases in the frequency of LNG tankers anchoring at these sites. Evidence of substantial disturbance to the seafloor, such as turned over boulders and areas of shell lag, were observed at northern reference sites T7-2 in 2006 and T7-1 in 2007. Lush epifaunal growth continues to thrive on the diffuser heads surveyed for this study and throughout many of the other stations visited. However, despite the fact that outfall impacts appear to be minimal at this time, changes in the hard-bottom communities could be chronic and/or cumulative, and may take a longer time to manifest themselves.

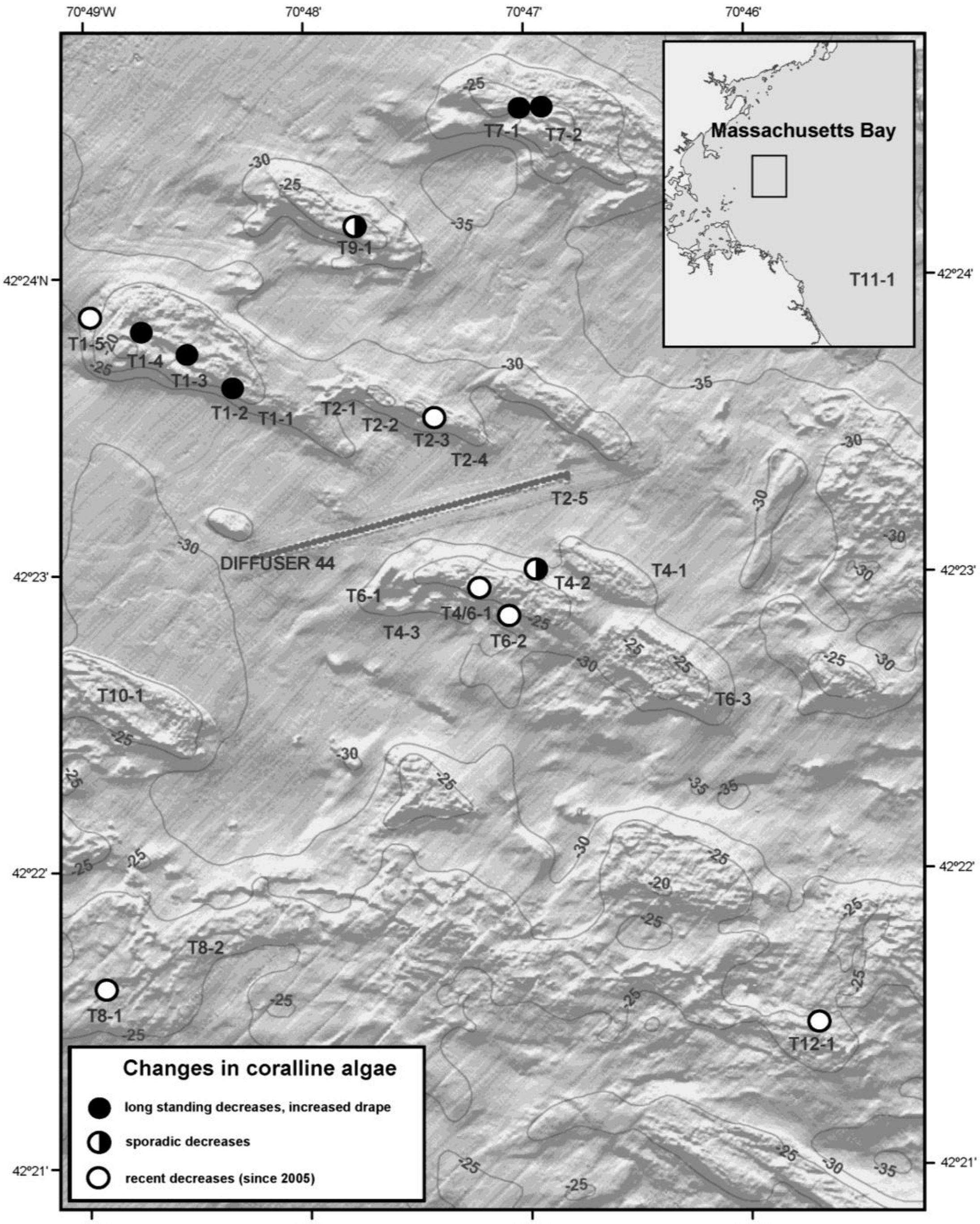


Figure 6-18. Map of changes observed in percent cover of coralline algae.

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