2005 Boston Harbor benthic monitoring report

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EXECUTIVE SUMMARY

The direct discharge of waste products into Boston Harbor has had a profound impact on the composition of biological communities in the harbor. Most pollutants are particle reactive; therefore the sediments become the final sinks for these pollutants and represent the part of the ecosystem where disruption by toxic or enrichment effects is expected. Surficial sediments are critical to many ecosystem functions with energy flows (organic carbon, living biomass, secondary production) and nutrients (nitrogen, phosphorus) regulated by processes at the sediment-water interface. Thus, characterization of the benthic environment from physical and biological points of view has been a key part of the MWRA long-term sediment monitoring within Boston Harbor. As the MWRA improved the quality of the discharge and then diverted it to the new offshore outfall in September 2000, monitoring was conducted twice a year, in April and August, to track changes in the sediments and the biological communities. In 2003, sampling was reduced to once a year (August), and in 2004, an additional station was added in the inner harbor near a Combined Sewer Overflow (CSO). All stations were reoccupied in August 2005.

An unusually low TOC content was measured at T03 in 2005, and TOC content at many harbor stations in 2005 were among the lowest, or were the lowest, measured values during the monitoring period (1991–2005, August/September surveys). A corresponding coarsening of grain-size (from loss of fines) was also observed in 2005 at harbor station T08, and to a lesser extent at T01 and T03. The reduced TOC content and coarsening of grain size is likely associated with sediment bed disturbance resulting from the May 2005 nor'easter, the strongest late May winterlike nor'easter since 1967. Since 1991, TOC content has decreased significantly at T01 and T03, suggesting a reduction in carbon loading to the northern harbor consistent with the improvements to wastewater treatment practices.

Clostridium perfringens, an anaerobic bacterium found in the intestinal track of mammals, is one of the most commonly used tracers of sewage-derived sources in marine systems. Abundance of *C. perfringens* (normalized to percent fines) has decreased significantly in harbor sediments over time (1991–2005), indicating that actions taken by the Massachusetts Water Resources Authority to minimize wastewater impacts to Boston Harbor have improved the quality of sediment in the harbor.

In August 2005, 123 species of benthic infauna occurred in the samples, including four species that were recorded in the harbor for the first time. These four species included two polychaetes, *Euclymene collaris* and *Scolelepis foliosa* (previously reported as *S.* nr. *tridentata*), one isopod, *Pleurogonium rubicundum*, and one gastropod, *Boonea seminuda*, which is also newly reported for the MWRA Massachusetts Bay/Boston Harbor database. For the period 1991–2005, 255 identified species have been recorded in the summer samples.

Values of all benthic community parameters, including density, species richness, Shannon diversity, evenness, and log-series *alpha*, declined in the harbor overall in 2005 compared with 2004. Mean Shannon diversity declined at five (T01, T02, T04, T07, and CO19) of the nine stations, in some cases significantly so (T02, T04, T07, CO19). At T03, T05A, and T06, where amphipods were absent, and densities and species richness were also lower, and at T08 where these parameters were similar between 2004 and 2005, the Shannon diversity was similar to that recorded in 2004. Mean Shannon diversity was lowest at CO19 (0.34±0.04) and T04 (0.79±0.24) and highest at T08 (3.85±0.39), a pattern similar to that recorded in previous years. Diversity as measured by Fisher's log-series *alpha* declined at all nine stations in 2005 (Figure 5-2). Earlier station patterns were repeated in 2005: the lowest mean value was recorded at CO19 (1.99±0.20) and T04 (2.68±0.19) and the highest at T05A (9.79±0.59) and T08 (10.60±2.40).

The occurrence, spread and retreat of *Ampelisca* tube mats has been followed closely. Because members of this genus are considered (by some) to be indicative of clean environments, population levels of *Ampelisca* have been considered key in following the status of the infaunal community of the harbor. Reish and Barnard (1979) found that slight increases in organic matter resulted in increased amphipod abundance, but beyond a certain level, amphipod numbers decreased. In 2005, amphipods were essentially absent from the grab samples, and tube mats were not detected with SPI. The decline in amphipod populations from a high in 2003 to virtual absence in 2005 is possibly partially attributable to the storms recorded in December 2003, December 2004, and May 2005, which affected the bottom substrate, altering the sediment texture and bottom habitats. Additionally, the reduction of available particulate organic carbon in recent years may be a contributing factor.

Long-term Patterns: Has the Harbor Changed?

Taylor (2005) summarized the major patterns in freshwater flows and loadings of total nitrogen (TN), total phosphorus (TP), total suspended solids (TSS), and particulate organic carbon (POC) to Boston Harbor between 1995 and 2003. He found three periods, which were related to the timing of improvements to the wastewater treatment in the harbor: Period A, from 1995 through mid-1998, Period B, from mid-1998 to 2000, and Period C, which began in 2000 with the September transfer of the discharge to the new offshore outfall.

Benthic community parameters, including total abundance, species richness, *Ampelisca* per sample, and diversity as measured by log-series *alpha*, were evaluated according to Taylor's periods (Table 1). Although all community parameters declined in 2005, the differences among the three periods indicate that as improvements have been made to wastewater treatment, there has been a harbor-wide increase in species richness and diversity. Detailed analyses of the infaunal communities at the individual stations, as well as other lines of evidence, such as the decrease in levels of the sewage marker *Clostridium perfringens* strongly support the conclusion that the benthic environment in the harbor is indeed recovering from decades of pollutant input.

Table 1. Benthic community characteristics for Boston Harbor grab stations summarized by time periods defined by Taylor (2005).

Parameter	Period		
	A	B	C
	1991–1998	1999–2000	2001–2005
	n = 192	*n*= 47	*n* = 120
Number of Species	32.3 ± 14.3	32.0±12.5	42.3 ± 18.0
H′	2.3 ± 0.9	2.8 ± 0.8	2.9 ± 0.8
log-series *alpha*	5.2 ± 2.1	5.9 ± 1.9	7.7 ± 3.0
Rarefaction curves (Figure 5-9)	low	high	highest
Fauna	higher abundances of opportunistic species such as *Streblospio benedicti* and *Polydora cornuta*		fewer opportunists, more oligochaetes, some species from Massachusetts Bay.

1. INTRODUCTION

1.1 Background

1.1.1 History of Discharges to Boston Harbor

Boston Harbor has had a long history of anthropogenic impacts dating back at least to colonial times (Loud 1923). In addition to the damming of rivers and the filling of salt marshes and shallow embayments to create the present footprint of the city, the direct discharge of waste products has had a profound impact on the composition of the biological communities in the harbor. Prior to the 1950s, raw sewage was discharged into Boston Harbor primarily from three locations: Moon Island, Nut Island, and Deer Island. In 1952, the Nut Island treatment plant became operational and began treating sewage from the southern part of Boston's metropolitan area. The Deer Island treatment plant was completed in 1968, thus providing treatment for sewage from the northern part of the area. (The third location, Moon Island, was relegated to emergency status at that time and not used routinely thereafter.) The effluent was discharged continuously from both plants; an annual average of 120 million gallons per day (MGD) from Nut Island and 240 MGD from Deer Island. Storm events caused up to 3.8 billion gallons per year (BGY) of additional material to be occasionally discharged to the harbor through the system of combined sewer overflows (CSOs) (Rex *et al.* 2002).

Sludge, which was separated from the effluent, was digested anaerobically prior to discharge. Digested sludge from Nut Island was pumped across Quincy Bay and discharged through an outfall near Long Island on the southeastern side of President Roads. Sludge from Deer Island was discharged through that plant’s effluent outfalls on the northern side of President Roads. Sludge discharges were timed to coincide with the outgoing tide, under the assumption that the tide would carry the discharges out of the harbor and away offshore. Unfortunately, studies have shown that the material from Nut Island often was trapped near the tip of Long Island and carried back into the harbor on incoming tides (McDowell *et al.* 1991).

In 1972, the Federal Clean Water Act (CWA) mandated secondary treatment for all sewage discharges to coastal waters, but an amendment allowed communities to apply for waivers from this requirement. The metropolitan Boston area’s application for such a waiver was denied by the US Environmental Protection Agency (EPA), partly on the basis of the observed degradation of the benthic communities in Boston Harbor. In 1985, in response to both the EPA mandate to institute secondary treatment and a Federal Court order to improve the condition of Boston Harbor, the Massachusetts Water Resources Authority (MWRA) was created. The MWRA instituted a multifaceted approach to upgrading the sewage treatment system, including an upgrade in the treatment facility itself and construction of a new outfall pipe to carry the treated effluent to a diffuser system in Massachusetts Bay located 9.5 mi offshore in deep water.

In 1989, discharge of more than 10,000 gallons per day of floatable pollutants comprising grease, oil, and plastics from the Deer Island and Nut Island treatment plants was ended. Sludge discharge ceased in December 1991, marking the end of one of the most significant inputs of pollutants to Boston Harbor. In 1995, a new primary treatment plant at Deer Island was completed, increasing the system's overall capacity and the effectiveness of the treatment. In August 1997, the first phase of secondary treatment was completed, increasing the level of solids removal to 80%. For the first time, the MWRA's discharge met the requirements of the CWA (Rex *et al.* 2002).

In July 1998, a new screening facility at Nut Island became operational, with sand, gravel, and large objects being removed from the wastewater flow prior to transport via tunnel to Deer Island for further processing. In October 1998, the old Nut Island plant was officially decommissioned, ending more than 100 years of wastewater discharges to the shallow waters of Quincy Bay. By 2000, the average effluent solids loading to the harbor had decreased to less than 35 tons per day (TPD), reduced from the 138 TPD discharged through the 1980s. On September 6, 2000, all wastewater discharges were diverted to the new outfall in Massachusetts Bay, and in early 2001, the final battery of secondary treatment became operational.

Ongoing MWRA pollution abatement projects for Boston Harbor involve reducing the number and discharge volumes from Combined Sewer Overflows (CSOs). In 1988, 88 CSOs discharged a total of about 3.3 billion gallons per year (BGY). By 1998, 23 CSOs had been closed, and pumping improvements reduced discharges to about 1 BGY, of which about 58% is screened and disinfected. By 2008, ongoing projects will reduce the number of CSO outfalls to fewer than 50, with an estimated discharge of 0.4 BGY, of which 95% will be treated by screening and disinfection (Rex *et al.* 2002).

Taylor (2005) summarized the major patterns in freshwater flows and loadings of total nitrogen (TN), total phosphorus (TP), total suspended solids (TSS), and particulate organic carbon (POC) to Boston Harbor between 1995 and 2003. He found three major periods of pollutant loadings (Figure 1-1):

- Period A was from 1995 through mid-1998, when the Nut Island discharge was diverted to Deer Island; the harbor received elevated freshwater flows and high loadings of TN, TP, TSS, and POC. Rivers provided most of the freshwater flows and wastewater treatment facilities contributed most of the TN, TP, TSS, and POC loadings.

- Period B was from mid-1998 to 2000, when discharges from Nut Island were transferred and released after treatment at Deer Island. Freshwater flows remained moderately elevated above the long-term average, but loadings of TSS and POC, and to a lesser extent TN and TP, decreased.

- Period C began in 2000 with the transfer of the discharge offshore. Loadings of TSS and POC were further reduced, but the largest decrease was observed for TN and TP. Freshwater flows declined for period C.

The changes in wastewater discharge from 1995 to 2003 resulted in about a 90% decrease in loadings to Boston Harbor. For TSS and POC, most of the decreases occurred between Periods A and B, presumably in response to the transfer of the Nut Island discharge to Deer Island and treatment upgrade. For TN and TP, most of the decreases occurred between Periods B and C, in response to transfer of the discharge offshore (Taylor 2005).

1.1.2 Benthic Studies in Boston Harbor

The first extensive studies of the infaunal benthos of Boston Harbor were conducted in the summers of 1978, 1979, and 1982 in support of the secondary treatment waiver application (Maciolek 1978, 1980; McGrath *et al.* 1982). These studies documented spatial and temporal variability in infaunal communities in Boston Harbor prior to any pollution abatement projects, and informed the design of the current monitoring program.

As MWRA's long-term sediment monitoring was being developed, reconnaissance surveys were carried out using sediment profile imaging in 1989 and 1990 (SAIC 1990). This technique provides information on the depth of the apparent redox potential discontinuity (RPD), an estimation of sediment grain-size composition, the successional stage of the infauna, and the presence of any biogenic features such as burrows and tubes (Rhoads and Germano 1986). The sediment profile stations provided the means to assess benthic conditions over most of the outer Boston Harbor and Dorchester, Quincy, Hingham, and Hull Bays.

Quantitative infaunal sampling was initiated in 1991and was intended to characterize the infauna of Boston Harbor so that changes following the various phases of the Boston Harbor Project (*e.g.*, sludge abatement) could be documented. Eight stations (one was later relocated) were positioned near the major effluent and sludge discharges and in key reference locations. Benthic infaunal communities and correlated sediment parameters were first sampled in September 1991, approximately three months prior to the cessation of sludge discharge. Post-abatement surveys were conducted in April/May and August 1992 to 2002; beginning in 2003 samples were collected only in August.

In 2004, a new station in the inner harbor, C019, was added to the benthic monitoring program. Sediment contaminants have been monitored at this site periodically since 1994 as part of an MWRA study of the effect of CSOs on sediment contamination in Dorchester Bay (Durell 1995, Lefkovitz *et al.* 1999). MWRA's system upgrades will greatly reduce the amount of CSO discharge to the Fort Point Channel and the bulk of the remaining flow will be treated; therefore, C019 was added to help identify environmental improvements that may result from these upgrades.

Reconnaissance surveys at 25–50 additional stations using sediment profile imaging and rapid partial grab analyses, or both, have been carried out annually through 2004. Reports to the MWRA on the results of these surveys have been prepared and can be requested from the MWRA through their website (http://www.mwra.state.ma.us).

Results from the 2005 harbor benthic survey are presented in this report and compared with results from previous years. Recent reports (Maciolek *et al.* 2004, 2005, 2006a) have suggested that the infaunal community is responding to some degree to changes in the discharges to the harbor. The occurrence and spread or retreat of *Ampelisca abdita* tube mats, and the increase in species numbers and diversity at some of the stations are considered especially important.

1.2 Report Overview

The Boston Harbor benthic monitoring program includes three components: determination of sedimentary parameters, imaging of sediments (SPI), and analysis of benthic infaunal communities. The sampling design and field methods are presented in Chapter 2. Sediment studies, based on grab samples taken at nine stations in August 2004, consist of grain-size analysis, total organic carbon (TOC) content determination, and quantification of the sewage tracer, *Clostridium perfringens*. These analytical results are presented in Chapter 3. Sediment images were collected in August 2004 at 61 stations; Chapter 4 discusses these images as part of a long-term evaluation of the SPI data. The benthic communities were sampled at nine stations in August 2004; the results are presented in Chapter 5. The raw data generated for all of these components are available from the MWRA; summaries are included in the appendices to this report.

2. 2005 HARBOR FIELD OPERATIONS

by Isabelle P. Williams

2.1 Sampling Design

The station array provides spatial coverage of the major bays that make up Boston Harbor (Figure 2-1). The nine stations designated as "traditional" are those that are sampled for benthic infauna, followed by a full taxonomic analysis of the organisms in each sample. These station locations were selected after consideration of previous sampling programs in the harbor (*e.g.,* those conducted for the 301(h) waiver application) and consideration of water circulation patterns and other inputs to the harbor (*e.g*., combined sewer overflow). The 52 stations designated as "reconnaissance" are those at which only sediment profile images (SPI) are taken.

2.1.1 Sediment Profile Images

The Boston Harbor SPI survey was conducted in August 2005 at the nine traditional and 52 reconnaissance stations (Figure 2-1). The SPI data supplement the infaunal data to provide a large-scale picture of benthic conditions in the harbor. Sediment profile imagery permits a faster evaluation of the benthos than can be made by traditional infaunal analyses. This qualitative evaluation can then be integrated with the quantitative results from the infaunal and sediment chemistry analyses. The target locations for Boston Harbor SPI stations are listed in Table 2-1. Field data and specific locations of all sediment profile images collected in 2005 are listed in Appendix A1 (Tables A1-1 and A1-2).

2.1.2 Sediment Samples

In 2005, the Boston Harbor benthic infaunal survey was conducted in August. Samples for analysis of benthic infauna and sedimentary parameters were collected from nine traditional stations (Figure 2-1). Target locations for these stations are given in Table 2-1. Field data and actual station coordinates for each biology and chemistry grab sample, along with a brief description of each sample, is given in Appendix A2 (Tables A2-1 and A2-2).

2.2 Field Program Results

2.2.1 Survey Dates and Samples Collected

A summary of the samples collected during the 2005 Boston Harbor surveys is given in Table 2-2.

2.2.2 Vessel and Navigation

The 2005 Boston Harbor benthic surveys were conducted from Battelle's research vessel, the R/V *Aquamonitor*. On the R/V *Aquamonitor*, vessel positioning was accomplished with the Battelle Oceans Sampling Systems (BOSS) Navigation system. BOSS consists of a Northstar differential global positioning system (DGPS) interfaced to an on-board computer. The GPS receiver has six dedicated channels and is capable of locking onto six satellites at once. Data were recorded and reduced using NAVSAM© data acquisition software. The system was calibrated at the dock using coordinates obtained from NOAA navigation charts at the beginning and end of each survey day.

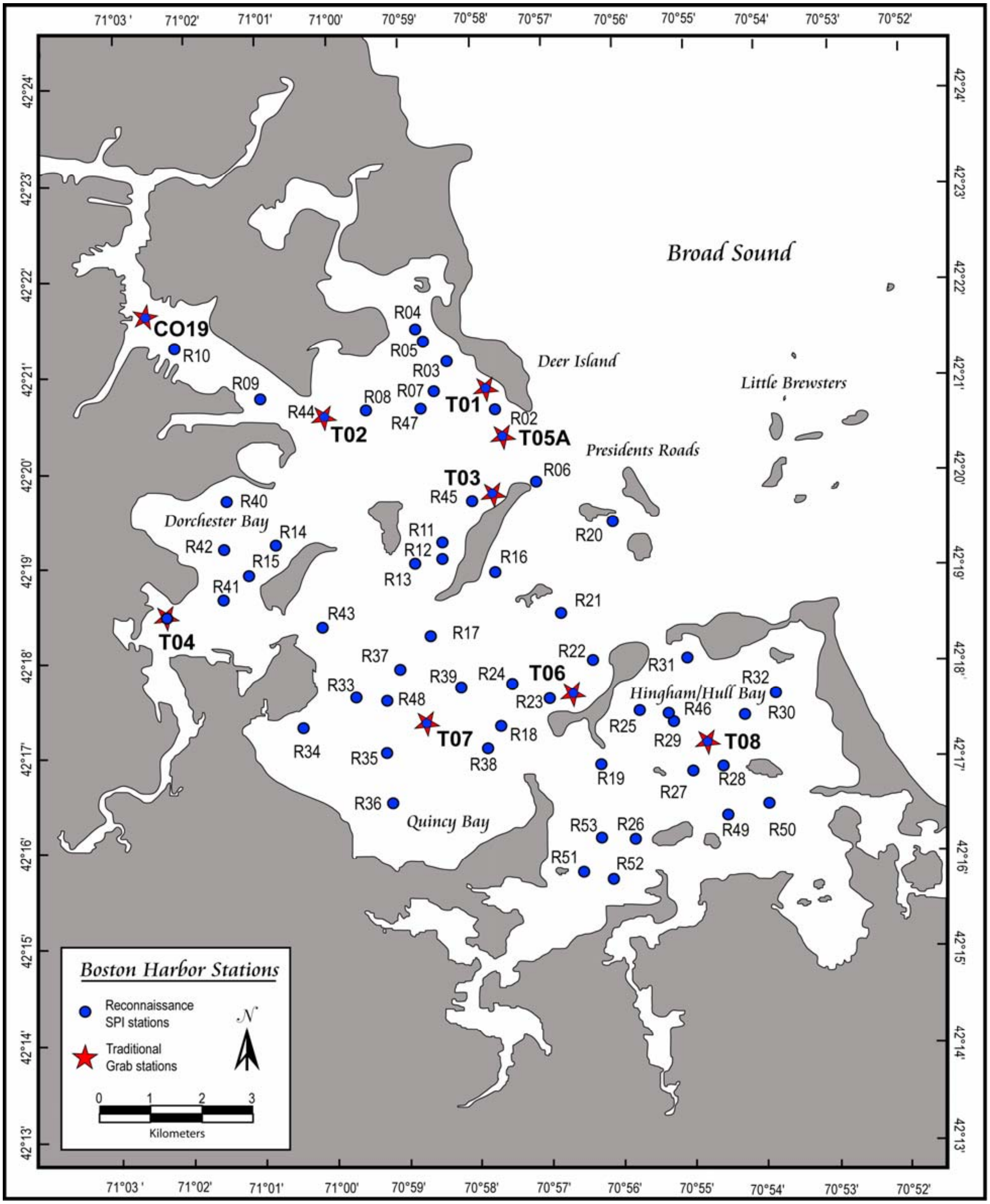

Figure 2-1. Locations of Boston Harbor grab and SPI stations sampled in 2005.
Circles indicate reconnaissance SPI stations sampled in August.
Stars show traditional stations sampled by grab and SPI in August.

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

Station	Latitude	Longitude	Depth (m)
Traditional Stations			
C019	42°21.55'N	71°02.71'W	7.9
T01	42°20.95'N	70°57.81'W	4.9
T02	42°20.57'N	71°00.12'W	6.8
T03	42°19.81'N	70°57.72'W	8.7
T04	42°18.60'N	71°02.49'W	3.2
T05A	42°20.38'N	70°57.64'W	17.5
T06	42°17.61'N	70°56.66'W	6.6
T07	42°17.36'N	70°58.71'W	5.9
T08	42°17.12'N	70°54.75'W	11.3
Reconnaissance Stations			
R02	42°20.66'N	70°57.69'W	13.8
R03	42°21.18'N	70°58.37'W	4.5
R04	42°21.52'N	70°58.78'W	7.2
R05	42°21.38'N	70°58.68'W	5.7
R06	42°19.91'N	70°57.12'W	10.9
R07	42°20.85'N	70°58.53'W	5.6
R08	42°20.66'N	70°59.50'W	2.6
R09	42°20.80'N	71°00.98'W	11.6
R10	42°21.32'N	71°02.20'W	12.8
R11	42°19.28'N	70°58.48'W	7.3
R12	42°19.10'N	70°58.47'W	6.1
R13	42°19.03'N	70°58.84'W	6.7
R14	42°19.25'N	71°00.77'W	7.0
R15	42°18.92'N	71°01.15'W	3.2
R16	42°18.95'N	70°57.68'W	8.0
R17	42°18.29'N	70°58.63'W	8.1
R18	42°17.33'N	70°57.67'W	8.0
R19	42°16.92'N	70°56.27'W	9.2
R20	42°19.49'N	70°56.10'W	11.2
R21	42°18.53'N	70°56.78'W	8.7
R22	42°18.02'N	70°56.37'W	9.4
R23	42°17.63'N	70°57.00'W	10.8
R24	42°17.78'N	70°57.51'W	7.4

Station	Latitude	Longitude	Depth (m)
R25	42°17.48'N	70°55.72'W	7.3
R26	42°16.13'N	70°55.80'W	7
R27	42°16.83'N	70°54.98'W	6
R28	42°16.90'N	70°54.52'W	7
R29	42°17.38'N	70°55.25'W	11
R30	42°17.43'N	70°54.25'W	5
R31	42°18.05'N	70°55.03'W	10
R32	42°17.68'N	70°53.82'W	5
R33	42°17.65'N	70°59.67'W	5
R34	42°17.33'N	71°00.42'W	4
R35	42°17.05'N	70°59.28'W	6
R36	42°16.53'N	70°59.20'W	5
R37	42°17.93'N	70°59.08'W	6
R38	42°17.08'N	70°57.83'W	7
R39	42°17.73'N	70°58.22'W	8
R40	42°19.73'N	71°01.45'W	2
R41	42°18.67'N	71°01.50'W	4
R42	42°19.18'N	71°01.50'W	2
R43	42°18.40'N	71°00.13'W	3
R44	42°20.62'N	71°00.13'W	9.3
R45	42°19.70'N	70°58.05'W	6.8
R46	42°17.46'N	70°55.33'W	10.5
R47	42°20.67'N	70°58.72'W	6.5
R48	42°17.61'N	70°59.27'W	5.9
R49	42°16.39'N	70°54.49'W	6.1
R50	42°16.50'N	70°53.92'W	6.1
R51	42°15.80'N	70°56.53'W	5.3
R52	42°15.71'N	70°56.09'W	5.2
R53	42°16.15'N	70°56.27'W	6

Table 2-2. Survey dates and numbers of samples collected on Boston Harbor benthic surveys in 2005.

Survey Type	Survey ID	2005 Date(s)	Samples Collected				
			Inf	TOC	GS	Cp	SPI
SPI	HR051	22–23 Aug					203
Benthic	HT051	3 August	27	9	9	9	

Key: Inf: Infauna, TOC: total organic carbon, GS: grain size, Cp: *Clostridium perfringens*, SPI: individual sediment profile images.

At each sampling station, the vessel was positioned as close to target coordinates as possible. The NAVSAM© navigation and sampling software collected and stored navigation data, time, and station depth every 2 seconds throughout the sampling event, and assigned a unique designation to each sample when the sampling instrument hit the bottom. The display on the BOSS computer screen was 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 in Boston Harbor.

2.2.3 Sediment Profile Imagery (SPI)

Dr. Robert Diaz was the Senior Scientist for the SPI survey (HR051). Three replicate SPI images were successfully collected at 52 long-term reconnaissance and nine traditional stations. The digital camera used captured a 5.2-megapixel image that produced a 14.1-megabyte RBG image that was recorded to an IBM 1-gigabyte microdrive. The camera was also equipped with a video-feed that sent images to the surface via cable so that prism penetration could be monitored in real-time. In addition, the camera frame supported a video-plan camera mounted to view the surface of the seabed. These images were also relayed to the surface via the video cable and permitted the camera operator viewing a video monitor to see the seafloor and know exactly when the camera had reached the bottom. The camera operator then switched to the digital still camera and while viewing the camera penetration, chose exactly when to record sediment profile images. Images were usually taken at about 1 and 15 sec after bottom contact.

This sampling protocol helped ensure that at least one usable photograph was produced during each lowering of the camera. The video signal from the video camera showing the surface of the seafloor was recorded on 8-mm videotape for later review. Because the images were viewed by video in real time, it was only occasionally necessary to lower the camera to the seafloor more than three times at each station. The date, time, station, water depth, photo number, and estimated camera penetration were recorded in the field log, with each touchdown of the camera also marked as an event on the NAVSAM©.

The microdrive was capable of recording more images than could be collected during a day of sampling. Consequently, the camera housing did not have to be taken apart as long as the batteries supplying the camera or the strobe did not fail. Camera system upgrades made subsequent to the 2004 SPI survey used the video cable to send some recharging capability to the batteries and so permitted longer deployments. Consequently, during this survey, the microdrive was replaced and new batteries installed only at the end of each survey day. Images were downloaded from the used microdrive to the laptop computer at that time. Digital capability allowed a review of the collected images within 20 min of downloading the microdrive so that it was possible to determine quickly whether or not three analyzable images had been collected at each station. Test shots on deck were not necessary, as loss of battery power to the strobe or camera would have been noticed immediately when the video cable failed to relay any images. While still in the field, images were transferred from the microdrive to a computer and then to a compact disc (CD) for long-term storage.

2.2.4 Grab Sampling

A 0.04-m^2 Young-modified Van Veen grab sampler was used to collect three replicate samples at each station for infaunal analysis. One sample for analysis of sedimentary parameters (*Clostridium perfringens*, sediment grain-size, and TOC) was obtained using the 0.10-m^2 Kynar-coated grab. In addition, following the apportionment of the required sedimentary samples, a subsample of the remaining homogenized sediment was reserved for a UMass Boston doctoral student studying diatoms in Massachusetts Bay. No samples for organics or metals analysis were collected in 2005.

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 were removed with a Kynar-coated scoop and homogenized in a clean glass bowl before being distributed to appropriate storage containers. The TOC samples were frozen, whereas the *C. perfringens*, grain size, and diatom samples were stored on ice in coolers.

3. 2005 SEDIMENT PROPERTIES

by Deirdre T. Dahlen and Carlton Hunt

3.1 Introduction

Surface sediment samples have been collected at eight stations throughout Boston Harbor (Figure 2-1) since 1991 to characterize the sediments and evaluate changes in sediment parameters (*e.g.,* grain-size composition, total organic carbon (TOC), and *Clostridium perfringens*) that may have resulted from improvements to wastewater treatment practices. *C. perfringens,* an anaerobic bacterium common to the intestinal track of mammals, is one of the most commonly used tracers of sewage-derived sources in marine systems. Historically, sewage effluent was one of many sources of pollution to the harbor system although industrial and household hook-ups to the sewage collection system and street runoff through combined sewer and street drainage systems were the ultimate sources of the pollutants. The Boston sewer system, which has transported the contaminants of concern from their sources to the coast since the 1800s, also carried unique tracers of the sewage and industrial processes. The signature of these inputs to the system is readily captured in the sediments. Thus, sediment data are evaluated here to better understand the response of sewage tracers in sediments to the harbor clean-up effort (see Section 1.1.1 for a description of harbor cleanup efforts) and assess how the system reacted when the intensity of sewage sources were reduced in the 1990s.

3.2 Methods

Benthic investigations were conducted annually in April (or May) from 1993 to 2003 and in August (or September) from 1991 to 2005. Surface (top 2 cm) sediment samples were collected at eight traditional stations located throughout Boston Harbor (Figure 2-1). Consistent with recent revisions to the monitoring program (MWRA, 2004), the April monitoring was discontinued in 2003.

Sediment data for station CO19, located in Boston's Inner Harbor near the Fort Point Channel, were also collected in 2004 and 2005 to track changes after improvement to the CSO in the area. Sediments at CO19 had been sampled in triplicate in 1994, 1998, and 2002 as part of a separate MWRA study (Durell 1995, Lefkovitz *et al.* 1999, and Lefkovitz *et al.* 2005).

Surface sediment samples collected in August 2005 were analyzed for sediment grain size, TOC, and *C. perfringens* according to Williams *et al.* (2005). Testing procedures are summarized in Section 3.2.1. Section 3.2.2 describes how the data were evaluated to characterize the sediments and assess changes in sediment quality that may have resulted from the harbor cleanup effort. Complete details regarding the data analyses and those data excluded from the evaluations are provided in Appendix B1.

3.2.1 Laboratory Analyses for Ancillary Measurements

Grain Size—Samples were analyzed for grain-size distribution by a sequence of wet and dry sieving methodologies following Folk (1974). Data were presented in 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 GeoPlan Associates.

Total Organic Carbon (TOC)—Samples were analyzed for TOC by using a DC-190 analyzer following Prasse *et al.* (2004). 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 those developed by Emerson and Cabelli (1982), as modified by Saad (1992). Data are reported here as colony-forming units (cfu) per gram dry weight of sediment. This analysis was performed by MTH Environmental Associates.

3.2.2 Data Terms and Analyses

Sediment data from the August/September surveys were used in the evaluations because these data represent a consistent seasonal dataset collected over the entire monitoring period. April/May survey data, which are available from 1993 to 2003, were excluded from the data evaluations; these data were evaluated most recently in Maciolek *et al.* (2006a).

Because the distribution of *C. perfringens* has been found to vary with the amount of fine-grained sediments (Parmenter and Bothner, 1993), these data were normalized to the percent fines in the sediments and are hereafter referred to as 'normalized *C. perfringens*' or 'normalized abundances of *C. perfringens*'. This provides a more conservative means of evaluating the data for trends.

Microsoft® Excel 2003, SAS, and JMP (The Statistical Discovery Software, a business unit of SAS Institute, Inc.) were used to analyze the sediment data. Graphical representations of the results are presented as ternary plots that visualize the grain-size composition; distribution plots that visualize the data distribution; and line charts and regression plots that visualize the temporal trends in these data.

Statistical analyses were conducted by using SAS and included (1) identification and evaluation of statistical outliers, (2) trend analyses, and (3) correlation analysis. These are discussed briefly below.

Outlier Identification—An outlier analysis was conducted to determine whether there were any data that did not fit the general patterns established by the majority of the observations. Results from the outlier analysis, as well as a more detailed description of this analysis, are provided in Appendix B1. Overall, the outlier analysis showed that the greatest number of outliers was associated with the normalized *C. perfringens* data, especially for 1991, 1996, and 1997. For example, the analysis identified outliers in normalized *C. perfringens* at five stations in 1991 (T03, T04, T06, T07, and T08), at one station in 1992 (T03), at one station in 1995 (T01), at four stations in 1996 (T02, T04, T06, and T07), at three stations in 1997 (T02, T06, T07), and at one station in 2000 (T05A). The 1991 outliers likely reflect that this was a period of active sewage sludge discharge to the harbor, as all but one of the outliers are associated with unusually high *C. perfringens* data (T08 was lower than expected). An explanation for the 1996 and 1997 outliers is not evident, although all but one of the stations were sampled more than 30-m from the target coordinates in 1996.

Temporal Trend Analysis—Station mean data were used to evaluate temporal trends and determine if there was a station-specific significant change (at the 95% confidence level) in percent fines, TOC, and normalized C. *perfringens* during the course of the monitoring period (1991–2005). This analysis consisted of three components: (1) parametric (Pearson) regression analysis to estimate temporal trends, (2) nonparametric (Kendall) regression analysis (Mann, 1945; Kendall, 1938; Sen, 1968) to estimate the trends, and (3) Spearman correlation analyses (concentration versus time) to test for the presence of consistent trends in the measured variables. Both the parametric and nonparametric regression analyses used the natural logarithms of the TOC, normalized *C. perfringens*, and percent fines because this transformation stabilized the variance and better represented the apparent temporal trends in the data. The regression model that was fitted is

$$\ln C = \alpha + \beta y ,$$

where y is the year of the sample and C is the concentration (TOC, normalized *C. perfringens*, percent fines). The estimates of **\$** in the regression models provide information about the trend (**\$** is the slope and α is the intercept). The temporal trend analysis was run twice, first with data from all years excluding 1991, 1996, and 1997, which were excluded because of the frequency of outliers. The trends analysis was run a second time; however, to include data from 1991 because while there were numerous outliers in 1991, these data are representative of the harbor system during discharge of sewage sludge. Test results with the 1991 data are reported in Section 3.3; results from both tests (with and without 1991) are provided in Appendix B.

Correlation Analysis—Individual replicate sediment data were used to evaluate the relationships between sediment variables (percent fines, TOC, and normalized *C. perfringens*) on a harbor-wide and station-specific basis. Evaluations were performed by using parametric (Pearson) and nonparametric (Kendall, Spearman) correlation analyses, as follows:

- Harbor-wide analysis within each of the four major cleanup events and across all stations. The four major cleanup events are defined as (1) Pre-period A, including data from 1991 to 1994, (2) Period A, including data from 1995 to 1998 (although data from 1996 and 1997 were excluded because of the frequency of outliers), (3) Period B, including data from 1999 and 2000, and (4) Period C, including data from 2001 to 2005. Periods A, B, and C are consistent with Taylor (2005) and correspond with the major periods of pollutant loadings and milestones of MWRA as described in Section 1.1.1. Pre-period A is representative of system conditions during discharge of sewage sludge to the harbor (1991); after cessation sludge discharge to the harbor; and prior to advanced primary treatment coming on-line in 1995.

  Grouping data across all stations allowed for an evaluation of the harbor-wide response with a sufficient number of observations within each of the four cleanup events.

- Station-specific analysis within each station over all sampling events. Data were not further aggregated by the four major cleanup events because this aggregation yielded sample sizes that were too small (*i.e., n* ranged from 2 (all stations, Period B) to 7 (all stations, Period C)) for a meaningful analysis.

Consistent with the temporal trends analysis, the correlation analysis was run twice. First using all data except 1991, 1996, and 1997, which were excluded because of the frequency of outliers, and a second time to include data from 1991. Test results with the 1991 data are reported in Section 3.3; results from both tests (with and without 1991) are provided in Appendix B.

3.3 Results and Discussion

Harbor sediment data from 1991 to 2005 were evaluated and results from the evaluations are discussed below; detailed output from the evaluations are provided as appendices to this report (grain size, TOC, and *C. perfringens* output provided in Appendices B2, B3, and B4, respectively). All sediment results discussed in this section are expressed as dry weight.

3.3.1 Grain Size 1991–2005

Harbor stations include locations with dissimilar grain-size characteristics. Harbor stations T01, T05A, and T08 generally have coarse-grained sediments; stations T04 and CO19 have fine-grained (silty) sediment; and stations T02, T03, T06, and T07 were comprised of sediments with roughly equal parts coarse- and fine-grained material (representative stations T03, T04, and T05A are shown in Figure 3-1; ternary plots by station are presented in Appendix B2, Figures B2-1 through B2-5).

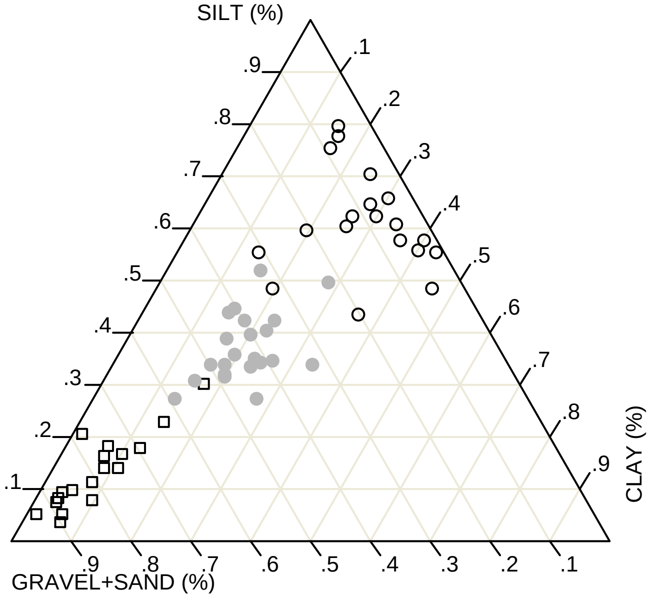

Figure 3-1. Ternary plot showing the distribution of percentages gravel + sand, silt, and clay at stations T03 (●), T04 (○), and T05A (□) from 1991 to 2005, August/September surveys only.

Grain-size composition changed significantly over time (1991–2005) at station T02, evidenced by a significant increase in percent fines (Figure 3-2, $p = 0.015$; decrease also significant ($p = 0.028$) without 1991 data, see Figure B2-9, Appendix B2). Temporal changes in sediment environments at the other harbor stations were difficult to discern because of the high variability among the data over time (Appendix B2, Table B2-1 and Figures B2-6 through B2-10). For example, the coefficients of variation in grain-size components from 1991 to 2005 at individual stations ranged from 11% to 257%, and were frequently greater than 30% for many stations and grain-size fractions (Appendix B2, Table B2-1).

Marked changes in grain-size composition were observed sporadically throughout the monitoring program, and likely reflect natural variability, storm activity, small changes in sampling location, or a combination of these factors. Natural variability can be extreme depending on the location. For example, sediment at station T06 appears to be naturally heterogeneous comprised of coarse-grain sediment some years and more fine-grained sediments other years (Appendix B2, Figure B2-3).

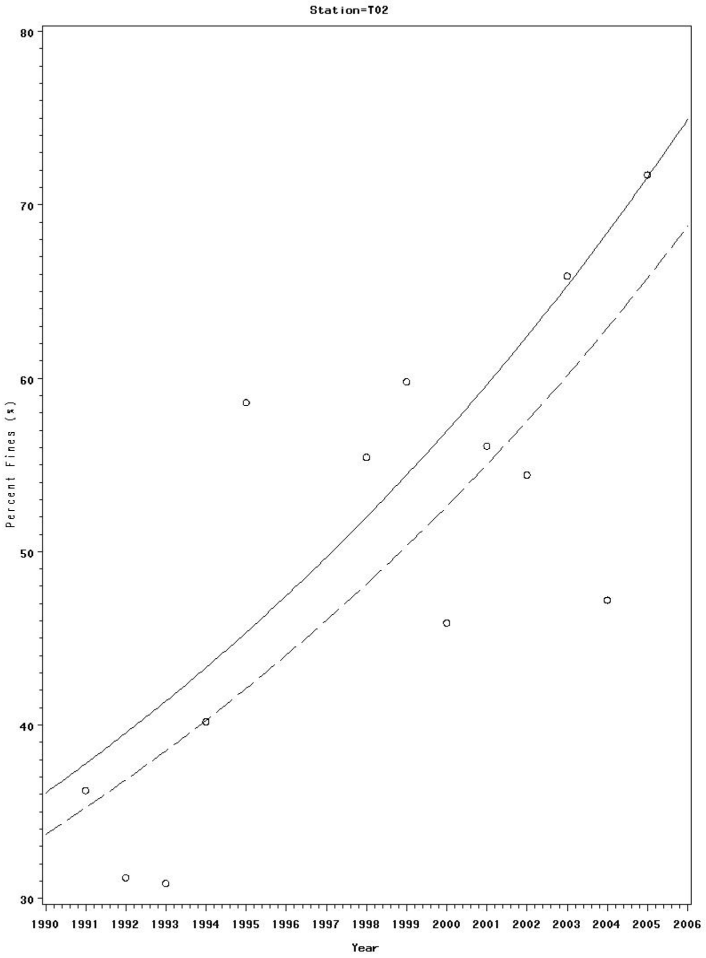

Figure 3-2. Significant increase in percent fines at station T02 from 1991 to 2005, August/September surveys only. The solid line represents the nonparametric regression and the dashed line represents the parametric regression. Data from monitoring years 1996 and 1997 excluded from the trends analysis.

Storm activity can disturb sediment and may contribute to a loss of fines in some locations and deposition of fine-grained material at others. For example, sediment at T08 was very silty (88% fines) in 1991, but since 1992 sediment at this location has been coarser (>80% sand) (see Figures B2-4 and B2-14 in Appendix B2). Sediment bed disturbance associated with the Perfect Storm in October 1991 (http://lwf.ncdc.noaa.gov/oa/satellite/satelliteseye/cyclones/pfctstorm91/pfctstorm.html), which brought wind gusts of above hurricane force, damaging heavy surf and coastal flooding, and waves 10 to 30 feet high, may have contributed to the substantive change in grain-size composition observed at T08 between 1991 and 1992. Sediments have continued to be coarse-grained at this location since 1992, and in 2005 the percentages of gravel and sand were higher compared to all other monitoring years. The coarsening of grain size (from loss of fines) observed at T08 in 2005 is likely associated with sediment bed disturbance from the May 2005 nor'easter, which according to the National Oceanic and Atmospheric Administration's National Climatic Data Center (NCDC) (http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwevent~ShowEvent~583396) was the strongest late-May nor'easter since 1967. Together, these data suggest that harbor station T08 is influenced by significant storm activity. Storm activity may have also contributed to sporadic changes in grain-size composition observed at T04 and

T07 in 1991, at T01 in 1992, and at T04 in 2000 (Appendix B2, Figures B2-11 for T01, B2-12 for T04, and B2-14 for T07)[1]. Consistent with findings from the Outfall Monitoring Program (Maciolek *et al.* 2006b), the May 2005 nor'easters may also have contributed to a coarsening of grain size (from loss of fines) observed at harbor station T08, and to a lesser extent T03 and T01 in 2005 (Appendix B2, Figure B2-16).

Small changes in sampling location may also contribute to sporadic changes in grain-size composition. For example, many of the stations sampled in 1996 were sampled more than 30 m from the target coordinates (Maciolek *et al.* 2006a). A coincident change in grain-size composition and distance from target location was observed at T06; that is, sediment at T06 was comprised of higher silt content and lower sand content in 1996 compared to other monitoring years (Appendix B2, Figures B2-3 and B2-13).

Finally, an obvious explanation for the marked change in grain-size composition at T01 in 1995 (Appendix B2, Figure B2-1) is not apparent; this location was sampled within 30-m of the target coordinates and no storms were documented in the region prior to sampling.

3.3.2 Total Organic Carbon 1991–2005

TOC results for 2005 are consistent with historical data (1991–2004) in that fine-grained sediments (*e.g.,* T04) typically had higher TOC compared with coarse-grained sediments (*e.g.,* T05A and T08) (see Section 3.3.4 for discussion of sediment correlations). Station T04, located in a depositional area which is known to be affected by nearby combined sewer overflow discharge (Lefkovitz *et a1.*, 1999) and is considered to be a focus area for accumulation of sediment and contaminants entering Boston Harbor (Wallace *et al.* 1991; Stolzenbach and Adams 1998), consistently had the highest TOC (grand station mean = 4.2%) relative to other harbor stations (Appendix B3, Table B3-1). The lowest TOC was measured at stations T08 and T05A (grand station mean values <1%).

TOC content decreased significantly over time ($p = 0.001$ with 1991, $p = 0.002$ excluding 1991) at harbor station T01 (Figure 3-3), which is located in the north harbor near the Deer Island Treatment Plant. TOC content also decreased significantly over time (with or without 1991 data) at north harbor station T03 ($p = 0.009$ with 1991, $p = 0.033$ excluding 1991), although the significance of the decrease may be influenced by the unusually low TOC content in 2005 (Figure 3-3). Significant changes in TOC over time at other harbor stations (Appendix B3, Figures B3-1 through B3-5) were not evident, possibly because of the high variability among the data. For example, CVs ranged from 7% (CO19) to 51% (T08), and were more than 30% at half of the traditional harbor stations (T01, T04, T05A, and T08) (Appendix B3, Table B3-1). The Benthic Nutrient Flux program also observed pronounced decreases in TOC at selected harbor locations (BH03, followed by BH08A and QB01; Tucker *et al.* 2006).

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[1] According to NCDC, a thunderstorm with 60 knot winds occurred in Suffolk County on June 1991. Little additional detail is provided regarding this storm event; however, it may have contributed to the unusually high sand content measured at T04 and T07 in 1991. The Perfect Storm of October 1991 may have contributed to the marked change in grain-size composition observed at T01 in 1992. Notably, gravel content increased substantially at this station in 1992. Gravel content was typically below 10% during the monitoring program, but in 1992 was measured at 65%. A coincident decrease in sand content was observed; sand content was typically >60% during the monitoring program, but in 1992 was measured at 19%. A June 2000 nor'easter brought strong winds (averaging 25 to 35 mph, with gusts as high as 50 mph), heavy rain, and a brief period of flooding to Massachusetts. This storm may have contributed to the unusually high sand content measured at T04 in August 2000.

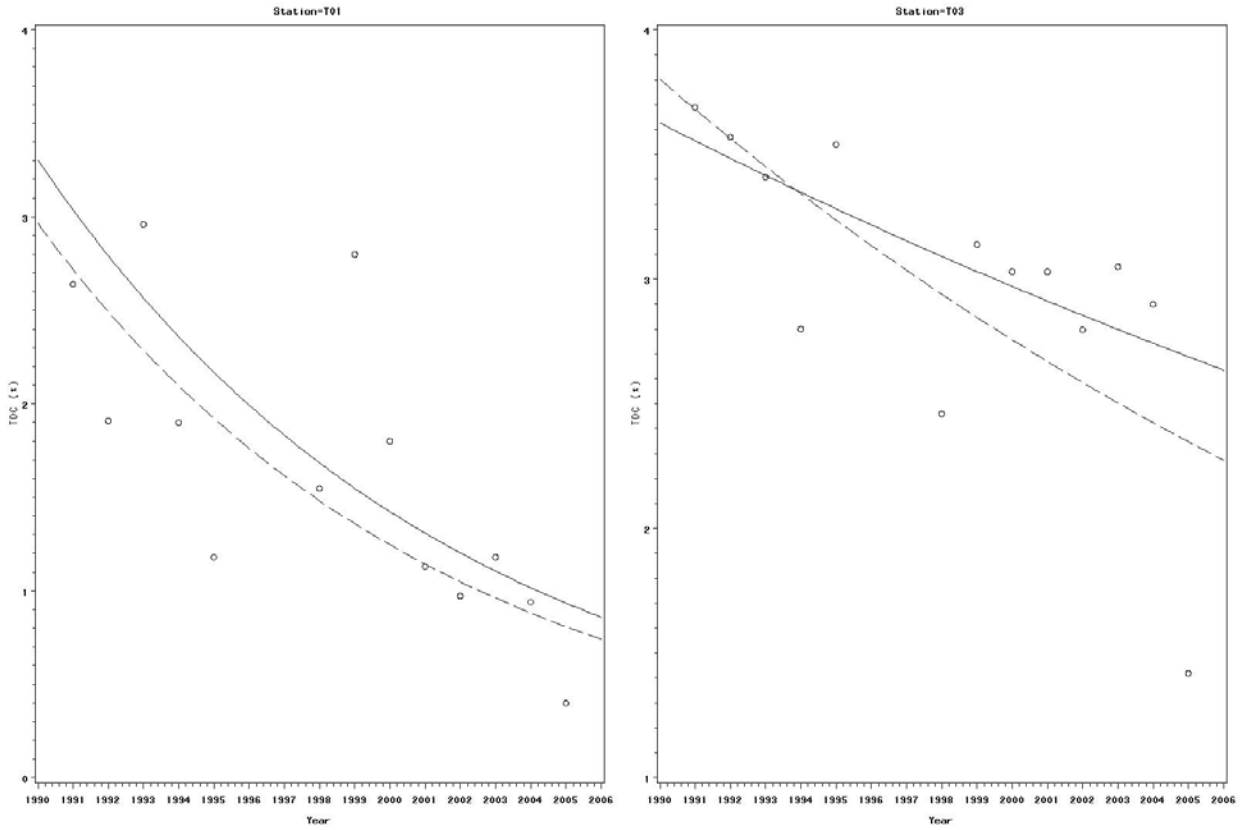

Figure 3-3. Significant decrease in total organic carbon content at stations T01 and T03 from 1991 to 2005, August/September surveys only. The solid line represents the nonparametric regression and the dashed line represents the parametric regression. Data from monitoring years 1996 and 1997 excluded from the trends analysis.

An unusually high TOC content was measured at T06 in 1996 and at T04 in 1998 (Figure 3-4). The unusually high TOC at T06 in 1996 was coincident with a change in grain-size composition (*i.e.,* increase in silt content), which may be associated with a small change in the sampling location (see Section 3.3.1). The unusually high TOC at T04 in 1998 was attributed to localized inputs from two major storm events, the May 1998 nor'easter (http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwevent~ShowEvent~336645) and the June 1998 storm (http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwevent~ShowEvent~333238) that led to widespread urban, small stream, and river flooding. These findings are consistent with other harbor investigations which have indicated that station T04 is located in a dynamic area of the harbor affected by nearby CSO discharge (Lefkovitz *et al.* 1999) and is also considered to be a focus area for accumulation of sediment and contaminants entering Boston Harbor (Wallace *et al.* 1991; Stolzenbach and Adams 1998). TOC decreased in September 1999 at T04 to previous conditions, typical of the mid-1990s (Figure 3-4). This decrease is possibly due to the rapid sedimentation rate (approximately 4 cm/year) observed at the site by Gallagher *et al.* (1992) and Wallace *et al.* (1991).

An unusually low TOC content was measured at T03 in 2005 (Figure 3-3 and Appendix B3 Figure B3-7), and TOC content at many harbor stations in 2005 were among the lowest, or the lowest, measured values during the monitoring period (1991–2005) (Appendix B3, Figure B3-11). A corresponding coarsening of grain-size (from loss of fines) was also observed at harbor stations T08, and to a lesser extent T03 and T01. The reduced TOC content and coarsening of grain size is likely associated with sediment bed disturbance resulting from the May 2005 nor'easter, the strongest late May winterlike nor'easter since 1967[2]. Similar impacts were also observed at selected Massachusetts Bay stations (Maciolek *et al.* 2006b).

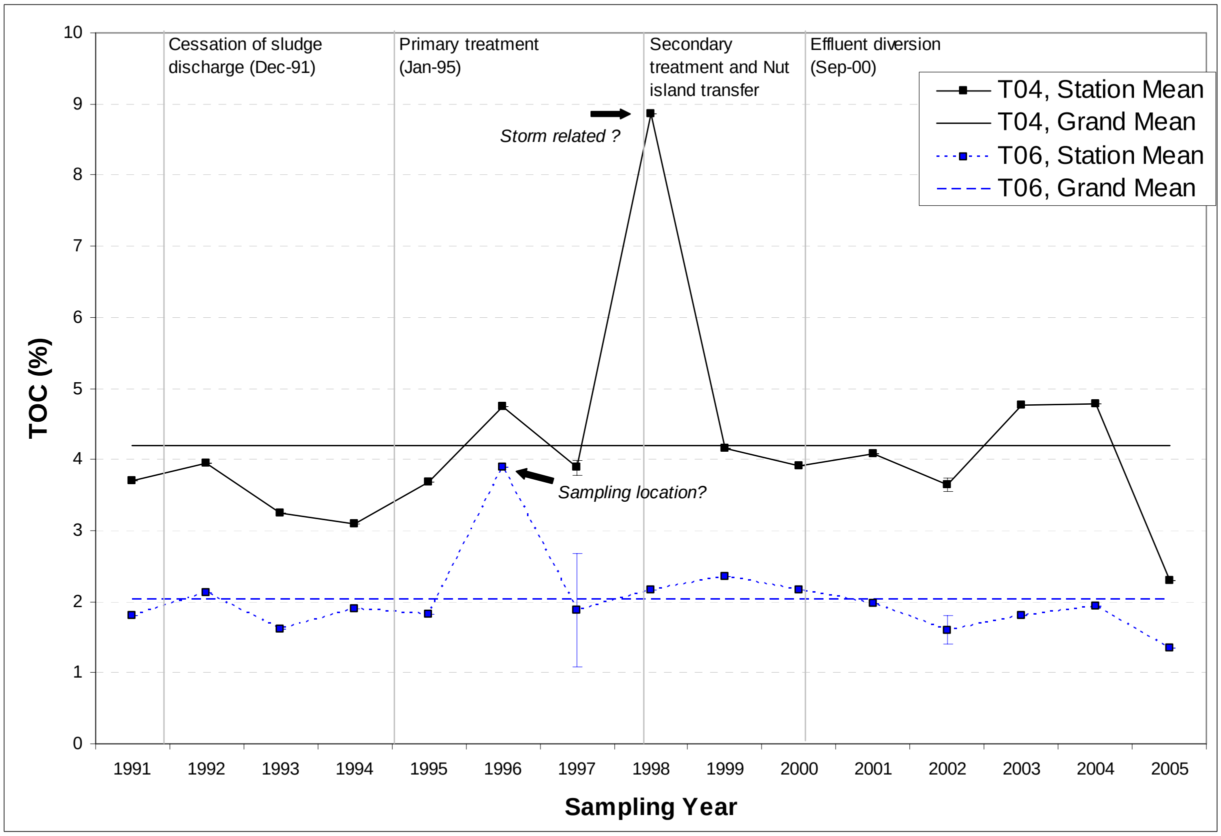

Figure 3-4. Station mean and grand station mean values of total organic carbon content at T04 and T06 from 1991 to 2005, August/September surveys only. Vertical bars represent one standard deviation. Station mean values are the average of all replicates for a given year (August/September surveys only), by station. The grand mean is the average of all yearly station means values (1991–2005).

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[2] According to the National Oceanic and Atmospheric Administration's NCDC 'an unusually usual late season and long duration nor'easter brought strong winds, heavy rainfall, and coastal flooding to eastern Massachusetts'. Moderate coastal flooding occurred during two high tide cycles and numerous shore roads were flooded and impassible for a time. The nor'easter was approximately nine hours in duration, beginning at May 24, 2005 at 2:50PM and ending at May 24, 2005 at 11:35PM. The magnitude of storm is reported by NCDC as 50 knots.

3.3.3 *Clostridium perfringens* 1991–2005

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 *C. perfringens,* an anaerobic bacterium common to the intestinal tract of mammals (Emerson and Cabelli 1982).

In the early 1990s, when MWRA began its systematic monitoring of the harbor and bays, *C. perfringens* levels in Boston Harbor were high and variable (data for regional areas of the harbor are shown in Figure 3-5; station-specific time series data are shown in Appendix B4, Figures B4-6 through B4-10). In 1991, the mean level measured in the outer harbor (*i.e.,* T01, T03, and T05A[3]) was approximately 1,600 colony forming units for each gram of dry, fine-grained sediment (cfu/g dw/% fines) (Figure 3-5). Within this region, the highest abundances of *C. perfringens* were measured at T03 (Figure 3-6), which is located south of the Deer Island Treatment Plant near the former Nut Island sludge discharge location. Normalized *C. perfringens* abundances at T03 in 1991 were 5 to 16 times higher than levels at T01 and T05A (Figure 3-6). Other areas of the harbor such as Quincy Bay (*i.e.,* T06 and T07) and regions north and south of Dorchester Bay (*i.e.,* stations T02 and T04) had considerably lower levels (~500 to 600 cfu/g dw/% fines) (Figure 3-5). Since that time, trends in decreasing abundances have been observed at all harbor stations except T04, which is located in a focus area for accumulation of sediment, and CO19, which is located in the Inner Harbor. Overall, a "harbor-wide" average trend estimate[4] showed a significant harbor-wide decrease in normalized abundances of *C. perfringens* during the course of the monitoring period. Further, a statistically significant decrease[5] in normalized abundances of *C. perfringens* was also observed at five of the eight traditional harbor stations (T01, T02, T05A, T06, and T08; representative stations T02 and T08 shown in Figure 3-7; all data in Appendix B4). While not significant at the 95% confidence level, normalized abundances also decreased over time (1991–2005) at stations T03 (p = 0.272, with 1991) and T07 (p = 0.088, with 1991).

The normalized *C. perfringens* abundance decrease in the harbor was especially dramatic between 1991 and 1992 reflecting the first step in the cleanup of Boston Harbor, the cessation of sludge discharge in 1991 (Figure 3-5). The trends analyses supported this, as evidenced by statistically stronger decreasing trends (lower p values) in normalized *C. perfringens* when the 1991 data are used in the analysis (Appendix B4, Tables B4-2 and B4-3).

In the mid-1990s (*i.e.,* 1995 through 1998, Taylor Period A) the normalized *C. perfringens* levels generally ranged between 100 and 700 cfu/g dw/% fines throughout the harbor, but converged to values near 170 cfu/g dw/% fines by 1998, likely in response to the second major step in the harbor cleanup, start-up of the advanced primary treatment at Deer Island in 1995 (Figure 3-5). Subsequent improvements to sewage treatment (*i.e*., phase-in of secondary treatment starting in the fall of 1997), have also had a further positive influence on Boston Harbor sediments as documented by this sewage tracer

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[3] Reconnaissance station R-6 was redesignated as traditional station T05A in 1993; data from 1991 for T05A is based on R-6.

[4] This analysis fits a common slope to all stations, using different intercepts to allow for differences in magnitude across locations. Including all nine harbor locations, the average trend slope estimate yields slope values of -0.0954 (parametric) and -0.1019 (nonparametric), both of which are statistically significantly less than zero (i.e., indicative of a downward trend on average) at p <0.001. These results exclude 1991, 1996, and 1997 data. Similar results are expected with 1991 data. If harbor stations T04 and CO19 are removed, the "average" slope estimates are -0.1097 (parametric) and -0.1161 (nonparametric); both are highly significant.

[5] Decrease significant at T02, T05A, T06, and T08, with or without 1991 data; Appendix B4, Tables B4-2 and B4-3.

(Maciolek *et al.* 2004, 2005). Stations located near the former Nut Island Treatment Plant in Hingham/Hull Bay (*i.e.,* T08), and to a lesser extent Quincy Bay (*i.e.,* T06 and T07), showed substantial decreases following the 1998 transfer of Nut Island treatment and effluent discharge to Deer Island (Figure 3-5). There have been no substantial changes in normalized *C. perfringens* abundances in Boston Harbor following diversion of effluent discharge from the harbor to the offshore outfall in September 2000.

The significant decrease observed at many of the harbor stations and reduced temporal variability in the *C. perfringens* data clearly trace the major improvements made in sewage treatment and discharge in Boston Harbor since 1991 and demonstrate less influence of effluent on the harbor sediments. Sediments located in the transition area between the mouth of the harbor and the offshore outfall showed similar improvements (Maciolek *et al.* 2006b).

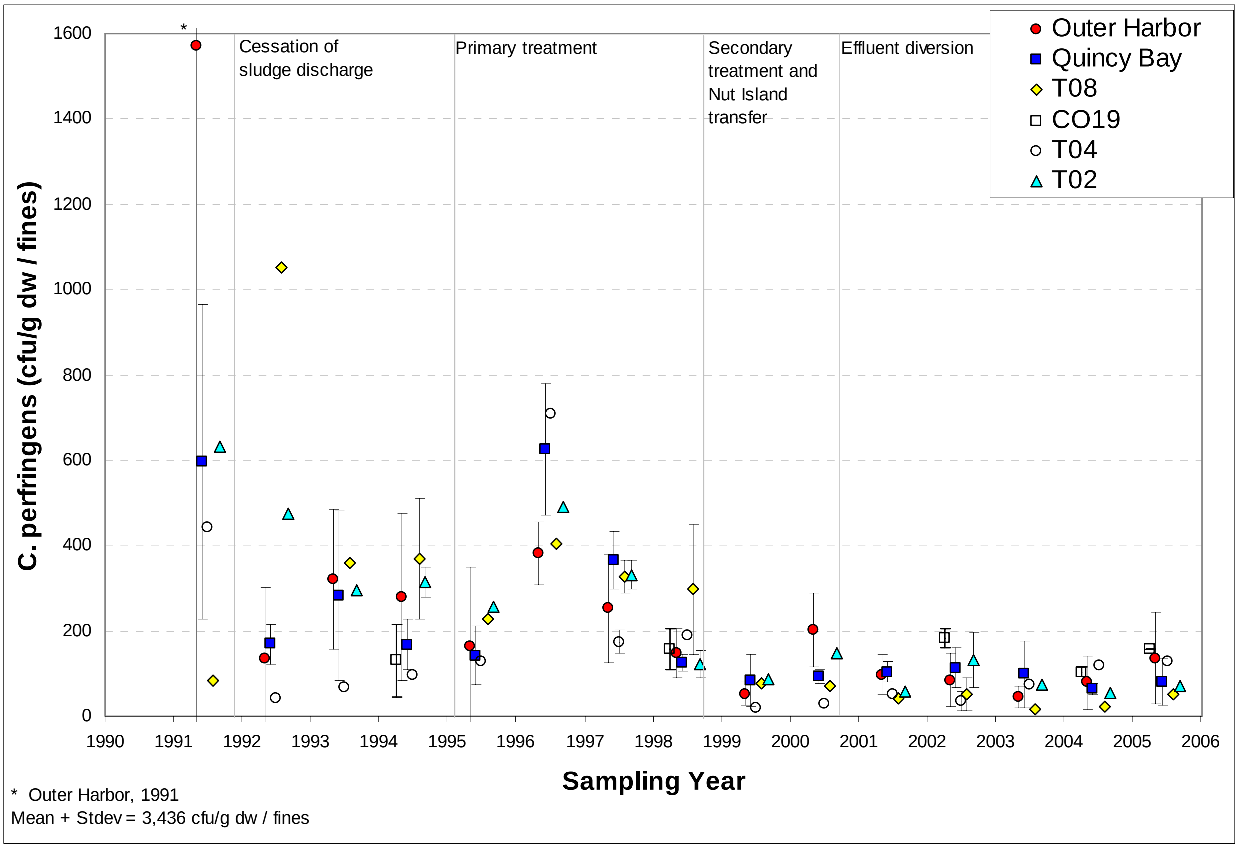

Figure 3-5. Station mean abundances of normalized *Clostridium perfringens* in Boston Harbor from 1991 to 2005, August/September surveys only. Vertical bars represent one standard deviation. Station mean values are the average of all stations and replicates for a given year (August/September surveys only), by region where Outer Harbor includes stations T01, T03, T05A; Quincy Bay includes stations T06 and T07.

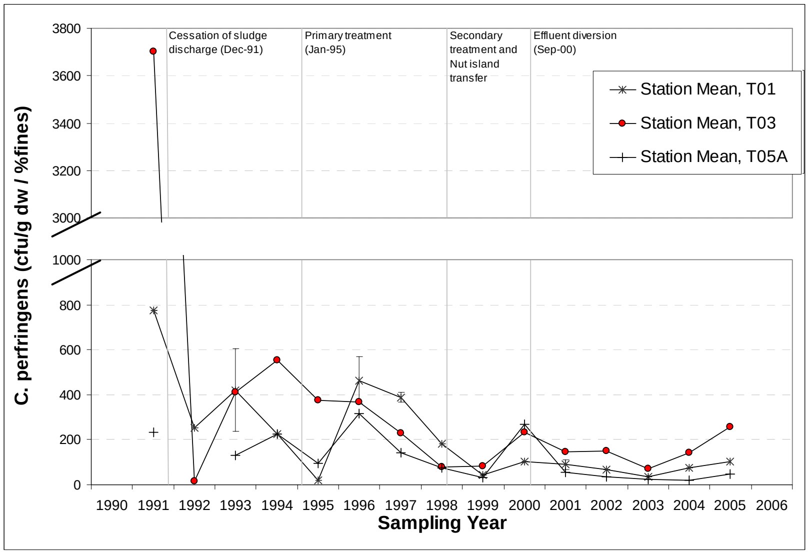

Figure 3-6. Station mean abundances of normalized *Clostridium perfringens* at outer harbor stations T01, T03, and T05A from 1991 to 2005, August/September surveys only. Vertical bars represent one standard deviation. Station mean values are the average of all replicates for a given year (August/September surveys only), by station.

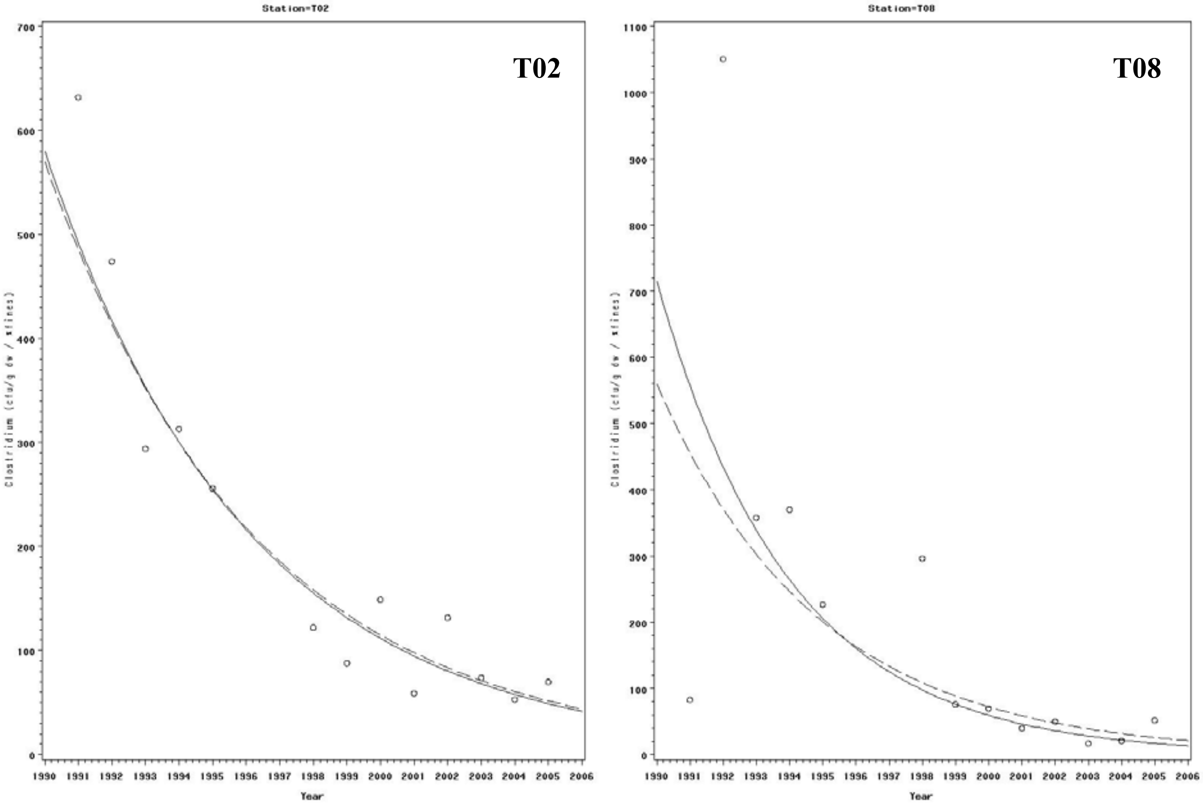

Figure 3-7. Significant decrease in normalized abundances of *Clostridium perfringens* at T02 and T08 from 1991 to 2005, August/September surveys only. The solid line represents the nonparametric regression and the dashed line represents the parametric regression. Data from monitoring years 1996 and 1997 excluded from the trends analysis.

3.3.4 Sediment Correlations

Results from the harbor-wide correlation analyses are summarized in Table 3-1; parametric and nonparametric correlation results were generally similar. On a harbor-wide basis (within cleanup events and across all stations), percent fines and TOC were positively and significantly correlated across all cleanup events (Table 3-1), suggesting that the relationship between fines and TOC did not change over time or in response to harbor cleanup efforts. The relationship between the sewage tracer, *C. perfringens* (normalized), and bulk sediment properties (TOC and percent fines) did change, suggesting that normalized *C. perfringens* showed an independent response within the cleanup events. For example, the correlation between normalized *C. perfringens* and TOC was not significant in the 1990s (Periods pre-A, B, and C; Table 3-1), but the relationship was significant in the 2000s (Period C, Table 3-1), albeit the correlation coefficient was not very strong ($r < 0.5$). Normalized *C. perfringens* were significantly correlated with percent fines in the early 1990s (Pre-period A, Table 3-1), yet as major improvements to wastewater treatment were implemented (*i.e.,* primary and secondary treatment and effluent diversion) the correlation degraded (Periods A and B, Table 3-1), suggesting that the system was in flux as the magnitude and type of sewage inputs to the system were changing in response to continued harbor cleanup efforts. Since the early 2000s, however, normalized *C. perfringens* have been significantly correlated with percent fines (Period C, Table 3-1), suggesting that the system has stabilized. Interestingly the correlation between normalized *C. perfringens* and percent fines switched from a significantly *negative* correlation in the early 1990s to a significantly *positive* correlation in the 2000s (Table 3-1); this switch appears to be an artifact of using normalized *C. perfringens* data in the analysis.

Table 3-1. Harbor-wide correlation results, parametric and nonparametric, within cleanup event periods. [(a)]

Method	Period	n	Correlation coefficient (r)			p-value		
			C-T	C-F	T-F	C-T	C-F	T-F
Spearman	Pre-A	43	-0.161	**-0.506**	**0.695**	0.303	**0.0005**	**<0.0001**
	A	31	-0.0361	-0.301	**0.836**	0.847	0.1	**<0.0001**
	B	16	-0.244	-0.185	**0.806**	0.362	0.492	**0.0002**
	C	63	**0.465**	**0.475**	**0.882**	**0.0001**	**<0.0001**	**<0.0001**
Kendall	Pre-A	43	-0.114	**-0.344**	**0.532**	0.281	**0.0011**	**<0.0001**
	A	31	0.00431	-0.213	**0.663**	0.973	0.0923	**<0.0001**
	B	16	-0.183	-0.167	**0.683**	0.322	0.368	**0.0002**
	C	63	**0.338**	**0.322**	**0.711**	**<0.0001**	**0.0002**	**<0.0001**
Pearson	Pre-A	43	0.149	-0.123	**0.637**	0.34	0.432	**<0.0001**
	A	31	-0.0286	-0.287	**0.654**	0.879	0.117	**<0.0001**
	B	16	-0.240	-0.265	**0.828**	0.37	0.321	**<0.0001**
	C	63	**0.391**	**0.403**	**0.873**	**0.0015**	**0.0011**	**<0.0001**

(a) Data from 1996 and 1997 excluded because of the frequency of outliers (see Section 3.2.2). Correlation results excluding 1991 are provided in Appendix B5, Table B5-2.

C-T, correlation between normalized C. perfringens and TOC.

C-F, correlation between normalized C. perfringens and percent fines.

T-F, correlation between TOC and percent fines.

Bold values indicate significant (at 95% confidence level) correlations.

Results from the station-specific correlation analysis, *i.e*., within station and across all years (Appendix B5, Tables B5-3 and B5-4) were less meaningful compared to the harbor-wide (Table 3-1) analysis. For example, percent fines and TOC were not significantly correlated at any of the harbor stations except T08 (Appendix B5, Tables B5-3 and B5-4); the weaker correlation simply reflects that the grain size and TOC data are more tightly clustered within a station, as compared to the harbor-wide analysis which included a mix of sediment types (coarse- to fine-grained sediments) with varying levels of TOC. Overall, aggregating data by cleanup event (*i.e.,* harbor-wide correlation analysis) presents a clearer story of how sediment relationships may or may not have changed during periods of known physical interventions to the system, which occurred since the 1990s in Boston Harbor as improvements to wastewater treatment were implemented.

3.4 Conclusions

Since 1992, a statistically significant decrease in TOC was evident at stations T01 and T03, which are located in the north harbor near the Deer Island Treatment Plant. These findings suggest a reduction in carbon loading to the northern harbor consistent with the improvements to wastewater treatment practices. Decreasing trends in the sewage tracer, *C. perfringens* (normalized to percent fines), were also observed at all harbor stations, except T04, which is considered to be a focus area for accumulation of sediment and CO19, which is located in the Inner Harbor. The *Clostridium* decrease was significant at the 95% confidence level at harbor stations T01, T02, T05A, T06, and T08; decreasing trends were also observed at T03 ($p = 0.272$) and T07 ($p = 0.088$). The harbor-wide correlation between normalized *C. perfringens* and bulk sediment properties also illustrates the independent response of this sewage tracer as the magnitude and types of sewage inputs to the harbor changed following cleanup efforts. Findings from the trends and correlation analyses, which used different aggregations of the data to answer different questions, must be carefully evaluated when making general statements regarding station-specific vs. harbor-wide changes. Overall, the monitoring data indicate that actions taken by the MWRA to minimize wastewater impacts to Boston Harbor, beginning with the cessation of sludge discharge in 1991 and continued through 2000 with major facility improvements and effluent diversion, have improved the quality of sediment in Boston Harbor. These findings are consistent with Hunt *et al.* (2006), which concluded that source reduction actions have demonstrably decreased chemical contaminant levels in surface sediments of Boston Harbor and that MWRA source reduction efforts and facility improvements have measurably reduced contaminant loading to the system over the past ten years.

4. 2005 SPI: LONG-TERM TRENDS OF BENTHIC HABITATS RELATED TO REDUCTION IN WASTEWATER DISCHARGE TO BOSTON HARBOR AS DISCERNED BY SEDIMENT PROFILE IMAGING

by

Robert J. Diaz

4.1 Introduction

Response of the Boston Harbor ecosystem following major reductions in inputs of pollutants, both organic and chemical, is key to our understanding of the restoration of ecosystem function within the harbor. These improvements started in the late 1980s with the formation of the Massachusetts Water Resources Authority (MWRA), which improved treatment facilities and moved sewage discharge to an offshore location over a period of about 15 years. In the 1980s, nutrient loadings to Boston Harbor were among the highest in the world (Kelly 1997). Bothner *et al.* (1998) and Gallagher and Keay (1998) present a history of environmental degradation within Boston Harbor and showed that sediment quality did improve after reductions in pollutant inputs in the 1990s, but that contaminated sediments remain a "lingering legacy of the long history of contaminant discharge." Reductions of heavy metal concentrations in surficial sediments were also reported by Zago *et al.* (2001). The main issues that still need to be addressed, however, relate to the response of the benthos and restoration of ecosystem function following the cessation of wastewater discharge within the harbor in September 2000, which reduced carbon and nutrient loading to the harbor by over 90% (Taylor 2005).

Given that most pollutants are particle reactive, the sediments are the final sinks where pollutant accumulation occurs (Olsen *et al.* 1982) and where ecosystem function is most likely to be disrupted by toxic or enrichment effects (Kimball and Levin 1985). Surficial sediments are critical to many ecosystem functions with flows of energy (organic carbon, living biomass, and secondary production) and nutrients (nitrates and phosphates) all regulated by processes at or near the sediment-water interface (Rhoads 1974, Pearson and Rosenberg 1978, Diaz and Schaffner 1990). In shallow coastal systems, factors structuring surface sediments, down to 20–30 cm from the sediment-water-interface (SWI), are a combination of physical, chemical, and biological processes. While physical processes deliver sediment to the seafloor, it is the activities of benthic organisms, or bioturbation, that alter primary physical sedimentary structures, such as laminations, and produce secondary structures, such as defecation mounds or feeding pits, and influence the role and depth of solute exchange (Aller and Aller 1998). Surface and near-surface sedimentary structures are then a time-integrated record of recent biological and physical-chemical processes, which can be used to evaluate the trends in ecosystem recovery.

To investigate processes structuring the sediment-water interface, Rhoads and Cande (1971) developed the sediment profile camera as a means of obtaining *in situ* data on the dynamics of seafloor processes and biogenic activity. The technology of remote ecological monitoring of the sea floor (REMOTS™) or sediment profile imaging (SPI) has allowed the development of a better understanding of the complexity of sediment dynamics, from both biological and physical points of view (Nilsson and Rosenberg 2000, Rosenberg *et al.* 2001, Solan *et al.* 2005). In this paper, we used SPI to characterize the benthic environment from both physical and biological perspectives and related trends to major changes in wastewater disposal within Boston Harbor to long-term changes in habitat condition and quality that could be related to reductions in sewage discharge to the harbor.

4.2 Methods

Reconnaissance surveys were carried out from 1989 to 1990 to locate soft-sediment areas throughout the harbor that would likely be depositional or at least low-energy bottoms with a higher likelihood of responding to effects related to wastewater discharge effects (SAIC 1990). In 1993, SPI monitoring started with summer (August) sampling at a series of 42 reconnaissance (R) stations and eight traditional (T) stations. In 1995, an additional eight reconnaissance stations were added (Figure 2-1). In 2004 another traditional station (C019) was added, but was not included in this long-term analysis.

At each station, a Hulcher sediment profile camera was deployed a minimum of three times. From 1993 to 2000, a 35-mm film camera was used with Fujichrom 100P film. Starting in 2001, a digital Minolta Dimage-7i camera (2560 X 1920 pixels) that captured a 5.2-megapixel image was used. Approximately 75 to 150 pounds of lead were added to the camera frame to improve penetration at all stations. After development the film images were digitized at a resolution similar to the digital images. Analysis of the SPI followed the methods of Rhoads and Germano (1986), Diaz and Schaffner (1988), and Williams *et al.* (2005). Parameters evaluated from SPI included prism penetration, modal sediment grain-size, processes structuring sediment surface, thickness of apparent color RPD layer, presence of biogenic structures, and estimation of infaunal community maturity. For quantitative variables, data from the three replicates were averaged. For categorical variables, the median or modal value was assigned to a station.

Given the nonrandom selection of station locations, fixed-effect longitudinal designs were used to analyze patterns in the data. Generalized estimating equations (GEE) were applied with two basic model structures (Zeger *et al.* 1988). For binary dependent variables, the binomial distribution was used as the random component and the logit as the link function. For continuous variables, the normal distribution and identity link were applied. In both models the cross-station correlations were assumed to be equal. 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. Fisher Exact Test was used for comparison involving odds and odds ratios (Agresti 1990). All statistical tests were conducted using SAS® (SAS Institute, Inc.) (Allison 1999).

4.3 Results

4.3.1 Regional Harbor Trends

From 1993 to 2005 the predominant sediment type at the stations sampled appeared to be mixed fine-sand-silt-clay (modal Phi 4.5 to 5.5) and was found at 45% of 758 station-year combinations. Sediments appeared to be finer silt-clay (modal Phi >6) 39% of the time and sandy, mostly fine- to medium-sands with a few coarser stations (modal Phi <3), for 16% of the station-year combinations. As the stations sampled were not randomly selected, our observed distribution of grain size was not representative of Boston Harbor, which has a significant amount of hard bottom from pebble-sized grains and larger. Knebel and Circé (1995) characterized the harbor seabed as a patchwork with over 51% being long-term depositional, 29% being reworked sediments containing patches of fine-grained sediments, and 20%

erosional/nondepositional. Overall, sediments in 1993 appeared to be sandier than previously found with the odds of encountering a sandy station versus a muddy station (>4.5 Phi) at 1.9. In 1994 the odds of encountering a sandy station declined to 0.3 and from 1995 and later, the odds declined further to <0.2. This harbor-wide trend towards finer grain-size, declining odds of encountering sandy sediment, was significant (repeated measure GEE, Chi Sq = 8.5, p = 0.004). When yearly odds of a station being sandy were examined relative to 2005, only 1993 and 1994 were significantly sandier, however, the odds for the occurrence of finer-grained sediments tended to indicate 1999 was the muddiest year with 62% of the stations being silt-clay (>6 Phi). The range in grain-size distributions observed at 21 stations was fine-sand-silt-clay to silt-clay. At 38 stations sediments appeared to be sandy at least in one year. The only station to be sandy all years was R23 in Nantasket Roads. Two other stations (R06 off Long Island and T08 in Hingham Bay) were sandy in all years except 2005 for R06 and 1999 for T08 (Table 4-1). When maximum grain-size as seen in SPI was recorded from 2002 to 2005, pebble size grains occurred at 10% to 17% of stations. Spatially, there were the same proportion of sandy and muddy stations located in the inner and outer half of the Harbor. Regionally, stations in Nantasket Roads, Hingham Bay, Deer Island Flats, and off Long Island all had the same odds of having sandy stations. These areas were sandier than stations in Dorchester Bay (odds ratio 3.8, Fisher's Exact test, p = 0.013), or Quincy Bay (3.6, p = 0.007), or Charles River (11.1, p = 0.026).

The range of sedimentary habitats within the harbor was also reflected in the average station prism penetration depth, which is a proxy for sediment compaction, with deeper prism penetration in higher-water-content, less-consolidated sediments. Prism penetration depth across all years was significantly lower, representing more compact sediments, at coarser sand-gravel stations (3.7±0.5 cm, mean±SE, N = 72) than at fine-sand stations (7.5± 0.6, N = 49) than at fine-sand-silt-clay stations (11.3±0.2 cm, N = 339) than at silt-clay stations (16.3±0.2 cm, N = 297), (Welch ANOVA, df = 3, p = <0.0001), which likely had the highest water content. At physically dominated stations with coarse sandy sediments, surface relief was due to sediment grain size (gravel, pebble, or cobble) and bedforms. At biologically dominated stations, surface relief was typically biogenic structures produced by benthic organisms. *Ampelisca* spp. tubes were the primary relief-creating biogenic features, followed by what appeared to be feeding pits or mounds (Figure 4-1).

The thickness of what appeared to be geochemically oxidized sediments (aRPD) was related to time, region within the harbor, and presence of *Ampelisca* spp. tube mats, (Longitudinal GEE model, Table 4-2). While there was a significant relationship with year in the GEE model, the trend in the thickness of the aRPD was small and ranged about 2.5 cm over the 13 years. When stations were grouped by harbor region, the area off Long Island (3.7±0.19 cm, mean±SE) and Nantasket Roads (3.1±0.16 cm) had significantly thicker aRPD layers relative to the rest of the Harbor (ANCOVA, year p = 0.816, df = 6, F = 260.0, p = <0.001). Deer Island Flats (2.4±0.14 cm) and Hingham Bay (2.3±0.12 cm) stations had thicker aRPD layers than Quincy Bay (2.0±0.14 cm), Charles River (1.7±0.31 cm), and Dorchester Bay (1.5±0.17 cm). Dorchester Bay had the thinnest layers of all the harbor areas.

It was biogenic activity associated with the presence of *Ampelisca* spp. that had the most influence in deepening the aRPD. When controlling for presence of *Ampelisca* spp. tube mats (tube mats are defined as more than 50 tubes per image), the thickness of the aRPD was not related to sediment type. The tubes observed in Boston Harbor were similar in size and shape to those described by Mills (1967), being about 3.5 x 0.2-0.3 cm with about 1 cm above sediment (Figure 4-1). Where *Ampelisca* spp. tubes were at mat densities, mean aRPD depth, controlling for sediment type and year, was significantly deeper (3.4±0.09 cm, mean±SE) than at stations without *Ampelisca* spp. (1.5±0.09 cm) or at stations with *Ampelisca* spp. present, but at less than tube-mat densities (1.9±0.12 cm) (ANCOVA, sediment type p = 0.914, year p = <0.001, df = 2, F = 101.4, p = <0.001). In 1992, prior to the start of annual SPI monitoring, about 40% of stations sampled for establishing the long-term stations had mat densities of *Ampelisca* spp. tubes.

Table 4-1. Modal grain-size estimated from SPI from 1993 to 2005. Sandy sediments were categorized as fine-sand (FS) and coarser (SA), and muddy sediments as mixed fine-sand-silt-clay (FSSICL) or finer silt-clay (SICL).

Sta.	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
R02	SICL	SICL	FSSICL	FSSICL	FSSICL	SICL	SICL	SICL	SICL	SICL	SICL	FSSICL	FSSICL
R03	FS	FSSICL	SA	FSSICL	FSSICL	SICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
R04	FS	FSSICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL
R05	FS	FSSICL	SICL	SICL	FSSICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL
R06	FS	SA	SA	SA	SA	SA	SA	SA	SA	SA	SA	SA	FSSICL
R07	FS	FSSICL	SICL	FSSICL	FSSICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL
R08	SA	FS	SA	FSSICL	SA	FS	FSSICL	FSSICL	FSSICL	FS	FS	FS	FS
R09	FS	SICL	SICL	FSSICL	FSSICL	SICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
R10	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL
R11	FSSICL	SICL	FSSICL	SICL	SICL	SICL	SICL	SICL	SICL	FSSICL	FSSICL	SICL	SICL
R12	FSSICL	SICL	FSSICL	SICL	FSSICL	SICL	SICL	SICL	SICL	FSSICL	SICL	SICL	SICL
R13	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	SA	SICL	SICL	SICL	FSSICL	FSSICL	FSSICL	SA
R14	FS	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
R15	FSSICL	SICL	FSSICL	FSSICL	FSSICL	SICL	FSSICL	SICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
R16	FSSICL	SICL	FSSICL	FSSICL	FS	SICL	SICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
R17	FSSICL	SICL	FSSICL	FSSICL	SICL	SICL	SICL	SICL	FSSICL	SICL	SICL	SICL	SICL
R18	FSSICL	FSSICL	FSSICL	FSSICL	SICL	SICL	SICL	SICL	SICL	FSSICL	FSSICL	SICL	SICL
R19	SA	SA	SA	FSSICL	SA	SA	FSSICL	SA	SA	SA	SA	SA	SA
R20	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	SA	SICL	SICL	SICL	FSSICL	FSSICL	SICL	FSSICL
R21	FS	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	SICL	SICL
R22	FS	FS	SA	SA	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	SA	SA	FSSICL
R23	FS	FS	SA	SA	SA	FS	SA	SA	SA	SA	SA	SA	SA
R24	FS	FS	FSSICL	FSSICL	FSSICL	SICL	SICL	SICL	SICL	FSSICL	FSSICL	SICL	SICL
R25	FSSICL	FSSICL	SICL	SICL	FSSICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL
R26	FS	FSSICL	SICL	FSSICL	SA	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL
R27	FS	FSSICL	FSSICL	SICL	FSSICL	SICL	SICL	SICL	SICL	FSSICL	FSSICL	SICL	SICL
R28	FS	FSSICL	FSSICL	SICL	FSSICL	FSSICL	FSSICL	SICL	SICL	FSSICL	FSSICL	SICL	FSSICL
R29	FS	FSSICL	FSSICL	SICL	FSSICL	FSSICL	SICL	SICL	SICL	FSSICL	FSSICL	SICL	SICL
R30	FS	FSSICL	FSSICL	SICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	SICL	SICL

Sta.	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
R31	FS	FSSICL	FSSICL	SICL	FSSICL	SICL	SICL	SICL	SICL	FSSICL	FSSICL	SICL	SICL
R32	FS	FSSICL	SICL	SICL	FSSICL	SICL	SICL	SICL	SICL	FSSICL	SICL	SICL	SICL
R33	FS	FSSICL	FSSICL	SICL	FSSICL	SICL	SICL	SICL	SICL	FSSICL	SICL	SICL	SICL
R34	FS	FSSICL	FSSICL	SICL	FSSICL	SICL	SICL	SICL		FSSICL	SICL	SICL	SICL
R35	FS	FSSICL	SICL	SICL	FSSICL	SICL	SICL	SICL		FSSICL	SICL	SICL	SICL
R36	SA	SA	SA	SA	SA	FSSICL	FSSICL	FSSICL	SA	FSSICL	FSSICL	FS	FS
R37	FS	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	SICL	FSSICL	FSSICL	FSSICL	FSSICL	SICL	SICL
R38	FSSICL	FSSICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	FSSICL	SICL	SICL	SICL
R39	FSSICL	FSSICL	SA	FSSICL	FSSICL	SICL	SICL	SICL	SICL	FSSICL	SICL	SICL	SICL
R40	FS	FS	SICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	SICL
R41	FS	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	SICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	SICL
R42	FS	FS	FSSICL	SA	FSSICL	FS	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
R43	FS	SICL	FSSICL	FSSICL	FSSICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL
R44			FSSICL	SICL	FSSICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL
R45			FSSICL	FSSICL	FSSICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL
R46			FSSICL	FSSICL	FSSICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL
R47			SICL	FSSICL	FSSICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL
R48			FSSICL	FSSICL	FSSICL	FSSICL	SICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
R49			FSSICL	SICL	FSSICL	FSSICL	SICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	SICL
R50			FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
R51			FSSICL	SICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
R52			FSSICL	SICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
R53			FSSICL	FSSICL	SA	FSSICL	FSSICL	FSSICL	FSSICL	FS	FS	FSSICL	FSSICL
T01	FS	SA	FSSICL	SA	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
T02	FSSICL	FSSICL	SICL	SA	FSSICL	SICL	SICL	FSSICL	FSSICL	SICL	SICL	SICL	SICL
T03	FSSICL	SICL	SICL	FSSICL	FSSICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL
T05		SICL	SICL	SICL	FSSICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL
T04	SICL	FS	FSSICL	SA	SA	FS	FSSICL	SA	SA	SA	FSSICL	FSSICL	FSSICL
T06	FS	FSSICL	SICL	SICL	FSSICL	FSSICL	FSSICL	SICL	SICL	FSSICL	FSSICL	FSSICL	FSSICL
T07	FSSICL	FSSICL	SICL	FSSICL	FSSICL	SICL	SICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
T08	SA	SA	SA	SA	SA	FS	FSSICL	SA	SA	SA	SA	SA	SA

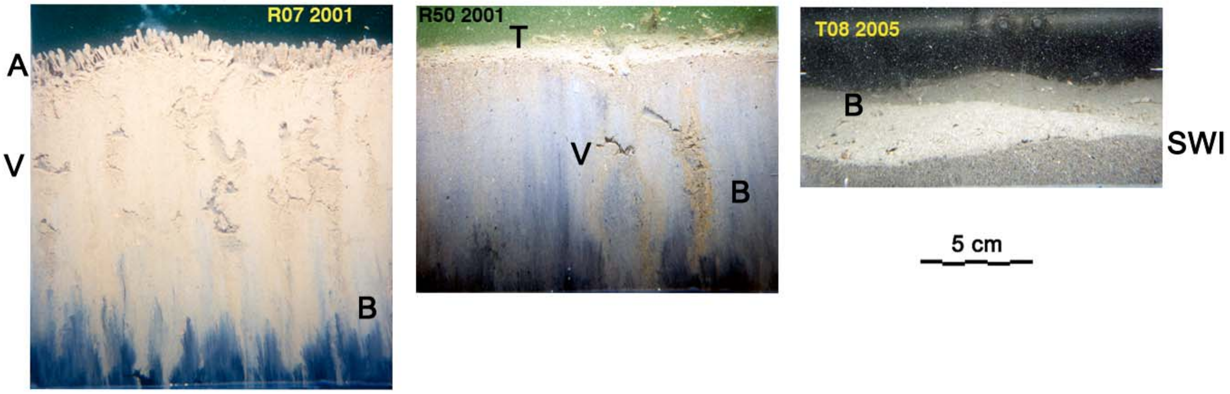

Figure 4-1. SPI showing: R07 for 2001, sediments are silt-clay, surface has a dense *Ampelisca* spp. tube mat (A) with a thick apparent color RPD layer (light brown colored sediment), and other biogenic structures (V – oxic voids and B – burrows); R50 for 2001, sediments are fine-sand-silt-clay, surface has several small tubes, aRPD was about 2.5 cm thick but extended to the bottom of the image by biogenic activities; T08 for 2005, sediments are fine-medium sand with small bedforms (B). SWI is the sediment-water-interface.

Table 4-2. Thickness of the apparent color RPD layer (cm) averaged by Boston Harbor region and presence/absence of *Ampelisca* spp. tube mats through time. N is the number of SPI in each mean.

		Charles River			Dorchester Bay			Deer Island Flats			off Long Island			Nantasket Roads			Quincy Bay			Hingham Bay		
Year	***Ampelisca***	**N**	**Mean**	**SD**	**N**	**Mean**	**SD**	**N**	**Mean**	**SD**	**N**	**Mean**	**SD**	**N**	**Mean**	**SD**	**N**	**Mean**	**SD**	**N**	**Mean**	**SD**
1993	No Mat	2	0.8	0.49	7	1.4	0.61	7	1.0	0.31	2	3.9	2.83				6	1.0	0.16	3	1.3	0.07
	Mat							1	0.6	.	3	2.8	1.12	8	3.9	1.49	3	2.4	1.28	7	2.5	1.07
1994	No Mat	1	1.8		5	1.1	0.50	3	0.5	.	1	.	.	1	1.0	.	6	0.7	0.12	3	1.6	1.17
	Mat	1	1.3		2	1.5	0.42	6	1.7	0.38	4	4.4	2.18	7	1.9	0.78	3	1.7	0.75	7	2.3	0.98
1995	No Mat	2	1.4	0.12	4	2.0	1.88	3	1.7	1.05	2	1.9	0.64				5	2.7	2.80	7	1.2	0.44
	Mat				3	5.4	3.11	8	2.1	0.87	4	7.2	0.94	8	4.2	2.53	5	2.2	0.58	9	2.4	1.12
1996	No Mat	1	1.8		5	1.4	0.56	6	2.0	1.25	2	2.0	.	2	1.5	0.35	6	2.0	0.56	1	3.1	.
	Mat	1	2.8		2	1.7	0.02	5	2.2	0.73	4	5.4	2.08	6	3.2	1.50	4	1.8	0.54	15	3.4	2.12
1997	No Mat	1	1.6		5	0.9	0.04	5	1.5	0.42	2	.	.	1	.	.	8	1.6	1.88	7	0.8	0.12
	Mat	1	1.5		2	2.9	1.87	6	3.2	1.75	4	4.6	0.69	7	3.6	1.09	2	5.2	0.12	9	2.6	0.98
1998	No Mat	1	1.5		6	0.9	0.58	6	1.5	0.48	2	1.0	.	2	0.8	.	7	0.6	0.23	8	0.9	0.17
	Mat	1	1.0		1	1.9	.	5	2.1	1.33	4	4.3	2.64	6	2.3	1.18	3	3.7	1.68	8	3.7	0.91
1999	No Mat				7	0.5	0.21	8	0.9	0.36	2	0.6	0.17	1	.	.	8	0.8	0.45	9	0.8	0.20
	Mat	2	2.8	0.85				3	5.3	2.80	4	5.4	2.10	7	3.9	2.62	2	6.2	0.78	7	2.9	1.13
2000	No Mat	2	1.4	0.58	7	1.0	0.57	9	1.6	1.27	2	1.0	0.49	1	2.2	.	10	1.3	0.54	9	1.0	0.62
	Mat							2	3.8	1.17	4	5.2	0.96	7	2.4	0.57	5	2.6	2.10	7	2.3	0.56
2001	No Mat	1	1.8	.	6	1.1	0.40	5	2.1	0.76	1	1.9	.	2	3.7	0.31	2	5.9	2.30	8	2.4	1.97
	Mat	1	2.4	.	1	3.4	.	6	4.7	2.94	5	4.7	0.95	6	4.3	1.61	1	.	.	8	4.6	2.23
2002	No Mat	2	1.3	0.24	6	1.3	0.42	8	2.0	0.49	2	2.0	0.34	6	1.8	0.76	9	1.7	1.07	14	1.8	0.54
	Mat				1	1.9	.	3	2.7	1.27	4	2.4	0.71	2	1.5	0.15	1	3.0	.	2	2.1	0.71
2003	No Mat	2	2.1	0.55	7	1.9	0.63	7	3.8	1.45	4	3.9	2.27	5	3.7	1.85	8	2.4	0.86	9	2.1	1.22
	Mat							4	3.7	1.80	2	4.8	0.38	3	2.5	0.69	2	5.9	1.35	7	3.0	1.55
2004	No Mat	2	1.5	0.02	7	1.3	0.22	10	2.4	1.48	5	2.2	0.72	5	2.8	1.39	10	1.9	0.51	13	1.6	0.57
	Mat							1	2.7	.	1	2.6	.	3	3.1	2.29				3	4.5	0.22
2005	No Mat	2	2.1	1.49	7	1.8	0.73	11	3.1	1.92	6	1.6	0.39	8	3.3	2.23	10	1.7	0.69	16	1.8	1.01

At some time from 1990 to 1992 there appeared to be an increase in the occurrence of *Ampelisca* spp. tube mats. About 20% of images from 1990 had mat densities of *Ampelisca* spp. (SAIC 1992). In 1992, mats increased to about 40% of stations (Blake *et al.* 1993) and continued to increase with peaks at 60 to 65% from 1994 to 1997. Mat densities of *Ampelisca* spp. declined starting in 1998 to 45% and were 13% by 2004 with no tube mats observed in SPI in 2005 (Figure 4-2). The total number of stations with *Ampelisca* spp. tubes at any density, from a few tubes to mat densities, also followed a similar pattern (Figure 4-2).

Ampelisca spp., and other types of tubes and feeding structures, were common biogenic features observed at the sediment surface and appeared to structure surficial sediments at many stations. Starting in 1998, information on the processes structuring surficial sediments was assessed from SPI. It appeared that 31% of all year-station combinations were dominated by biological processes as evidenced by the widespread biogenic activity associated with more mature successional stage infauna (Rosenberg 2001). At 41% of year-station combinations, it appeared that both biological and physical processes were active in structuring bed roughness and physical processes dominating at the remaining 28% of the year-station combinations. There was a significant decline in the odds of a station having a biologically dominated sediment surface through time (data for 1998 to 2005), even when accounting for the declining trend in *Ampelisca* spp. tubes and sediment type (Repeated measure GEE, sediment effect on odds 11.3, p = 0.006, *Ampelisca* spp. effect on odds 79.2, p = <0.001; year effect on odds 0.25, p = <0.001). It also appeared that stations classified as having biologically dominated surface sediments had higher infaunal biogenic activity (infaunal organisms, burrows, feeding voids). The number of infaunal organisms per image was significantly higher at stations with biological or biological and physically dominated surfaces (2.2±0.15 and 2.0±0.13 infauna/image, mean±SE) relative to physically dominated surfaces (0.8±0.16 infauna/image) (Welch ANOVA, df = 2, F = 41.7, p = <0.001). Similarly significant patterns of higher mean values at biologically dominated stations were observed for number of burrows and feeding voids per image. Gas-filled voids, indicative of high rates of methanogenesis, were not related to year or processes structuring surficial sediments. The high degree of biogenic sediment reworking observed at many stations was consistent with the presence of a more mature infaunal community. Evidence of equilibrium successional Stage III fauna, the presence of feeding voids (oxic and anaerobic), was observed at 78% of year-station combinations for 1993–1994 and 1998–2005; the presence of voids was not recorded from 1995 to 1997. Through time there was a significant increase in the odds of a station having feeing voids, which implies an increasing trend in the presence of deeper subsurface feeding species (Repeated measure GEE, sediment effect on odds 23.4, p = <0.001, *Ampelisca* spp. effect on odds 4.1, p = <0.001; year effect on odds 1.2, p = <0.001). Recruitment by small (<1 mm diameter) tube building species, likely pioneering successional Stage I fauna, was evidence at 74% of year-station combinations, with the odds of small tubes being present increasing with time when controlling for the effects of sediment type and surface processes (Repeated measure GEE, sediment effect, p = 0.871, *Ampelisca* spp. effect on odds 0.1, p = <0.001; year effect on odds 1.23, p = 0.006). Much of the increase in odds of small tubes being present appeared due to the decline in *Ampelisca* spp. tubes.

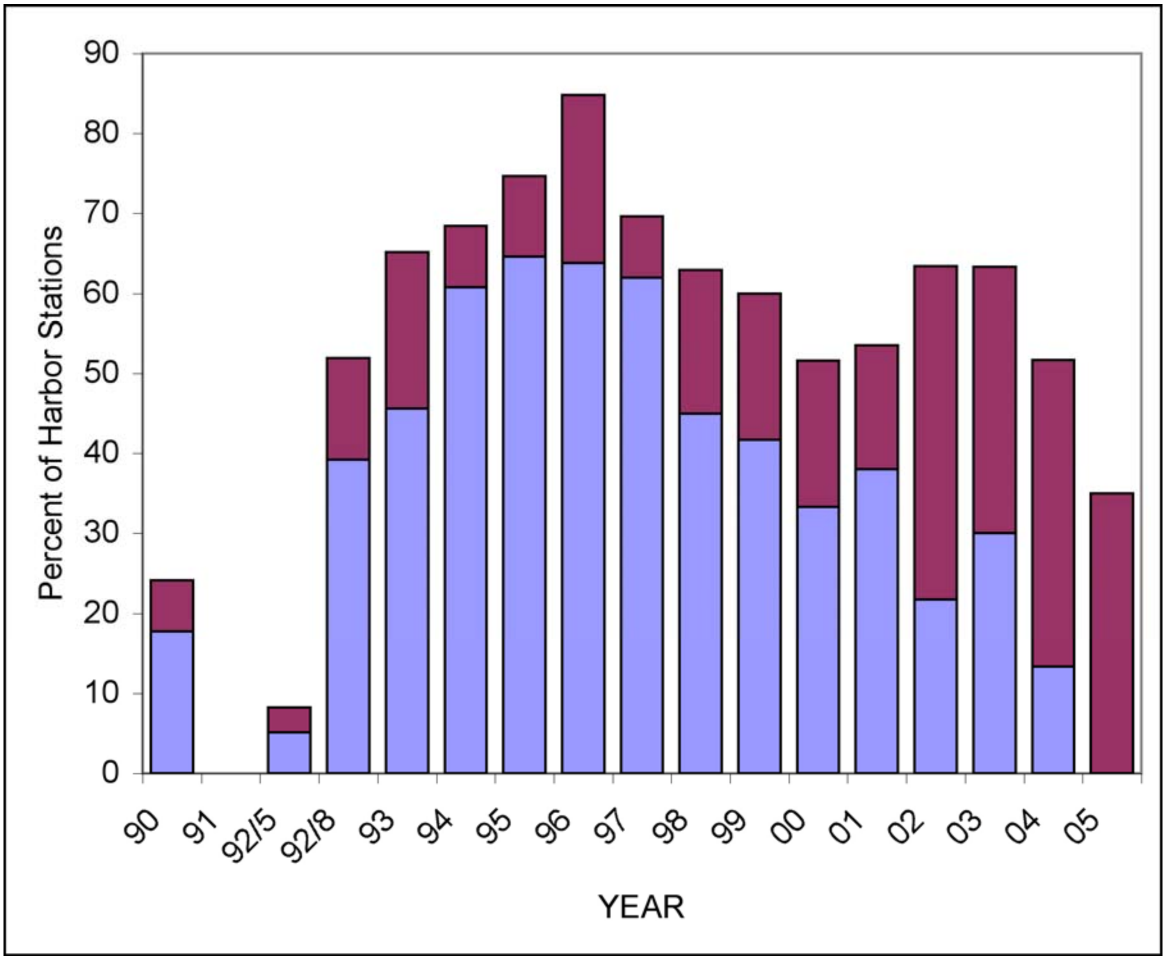

Figure 4-2. Histogram showing the percentage of stations with *Ampelisca* spp. tube mats (bottom portion of bar) and the total percentage of stations with *Ampelisca* spp. tubes. Data prior to 1993 are from SAIC (1992) and Blake *et al.* (1993).

4.3.2 Trends Linked to Changes in Loadings from Wastewater

Prior to the initiation of long-term SPI monitoring, sludge discharge from primary wastewater treatment, which accounted for about 40 tons of solids per day or about 25% of solid loading to the harbor (Werme and Hunt 2004), was ended in 1991. During the monitoring period, two major changes occurred in wastewater discharge. One occurred in June 1998 when discharges near Nut Island in Quincy Bay were transferred to Deer Island at the mouth of the harbor and treatment was upgraded to secondary. The other occurred in September 2000 when all wastewater discharges were transferred to the new ocean outfall. To look for patterns relative to changes in wastewater discharges and loading to the harbor, the SPI data were grouped into the three periods based on Taylor's (2005) summary of major patterns in freshwater flows and loadings of total nitrogen (TN), total phosphorus (TP), total suspended solids (TSS), and particulate organic carbon (POC) to Boston Harbor between 1995 and 2003. Taylor period A was from 1995 through mid-1998 when wastewater was discharged in Quincy Bay off Nut Island. During period A, the harbor received elevated freshwater flows and high loadings of TN, TP, TSS, and POC. On average, wastewater flows were 39% (SD = 20%) of the 1.85 x 106 m^3 d-1 (SD = 1.33) river flows. Period B was from mid-1998 to 2000 when the Nut Island discharges were transferred to off Deer Island and secondary treatment was improved. Freshwater flows, at 1.7 x 106 m^3 d-1 (SD = 1.2), remained moderately elevated above the long-term average, but loadings of TSS and POC, and to a lesser extent TN and TP, decreased. During summer low flows within Periods A and B, wastewater accounted for almost half of all freshwater entering the harbor (Taylor 2005). Period C was post-transfer of the Deer Island discharge offshore in 2000. Loadings of TSS and POC were further reduced, but the largest decrease was observed for TN and TP. River flows declined during period C to an average of 1.3 x 106 m^3 d-1 (SD = 1.1), but the largest decline in freshwater flows was primarily due to moving wastewater discharge offshore. The changes in wastewater discharge in 1998 and again in 2000 resulted in about a 90% decrease in loadings to Boston Harbor. For TSS and POC, most of the decreases occurred between Periods A and B, presumably in response to the transfer of the Nut Island discharge to Deer Island and treatment upgrade. For TN and TP, most of the decreases occurred between Periods B and C, in response to transfer of the discharge offshore (Taylor 2005).

SPI data from 1993 to 1998 were grouped for period A. Both 1993 and 1994 were included because USGS stream flow data (http://waterdata.usgs.gov/ma/nwis/sw) and loadings data (Werme and Hunt 2004) indicated these years were similar in river flows and loadings to other years in the period. Period B was SPI data for 1999 and 2000, and 2001 to 2005 for period C. 2004 and 2005 were included as part of period C for similar reasoning that put 1993 and 1994 into period A.

Had the reductions in loadings associated with reduced wastewater discharge and improved treatment affected benthic habitat quality for infauna within the harbor, the largest effects should have been observed at stations closest to the outfalls. Based on this hypothesis of localized wastewater discharge impacts, stations nearest Nut Island (within 2 km: R18, R22, R23, R24, and T06; within 4 km: R21, R38, R39, and T07) and Deer Island (within 2 km: R02, R03, R07, R47, T01, and T05A; across channel: R06, R45, and T03) outfalls should have shown the greatest change relative to relocation of discharges and improved treatment (Figure 2-1). Based on the results of harbor-wide trends, which indicated that sediment type and presence of *Ampelisca* spp. tube mats controlled many of the SPI parameter associations, GEE models were constructed controlling for these variables to determine effects of proximity to an outfall (<2 km and <4 km) and Taylor periods (A, B, and C).

For Nut Island, there was no significant effect of proximity to outfalls for any of the SPI parameters examined (Table 4-3). At Deer Island, there were significant differences in burrows and oxic voids, both indicators of subsurface biogenic activity. The odds of burrows being present was greater further away from the outfalls. For oxic voids, the odds were greater nearer the old outfalls. For the Nut Island stations, the odds of an *Ampelisca* spp. tube mat occurring declined from period A to B to C. For Deer Island, most of the decline in the odds of tube mats being present occurred from period A to B. There was no significant difference between periods B and C (Figure 4-3). The harbor-wide decline in tube mats was consistent with reduced loadings from 1993 to 2000. There were no significant patterns in the depth of the apparent color RPD layer related to Taylor periods. Patterns in biogenic activity relative to Taylor periods was mixed. The number of infauna and oxic voids observed in SPI was significantly higher in period C for both Nut and Deer Islands, but the odds of burrows and tubes being present declined for period C only for Deer Island (Figure 4-4). At Nut Island the patterns for burrows and tubes were not significant.

The patterns of biological change observed in SPI, the most obvious being the reduction in *Ampelisca* spp. tube mats, may be related to changes in organic matter stored in the sediment. With the reductions in loadings to the harbor, benthos may have relied on inventories of organic matter stored in the sediment for maintaining large populations. Measurements of TOC at T02 (flux station BH02) and T03 (BH03) found TOC was less variable and declined slightly in periods B and C relative to period A. For station T03, the decline in TOC for periods B and C was more pronounced (Tucker *et al.* 2004). The significant decline in the odds of a tube mat being present at a station from periods A to C would also be consistent with reduction of sediment organic inventories as large amounts of organic matter are needed to sustain mat densities of *Ampelisca* spp., which McCall (1977) considered to be an opportunistic r-strategist. High densities of *Ampelisca abdita*, up to 94,000 m^2, in Jamaica Bay, New York, were sustained by large amounts of particulate organic carbon—much of which was contributed indirectly from wastewater effluents and incorporated into sediments (Franz and Tanacredi 1992). To estimate the amount of organic matter needed to support mat densities, we assumed that *Ampelisca* spp. in Boston Harbor had a similar life history to *A. abdita* in Jamaica Bay. Franz and Tanacredi (1992) estimated mat densities of *A. abdita* to produce at 25 to 47 g DW/m^2/year or 12 to 24 g C/m^2/yr. Assuming a 10% trophic level transfer efficiency then 120 to 240 g C/m^2/yr are needed to support mat densities. Based on carbon inputs to Boston Harbor, it then seems that *Ampelisca* spp. consumed from 7% to 18% of the total carbon (Table 4-4). While the total annual carbon budget for Boston Harbor should be sufficient to support high densities of *Ampelisca* in any one year, the increases and declines observed from 1993 to 2005 may be related to a shift from wastewater to phytoplankton-derived carbon.

Table 4-3. Summary of longitudinal analyses for SPI variables from stations within 4 km of either Deer or Nut Island outfalls. Taylor A, B, and C refer to periods of loading reductions to Boston Harbor. A-C is the effect between periods A and C, and similarly B-C is the effect of period B to C. Negative estimates indicate an increase in the variable going toward period C. Near vs. Far, contrast stations <2 km (Near) to stations <4 km (Far) of the outfalls. A positive estimate indicates an increase at <2 km stations. Sediment class and *Ampelisca* spp. tube mats were included as covariates, with negative estimates indicating a decline in the variable as sediments became finer and mats increased.

		Deer Island			**Nut Island**	
			Ampelisca spp. Tube Mat			
Parameter	Estimate	SE	P	Estimate	SE	P
Intercept	3.069	0.932	0.001	0.720	0.485	0.138
Sediment	-1.741	0.470	<0.001	-0.209	0.345	0.544
Taylor A-C	-2.248	0.629	<0.001	-2.397	0.359	<0.001
Taylor B-C	-0.497	0.584	0.395	-1.127	0.415	0.007
Near vs. Far	0.078	0.516	0.880	-0.620	0.840	0.461
			aRPD Thickness			
Parameter	Estimate	SE	P	Estimate	SE	P
Intercept	2.193	0.461	<0.001	1.980	0.189	<0.001
Sediment	0.448	0.393	0.255	0.416	0.248	0.094
Ampelisca Mat	0.412	0.171	0.016	0.652	0.183	<0.001
Taylor A-C	-0.653	0.614	0.287	-0.394	0.411	0.338
Taylor B-C	-0.460	0.432	0.287	-0.626	0.341	0.067
Near vs. Far	-0.482	0.440	0.274	0.210	0.379	0.579
			Infauna per Image			
Parameter	Estimate	SE	P	Estimate	SE	P
Intercept	0.919	0.545	0.092	1.933	0.853	0.023
Sediment	1.969	0.416	<0.001	0.020	0.552	0.972
Ampelisca Mat	-0.363	0.323	0.261	0.286	0.279	0.305
Taylor A-C	-1.128	0.505	0.026	-1.050	0.592	0.076
Taylor B-C	-1.220	0.372	0.001	-0.877	0.370	0.018
Near vs. Far	0.694	0.410	0.090	-0.573	0.848	0.499
			Oxic Voids per Image			
Parameter	Estimate	SE	P	Estimate	SE	P
Intercept	1.626	0.509	0.001	0.766	0.414	0.064
Sediment	0.764	0.320	0.017	0.610	0.294	0.038
Ampelisca Mat	0.094	0.209	0.652	0.579	0.168	0.001
Taylor A-C	-1.445	0.499	0.004	-1.959	0.491	<0.001
Taylor B-C	-1.359	0.326	<0.001	-1.422	0.233	<0.001
Near vs. Far	1.099	0.366	0.003	-0.177	0.453	0.696
			Burrows present/absent			
Parameter	Estimate	SE	P	Estimate	SE	P
Intercept	-0.943	0.497	0.058	-0.231	0.578	0.689
Sediment	-2.322	0.622	<0.001	-1.476	0.565	0.009
Taylor A-C	1.513	0.605	0.012	0.662	0.625	0.290
Taylor B-C	0.833	0.259	0.001	0.095	0.443	0.830
Near vs. Far	-2.259	0.877	0.010	0.729	0.743	0.326
			Tubes present/absent			
Parameter	Estimate	SE	P	Estimate	SE	P
Intercept	-3.813	1.114	0.001	-4.940	1.625	0.002
Sediment	-0.793	0.980	0.419	0.354	0.555	0.524
Ampelisca Mat	2.636	1.145	0.021	1.967	0.422	<0.001
Taylor A-C	2.430	1.216	0.046	1.285	0.780	0.099
Taylor B-C	1.467	0.625	0.019	1.119	0.750	0.136
Near vs. Far	0.084	0.559	0.881	-0.511	0.858	0.552

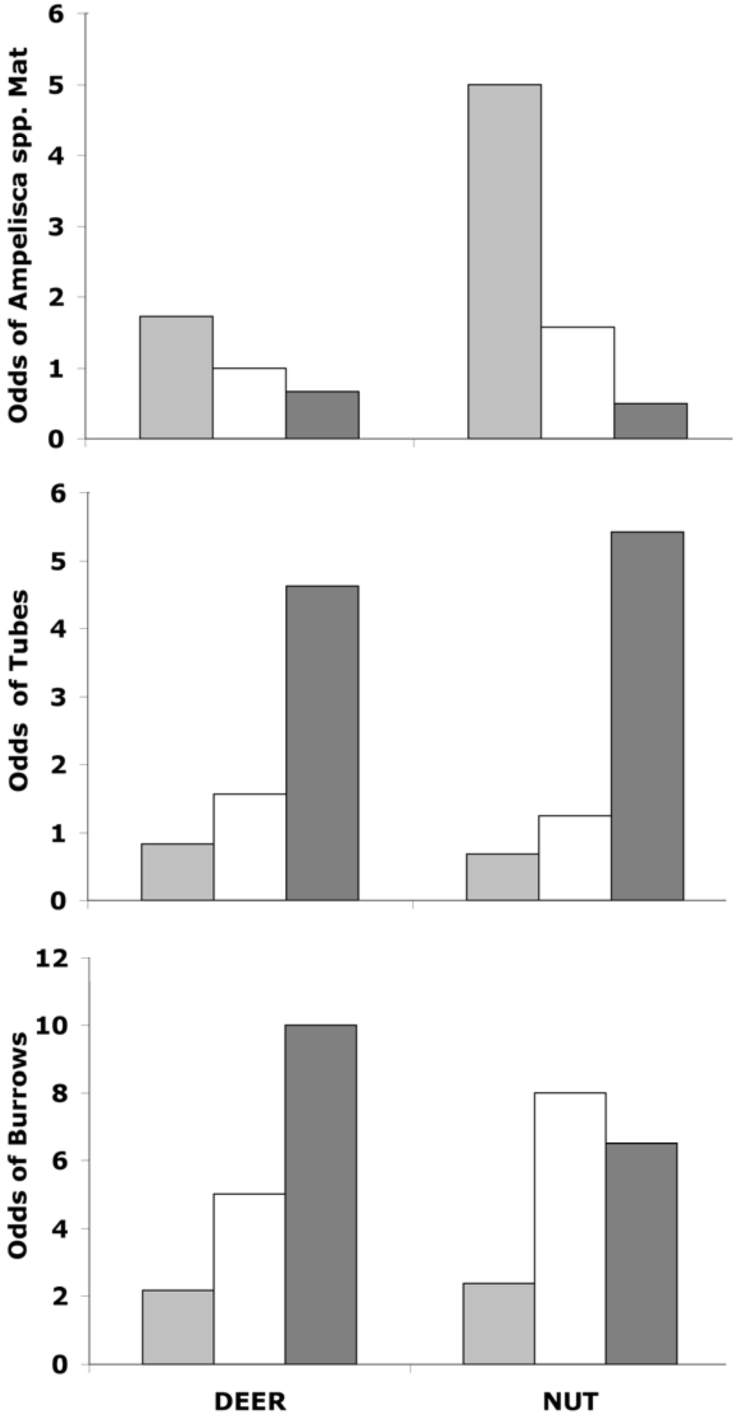

Figure 4-3. Histograms depicting the change in odds for *Ampelisca* spp. tube mats, other tubes, and burrows moving from Taylor (1995) periods A (light gray), B (open bar), and C (dark gray) for each of the harbor outfall areas.

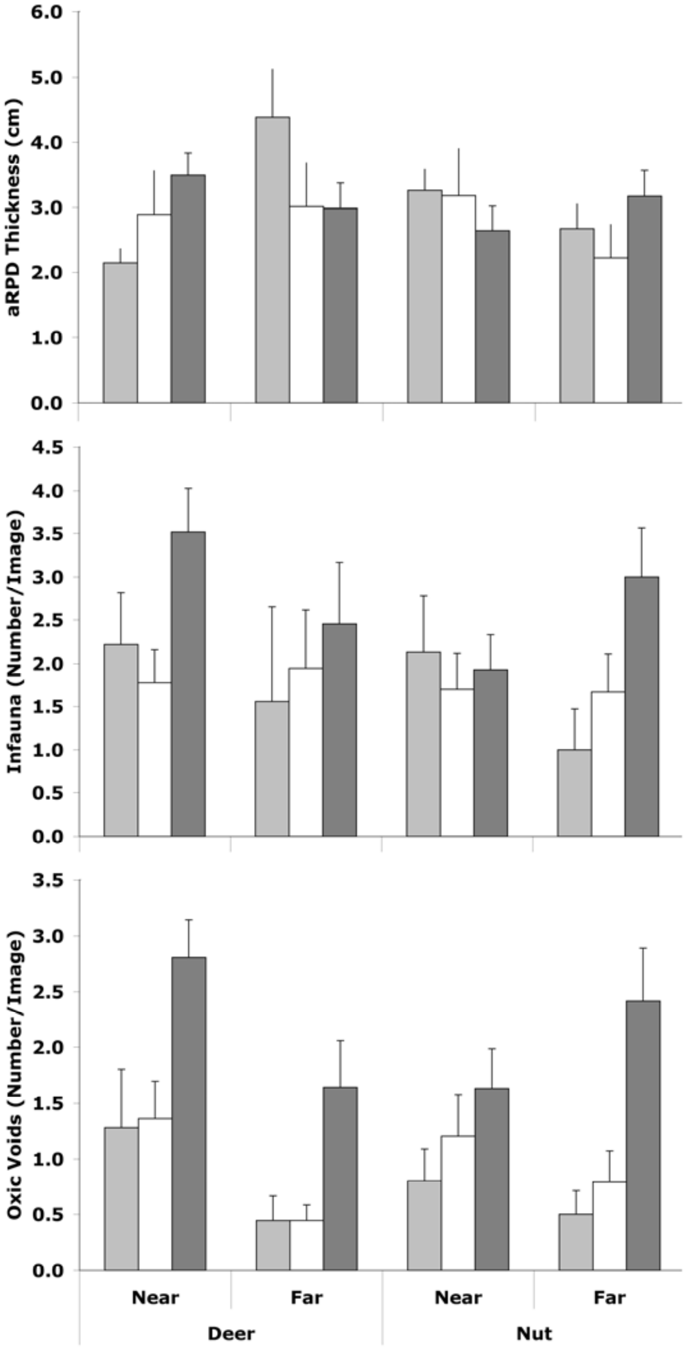

Figure 4-4. Histograms depicting the mean (+/-SE) for thickness of the apparent color RPD layer, number of infauna per image, and number oxic voids per image by Taylor (1995) periods A (light gray), B (open bar), and C (dark gray). Stations were blocked by distance to outfall for each of the harbor outfall areas.

Table 4-4. Estimated organic carbon inputs to Boston Harbor and percentage of carbon flowing through *Ampelisca* spp. over time blocked by Taylor periods. Wastewater carbon estimates were derived from Taylor (2005), primary production (PP) was estimated from (Keller *et al.* 2001, Oviatt personal communication), *Ampelisca* production from Franz and Tanacredi (1992).

	Taylor Period	Wastewater g C/m2/yr	PP g C/m2/yr	Total C g C/m2/yr	Total C Wastewater %	Total C PP %	*Ampelisca* % 120 gC/m2/yr	*Ampelisca* % 240 gC/m2/yr
	A	92	700	792	12%	88%	15%	30%
	B	32	600	632	5%	95%	19%	38%
	C	9	350	359	3%	97%	33%	67%

Taylor Period	Wastewater mt C/yr	PP mt C/yr	Total mt C/yr	Mat % stations	Mat Area Km2	mt C @ 120 gC/m2	C to support *Ampelisca* at Mat Densities:		
							% of C	mt C @ 240 gC/m2	% of C
A	11450	87500	98950	0.59	74	8850	9	17700	18
B	4000	75000	79000	0.38	48	5700	7	11400	14
C	1150	43750	44900	0.26	33	3900	9	7800	17

4.4 Discussion

From 1991 to the start of outfall operation in 2000, a series of regional events transpired that influenced all of Boston Harbor. Climatologically, severe storms passed over the region in October 1991 and May 2005 representing the highest and second highest bottom stress on record, respectively (Butman *et al*. In Preparation). Freshwater flow was elevated for much of the study period except for 1995, which was a low-flow year (Taylor 2005). 1991 was also the year sludge dumping within Boston Harbor ended (Taylor 2005). 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 down to about 4,000 mt C/yr from a high of about 11,400 mt C/yr. Starting in late 2000, the offshore discharge went into operation and diverted about an additional 2,800 mt C/yr out of the Harbor (Taylor 2005). Overall, the changes in wastewater discharge and improved treatment from 1995 to 2000 resulted in about a 90% decrease in loadings to Boston Harbor to about 1,200 mt C/yr. The reductions in loadings within the harbor were due to a combination of treatment upgrades and transfer of the discharge offshore.

It is possible that the major climatological event and cessation of primary discharges in the early 1990s set the stage for harbor benthic conditions prior to the start of our study. The most apparent change in harbor benthos was the widespread increase in *Ampelisca* spp. that took place in 1992 (Figure 4-2). The tube-building amphipods in the genus *Ampelisca*, which seem to have a life history that reflects a combination of opportunism in responding to organic matter (McCall 1977) and sensitivity to pollutants (Wolfe *et al.* 1996) could be considered an indicator of improving benthic habitat quality and intermediate along a path of community maturation (Rhoads and Germano 1986). *Ampelisca* spp. seem to thrive in high organic input areas with good water quality (Stickney and Stringer 1957). Based on grab-sample data, *Ampelisca* spp. tube mats were not broadly distributed in Boston Harbor prior to mid-1992 (Hilbig *et al.* 1997). While organic loads were high prior to 1992, water quality may have been poor. In late 1992, there was about a doubling of stations with *Ampelisca* spp. tube mats from <20% to about 40%. From 1993 to 1995, the spatial distribution of tube mats increased to >60% of stations and remained at >60% until 1998 when the distribution of tube mats started to contract and dropped to about 20% by 2000. In 2003, there was a rebound to about 30% and then a decline in 2004 to 13%. In 2005, *Ampelisca* spp. tubes did not occur at mat densities at any of the 60 monitoring stations. This progression of higher percentages of tube mat stations in the 1990s and generally declining percentages from 2000 is consistent with the shifting organic loading to the harbor and a lagged response of *Ampelisca* spp. As stores of organic carbon in the sediments were depleted amphipod densities declined. Based on energetics, large amounts of organic matter are required to maintain mat densities of *Ampelisca* spp. because of their high productivity and turn-over ratio (Robertson 1979, Franz and Tanacredi 1992).

Regionally within Boston Harbor, it appears that from 1993 to 2005 benthic habitat conditions as measured by SPI did not changed appreciably, except as noted for *Ampelisca* spp. tube mats. Throughout this period, stations in Nantasket Roads, Hingham Bay, Deer Island Flats, and off Long Island tended to be sandier than stations in Dorchester Bay, Quincy Bay, or Charles River. There was also a long-term increase in what appeared to be reddish-brown geochemically oxidized sediments (Jørgensen and Revsbech 1985), thickness of the apparent color RPD layer (aRPD) in SPI, which would be consistent with either reductions in organic loading or increases in bioturbation, or both. The increase in aRPD thickness was a harbor-wide trend even controlling for regions within the harbor and presence of *Ampelisca* spp. tube mats. The thinnest aRPD layers occurred in Dorchester Bay, which also had the stations with the poorest habitat quality. Poor habitat quality stations tended to be mud stations in Dorchester Bay (T04 and R43), which exhibited little evidence of surface or subsurface biogenic activity.

Station T04 appeared to be the most highly stressed soft-bottom benthic habitat in the harbor, likely from a combination of high TOC (range of 3.1 to 8.9%) and poor water quality. This level of TOC is highly correlated with altered community structure and reduced benthic habitat quality for infauna (Pearson and Rosenberg 1978, Hyland *et al.* 2005) Infauna at station T04 consistently had the lowest community structure statistics of all stations sampled within the Harbor (Maciolek *et al.* 2006). Conversely, Stations T03 along the western side of Long Island had consistently good benthic habitat quality and infaunal communities despite the fact that it was across the channel from the Deer Island outfall and had TOC that ranged from 2.5% to 3.8% over the years sampled. This is an indication that habitat quality cannot be determined solely by the quantity of organic matter. Other factors such as quality of the organic matter (Marsh and Tenore 1990) and hydrodynamics (Nowell and Jumars 1984) may be more important determinants of benthic habitat quality.

The functioning of a marine coastal ecosystem is dependent on a complex of processes, many of which are related to the sediment, infauna, and SPI variables examined. For example, bioturbation is a primary determinant of sediment oxygen concentration, which in turn influences biomass, the rate of organic matter decomposition, and regeneration of nutrients (Giblin *et al.* 1997, Nowicki *et al*. 1997, Aller and Aller 1998). The magnitude and importance of bioturbation is primarily a function of biodiversity, species life histories, and abundance patterns (Diaz and Schaffner 1990, Solan *et al*. 2004). Sediment grain-size and hydrodynamic processes are also important in determining the relative importance of biogenic to physical mixing processes. Thus, infaunal benthic habitat quality can be associated with the level of bioturbation.

5. 2005 SOFT-BOTTOM INFAUNAL COMMUNITIES

by Nancy J. Maciolek

5.1 Introduction

Nine stations in Boston Harbor were sampled in August 2005 for soft-bottom benthic infauna. Seven of these stations have been sampled consistently since September 1991; the eighth, T05A, replaced T05 in 1993. A ninth station, C019, was added in 2004 to monitor changes that may occur during upgrading of the combined sewer overflow (CSO) system. Station locations are indicated in Figure 2-1 (Chapter 2, this report).

In the early years of sampling in Boston Harbor, stations in the northern part of the harbor, particularly those near Deer Island flats, were characterized as polluted, with low species richness, diversity, and evenness (Blake and Maciolek 1990, Maciolek *et al.* 2004). Stations in the southern harbor, *i.e.*, Quincy, Hingham, and Hull Bays, were noticeably different, with a richer, more diverse fauna. As changes in terms of the character and amount of sewage dumped into the harbor have been implemented, the stations in the northern part of the harbor have exhibited more changes in the number of species and diversity of the benthic fauna than have the stations in the southern part.

5.2 Methods

5.2.1 Laboratory Analyses

Samples were preserved with formalin in the field (see Chapter 2), and in the laboratory were rinsed with fresh water 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. After the samples were sorted, the organisms were identified to the lowest practical taxonomic category, usually species. Voucher specimens of any species newly identified from the harbor samples were kept as part of the MWRA reference collection.

5.2.2 Data Analysis

Preliminary Data Treatment—Prior to performing any analyses, several modifications were made to the database (Appendix C1). These modifications were generally similar to those performed in previous years as given in the standard operating procedure (SOP) for this project (Williams *et al.* 2005). 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, cluster and principle components analysis) included only those taxa identified to species level, or those treated as such.

Statistical Analysis—Initial inspection of the benthic data included production of summaries of species densities by sample, tables of species dominance, and lists 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, univariate and multivariate methods were used to assess community patterns and structure.

Univariate Measures —PRIMER v.5 (Clarke and Gorley 2001) 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.

A PRIMER routine was also used to calculate a species-area curve for the 15-year monitoring period. Gallagher's program *rarefyl* was used to construct rarefaction curves for the same period.

***Multivariate Measures* —Similarity analysis** was performed using both CNESS (chord-normalized expected species shared) (Trueblood *et al.* 1994) and the Bray-Curtis index (Bray and Curtis 1957). For the analysis of the 1991–2005 samples, replicates were pooled to one sample per year (*i.e.*, all samples from all stations pooled to one annual sample). All similarity matrices were clustered using a hierarchical agglomerative clustering technique, with group average sorting.

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 annual data and 20 for multiyear comparisons. CNESS is included in the COMPAH96 package, 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).

The Bray-Curtis similarity analyses were based on a fourth-root transformation of the data (performed in order to diminish the impact of numerically dominant species) and were carried out in PRIMER v.5 (Clarke and Gorley 2001).

The PRIMER routine ANOSIM (analysis of similarities) was used to test the null hypothesis that there are no differences in harbor communities, either within 2005 or between years. This test is based on the matrix generated by a similarity test, in this case, Bray-Curtis. Clarke and Gorley (2001) discuss the use of this test as a replacement for ANOVA, and interpretation of R values is discussed in Chapman and Underwood (1999).

Ordination techniques used to visualize distances among samples include Principal Components Analysis of hypergeometric probabilities (PCA-H) applied to the CNESS results (see Trueblood *et al.* 1994 for details), and non-metric multidimensional scaling (NMDS) applied to the Bray-Curtis results (Clarke and Gorley 2001).

The PCA-H method is a multistep analysis that produces a metric scaling of the samples in multidimensional space, as well as a Euclidean distance biplot (Gabriel 1971) of the major sources of CNESS variation, *i.e.*, the species that contribute the most to the distances among samples. These species are determined using matrix methods adapted from Greenacre's correspondence analysis (Greenacre 1984) and are plotted as vectors in the Euclidean distance biplot. PCA-H analysis was performed using MATLAB as an operating platform and programs written by Dr. E.D. Gallagher.

NMDS (Kruskal and Wish 1978, Kenkel and Orloci 1986, Clarke and Gorley 2001) also produces a two (or more)-dimensional map that demonstrates the relative distances between samples. This ordination technique is recommended over typical PCA procedures (other than PCA-H discussed above), since it is better at preserving sample distances and makes few assumptions about the nature of the data (Clarke and Gorley 2001).

5.3 Results and Discussion

5.3.1 Species Composition of 2005 Samples and 1991–2005 Taxonomic Summary

In August 2005, 123 species of benthic infauna occurred in the samples, including four species that were recorded in the harbor for the first time (Appendix C2). These four species included two polychaetes, *Euclymene collaris* and *Scolelepis foliosa* (previously reported as *S.* nr. *tridentata*), one isopod, *Pleurogonium rubicundum*, and one gastropod, *Boonea seminuda*, which is also newly reported for the MWRA Massachusetts Bay/Boston Harbor database. For the period 1991–2005, 255 identified species have been recorded in the summer samples (Appendix C2).

***Ampelisca* spp.** Two species of *Ampelisca* are found in Boston Harbor: *A. abdita* and *A. vadorum*, but are combined with juveniles and otherwise unidentifiable individuals to the taxon *Ampelisca* spp. for report purposes. This is necessary because early in the initial years of the monitoring program the taxonomic team did not discriminate between different species of *Ampelisca*. *A. abdita* is associated with fine sand to muddy substrates, and *A. vadorum* with coarse sand (Mills 1967). Early populations of *A. vadorum* have largely been replaced by *A. abdita*, which has accounted for nearly 97% of the *Ampelisca* identified since 1995. The two species have often co-occurred at T06 and T08.

Because members of this genus are considered (by some) to be indicative of clean environments, population levels of *Ampelisca* have been considered key in following the status of the infaunal community of the harbor. Reish and Barnard (1979) found that slight increases in organic matter resulted in increased amphipod abundance, but beyond a certain level, amphipod numbers decreased.

In the 1978–1982 waiver and outfall siting studies, ampeliscid amphipods were numerous only at T06; only a few, if any, occurred elsewhere in the harbor (Maciolek *et al.* 2003). The high levels of organic carbon in the harbor before the curtailment of sludge dumping were thought to impede the development of the ampeliscid populations, and a storm recorded in June 1991 may have removed any population that was present before sampling began (see Chapter 3, this report). The population density of *Ampelisca* spp. in the harbor increased each year from 1991 through 1994, and then fluctuated over the next several years (Figure 5-1); this increase was interpreted as a response to cleaner sediments.

In 2002, the grab samples yielded fewer *Ampelisca* than in any monitoring year since 1991, but the results from SPI, which covers a greater number of stations throughout the harbor, suggested that although areas of high-density amphipod mats had declined compared with 2001, the number of stations where *Ampelisca* was found in any density had increased (Maciolek *et al.* 2003, Figure 4-2 this report). The following August (2003), grab samples at the infaunal stations yielded the highest numbers of *Ampelisca* spp. recorded since the initiation of monitoring (Figure 5-1), and this taxon accounted for more than 55% of all the organisms collected (Table 5-1). The areal distribution of *Ampelisca* spp. tube mats as measured with SPI expanded from 22% of the stations in 2002 to 30% in 2003, although the percentage of stations with *Ampelisca* spp. tubes at any density remained at 63.

In 2004, the number of amphipods declined sharply and in 2005 were essentially absent from the grab samples (Table 5-1, Figure 5-1). The decline from 2003 to 2005 is possibly partially attributable to the storms recorded in December 2003, December 2004, and May 2005, which affected the bottom substrate, altering the sediment texture (see Chapter 3) and bottom habitats.

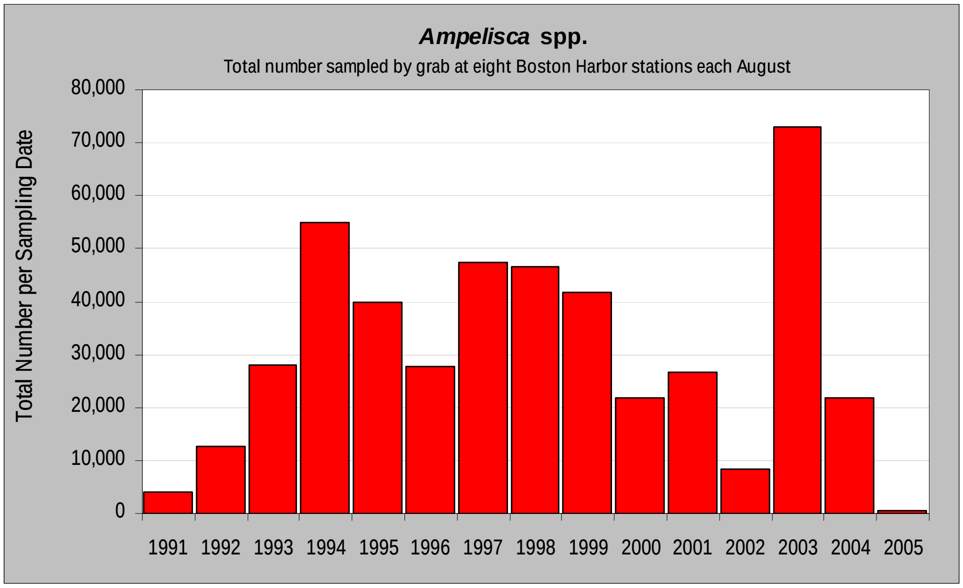

Figure 5-1. *Ampelisca* spp. at eight Boston Harbor stations.

Table 5-1. Amphipod species present in Boston Harbor samples taken in August 2003–2005.

Amphipod Species	Total Abundance in 2003 samples (8 stations)	Total Abundance in 2004 samples (8 stations)	Total Abundance in 2005 samples (8 stations)
Ampelisca spp.	73,112	21,728	614
Leptocheirus pinguis	4,735	1,734	97
Unciola irrorata	3,841	756	18
Crassicorophium bonnelli	2,148	9	1
Photis pollex	2,108	1,677	100
Orchomenella minuta	1,194	1,230	21
Dyopedos monacanthus	1,029	1	0
Phoxocephalus holbolli	96	153	0
Microdeutopus anomalus	39	3	2
Crassicorophium crassicorne	17	11	0
Ischyrocerus anguipes	9	2	0
Pontogeneia inermis	9	1	0
Jassa marmorata	2	1	0
Harpinia propinqua	1	0	0
Metopella angusta	1	3	0
Totals	88,341	27,309	853

Recolonization is dependent on larval dispersion and recruitment (Mills 1967, Reish and Barnard 1979), and when the overwintering population is sparse, reestablishment of the species in the harbor may take time. Breeding starts when water temperatures reach 8°C, which is usually late April to early May. Young produced by this overwintering generation attain breeding size in June or July and over the course of the next few months produce the next over-wintering generation. Adults swim freely in the water column to mate, and the ovigerous females will settle into previously unoccupied areas to release their young, causing a physical shift in the location of the population from areas of old, silted-in tubes to unmodified sediments. The adults do not survive beyond breeding, but the juveniles quickly begin building tubes (Mills 1967).

Establishment of a population and expansion within a suitable area results in modification of the environment. The amphipod tubes trap sediment and detritus and result in a much more complex habitat than was previously available, allowing other species to colonize the area. Ultimately, the *Ampelisca* may leave the area, either through the reproductive behavior noted above or unavailability of the preferred clean fine-sand substrate (Mills 1969). The storm in late October 1991 that scoured bottom areas of Massachusetts Bay and Boston Harbor likely caused the disappearance of the *Ampelisca* mats that had been seen in sediment profiling surveys in previous years (SAIC 1992), with the resultant low densities in spring 1992 (see Figure 5-1). However, this storm action may also have provided clean uncolonized areas of suitable substrate for *Ampelisca* to become reestablished, after which large populations were able to develop. A similar clean sweep of the bottom may have occurred in spring 2005.

The periodic explosion and decline of amphipod populations dominated by *Ampelisca* spp.(Table 5-2) would suggest that infaunal succession patterns are being held in the Stage I and II seres as defined by Rhoads and Germano (1986). In recent years, physical processes such as storms scouring the bottom are one probable cause of low population numbers; additionally, the reduction of available particulate organic carbon in recent years is a contributing factor (see Chapter 4, this report).

Table 5-2. Summary of amphipod population status in Boston Harbor as determined by grab sampling (see Table 5-1 for species).

Year	Amphipod Population Status
late 1970–1980s	several stations with *Ampelisca*, other species; variable between sampling years (high organic load to harbor)
1991	Sept 91 – *Ampelisca* present (severe storms in June, October)
1992–2001	amphipod populations grow, fluctuate (TOC reduced when sludge dumping stops, no bad storms)
2002	low numbers of amphipods
2003	highest levels of *Ampelisca* and other species
2004	major decline in amphipod populations
2005	essentially no *Ampelisca* or other amphipods (major storm in May)

5.3.2 Benthic Community Analysis for 2005

Values of all parameters declined in the harbor overall in 2005 compared with 2004, including density, species richness, Shannon diversity, evenness, and log-series *alpha*. As in previous years, each station exhibited a different trend.

***Density, Species Richness, Diversity, and Evenness*—**Community parameters for the grab samples collected in 2005 at the nine harbor stations are shown in Figure 5-2 and Table 5-3. For comparison with earlier dates, data for 2004 are included in Figure 5-2.

***Density*—**Total abundances were significantly lower at harbor stations T03, T05A, and T06, where amphipods are often present in large numbers but were generally absent in 2005. At the remaining stations, densities were either identical to those recorded in 2004 (T01, T07, T08) or slightly higher (T02, T04, CO19).

***Species Richness* —**The mean number of species per sample was lower at eight of the nine harbor stations in 2005 compared with 2004. Station T04 was the only exception, with an increase from a mean of 9.7±2.3 species per sample in 2004 to 14.7±1.5 in 2005 (Figure 5-2). CO19 had the lowest species richness of all harbor stations, with 12.7±1.5 species per sample, an average of three fewer species per sample than in 2004.

At the remaining stations, the drop in the average number of species per sample was greatest at T05A, from 76.3 ±5.8 in 2004 to 47.0±3.6 in 2005. T03 and T06, both stations where amphipods are usually common, exhibited the second and third greatest declines in species richness, from 59.0 to 46.7 species per sample at T03 and from 48.7 to 30.3 species per sample at T06. Species richness at other stations declined by four to eight species compared with 2004 levels.

***Diversity* —**Mean Shannon diversity declined at five (T01, T02, T04, T07, and CO19) of the nine stations, in some cases significantly so (T02, T04, T07, CO19) (Figure 5-2, Table 5-3). At T03, T05A, and T06, where amphipods were absent, and densities and species richness were also lower, and at T08 where these parameters were similar between 2004 and 2005, the Shannon diversity was similar to that recorded in 2004 (Table 5-3, Figure 5-2). Mean Shannon diversity was lowest at CO19 (0.34±0.04) and T04 (0.79±0.24) and highest at T08 (3.85±0.39), a pattern similar to that recorded in previous years.

Diversity as measured by Fisher's log-series *alpha* declined at all nine stations in 2005 (Figure 5-2). Earlier station patterns were repeated in 2005: the lowest mean value was recorded at CO19 (1.99±0.20) and T04 (2.68±0.19) and the highest at T05A (9.79±0.59) and T08 (10.60±2.40).

***Evenness*—**Evenness values in 2005 compared with 2004 (Figure 5-2) were significantly lower at T02, T04, T07, and CO19; slightly lower or identical at T01 and T08; and slightly higher at T03, T05A, and T06, where the absence of overwhelming amphipod populations resulted in a more equitable community structure.

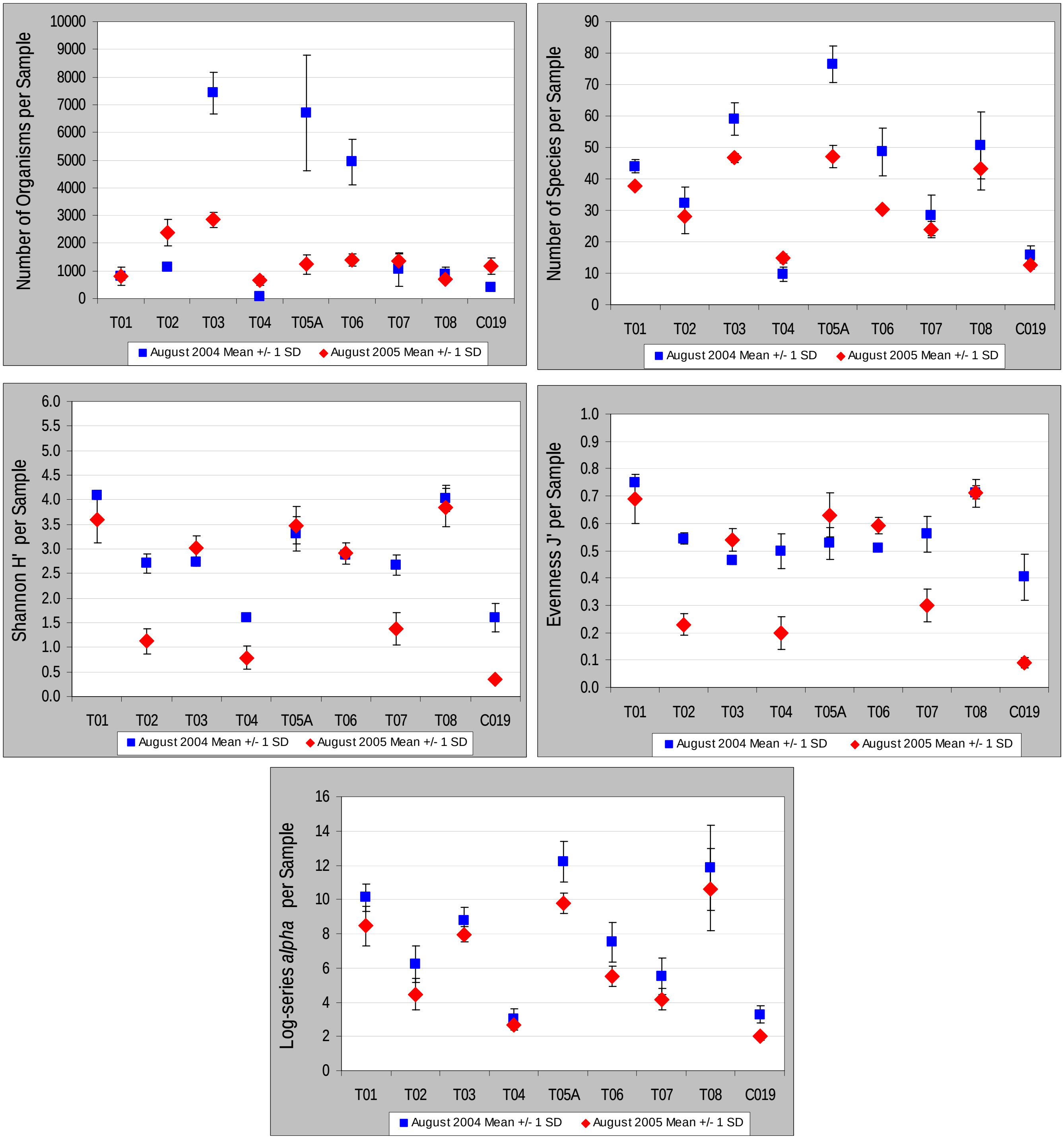

Figure 5-2. Mean ± 1SD of five benthic infaunal community parameters for the Boston Harbor stations sampled by grab in August 2005. The 2004 values are included for comparison.

Table 5-3. Benthic community parameters for samples taken at Boston Harbor traditional stations in August 2005.

Station	Replicate	Total Abundance	No. Species	H′ (base 2)	J′	Log-series *alpha*
T01	1	1145	37	3.12	0.60	7.33
	2	496	38	4.09	0.78	9.63
	3	765	38	3.59	0.68	8.42
	Mean ± SD	802±326.1	37.7±0.6	3.60±0.48	0.69±0.09	8.46±1.15
T02	1	2924	32	1.29	0.26	5.03
	2	2207	22	0.82	0.18	3.40
	3	2019	30	1.26	0.26	5.00
	Mean ± SD	2383.3±477.6	28±5.3	1.12±0.26	0.23±0.04	4.47±0.93
T03	1	3152	45	2.78	0.51	7.44
	2	2599	47	3.01	0.54	8.15
	3	2782	48	3.26	0.58	8.24
	Mean ± SD	2844.3±281.7	46.7±1.5	3.02±0.24	0.54±0.04	7.95±0.44
T04	1	758	16	1.04	0.26	2.87
	2	737	15	0.77	0.20	2.67
	3	454	13	0.55	0.15	2.50
	Mean ± SD	649.7±169.8	14.7±1.5	0.79±0.24	0.2±0.06	2.68±0.19
T05A	1	1464	51	3.26	0.58	10.29
	2	822	44	3.92	0.72	9.94
	3	1402	46	3.26	0.59	9.14
	Mean ± SD	1229.3±354.1	47±3.6	3.48±0.38	0.63±0.08	9.79±0.59
T06	1	1505	28	2.70	0.56	4.88
	2	1145	32	3.14	0.63	6.11
	3	1522	31	2.91	0.59	5.51
	Mean ± SD	1390.7±212.9	30.3±2.1	2.91±0.22	0.59±0.03	5.5±0.61
T07	1	1474	21	1.00	0.23	3.47
	2	1549	26	1.60	0.34	4.44
	3	1042	25	1.54	0.33	4.61
	Mean ± SD	1355±273.6	24±2.6	1.38±0.33	0.3±0.06	4.17±0.61
T08	1	754	49	4.28	0.76	11.88
	2	770	36	3.53	0.68	7.83
	3	550	45	3.73	0.68	12.07
	Mean ± SD	691.3±122.7	43.3±6.7	3.85±0.39	0.71±0.05	10.6±2.40
CO19	1	1279	14	0.31	0.08	2.20
	2	1400	13	0.32	0.09	1.98
	3	827	11	0.38	0.11	1.79
	Mean ± SD	1168.7±302	12.7±1.5	0.34±0.04	0.09±0.02	1.99±0.20

Dominant Species **—**The numerically dominant species and their percent contribution to the fauna at each harbor station in August 2005 are given in Appendix C3. As discussed above, the density of *Ampelisca* spp. declined significantly in 2005 compared with 2003 and 2004, but this taxon was still recorded among the numerically common species at several stations, although inmost instances was not one of the ten most numerous species. T03 was the only station where *Ampelisca* spp. was among the ten most common species, ranking sixth with a mean abundance of 160.0±72.6, and accounting for less than 6% of the fauna at that station.

The polychaete species, *Nephtys cornuta*, a small jawed omnivore, was a numerical dominant at several stations in 2005, exceeding densities recorded in 2004. It accounted for as much as 96% of the fauna at CO19 and was the numerical dominant at T01 (ca. 32%), T02 (ca. 82%), T06 (ca. 38%) and T07 (ca.74%). At all of these stations, its abundance and proportion of the fauna increased compared with previous years. Although this is a small-bodied species, the animals found in these samples were not juveniles and included sexually mature specimens (R.E. Ruff and T. Morris, project taxonomists, pers. comm. October 2006).

In 2002 and 2003, the spionid polychaete *Prionospio steenstrupi* was a numerical dominant at several harbor stations, although in 2003 it was eclipsed in numbers by several species of amphipods. In 2004, *P. steenstrupi* was among the numerical dominants at only two stations, T05A and T06, where it accounted for only 0.8% and 0.5% of the total fauna, respectively. In 2005, it was present but not common at all stations except T04. At T05A, it was the second most numerous species and accounted for slightly more than 9% of the fauna; at T03 and T06, it accounted for 6.9% and 6.3 % of the fauna, respectively

The community at T04 remained less species rich compared with the infauna at all other stations; in August 2005, as in several previous years, the overwhelming numerical dominant was *Streblospio benedicti* (88.7% of the fauna).

Station CO19, although sampled in 2004 for the first time in this program, had been sampled in 1989 as part of the Sediment-Water Exchange (SWEX) study (Gallagher and Keay 1998). At that time, 94–96 % of the fauna was comprised of *Streblospio benedicti* and a cirratulid identified as *Chaetozone setosa*; only a few individuals of four additional taxa were identified from the samples (oligochaetes, *Polydora* sp., *Mya arenaria*, and *Pectinaria gouldi*). In 2005, as in 2004, the fauna at this station was overwhelmingly dominated by *Nephtys cornuta*, although 18 additional taxa were also found there.

5.3.3 Multivariate Community Analysis of the 2005 Data

Similarity and Ordination Analysis with CNESS—The CNESS analysis of the 27 samples taken at nine stations in August showed five groups of stations at the CNESS level 0.85, with several clusters comprised of replicates from a single station (Figure 5-3):

Cluster 1.	T04
Cluster 2.	subgroup a: CO19, T02, T07
	subgroup b: T03 and T06
Cluster 3.	T01
Cluster 4.	T05A
Cluster 5.	T08

The pattern seen in previous years of samples from a station almost always being more similar to samples from the same station than to those from other stations was again very clear in 2005. Within-station similarity was highest at T03 and CO19. In 2003, T01 clustered with T08 when a large set of juvenile maldanids was seen at both stations; however, T01 usually has a unique station signature with low similarity to the other stations, as reflected in the results for 2004 (Maciolek *et al*. 2005) and 2005 (Figure 5-3). Station C019 was again most similar to stations T02 and T07, reflecting the similar species composition found at those stations (Table 5-2). The small omnivorous polychaete *Nephtys cornuta* was again common at all three stations in 2005 (see section 5.3.2 Dominant Species, above).

This pattern of station associations generally corresponds to the varying sediment types within the harbor, which have remained fairly consistent over the monitoring period (see Chapter 3, this report). The coarsest sediments, and also those with the lowest TOC content, are seen at T01, T05A, and T08. T04 has the siltiest sediments, and also the highest TOC. The remaining stations—T02, T03, T06, and T07—range from sandy to silty, and have been more variable over time.

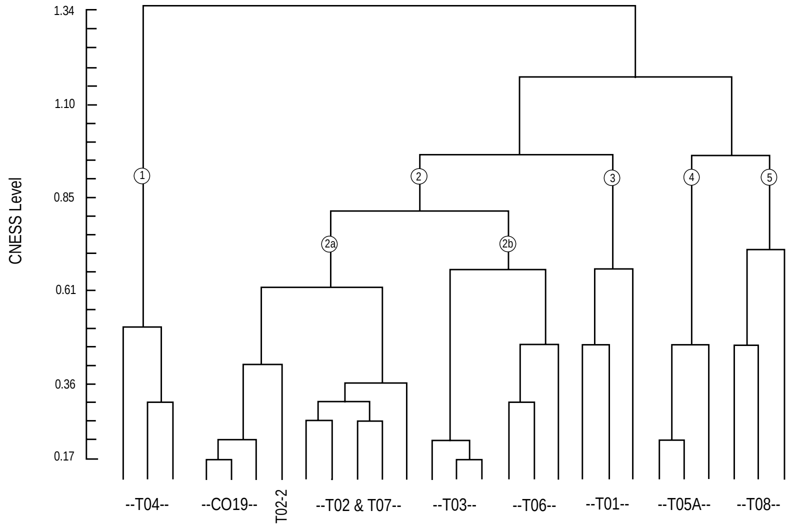

Figure 5-3. Cluster dendrogram of the 27 samples collected at the eight Boston Harbor traditional stations and C019 in 2005; based on CNESS similarity with m set at 15 and group average sorting.

PCA-H Analysis**—**The metric scaling of the 2005 samples on the first two PCA-H axes, which accounted for 61% of the CNESS variation in the communities, is shown in Figure 5-4. The clear separation along axis 2 of the T04 samples from the remaining stations is apparent in this diagram; axis 2 likely represents carbon loading and perhaps sediment grain size. The high similarity of stations T02 and T07, and the grouping of the remaining stations as indicated by the CNESS analysis are also apparent. Stations other than T04 separated along axis 1, which most likely reflect some measure of sediment texture.

The next step of the PCA-H analysis indicated which of the 123 species in the samples were responsible for the relationships among samples as reflected in the metric scaling. With CNESS (*m*=15), 11 species contributed 2% or more of the total variation on PCA-H axes 1, 2, and 3 (Table 5-4). The Gabriel Euclidean distance biplots for axes 1 v. 2, 1 v. 3, and 2 v. 3 (Figure 5-5) show those species superimposed over the metric scaling of the stations.

The polychaete *Nephtys cornuta,* which had not been especially abundant in the harbor before 2004, was identified by the PCA-H analysis as the most important species in structuring the fauna in 2005 (Table 5-4), as it was in 2004. In particular, *N. cornuta* influenced the CNESS distances of CO19, T01 and T02. The polychaete *Streblospio benedicti* and the oligochaete *Tubificoides* sp. 2 distinguished T04 from the other stations. The oligochaetes *T. apectinatus* and *T.* nr. *pseudogaster,* along with the polychaetes *A. catherinae* and *P. steenstrupi* were important at T01, T03, and T05A. The polychaetes *Spiophanes bombyx* and *Exogone hebes*, typically found in sandy environments from shallow to continental shelf depths, as well as the annelid *Polygordius* sp. A, were responsible for differentiating T08 from the remaining stations.

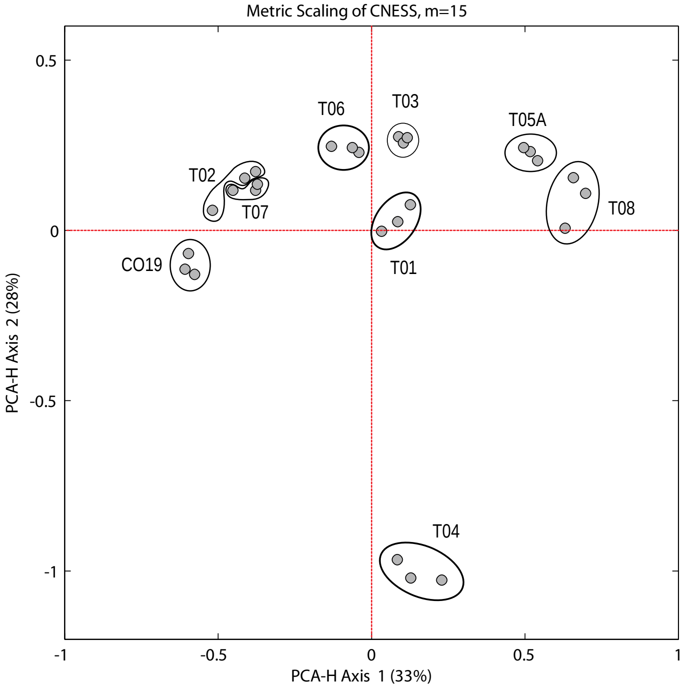

Figure 5-4. Metric scaling of the 2005 Boston Harbor samples, axis 1 v. axis 2, based on CNESS m set at 15.

Table 5-4. Contributions to PCA-H axes by species accounting for at least 2% of the CNESS variation among the infaunal samples collected in Boston Harbor 2005 (see Figure 5-6).

Important species: Axis 1 vs. 2

PCA-H Rank	Species	Contr.[a]	Total Contr.	Axis 1	Axis 2
1	*Nephtys cornuta*	32	32	59	2
2	*Streblospio benedicti*	22	54	1	47
3	*Tubificoides apectinatus*	9	64	3	17
4	*Prionospio steenstrupi*	5	68	4	6
5	*Tubificoides* nr. *pseudogaster*	5	73	2	7
6	*Spiophanes bombyx*	4	77	7	0
7	*Polygordius* sp. A	4	81	7	1
8	*Tubificoides* sp. 2	4	85	0	8
9	*Nephtys ciliata*	4	88	6	1
10	*Aricidea catherinae*	4	92	2	5

Important species: Axis 1 vs. 3

PCA-H Rank	Species	Contr.[a]	Total Contr.	Axis 1	Axis 3
1	*Nephtys cornuta*	45	45	59	7
2	*Tubificoides apectinatus*	14	59	3	45
3	*Spiophanes bombyx*	6	65	7	3
4	*Polygordius* sp. A	5	70	7	0
5	*Nephtys ciliata*	5	75	6	2
6	*Prionospio steenstrupi*	4	78	4	2
7	*Exogone hebes*	3	82	2	8
8	*Tubificoides* nr. *pseudogaster*	2	84	2	3
9	*Streblospio benedicti*	2	86	1	6
10	*Aricidea catherinae*	2	88	2	2

Important species: Axis 2 vs. 3

PCA-H Rank	Species	Contr.[a]	Total Contr.	Axis 2	Axis 3
1	*Streblospio benedicti*	35	35	47	6
2	*Tubificoides apectinatus*	25	60	17	45
3	*Tubificoides* nr. *pseudogaster*	6	66	7	3
4	*Tubificoides* sp. 2	6	72	8	1
5	*Prionospio steenstrupi*	4	76	6	2
6	*Aricidea catherinae*	4	80	5	2
7	*Nephtys cornuta*	3	84	2	7
8	*Exogone hebes*	3	86	0	8

[a] **Percent contributions are rounded up to the nearest whole number by the computer program.**

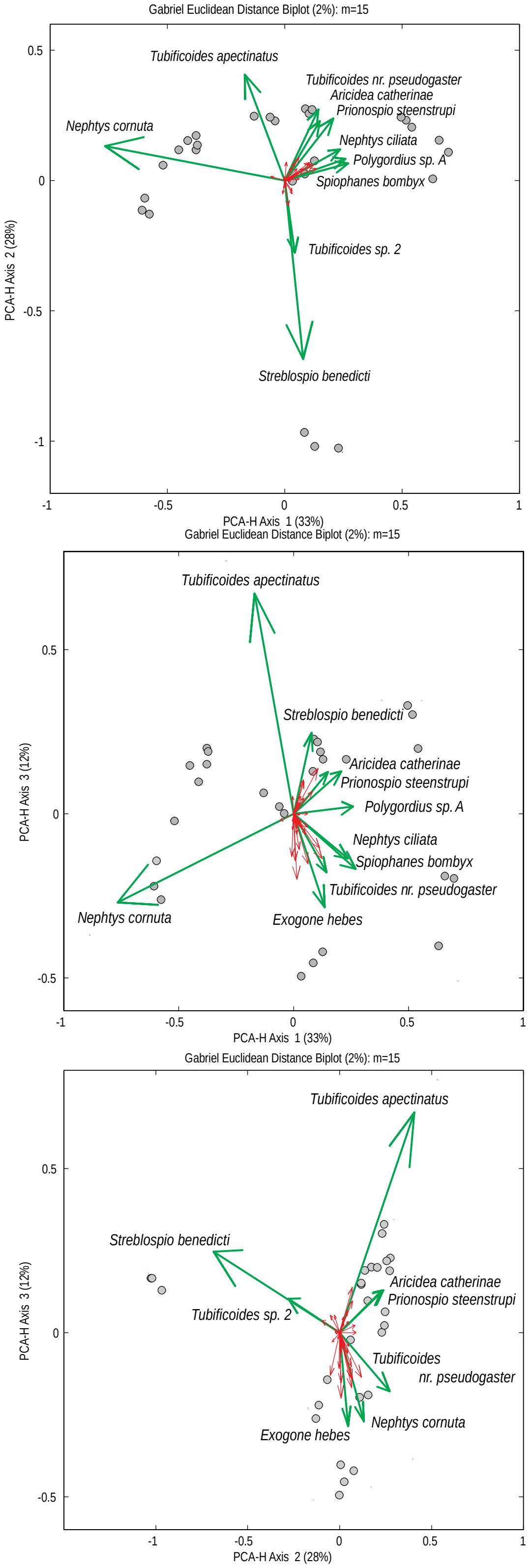

Figure 5-5. Gabriel Euclidean distance biplots of the 2005 Boston Harbor samples based on CNESS *m* set at 15. Species that account for at least 2% of the variation are labeled (see Table 5-4).

Similarity and Ordination Analysis with Bray-Curtis**—**Figure 5-6 shows the results of a similarity analysis using the Bray-Curtis algorithm, after a fourth-root transformation of the data. As with CNESS, within-station similarity is very high, with the exception of one replicate from T07 that joins a group of samples including T02 and T07. Three main groups can be identified from the dendrogram, as follows:

Cluster 1. T04
Cluster 2. CO19, T02, and T07
Cluster 3. subgroup a: T08
subgroup b: T03, T05A, T06 ,T01

Ordination of these samples by non-metric multidimensional scaling (NMDS) is shown in Figure 5-7. The low stress level (0.08) indicates that this sample map is a good representation of the multidimensional space occupied by the 27 samples, and indicates relative distances better than portrayed by the dendrogram.

Both CNESS and the Bray-Curtis show

- strong within-station similarity
- low similarity of T04 with remaining stations
- grouping of CO19, T02, and T07
- similarity between T05A and T08 (higher with CNESS)

The two algorithms differ in the way they assign similarities among stations T01, T03, and T06, but the three replicates from each of these stations cluster together first, as with CNESS.

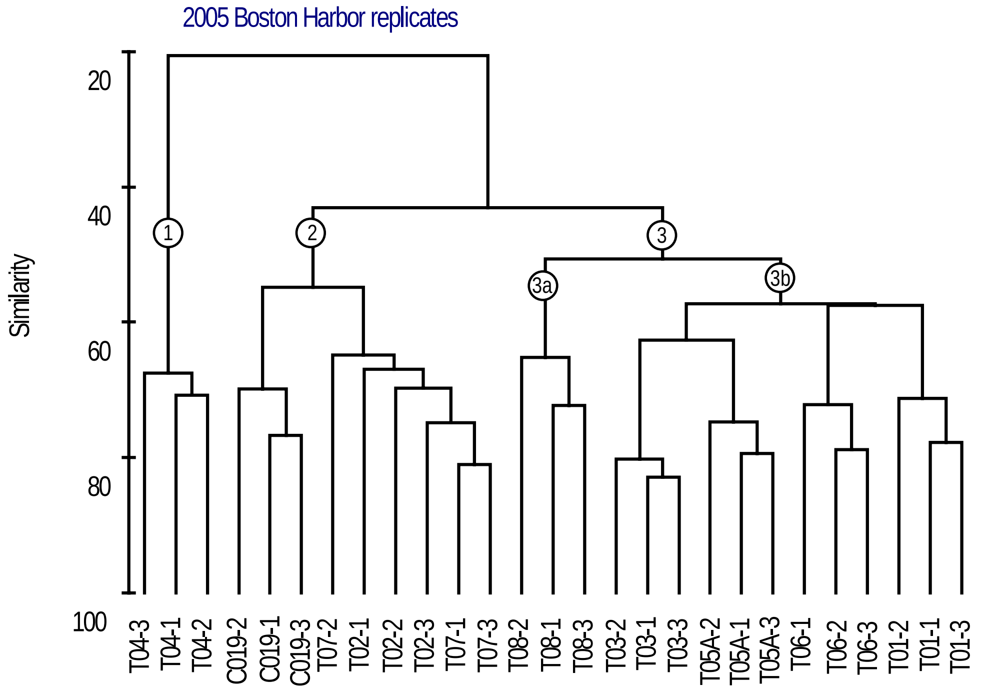

Figure 5-6. Cluster dendrogram of the 27 samples collected in 2005 at nine Boston Harbor stations. The analysis is based on a fourth-root transformation of the data, Bray-Curtis similarity, and group average sorting.

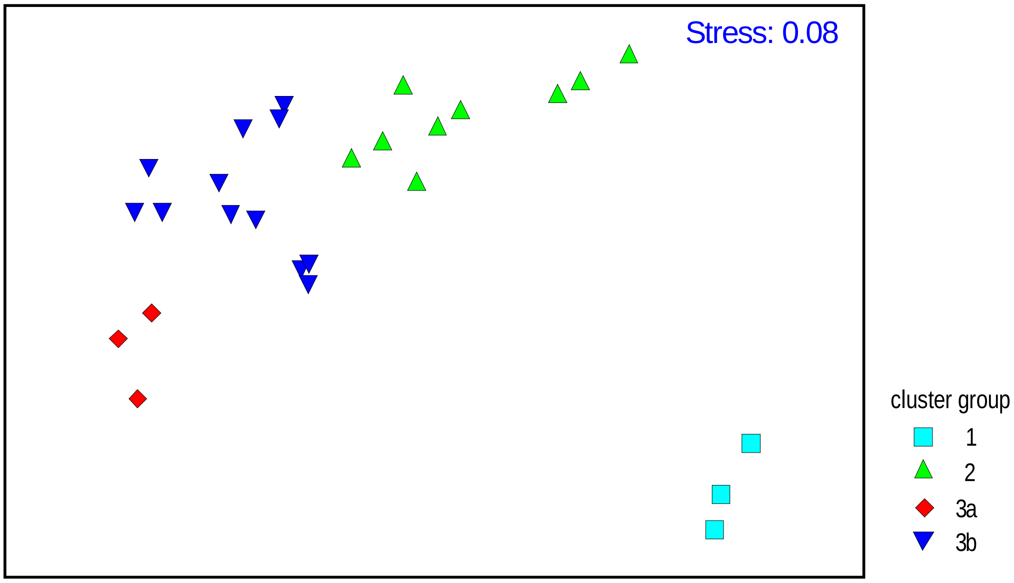

Figure 5-7. NMDS diagram of the clusters, derived from the similarity matrix based on a fourth-root transformation of the data, Bray-Curtis similarity, and group average sorting.

The ANOSIM statistic was applied to test the null hypothesis that there is no significant difference between stations. The resultant statistic (global R) was R= 0.979 with a significance level of 0.1%. An R value of 1 indicates that all replicates within a site are more similar to each other that to any replicates from different sites. The result of this test suggests that there are significant differences among stations, but does not indicate which ones. The test was repeated using selected stations pairs (CO19 v. T01, T02 v. T07, T05A v. T08, and T03 v. T05, and T01 v. T06). For four of these five tests, the global R= 1, indicating highly significant differences between stations (significance level = 10%). For the comparison of similarities between T02 and T07, R= 0.593, which was also significant at the 10% level. Thus, each site within the harbor can be considered to be significantly different from the others.

5.3.4 Long-term Monitoring (1991–2005): Annual Harborwide Changes

Monitoring at eight harbor stations has now continued for 15 years, during which time the pollutant load to the harbor has been significantly reduced. Additionally, severe weather events, including spring and winter nor'easters and heavy rainfall have impacted the harbor. These factors, combined with the natural expansion and reduction of biological populations, are integrated by the benthic populations and have resulted in the community patterns that have been recorded to date.

Parameters calculated for each replicate and then averaged for each year are shown in Figure 5-8. In general, all parameters except abundance trended upward over time, particularly after the diversion of the outfall offshore in 2000, suggesting an increase in diversity throughout the harbor.

The Shannon diversity index H′ ranged from a low of 2.11 in 1992 to a high of 3.00 in 2004 (Figure 5-8)[6]. Although the SE around each mean suggests that these values may not all be significantly different from each other, mean values are higher in years after the outfall diversion (2000) compared with earlier ones, and suggest higher species diversity in recent years. The typical range of this index is from 1.5 to 3.5 (Magurran 1988), it is unlikely that changes in H′ will provide detailed insight into trends over time for averaged harbor stations. The associated evenness index, J′, was lower in the early years of monitoring, indicating higher dominance by fewer species during those years (Figure 5-8). The average number of species per sample, the most direct measure of species richness, ranged from 18.4 in 1991 to 50.9 in 2003, with a subsequent drop to 34.0 in 2005 (Figure 5-8). The intervening years (1992–2002) evidenced few real changes in this measure, with a low of 29.0 in 1996 and a high of 40.8 in 1998 and an average of 34.3 species per sample for the period. Log-series *alpha* and the estimated number of species per 500 individuals exhibit the strongest upward trends over time, from low values in the early 1990s to higher values in recent years, with 2003 and 2004 in particular having higher mean values than in all previous years, and a subsequent drop in 2005 (Figure 5-8). May (1975) pointed out that Sanders' rarefaction curves for marine benthic communities are similar to log-series curves, so the similarity between the two plots is not surprising.

In order to examine the overall change in harbor benthic communities, samples were pooled to one sample per year (*i.e.*, all samples from all stations were pooled to one annual harbor-wide sample, resulting in 15 harbor samples) to examine harbor-wide averages.

The analyses of these pooled samples included data from T05 rather than T05A for 1991 and 1992; these samples were included to provide an equal number of samples in each year before pooling. Pooling across stations is probably not entirely valid because of the wide differences among stations in terms of sediment type and environmental conditions (*e.g.*, water circulation patterns, depth, etc.). However, because differences were seen at individual stations, both in terms of infaunal community structure, SPI, and sediment characteristics (Chapter 3, this report), averaged annual differences were investigated in order to determine if there were any apparent annual patterns as well. As discussed below, some analyses were more informative than others.

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[6] If the samples are first pooled and then the Shannon index is calculated based on one larger sample, the index ranges from 2.87 (2003) to 3.72 (2002), demonstrating the dependence of this index on sample size.

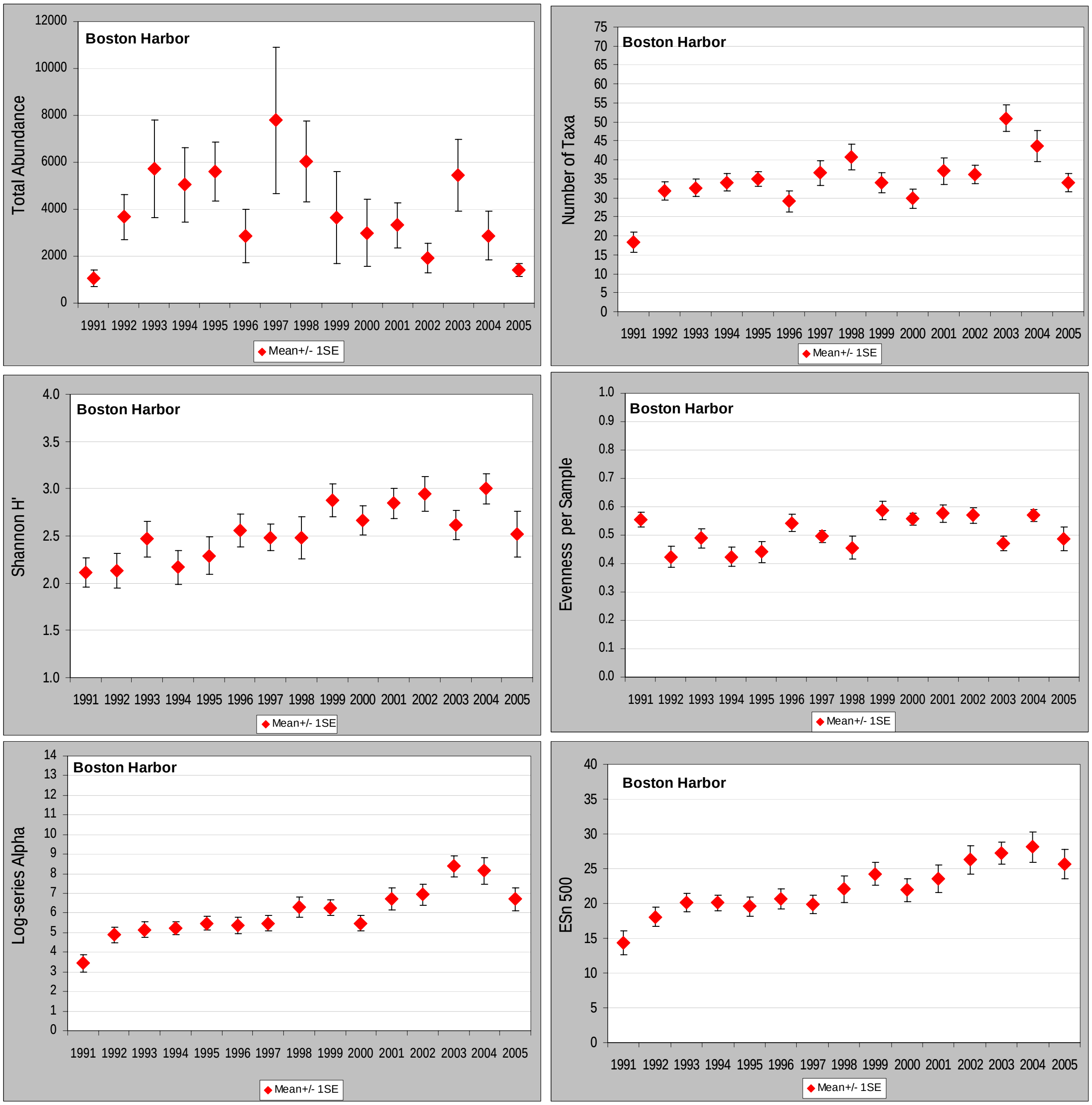


Figure 5-8. Benthic community parameters for Boston Harbor stations for each August (or September) sampling event from 1991–2005.

Rarefaction Analysis**—** Rarefaction analysis is essentially a measure of species richness, with loss of information about the relative abundances of each species (Magurran 1988). However, it is useful as a way to compare the overall diversity in the harbor for each year of the sampling program. The results indicate an increase in diversity since the early 1990s, with a clear increase after 2000, when the discharge was routed offshore (Figure 5-8, Figure 5-9). The curve for 2004 (Figure 5-9) was the highest reported to date (Maciolek *et al.* 2006); diversity as measured by this method was lower in 2005 than in 2004, but still higher than all other years. The values for ESn at 500 individuals (Figure 5-8) indicate that 2005 was slightly lower than the previous three years (2002–2004).

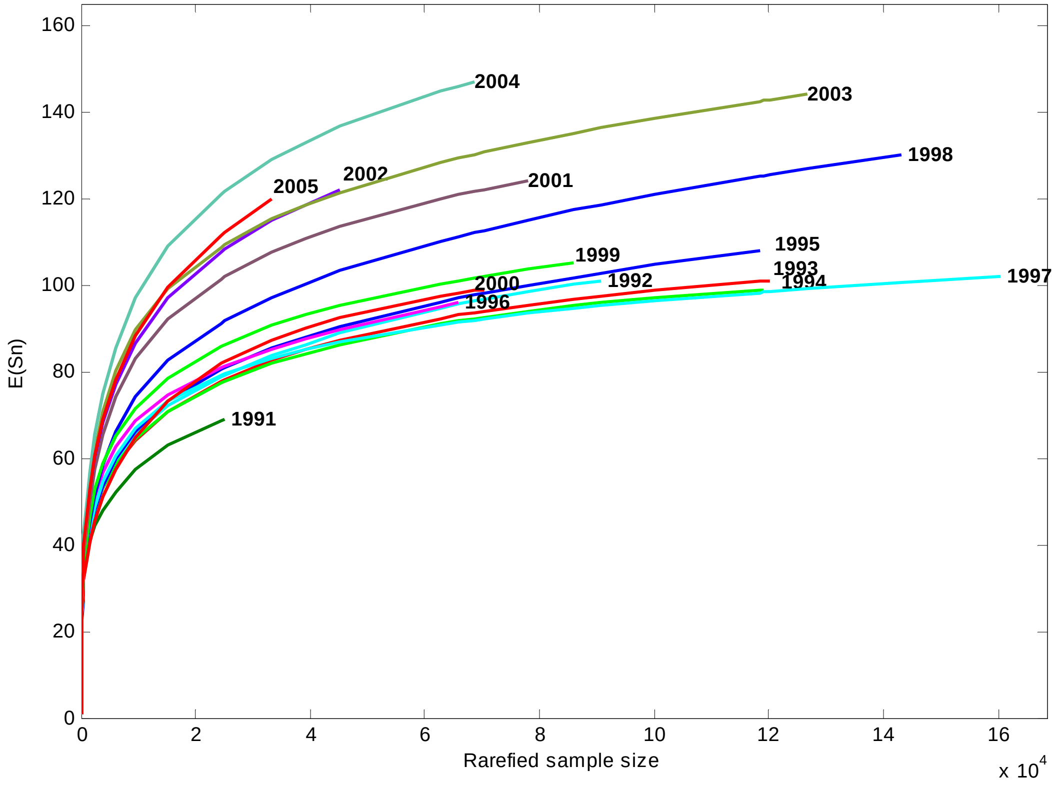
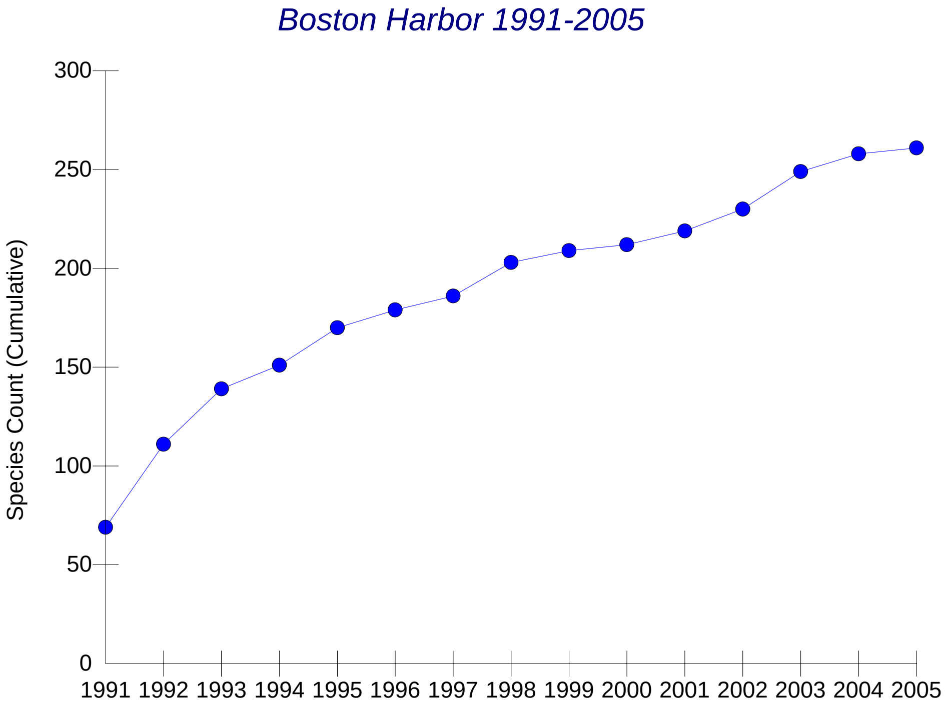


Figure 5-9. Rarefaction curves for August samples taken in Boston Harbor each year from 1991 through 2005; all samples pooled within each year.

Species–Area Curve—The species-area curve (Figure 5-10) indicates the accumulation of new species as samples (and therefore area sampled) are added each year. The slope of the curve is steeper in the very early years of the program, with other smaller "spurts" in 1995, 1998 and 2003. Even in 2005, when abundance and diversity were much lower than in the immediately previous years, three new species were added.



Year	**No. Species**
1991	69
1992	111
1993	139
1994	151
1995	170
1996	179
1997	186
1998	203
1999	209
2000	212
2001	219
2002	230
2003	249
2004	258
2005	261

Figure 5-10. Cumulative plot of the number of different species recorded in Boston Harbor as each year's samples are added, from 1991 through 2005.

Similarity and Ordination Analysis with CNESS—The dendrogram based on the CNESS similarity analysis indicated four major groups or clusters of annual samples (Figure 5-11). The highest possible CNESS dissimilarity value is √2 (1.41) (Trueblood *et al.*, 1994), therefore many years can be considered fairly similar to one another. However, using a criterion level of 0.60, four groups can be distinguished (Figure 5-9); these groups are identical to the three presented last year (Maciolek et al. 2005), with the addition of a very dissimilar group 4 , which contains only the 2005 sample. Cluster group 1 is the next most dissimilar group and includes years 1992–1998 (except 1996). Group 2 comprises only 1991, and Group 3 includes 1996 plus 1999–2004.

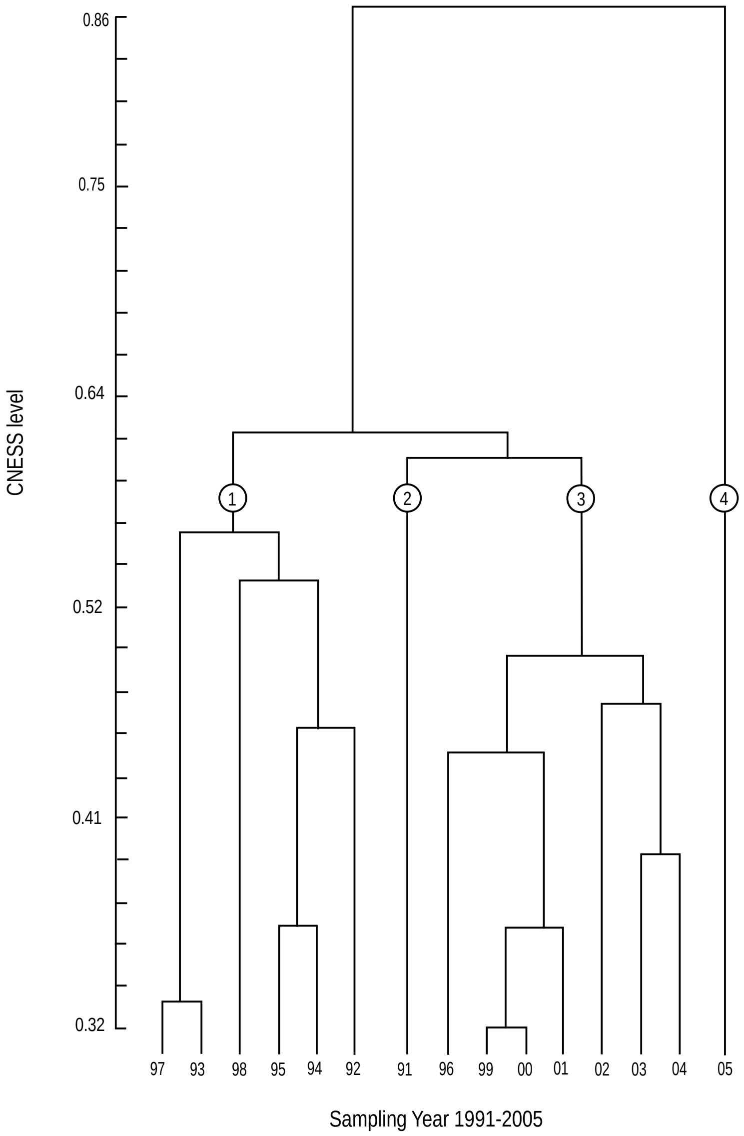


Figure 5-11. Station dendrogram for Boston Harbor 1991–2005 infauna. The lower the CNESS number, the more similar the stations. CNESS *m* = 20 and group average sorting were used. 261 taxa and 15 pooled annual samples were included.

PCA-H Analysis—The metric scaling of the 15 annual samples on the first two PCA-H axes accounted for 56% of the CNESS variation (Figure 5-12). The contribution of species to the PCA-H axes (Table 5-5) indicated that three species in particular influenced the metric scaling of the samples: the polychaete *Streblospio benedicti*, the oligochaete *Tubificoides apectinatus,* and the amphipod *Crassicorophium bonnelli*. Although *S. benedicti* continues to be found at T04, it was present in high numbers at other stations (*e.g.*, T02) only during the early years of monitoring. These species are also characteristic of sediment type and perhaps levels of environmental stress.

The Gabriel Euclidean distance biplot (Figure 5-13) shows species superimposed over the metric scaling of the stations. With CNESS (*m*=20), 10 species contributed 2% or more of the total variation on PCA-H axes 1 and 2 (Figure 5-10, Table 5-6).

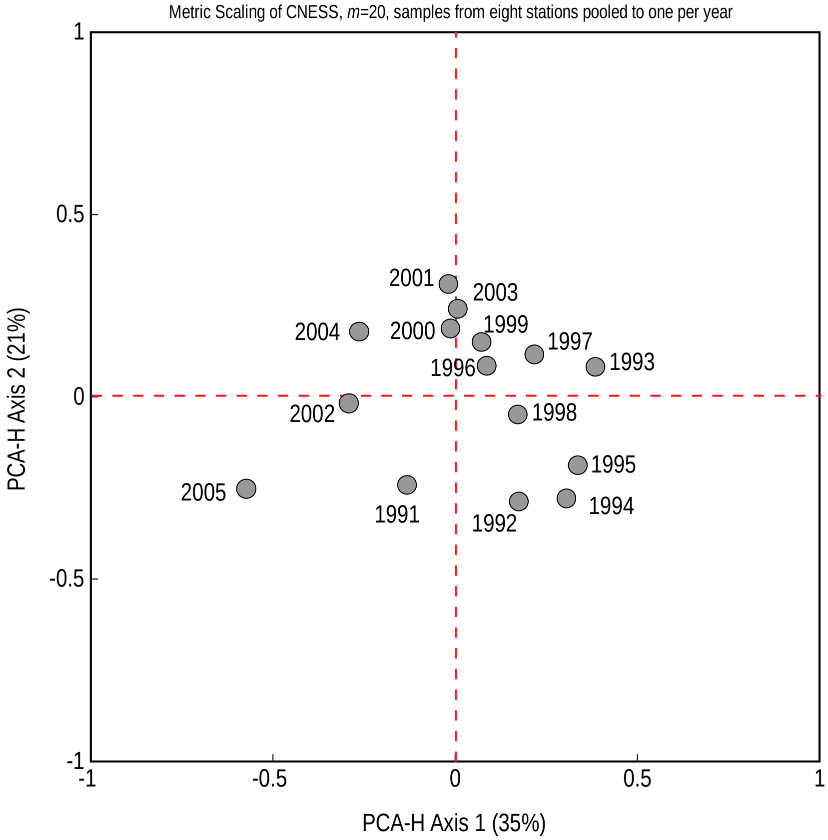


Figure 5-12. Metric scaling of 15 pooled samples taken in Boston Harbor from September 1991 through August 2005.

Table 5-5. Important species, their relative and cumulative contributions to PCA-H axes 1–7 of the metric scaling of CNESS distances of Boston Harbor samples within each year (see Figure 5-10).

PCA-H Rank	Species	% Contr.[a]	Cum. Contr.	Ax.1	Ax.2	Ax.3	Ax.4	Ax.5	Ax.6	Ax.7
1	*Tubificoides apectinatus*	11	11	24	9	0	1	4	2	3
2	*Streblospio benedicti*	10	21	3	43	1	3	0	1	0
3	*Crassicorophium bonelli*	9	31	7	6	34	3	17	0	14
4	*Polydora cornuta*	7	38	16	0	0	11	7	2	4
5	*Nephtys cornuta*	7	45	13	1	11	7	2	8	0
6	*Phoxocephalus holbolli*	6	51	3	4	13	1	4	36	1
7	*Leptocheirus pinguis*	6	57	2	7	1	4	40	0	6
8	*Capitella capitata complex*	6	62	1	2	6	39	0	2	23
9	*Unciola irrorata*	4	66	5	6	3	2	0	1	1
10	*Ampelisca* spp.	4	70	5	3	3	0	1	13	7
11	*Prionospio steenstrupi*	3	73	6	0	4	2	0	1	0
12	*Chaetozone vivipara*	3	77	3	2	2	0	3	1	22
13	*Tubificoides* nr. *pseudogaster*	3	79	1	0	9	5	1	0	0
14	*Aricidea catherinae*	2	82	3	0	0	6	1	10	3
15	*Photis pollex*	2	84	0	5	2	6	3	0	1
16	*Tharyx spp.*	2	86	1	0	0	2	0	2	0
17	*Spiophanes bombyx*	2	88	1	1	1	0	5	5	1
18	*Orchomenella minuta*	2	89	0	5	0	0	1	1	0
19	*Nucula delphinodonta*	1	91	0	1	0	0	3	4	0
20	*Phyllodoce mucosa*	1	92	0	2	0	0	3	1	0
21	*Nephtys ciliata*	1	93	2	0	1	0	0	0	0
22	*Polygordius* sp. A	1	93	0	0	2	0	0	1	0
23	*Microphthalmus pettiboneae*	1	94	0	0	3	1	0	0	1
24	*Tubificoides benedeni*	1	95	0	0	0	1	0	2	0
25	*Ilyanassa trivittata*	1	95	1	0	0	0	1	0	0

[a] Percent contributions are rounded up to the nearest whole number by the computer program.

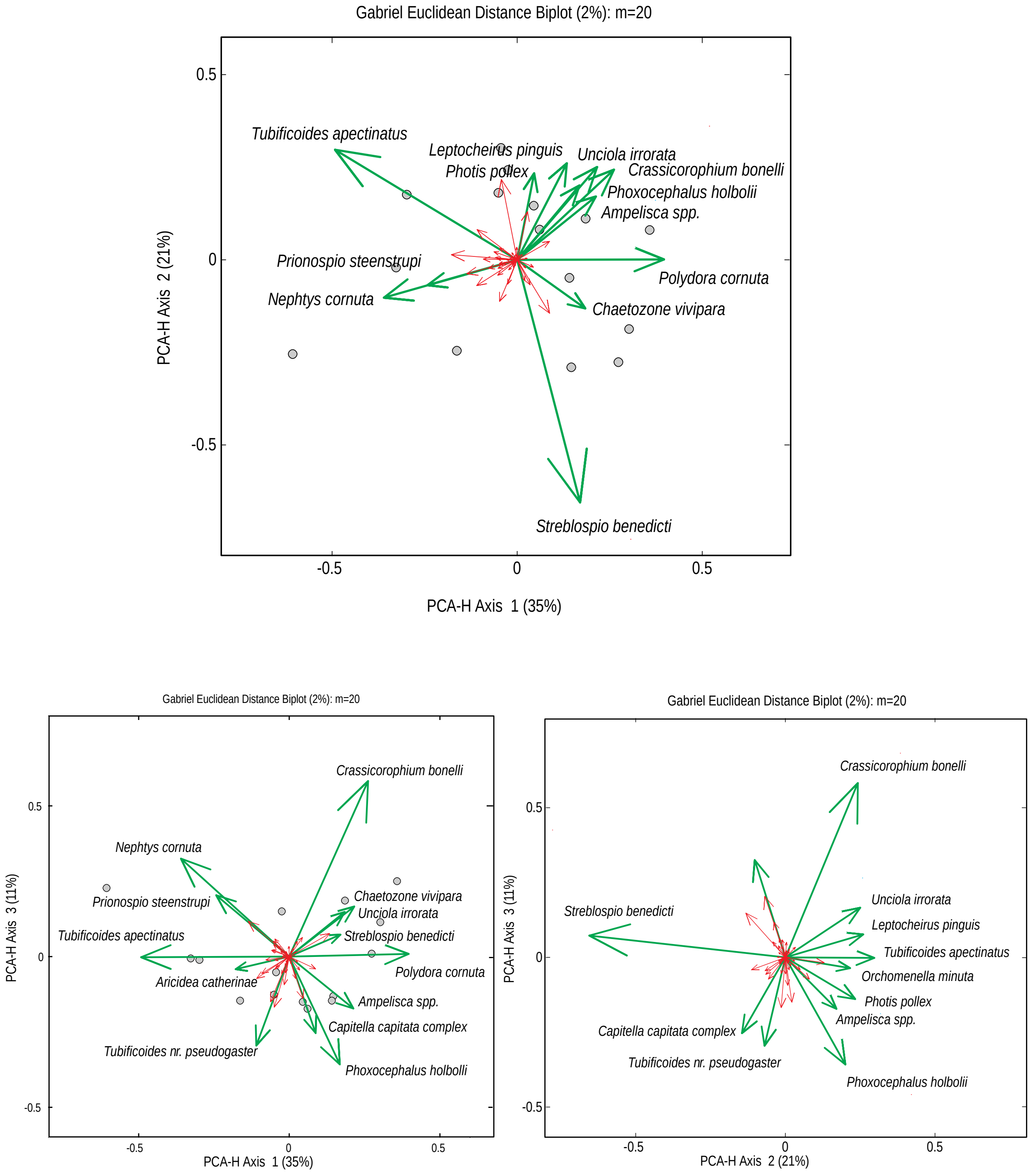


Figure 5-13. Gabriel Euclidean biplot of 15 annual pooled samples. Species vectors accounting for >2% of plot variation in green; other species vectors plotted in red and unlabeled.

Table 5-6. Contribution to PCA-H axes 1, 2, and 3 of the ten species accounting for at least 2% of the annual community variation at the Boston Harbor stations when samples are pooled to one per year for each of 15 years. (see Euclidean Distance Biplot, Figure 5-11.)

Important species: Axis 1 vs. 2					
PCA-H Rank	**Species**	**Contr.[a]**	**Total Contr.**	**Axis 1**	**Axis 2**
1	*Tubificoides apectinatus*	18	18	24	9
2	*Streblospio benedicti*	18	36	3	43
3	*Polydora cornuta*	10	46	16	0
4	*Nephtys cornuta*	8	55	13	1
5	*Crassicorophium bonelli*	6	61	7	6
6	*Unciola irrorata*	5	66	5	6
7	*Ampelisca* spp.	4	70	5	3
8	*Prionospio steenstrupi*	4	74	6	0
9	*Leptocheirus pinguis*	4	78	2	7
10	*Phoxocephalus holbolli*	3	81	3	4
11	*Chaetozone vivipara*	3	84	3	2
12	*Photis pollex*	2	86	0	5
Important species: Axis 1 vs. 3					
PCA-H Rank	**Species**	**Contr.[a]**	**Total Contr.**	**Axis 1**	**Axis 3**
1	*Tubificoides apectinatus*	18	18	24	0
2	*Crassicorophium bonelli*	13	32	7	34
3	*Nephtys cornuta*	12	44	13	11
4	*Polydora cornuta*	12	56	16	0
5	*Prionospio steenstrupi*	5	61	6	4
6	*Phoxocephalus holbolli*	5	67	3	13
7	*Unciola irrorata*	4	71	5	3
8	*Ampelisca* spp.	4	75	5	3
9	*Chaetozone vivipara*	3	78	3	2
10	*Tubificoides* nr. *pseudogaster*	3	81	1	9
11	*Aricidea catherinae*	2	84	3	0
12	*Streblospio benedicti*	2	86	3	1
13	*Capitella capitata complex*	2	88	1	6
Important species: Axis 2 vs. 3					
PCA-H Rank	**Species**	**Contr.[a]**	**Total Contr.**	**Axis 2**	**Axis 3**
1	*Streblospio benedicti*	28	28	43	1
2	*Crassicorophium bonelli*	16	44	6	34
3	*Phoxocephalus holbolli*	7	51	4	13
4	*Tubificoides apectinatus*	6	57	9	0
5	*Unciola irrorata*	5	62	6	3
6	*Leptocheirus pinguis*	5	66	7	1
7	*Nephtys cornuta*	4	71	1	11
8	*Photis pollex*	4	75	5	2
9	*Capitella capitata* complex	4	79	2	6
10	*Tubificoides* nr. *pseudogaster*	3	82	0	9
11	*Orchomenella minuta*	3	85	5	0
12	*Ampelisca* spp.	3	88	3	3

[a] Percent contributions are rounded up to the nearest whole number by the computer program.

Similarity and Ordination Analysis with Bray-Curtis**—**The Bray-Curtis similarity analysis returned results that first appear somewhat different that with CNESS. When the data were fourth-root-transformed prior to analysis, the abundant species such as *Ampelisca* spp. are severely down-weighted and the similarity values better reflect the uncommon species in the samples. In this analysis, three groups of years are evident (Figure 5-14):

Cluster 1. 1991
Cluster 2. 1992–2001
Cluster 3. 2002–2005

With CNESS (Figure 5-11), 2005 was the most dissimilar year, whereas with Bray-Curtis, it is 1991. Both Bray-Curtis and CNESS indicate a high similarity between years 2002 through 2004, and differentiate these from earlier years.

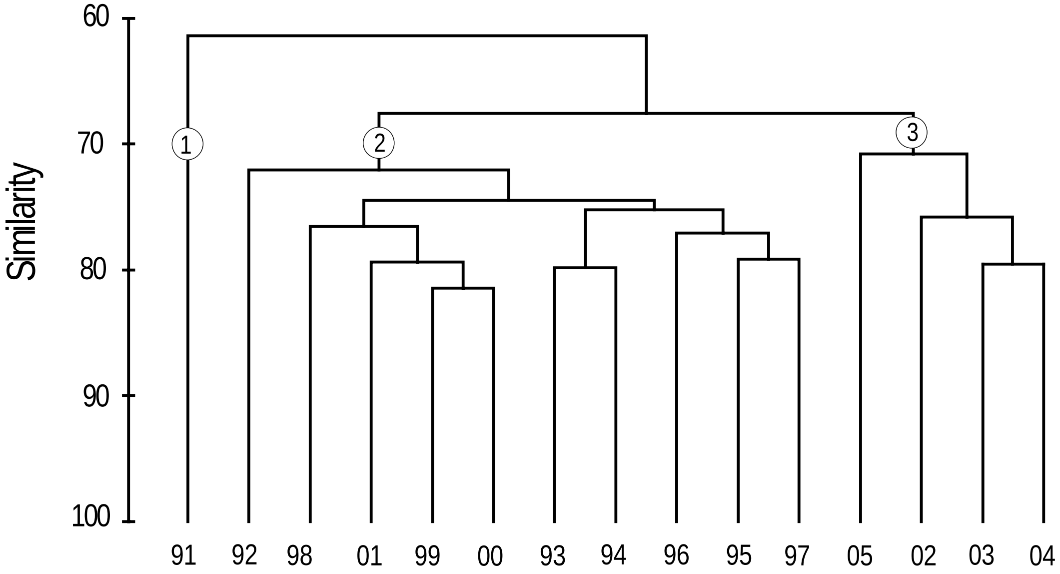


Figure 5-14. Cluster dendrogram based on the Bray-Curtis similarity analysis of Boston Harbor 1991–2005 infaunal data, after fourth-root-transformation of the data and group average clustering.

Ordination of these samples by non-metric multidimensional scaling (NMDS) is shown in Figure 5-15. The low stress level (0.07) indicates that this sample map is a good representation of the multidimensional space occupied by the annual samples. Because this map indicates relative distances among samples better than is portrayed by the dendrogram, it can be seen that with Bray-Curtis, as with CNESS, both 1991 and 2005 occupy different multidimensional space than the remaining samples, and that the early years are separated from recent years. Relative abundances of the ten species that were identified in the PCA-H Euclidean distance analysis as contributing the most to the variation among samples (Table 5-4) are shown as overlays in Figure 5-15 and 5-16. Differences in species composition among years are obvious from these plots; *e.g.*, *Phoxocephalus holbolli*, *Polydora cornuta, Streblospio benedicti*, and *Unciola irrorata* were abundant in early years while other species, such *Tubificoides apectinatus* were common more recently. Some species occurred only in a particular year (*Capitella capitata*, 1998; *Crassicorophium bonelli*, 1993 and 1997; *Nephtys cornuta* 2005)

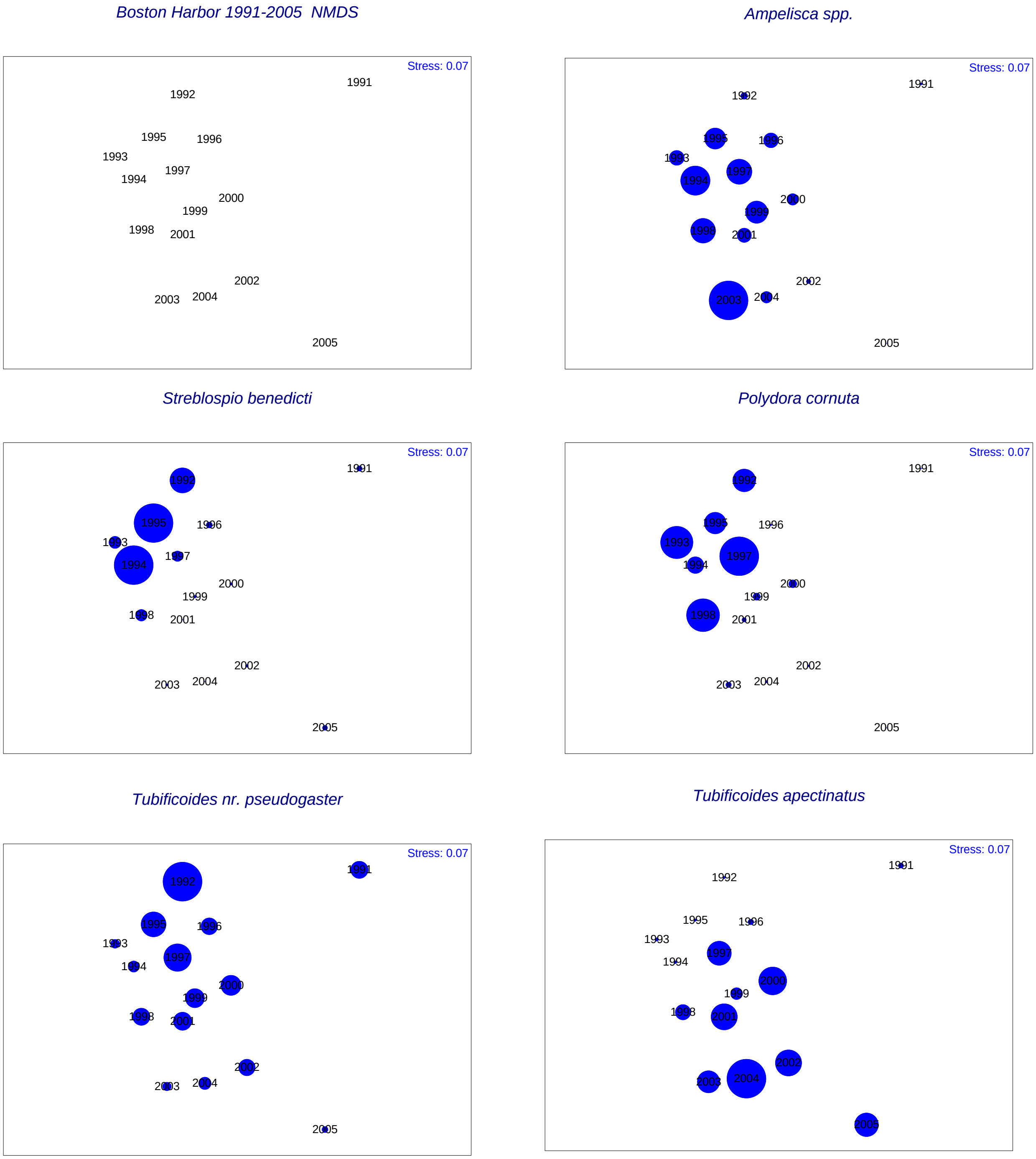
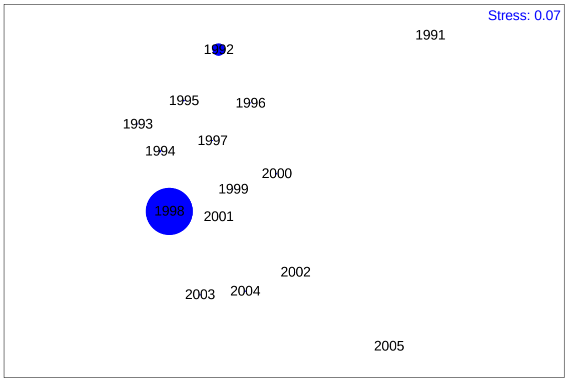
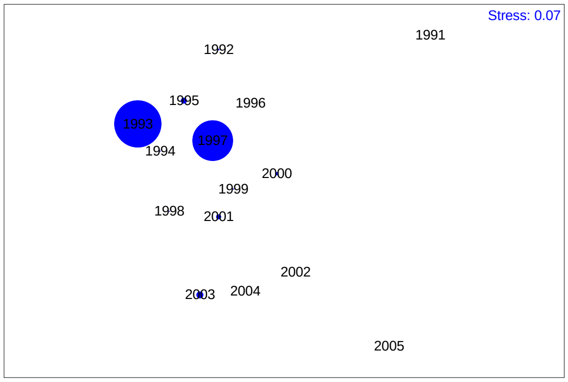


Figure 5-15. NMDS based on the Bray-Curtis similarity analysis of Boston Harbor 1991–2005 infaunal data, after fourth-root-transformation of the data. Graphs with species overlay indicate relative abundances of those species in each year.

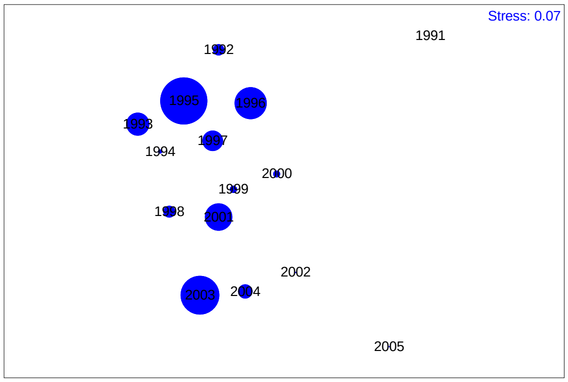
Capitella capitata complex



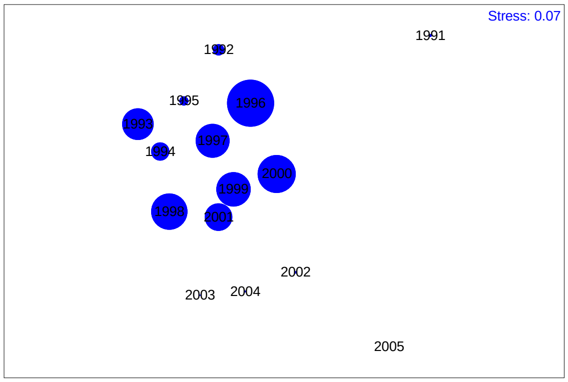
Crassicorophium bonelli



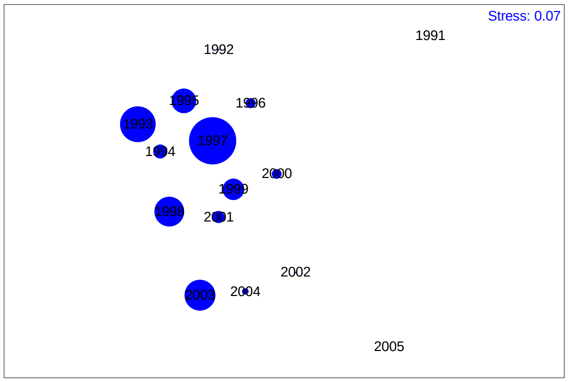
Leptocheirus pinguis



Phoxocephalus holbolli



Unciola irrorata



Nepthys cornuta

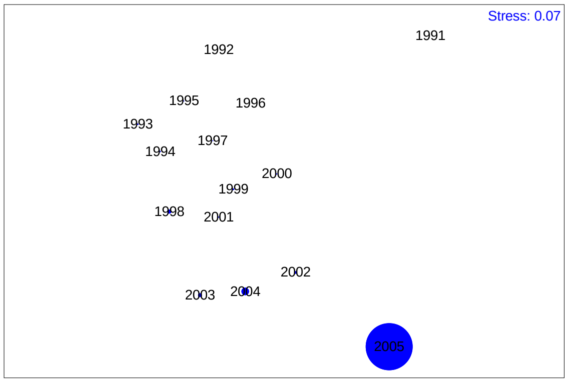


Figure 5-16. NMDS based on the Bray-Curtis similarity analysis of Boston Harbor 1991–2005 infaunal data, after fourth-root-transformation of the data. Graphs with species overlay indicate relative abundances of those species in each year.

A Bray-Curtis similarity analysis was run on all harbor infaunal replicates to investigate the difference among years more closely (Figure 5-17). This analysis supports the interpretation that each of the harbor stations has a unique signature: the majority of samples from any station are more similar to replicates from that station than to samples from another station. Stations T03 and T06, and to a lesser extent, stations T02 and T07 often have high similarities between stations in years when the amphipod populations were especially high. It can also be seen from this diagram that the years after the diversion of the outfall (September 2000) tend to have low similarity to years before the diversion.

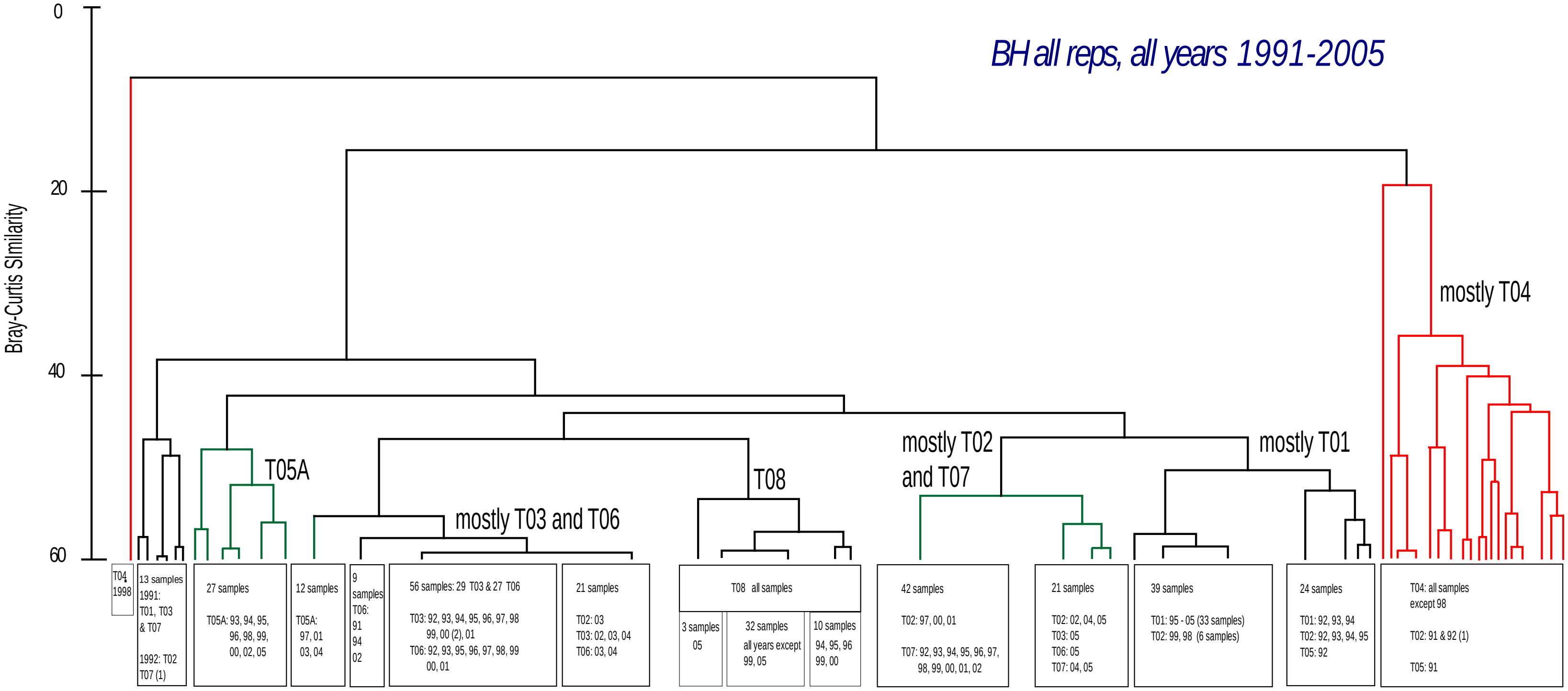


Figure 5-17. Similarity analysis of all Boston Harbor replicates considered separately.

Pre- and post-diversion differences can be also be investigated by examining stations separately (Maciolek *et al.* 2006). T01 is an example of a harbor station that has changed noticeably since it was first sampled in the late 1970s and early 1980s. At that time, this station, located off the Deer Island flats, exhibited the poor physical environment and low diversity of a severely stressed station. Over the course of the past 15 years, with the increasing removal of the pollutant load, the species composition of the station has changed, concomitant with a steady increase in diversity and species richness.

The early years of monitoring were marked by large seasonal fluctuations in abundances, with high densities in the August samples (Figure 5-18) and low densities in the spring samples (Maciolek *et al.* 2004). These fluctuations were due primarily to large numbers of *Polydora cornuta* (a suspension feeding spionid polychaete) and *Clymenella torquata* (a head-down deposit feeding maldanid polychaete) that settled in August but had migrated or died off by the following spring. *Clymenella torquata* was largely absent from this station in 1999 and 2000, but was again represented by a set of juveniles in 2001 and 2003 (Maciolek *et al.* 2005), resulting in some similarities with T08 in the southern part of the harbor. Fewer *C. torquata* were present in 2004, resulting in a weaker similarity with T08 than in 2003, and only 6.3 individuals per sample were recorded in 2005. The presence of this species is often highly correlated with sediment gain sizes, usually preferring sandy sediments. In general, the last several years of monitoring (*i.e.,* 1999–2005) have been marked by much lower abundances compared with the period prior to 1999 (Figure 5-18).

Community parameters, especially diversity, reflect the changes over time at T01 (Figure 5-18). Shannon diversity (H′) and log-series *alpha* both increased through 2004, but declined, as at other harbor stations, in 2005. The mean H′ was greater than 3.0 starting in August 1997, and reached a high of 4.1 in August 2004. Diversity as measured by log-series *alpha* has been more variable than Shannon H′, but has also increased over the past decade to a high of 10.1 in 2004. Rarefaction curves (Figure 5-19) based on samples pooled for each August sampling date demonstrate higher diversities in 2001–2004 compared with earlier years. As seen for the harbor overall, however, all of these parameters declined in 2005.

Changes in species composition at T01 are reflected in the multivariate analyses (Figure 5-20). Axes 1 and 2 in the PCA-H analysis accounted for 57% of the CNESS variation among samples (Figure 5-20A). Species that contributed 2% or more to the CNESS variation are indicated in the Gabriel Euclidean biplot (Figure 5-20B) and in Table 5-7. *Streblospio benedicti*, an opportunistic species tolerant of stressed environmental conditions, was once common at T01 but has been present in much lower densities since 1998: in the past three years, only 3–10 were present in the samples. Similarly, *Polydora cornuta,* which numbered 2000–12,000 in years prior to 1998, is now found in much lower numbers, typically 500 or fewer each year; in 2005, only 138 specimens were recorded. One species of oligochaete, *Tubificoides* nr. *pseudogaster*, was common in the early years of monitoring, but a second species, *Tubificoides* sp. 2, has been more common in recent years. Other species that were not found at T01 in the early monitoring years, but are now common, include *Nephtys ciliata*, *Leptocheirus pinguis*, *Exogone hebes,* and *Aricidea catherinae.*

The OSI measured by sediment profile imaging (Chapter 4, this report) increased from low values of 3.0-5.3 from 1992–2001 to highs of 8.0 and 9.3 in 2002 and 2003, respectively, but declined again in 2004 to 4.8 (Maciolek *et al.* 2006a). Sediments at T01 have been consistently high in sand content, with the exception of 1992 and 1995 (Maciolek *et al.* 2006a).

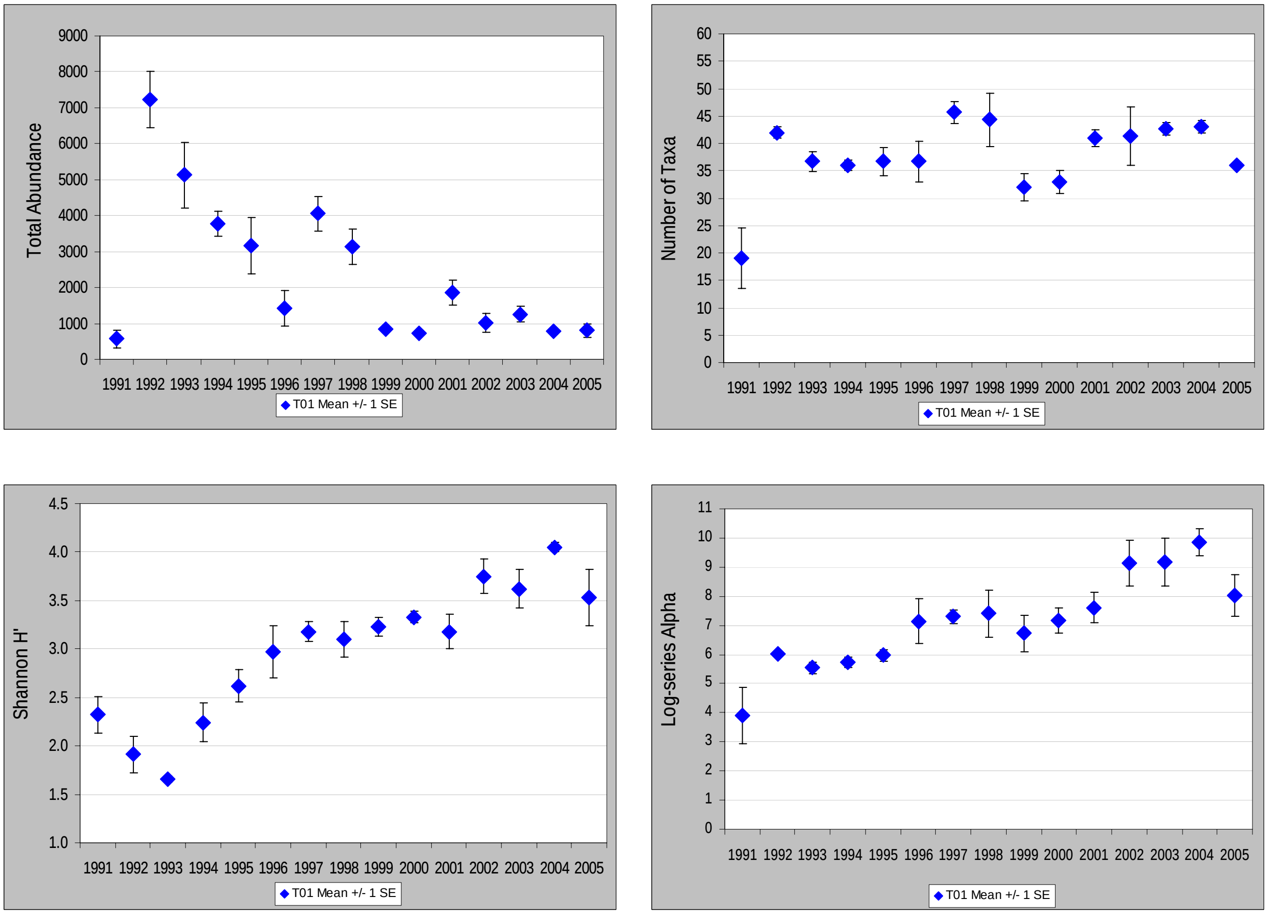


Figure 5-18. Benthic community parameters measured in August 1991 through 2005 at Boston Harbor station T01.

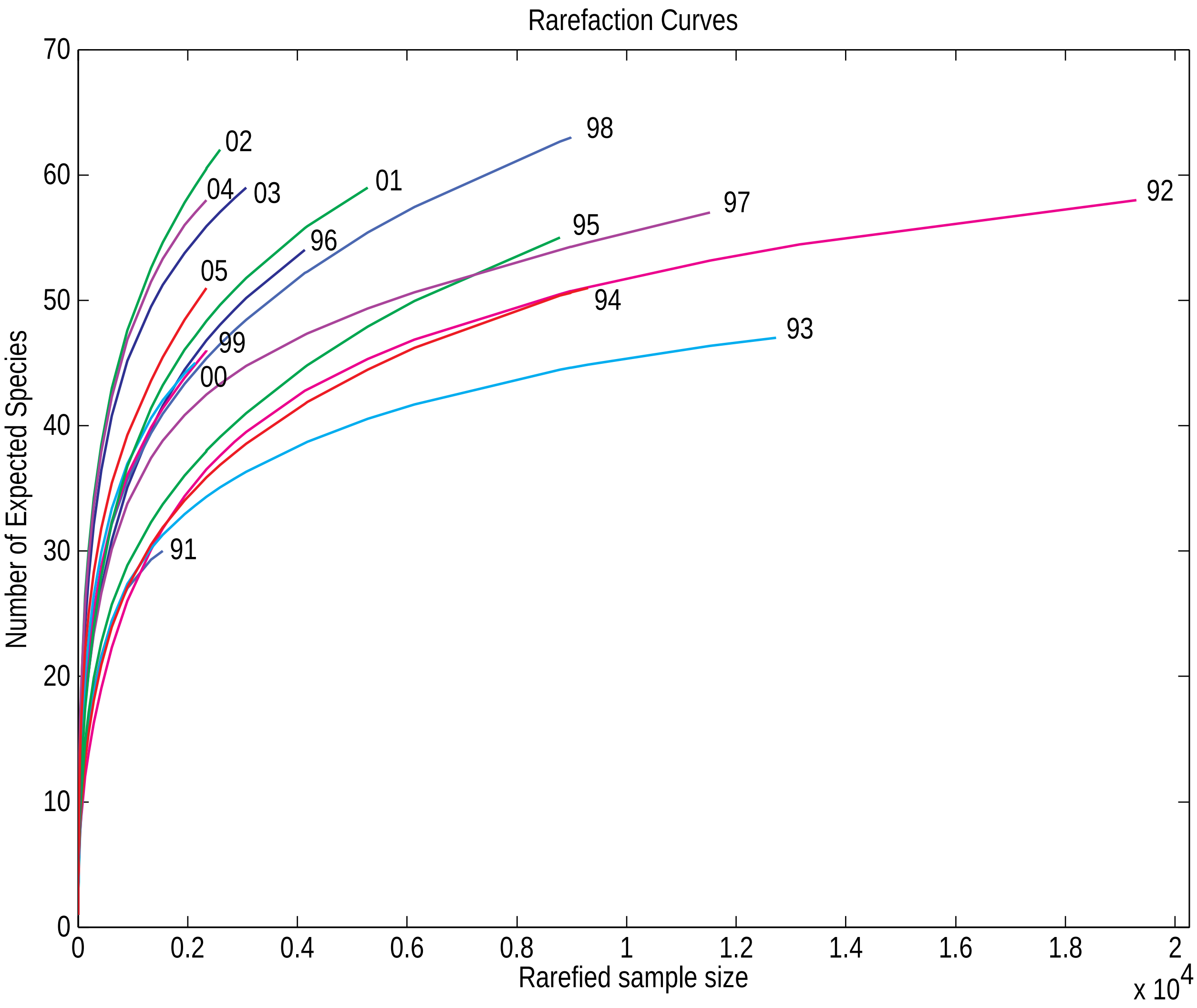


Figure 5-19. Rarefaction curves for T01, based on samples pooled for each August sampling date.

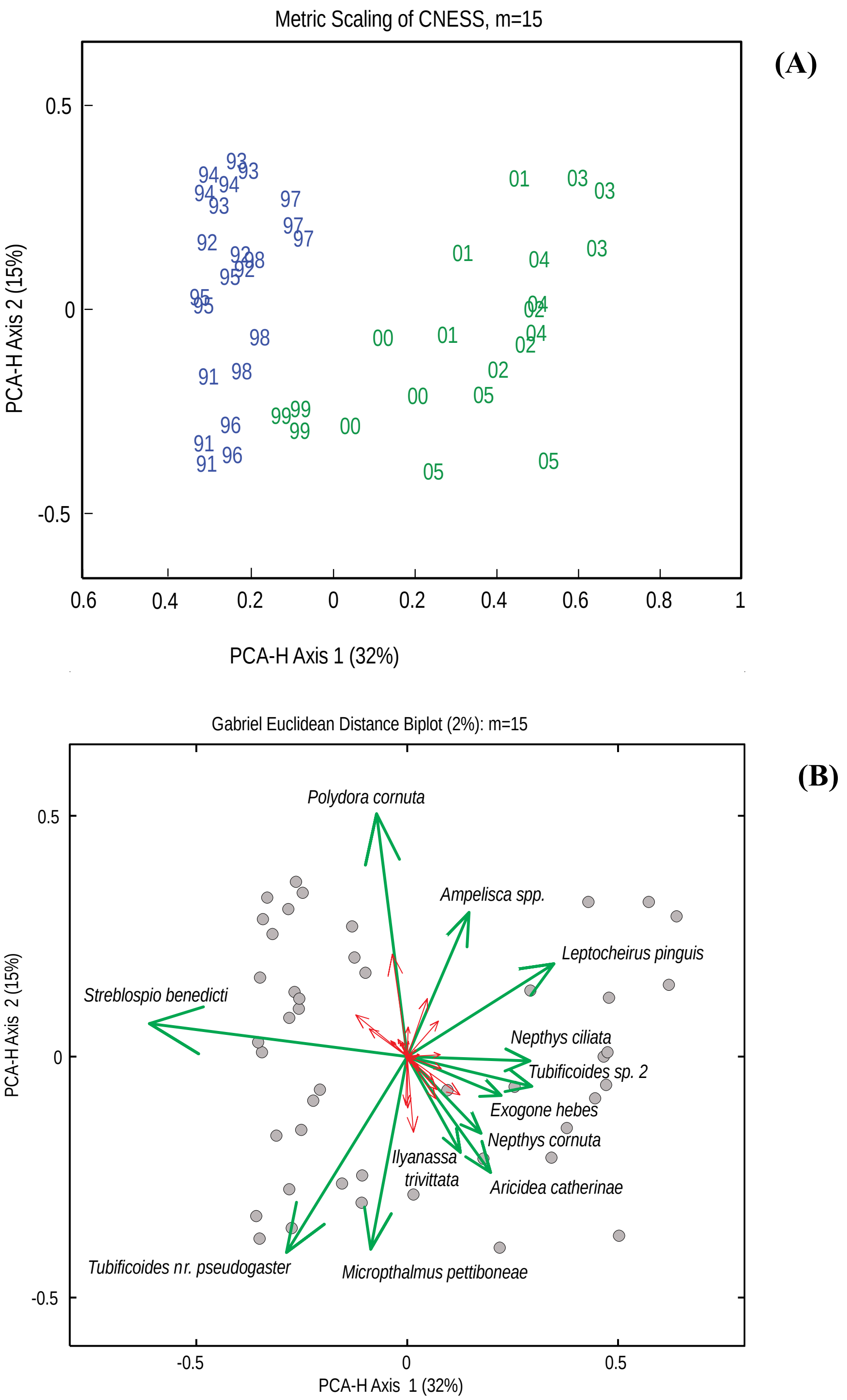


Figure 5-20. PCA-H analysis of 45 samples taken at T01 in September 1991 and August 1992-2005. (A) Metric scaling of CNESS distances; (B) Species vectors accounting for >2% of plot variation in green; other species vectors plotted in red and unlabeled.

Table 5-7. Contribution to PCA-H axes 1 and 2 of the 11 species accounting for at least 2% of the community variation at Boston Harbor Station T01 (see Figure 5-20B).

PCA-H Rank	Species	Contr.[a]	Total Contr.	Axis 1	Axis 2
1	*Streblospio benedicti*	25	25	37	0
2	*Tubificoides* nr. *pseudogaster*	11	36	8	17
3	*Leptocheirus pinguis*	9	46	12	4
4	*Polydora cornuta*	9	54	1	25
5	*Tubificoides* sp. 2	6	60	9	0
6	*Nephtys ciliata*	6	66	8	0
7	*Microphthalmus pettiboneae*	6	72	1	16
8	*Aricidea catherinae*	4	76	4	6
9	*Ampelisca* spp.	4	81	2	9
10	*Exogone hebes*	4	84	5	1
11	*Nephtys cornuta*	3	87	3	3
12	*Ilyanassa trivittata*	2	89	2	4

[a] Percent contributions are rounded up to the nearest whole number by the computer program.

5.3.5 Long-term Changes in the Infaunal Communities

Benthic communities in Boston Harbor were clearly impacted by decades of pollutant discharge. The early studies of benthic communities in Boston Harbor (1978, 1979, and 1982) indicated distinct groupings of stations that corresponded to (1) a progression from higher saline oceanic conditions in the outer harbor to estuarine conditions in the inner harbor and (2) known areas of pollution (Blake and Maciolek 1990, Maciolek *et al*. 2004). A distinct outer harbor assemblage that included species with close affinities to faunal communities in Massachusetts Bay changed in the middle of the harbor to one that included estuarine species and elements of so-called pollution indicators or stress-tolerant taxa.

All stations in the outer harbor assemblage had more species and higher species diversity values regardless of differences in sample size or analytical technique. Stations having high infaunal densities were found throughout the station array, but opportunistic species such as *Streblospio benedicti* were found only at the stations in the middle of the harbor. The early data also clearly indicated an obvious north/south pattern in the benthic communities, with stations near the northern Deer Island outfall being distinctly different from those near Nut Island in Hingham Bay in the southern part of the harbor. Tidal exchange through President Roads and Broad Sound appeared to be sufficient to maintain benthic assemblages that were only moderately stressed despite their proximity to the sewage and sludge outfalls. In contrast, shallow sites to the east and west of the outfall had low diversities and high densities of opportunistic stress-tolerant species.

Discharge of sludge into the harbor ended in 1991 and in 1998 all effluent discharge from Nut Island was discontinued and full secondary treatment of the effluent was implemented. On September 6, 2000, all wastewater discharges were diverted to the new outfall in Massachusetts Bay, and in early 2001, the final battery of secondary treatment became operational. Taylor (2005) summarized the major patterns in freshwater flows and loadings of total nitrogen (TN), total phosphorus (TP), total suspended solids (TSS), and particulate organic carbon (POC) to Boston Harbor between 1995 and 2003. He found three periods:

- Period A was from 1995 through mid-1998
  (Nut Island and Deer Island discharges received some improved treatment)
- Period B was from mid-1998 to 2000
  (the Nut Island discharge was diverted to Deer Island)
- Period C began in 2000
  (transfer of the discharge offshore in September)

The changes in wastewater discharge from 1995 to 2003 resulted in about a 90% decrease in loadings to Boston Harbor. For TSS and POC, most of the decreases occurred between Periods A and B, presumably in response to the transfer of the Nut Island discharge to Deer Island and treatment upgrade. For TN and TP, most of the decreases occurred between Periods B and C, in response to transfer of the discharge offshore (Taylor 2005).

Recovery of areas degraded by the long-term disposal of sludge and effluents may involve a transitional stage of undetermined length before an equilibrium community is established. This intermediate stage involves the appearance of a diverse assemblage of tube-dwelling amphipods, molluscs, and polychaetes. The periodic explosion and decline of amphipod populations dominated by *Ampelisca* spp. suggests that infaunal succession patterns are being held in the Stage I and II seres as defined by Rhoads and Germano (1986). As noted in Chapter 4 (this report), *Ampelisca* spp. thrive in areas with high organic input and good water quality (Stickney and Stringer 1957). Beginning in 1993, the *Ampelisca* spp. population in the harbor spread and then declined; however, in 2003 the populations of this and other species of amphipods accounted for 75 % of the sampled fauna, the second highest density since 1998. In 2004 the amphipod populations had declined once again and by 2005, this major faunal component, which had dominated much of the harbor benthos over the 15 years of this study, was almost entirely absent. Given the physical and oceanographic attributes of the study area (*i.e.*, near-coastal environment, relatively shallow compared with offshore areas, continuing pollutant load, albeit reduced, from CSOs or other industrial sources), it is probable that the harbor benthos will continue to evidence this episodic rise and decline of amphipod populations, and will remain in a Stage I/Stage II pattern. Alternatively, large amounts of organic matter are needed to sustain the high population levels recorded during some years of this program, and if the available carbon has been consumed and not replaced, a permanent decline in the amphipod population would follow (see Chapter 4, this report).

The addition of station CO19 in the inner harbor will allow tracking of changes that take place after a planned upgrade of the nearby CSO as part of the MWRA's continuing program to upgrade and/or close CSOs.

Mean parameters for the harbor overall were not significantly different between Taylor's time periods A and B, but differed the most between A and C (Table 5-8). Lines of evidence from other components of this monitoring program suggest that, when taken as a whole, the harbor has not changed significantly over the past decade. For example, based on the SPI sampling, no station showed a monotonic trend of either improvement or decline (Chapter 4, this report). However, detailed analyses of the infaunal communities at the traditional stations, as well as other lines of evidence, such as the decrease in levels of the sewage marker *Clostridium perfringens* (Chapter 3, this report) strongly support a different conclusion: that the benthic environment in the harbor is indeed recovering from years of pollutant input. When stations are evaluated individually (Maciolek *et al*. 2006), it is clear that the communities present in the harbor today differ from those present before the major reduction in pollutant loads, and that species richness and diversity (as measured by log-series *alpha*) have increased at each of the eight traditional harbor stations over the 15-year time period.

Table 5-8. Characteristics for Boston Harbor traditional stations summarized by time periods defined by Taylor (2005).

Parameter	**Period**		
	A	**B**	**C**
	1991–1998	**1999–2000**	**2001–2005**
	***n* = 192**	***n*= 47**	***n* = 120**
Number of Species	32.3 ± 14.3	32.0±12.5	42.3 ± 18.0
H′	2.3 ± 0.9	2.8 ± 0.8	2.9 ± 0.8
log-series *alpha*	5.2 ± 2.1	5.9 ± 1.9	7.7 ± 3.0
Rarefaction curves (Figure 5-8)	low	high	highest
Fauna	higher abundances of opportunistic species such as *Streblospio benedicti* and *Polydora cornuta*		fewer opportunists, more oligochaetes, some species from Massachusetts Bay.

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APPENDIX A1

Station Data:
Sediment Profile Images (HR051)

Table A1-1. Field data for sediment profile image survey HR051.

(Times are reported in Eastern Standard Time)

STUDY_ID	EVENT_ID	STAT_ID	LOC_DESC	STAT_ARRIV (EST)	BEG_LATITUDE	BEG_LONGITUDE	DEPTH_TO_BOTTOM	DEPTH_UNIT_CODE	NAVIGATION_CODE	NAV_QUAL
BHSOFT	HR051	C019	FORT POINT CHANNEL	8/22/05 13:36	42.358982	-71.0452651	10.7	m	DGPS	+/- 10m
BHSOFT	HR051	R02	DEER ISLAND FLATS	8/22/05 11:49	42.3442001	-70.9614028	15.7	m	DGPS	+/- 10m
BHSOFT	HR051	R03	DEER ISLAND FLATS	8/22/05 12:21	42.3529014	-70.9728469	6.2	m	DGPS	+/- 10m
BHSOFT	HR051	R04	DEER ISLAND FLATS	8/22/05 12:35	42.3586997	-70.9795684	9	m	DGPS	+/- 10m
BHSOFT	HR051	R05	DEER ISLAND FLATS	8/22/05 12:28	42.3564338	-70.9782028	7.5	m	DGPS	+/- 10m
BHSOFT	HR051	R06	OUTER HARBOR	8/23/05 10:44	42.3317489	-70.9524002	6.3	m	DGPS	+/- 10m
BHSOFT	HR051	R07	DEER ISLAND FLATS	8/22/05 12:14	42.3477516	-70.9754486	7.8	m	DGPS	+/- 10m
BHSOFT	HR051	R08	OFF LOGAN AIRPORT	8/22/05 12:48	42.3442001	-70.9916839	5	m	DGPS	+/- 10m
BHSOFT	HR051	R09	CHARLES RIVER	8/22/05 13:14	42.3466987	-71.0163192	14	m	DGPS	+/- 10m
BHSOFT	HR051	R10	CHARLES RIVER	8/22/05 13:26	42.3553657	-71.0369796	15.4	m	DGPS	+/- 10m
BHSOFT	HR051	R11	OFF LONG ISLAND	8/23/05 11:10	42.3212165	-70.9747695	7.4	m	DGPS	+/- 10m
BHSOFT	HR051	R12	OFF LONG ISLAND	8/23/05 11:17	42.3182678	-70.9744033	5.6	m	DGPS	+/- 10m
BHSOFT	HR051	R13	OFF LONG ISLAND	8/23/05 11:27	42.3170814	-70.9805679	5.9	m	DGPS	+/- 10m
BHSOFT	HR051	R14	DORCHESTER BAY	8/23/05 12:01	42.3207168	-71.0128021	8.5	m	DGPS	+/- 10m
BHSOFT	HR051	R15	DORCHESTER BAY	8/23/05 12:30	42.3150672	-71.0195159	4.8	m	DGPS	+/- 10m
BHSOFT	HR051	R16	OFF LONG ISLAND	8/23/05 10:14	42.3158149	-70.9615325	7.2	m	DGPS	+/- 10m
BHSOFT	HR051	R17	OFF LONG ISLAND	8/22/05 14:02	42.3049163	-70.9773025	8.4	m	DGPS	+/- 10m
BHSOFT	HR051	R18	QUINCY BAY	8/23/05 8:54	42.2889823	-70.9610977	7.1	m	DGPS	+/- 10m
BHSOFT	HR051	R19	HINGHAM BAY	8/23/05 8:43	42.282135	-70.9378967	8	m	DGPS	+/- 10m
BHSOFT	HR051	R20	OUTER HARBOR	8/23/05 10:30	42.3247489	-70.9350814	9.3	m	DGPS	+/- 10m
BHSOFT	HR051	R21	NANTASKET ROADS	8/23/05 10:01	42.308834	-70.9466323	6.2	m	DGPS	+/- 10m
BHSOFT	HR051	R22	NANTASKET ROADS	8/23/05 9:53	42.3003654	-70.93927	8.2	m	DGPS	+/- 10m
BHSOFT	HR051	R23	NANTASKET ROADS	8/23/05 9:36	42.2938003	-70.9499511	9.2	m	DGPS	+/- 10m
BHSOFT	HR051	R24	NANTASKET ROADS	8/23/05 9:27	42.2964515	-70.9585494	5.9	m	DGPS	+/- 10m
BHSOFT	HR051	R25	HINGHAM BAY	8/23/05 8:32	42.2913665	-70.9286804	4.7	m	DGPS	+/- 10m
BHSOFT	HR051	R26	HINGHAM BAY	8/23/05 6:42	42.2687988	-70.9300003	5.5	m	DGPS	+/- 10m
BHSOFT	HR051	R27	HINGHAM BAY	8/23/05 7:25	42.2803649	-70.9164505	3.4	m	DGPS	+/- 10m
BHSOFT	HR051	R28	HINGHAM BAY	8/23/05 7:17	42.2816314	-70.9088516	6.7	m	DGPS	+/- 10m
BHSOFT	HR051	R29	HINGHAM BAY	8/23/05 8:24	42.2896499	-70.9207687	7.6	m	DGPS	+/- 10m
BHSOFT	HR051	R30	HINGHAM BAY	8/23/05 7:42	42.2903823	-70.9041671	2.2	m	DGPS	+/- 10m
BHSOFT	HR051	R31	HINGHAM BAY	8/23/05 8:06	42.3009834	-70.9169998	8.6	m	DGPS	+/- 10m
BHSOFT	HR051	R32	HINGHAM BAY	8/23/05 7:51	42.2947349	-70.8970489	2.6	m	DGPS	+/- 10m
BHSOFT	HR051	R33	QUINCY BAY	8/22/05 14:24	42.2943	-70.9946136	5.3	m	DGPS	+/- 10m
BHSOFT	HR051	R34	QUINCY BAY	8/22/05 14:36	42.2888679	-71.0068817	4.4	m	DGPS	+/- 10m
BHSOFT	HR051	R35	QUINCY BAY	8/22/05 14:46	42.2842483	-70.9880142	5.4	m	DGPS	+/- 10m
BHSOFT	HR051	R36	QUINCY BAY	8/22/05 14:54	42.2755508	-70.9863815	4.3	m	DGPS	+/- 10m
BHSOFT	HR051	R37	QUINCY BAY	8/22/05 14:12	42.2986984	-70.9846801	6.6	m	DGPS	+/- 10m
BHSOFT	HR051	R38	QUINCY BAY	8/22/05 15:06	42.2846984	-70.9639816	6.5	m	DGPS	+/- 10m
BHSOFT	HR051	R39	QUINCY BAY	8/23/05 9:15	42.2956008	-70.9702529	5.8	m	DGPS	+/- 10m

STUDY_ID	EVENT_ID	STAT_ID	LOC_DESC	STAT_ARRIV (EST)	BEG_LATITUDE	BEG_LONGITUDE	DEPTH_TO_BOTTOM	DEPTH_UNIT_CODE	NAVIGATION_CODE	NAV_QUAL
BHSOFT	HR051	R40	DORCHESTER BAY	8/23/05 12:12	42.3288993	-71.0242004	5.1	m	DGPS	+/- 10m
BHSOFT	HR051	R41	DORCHESTER BAY	8/23/05 12:38	42.3111495	-71.0248489	6.1	m	DGPS	+/- 10m
BHSOFT	HR051	R42	DORCHESTER BAY	8/23/05 12:22	42.3194351	-71.0250473	4.4	m	DGPS	+/- 10m
BHSOFT	HR051	R43	DORCHESTER BAY	8/23/05 13:18	42.3068161	-71.002037	5.3	m	DGPS	+/- 10m
BHSOFT	HR051	R44	OFF LOGAN AIRPORT	8/22/05 13:06	42.3437652	-71.0022354	11.4	m	DGPS	+/- 10m
BHSOFT	HR051	R45	OFF LONG ISLAND	8/23/05 11:02	42.3282661	-70.9674987	7.9	m	DGPS	+/- 10m
BHSOFT	HR051	R46	HINGHAM BAY	8/23/05 8:13	42.2910003	-70.922264	7.1	m	DGPS	+/- 10m
BHSOFT	HR051	R47	DEER ISLAND FLATS	8/22/05 12:07	42.3444519	-70.9783859	7	m	DGPS	+/- 10m
BHSOFT	HR051	R48	QUINCY BAY	8/22/05 14:18	42.2936515	-70.9879989	5.9	m	DGPS	+/- 10m
BHSOFT	HR051	R49	HINGHAM BAY	8/23/05 6:54	42.2732009	-70.9083023	4.7	m	DGPS	+/- 10m
BHSOFT	HR051	R50	HINGHAM BAY	8/23/05 7:09	42.2749824	-70.8985824	5.3	m	DGPS	+/- 10m
BHSOFT	HR051	R51	HINGHAM BAY	8/23/05 6:21	42.2631835	-70.9423522	2.6	m	DGPS	+/- 10m
BHSOFT	HR051	R52	HINGHAM BAY	8/23/05 6:12	42.2617835	-70.9347305	2.5	m	DGPS	+/- 10m
BHSOFT	HR051	R53	HINGHAM BAY	8/23/05 6:32	42.2692184	-70.9379806	2.9	m	DGPS	+/- 10m
BHSOFT	HR051	T01	OFF DEER ISLAND WEST SIDE	8/22/05 11:57	42.348999	-70.9633865	5.9	m	DGPS	+/- 10m
BHSOFT	HR051	T02	PRESIDENT ROADS	8/22/05 12:57	42.3428993	-71.0021514	9	m	DGPS	+/- 10m
BHSOFT	HR051	T03	OFF NORTH EAST TIP OF LONG ISLAND	8/23/05 10:53	42.3302497	-70.9617309	8.3	m	DGPS	+/- 10m
BHSOFT	HR051	T04	DORCHESTER BAY	8/23/05 12:56	42.3098983	-71.041603	3.9	m	DGPS	+/- 10m
BHSOFT	HR051	T05A	PRESIDENT ROADS	8/22/05 11:39	42.3396148	-70.9606704	18.8	m	DGPS	+/- 10m
BHSOFT	HR051	T06	NANTASKET ROADS	8/23/05 9:42	42.2934837	-70.9441146	4.2	m	DGPS	+/- 10m
BHSOFT	HR051	T07	QUINCY BAY	8/23/05 9:06	42.2893829	-70.9786148	4.2	m	DGPS	+/- 10m
BHSOFT	HR051	T08	HINGHAM BAY	8/23/05 7:34	42.2852516	-70.9124984	9.9	m	DGPS	+/- 10m

Table A1-2. Station data from SPI survey conducted in August 2005 (HR051).

SurveyID	SampleID	Sample Date/Time	StationID	Replicate *not analyzed	Longitude	Latitude
HR051	HR051101	8/22/05 14:37:26	C019	1	-71.0453	42.3590
HR051	HR051102	8/22/05 14:37:49	C019	2	-71.0453	42.3590
HR051	HR051103	8/22/05 14:38:23	C019	3	-71.0453	42.3590
HR051	HR0510B0	8/22/05 12:50:52	R02	1	-70.9614	42.3442
HR051	HR0510B1	8/22/05 12:51:46	R02	2*	-70.9613	42.3442
HR051	HR0510B2	8/22/05 12:52:35	R02	3	-70.9613	42.3442
HR051	HR0510B3	8/22/05 12:53:20	R02	4	-70.9613	42.3442
HR051	HR0510CB	8/22/05 13:22:19	R03	1	-70.9728	42.3529
HR051	HR0510CC	8/22/05 13:23:18	R03	2	-70.9727	42.3529
HR051	HR0510CD	8/22/05 13:23:58	R03	3	-70.9727	42.3529
HR051	HR0510D8	8/22/05 13:36:53	R04	1	-70.9796	42.3587
HR051	HR0510D9	8/22/05 13:37:50	R04	2	-70.9796	42.3587
HR051	HR0510DA	8/22/05 13:38:42	R04	3	-70.9796	42.3587
HR051	HR0510D1	8/22/05 13:29:27	R05	1	-70.9782	42.3564
HR051	HR0510D2	8/22/05 13:30:46	R05	2*	-70.9782	42.3564
HR051	HR0510D3	8/22/05 13:31:28	R05	3	-70.9782	42.3564
HR051	HR0510D4	8/22/05 13:32:33	R05	4	-70.9781	42.3565
HR051	HR0511F4	8/23/05 11:47:01	R06	1	-70.9524	42.3317
HR051	HR0511F5	8/23/05 11:48:02	R06	2	-70.9522	42.3318
HR051	HR0511F6	8/23/05 11:49:06	R06	3	-70.9521	42.3318
HR051	HR0510C4	8/22/05 13:14:59	R07	1	-70.9754	42.3478
HR051	HR0510C5	8/22/05 13:16:36	R07	2	-70.9753	42.3476
HR051	HR0510C6	8/22/05 13:17:12	R07	3	-70.9752	42.3477
HR051	HR0510C7	8/22/05 13:17:21	R07	4*	-70.9751	42.3477
HR051	HR0510DE	8/22/05 13:49:22	R08	1	-70.9917	42.3442
HR051	HR0510DF	8/22/05 13:50:21	R08	2	-70.9917	42.3442
HR051	HR0510E0	8/22/05 13:50:59	R08	3	-70.9917	42.3442
HR051	HR0510F2	8/22/05 14:15:24	R09	1	-71.0163	42.3467
HR051	HR0510F3	8/22/05 14:16:21	R09	2	-71.0164	42.3468
HR051	HR0510F4	8/22/05 14:17:01	R09	3	-71.0164	42.3468
HR051	HR0510F8	8/22/05 14:27:04	R10	1*	-71.0370	42.3554
HR051	HR0510F9	8/22/05 14:27:48	R10	2	-71.0369	42.3554
HR051	HR0510FA	8/22/05 14:28:32	R10	3*	-71.0369	42.3553
HR051	HR0510FB	8/22/05 14:29:26	R10	4*	-71.0369	42.3554
HR051	HR0510FC	8/22/05 14:30:09	R10	5	-71.0369	42.3553
HR051	HR0510FD	8/22/05 14:30:47	R10	6	-71.0369	42.3553
HR051	HR051206	8/23/05 12:11:42	R11	1	-70.9748	42.3212
HR051	HR051207	8/23/05 12:13:02	R11	2	-70.9747	42.3212
HR051	HR051208	8/23/05 12:13:44	R11	3	-70.9747	42.3212
HR051	HR05120C	8/23/05 12:18:27	R12	1*	-70.9744	42.3183
HR051	HR05120D	8/23/05 12:19:54	R12	2	-70.9743	42.3183
HR051	HR05120E	8/23/05 12:20:45	R12	3	-70.9743	42.3183
HR051	HR05120F	8/23/05 12:22:09	R12	4	-70.9744	42.3183
HR051	HR051213	8/23/05 12:28:32	R13	1*	-70.9806	42.3171
HR051	HR051214	8/23/05 12:29:17	R13	2	-70.9805	42.3170
HR051	HR051215	8/23/05 12:30:45	R13	3	-70.9805	42.3170

SurveyID	SampleID	Sample Date/Time	StationID	Replicate *not analyzed	Longitude	Latitude
HR051	HR051216	8/23/05 12:31:01	R13	4	-70.9805	42.3171
HR051	HR05121A	8/23/05 13:03:36	R14	1	-71.0128	42.3207
HR051	HR05121B	8/23/05 13:04:40	R14	2	-71.0129	42.3208
HR051	HR05121C	8/23/05 13:05:41	R14	3	-71.0129	42.3208
HR051	HR05122D	8/23/05 13:32:22	R15	1	-71.0195	42.3151
HR051	HR05122E	8/23/05 13:33:14	R15	2	-71.0195	42.3152
HR051	HR05122F	8/23/05 13:34:48	R15	3	-71.0192	42.3153
HR051	HR0511E0	8/23/05 11:16:24	R16	1	-70.9615	42.3158
HR051	HR0511E1	8/23/05 11:17:01	R16	2	-70.9616	42.3158
HR051	HR0511E2	8/23/05 11:17:58	R16	3	-70.9616	42.3158
HR051	HR05110B	8/22/05 15:03:39	R17	1	-70.9773	42.3049
HR051	HR05110C	8/22/05 15:04:17	R17	2*	-70.9773	42.3050
HR051	HR05110D	8/22/05 15:05:05	R17	3	-70.9774	42.3050
HR051	HR05110E	8/22/05 15:06:01	R17	4	-70.9772	42.3050
HR051	HR0511AD	8/23/05 09:56:17	R18	1	-70.9611	42.2890
HR051	HR0511AE	8/23/05 09:57:15	R18	2	-70.9612	42.2889
HR051	HR0511AF	8/23/05 09:58:26	R18	3	-70.9612	42.2889
HR051	HR0511A6	8/23/05 09:45:32	R19	1*	-70.9379	42.2821
HR051	HR0511A7	8/23/05 09:46:24	R19	2	-70.9380	42.2821
HR051	HR0511A8	8/23/05 09:47:25	R19	3	-70.9380	42.2821
HR051	HR0511A9	8/23/05 09:47:45	R19	4	-70.9380	42.2821
HR051	HR0511EE	8/23/05 11:31:53	R20	1	-70.9351	42.3247
HR051	HR0511EF	8/23/05 11:33:39	R20	2	-70.9349	42.3247
HR051	HR0511F0	8/23/05 11:36:15	R20	3	-70.9351	42.3250
HR051	HR0511D9	8/23/05 11:02:51	R21	1	-70.9466	42.3088
HR051	HR0511DA	8/23/05 11:04:15	R21	2	-70.9465	42.3087
HR051	HR0511DB	8/23/05 11:05:23	R21	3*	-70.9464	42.3088
HR051	HR0511DC	8/23/05 11:06:44	R21	4	-70.9463	42.3088
HR051	HR0511D3	8/23/05 10:54:06	R22	1	-70.9393	42.3004
HR051	HR0511D4	8/23/05 10:54:57	R22	2	-70.9394	42.3003
HR051	HR0511D5	8/23/05 10:56:02	R22	3	-70.9396	42.3002
HR051	HR0511C7	8/23/05 10:37:04	R23	1	-70.9500	42.2938
HR051	HR0511C8	8/23/05 10:37:45	R23	2	-70.9500	42.2938
HR051	HR0511C9	8/23/05 10:38:30	R23	3	-70.9501	42.2938
HR051	HR0511C1	8/23/05 10:28:21	R24	1	-70.9585	42.2965
HR051	HR0511C2	8/23/05 10:29:13	R24	2	-70.9587	42.2964
HR051	HR0511C3	8/23/05 10:30:24	R24	3	-70.9588	42.2962
HR051	HR05119F	8/23/05 09:33:54	R25	1*	-70.9287	42.2914
HR051	HR0511A0	8/23/05 09:35:46	R25	2	-70.9289	42.2913
HR051	HR0511A1	8/23/05 09:36:24	R25	3	-70.9290	42.2913
HR051	HR0511A2	8/23/05 09:37:09	R25	4	-70.9290	42.2912
HR051	HR05115B	8/23/05 07:44:08	R26	1	-70.9300	42.2688
HR051	HR05115C	8/23/05 07:44:56	R26	2	-70.9300	42.2688
HR051	HR05115D	8/23/05 07:45:53	R26	3	-70.9299	42.2688
HR051	HR051173	8/23/05 08:27:27	R27	1	-70.9165	42.2804
HR051	HR051174	8/23/05 08:29:07	R27	2	-70.9165	42.2804
HR051	HR051175	8/23/05 08:29:57	R27	3	-70.9165	42.2804
HR051	HR05116D	8/23/05 08:18:26	R28	1	-70.9089	42.2816
HR051	HR05116E	8/23/05 08:19:37	R28	2	-70.9090	42.2817
HR051	HR05116F	8/23/05 08:21:16	R28	3	-70.9088	42.2817
HR051	HR051199	8/23/05 09:25:20	R29	1	-70.9208	42.2896

SurveyID	SampleID	Sample Date/Time	StationID	Replicate *not analyzed	Longitude	Latitude
HR051	HR05119A	8/23/05 09:26:32	R29	2	-70.9208	42.2896
HR051	HR05119B	8/23/05 09:27:47	R29	3	-70.9207	42.2896
HR051	HR05117F	8/23/05 08:43:40	R30	1	-70.9042	42.2904
HR051	HR051180	8/23/05 08:44:45	R30	2	-70.9040	42.2904
HR051	HR051181	8/23/05 08:45:51	R30	3	-70.9039	42.2904
HR051	HR05118C	8/23/05 09:07:05	R31	1	-70.9170	42.3010
HR051	HR05118D	8/23/05 09:08:15	R31	2	-70.9171	42.3010
HR051	HR05118E	8/23/05 09:09:24	R31	3	-70.9172	42.3009
HR051	HR051185	8/23/05 08:52:47	R32	1	-70.8970	42.2947
HR051	HR051186	8/23/05 08:54:01	R32	2	-70.8970	42.2947
HR051	HR051187	8/23/05 08:55:01	R32	3	-70.8970	42.2947
HR051	HR051188	8/23/05 08:56:10	R32	4*	-70.8970	42.2946
HR051	HR05111E	8/22/05 15:26:09	R33	1	-70.9946	42.2943
HR051	HR05111F	8/22/05 15:26:59	R33	2	-70.9946	42.2943
HR051	HR051120	8/22/05 15:28:00	R33	3	-70.9946	42.2942
HR051	HR051121	8/22/05 15:29:20	R33	4*	-70.9947	42.2942
HR051	HR051125	8/22/05 15:37:47	R34	1	-71.0069	42.2889
HR051	HR051126	8/22/05 15:38:30	R34	2	-71.0069	42.2889
HR051	HR051127	8/22/05 15:39:25	R34	3	-71.0070	42.2890
HR051	HR05112B	8/22/05 15:47:03	R35	1	-70.9880	42.2842
HR051	HR05112C	8/22/05 15:48:08	R35	2	-70.9880	42.2843
HR051	HR05112D	8/22/05 15:49:02	R35	3	-70.9880	42.2844
HR051	HR051131	8/22/05 15:55:41	R36	1	-70.9864	42.2756
HR051	HR051132	8/22/05 15:57:19	R36	2	-70.9865	42.2754
HR051	HR051133	8/22/05 15:58:14	R36	3	-70.9866	42.2755
HR051	HR051112	8/22/05 15:13:04	R37	1	-70.9847	42.2987
HR051	HR051113	8/22/05 15:13:26	R37	2	-70.9846	42.2987
HR051	HR051114	8/22/05 15:14:17	R37	3	-70.9846	42.2987
HR051	HR051137	8/22/05 16:07:46	R38	1	-70.9640	42.2847
HR051	HR051138	8/22/05 16:08:38	R38	2	-70.9640	42.2847
HR051	HR051139	8/22/05 16:09:23	R38	3	-70.9641	42.2847
HR051	HR0511BB	8/23/05 10:16:28	R39	1	-70.9703	42.2956
HR051	HR0511BC	8/23/05 10:17:28	R39	2	-70.9703	42.2956
HR051	HR0511BD	8/23/05 10:18:47	R39	3	-70.9704	42.2956
HR051	HR051220	8/23/05 13:13:20	R40	1	-71.0242	42.3289
HR051	HR051221	8/23/05 13:14:09	R40	2	-71.0243	42.3290
HR051	HR051222	8/23/05 13:14:56	R40	3	-71.0245	42.3290
HR051	HR051233	8/23/05 13:40:18	R41	1	-71.0248	42.3111
HR051	HR051234	8/23/05 13:41:42	R41	2	-71.0247	42.3111
HR051	HR051235	8/23/05 13:42:49	R41	3	-71.0246	42.3111
HR051	HR051227	8/23/05 13:24:52	R42	1	-71.0250	42.3194
HR051	HR051228	8/23/05 13:25:37	R42	2	-71.0250	42.3195
HR051	HR051229	8/23/05 13:26:25	R42	3	-71.0250	42.3196
HR051	HR051248	8/23/05 14:19:32	R43	1	-71.0020	42.3068
HR051	HR051249	8/23/05 14:20:25	R43	2	-71.0020	42.3068
HR051	HR05124A	8/23/05 14:21:24	R43	3	-71.0020	42.3067
HR051	HR0510EB	8/22/05 14:07:06	R44	1*	-71.0022	42.3438
HR051	HR0510EC	8/22/05 14:07:36	R44	2	-71.0023	42.3438
HR051	HR0510ED	8/22/05 14:08:04	R44	3	-71.0023	42.3439
HR051	HR0510EE	8/22/05 14:08:57	R44	4	-71.0023	42.3438
HR051	HR051200	8/23/05 12:03:08	R45	1	-70.9675	42.3283

SurveyID	SampleID	Sample Date/Time	StationID	Replicate *not analyzed	Longitude	Latitude
HR051	HR051201	8/23/05 12:04:18	R45	2	-70.9675	42.3283
HR051	HR051202	8/23/05 12:04:56	R45	3	-70.9675	42.3283
HR051	HR051192	8/23/05 09:15:00	R46	1	-70.9223	42.2910
HR051	HR051193	8/23/05 09:16:21	R46	2*	-70.9223	42.2910
HR051	HR051194	8/23/05 09:17:22	R46	3	-70.9224	42.2910
HR051	HR051195	8/23/05 09:18:19	R46	4	-70.9224	42.2910
HR051	HR0510BD	8/22/05 13:08:13	R47	1	-70.9784	42.3445
HR051	HR0510BE	8/22/05 13:09:55	R47	2	-70.9786	42.3446
HR051	HR0510BF	8/22/05 13:10:33	R47	3	-70.9785	42.3446
HR051	HR051118	8/22/05 15:19:20	R48	1	-70.9880	42.2937
HR051	HR051119	8/22/05 15:20:54	R48	2	-70.9879	42.2936
HR051	HR05111A	8/22/05 15:21:06	R48	3	-70.9879	42.2936
HR051	HR051161	8/23/05 07:56:27	R49	1	-70.9083	42.2732
HR051	HR051162	8/23/05 07:57:19	R49	2	-70.9084	42.2732
HR051	HR051163	8/23/05 07:58:04	R49	3	-70.9084	42.2733
HR051	HR051167	8/23/05 08:10:44	R50	1	-70.8986	42.2750
HR051	HR051168	8/23/05 08:11:23	R50	2	-70.8986	42.2750
HR051	HR051169	8/23/05 08:12:54	R50	3	-70.8986	42.2750
HR051	HR05114C	8/23/05 07:22:14	R51	1	-70.9424	42.2632
HR051	HR05114D	8/23/05 07:23:07	R51	2	-70.9423	42.2632
HR051	HR05114E	8/23/05 07:24:26	R51	3	-70.9423	42.2632
HR051	HR05114F	8/23/05 07:26:10	R51	4*	-70.9422	42.2634
HR051	HR051141	8/23/05 07:14:45	R52	1	-70.9347	42.2618
HR051	HR051142	8/23/05 07:15:20	R52	2	-70.9347	42.2618
HR051	HR051143	8/23/05 07:16:16	R52	3	-70.9345	42.2618
HR051	HR051153	8/23/05 07:33:14	R53	1*	-70.9380	42.2692
HR051	HR051154	8/23/05 07:34:17	R53	2	-70.9380	42.2693
HR051	HR051155	8/23/05 07:36:35	R53	3	-70.9377	42.2691
HR051	HR051157	8/23/05 07:37:45	R53	4	-70.9377	42.2692
HR051	HR0510B7	8/22/05 12:58:58	T01	1	-70.9634	42.3490
HR051	HR0510B8	8/22/05 12:59:40	T01	2	-70.9633	42.3490
HR051	HR0510B9	8/22/05 13:00:29	T01	3	-70.9632	42.3490
HR051	HR0510E4	8/22/05 13:58:18	T02	1	-71.0022	42.3429
HR051	HR0510E5	8/22/05 13:59:10	T02	2	-71.0021	42.3430
HR051	HR0510E6	8/22/05 13:59:59	T02	3	-71.0021	42.3430
HR051	HR0511FA	8/23/05 11:55:18	T03	1	-70.9617	42.3302
HR051	HR0511FB	8/23/05 11:56:10	T03	2	-70.9618	42.3302
HR051	HR0511FC	8/23/05 11:57:10	T03	3	-70.9619	42.3303
HR051	HR05123B	8/23/05 13:58:23	T04	1	-71.0416	42.3099
HR051	HR05123F	8/23/05 14:00:58	T04	2	-71.0417	42.3100
HR051	HR051241	8/23/05 14:02:31	T04	3*	-71.0417	42.3100
HR051	HR051243	8/23/05 14:03:54	T04	4	-71.0416	42.3101
HR051	HR0510A9	8/22/05 12:43:12	T05A	1	-70.9607	42.3396
HR051	HR0510AA	8/22/05 12:44:17	T05A	2	-70.9607	42.3396
HR051	HR0510AB	8/22/05 12:44:45	T05A	3	-70.9607	42.3396
HR051	HR0510AC	8/22/05 12:45:22	T05A	4*	-70.9607	42.3396
HR051	HR0511CD	8/23/05 10:44:39	T06	1	-70.9441	42.2935
HR051	HR0511CE	8/23/05 10:45:42	T06	2	-70.9441	42.2935
HR051	HR0511CF	8/23/05 10:46:38	T06	3	-70.9442	42.2935
HR051	HR0511B4	8/23/05 10:07:04	T07	1	-70.9786	42.2894
HR051	HR0511B5	8/23/05 10:07:59	T07	2	-70.9787	42.2894

SurveyID	SampleID	Sample Date/Time	StationID	Replicate *not analyzed	Longitude	Latitude
HR051	HR0511B6	8/23/05 10:08:48	T07	3	-70.9787	42.2894
HR051	HR051179	8/23/05 08:36:12	T08	1	-70.9125	42.2853
HR051	HR05117A	8/23/05 08:37:02	T08	2	-70.9124	42.2853
HR051	HR05117B	8/23/05 08:37:51	T08	3	-70.9123	42.2853

APPENDIX A2

Station Data:
Benthic Grab Samples (HT051)

Table A2-1. Listing of field data from harbor traditional benthic survey HT051.

(Times are reported as Eastern Standard Time)

STUDY_ID	EVENT_ID	STAT_ID	STAT_ARRIV (EST)	BEG_LATITUDE	BEG_LONGITUDE	DEPTH_TO_BOTTOM	DEPTH_UNIT_CODE	NAVIGATION_CODE	NAV_QUAL	MATRIX_CODE	GEAR_CODE	DEPTH	DEPTH_TOP	DEPTH_UNIT_CODE	SAMPLE_ID	SAMP_VOL	SAMP_VOL_UNIT_CODE	DEPTH_CLASS_CODE
BHSOFT	HT051	C019	08/03/2005 10:12:37	42.359066	-71.0451354	9.6	m	DGPS	+/- 10m	SED	VV04	9.5	0	cm	HT05102E	3.25	L	E
BHSOFT	HT051	C019	08/03/2005 10:12:37	42.359066	-71.0451354	9.6	m	DGPS	+/- 10m	SED	VV01	14.5	0	cm	HT05102F	11	L	E
BHSOFT	HT051	C019	08/03/2005 10:12:37	42.359066	-71.0451354	9.6	m	DGPS	+/- 10m	SED	VV04	9.5	0	cm	HT05102D	3.25	L	E
BHSOFT	HT051	C019	08/03/2005 10:12:37	42.359066	-71.0451354	9.6	m	DGPS	+/- 10m	SED	VV04	9	0	cm	HT051032	3	L	E
BHSOFT	HT051	T01	08/03/2005 11:14:40	42.3489341	-70.9634323	5.4	m	DGPS	+/- 10m	SED	VV04	9.5	0	cm	HT051043	3.25	L	E
BHSOFT	HT051	T01	08/03/2005 11:14:40	42.3489341	-70.9634323	5.4	m	DGPS	+/- 10m	SED	VV01	12	0	cm	HT051040	10	L	E
BHSOFT	HT051	T01	08/03/2005 11:14:40	42.3489341	-70.9634323	5.4	m	DGPS	+/- 10m	SED	VV04	7	0	cm	HT05103F	2.25	L	E
BHSOFT	HT051	T01	08/03/2005 11:14:40	42.3489341	-70.9634323	5.4	m	DGPS	+/- 10m	SED	VV04	9	0	cm	HT05103B	3	L	E
BHSOFT	HT051	T02	08/03/2005 09:29:53	42.342884	-71.0019302	8.2	m	DGPS	+/- 10m	SED	VV04	9.5	0	cm	HT051029	3.25	L	E
BHSOFT	HT051	T02	08/03/2005 09:29:53	42.342884	-71.0019302	8.2	m	DGPS	+/- 10m	SED	VV01	14	0	cm	HT051028	11	L	E
BHSOFT	HT051	T02	08/03/2005 09:29:53	42.342884	-71.0019302	8.2	m	DGPS	+/- 10m	SED	VV04	9	0	cm	HT051027	3	L	E
BHSOFT	HT051	T02	08/03/2005 09:29:53	42.342884	-71.0019302	8.2	m	DGPS	+/- 10m	SED	VV04	9	0	cm	HT051026	3	L	E
BHSOFT	HT051	T03	08/03/2005 12:58:11	42.3301315	-70.9619369	8.3	m	DGPS	+/- 10m	SED	VV04	9.5	0	cm	HT051053	3.25	L	E
BHSOFT	HT051	T03	08/03/2005 12:58:11	42.3301315	-70.9619369	8.3	m	DGPS	+/- 10m	SED	VV04	9.5	0	cm	HT051050	3.25	L	E
BHSOFT	HT051	T03	08/03/2005 12:58:11	42.3301315	-70.9619369	8.3	m	DGPS	+/- 10m	SED	VV04	10	0	cm	HT051051	3.25	L	E
BHSOFT	HT051	T03	08/03/2005 12:58:11	42.3301315	-70.9619369	8.3	m	DGPS	+/- 10m	SED	VV01	14	0	cm	HT051052	11	L	E
BHSOFT	HT051	T04	08/03/2005 08:42:15	42.3101158	-71.041603	2.9	m	DGPS	+/- 10m	SED	VV04	9	0	cm	HT05101B	3	L	E
BHSOFT	HT051	T04	08/03/2005 08:42:15	42.3101158	-71.041603	2.9	m	DGPS	+/- 10m	SED	VV04	9	0	cm	HT05101C	3	L	E
BHSOFT	HT051	T04	08/03/2005 08:42:15	42.3101158	-71.041603	2.9	m	DGPS	+/- 10m	SED	VV04	9.5	0	cm	HT05101D	3.25	L	E
BHSOFT	HT051	T04	08/03/2005 08:42:15	42.3101158	-71.041603	2.9	m	DGPS	+/- 10m	SED	VV01	14.5	0	cm	HT05101F	11	L	E
BHSOFT	HT051	T05A	08/03/2005 12:15:07	42.3395996	-70.9605636	17.9	m	DGPS	+/- 10m	SED	VV04	9	0	cm	HT051049	3	L	E
BHSOFT	HT051	T05A	08/03/2005 12:15:07	42.3395996	-70.9605636	17.9	m	DGPS	+/- 10m	SED	VV04	9	0	cm	HT05104C	3	L	E
BHSOFT	HT051	T05A	08/03/2005 12:15:07	42.3395996	-70.9605636	17.9	m	DGPS	+/- 10m	SED	VV04	9	0	cm	HT05104A	3	L	E
BHSOFT	HT051	T05A	08/03/2005 12:15:07	42.3395996	-70.9605636	17.9	m	DGPS	+/- 10m	SED	VV01	14	0	cm	HT05104B	11	L	E
BHSOFT	HT051	T06	08/03/2005 07:16:18	42.2934684	-70.944313	5	m	DGPS	+/- 10m	SED	VV04	9.5	0	cm	HT051014	3.25	L	E
BHSOFT	HT051	T06	08/03/2005 07:16:18	42.2934684	-70.944313	5	m	DGPS	+/- 10m	SED	VV01	14.5	0	cm	HT051016	11	L	E
BHSOFT	HT051	T06	08/03/2005 07:16:18	42.2934684	-70.944313	5	m	DGPS	+/- 10m	SED	VV04	9.5	0	cm	HT051015	3.25	L	E
BHSOFT	HT051	T06	08/03/2005 07:16:18	42.2934684	-70.944313	5	m	DGPS	+/- 10m	SED	VV04	9	0	cm	HT051017	3	L	E
BHSOFT	HT051	T07	08/03/2005 06:33:50	42.2891998	-70.97863	5.1	m	DGPS	+/- 10m	SED	VV04	9.5	0	cm	HT05100F	3.25	L	E
BHSOFT	HT051	T07	08/03/2005 06:33:50	42.2891998	-70.97863	5.1	m	DGPS	+/- 10m	SED	VV01	14.5	0	cm	HT05100D	11	L	E
BHSOFT	HT051	T07	08/03/2005 06:33:50	42.2891998	-70.97863	5.1	m	DGPS	+/- 10m	SED	VV04	9.5	0	cm	HT05100C	3.25	L	E
BHSOFT	HT051	T07	08/03/2005 06:33:50	42.2891998	-70.97863	5.1	m	DGPS	+/- 10m	SED	VV04	9.5	0	cm	HT051010	3.25	L	E
BHSOFT	HT051	T08	08/03/2005 13:51:50	42.2851829	-70.9125976	11.1	m	DGPS	+/- 10m	SED	VV04	9	0	cm	HT051063	3	L	E
BHSOFT	HT051	T08	08/03/2005 13:51:50	42.2851829	-70.9125976	11.1	m	DGPS	+/- 10m	SED	VV04	8.5	0	cm	HT05105B	3	L	E
BHSOFT	HT051	T08	08/03/2005 13:51:50	42.2851829	-70.9125976	11.1	m	DGPS	+/- 10m	SED	VV01	13	0	cm	HT05105E	11	L	E
BHSOFT	HT051	T08	08/03/2005 13:51:50	42.2851829	-70.9125976	11.1	m	DGPS	+/- 10m	SED	VV04	8.5	0	cm	HT05105D	3	L	E

Table A2-2. Station data and field observations for individual infauna and chemistry soft-bottom grab samples collected in August 2005 (HT051).

Station ID	Sample ID	Date/Time (EDT)	Latitude (N)	Longitude (W)	Sample Type	RPD Depth (cm)	Sediment Texture	Fauna and Miscellaneous Observations
C019	HT05102D	8/3/05 11:16	42.35907	-71.04514	Biol	0.4	silt	Bacterial/micro-algal patch, snail
	HT05102E	8/3/05 11:21	42.35918	-71.04522	Biol	0.4	silt	Bacterial/micro-algal patch, snail, sand shrimp
	HT05102F	8/3/05 11:27	42.35921	-71.04523	Chem	0.4	silt	Bacterial/micro-algal patch, snail, sand shrimp
	HT051032	8/3/05 11:40	42.35917	-71.04520	Biol	0.3	silt	Sand shrimp
T01	HT05103B	8/3/05 12:29	42.34893	-70.96343	Biol	<0.2	v. fine sandy silt	
	HT05103F	8/3/05 12:44	42.34912	-70.96367	Biol	0.3	v. fine sandy silt	
	HT051040	8/3/05 12:48	42.34920	-70.96342	Chem	0.1	v. fine sandy silt	
	HT051043	8/3/05 13:04	42.34913	-70.96360	Biol	0.4	fine/med. sandy silt	
T02	HT051026	8/3/05 10:33	42.34288	-71.00193	Biol	1.0	v. fine sandy silt	No fauna observed
	HT051027	8/3/05 10:42	42.34273	-71.00197	Biol	0.3	v. fine sandy silt	Tubes, snail
	HT051028	8/3/05 10:48	42.34285	-71.00200	Chem	0.4	v. fine sandy silt	Tubes, snails, sand shrimp
	HT051029	8/3/05 10:53	42.34290	-71.00170	Biol	0.4	v. fine sandy silt	Worm tubes
T03	HT051050	8/3/05 14:01	42.33013	-70.96194	Biol	0.2	v. fine sandy silt	Hermit crab, snails
	HT051051	8/3/05 14:08	42.33023	-70.96201	Biol	0.3	v. fine sandy silt	Amphipod tubes, snail
	HT051052	8/3/05 14:14	42.33025	-70.96205	Chem	0.2	v. fine sandy silt	Tubes, crab, snail, sand shrimp
	HT051053	8/3/05 14:20	42.33030	-70.96190	Biol	0.3	v. fine sandy silt	
T04	HT05101B	8/3/05 09:44	42.31012	-71.04160	Biol	0.05	v. fine sandy silt	Crab, sand shrimp, jelly-like surface
	HT05101C	8/3/05 09:49	42.31015	-71.04163	Biol	<0.1	v. fine sandy silt	Hermit crab, jelly-like surface
	HT05101D	8/3/05 09:55	42.31007	-71.04153	Biol	<0.1	v. fine sandy silt	Hermit crab, jelly-like surface
	HT05101F	8/3/05 10:05	42.31008	-71.04142	Chem	<0.1	v. fine sandy silt	Sand shrimp, snail, tubes, jelly-like surface
T05A	HT051049	8/3/05 13:21	42.33960	-70.96056	Biol	0.2	Silty fine sand	Snails, tubes
	HT05104A	8/3/05 13:28	42.33943	-70.96062	Biol	0.3	Silty fine sand	Snail, sand shrimp, worm tubes
	HT05104B	8/3/05 13:40	42.33955	-70.96062	Chem	0.7	Silty fine sand	Snail, tubes
	HT05104C	8/3/05 13:45	42.33958	-70.96052	Biol	0.6	Silty fine sand	Amphipods, snails, tubes
T06	HT051014	8/3/05 08:18	42.29347	-70.94431	Biol	0.2	v. fine sandy silt	Bacterial/micro-algal mat, sand shrimp
	HT051015	8/3/05 08:25	42.29345	-70.94438	Biol	0.2	v. fine sandy silt	Bacterial/micro-algal mat, one amphipod
	HT051016	8/3/05 08:31	42.29348	-70.94442	Chem	0.2	v. fine sandy silt	Bacterial/micro-algal mat, two crabs
	HT051017	8/3/05 08:38	42.29352	-70.94437	Biol	0.3	Not recorded	Bacterial/micro-algal mat
T07	HT05100C	8/3/05 07:41	42.28920	-70.97863	Biol	0.2	v. fine sandy silt	Burrows, flocculent
	HT05100D	8/3/05 07:44	42.28930	-70.97852	Chem	0.3	v. fine sandy silt	Amphipods, snails, tubes, shell hash
	HT05100F	8/3/05 07:49	42.28925	-70.97852	Biol	0.2	v. fine sandy silt	Shell hash, mussel shells
	HT051010	8/3/05 07:57	42.28930	-70.97860	Biol	0.1	v. fine sandy silt	Snails, dead mussel shells below surface
T08	HT05105B	8/3/05 15:05	42.28518	-70.91260	Biol	1.3	silty fine sand	Amphipod and worm tubes
	HT05105D	8/3/05 15:15	42.28535	-70.91255	Biol	1.2	silty fine sand	Worm tubes, snail, worm
	HT05105E	8/3/05 15:20	42.28535	-70.91243	Chem	1.3	silty fine sand	Tubes, snails, shell hash
	HT051063	8/3/05 15:44	42.28537	-70.91228	Biol	1.4	fine sand	Snails, sand shrimp, shell hash

APPENDIX B1

Sediment Properties
Data Terms and Analyses

Data Terms

Key terms used to describe the sediment data include:

- Percent Fines – sum of percent silt and clay
- Station Mean – average of all station replicates for a given year; August/September surveys only. Single grab samples were generally collected at all Traditional stations during most sampling years, but replicate grabs were also collected during some sampling years (*e.g.*, August 1994 and 1997). Station means were determined for each parameter within a given sampling year to assess the spatial and temporal distribution in bulk sediment properties and *C. perfringens* from 1991 to 2005
- Grand Station Mean – average over years for a given station, August/September surveys only. Grand station means were determined for each parameter over all sampling years to assess variability in the spatial and temporal distribution in bulk sediment properties and *C. perfringens* from 1991 to 2005.
- Harbor-wide – refers to all harbor stations, including T01 through T08 and CO19.

Data Analyses

Key data analyses conducted to assess spatial and temporal trends in the sediment data from 1991 to 2005 included:

- Ternary plots were used to visualize sediment grain-size composition. Ternary plots were prepared by using JMP (The Statistical Discovery Software, a business unit of SAS Institute, Inc.).
- Line charts were used to visualize temporal trends in sediment data. Line charts were prepared by using Microsoft® Excel 2003.
- Distribution plots were used to visualize the data distribution, and were prepared by using JMP (The Statistical Discovery Software, a product of SAS).
- Regression plots were used to visualize statistical trends in the sediment data, and were prepared by using SAS.

Statistical analyses were conducted by using SAS to determine if there was a significant change (at the 95% confidence level) in percent fines, TOC, and normalized *C. perfringens* (sewage tracer) in the harbor over time in response to harbor cleanup efforts. These cleanup efforts include (1) cessation of sewage sludge discharge in 1991, (2) primary treatment in 1995, (3) phased secondary treatment from 1997 to 2001, with diversion of effluent discharge from the Nut Island Treatment Plant to Deer Island in 1998, and (4) effluent diversion from the Harbor to the Massachusetts Bay outfall in September 2000. Data to assess the changes consists of annual monitoring data (August/September surveys only) collected from eight traditional harbor stations from 1991 to 2005; data from station CO19 (collected in 1994, 1998, 2002, 2004, and 2005) were also assessed. In most cases, there was a single sample, while for a few cases, there were triplicate samples. In the latter case, the triplicates were averaged to provide a single annual observation. The statistical analysis consisted of three components: (1) identification and evaluation of statistical outliers, (2) trend analyses, and, (3) correlation analysis. These are discussed briefly below.

Outlier Identification. An outlier analysis was conducted to determine whether there were any data that did not fit the general patterns established by the majority of the observations. Initial graphs of the data (line charts showing temporal trends – see Appendix B2 (grain size figures B2-11 through B2-15), Appendix B3 (TOC figures B3-6 through B3-10), and Appendix B4 (*Clostridium* figures B4-6 through B4-10) showed that most of the observations at each station showed a fairly consistent pattern, albeit with some amount of variability about the pattern. There were several observations, however, that appeared to deviate from the general pattern. "Deviant" observations were typically associated with data from monitoring years 1991, 1996, and 1997. For example, normalized *C. perfringens* data were frequently higher in 1991 compared to other monitoring years, which likely reflects that this was a period of active discharge of sewage sludge to the harbor. In addition, normalized *C. perfringens* increased in 1996 compared to 1995 levels at many stations, and levels remained high in 1997. This was unexpected given that levels generally appeared to decrease in the early 1990s, consistent with the harbor cleanup efforts (cessation of sludge disposal and primary treatment). A review of the 1996 survey data indicates, however, that all but one of the stations was sampled more than 30-m from the target coordinates (Maciolek *et al.* 2006a). To determine whether these "deviations" were within normal variability, an outlier analysis was performed on the data (*i.e.*, percent fines, TOC, and normalized *C. perfringens*) that fit a trend to the "non-deviant" points, assessed the variability within those points about the trend, and examined the "deviant" points to determine whether they were statistically different from the trend. Results from the outlier analysis are summarized below in Table B-1. Overall, the greatest number of outliers was associated with the normalized *C. perfringens* data, especially for monitoring years 1991, 1996, and 1997.

Trend Analysis. The temporal trend analyses consisted of three components: (1) parametric regression analysis to estimate temporal trends, (2) nonparametric regression analysis (Mann, 1945; Kendall, 1938; Sen, 1968) to estimate the trends, and (3) Spearman correlation analyses (concentration versus time) to test for the presence of consistent trends in the measured variables. Both the parametric and nonparametric regression analyses used the natural logarithms of the TOC, normalized *C. perfringens*, and percent fines because this transformation stabilized the variance and better represented the apparent trends in the data. Thus, the regression model that was fitted is

$$\ln C = \alpha + \beta y,$$

where y is the year of the sample and C is the concentration (TOC, normalized *C. perfringens*, percent fines). The estimates of β in the regression models provide information about the trend (β is the slope and " is the intercept) in TOC, normalized *C. perfringens*, and percent fines Results of the trend analysis are presented two ways: (1) tables of regression and correlation parameters, and (2) plots of trend lines superimposed over the data. The plots include both the parametric and nonparametric regression lines to illustrate the fitted trends. The temporal trend analysis was run twice, first with data from all years excluding 1991, 1996, and 1997, which were excluded because of the frequency of outliers. The trends analysis was run a second time; however, to include data from 1991 because while there were numerous outliers in 1991, these data are representative of the harbor system during discharge of sewage sludge. Test results with the 1991 data are reported in the body of the report (Section 3.3); results from both tests (with and without 1991) are provided in Appendices B2, B3, and B4.

Correlation Analysis. The relationships between sediment variables (percent fines, TOC, and normalized *C. perfringens*) were evaluated using parametric (Pearson) and nonparametric (Kendall, Spearman) correlation analyses. The Pearson correlation coefficient measures the degree to which two variables have a linear relationship if the variables have normal distributions. The Kendall *tau* correlation, on the other hand, measures the degree to which high concentrations of one variable are associated with high concentrations of the second variable. For both Pearson and Kendall correlations, 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.

The parametric and nonparametric coefficients for percent fines, TOC, and normalized *C. perfringens* were calculated on a harbor-wide and station-specific basis, as follows:

- Harbor-wide analysis – within each of the four major cleanup events and across all stations. The four major cleanup events are defined as (1) Pre-period A, including data from 1991 to 1994, (2) Period A, including data from 1995 to 1998 (although data from 1996 and 1997 were excluded because of the frequency of outliers), (3) Period B, including data from 1999 and 2000, and (4) Period C, including data from 2001 to 2005. Periods A, B, and C are consistent with Taylor (2005) and correspond with the major periods of pollutant loadings and milestones of MWRA as described in Section 1.1.1. Pre-period A is representative of system conditions during discharge of sewage sludge to the harbor (1991); after cessation sludge discharge to the harbor; and prior to advanced primary treatment coming on-line in 1995.

  Grouping data across all stations allowed for an evaluation of the harbor-wide response with a sufficient number of observations within each of the four cleanup events.
- Station-specific analysis– within each station over all sampling events. Data were not further aggregated by the four major cleanup events because this aggregation yielded sample sizes that were too small (*i.e.*, *n* ranged from 2 (all stations, Period B) to 7 (all stations, Period C)) for a meaningful analysis.

Sediment data from 1991, 1996, and 1997 were excluded from the correlation analyses because of the frequency of outliers. Consistent with the temporal trends analysis, the correlation analysis was run a second time to include data from 1991 because these data are representative of the harbor system during discharge of sewage sludge. Test results with the 1991 data are reported in the body of the report (Section 3.3); results from both tests (with and without 1991) are provided in Appendices B2, B3, and B4.

Table B-1. Outlier analysis output. Bold values are outliers

Station	Sampling Year	Station Mean Values			Standardized Residual (divided by standard deviation)		
		Normalized *Clostridium* (cfu/g dw/%fines)	TOC (%)	Fines (%)	Normalized *Clostridium*	TOC	Fines
T01	1991	774	2.64	15.11	1.730	-0.104	-1.506
T02	1991	632	1.75	36.23	1.246	0.179	0.212
T03	1991	3702	3.69	55.91	**3.364**	0.018	-0.208
T04	1991	443	3.70	67.74	**2.797**	-0.223	**-2.217**
T05A	1991	235	0.99	21.61	0.078	1.435	1.711
T06	1991	857	1.81	34.29	**2.898**	-0.812	-0.451
T07	1991	334	2.73	40.97	**3.726**	-0.198	**-3.567**
T08	1991	83	0.87	87.86	**-4.640**	1.038	**8.410**
T01	1992	253	1.91	17.00	0.421	-0.724	-1.180
T02	1992	474	1.71	31.20	0.772	0.048	-0.873
T03	1992	17	3.57	56.50	**-2.270**	0.013	-0.179
T04	1992	42	3.95	79.20	-0.578	-0.021	-0.688
T06	1992	201	2.12	34.80	-0.469	0.319	-0.452
T07	1992	136	3.18	55.30	-0.419	1.091	-0.067
T08	1992	1051	0.66	3.70	0.958	0.532	-0.415
T01	1993	421	2.96	16.71	1.191	0.658	-1.235
T02	1993	294	1.39	30.87	-0.358	-1.552	-1.186
T03	1993	410	3.41	49.22	1.059	-0.057	-0.669
T04	1993	67	3.25	86.08	0.079	-0.631	0.100
T05A	1993	130	0.88	14.68	-0.383	0.925	0.537
T06	1993	422	1.62	32.73	1.794	-1.414	-0.712
T07	1993	142	2.31	49.98	-0.108	-1.381	-1.341
T08	1993	358	0.37	4.42	-0.660	-0.647	-0.034
C019	1994	130	2.83	95.93	-0.425	-0.159	-0.547
T01	1994	224	1.90	31.05	0.506	-0.277	0.508
T02	1994	313	1.73	40.20	0.382	0.225	0.029
T03	1994	552	2.80	36.80	1.369	-0.886	-1.693
T04	1994	95	3.10	95.20	0.568	-0.780	1.064
T05A	1994	224	0.50	12.70	0.696	-0.770	0.062
T06	1994	210	1.90	33.80	0.359	-0.275	-0.654
T07	1994	125	2.50	58.10	-0.605	-0.677	0.381
T08	1994	370	0.90	5.40	-0.062	1.439	0.408
T01	1995	20	1.18	61.10	**-2.463**	-1.298	**2.412**
T02	1995	256	2.05	58.60	0.205	1.656	1.872
T03	1995	374	3.54	88.20	0.960	0.453	1.354
T04	1995	128	3.69	93.70	0.984	-0.238	0.844
T05A	1995	94	0.42	11.70	-0.427	-1.353	-0.270
T06	1995	93	1.83	66.40	-1.375	-0.456	1.595
T07	1995	190	3.17	57.80	1.482	1.288	0.249
T08	1995	227	0.21	4.20	-0.505	-1.691	-0.393

Table B-1. Outlier analysis output. Bold values are outliers

Station	Sampling Year	Station Mean Values			Standardized Residual (divided by standard deviation)		
		Normalized *Clostridium* (cfu/g dw/%fines)	TOC (%)	Fines (%)	Normalized *Clostridium*	TOC	Fines
T01	1996	463	1.90	20.30	1.672	0.185	-0.705
T02	1996	490	1.98	46.90	**2.968**	1.433	0.379
T03	1996	368	3.84	78.70	0.942	1.023	0.948
T04	1996	710	4.75	94.40	**3.422**	0.547	0.860
T05A	1996	318	0.88	10.70	1.705	0.661	-0.619
T06	1996	735	3.89	80.30	**4.292**	**4.670**	**2.191**
T07	1996	517	2.73	67.70	**6.325**	0.172	2.061
T08	1996	405	0.89	17.30	1.182	1.631	**3.393**
T01	1997	389	1.83	20.73	1.569	0.312	-0.652
T02	1997	332	1.46	55.50	**2.140**	-0.927	1.062
T03	1997	228	3.57	82.57	0.441	0.817	1.107
T04	1997	175	3.88	97.40	1.408	-0.085	1.119
T05A	1997	140	1.42	32.13	0.660	1.927	1.752
T06	1997	403	1.88	41.07	**3.106**	-0.122	-0.145
T07	1997	327	3.10	55.10	**4.269**	1.249	-0.460
T08	1997	326	0.45	5.97	1.282	0.206	0.355
C019	1998	157	2.87	96.67	0.410	-0.138	0.554
T01	1998	182	1.55	24.45	0.718	0.107	-0.193
T02	1998	122	1.50	55.45	-0.788	-0.676	0.804
T03	1998	77	2.46	88.30	-0.697	-0.892	1.334
T04	1998	190	8.86	79.60	1.518	**2.487**	-0.990
T05A	1998	75	0.62	18.60	-0.087	-0.510	0.357
T06	1998	119	2.17	61.20	0.331	0.899	1.162
T07	1998	126	2.21	62.43	-0.141	-1.355	0.955
T08	1998	297	0.40	6.23	1.623	0.055	0.362
T01	1999	43	2.80	21.50	-1.006	1.896	-0.562
T02	1999	88	1.61	59.80	-1.404	-0.058	0.970
T03	1999	85	3.14	91.10	-0.595	0.494	1.435
T04	1999	19	4.15	94.60	-1.781	0.121	0.705
T05A	1999	31	1.26	24.20	-1.234	1.418	0.814
T06	1999	41	2.36	62.40	-2.048	1.532	1.177
T07	1999	127	2.77	67.00	0.002	0.509	1.727
T08	1999	76	0.23	4.60	-0.563	-1.054	-0.579
T01	2000	104	1.80	30.00	0.242	0.965	0.372
T02	2000	149	1.51	45.90	0.936	-0.516	-0.755
T03	2000	231	3.03	49.00	0.449	0.476	-0.739
T04	2000	28	3.90	69.03	-1.237	-0.074	**-2.555**
T05A	2000	270	0.93	6.30	**2.374**	0.467	**-2.409**
T06	2000	83	2.16	41.50	0.121	1.009	-0.264
T07	2000	103	2.53	58.40	-0.882	-0.139	0.022
T08	2000	70	0.37	4.70	-0.195	0.112	-0.629

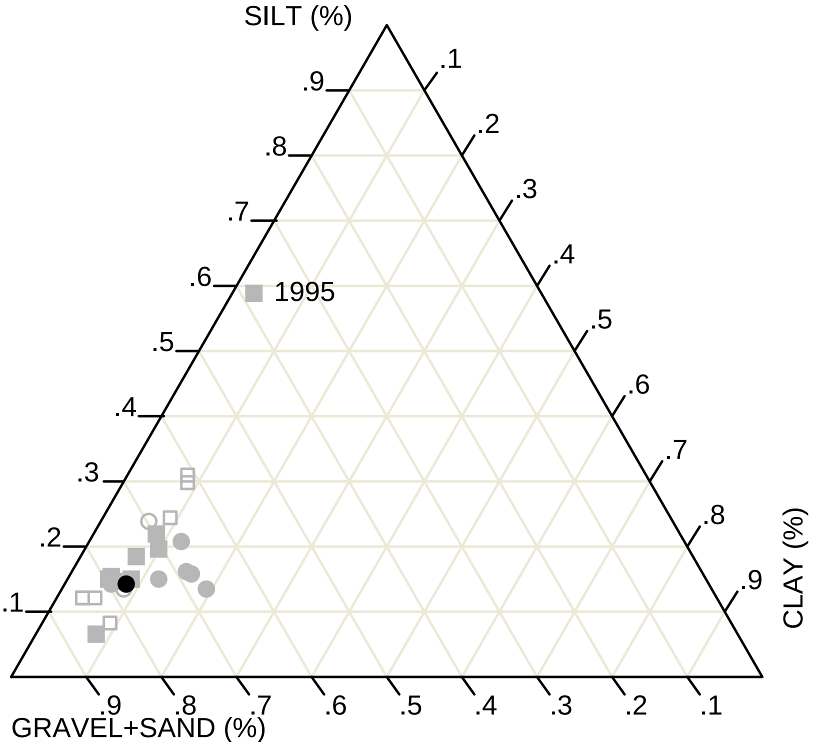
Table B-1. Outlier analysis output. Bold values are outliers

Station	Sampling Year	Station Mean Values			Standardized Residual (divided by standard deviation)		
		Normalized *Clostridium* (cfu/g dw/%fines)	TOC (%)	Fines (%)	Normalized *Clostridium*	TOC	Fines
T01	2001	89	1.13	32.71	0.163	-0.028	0.609
T02	2001	59	1.69	56.10	-1.745	0.436	0.108
T03	2001	147	3.03	65.45	-0.025	0.637	0.265
T04	2001	52	4.08	94.59	-0.363	0.065	0.587
T05A	2001	57	1.02	21.91	0.178	0.642	0.298
T06	2001	86	1.97	38.55	0.570	0.463	-0.566
T07	2001	122	2.60	56.69	0.025	0.153	-0.402
T08	2001	40	0.43	7.93	-0.780	0.555	0.701
C019	2002	183	3.03	97.00	1.104	0.480	1.180
T01	2002	68	0.97	31.83	-0.055	-0.190	0.526
T02	2002	132	1.77	54.43	1.549	0.844	-0.314
T03	2002	152	2.80	59.73	0.006	0.396	-0.063
T04	2002	35	3.64	90.77	-0.925	-0.290	0.109
T05A	2002	35	0.87	12.37	-0.367	0.113	-1.155
T06	2002	78	1.60	26.37	0.666	-0.861	-1.912
T07	2002	149	2.73	54.51	1.067	0.605	-0.939
T08	2002	50	0.50	10.43	0.210	0.985	1.347
T01	2003	34	1.18	26.83	-0.827	0.547	0.037
T02	2003	74	1.90	65.90	0.079	1.478	0.496
T03	2003	73	3.05	69.20	-0.760	0.992	0.444
T04	2003	72	4.76	90.80	0.082	0.542	0.054
T05A	2003	24	0.84	30.10	-0.709	-0.085	0.736
T06	2003	43	1.81	45.40	-0.495	0.036	-0.112
T07	2003	155	2.60	51.30	1.371	0.300	-1.731
T08	2003	17	0.49	13.40	-1.425	1.063	1.926
C019	2004	104	3.23	94.73	-1.504	1.270	-1.399
T01	2004	73	0.94	20.19	0.269	0.180	-0.772
T02	2004	53	1.45	47.21	-0.555	-0.625	-1.613
T03	2004	144	2.90	51.79	-0.050	0.900	-0.577
T04	2004	118	4.79	93.54	0.778	0.560	0.297
T05A	2004	19	1.22	36.61	-0.843	0.888	1.039
T06	2004	54	1.93	47.84	0.448	0.537	0.015
T07	2004	73	2.83	65.02	-2.085	1.050	1.020
T08	2004	21	0.29	4.22	-0.471	0.004	-1.362
C019	2005	158	2.65	96.03	0.415	-1.454	0.213
T01	2005	104	0.40	22.12	0.841	-1.836	-0.521
T02	2005	70	1.33	71.74	0.927	-1.261	0.461
T03	2005	257	1.42	47.15	0.554	**-2.527**	-0.912
T04	2005	127	2.29	95.74	0.873	-1.742	0.474
T05A	2005	47	0.50	24.66	0.801	-1.735	-0.009
T06	2005	41	1.35	59.79	0.098	-1.788	0.723
T07	2005	118	2.05	60.68	0.293	-1.445	0.127
T08	2005	52	0.15	4.44	1.870	-1.354	-1.331

Bold values are outliers.

APPENDIX B2

Grain Size
1991–2005 Sediment Data Evaluations
Ternary Plots, Station Grand Mean and Coefficient of Variation (CV), Statistics Output, Line Charts, and Box-plots



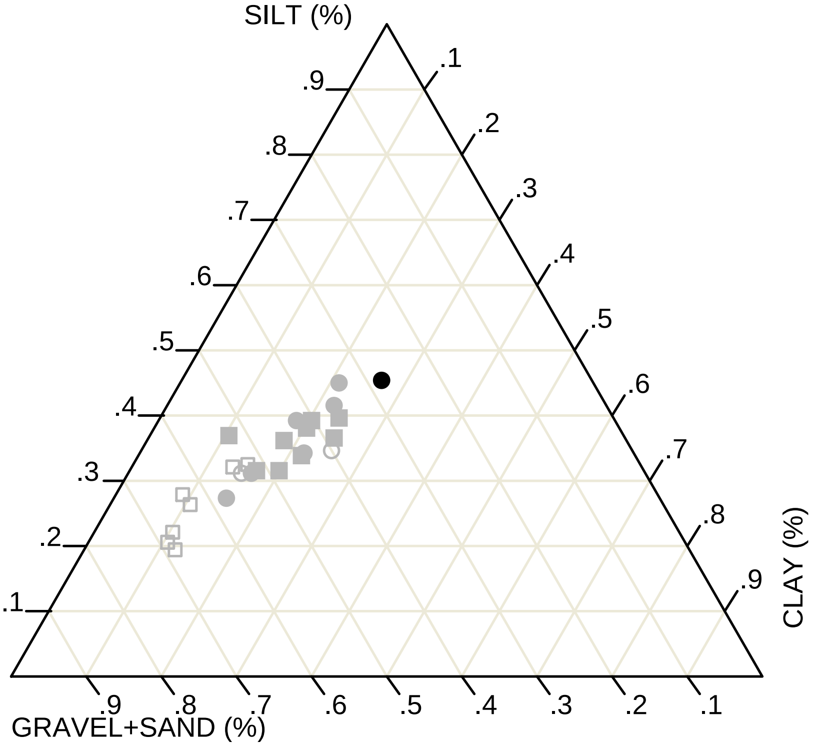
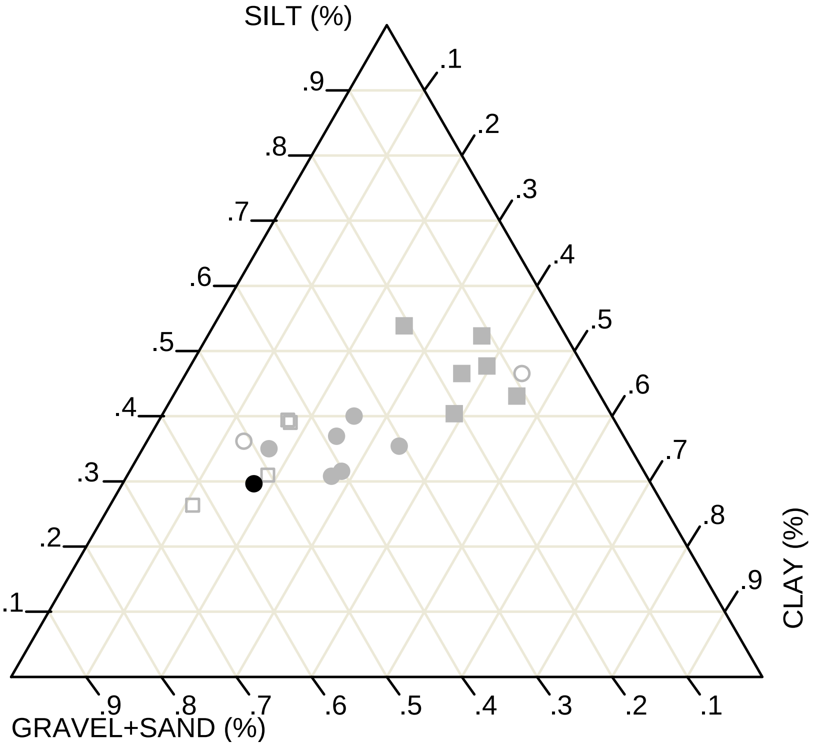


Figure B2-1. Distribution of percentages gravel + sand, silt and clay at stations T01 (top) and T02 (bottom) from 1991 to 2005; August/September surveys only. □ represents Pre-period A (1991 to 1994 data); ■ represents Period A (1995 to 1998 data); ○ represents Period B (1999 to 2000 data); and Period C (● 2001 to 2004 and ● 2005).



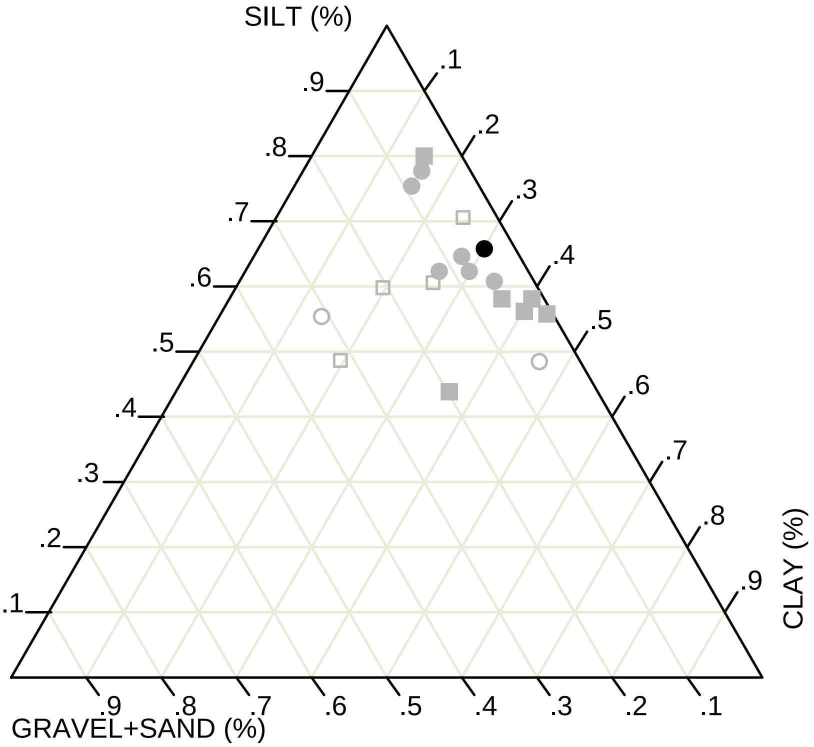
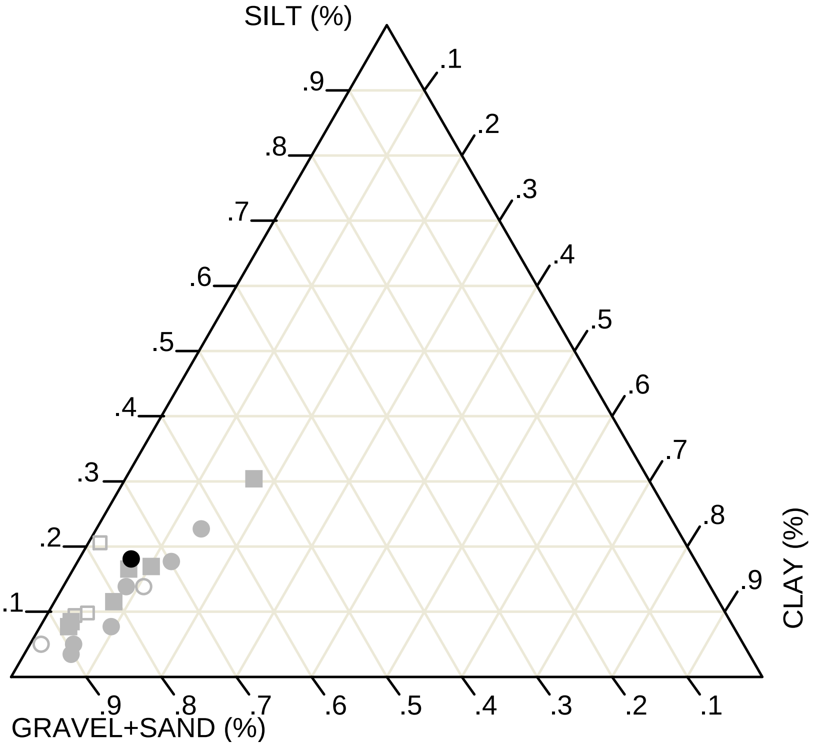


Figure B2-2. Distribution of percentages gravel + sand, silt and clay at stations T03 (top) and T04 (bottom) from 1991 to 2005; August/September surveys only. □ represents Pre-period A (1991 to 1994 data); ■ represents Period A (1995 to 1998 data); ○ represents Period B (1999 to 2000 data); and Period C (● 2001 to 2004 and ● 2005).



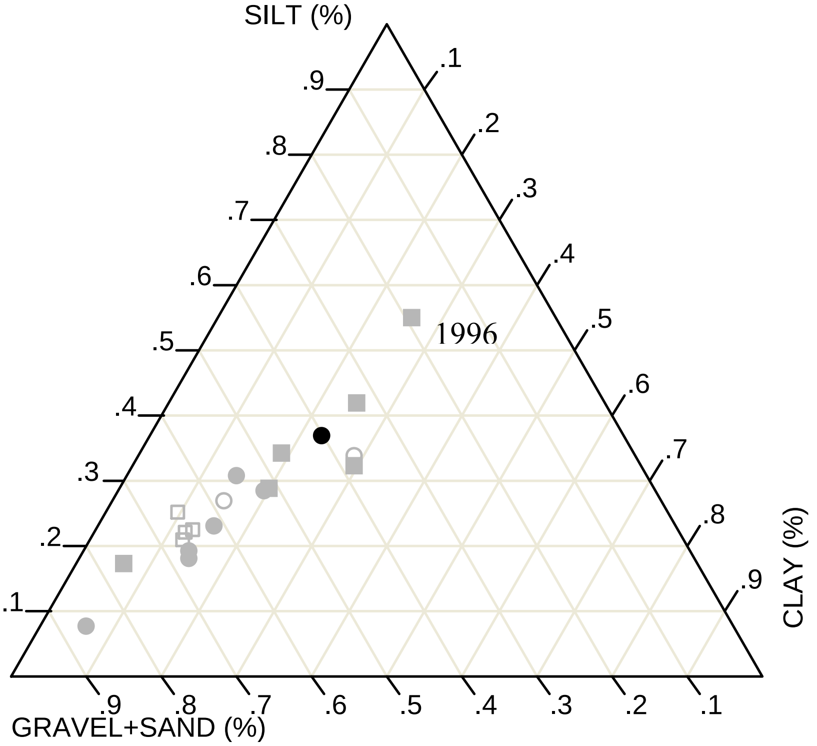
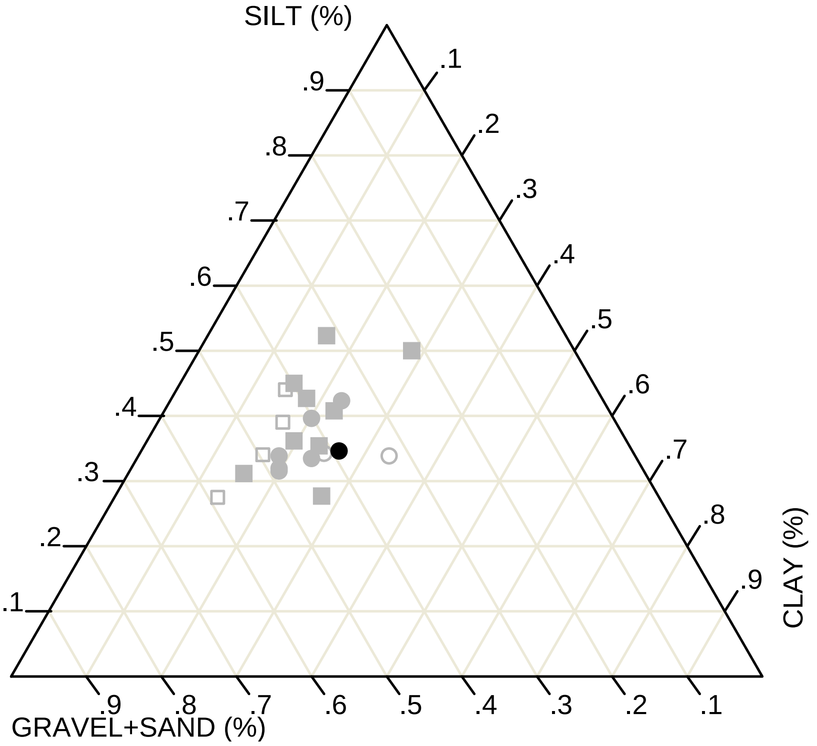


Figure B2-3. Distribution of percentages gravel + sand, silt and clay at stations T05A (top) and T06 (bottom) from 1991 to 2005; August/September surveys only. □ represents Pre-period A (1991 to 1994 data); ■ represents Period A (1995 to 1998 data); ○ represents Period B (1999 to 2000 data); and Period C (● 2001 to 2004 and ● 2005).



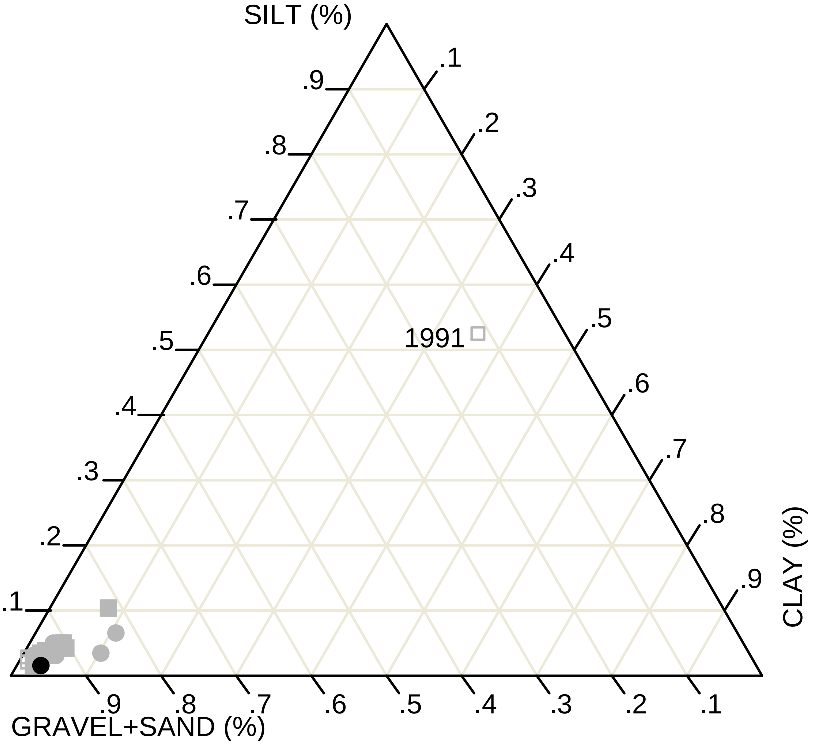


Figure B2-4. Distribution of percentages gravel + sand, silt and clay at stations T07 (top) and T08 (bottom) from 1991 to 2005; August/September surveys only. □ represents Pre-period A (1991 to 1994 data); ■ represents Period A (1995 to 1998 data); ○ represents Period B (1999 to 2000 data); and Period C (● 2001 to 2004 and ● 2005).

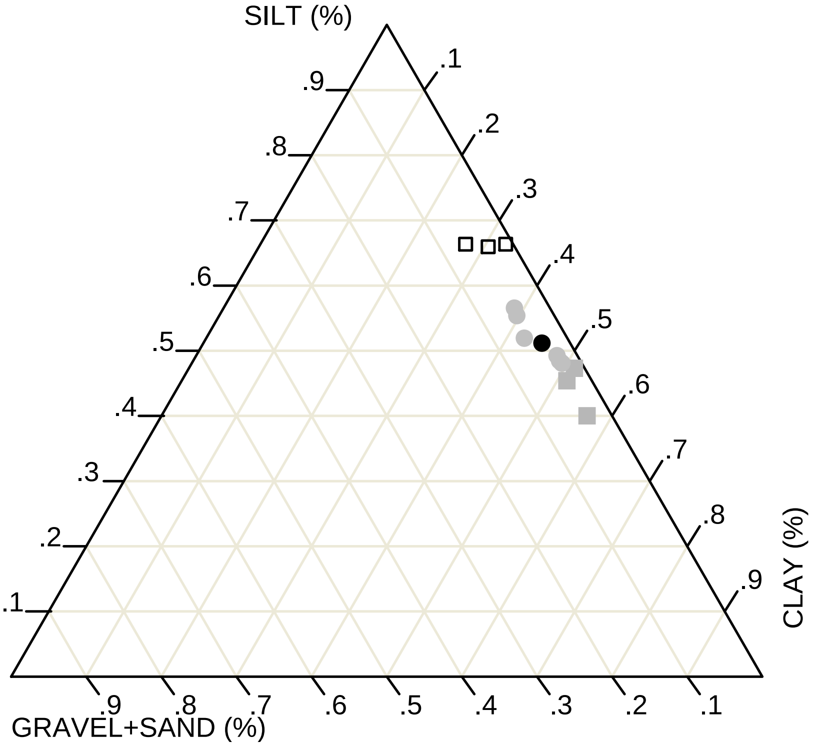


Figure B2-5. Distribution of percentages gravel + sand, silt and clay at station CO19 from 1994 to 2005; August/September surveys only. □ represents Pre-period A (1991 to 1994 data); ■ represents Period A (1995 to 1998 data); ○ represents Period B (1999 to 2000 data); and Period C (● 2001 to 2004 and ● 2005).

Table B2-1. Station grand mean and coefficient of variation (CV) between yearly station mean values for percentages gravel, sand, silt, and clay. Boston Harbor sediment data from 1991 to 2005, August/September surveys only.

Stat Id	Parameter	N	Station Grand Mean	Units	CV	Units
C019	Gravel	5	0.07	%	196	%
T01	Gravel	15	11.49	%	141	%
T02	Gravel	15	2.11	%	257	%
T03	Gravel	15	1.13	%	138	%
T04	Gravel	15	0.55	%	193	%
T05A	Gravel	14	0.21	%	72	%
T06	Gravel	15	0.71	%	112	%
T07	Gravel	15	9.00	%	67	%
T08	Gravel	15	1.33	%	84	%
C019	Sand	5	3.85	%	20	%
T01	Sand	15	62.41	%	27	%
T02	Sand	15	47.49	%	22	%
T03	Sand	15	34.24	%	48	%
T04	Sand	15	11.29	%	87	%
T05A	Sand	14	79.93	%	11	%
T06	Sand	15	52.19	%	30	%
T07	Sand	15	33.62	%	27	%
T08	Sand	15	86.36	%	24	%
C019	Silt	5	52.86	%	16	%
T01	Silt	15	18.32	%	65	%
T02	Silt	15	33.14	%	22	%
T03	Silt	15	38.90	%	20	%
T04	Silt	15	61.58	%	18	%
T05A	Silt	14	12.98	%	46	%
T06	Silt	15	29.27	%	34	%
T07	Silt	15	36.84	%	16	%
T08	Silt	15	6.48	%	197	%
C019	Clay	5	43.21	%	20	%
T01	Clay	15	7.79	%	47	%
T02	Clay	15	17.27	%	33	%
T03	Clay	15	25.74	%	44	%
T04	Clay	15	26.58	%	39	%
T05A	Clay	14	6.90	%	59	%
T06	Clay	15	17.83	%	38	%
T07	Clay	15	20.56	%	26	%
T08	Clay	15	5.84	%	147	%

N, number of observations.

CV, coefficient of variation.

Table B2-2. Regression and probability results from the percent fines trends analysis. Sediment data from all years excluding 1996 and 1997 were used in the analysis.

Station ID	No samp	Parametric Regression		Nonparametric Regression		Spearman Correlation	
		Slope	p-value	Slope	p-value	Slope	p-value
CO19	4	-0.0005	0.6747	-0.0004	1.0000	1.0000	0.8729
T01	13	0.0164	0.4906	0.0228	0.3290	0.0005	0.2547
T02	13	0.0446	**0.0018 ***	0.0457	**0.0147 ***	0.4262	**0.0073 ***
T03	13	0.0038	0.8303	-0.0021	0.9029	0.0115	0.9716
T04	13	0.0115	0.1199	0.0121	0.0876	0.5905	0.0985
T05A	12	0.0382	0.2509	0.0487	0.1314	0.8203	0.0849
T06	13	0.0186	0.3199	0.0227	0.3290	0.5285	0.3064
T07	13	0.0138	0.0709	0.0104	0.1795	0.4700	0.1497
T08	13	-0.0409	0.4517	0.0125	0.4641	0.1047	0.7615

* Significant at 95% confidence level

Table B2-3. Regression and probability results from the percent fines trends analysis. Sediment data from all years excluding 1991, 1996, and 1997 were used in the analysis.

Station ID	No samp	Parametric Regression		Nonparametric Regression		Spearman Correlation	
		Slope	p-value	Slope	p-value	Slope	p-value
C019	4	-0.0005	0.6747	-0.0004	1.0000	-0.1000	0.8729
T01	12	0.0023	0.9289	0.0061	0.7839	0.1608	0.6175
T02	12	0.0456	**0.0051 ***	0.0479	**0.0282 ***	0.6434	**0.0240 ***
T03	12	0.0022	0.9149	-0.0054	0.7839	-0.0420	0.8970
T04	12	0.0058	0.4272	0.0042	0.2726	0.3357	0.2861
T05A	11	0.0631	0.1107	0.0746	0.0734	0.5909	0.0556
T06	12	0.0151	0.4859	0.0231	0.4929	0.2168	0.4986
T07	12	0.0059	0.3477	0.0044	0.4929	0.2657	0.4038
T08	12	0.0397	0.1558	0.0333	0.0998	0.3916	0.2081

* Significant at 95% confidence level

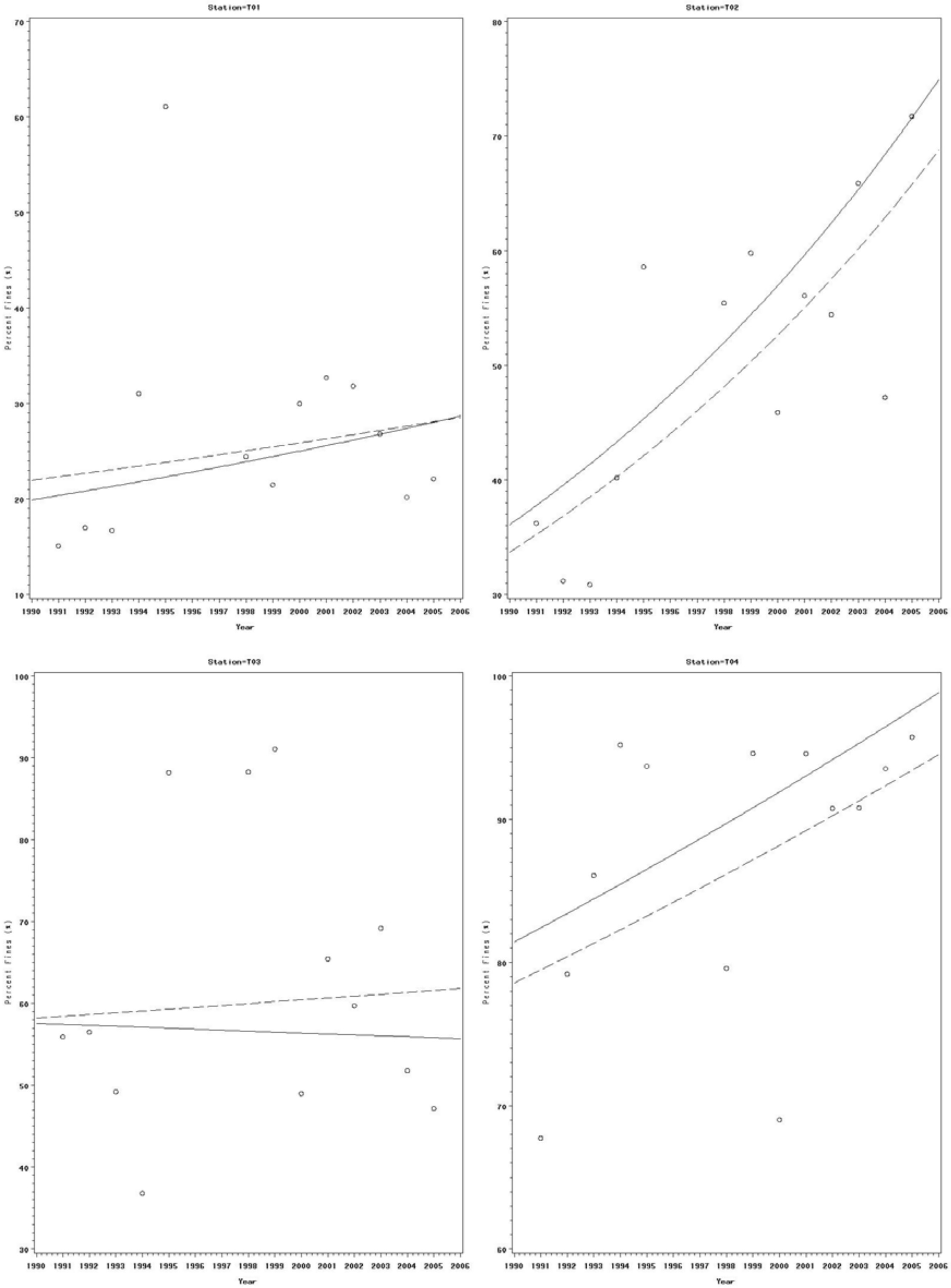


Figure B2-6. Temporal trends in percent fines at Boston Harbor stations T01, T02, T03, and T04, 1991 to 2005, August/September surveys only. The solid line represents the nonparametric regression and the dashed line represents the parametric regression. Data from monitoring years 1996 and 1997 excluded from the trends analysis.

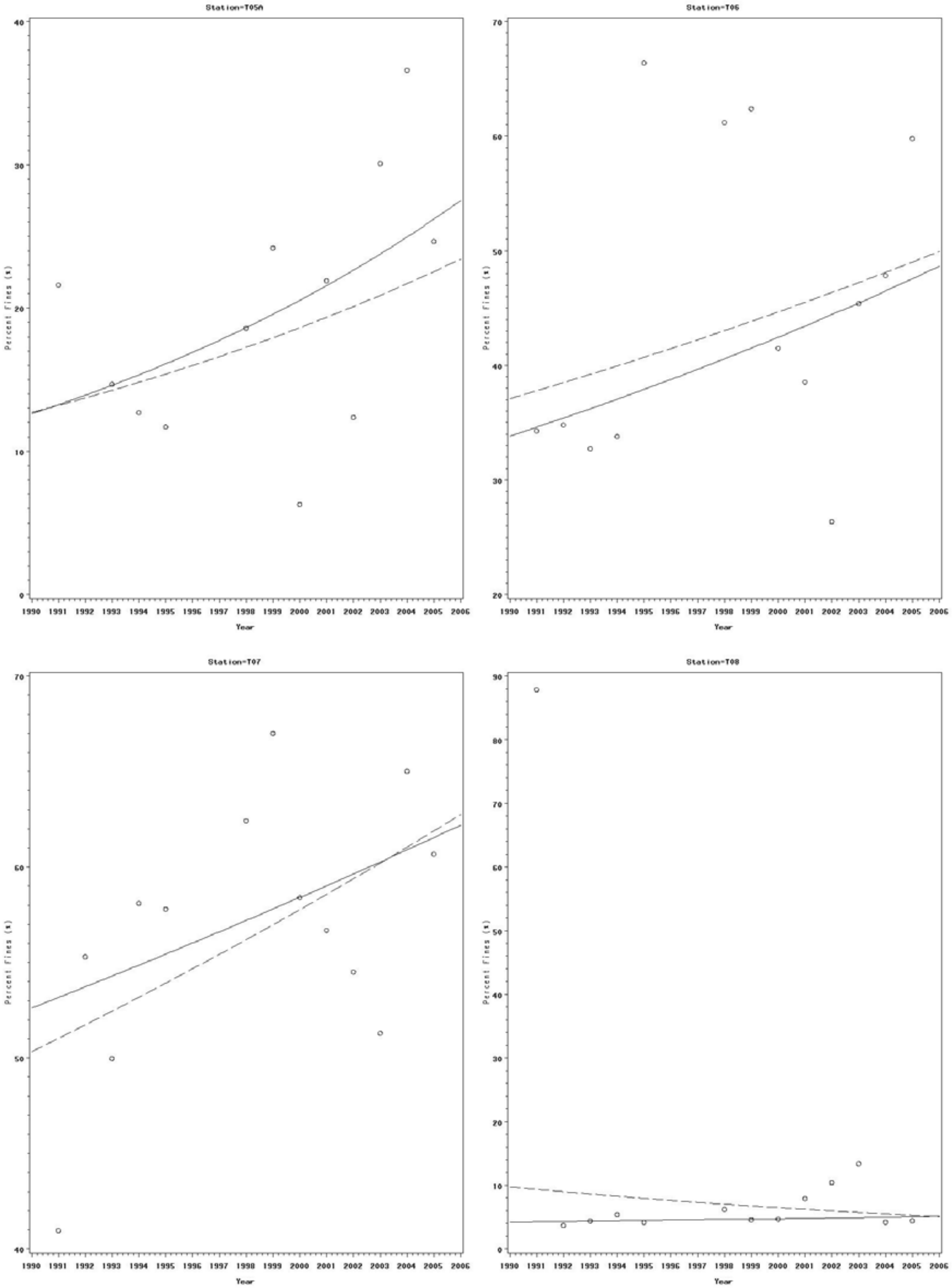


Figure B2-7. Temporal trends in percent fines at Boston Harbor stations T05A, T06, T07, and T08, 1991 to 2005, August/September surveys only. The solid line represents the nonparametric regression and the dashed line represents the parametric regression. Data from monitoring years 1996 and 1997 excluded from the trends analysis.

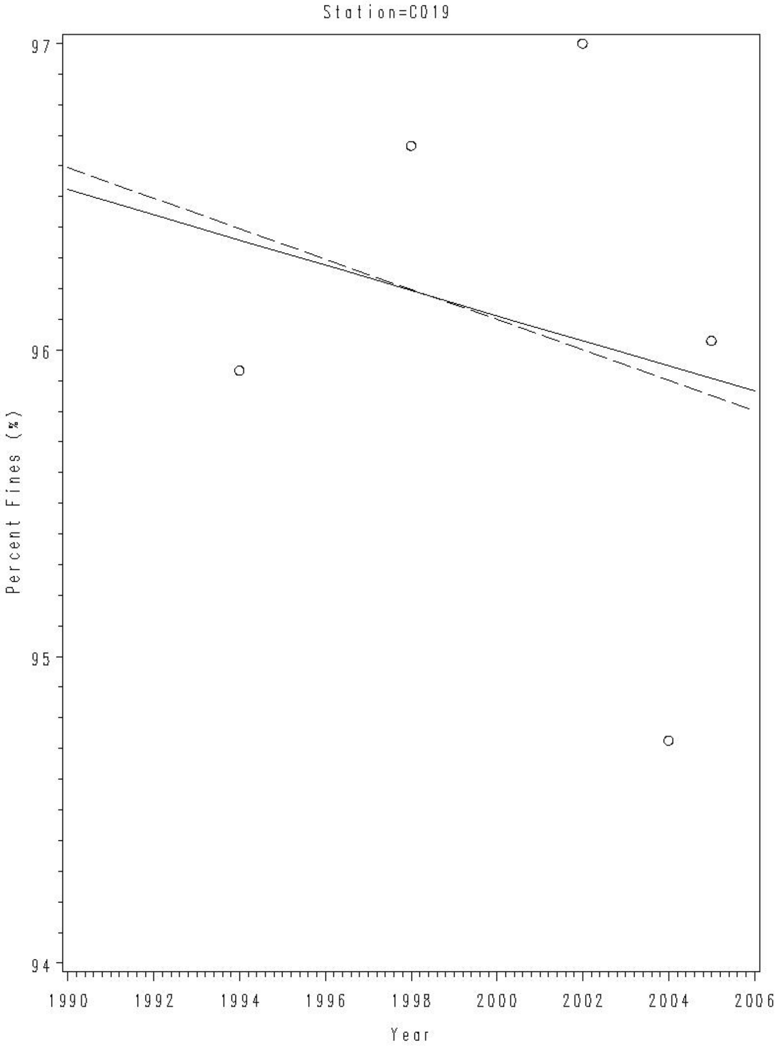


Figure B2-8. Temporal trends in percent fines at Boston Harbor station CO19, 1994 to 2005, August/September surveys only. The solid line represents the nonparametric regression and the dashed line represents the parametric regression. Data only available from 1994, 1998, 2002, 2004, and 2005.

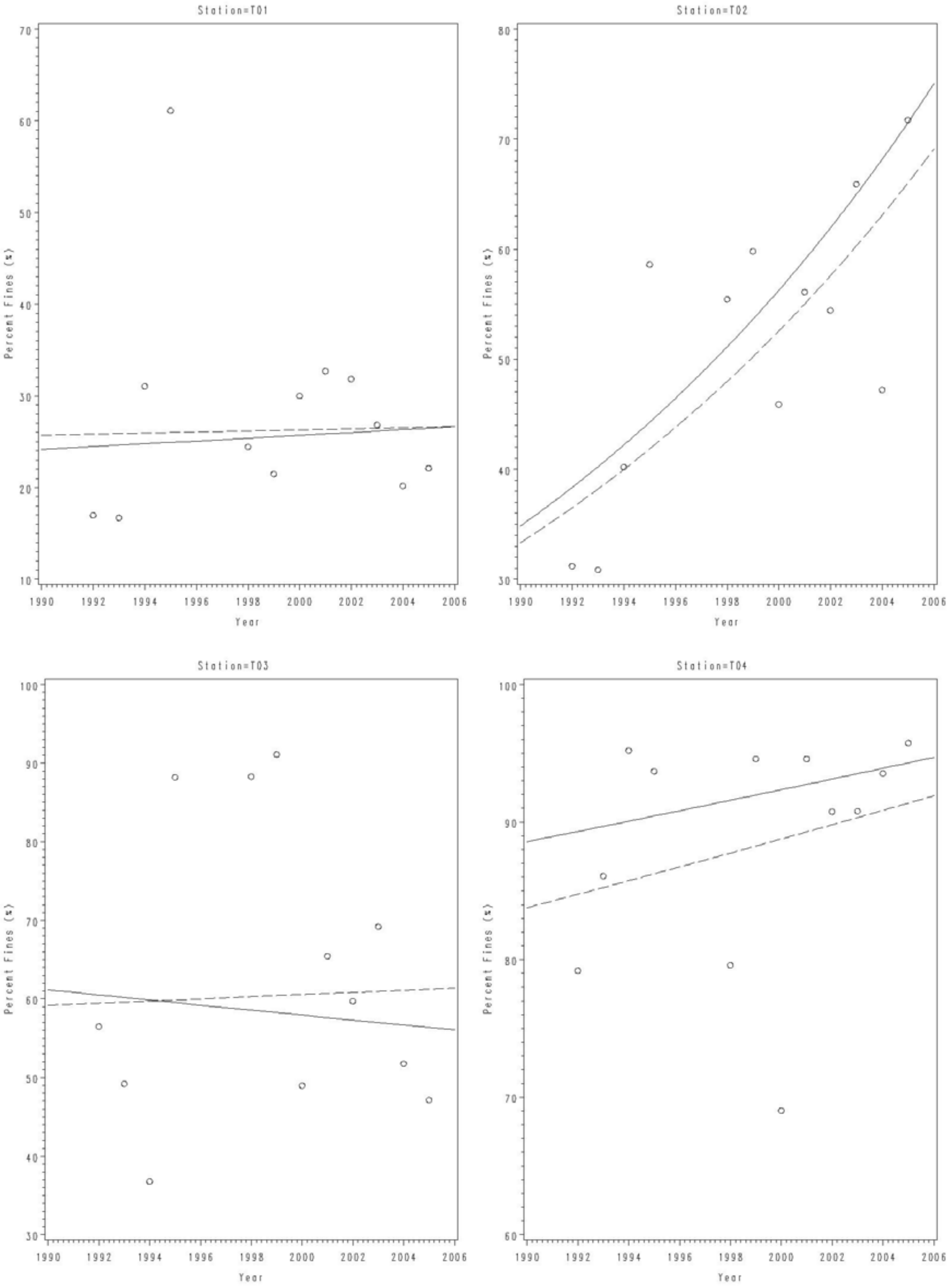


Figure B2-9. Temporal trends in percent fines at Boston Harbor stations T01, T02, T03, and T04, 1992 to 2005, August/September surveys only. The solid line represents the nonparametric regression and the dashed line represents the parametric regression. Data from monitoring years 1991, 1996, and 1997 excluded from the trends analysis.

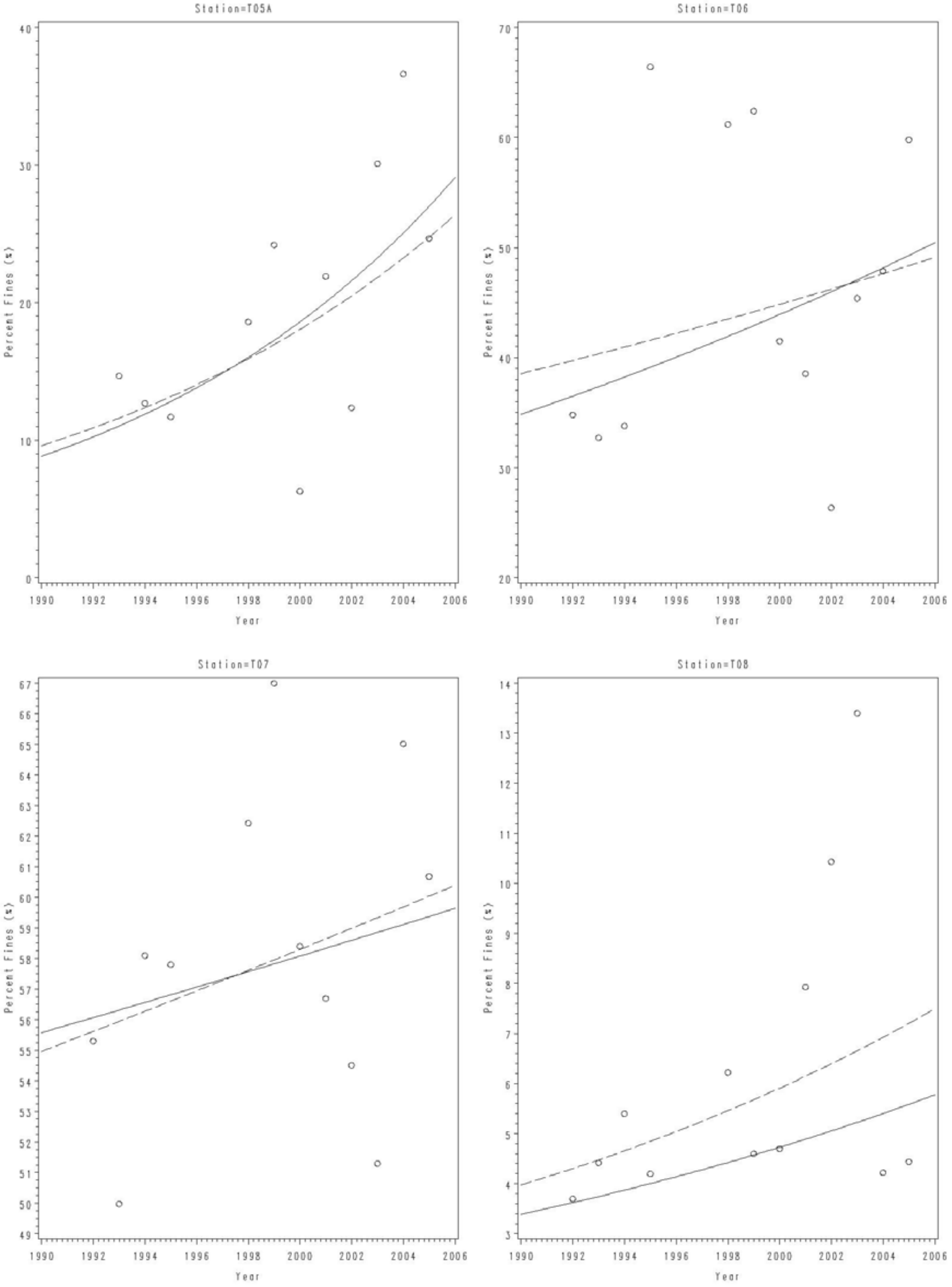
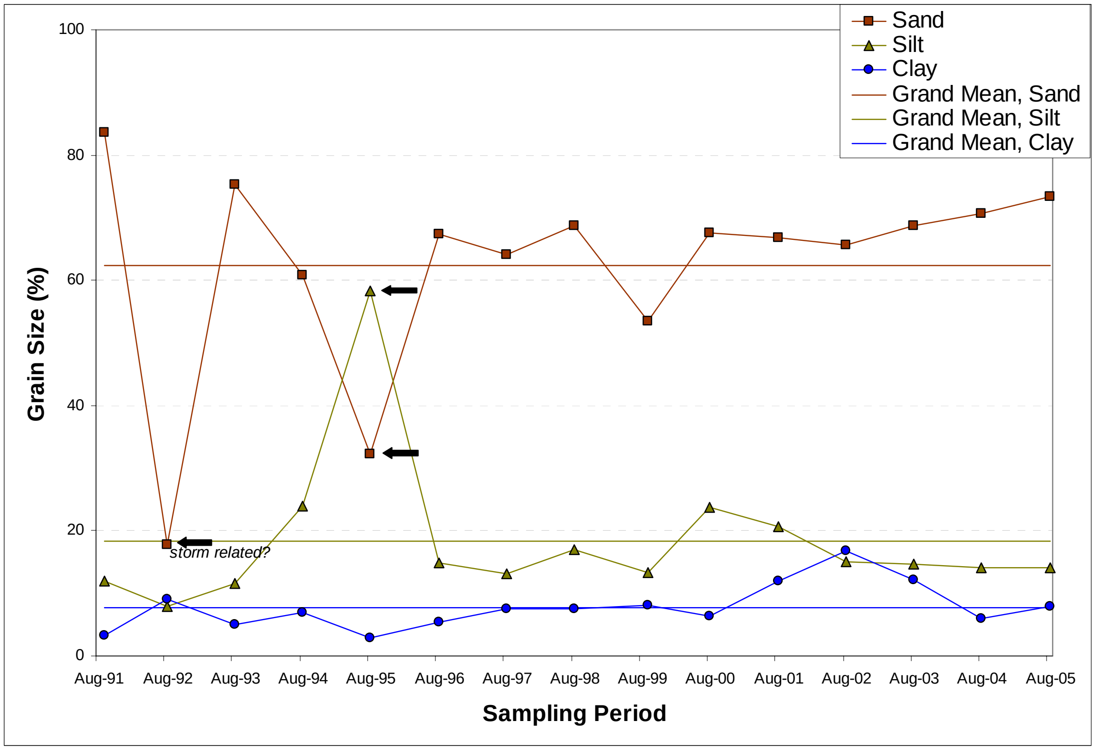


Figure B2-10. Temporal trends in percent fines at Boston Harbor stations T05A, T06, T07, and T08, 1992 to 2005, August/September surveys only. The solid line represents the nonparametric regression and the dashed line represents the parametric regression. Data from monitoring years 1991, 1996, and 1997 excluded from the trends analysis.



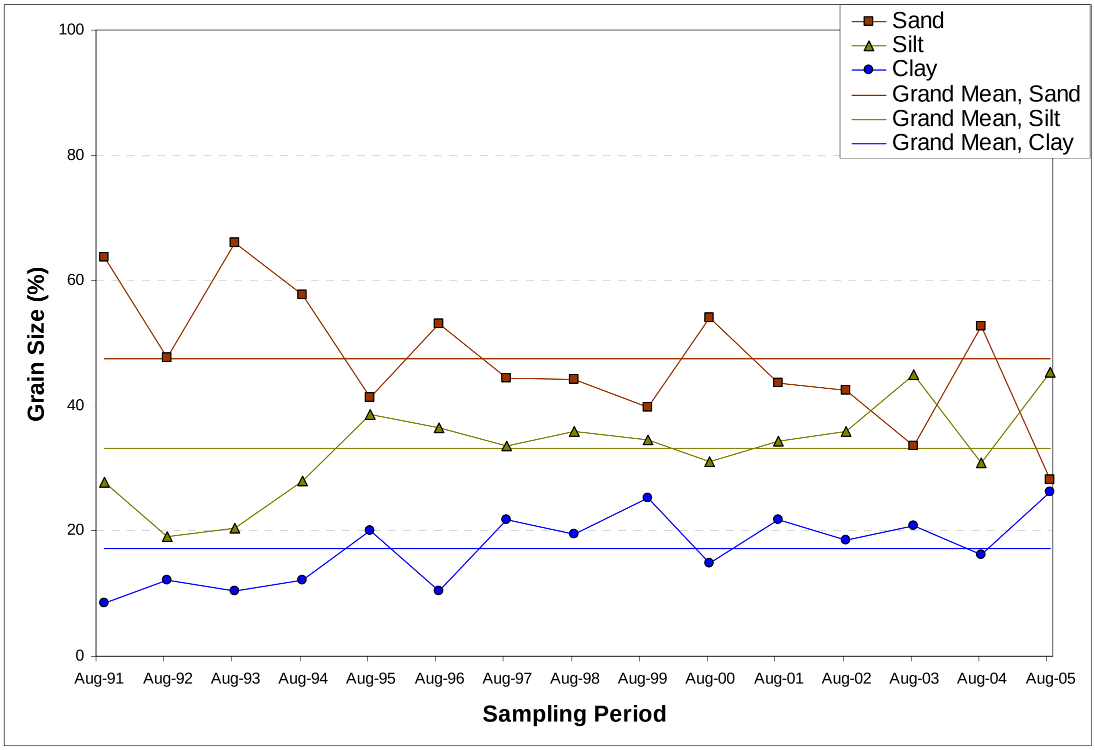
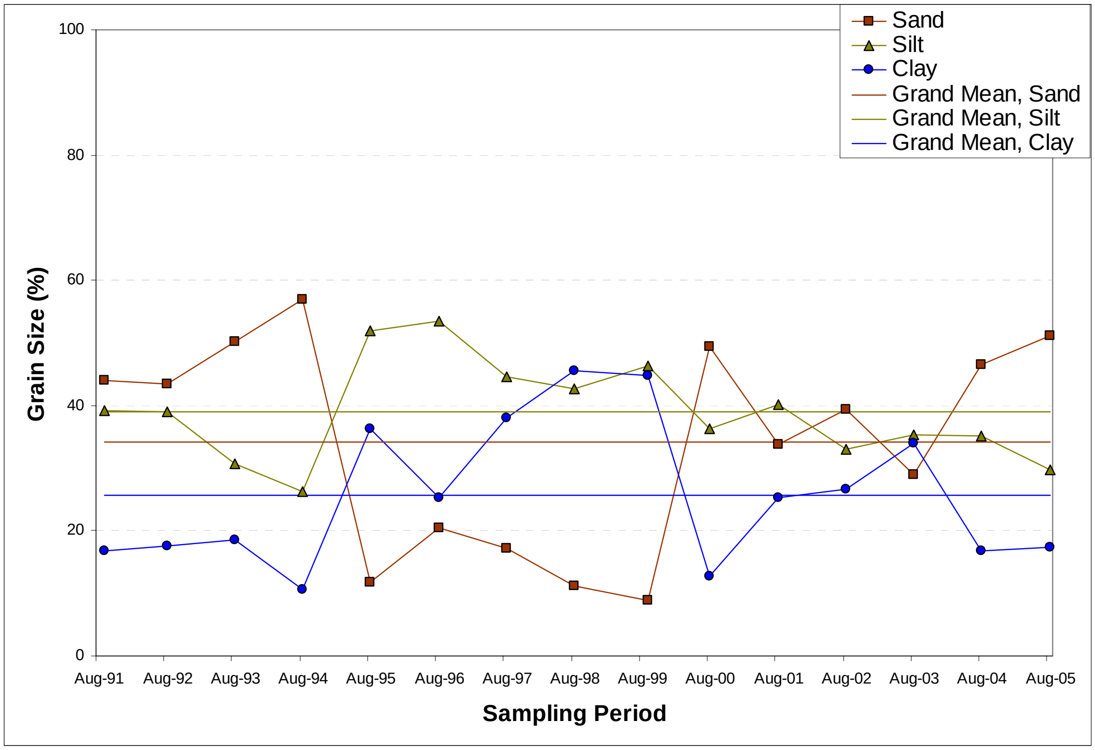


Figure B2-11. Station mean and grand mean values of sand, silt, and clay content at stations T01 (top) and T02 (bottom) from 1991 to 2005, August/September surveys only. Station mean values are the average of all replicates for a given year (August/September surveys only), by station. The grand mean values are the average of all station mean values from 1991 to 2005.



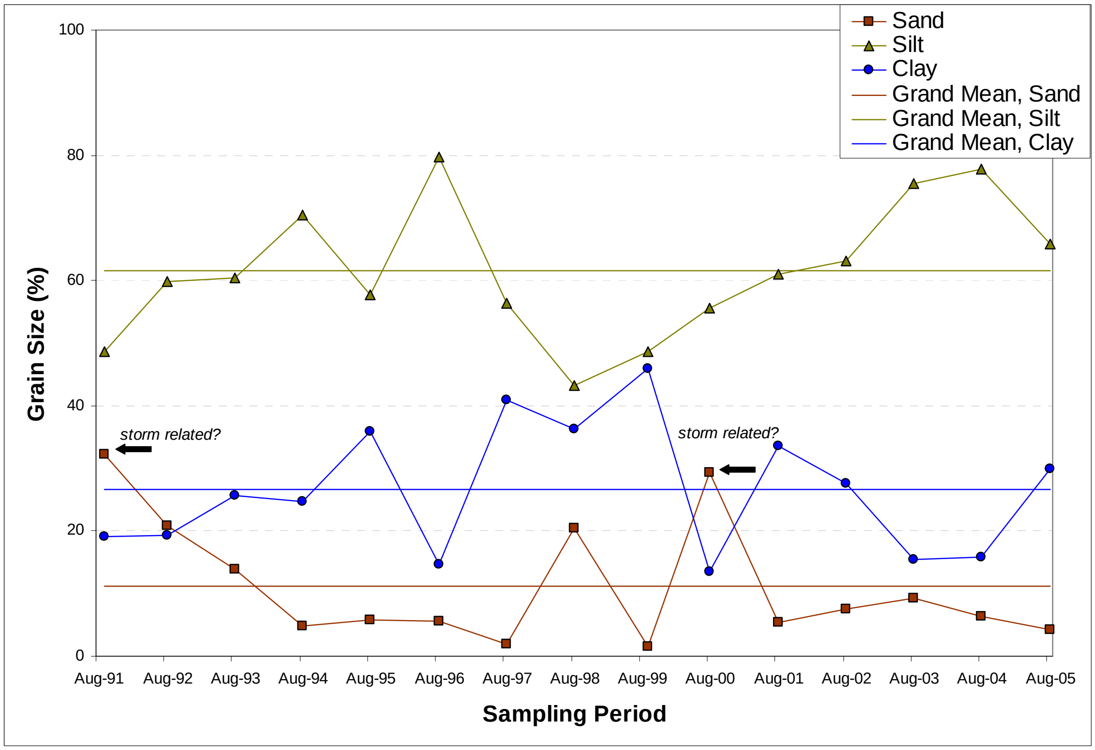
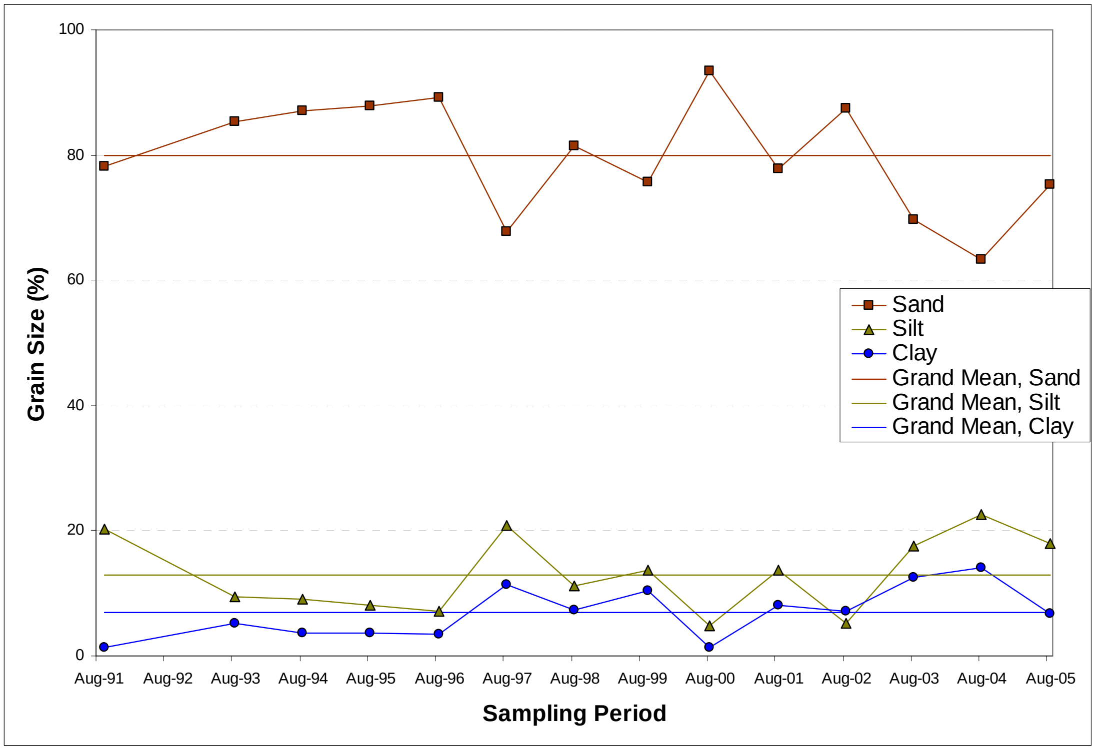


Figure B2-12. Station mean and grand mean values of sand, silt, and clay content at stations T03 (top) and T04 (bottom) from 1991 to 2005, August/September surveys only. Station mean values are the average of all replicates for a given year (August/September surveys only), by station. The grand mean values are the average of all station mean values from 1991 to 2005.



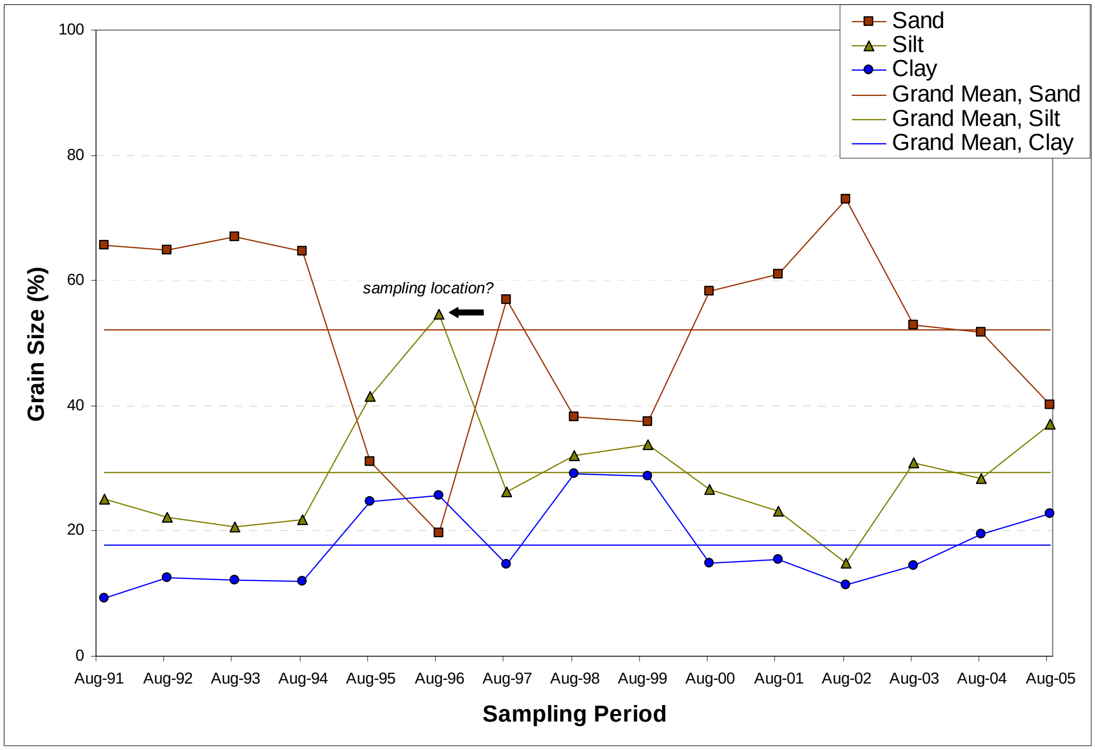


Figure B2-13. Station mean and grand mean values of sand, silt, and clay content at stations T05A (top) and T06 (bottom) from 1991 to 2005, August/September surveys only. Station mean values are the average of all replicates for a given year (August/September surveys only), by station. The grand mean values are the average of all station mean values from 1991 to 2005.

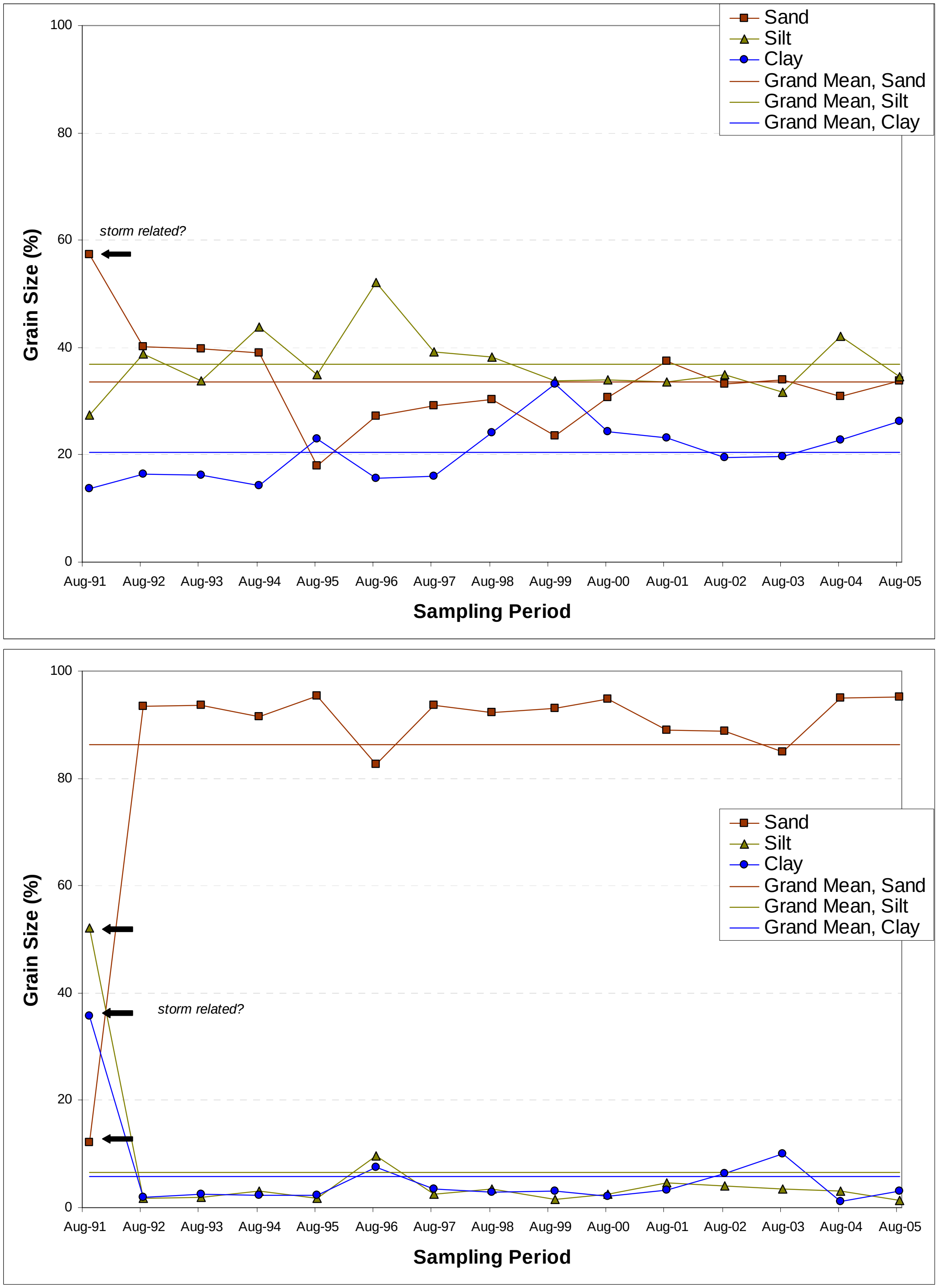


Figure B2-14. Station mean and grand mean values of sand, silt, and clay content at stations T07 (top) and T08 (bottom) from 1991 to 2005, August/September surveys only. Station mean values are the average of all replicates for a given year (August/September surveys only), by station. The grand mean values are the average of all station mean values from 1991 to 2005.

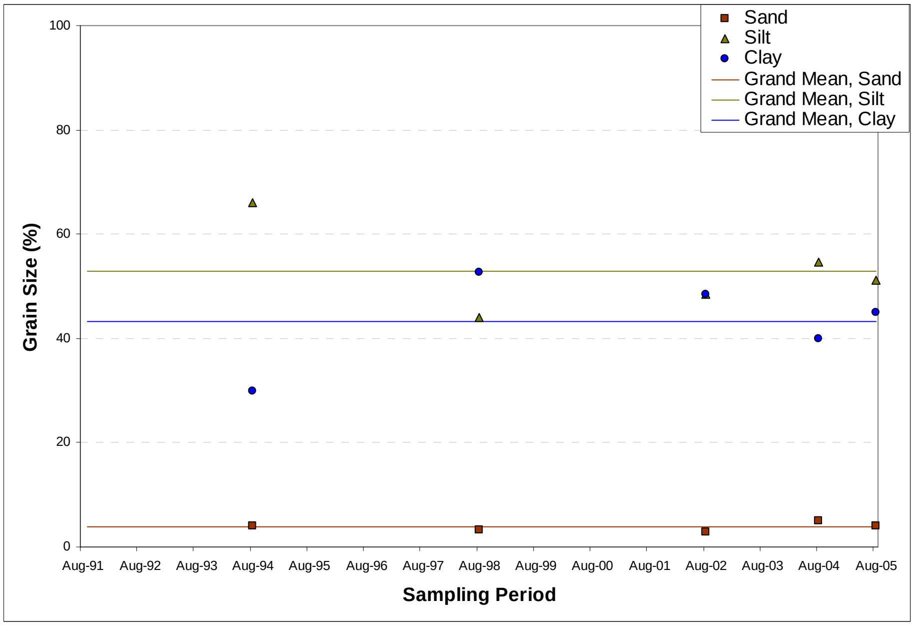


Figure B2-15. Station mean and grand mean values of sand, silt, and clay content at station CO19 from 1994 to 2005, August/September surveys only. Station mean values are the average of all replicates for a given year (August/September surveys only), by station. The grand mean values are the average of all station mean values from 1994 to 2005.

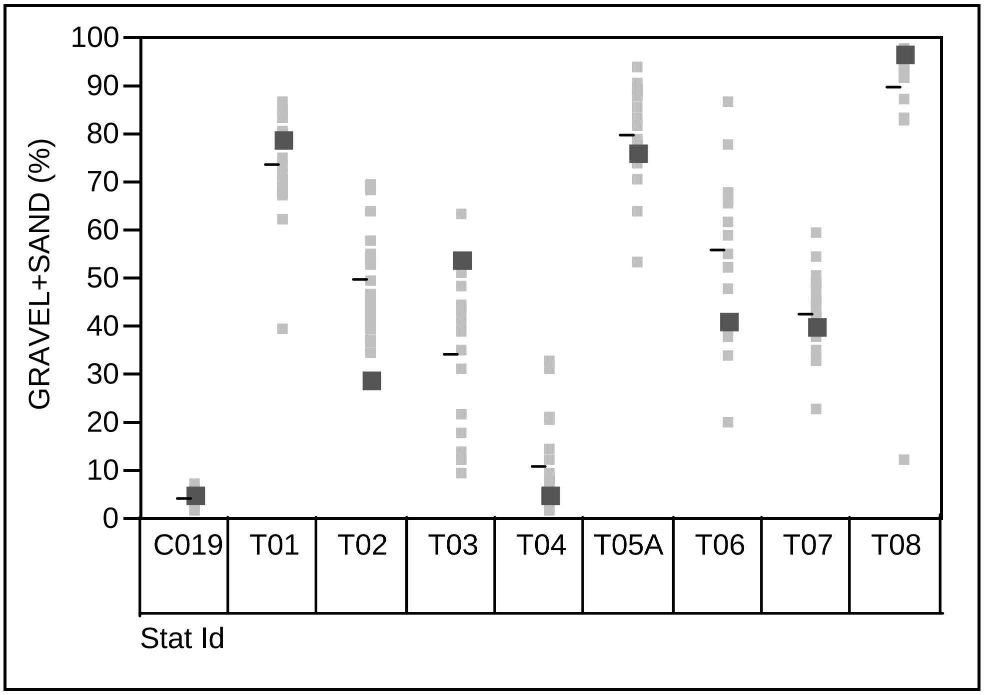


Figure B2-16. Distribution of percentages gravel + sand at harbor stations from 1991 to 2005, August /September surveys only. ▪ represents 1991 to 2004 data and ■ represents 2005 data.

APPENDIX B3

Total Organic Carbon Content 1991–2005 Sediment Data Evaluations Station Grand Mean and Coefficient of Variation (CV), Statistics Output, Line Charts, and Box-plots

Table B3-1. Station grand mean and coefficient of variation (CV) between yearly station mean values for total organic carbon content. Boston Harbor sediment data from 1991 to 2005, August/September surveys only.

Stat Id	N	Station Grand Mean	Units	CV	Units
C019	5	2.92	%	7	%
T01	15	1.67	%	44	%
T02	15	1.65	%	13	%
T03	15	3.08	%	20	%
T04	15	4.19	%	35	%
T05A	14	0.88	%	34	%
T06	15	2.03	%	28	%
T07	15	2.67	%	12	%
T08	15	0.48	%	51	%

N, Number of observations.
CV, coefficient of variation.

Table B3-2. Regression and probability results from the TOC trends analysis. Sediment data from all years excluding 1996 and 1997 were used in the analysis.

Station ID	No samp	Parametric Regression		Nonparametric Regression		Spearman Correlation	
		Slope	p-value	Slope	p-value	Slope	p-value
CO19	4	0.0025	0.8020	0.0057	0.6242	-0.1000	0.7471
T01	13	-0.0867	**0.0031 ***	-0.0842	**0.0012 ***	0.3407	**0.0241 ***
T02	13	-0.0073	0.3558	-0.0071	0.4641	0.7033	**0.0000 ***
T03	13	-0.0321	**0.0217 ***	-0.0199	**0.0086 ***	-0.0110	0.2886
T04	13	0.0024	0.9030	0.0104	0.5418	0.4780	0.6415
T05A	12	0.0140	0.5810	0.0015	0.9452	0.5175	**0.0074 ***
T06	13	-0.0073	0.4415	-0.0073	0.5014	0.3077	**0.0001 ***
T07	13	-0.0086	0.2799	-0.0051	0.5822	0.4231	0.0780
T08	13	-0.0611	0.0524	-0.0642	0.1598	0.0934	**0.0003 ***

* Significant at 95% confidence level

Table B3-3. Regression and probability results from the TOC trends analysis. Sediment data from all years excluding 1991, 1996, and 1997 were used in the analysis.

Station ID	No samp	Parametric Regression		Nonparametric Regression		Spearman Correlation	
		Slope	p-value	Slope	p-value	Slope	p-value
C019	4	0.0025	0.8020	0.0057	0.6242	0.0000	1.0000
T01	12	-0.0877	**0.0088 ***	-0.0878	**0.0020 ***	-0.8336	**0.0008 ***
T02	12	-0.0067	0.4688	-0.0047	0.6808	-0.1958	0.5419
T03	12	-0.0320	**0.0471 ***	-0.0183	**0.0331 ***	-0.5849	**0.0457 ***
T04	12	0.0005	0.9818	0.0119	0.5833	0.1469	0.6488
T05A	11	0.0309	0.3103	0.0185	0.6394	0.1959	0.5637
T06	12	-0.0105	0.3437	-0.0148	0.2726	-0.3217	0.3079
T07	12	-0.0093	0.3228	-0.0069	0.7311	-0.1611	0.6169
T08	12	-0.0488	0.1578	-0.0417	0.3716	-0.3468	0.2695

* Significant at 95% confidence level

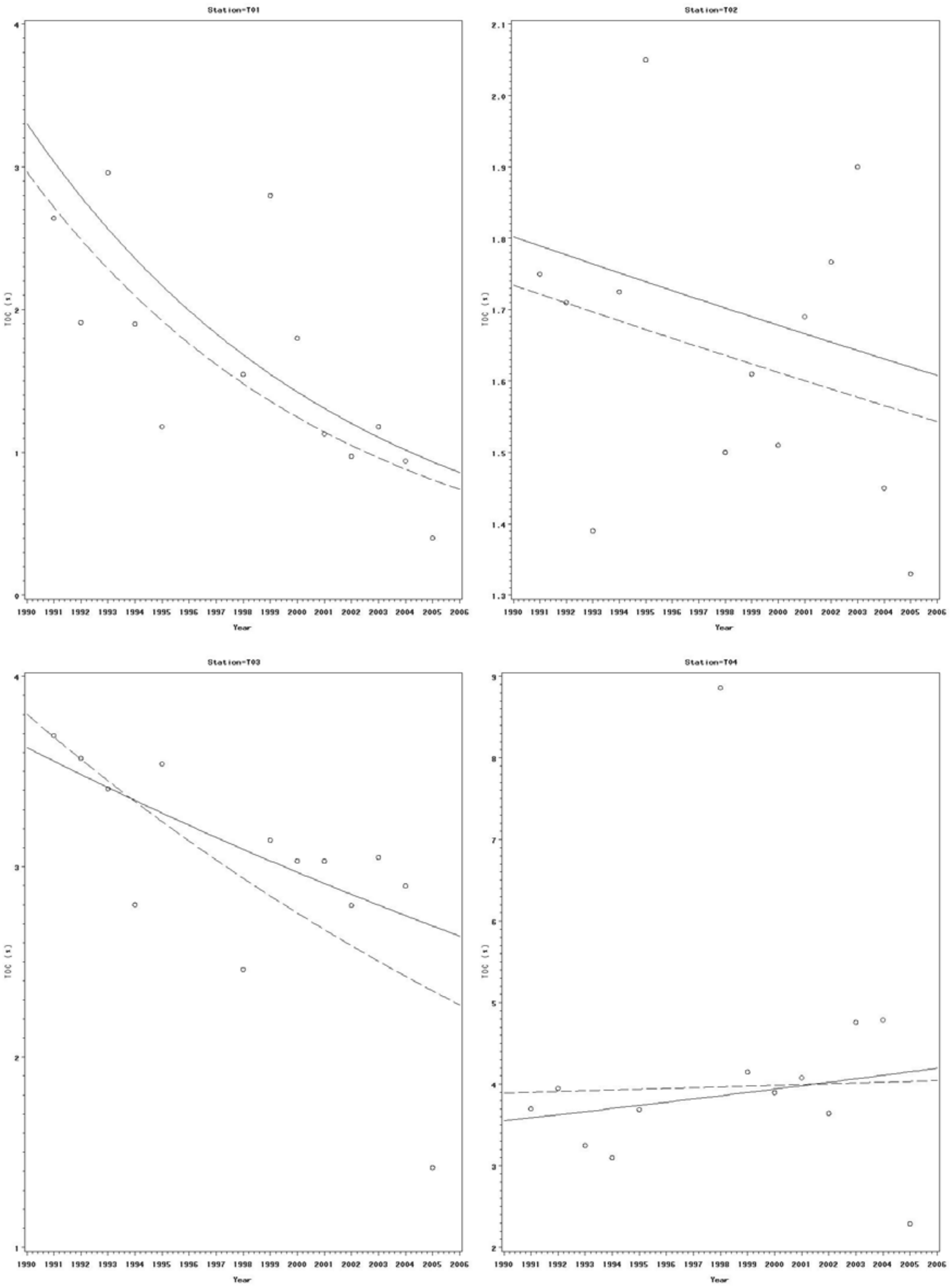


Figure B3-1. Temporal trends in total organic carbon content at Boston Harbor stations T01, T02, T03, and T04, 1991 to 2005, August/September surveys only. The solid line represents the nonparametric regression and the dashed line represents the parametric regression. Data from monitoring years 1996 and 1997 excluded from the trends analysis.

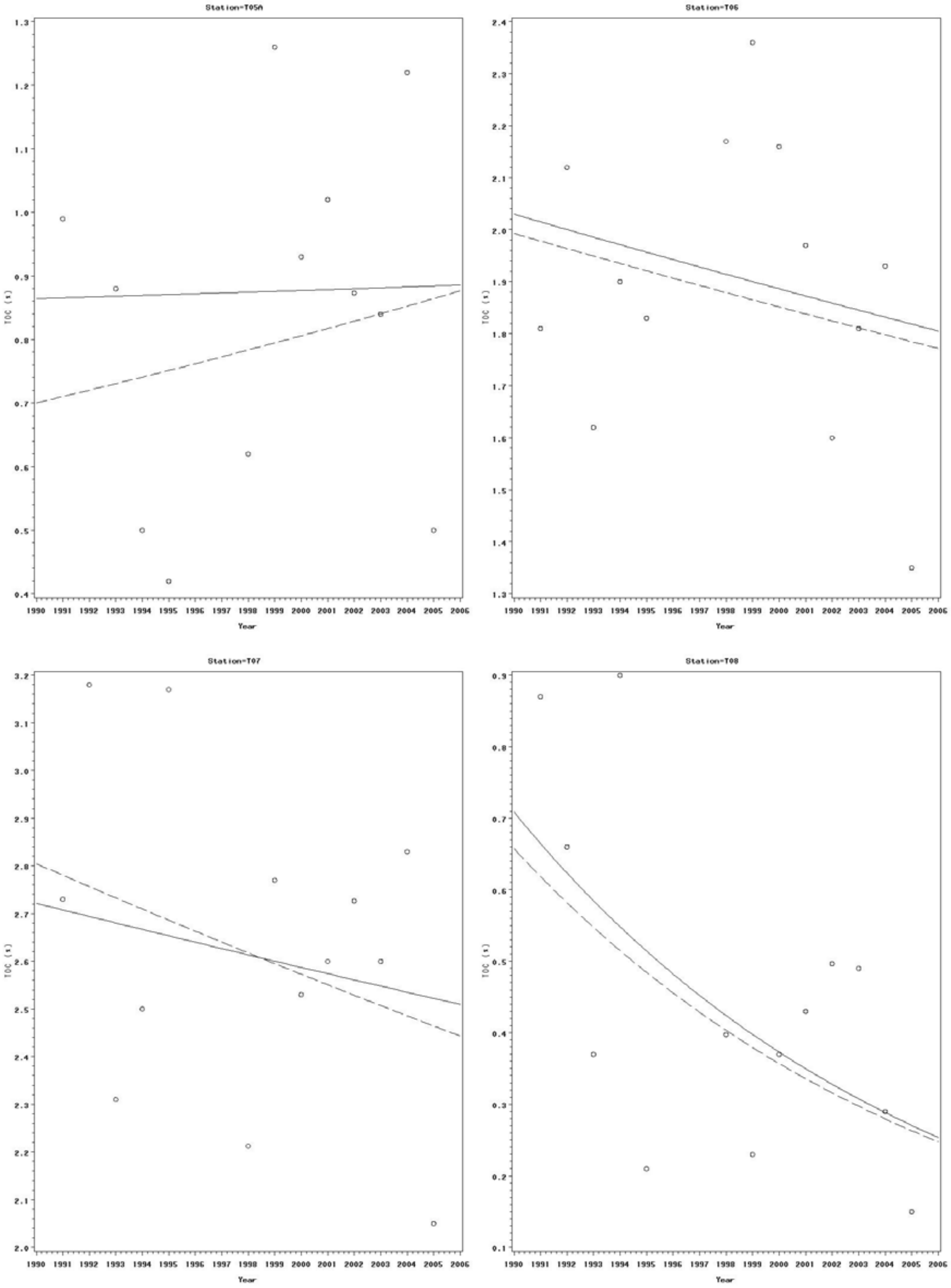


Figure B3-2. Temporal trends in total organic carbon content at Boston Harbor stations T05A, T06, T07, and T08, 1991 to 2005, August/September surveys only. The solid line represents the nonparametric regression and the dashed line represents the parametric regression. Data from monitoring years 1996 and 1997 excluded from the trends analysis.

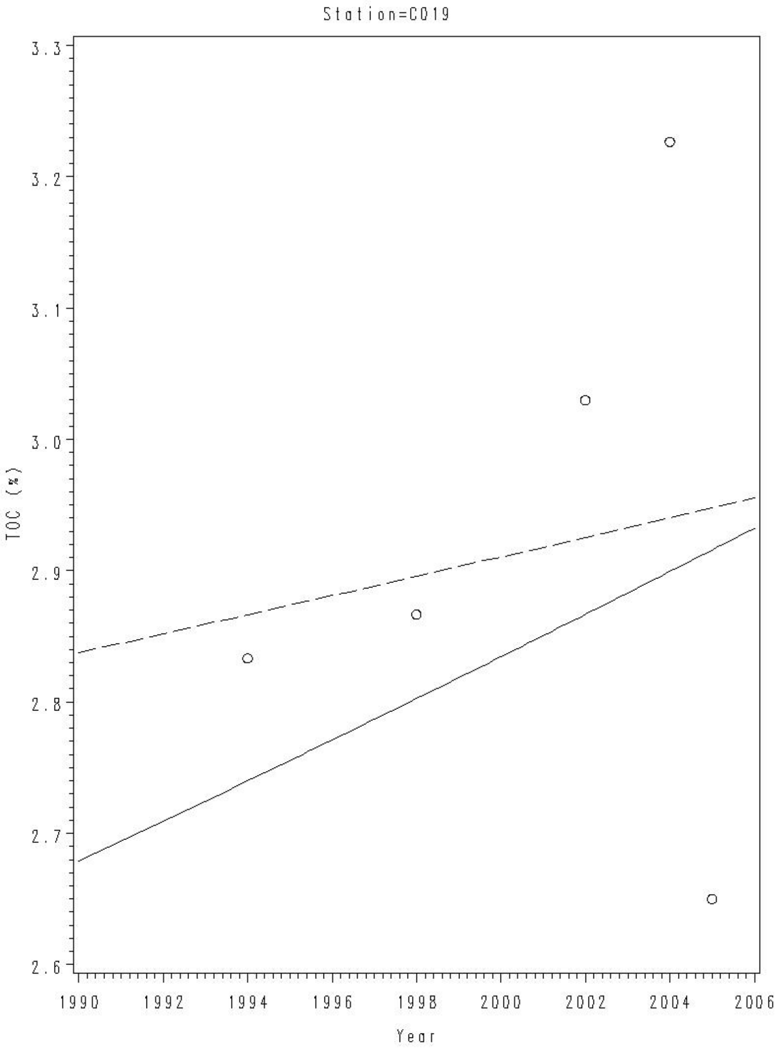


Figure B3-3. Temporal trends in total organic carbon content at Boston Harbor station CO19, 1994 to 2005, August/September surveys only. The solid line represents the nonparametric regression and the dashed line represents the parametric regression. Data only available from 1994, 1998, 2002, 2004, and 2005.

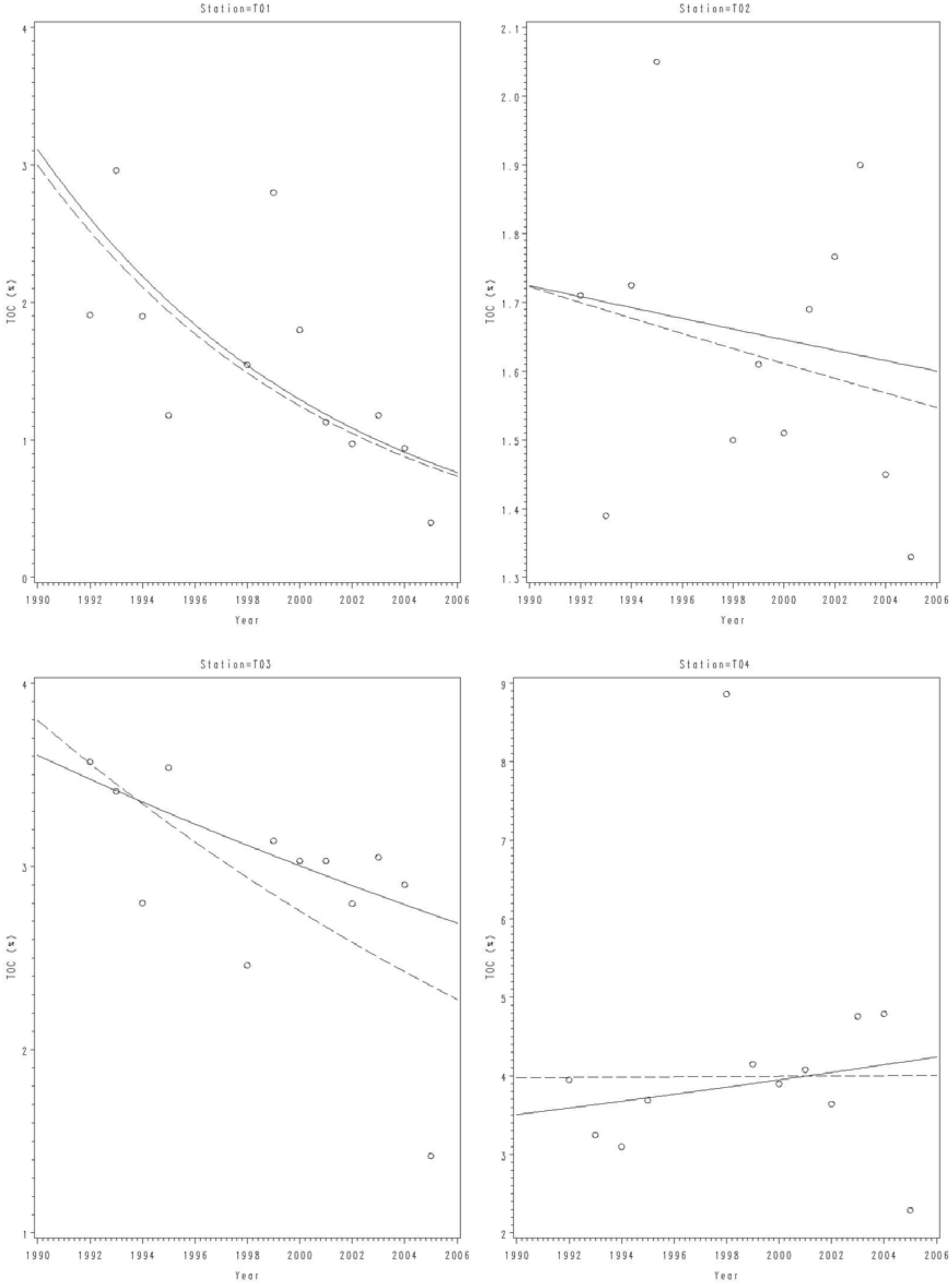


Figure B3-4. Temporal trends in total organic carbon content at Boston Harbor stations T01, T02, T03, and T04, 1992 to 2005, August/September surveys only. The solid line represents the nonparametric regression and the dashed line represents the parametric regression. Data from monitoring years 1991, 1996, and 1997 excluded from the trends analysis.

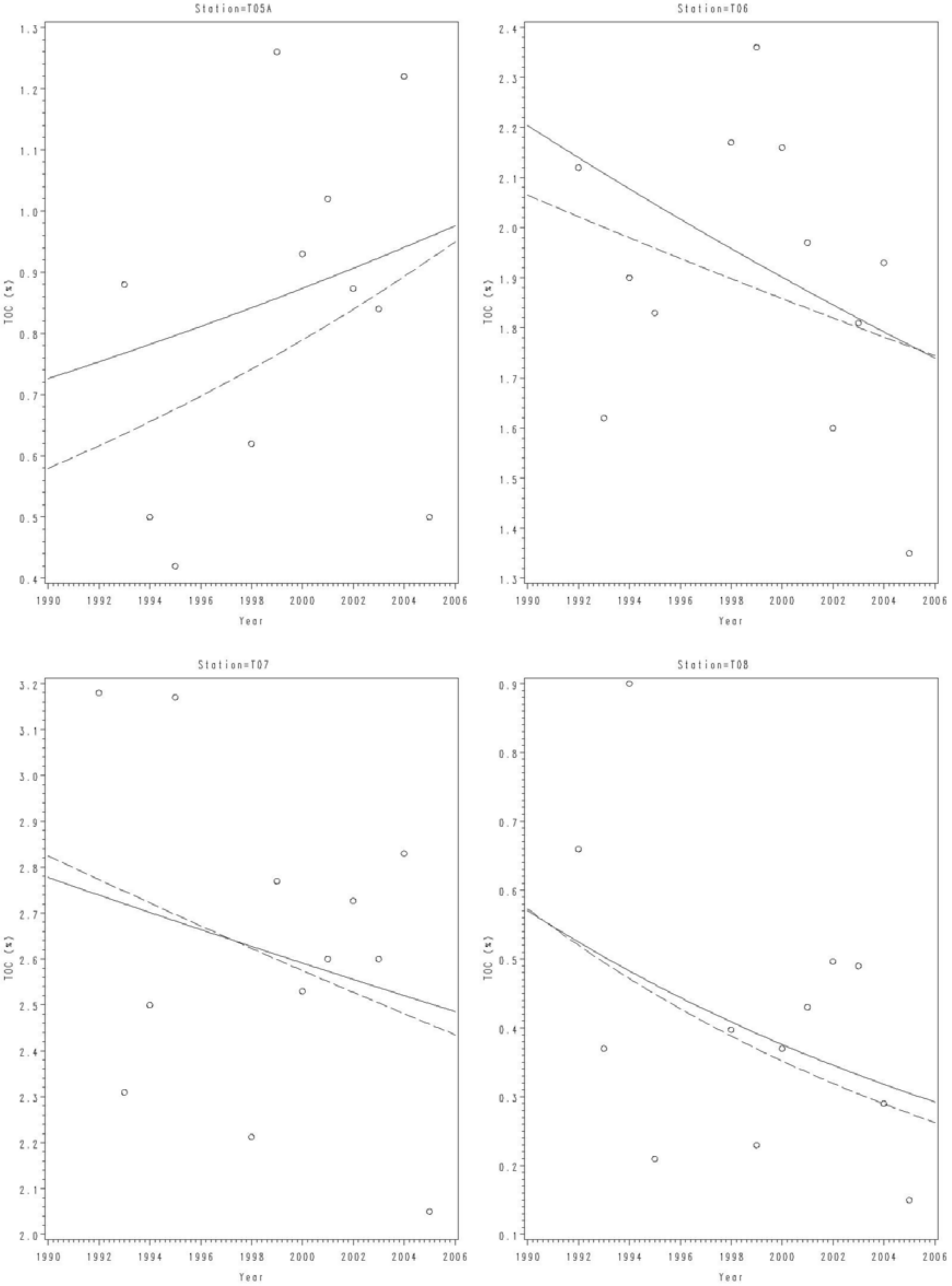
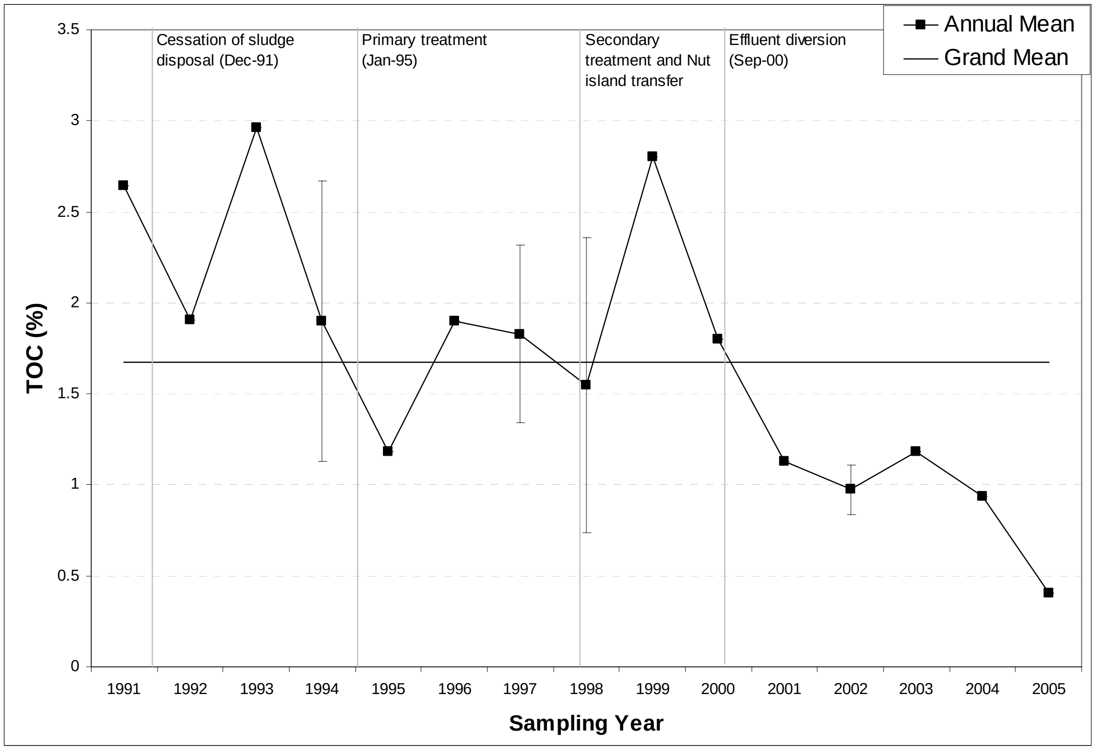


Figure B3-5. Temporal trends in total organic carbon content at Boston Harbor stations T05A, T06, T07, and T08, 1992 to 2005, August/September surveys only. The solid line represents the nonparametric regression and the dashed line represents the parametric regression. Data from monitoring years 1991, 1996, and 1997 excluded from the trends analysis.



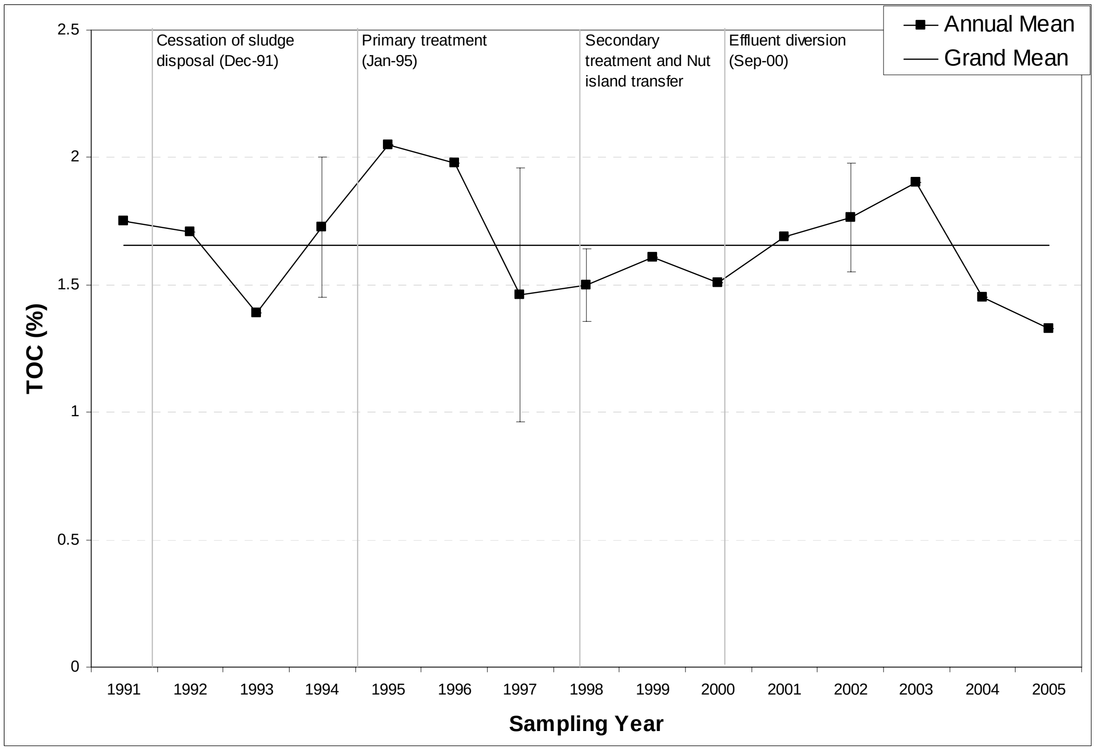


Figure B3-6. Station mean and grand mean values of total organic carbon content at stations T01 (top) and T02 (bottom) from 1991 to 2005, August/September surveys only. Vertical bars represent one standard deviation. Station mean values are the average of all replicates for a given year (August/September surveys only), by station. The grand mean values are the average of all station mean values from 1991 to 2005.

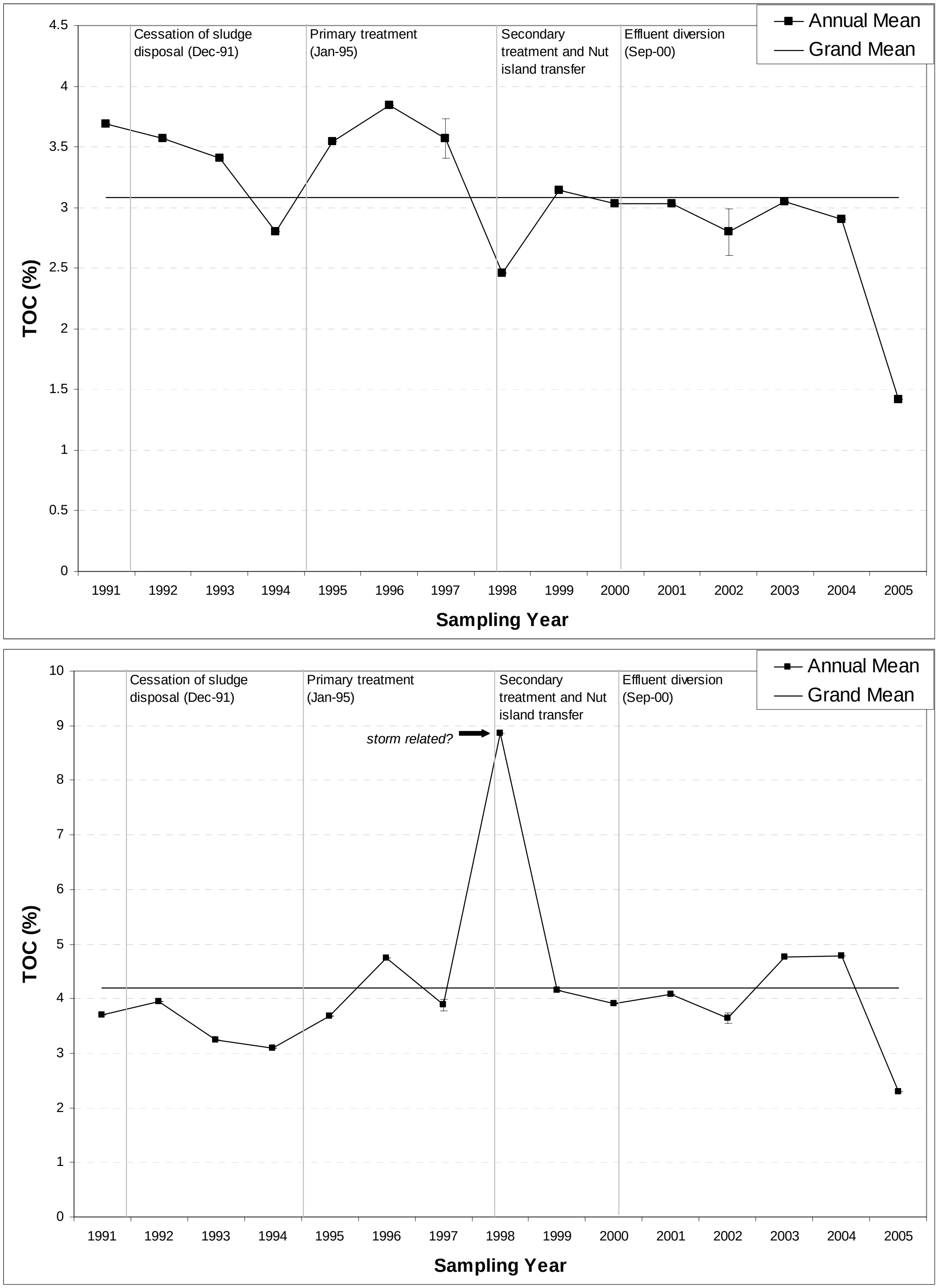
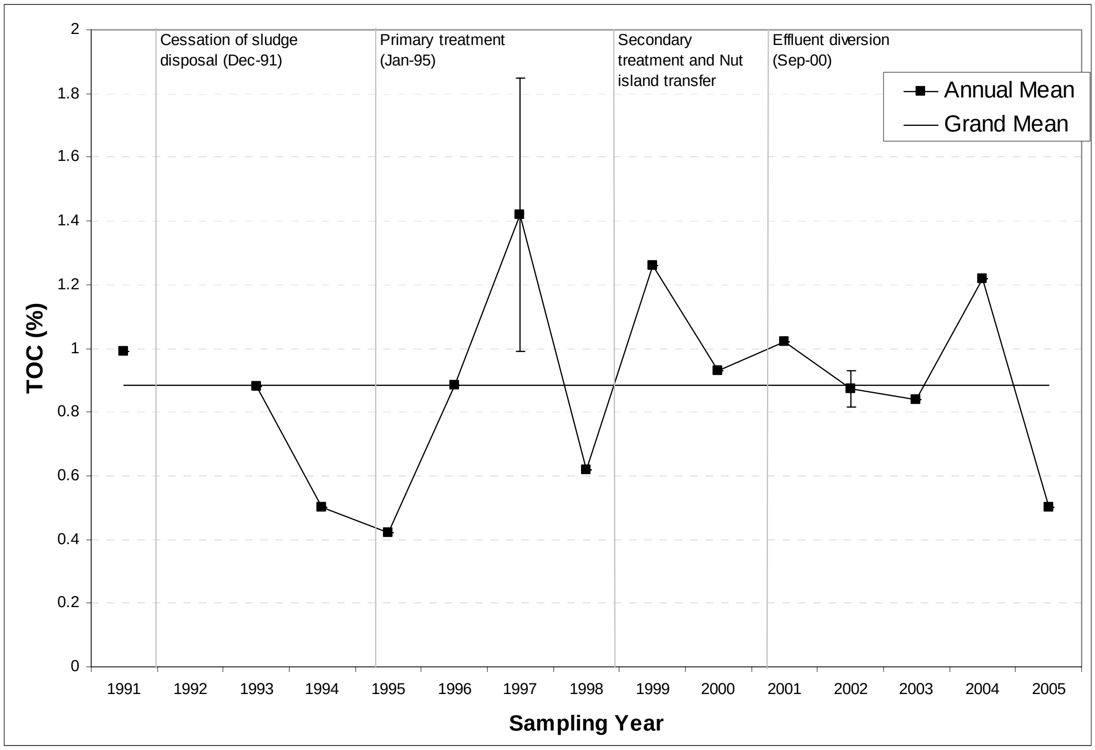


Figure B3-7. Station mean and grand mean values of total organic carbon content at stations T03 (top) and T04 (bottom) from 1991 to 2005, August/September surveys only. Vertical bars represent one standard deviation. Station mean values are the average of all replicates for a given year (August/September surveys only), by station. The grand mean values are the average of all station mean values from 1991 to 2005.



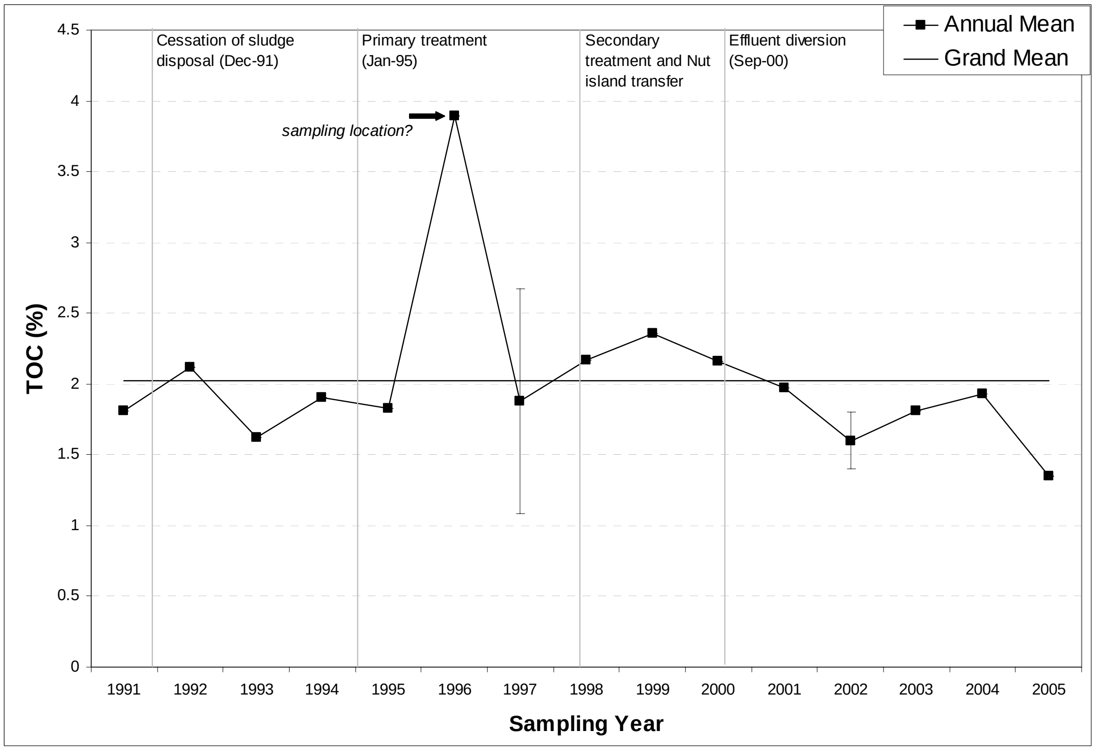


Figure B3-8. Station mean and grand mean values of total organic carbon content at stations T05A (top) and T06 (bottom) from 1991 to 2005, August/September surveys only. Vertical bars represent one standard deviation. Station mean values are the average of all replicates for a given year (August/September surveys only), by station. The grand mean values are the average of all station mean values from 1991 to 2005.

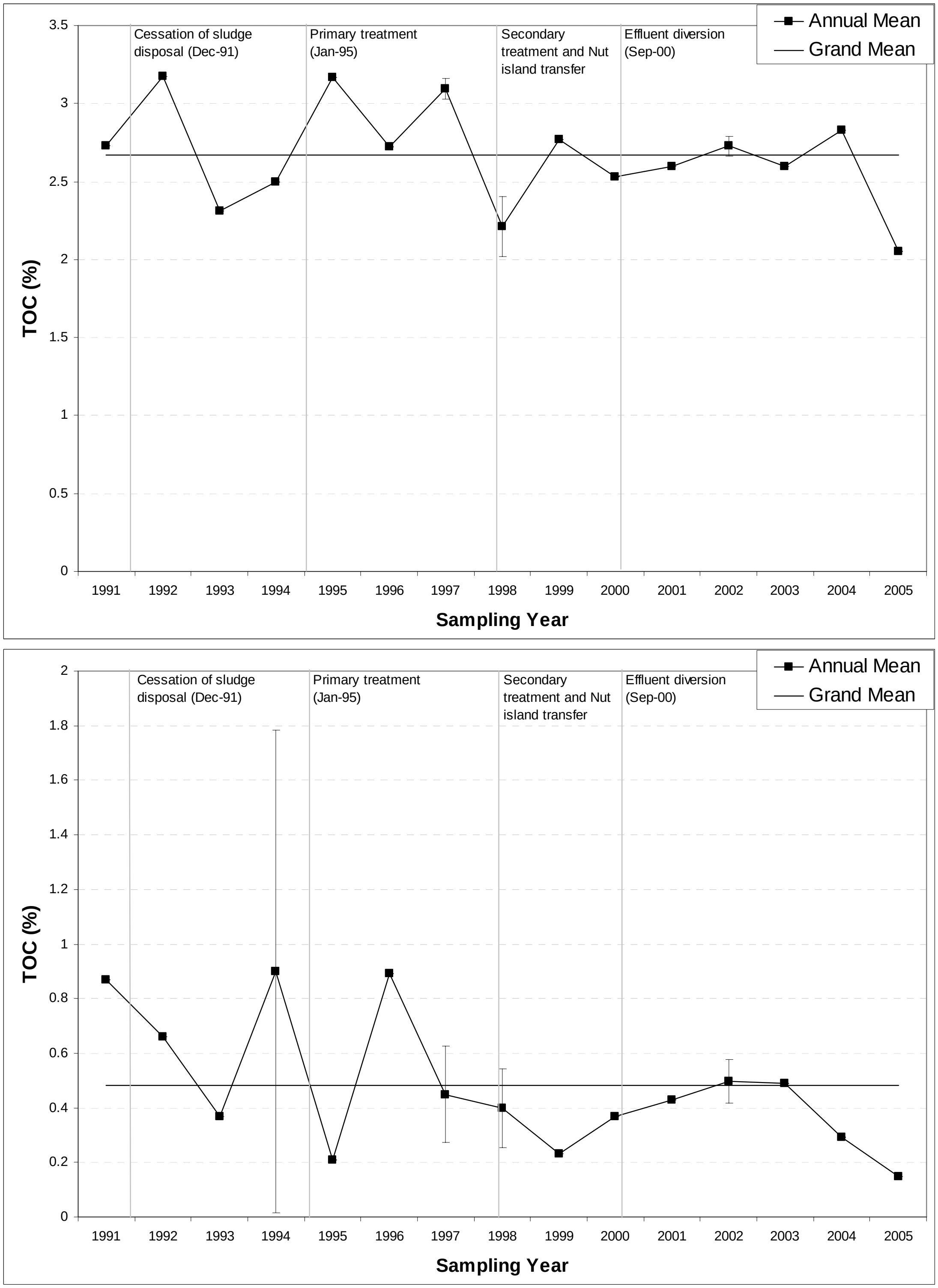


Figure B3-9. Station mean and grand mean values of total organic carbon content at stations T07 (top) and T08 (bottom) from 1991 to 2005, August/September surveys only. Vertical bars represent one standard deviation. Station mean values are the average of all replicates for a given year (August/September surveys only), by station. The grand mean values are the average of all station mean values from 1991 to 2005.

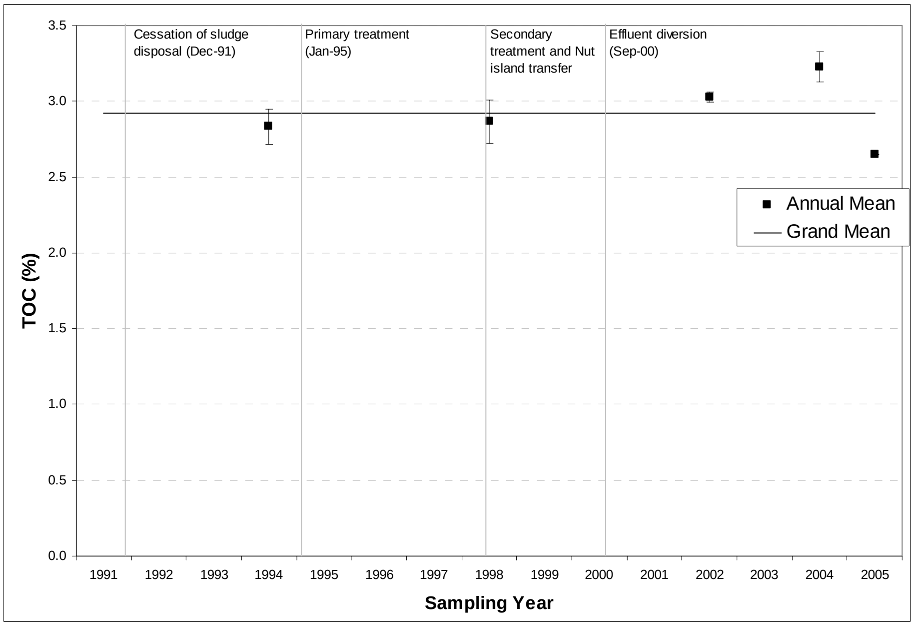


Figure B3-10. Station mean and grand mean values of total organic carbon content at station CO19 from 1994 to 2005, August/September surveys only. Vertical bars represent one standard deviation. Station mean values are the average of all replicates for a given year (August/ September surveys only), by station. The grand mean values are the average of all station mean values from 1994 to 2005. No data from monitoring years 1995 to 1997, 1999 to 2001, and 2003.

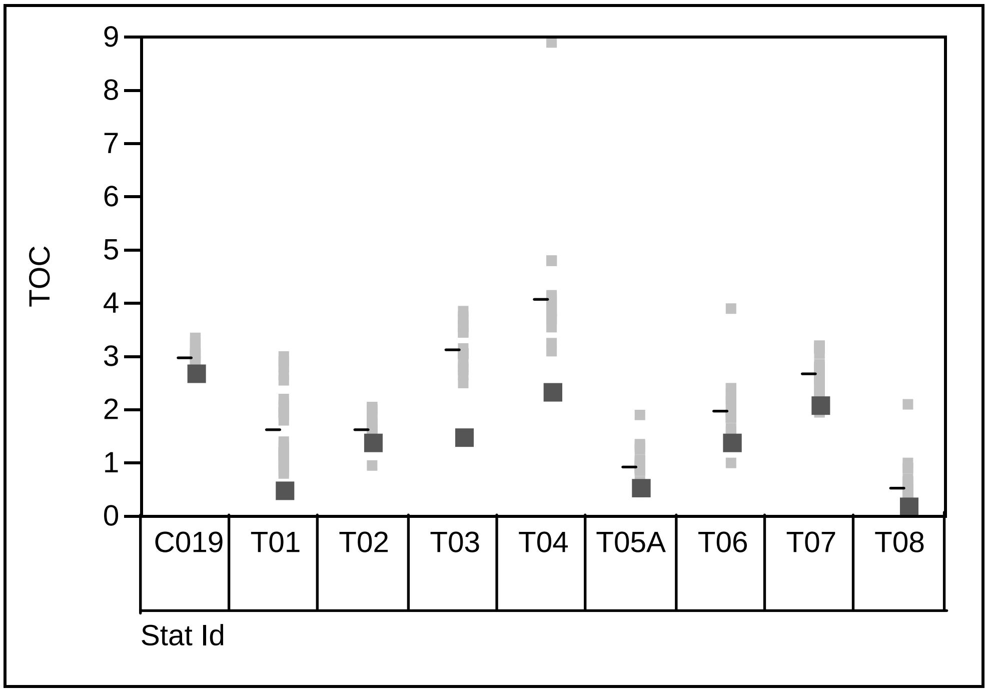


Figure B3-11. Distribution of total organic carbon content at harbor stations from 1991 to 2005, August surveys only. ▪ represents 1991 to 2004 data and ■ represents 2005 data.

APPENDIX B4

Clostridium perfringens
1991–2005 Sediment Data Evaluations
Station Grand Mean and Coefficient of Variation (CV), Statistics Output, and Line Charts

Table B4-1. Station grand mean and coefficient of variation between station mean values for *Clostridium perfringens*, raw and normalized to percent fines. Boston Harbor sediment data from 1991 to 2005, August/September surveys only.

Stat Id	Parameter	N	Station Grand Mean	Units	CV	Units
C019	*C. perfringens*	5	14104	cfu/g dw	21	%
T01		15	4337	cfu/g dw	76	%
T02		15	10463	cfu/g dw	66	%
T03		15	26561	cfu/g dw	191	%
T04		15	13393	cfu/g dw	124	%
T05A		14	1910	cfu/g dw	76	%
T06		15	11007	cfu/g dw	139	%
T07		15	10449	cfu/g dw	72	%
T08		15	1900	cfu/g dw	125	%
C019	Normalized *C. perfringens*	5	146	cfu/g dw / %fines	21	%
T01		15	216	cfu/g dw / %fines	98	%
T02		15	236	cfu/g dw / %fines	78	%
T03		15	455	cfu/g dw / %fines	200	%
T04		15	153	cfu/g dw / %fines	121	%
T05A		14	121	cfu/g dw / %fines	83	%
T06		15	231	cfu/g dw / %fines	113	%
T07		15	183	cfu/g dw / %fines	65	%
T08		15	230	cfu/g dw / %fines	117	%

cfu/g dw = colony forming units per gram dry weight.

Table B4-2. Regression and probability results from the trends analysis using normalized *Clostridium perfringens* sediment data from all years excluding 1996 and 1997.

Station ID	No samp	Parametric Regression		Nonparametric Regression		Spearman Correlation	
		Slope	p-value	Slope	p-value	Slope	p-value
CO19	4	0.0007	0.9801	0.0092	0.6242	0.2000	0.0000
T01	13	-0.1294	**0.0295 ***	-0.1460	**0.0237 ***	-0.6190	-0.8253
T02	13	-0.1601	**0.0000 ***	-0.1647	**0.0003 ***	-0.8956	-0.2418
T03	13	-0.0835	0.2980	-0.0885	0.2721	-0.3187	-0.6740
T04	13	-0.0446	0.4100	0.0032	1.0000	-0.1429	0.1648
T05A	12	-0.1497	**0.0052 ***	-0.1698	**0.0061 ***	-0.7273	0.0736
T06	13	-0.1690	**0.0001 ***	-0.1549	**0.0005 ***	-0.8693	-0.1926
T07	13	-0.0433	**0.0326 ***	-0.0220	0.0876	-0.5055	-0.2201
T08	13	-0.2051	**0.0012 ***	-0.2490	**0.0015 ***	-0.8407	-0.4704

* Significant at 95% confidence level

Table B4-3. Regression and probability results from the trends analysis using normalized *Clostridium perfringens* sediment data from all years excluding 1991, 1996, and 1997.

Station ID	No samp	Parametric Regression		Nonparametric Regression		Spearman Correlation	
		Slope	p-value	Slope	p-value	Slope	p-value
C019	4	0.0007	0.9801	0.0092	0.6242	0.2000	0.7471
T01	12	-0.0937	0.1230	-0.1142	0.0857	-0.5149	0.0867
T02	12	-0.1506	**0.0000 ***	-0.1531	**0.0010 ***	-0.8671	**0.0003 ***
T03	12	0.0013	0.9853	-0.0317	0.6808	-0.1329	0.6806
T04	12	0.0070	0.8913	0.0524	0.4106	0.0909	0.7787
T05A	11	-0.1481	**0.0197 ***	-0.1689	**0.0158 ***	-0.7000	**0.0165 ***
T06	12	-0.1393	**0.0005 ***	-0.1380	**0.0020 ***	-0.8336	**0.0008 ***
T07	12	-0.0225	0.1652	-0.0122	0.2726	-0.3706	0.2356
T08	12	-0.2664	**0.0000 ***	-0.2738	**0.0006 ***	-0.9021	**0.0001 ***

* Significant at 95% confidence level

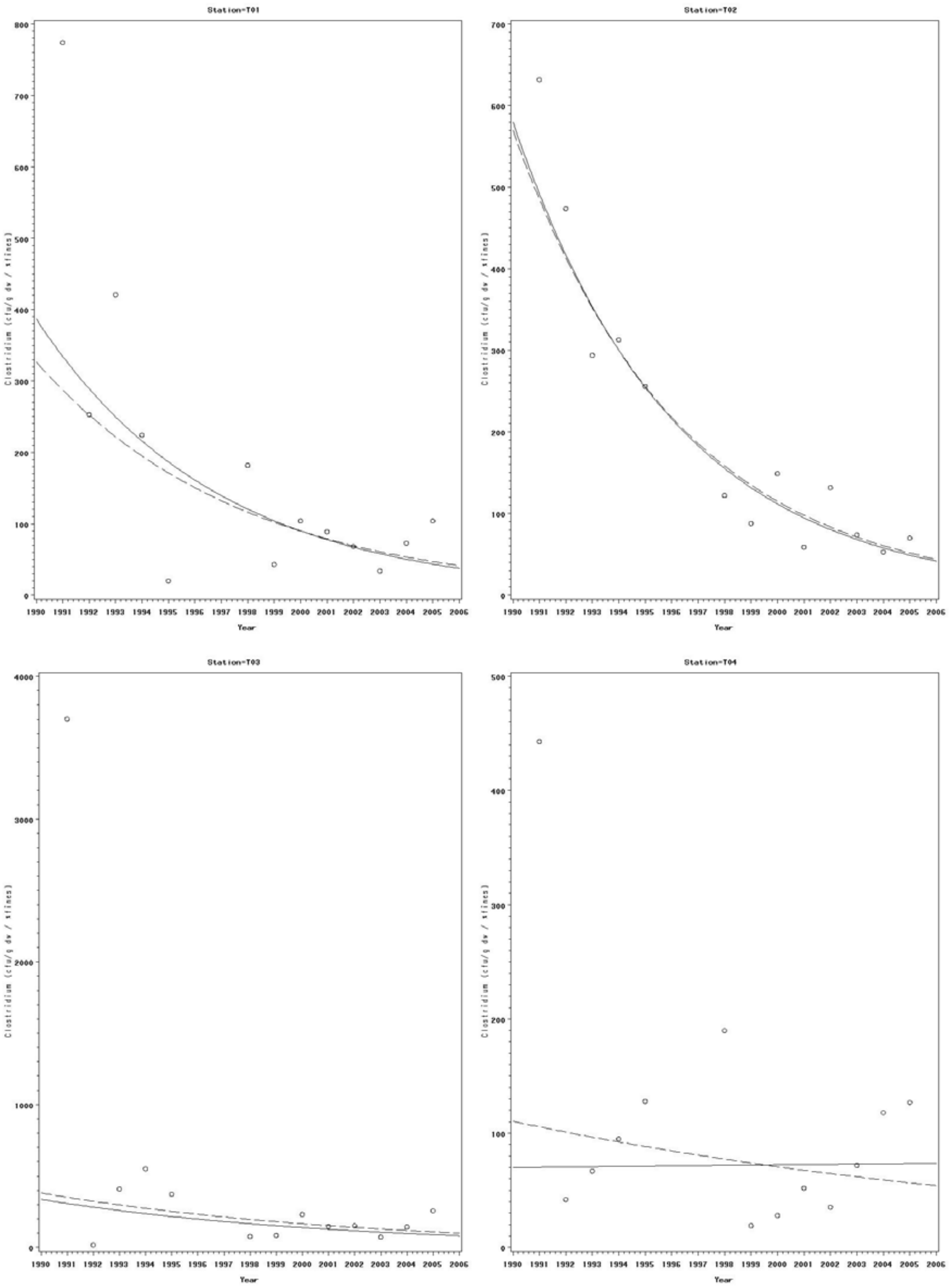


Figure B4-1. Temporal trends in normalized abundances of *Clostridium perfringens* at Boston Harbor stations T01, T02, T03, and T04, 1991 to 2005, August/September surveys only. The solid line represents the nonparametric regression and the dashed line represents the parametric regression. Data from monitoring years 1996 and 1997 excluded from the trends analysis.

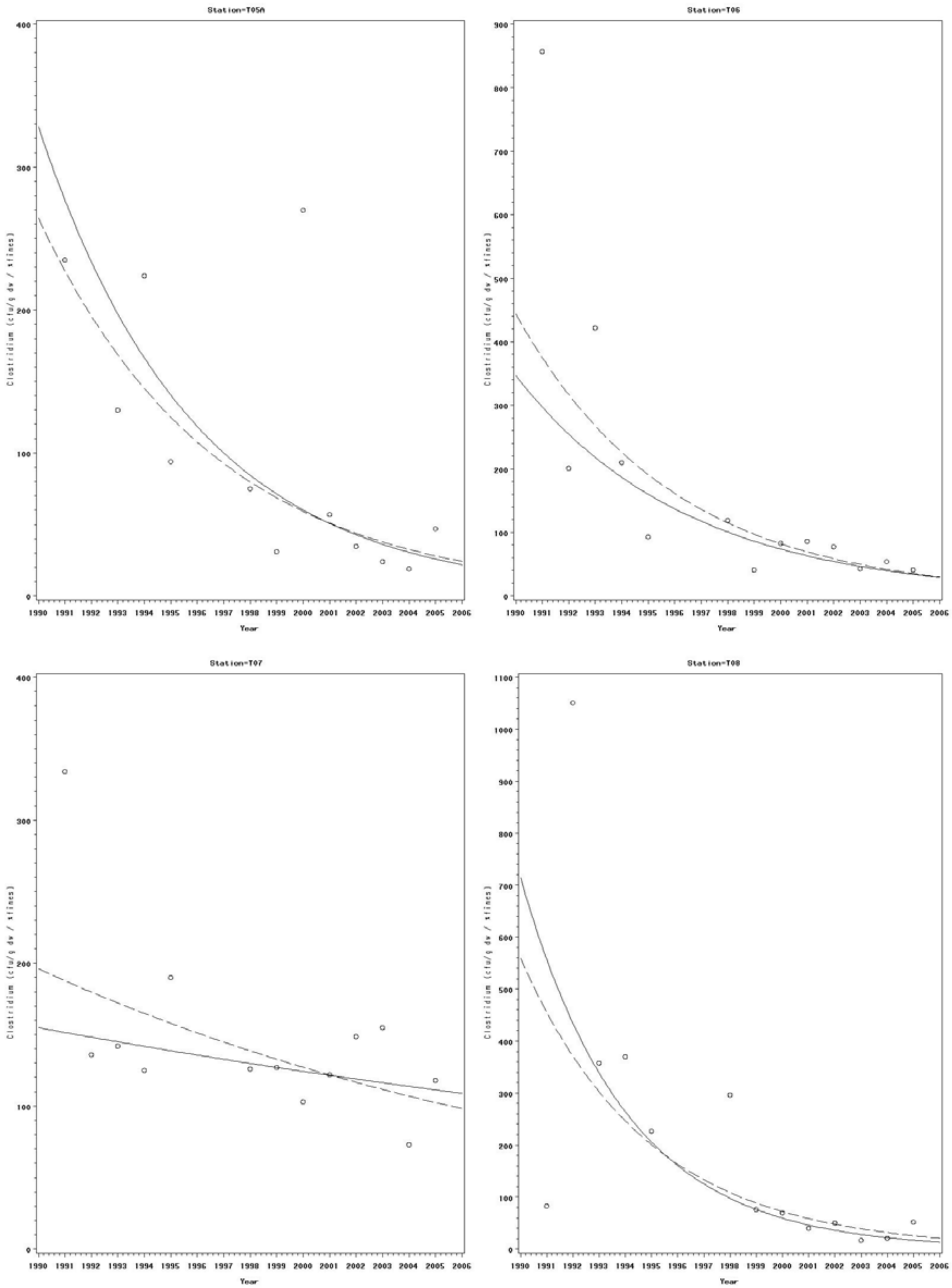


Figure B4-2. Temporal trends in normalized abundances of *Clostridium perfringens* at Boston Harbor stations T05A, T06, T07, and T08, 1991 to 2005, August/September surveys only. The solid line represents the nonparametric regression and the dashed line represents the parametric regression. Data from monitoring years 1996 and 1997 excluded from the trends analysis.

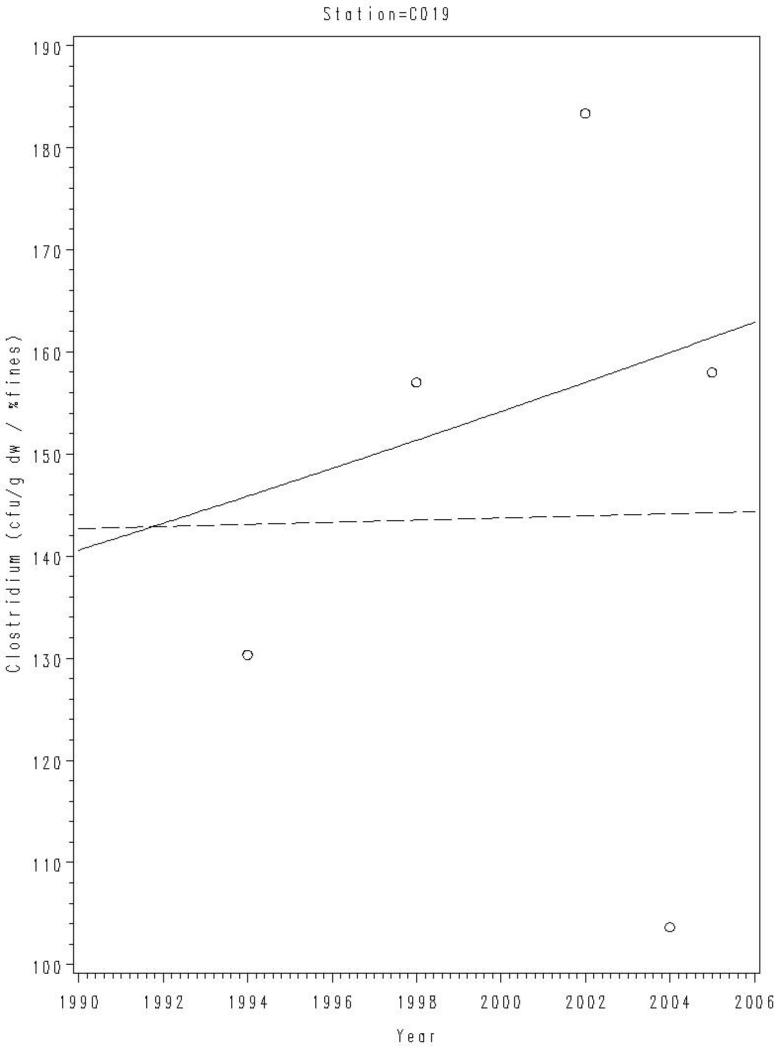


Figure B4-3. Temporal trends in normalized abundances of *Clostridium perfringens* at Boston Harbor station CO19, 1994 to 2005, August/September surveys only. The solid line represents the nonparametric regression and the dashed line represents the parametric regression. No data for monitoring years 1995 to 1997, 1999 to 2001, and 2003.

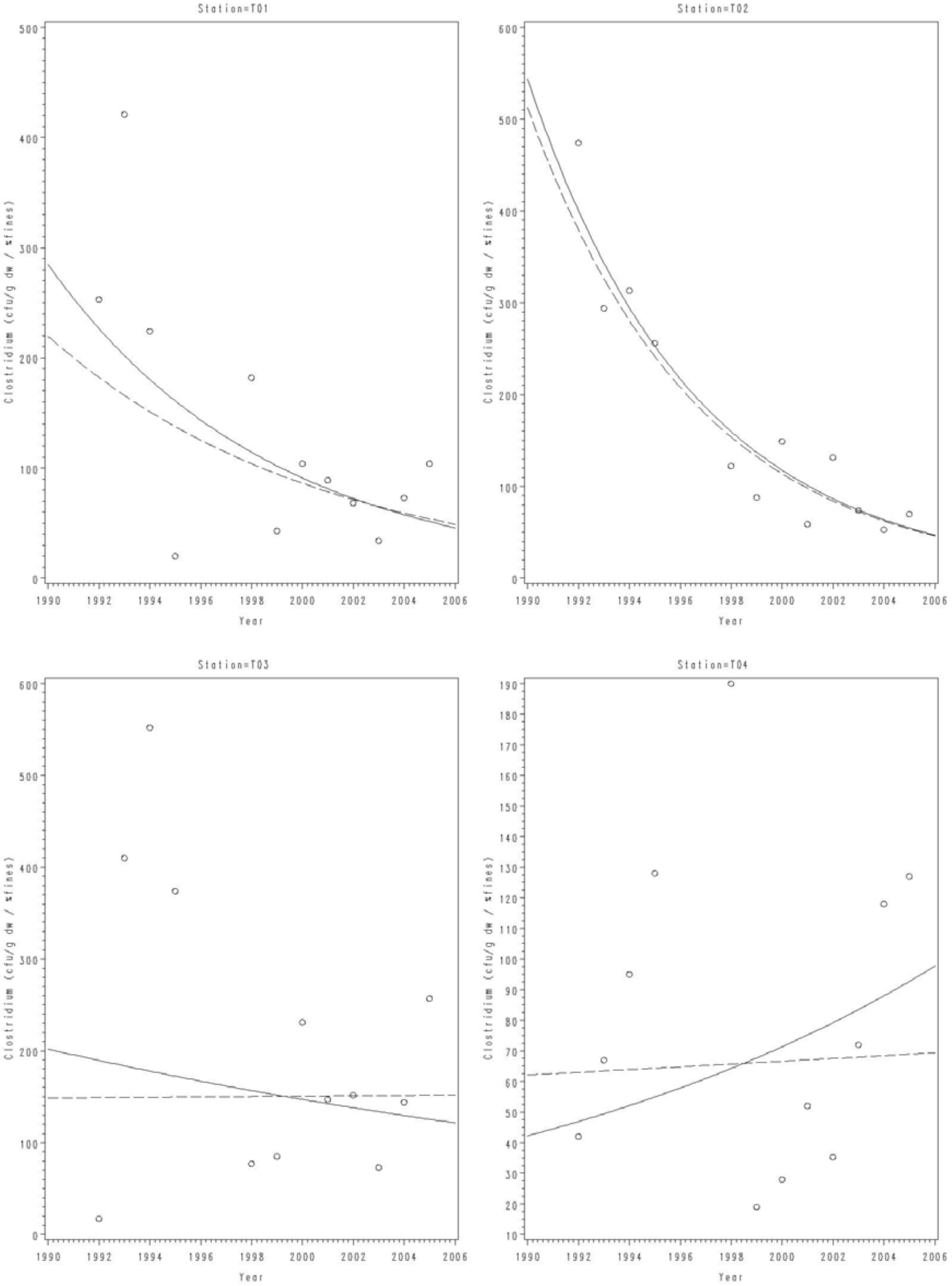


Figure B4-4. Temporal trends in normalized abundances of *Clostridium perfringens* at Boston Harbor stations T01, T02, T03, and T04, 1992 to 2005, August/September surveys only. The solid line represents the nonparametric regression and the dashed line represents the parametric regression. Data from monitoring years 1991, 1996, and 1997 excluded from the trends analysis.

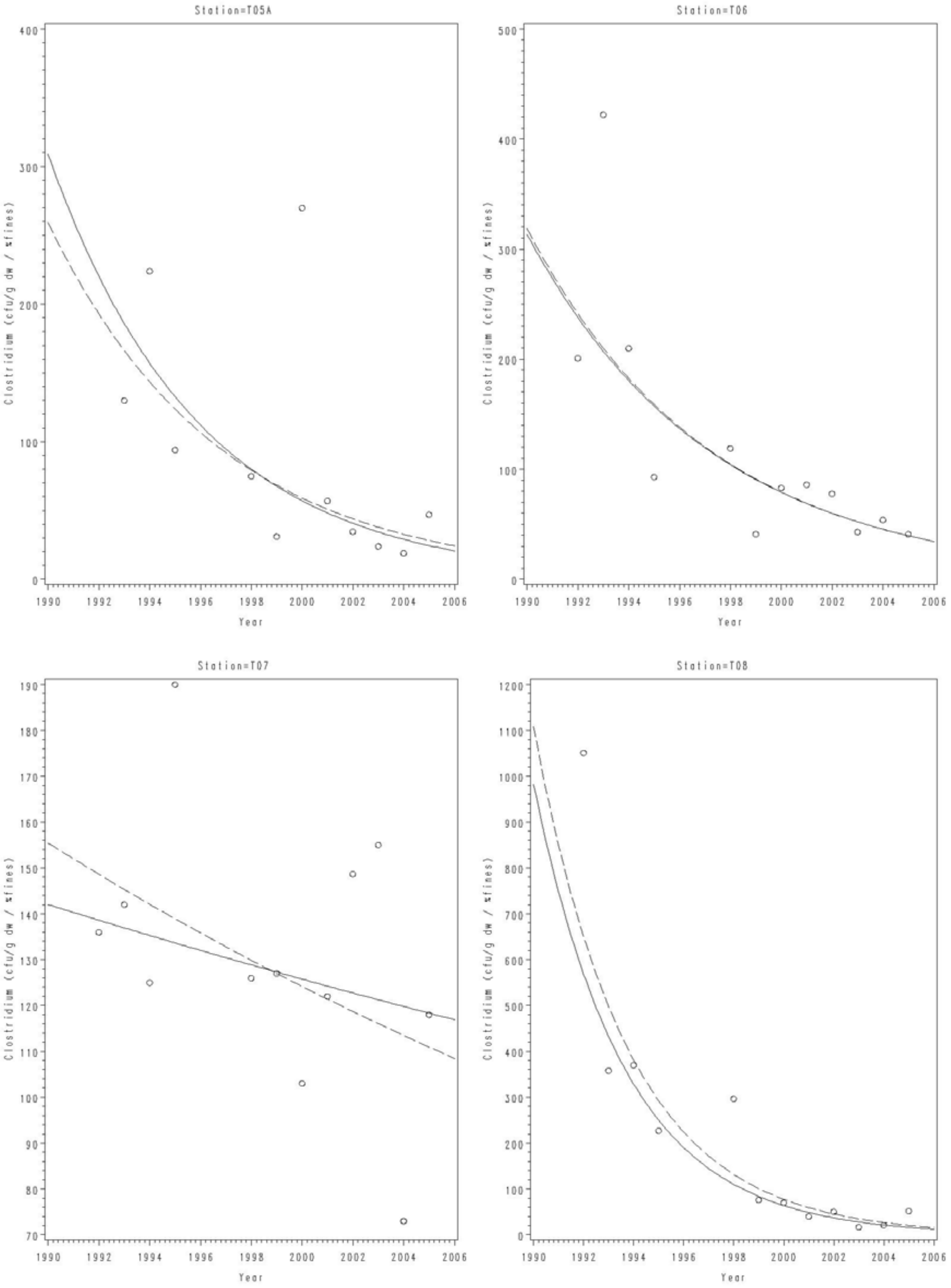
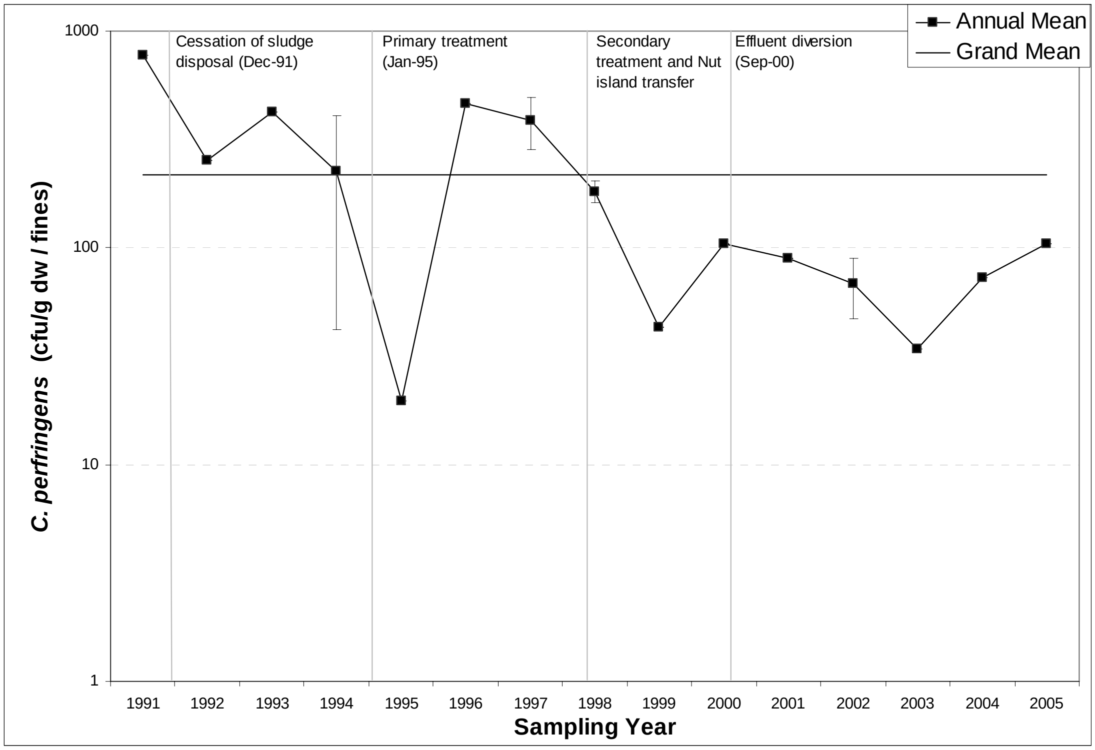


Figure B4-5. Temporal trends in normalized abundances of *Clostridium perfringens* at Boston Harbor stations T05A, T06, T07, and T08, 1992 to 2005, August/September surveys only. The solid line represents the nonparametric regression and the dashed line represents the parametric regression. Data from monitoring years 1991, 1996, and 1997 excluded from the trends analysis.



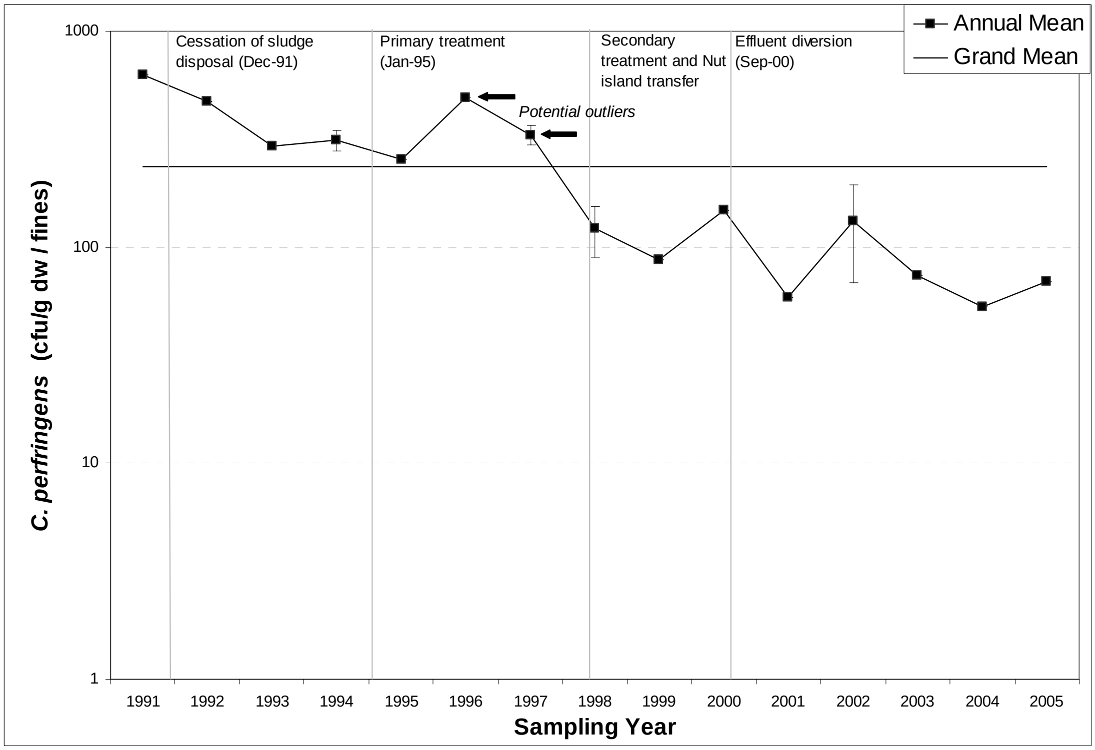


Figure B4-6. Station mean and grand mean values of *Clostridium perfringens*, normalized to percent fines, at stations T01 (top) and T02 (bottom) from 1991 to 2005, August/September surveys only. Data shown on log scale. Vertical bars represent one standard deviation. Station mean values are the average of all replicates for a given year (August/September surveys only), by station. The grand mean values are the average of all station mean values from 1991 to 2005.

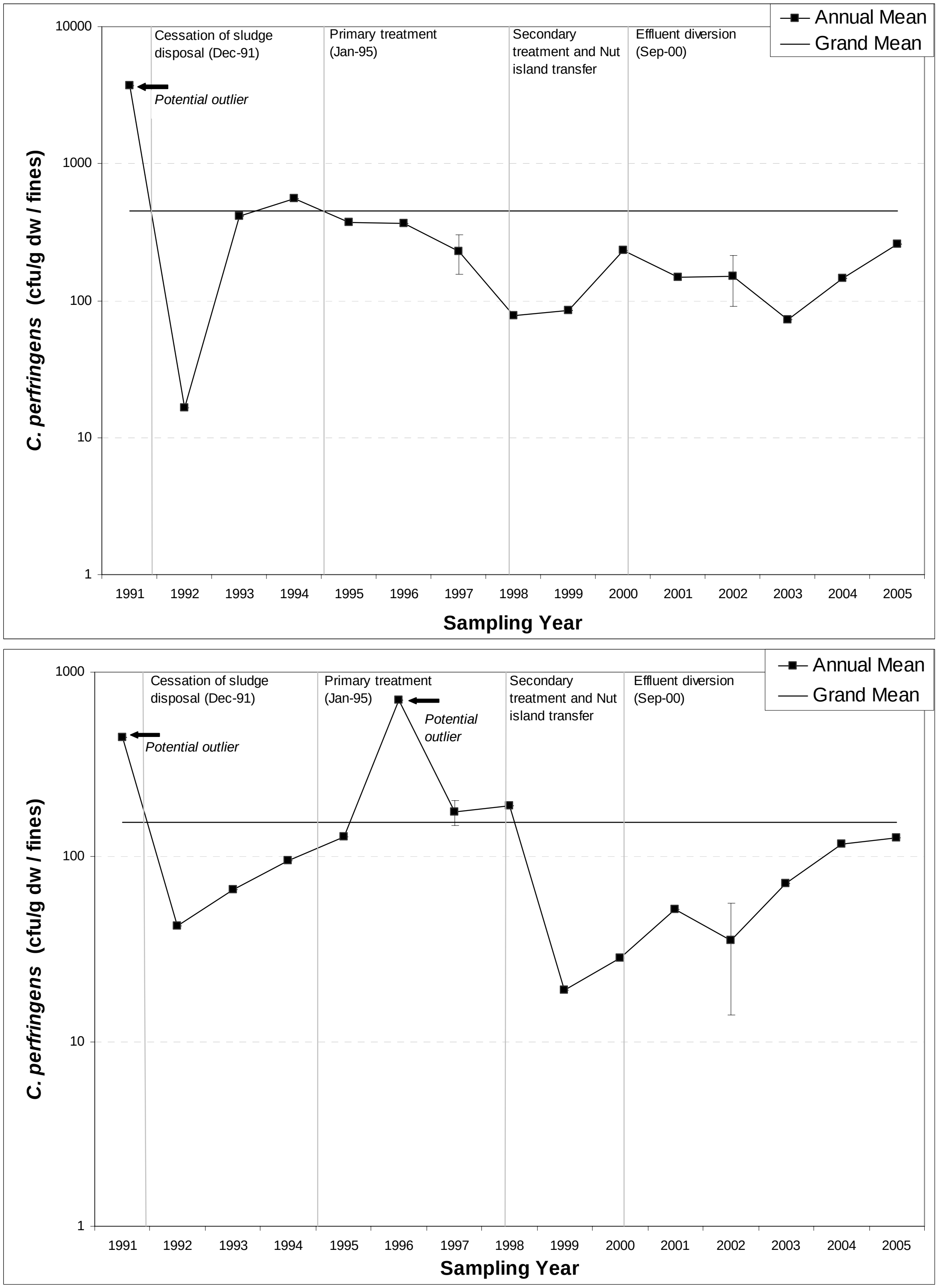
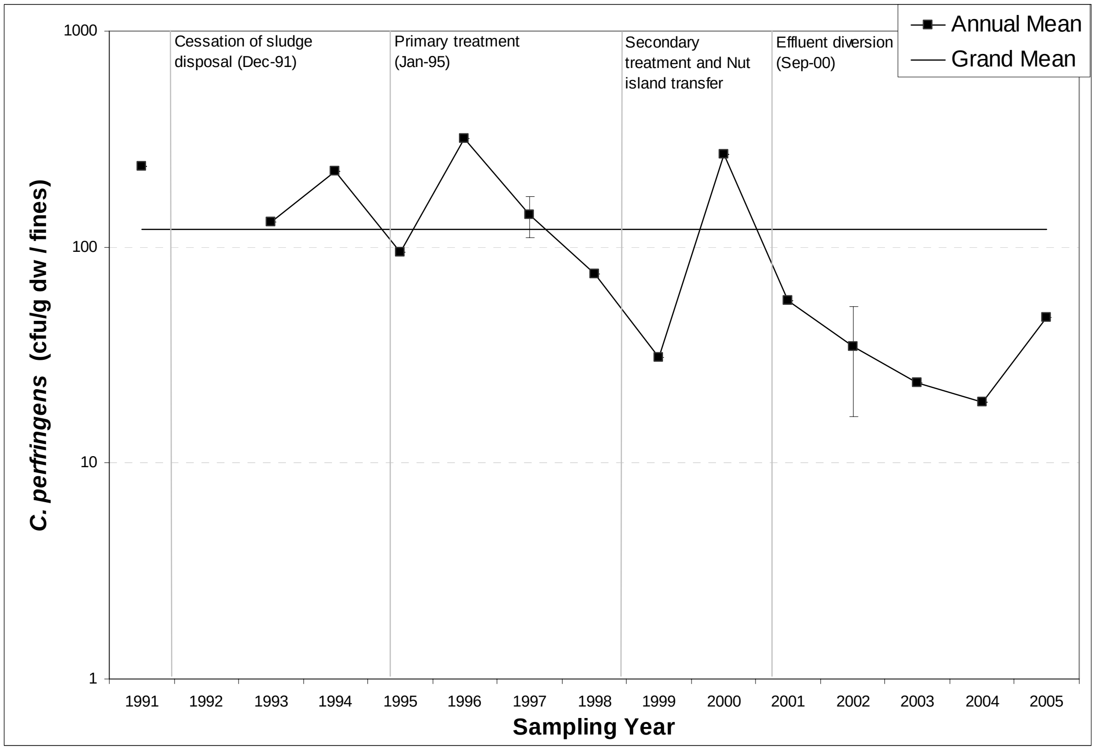


Figure B4-7. Station mean and grand mean values of *Clostridium perfringens*, normalized to percent fines, at stations T03 (top) and T04 (bottom) from 1991 to 2005, August/September surveys only. Data shown on log scale. Vertical bars represent one standard deviation. Station mean values are the average of all replicates for a given year (August/September surveys only), by station. The grand mean values are the average of all station mean values from 1991 to 2005.



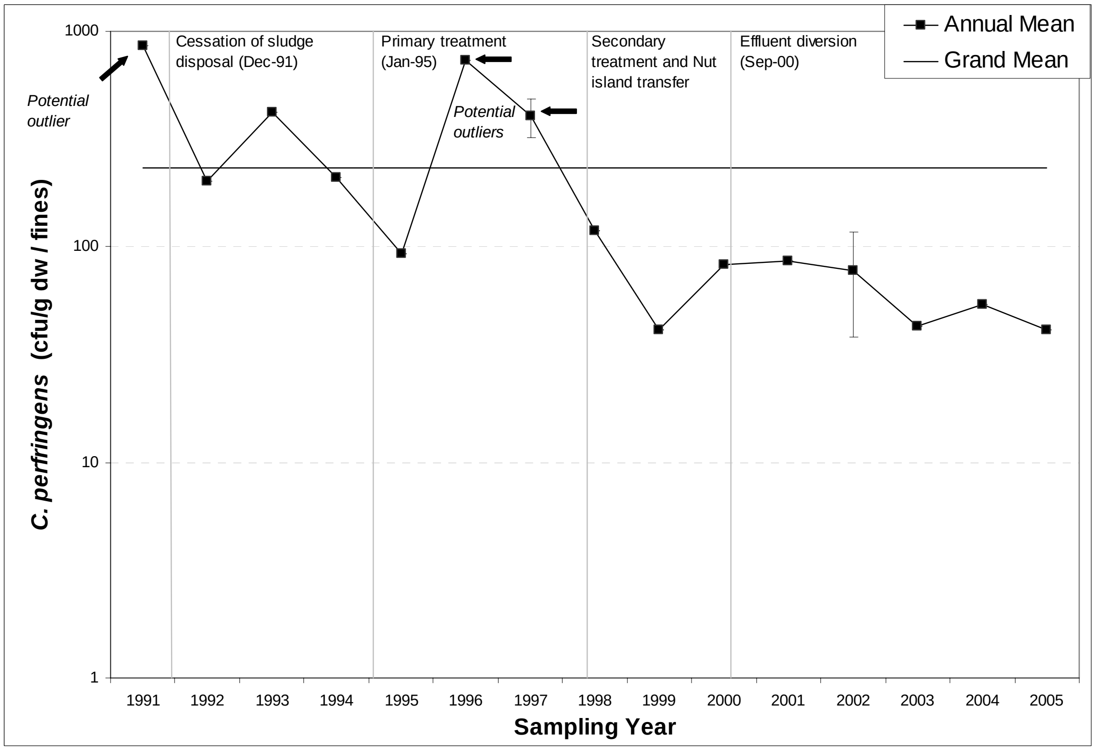
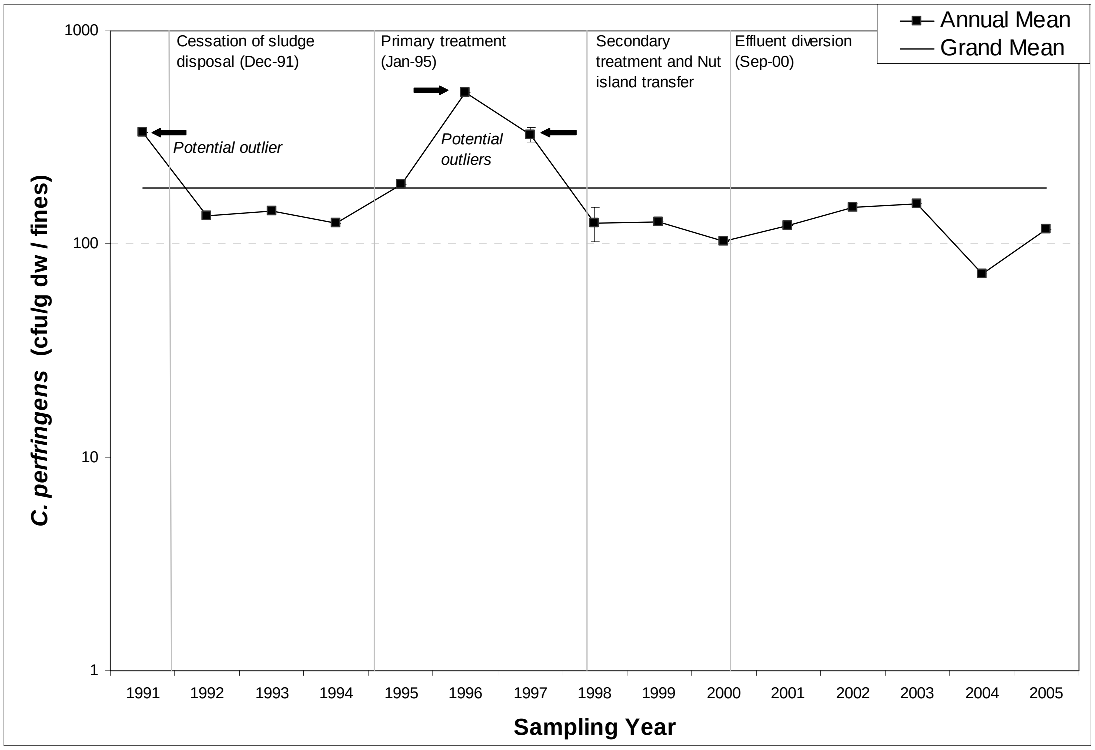


Figure B4-8. Station mean and grand mean values of *Clostridium perfringens*, normalized to percent fines, at stations T05A (top) and T06 (bottom) from 1991 to 2005, August/ September surveys only. Data shown on log scale. Vertical bars represent one standard deviation. Station mean values are the average of all replicates for a given year (August/September surveys only), by station. The grand mean values are the average of all station mean values from 1991 to 2005.



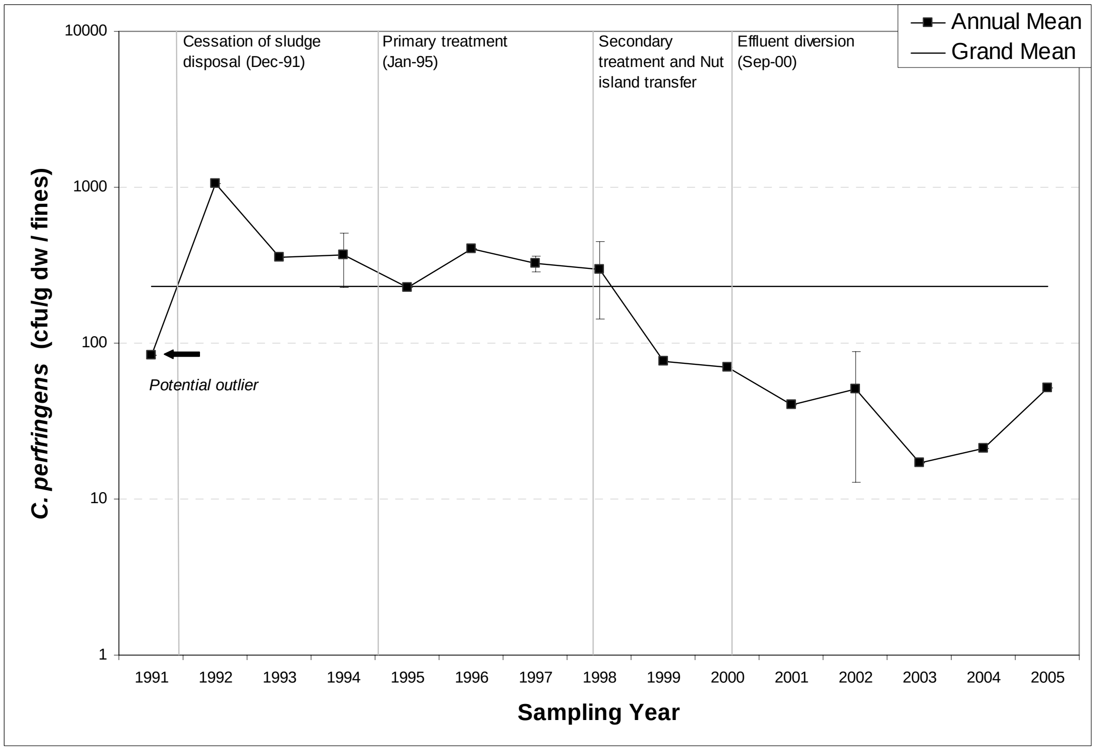


Figure B4-9. Station mean and grand mean values of *Clostridium perfringens*, normalized to percent fines, at stations T07 (top) and T08 (bottom) from 1991 to 2005, August/September surveys only. Data shown on log scale. Vertical bars represent one standard deviation. Station mean values are the average of all replicates for a given year (August/September surveys only), by station. The grand mean values are the average of all station mean values from 1991 to 2005.

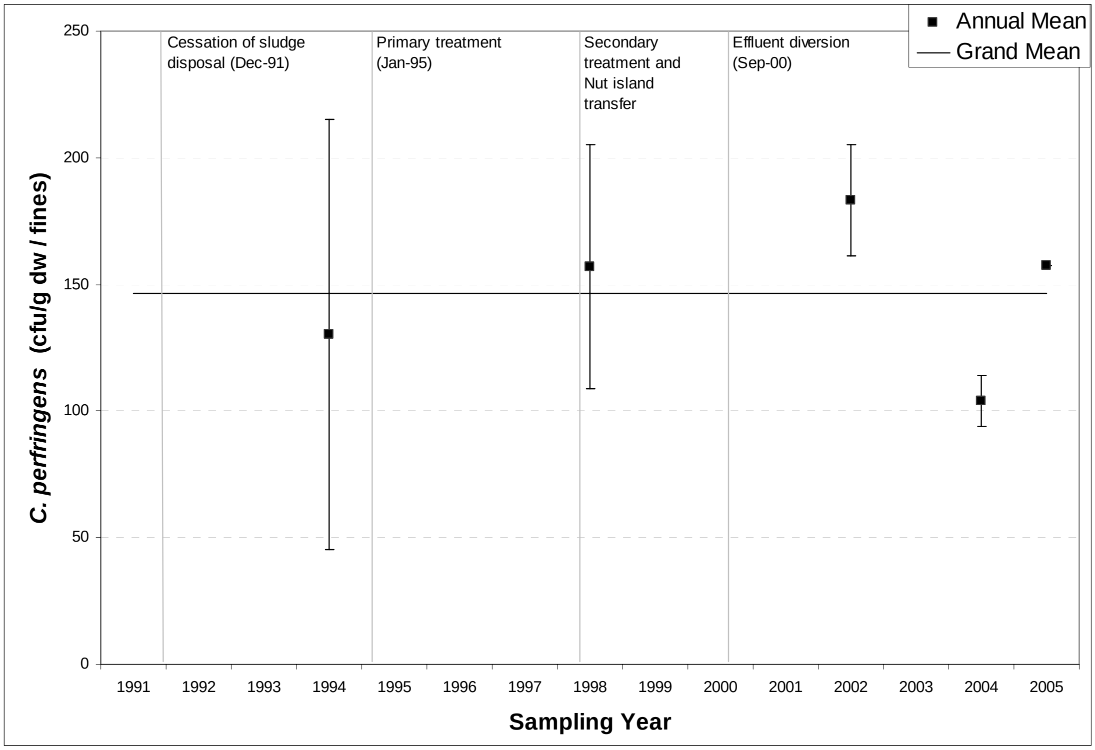


Figure B4-10. Station mean and grand mean values of *Clostridium perfringens*, normalized to percent fines, at station CO19 from 1994 to 2005, August/September surveys only. Data shown on log scale. Vertical bars represent one standard deviation. Station mean values are the average of all replicates for a given year (August/September surveys only), by station. The grand mean values are the average of all station mean values from 1994 to 2005. No data from monitoring years 1995 to 1997, 1999 to 2001, and 2003.

APPENDIX B5

Parametric and Nonparametric Correlation Results
1991–2005 Sediment Data Evaluations

Table B5-1. Harbor-wide correlation results, parametric and nonparametric. Data from monitoring years 1996 and 1997 excluded.

Method	Period	n	Correlation coefficient (*r*)			p-value		
			C-T	C-F	T-F	C-T	C-F	T-F
Spearman	pre-A	43	-0.16064	**-0.50574**	**0.69476**	0.3034	0.0005	<.0001
	A	31	-0.0361	-0.30087	**0.83577**	0.8471	0.1	<.0001
	B	16	-0.24412	-0.18529	**0.80588**	0.3622	0.4921	0.0002
	C	63	**0.46467**	**0.47483**	**0.88167**	0.0001	<.0001	<.0001
Kendall	pre-A	43	-0.11445	**-0.34441**	**0.53223**	0.2809	0.0011	<.0001
	A	31	0.00431	-0.21336	**0.66308**	0.9729	0.0923	<.0001
	B	16	-0.18333	-0.16667	**0.68333**	0.3219	0.3679	0.0002
	C	63	**0.33822**	**0.3216**	**0.71062**	<.0001	0.0002	<.0001
Pearson	pre-A	43	0.14914	-0.12299	**0.63732**	0.3398	0.432	<.0001
	A	31	-0.02864	-0.28724	**0.65439**	0.8785	0.1172	<.0001
	B	16	-0.24041	-0.2652	**0.82844**	0.3698	0.3209	<.0001
	C	63	**0.39139**	**0.403**	**0.87341**	0.0015	0.0011	<.0001

C-T, correlation between normalized C. perfringens and TOC
C-F, correlation between C. perfringens and percent fines
T-F, correlation between TOC and percent fines.
Bold values indicate significant (at 95% confidence level) correlations

Table B5-2. Harbor-wide correlation results, parametric and nonparametric. Data from monitoring years 1991, 1996, and 1997 excluded.

Method	Period	n	Correlation coefficient (*r*)			p-value		
			C-T	C-F	T-F	C-T	C-F	T-F
Spearman	pre-A	35	**-0.41197**	**-0.64314**	**0.78092**	0.0139	<.0001	<.0001
	A	31	-0.0361	-0.30087	**0.83577**	0.8471	0.1	<.0001
	B	16	-0.24412	-0.18529	**0.80588**	0.3622	0.4921	0.0002
	C	63	**0.46467**	**0.47483**	**0.88167**	0.0001	<.0001	<.0001
Kendall	pre-A	35	**-0.30237**	**-0.4521**	**0.59629**	0.011	0.0001	<.0001
	A	31	0.00431	-0.21336	**0.66308**	0.9729	0.0923	<.0001
	B	16	-0.18333	-0.16667	**0.68333**	0.3219	0.3679	0.0002
	C	63	**0.33822**	**0.3216**	**0.71062**	<.0001	0.0002	<.0001
Pearson	pre-A	35	**-0.37526**	**-0.56489**	**0.74408**	0.0263	0.0004	<.0001
	A	31	-0.02864	-0.28724	**0.65439**	0.8785	0.1172	<.0001
	B	16	-0.24041	-0.2652	**0.82844**	0.3698	0.3209	<.0001
	C	63	**0.39139**	**0.403**	**0.87341**	0.0015	0.0011	<.0001

C-T, correlation between normalized C. perfringens and TOC
C-F, correlation between C. perfringens and percent fines
T-F, correlation between TOC and percent fines.
Bold values indicate significant (at 95% confidence level) correlations

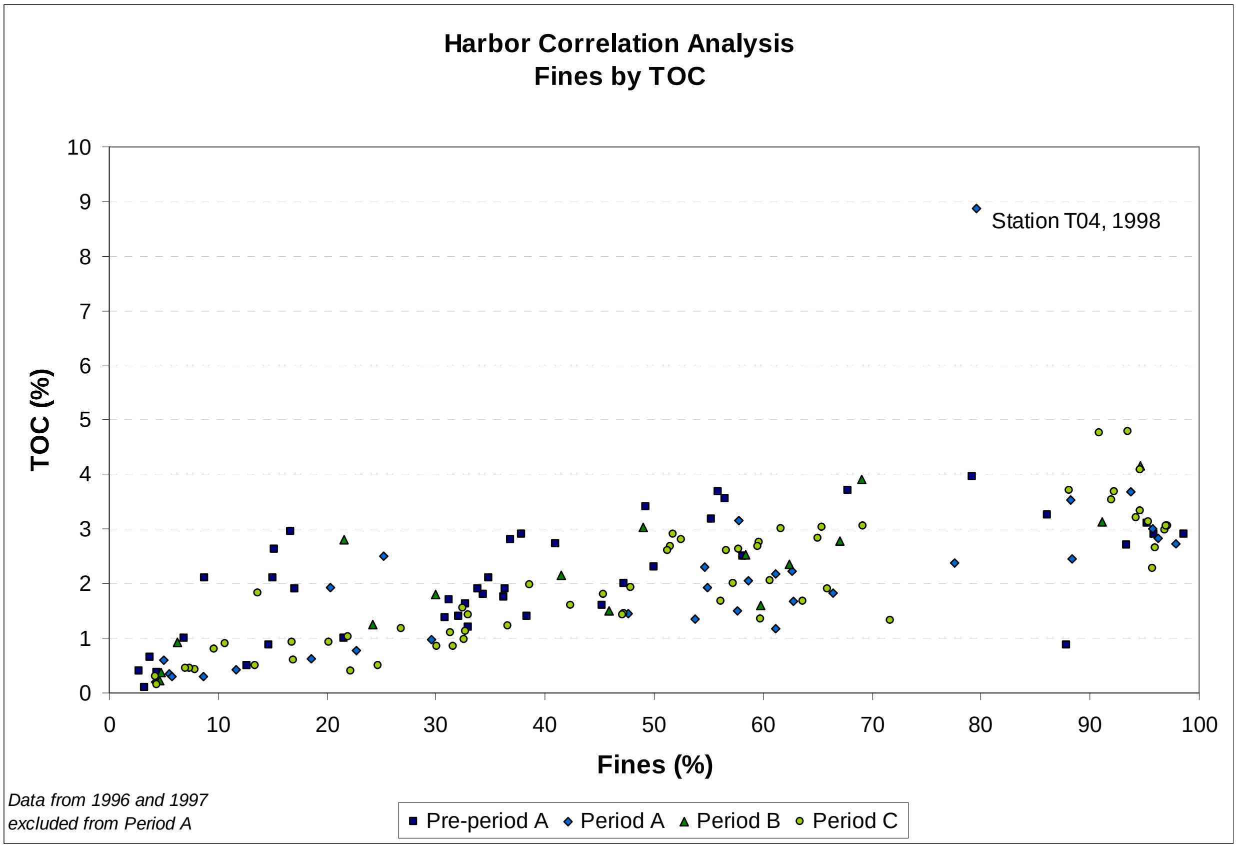


Figure B5-1. Correlation between percent fines and TOC across all harbor stations by cleanup events. Pre-period A includes data from 1991 to 1994; Period A includes data from 1995 and 1998 (1996 and 1997 were excluded because of frequency of outliers); Period B includes data from 1999 and 2000; and Period C includes data from 2001 to 2005. Individual replicate values used; August/September surveys only.

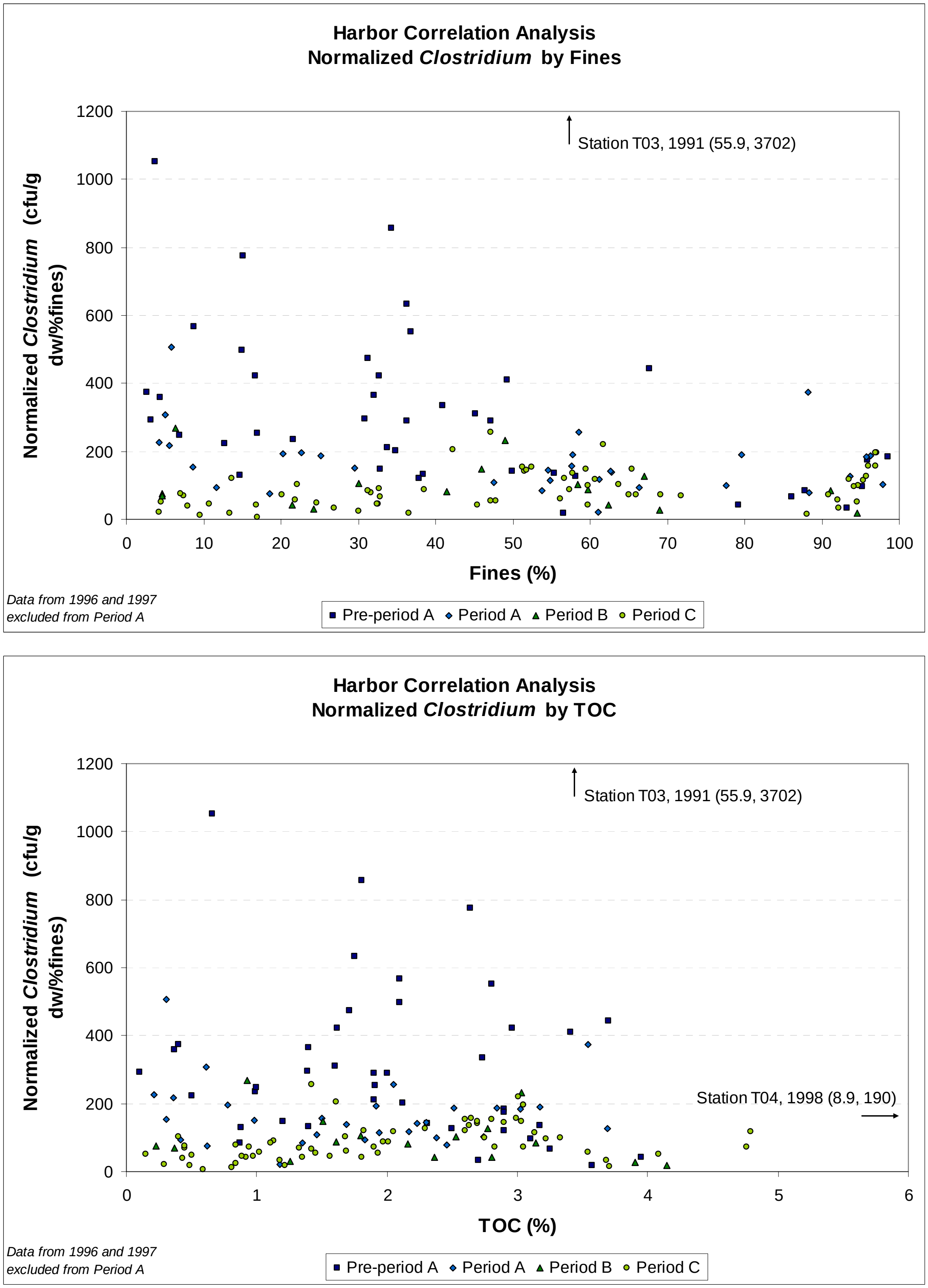


Figure B5-2. Correlation between normalized *Clostridium perfringens* and fines (top) and normalized *Clostridium perfringens* and TOC (bottom) across all harbor stations by cleanup events. Pre-period A, 1991 to 1994; Period A, 1995 and 1998 (1996 and 1997 were excluded because of frequency of outliers); Period B, 1999 and 2000; and Period C, 2001 to 2005. Individual replicate values used; August/September surveys only.

Table B5-3. Station-specific correlation results, parametric and nonparametric. Data from monitoring years 1996 and 1997 excluded.

Method	Station	n	Correlation Coefficient (r)			p-value		
			C-T	C-F	T-F	C-T	C-F	T-F
Spearman	C019	13	-0.00276	**0.67493**	-0.25344	0.9929	0.0114	0.4034
	T01	21	0.41261	**-0.55018**	-0.27152	0.0631	0.0098	0.2338
	T02	21	0.20085	**-0.72987**	0.09555	0.3827	0.0002	0.6803
	T03	15	0.13584	**-0.56071**	0.15728	0.6293	0.0297	0.5756
	T04	15	-0.06071	0.01429	-0.275	0.8298	0.9597	0.3212
	T05A	14	-0.1641	-0.40924	0.32123	0.5751	0.1462	0.2628
	T06	15	0.07871	-0.42895	0.46113	0.7804	0.1106	0.0836
	T07	18	0.31851	**-0.59711**	-0.04959	0.1977	0.0089	0.8451
	T08	21	0.15085	-0.39623	**0.55054**	0.514	0.0754	0.0097
Kendall	C019	13	0.01316	**0.5455**	-0.20781	0.951	0.0101	0.3272
	T01	21	0.28708	**-0.42482**	-0.14797	0.0698	0.0072	0.349
	T02	21	0.13909	**-0.54286**	0.08154	0.3805	0.0006	0.6072
	T03	15	0.11483	**-0.39048**	0.15311	0.5521	0.0425	0.4279
	T04	15	-0.02857	0.02857	-0.1619	0.882	0.882	0.4002
	T05A	14	-0.12222	-0.3536	0.2652	0.5458	0.0794	0.1882
	T06	15	0.02885	-0.32536	0.3445	0.8817	0.0921	0.0745
	T07	18	0.24503	**-0.4408**	-0.04605	0.1599	0.011	0.7906
	T08	21	0.07692	-0.29117	**0.40768**	0.6284	0.0654	0.0102
Pearson	C019	13	0.02669	**0.67947**	-0.2216	0.931	0.0106	0.4669
	T01	21	**0.50988**	**-0.56643**	-0.30018	0.0182	0.0074	0.1861
	T02	21	0.17965	**-0.7283**	0.11515	0.4358	0.0002	0.6192
	T03	15	0.36081	-0.16702	0.18372	0.1864	0.5519	0.5122
	T04	15	0.16643	-0.48071	-0.24656	0.5533	0.0697	0.3757
	T05A	14	-0.17681	-0.45478	0.40842	0.5454	0.1023	0.1471
	T06	15	-0.05824	-0.29889	0.24923	0.8367	0.2792	0.3704
	T07	18	0.24872	**-0.67342**	-0.10511	0.3196	0.0022	0.6781
	T08	21	0.33964	-0.19663	0.24416	0.132	0.3929	0.2861

C-T, correlation between normalized C. perfringens and TOC
C-F, correlation between C. perfringens and percent fines
T-F, correlation between TOC and percent fines.

Bold values indicate significant (at 95% confidence level) correlations

Table B5-4. Station-specific correlation results, parametric and nonparametric. Data from monitoring years 1991, 1996, and 1997 excluded.

Method	Station	n	Correlation Coefficient (r)			p-value		
			C-T	C-F	T-F	C-T	C-F	T-F
Spearman	C019	13	-0.00276	**0.67493**	-0.25344	0.9929	0.0114	0.4034
	T01	20	0.36494	**-0.48063**	-0.19857	0.1136	0.0319	0.4013
	T02	20	0.14829	**-0.69774**	0.14076	0.5327	0.0006	0.5539
	T03	14	-0.06381	**-0.54725**	0.23762	0.8284	0.0428	0.4133
	T04	14	-0.0022	0.24835	-0.32308	0.9941	0.3919	0.2599
	T05A	13	-0.29614	-0.46217	0.24759	0.3259	0.1118	0.4147
	T06	14	0.14962	-0.41584	0.43297	0.6097	0.1392	0.122
	T07	17	0.28747	**-0.52147**	0.00368	0.2632	0.0318	0.9888
	T08	20	0.1634	-0.41519	**0.49605**	0.4912	0.0687	0.0261
Kendall	C019	13	0.01316	**0.5455**	-0.20781	0.951	0.0101	0.3272
	T01	20	0.24339	**-0.37467**	-0.10026	0.1352	0.0212	0.5374
	T02	20	0.1008	**-0.52632**	0.11141	0.537	0.0012	0.495
	T03	14	-0.0221	**-0.40659**	0.221	0.9127	0.0428	0.2728
	T04	14	-0.01099	0.18681	-0.20879	0.9563	0.352	0.2983
	T05A	13	-0.20779	**-0.42582**	0.19355	0.3272	0.0437	0.3592
	T06	14	0.0884	-0.3315	0.31868	0.6609	0.1	0.1124
	T07	17	0.22388	**-0.37038**	0	0.215	0.0391	1
	T08	20	0.07447	-0.31135	**0.36606**	0.649	0.0555	0.0249
Pearson	C019	13	0.02669	**0.67947**	-0.2216	0.931	0.0106	0.4669
	T01	20	**0.44855**	**-0.56895**	-0.23712	0.0473	0.0088	0.3141
	T02	20	0.14691	**-0.75842**	0.14835	0.5365	0.0001	0.5325
	T03	14	0.0142	-0.4192	0.23805	0.9616	0.1357	0.4125
	T04	14	0.51102	0.10445	-0.35926	0.0618	0.7223	0.2071
	T05A	13	-0.29145	**-0.57148**	0.39904	0.334	0.0413	0.1768
	T06	14	-0.04134	-0.35128	0.24559	0.8884	0.2181	0.3974
	T07	17	0.30821	**-0.52115**	-0.05139	0.2288	0.0319	0.8447
	T08	20	0.37594	-0.34751	0.2964	0.1024	0.1333	0.2045

C-T, correlation between normalized C. perfringens and TOC
C-F, correlation between C. perfringens and percent fines
T-F, correlation between TOC and percent fines.
Bold values indicate significant (at 95% confidence level) correlations

APPENDIX C1

Data Manipulations on Infaunal Data
Prior to Statistical Analyses

These merges are based on the entire data set, which includes April samples. There may or may not be any of these taxa in the August-samples-only data.

Merge for 1991-2004 Export for Report Only (use final name and code):

NODC Code	**Taxon**		**Comment**
6169020108	*Ampelisca abdita*		
6169020109	*Ampelisca vadorum*		
61690201SPP	*Ampelisca* spp.	use	
50010601TECT	*Pholoe tecta*		
5001060101	*Pholoe minuta*	use	
5001670216	*Ampharete baltica*		
5001670208	*Ampharete acutifrons*	use	
50014304SPP	*Polydora* spp.		
5001430448	*Polydora cornuta*	use	
8401SPP	*Ascidiacea* spp.		
84060301SPP	*Molgula* spp.		
8406030108	*Molgula manhattensis*	use	
500162SPP	*Arenicolidae* spp.		
5001620204	*Arenicola marina*	use	
55151901SPP	*Astarte* spp.		
5515190113	*Astarte undata*	use	
50017013SPP	*Fabricia* spp.		
50017013STEL	*Fabricia stellaris stellaris*	use	
61692107SPP	*Gammarus* spp.		
6169210713	*Gammarus lawrencianus*	use	
61692702SPP	*Ischyrocerus* spp.		
6169270202	*Ischyrocerus anguipes*	use	
50010211SPP	*Lepidonotus* spp.		
5001021103	*Lepidonotus squamatus*	use	
50016303SPP	*Maldane* spp.		
5001630302	*Maldane glebifex*	use	probably is *M. sarsi*

NODC Code	Taxon		Comment
61631202SPP	*Pleurogonium* spp.		
6163120204	*Pleurogonium inerme*	use	
8201SPP	Enteropneusta spp.		
8201010303	*Saccoglossus bromophenolosus*	use	JAB questions species name.
5520050206	*Lyonsia hyalina*		
55200502SPP	*Lyonsia spp.*		
5520050201	*Lyonsia arenosa*	use	
61690604SPP	*Microdeutopus* spp.		
6169060402	*Microdeutopus anomalus*	use	
50016806SPP	*Nicolea* spp.		
5001680602	*Nicolea zostericola*	use	
5001680805	*Polycirrus* cf. *haematodes*		
5001680807	*Polycirrus phosphoreus*	use	could be classified as a name change
55200201SPP	*Pandora* spp.		
5520020107	*Pandora gouldiana*	use	
50014016SPP	*Leitoscoloplos* spp.		
5001400304	*Leitoscoloplos robustus*	use	
50014003SPP	*Scoloplos* spp.		
5001400301	*Scoloplos armiger*	use	
50012308SPP	*Sphaerosyllis* spp.		
5001230817	*Sphaerosyllis longicauda*		
5001230801	*Sphaerosyllis erinaceus*		Name may have been changed as for MB data, I am not certain.
5001500305	*Tharyx acutus*		
50015003SP02	*Tharyx* sp. A		
50015003SPP	*Tharyx* spp.		
50014502SPP	*Trochochaeta* spp.		
5001450203	*Trochochaeta multisetosa*		
61691507SPP	*Unciola* spp.		
6169150703	*Unciola irrorata*		

Excluded from data prior to analyses:

NODC Code	Taxon
510205SPP	Acmaeidae spp.
6171010801	*Aeginina longicornis*
5509090202	*Anomia simplex*
6134020104	*Balanus crenatus*
6134020114	*Balanus improvisus*
61340201SPP	*Balanus* spp.
6171010703	*Caprella linearis*
6171010727	*Caprella penantis*
61710107SPP	*Caprella* spp.
617101SPP	*Caprellidae* spp.
5103640204	*Crepidula fornicata*
5103640207	*Crepidula plana*
51036402SPP	*Crepidula* spp.
5001430414	*Dipolydora concharum*
5001430410	*Dipolydora commensalis*
5001500501	*Dodecaceria concharum*
50015005SPP	*Dodecaceria* spp.
3701SPP	*Hydrozoa* spp.
6161050101	*Limnoria lignorum*
5103100108	*Littorina littorea*
5507010601	*Modiolus modiolus*
550701SPP	*Mytilidae* spp.
5507010101	*Mytilus edulis*
500201SPP	*Nerillidae* spp.
6171010901	*Paracaprella tenuis*
5001430412	*Polydora websteri*
5001650202	*Sabellaria vulgaris*

APPENDIX C2

Benthic Species identified from Boston Harbor Monitoring Program Samples 1991–2005

Table C2-1. Species identified from Boston Harbor Monitoring Program samples from 1991-2005 and used in the 2005 community analysis. Species collected in August 2005 samples are marked with an asterisk (*). Species new to the MWRA database in 2005 are bolded and underlined; species new to the Boston Harbor list are underlined.

CNIDARIA

- *Ceriantheopsis americanus* (Verrill, 1866)
- *Edwardsia elegans* Verrill, 1869 *
- Actiniaria sp. 2

PLATYHELMINTHES

- Turbellaria spp. *

NEMERTEA

- *Amphiporus caecus* Verrill, 1892
  - [formerly *A. angulatus* (Fabricius, 1774)]
- *Amphiporus bioculatus* McIntosh, 1873
- *Amphiporus cruentatus* Verrill, 1879 *
- *Amphiporus ochraceus* (Verrill, 1873)
- *Amphiporus* sp. 1
- *Carinomella lactea* Coe, 1905*
- Cephalothricidae sp. 1 *
- *Cerebratulus lacteus* (Leidy, 1851) *
- *Micrura* spp.
- Nemertea sp. 2 *
- Nemertea sp. D
- Nemertea sp. 5
- Nemertea sp. 12 *
- Nemertea sp. 13
- *Proneurotes* spp.
- *Tetrastemma elegans* (Girard, 1852)
- *Cyanophthalmus cordiceps* (Friedrich, 1933)
  - (formerly *Tetrastemma vittatum* Verrill, 1874)
- *Tubulanus pellucidus* (Coe, 1895)

ANNELIDA

- Polychaeta
  - Ampharetidae
    - *Ampharete acutifrons* (Grube, 1860)
    - *Ampharete baltica* Eliason, 1955 *
      - (merged with *A. acutifrons*. for report)
    - *Ampharete finmarchica* (Sars, 1865)
    - *Ampharete lindstroemi* Malmgren, 1867 *
    - *Anobothrus gracilis* (Malmgren, 1866)
    - *Asabellides oculata* (Webster, 1879)
  - Amphinomidae
    - Amphinomidae spp.
  - Arenicolidae
    - *Arenicola marina* (Linnaeus, 1758)
    - *Branchiomaldane* spp.
    - Arenicolidae spp.
      - (merged with *Arenicola marina* for report)
  - Capitellidae
    - *Capitella capitata* complex (Fabricius, 1780) *
    - *Heteromastus filiformis* (Claparède, 1864)
    - *Mediomastus ambiseta* (Hartman, 1947)
    - *Mediomastus californiensis* Hartman, 1944 *
  - Cirratulidae
    - *Aphelochaeta marioni* (Saint-Joseph, 1894) *
    - *Aphelochaeta monilaris* (Hartman, 1960)
    - *Aphelochaeta* sp. 1
    - *Caulleriella* sp. B
    - *Chaetozone* cf. *setosa* (Boston Harbor) Malmgren, 1867 *
    - *Chaetozone vivipara* (Christie, 1985) *
    - *Cirratulus cirratus* (O.F. Müller, 1776)
    - *Cirratulus* sp. 1
    - *Cirriformia grandis* (Verrill, 1873) *
    - *Monticellina baptisteae* Blake, 1991 *
    - *Monticellina dorsobranchialis* (Kirkegaard, 1959) *
    - *Tharyx acutus* Webster & Benedict, 1887 *
      - (merged with *T*. spp. for report)
    - *Tharyx* sp. A *
      - (merged with *T*. spp. for report)
    - *Tharyx* sp. B *
  - Cossuridae
    - *Cossura longocirrata* Webster & Benedict, 1887
    - *Cossura* sp. 1
  - Dorvilleidae
    - Dorvilleidae sp. A
    - *Ophryotrocha* spp.
    - *Parougia caeca* (Webster & Benedict, 1884) *
    - *Protodorvillea gaspeensis* Pettibone, 1961
  - Flabelligeridae
    - *Brada villosa* (Rathke, 1843) *
    - *Diplocirrus hirsutus* (Hansen, 1879)
    - *Flabelligera affinis* Sars, 1829
    - *Pherusa affinis* (Leidy, 1855) *
    - *Pherusa plumosa* (O.F. Müller, 1776)
  - Glyceridae
    - *Glycera americana* Leidy, 1855
    - *Glycera dibranchiata* Ehlers, 1868 *
  - Goniadidae
    - *Goniada maculata* Oersted, 1843
  - Hesionidae
    - *Microphthalmus pettiboneae* Riser, 2000 *
  - Lumbrineridae
    - *Ninoe nigripes* Verrill, 1873 *
    - *Scoletoma acicularum* (Webster & Benedict, 1887)
    - *Scoletoma fragilis* (O.F. Mhller, 1776)
    - *Scoletoma hebes* (Verrill, 1880) *
  - Maldanidae
    - *Clymenella torquata* (Leidy, 1855) *
    - *Euclymene collaris* (Claparède, 1870) *
    - *Maldane glebifex* Grube, 1860
    - *Sabaco elongatus* (Verrill, 1873)
  - Nephtyidae
    - *Aglaophamus circinata* (Verrill, 1874) *
    - *Nephtys caeca* (Fabricius, 1780) *
    - *Nephtys ciliata* (O.F. Müller, 1776) *
    - *Nephtys cornuta* Berkeley & Berkeley, 1945 *
    - *Nephtys incisa* Malmgren, 1865 *
    - *Nephtys longosetosa* Oersted, 1843
    - *Nephtys picta* Ehlers, 1868
  - Nereididae
    - *Neanthes virens* Sars, 1835 *
    - *Neanthes arenaceodentata* Moore, 1903
    - *Nereis diversicolor* O.F. Müller, 1776
    - *Nereis grayi* Pettibone, 1956 *
    - *Nereis zonata* Malmgren, 1867 *
  - Opheliidae
    - *Ophelina acuminata* Oersted, 1843 *
  - Orbiniidae
    - *Leitoscoloplos acutus* (Verrill, 1873)
    - *Leitoscoloplos robustus* (Verrill, 1873) *
    - *Naineris quadricuspida* (Fabricius, 1780)
    - *Scoloplos armiger* (O.F. Müller, 1776) *

- Oweniidae
  - *Galathowenia oculata* (Zachs, 1923)
- Paraonidae
  - *Aricidea catherinae* Laubier, 1967 *
  - *Aricidea quadrilobata* Webster & Benedict, 1887
  - *Levinsenia gracilis* (Tauber, 1879) *
  - *Paradoneis armatus* Gl**J**marec, 1966 *
  - *Paraonis fulgens* (Levinsen, 1883)
  - *Paraonis pygoenigmatica* Jones, 1968
- Pectinariidae
  - *Pectinaria gouldii* (Verrill, 1873)
  - *Pectinaria granulata* (Linnaeus, 1767) *
  - *Pectinaria hyperborea* (Malmgren, 1866)
- Pholoidae
  - *Pholoe minuta* (Fabricius, 1780) *
  - *Pholoe tecta* Stimpson, 1854 *
    - (merged with *P. minuta* for report)
- Phyllodocidae
  - *Eteone flava* (Fabricius, 1780)
  - *Eteone foliosa* Quatrefages, 1865
  - *Eteone heteropoda* Hartman, 1951
  - *Eteone longa* (Fabricius, 1780) *
  - *Eulalia bilineata* (Johnston, 1840)
  - *Eulalia viridis* (Linnaeus, 1767)
  - *Eumida sanguinea* (Oersted, 1843)
  - *Paranaitis speciosa* (Webster, 1870)
  - *Phyllodoce arenae* Webster, 1879
  - *Phyllodoce groenlandica* Oersted, 1843
  - *Phyllodoce maculata* (Linnaeus, 1767) *
  - *Phyllodoce mucosa* Oersted, 1843 *
- Polygordiidae
  - *Polygordius* sp. A *
- Polynoidae
  - *Enipo torelli* (Malmgren, 1865)
  - *Gattyana amondseni* (Malmgren, 1867)
  - *Gattyana cirrosa* (Pallas, 1766) *
  - *Harmothoe extenuata* (Grube, 1840)
  - *Harmothoe imbricata* (Linnaeus, 1767)
  - *Hartmania moorei* Pettibone, 1955 *
  - *Lepidonotus squamatus* (Linnaeus, 1758) *
- Sabellidae
  - *Euchone incolor* Hartman, 1978
  - *Fabricia stellaris stellaris* (Müller, 1784)
  - *Laonome kroeyeri* Malmgren, 1866
- Scalibregmatidae
  - *Scalibregma inflatum* Rathke, 1843
- Sigalionidae
  - *Sthenelais limicola* (Ehlers, 1864)
- Sphaerodoridae
  - *Sphaerodoridium* sp. A
- Spionidae
  - *Dipolydora caulleryi* Mesnil, 1897
  - *Dipolydora quadrilobata* Jacobi, 1883 *
  - *Dipolydora socialis* (Schmarda, 1861) *
  - *Polydora aggregata* Blake, 1969 *
  - *Polydora cornuta* Bosc, 1802 *
  - *Polydora* sp. 1
  - *Prionospio steenstrupi* Malmgren, 1867 *
  - *Pygospio elegans* Calparède, 1863 *
  - *Scolelepis bousfieldi* Pettibone, 1963 *
  - *Scolelepis foliosa* (Audoin & Milne-Edwards, 1833) *
  - *Scolelepis squamata* (O.F. M**h**ller, 1806)
  - *Scolelepis texana* Foster, 1971
  - *Spio filicornis* (O.F.Müller, 1766)
  - *Spio limicola* Verrill, 1880
  - *Spio setosa* Verrill, 1873
  - *Spio thulini* Maciolek, 1990
  - *Spiophanes bombyx* Claparède, 1870 *
  - *Streblospio benedicti* Webster, 1879 *
- Syllidae
  - *Autolytus fasciatus* (Bosc, 1802)
  - *Brania wellfleetensis* Pettibone, 1956
  - *Exogone arenosa* Perkins, 1980
  - *Exogone hebes* (Webster & Benedict, 1884) *
  - *Exogone verugera* (Claparède, 1868)
  - *Parapionosyllis longicirrata* (Webster & Benedict, 1884)
  - *Pionosyllis* spp.
  - *Proceraea cornuta* Agassiz, 1863 *
  - *Sphaerosyllis erinaceus* Clapar**J**de, 1863
  - *Syllides longocirrata* Oersted, 1845
  - *Typosyllis alternata* (Moore, 1908)
  - *Typosyllis cornuta* Rathke, 1843
  - *Typosyllis* sp. 1
- Terebellidae
  - *Lanassa* spp.
  - *Neoamphitrite figulus* (Dalyell, 1853)
  - *Nicolea zostericola* (Oersted, 1844)
  - *Nicolea* spp.
    - (merged with *N. zostericola* for report)
  - *Pista cristata* (O.F. Müller, 1776) *
  - *Polycirrus eximius* (Leidy, 1855) *
  - *Polycirrus medusa* Grube, 1850
  - *Polycirrus phosphoreus* Verrill, 1880 *
  - *Polycirrus* sp. A
- Trichobranchidae
  - *Terebellides atlantis* Williams, 1984
- Trochochaetidae
  - *Trochochaeta carica* (Birula, 1897)
  - *Trochochaeta multisetosa* (Oersted, 1844)

- Oligochaeta
  - Enchytraiedae
    - Enchytraiedae sp. 1
    - Enchytraiedae sp. 2
    - Enchytraiedae sp. 3
    - *Grania postclitellochaeta longiductа*
  - Naididae
    - *Paranais litoralis* (Müller, 1784) *
  - Tubificidae
    - Tubificidae sp. 2 *
    - *Tubificoides apectinatus* Brinkhurst, 1965 *
    - *Tubificoides benedeni* Udekem, 1855 *
    - *Tubificoides* nr. *pseudogaster* Dahl, 1960 *
    - *Tubificoides* sp. 1 *
    - *Tubificoides* sp. 2 *

- ARTHROPODA
  - Pycnogonida
    - *Achelia spinosa* (Stimpson, 1853) *
    - *Phoxichilidium femoratum* (Rathke, 1799)

- CRUSTACEA
  - Amphipoda
    - Ampeliscidae
      - *Ampelisca abdita* Mills, 1964 *
        - (merged with *Ampelisca* spp. for report)
      - *Ampelisca vadorum* Mills, 1963 *
        - (merged with *Ampelisca* spp. for report)
    - Ampithoidae
      - *Cymadusa compta* (Smith, 1873)
    - Aoridae
      - *Leptocheirus pinguis* (Stimpson, 1853) *
      - *Microdeutopous anomalus* (Rathke, 1843) *
      - *Pseudunciola obliquua* (Shoemaker, 1949)
      - *Unciola irrorata* Say, 1818 *
    - Argissidae
      - *Argissa hamatipes* (Norman, 1869) *

- Calliopiidae
    - *Calliopius laeviusculus* (Krøyer, 1838)
- Corophiidae
    - *Apocorophium acutum* Chevreus, 1908
    - *Crassicorophium crassicorne* (Bruzelius, 1859)
    - *Crassicorophium bonnelli* (Milne Edwards, 1830) *
    - *Monocorophium acherusicum* (Costa, 1857)
    - *Monocorophium insidiosum* (Crawford, 1937)
    - *Monocorophium tuberculatum* (Shoemaker, 1934)
    - Corophiidae sp. 1
- Dexaminidae
    - *Dexamine thea* Sars, 1893
- Eusiridae
    - *Pontogenia inermis* (Krøyer, 1842)
- Gammaridae
    - *Gammarus lawrencianus* Bousfield, 1956
- Isaeidae
    - *Photis pollex* Walker, 1895 *
    - *Protomedeia fasciata* Kr**r**yer, 1846
- Ischyroceridae
    - *Erichthonius brasiliensis* (Dana, 1853)
    - *Ischyrocerus anguipes* (Krøyer, 1842)
    - *Jassa marmorata* Holmes, 1903
- Liljeborgiidae
    - *Listriella barnardi* Wigley, 1966
- Lysianassidae
    - *Orchomenella minuta* (Krøyer, 1842) *
    - *Orchomene pinguis* (Boeck, 1861)
- Oedicerotidae
    - *Ameroculodes* sp. 1
    - *Deflexilodes tuberculatus* (Boeck, 1870)
- Phoxocephalidae
    - *Harpinia propinqua* Sars, 1895
    - *Phoxocephalus holbolli* (Krøyer, 1842)
    - *Rhepoxinius hudsoni* Barnard & Barnard, 1982
- Pleustidae
    - *Pleusymtes glaber* (Boeck, 1861)
- Podoceridae
    - *Dyopedos monacanthus* (Metzger, 1875)
- Stenothoidae
    - *Metopella carinata* Shoemaker, 1949
    - *Metopella angusta* Shoemaker, 1949
    - *Proboloides holmesi* Bousfield, 1973
    - *Stenothoe gallensis* Walker, 1904
    - *Stenothoe minuta* Holmes, 1905 *
    - Stenothoe sp. 1

- Cumacea
    - Diastylidae
        - *Diastylis polita* (S.I. Smith, 1879) *
        - *Diastylis sculpta* Sars, 1871 *
    - Lampropidae
        - *Lamprops quadriplicata* S.I. Smith, 1879
    - Leuconidae
        - *Eudorella hispida* Sars, 1871
        - *Eudorella pusilla* Sars, 1871 *

- Decapoda
    - Brachyura
        - Cancridae
            - *Cancer irroratus* Say, 1817 *
        - Portunidae
            - *Carcinus maenas* (Linnaeus, 1758) *
    - Caridea
        - Crangonidae
            - *Crangon septemspinosa* Say, 1818 *
        - Paguridae
            - *Pagurus acadianus* Benedict, 1901
            - *Pagurus annulipes* (Stimpson, 1860)
            - *Pagurus longicarpus* Say, 1817 *

- Isopoda
    - Anthuriidae
        - *Ptilanthura tenuis* Harger, 1879
    - Chaetiliidae
        - *Chiridotea tuftsi* (Stimpson, 1883)
    - Cirolanidae
        - *Politolana polita* (Stimpson, 1853)
    - Idoteidae
        - *Edotia triloba* (Say, 1818) *
        - *Erichsonella* spp.
        - *Idotea balthica* (Pallas, 1772)
    - Munnidae
        - *Munna* spp.
    - Paramunnidae
        - *Pleurogonium inerme* Sars, 1882 *
        - *Pleurogonium rubicundum* (Sars, 1863) *

- Mysidacea
    - *Heteromysis formosa* S.I. Smith, 1873
    - *Neomysis americana* (S.I. Smith, 1873) *

- Tanaidacea
    - Nototanaidae
        - *Tanaissus psammophilus* (Wallace, 1919) *

MOLLUSCA

- Bivalvia
    - Arcidae
        - *Arctica islandica* (Linnaeus, 1767) *
    - Astartidaeè
        - *Astarte undata* Gould, 1841 *
    - Cardiidae
        - *Cerastoderma pinnulatum* (Conrad, 1831) *
    - Carditidae
        - *Cyclocardia borealis* (Conrad, 1831)
    - Hiatellidae
        - *Hiatella arctica* (Linnaeus, 1767) *
    - Lasaeidae
        - *Aligena elevata* (Stimpson, 1851)
    - Lyonsiidae
        - *Lyonsia arenosa* Möller, 1842 *
        - *Lyonsia hyalina* Conrad, 1831 *
            (merged with *L. arenosa* for report)
    - Mactridae
        - *Mulinia lateralis* (Say, 1822) *
        - *Spisula solidissima* (Dillwyn, 1817)
    - Montacutidae
        - *Mysella planulata* (Stimpson, 1857) *
        - *Pythinella cuneata* Dall, 1899 *
    - Myidae
        - *Mya arenaria* Linnaeus, 1758 *
    - Mytilidae
        - *Crenella decussata* (Montagu, 1808)
        - *Musculus niger* (Gray, 1824)
    - Nuculanidae
        - *Yoldia limatula* (Say, 1831) *
        - *Yoldia sapotilla* (Gould, 1841) *
    - Nuculidae
        - *Nucula annulata* Hampson, 1971
        - *Nucula delphinodonta* Mighels & Adams, 1842 *
        - *Nuculoma tenuis* Montagu, 1808 *
    - Pandoridae
        - *Pandora gouldiana* Dall, 1886 *
    - Periplomatidae
        - *Periploma papyratium* (Say, 1822) *
    - Petricolidae
        - *Petricola pholadiformis* (Lamarck, 1818) *
    - Solenidae
        - *Ensis directus* Conrad, 1843 *
        - *Siliqua costata* Say, 1822

- Tellinidae
  - *Macoma balthica* (Linnaeus, 1758)
  - *Tellina agilis* Stimpson, 1857 *
- Thraciidae
  - *Bushia elegans* (Dall, 1886)
  - *Thracia conradi* Couthouy, 1838
- Thyasiridae
  - *Thyasira gouldi* Philippi, 1845
- Turtoniidae
  - *Turtonia minuta* (Fabricius, 1780)
- Veneridae
  - *Gemma gemma* (Totten, 1834)
  - *Pitar morrhuanus* Linsley, 1848
- Bivalvia sp. 1

- Gastropoda
  - Nudibranchia
    - Doridoida sp. A

  - Ophisthobranchia
    - Diaphanidae
      - *Diaphana minuta* (Brown, 1827) *
  - Prosobranchia
    - Columbellidae
      - *Mitrella lunata* (Say, 1826)
    - Lacunidae
      - *Lacuna vincta* (Montagu, 1803) *
    - Nassariidae
      - *Ilyanassa obsoleta* (Say, 1822) *
      - *Ilyanassa trivittata* (Say, 1822) *
    - Naticidae
      - *Euspira heros* (Say, 1822)
      - *Euspira triseriata* (Say, 1826)
      - *Polinices duplicatus* (Say, 1822)
    - Pyramidellidae
      - ***Boonea seminuda* (C.B. Adams, 1839) ***

- Scaphopoda
  - Dentaliidae
    - *Dentalium entale* (Linnaeus, 1758)

SIPUNCULA
- *Nephasoma diaphanes* (Gerould, 1913)
- *Phascolion strombi* (Montagu, 1804)

ECHIURA
- *Echiurus echiurus* (Pallas, 1767)

PHORONIDA
- *Phoronis architecta* Andrews, 1890 *

ECHINODERMATA
- Echinoidea
  - *Echinarachnius parma* (Lamarck, 1816) *
  - *Strongylocentrotus droebachiensis* (Müller, 1776)
- Ophiuroidea
  - *Axiognathus squamatus* (Delle Chiaje, 1828)
  - *Ophiura robusta* (Ayres, 1851)

HEMICHORDATA
- Harrimaniidae
  - *Saccoglossus bromophenolosus* King, Giray, & Kornfield, 1997 *

CHORDATA
- Ascidiacea spp.
  - Molgulidae
    - *Bostrichobranchus pilularis* (Verrill, 1871)
    - *Molgula manhattensis* (DeKay, 1843) *
    - *Molgula complanata* (Alder & Hancock, 1870)

Appendix C3

Dominant Species at Boston Harbor Stations

Station	2005 Rank	Species	Mean	Std. Dev.	% Total	% Ident.	Cum % (Total)	Cum % (Ident.)	2004 Rank
T01	1	*Nephtys cornuta*	254.7	165.7	31.8	32.1	31.8	32.1	11
	2	*Tubificoides* nr. *pseudogaster*	140.0	106.3	17.5	17.6	49.2	49.7	3
	3	*Nephtys ciliata*	50.3	20.6	6.3	6.3	55.5	56.0	3
	4	*Polydora cornuta*	46.0	33.7	5.7	5.8	61.2	61.8	1
	5	*Microphthalmus pettiboneae*	36.7	46.2	4.6	4.6	65.8	66.5	12
	6	Tubificidae sp. 2	32.0	4.6	4.0	4.0	69.8	70.5	-
	7	*Pholoe minuta*	28.3	16.9	3.5	3.6	73.3	74.1	-
	8	*Prionospio steenstrupi*	25.3	6.8	3.2	3.2	76.5	77.2	-
	9	*Ilyanassa trivittata*	24.0	13.0	3.0	3.0	79.5	80.3	8
	10	*Exogone hebes*	22.3	4.6	2.8	2.8	82.3	83.1	6
	11	*Aricidea catherinae*	18.0	7.0	2.2	2.3	84.5	85.3	5
	12	*Dipolydora socialis*	17.3	29.2	2.2	2.2	86.7	87.5	-
	13	*Ampelisca* spp.	11.7	7.6	1.5	1.5	88.1	89.0	10
	14	*Leptocheirus pinguis*	11.0	6.9	1.4	1.4	89.5	90.4	4
	15	*Tharyx* spp.	10.7	5.7	1.3	1.3	90.8	91.7	14
(No. Species)	(52)	Station Mean Abundance	802.0 (all) 794.0 (ident.)						(59)
T02	1	*Nephtys cornuta*	1959.7	372.6	82.2	82.4	82.2	82.4	1
	2	*Tubificoides apectinatus*	211.0	103.2	8.9	8.9	91.1	91.3	2
	3	*Tubificoides* nr. *pseudogaster*	46.0	23.5	1.9	1.9	93.0	93.2	6
	4	*Aricidea catherinae*	32.0	24.9	1.3	1.3	94.4	94.6	3
	5	*Prionospio steenstrupi*	22.0	10.1	0.9	0.9	95.3	95.5	-
	6	*Pholoe minuta*	21.3	29.2	0.9	0.9	96.2	96.4	10
	7	*Ninoe nigripes*	15.7	7.2	0.7	0.7	96.8	97.0	9
	8	*Nephtys incisa*	14.3	21.4	0.6	0.6	97.4	97.6	5
	9	*Microphthalmus pettiboneae*	8.3	7.6	0.3	0.4	97.8	98.0	4
	10	*Ilyanassa trivittata*	5.7	2.1	0.2	0.2	98.0	98.2	8
	10	*Polydora cornuta*	5.7	7.4	0.2	0.2	98.3	98.5	11
	11	*Ampelisca* spp.	4.3	4.0	0.2	0.2	98.4	98.7	7
	12	*Mediomastus californiensis*	4.0	4.4	0.2	0.2	98.6	98.8	14
(No. Species)	(42)	Station Mean Abundance	2383.3 (all) 2378.0 (ident.)						(48)

\- = not among the numerical dominants

Station	Rank	Species	Mean	Std. Dev.	% Total	% Ident.	Cum % (Total)	Cum % (Ident.)	2004 Rank
T03	1	*Tubificoides apectinatus*	991.3	188.9	34.85	34.93	34.85	34.93	2
	2	*Aricidea catherinae*	701.7	153.3	24.7	24.72	59.52	59.65	3
	3	*Tubificoides nr. pseudogaster*	235.7	38.4	8.3	8.30	67.81	67.96	4
	4	*Prionospio steenstrupi*	195.0	3.0	6.9	6.87	74.67	74.83	-
	5	*Nephtys cornuta*	187.3	24.4	6.6	6.60	81.25	81.43	-
	6	*Ampelisca* spp.	160.0	72.6	5.6	5.64	86.88	87.07	1
	7	*Polydora cornuta*	51.3	23.5	1.8	1.81	88.69	88.88	5
	8	*Nephtys ciliata*	44.3	12.1	1.6	1.56	90.24	90.44	-
	9	*Pholoe minuta*	26.7	13.6	0.9	0.94	91.18	91.38	-
	10	*Microphthalmus pettiboneae*	26.3	2.5	0.9	0.93	92.11	92.31	12
	11	*Monticellina dorsobranchialis*	23.7	7.6	0.8	0.83	92.94	93.14	-
	12	*Photis pollex*	22.0	13.5	0.8	0.78	93.71	93.92	7
	13	*Mediomastus californiensis*	21.3	1.2	0.8	0.75	94.46	94.67	10
	14	*Ninoe nigripes*	20.7	8.0	0.7	0.73	95.19	95.40	-
	15	*Ilyanassa trivittata*	19.3	8.6	0.7	0.68	95.87	96.08	15
(No. Species)	(60)	Station Mean Abundance	2844.3 (all) 2383.0 (ident.)						(81)
T04	1	*Streblospio benedicti*	576.3	131.2	88.7	88.7	88.7	88.7	1
	2	*Tubificoides sp. 2*	28.0	22.1	4.3	4.3	93.02	93.02	2
	3	*Paranais litoralis*	8.0	7.2	1.2	1.2	94.25	94.25	-
	4	*Nephtys cornuta*	7.3	4.0	1.1	1.1	95.38	95.38	3
	5	*Polydora cornuta*	7.0	7.8	1.1	1.1	96.45	96.45	-
	6	*Tubificoides benedeni*	4.7	4.0	0.7	0.7	97.17	97.17	-
	7	*Capitella capitata complex*	3.3	2.5	0.5	0.5	97.69	97.69	-
	8	*Neomysis americana*	2.7	1.5	0.4	0.4	98.10	98.10	-
	9	*Microphthalmus pettiboneae*	2.3	3.2	0.4	0.4	98.46	98.46	-
	10	*Crangon septemspinosa*	2.0	0.0	0.3	0.3	98.76	98.76	4
	11	*Tharyx sp. B*	1.3	1.5	0.2	0.2	98.97	98.97	5
	12	*Dipolydora socialis*	1.0	1.7	0.2	0.2	99.12	99.12	-
	12	*Nephtys caeca*	1.0	1.7	0.2	0.2	99.28	99.28	-
	12	*Pagurus longicarpus*	1.0	1.0	0.2	0.2	99.43	99.43	7
	13	*Ilyanassa trivittata*	0.7	1.2	0.1	0.1	99.53	99.53	8
(No. Species)	(22)	Station Mean Abundance	649.7 (all) 649.7 (ident.)						(16)

\- = not among the numerical dominants

Station	Rank	Species	Mean	Std. Dev.	% Total	% Ident.	Cum % (Total)	Cum % (Ident.)	2004 Rank
T05A	1	*Tubificoides apectinatus*	506.0	242.5	41.16	41.42	41.16	41.42	2
	2	*Prionospio steenstrupi*	111.7	44.6	9.08	9.14	50.25	50.56	15
	3	*Nephtys ciliata*	86.3	4.9	7.02	7.07	57.27	57.62	-
	4	*Polygordius* sp. A	85.0	24.6	6.91	6.96	64.18	64.58	7
	5	*Phoronis architecta*	58.3	18.9	4.75	4.77	68.93	69.36	-
	6	*Ilyanassa trivittata*	46.3	7.2	3.77	3.79	72.70	73.15	13
	7	*Tubificoides* nr. *pseudogaster*	38.3	15.5	3.12	3.14	75.82	76.29	-
	8	*Ninoe nigripes*	35.0	10.6	2.85	2.86	78.66	79.15	-
	9	*Spiophanes bombyx*	31.7	8.1	2.58	2.59	81.24	81.74	-
	10	*Aricidea catherinae*	30.3	16.1	2.47	2.48	83.71	84.23	11
	11	*Monticellina dorsobranchialis*	29.0	25.2	2.36	2.37	86.07	86.60	-
	12	*Edotia triloba*	18.7	15.3	1.52	1.53	87.58	88.13	-
	13	*Tharyx* spp.	15.0	5.6	1.22	1.23	88.80	89.36	5
	14	*Mediomastus californiensis*	13.7	8.4	1.11	1.12	89.92	90.48	-
	15	*Tubificoides benedeni*	9.3	4.6	0.76	0.76	90.67	91.24	-
(No. Species)	(63)	Station Mean Abundance	1229.3 (all) 1221.7 (ident.)						(102)
T06	1	*Nephtys cornuta*	523.7	91.3	37.65	37.72	37.65	37.72	-
	2	*Tubificoides nr. pseudogaster*	268.3	199.0	19.29	19.33	56.95	57.05	3
	3	*Tubificoides apectinatus*	201.7	55.7	14.50	14.53	71.45	71.57	4
	4	*Prionospio steenstrupi*	87.0	36.0	6.26	6.27	77.71	77.84	13
	5	*Nucula delphinodonta*	44.3	7.6	3.19	3.19	80.89	81.03	9
	6	*Pholoe minuta*	41.0	31.2	2.95	2.95	83.84	83.99	-
	7	*Scoletoma hebes*	34.0	13.2	2.44	2.45	86.29	86.44	6
	8	*Aricidea catherinae*	25.7	2.3	1.85	1.85	88.13	88.29	2
	9	*Tharyx spp.*	24.0	3.0	1.73	1.73	89.86	90.01	-
	10	*Exogone hebes*	23.0	39.8	1.65	1.66	91.51	91.67	-
	11	*Mediomastus californiensis*	15.7	6.7	1.13	1.13	92.64	92.80	10
	12	*Ninoe nigripes*	15.7	6.4	1.13	1.13	93.77	93.93	-
	13	*Phoronis architecta*	13.7	9.9	0.98	0.98	94.75	94.91	-
	14	*Ampelisca spp.*	10.7	2.5	0.77	0.77	95.52	95.68	1
	15	*Nephtys incisa*	10.7	4.0	0.77	0.77	96.28	96.45	-
(No. Species)	(46)	Station Mean Abundance	1390.7 (all) 1388.3 (ident.)						(64)

- = not among the numerical dominants

Station	Rank	Species	Mean	Std. Dev.	% Total	% Ident.	Cum % (Total)	Cum % (Ident.)	2004 Rank
T07	1	*Nephtys cornuta*	1003.7	239.0	74.07	74.11	74.07	74.11	3
	2	*Tubificoides apectinatus*	220.3	82.9	16.26	16.27	90.33	90.38	1
	3	*Tubificoides* nr. *pseudogaster*	32.0	12.5	2.36	2.36	92.69	92.74	4
	4	*Aricidea catherinae*	24.7	12.1	1.82	1.82	94.51	94.56	2
	5	*Polydora cornuta*	15.0	22.5	1.11	1.11	95.62	95.67	12
	6	*Leptocheirus pinguis*	9.3	14.4	0.69	0.69	96.31	96.36	10
	7	*Neomysis americana*	7.7	7.0	0.57	0.57	96.88	96.93	-
	8	*Tharyx* spp.	7.3	4.0	0.54	0.54	97.42	97.47	11
	9	*Ilyanassa trivittata*	6.7	5.5	0.49	0.49	97.91	97.96	7
	10	*Ampelisca* spp.	3.7	2.1	0.27	0.27	98.18	98.23	5
	11	*Microphthalmus pettiboneae*	3.3	3.2	0.25	0.25	98.43	98.48	6
	12	*Streblospio benedicti*	3.3	1.5	0.25	0.25	98.67	98.72	-
	13	*Nephtys incisa*	3.0	1.0	0.22	0.22	98.89	98.94	9
	14	*Pholoe minuta*	1.7	1.5	0.12	0.12	99.02	99.07	-
	15	*Ninoe nigripes*	1.3	1.2	0.10	0.10	99.11	99.17	13
	16	*Periploma papyratium*	1.3	0.6	0.10	0.10	99.21	99.26	-
(No. Species)	(37)	Station Mean Abundance	1355.0 (all) 1354. 3 (ident.)						(44)
T08	1	*Spiophanes bombyx*	151.0	97.9	21.84	21.84	22.87	22.87	1
	2	*Aricidea catherinae*	69.7	61.5	10.08	31.92	10.55	33.42	5
	3	*Exogone hebes*	62.7	78.7	9.07	40.99	9.49	42.91	2
	4	*Tubificoides nr. pseudogaster*	58.3	12.2	8.44	49.42	8.83	51.74	10
	5	*Polygordius* sp. A	45.0	21.8	6.51	55.93	6.82	58.56	3
	6	*Nucula delphinodonta*	44.0	30.5	6.36	62.30	6.66	65.22	11
	7	*Prionospio steenstrupi*	30.3	25.7	4.39	66.69	4.59	69.82	-
	8	*Nephtys ciliata*	24.3	9.0	3.52	70.21	3.69	73.50	-
	9	*Ilyanassa trivittata*	20.7	7.5	2.99	73.20	3.13	76.63	7
	10	Maldanidae spp.	18.0	15.9	2.60	75.80	2.73	79.36	-
	11	*Phyllodoce mucosa*	14.7	12.9	2.12	77.92	2.22	81.58	9
	12	*Ampelisca* spp.	12.3	8.0	1.78	79.70	1.87	83.45	4
	12	*Microphthalmus pettiboneae*	12.3	5.5	1.78	81.49	1.87	85.31	-
	13	*Aphelochaeta* spp.	11.3	18.8	1.64	83.13	1.72	87.03	-
	14	*Tharyx* spp.	9.3	1.5	1.35	84.48	1.41	88.44	13
(No. Species)	(65)	Station Mean Abundance	691.3 (all) 660.3 (ident.)						(75)

\- = not among the numerical dominants

Station	**2005 Rank**	**Species**	**Mean**	**Std. Dev.**	**% Total**	**% Ident.**	**Cum % (Total)**	**Cum % (Ident.)**	**2004 Rank**
C019	1	*Nephtys cornuta*	1124.0	297.3	96.2	96.3	96.2	96.3	1
	2	*Tubificoides apectinatus*	13.7	2.5	1.2	1.2	97.3	97.5	2
	3	*Ilyanassa trivittata*	7.7	8.1	0.7	0.7	98.0	98.1	7
	4	*Nephtys incisa*	5.3	1.2	0.5	0.5	98.5	98.6	5
	5	*Polydora cornuta*	3.3	2.1	0.3	0.3	98.7	98.9	6
	6	*Chaetozone vivipara*	2.0	1.7	0.2	0.2	98.9	99.1	4
	6	*Pholoe minuta*	2.0	2.0	0.2	0.2	99.1	99.2	-
	7	*Crangon septemspinosa*	1.7	0.6	0.1	0.1	99.2	99.4	9
	8	*Prionospio steenstrupi*	1.3	1.5	0.1	0.1	99.5	99.5	-
	9	*Microphthalmus pettiboneae*	1.0	1.0	0.09	0.09	99.6	99.6	10
	9	*Neomysis americana*	1.0	1.0	0.09	0.09	99.6	99.7	-
	9	*Tharyx spp.*	1.0	1.0	0.09	0.09	99.7	99.7	8
	10	*Ampelisca spp.*	0.7	0.6	0.06	0.06	99.8	99.8	12
	11	*Cerastoderma pinnulatum*	0.3	0.6	0.03	0.03	99.83	99.83	-
	11	*Leptocheirus pinguis*	0.3	0.6	0.03	0.03	99.85	99.86	-
(No. Species)	(19)	Station Mean Abundance	1169.0 (all) 1167.0 (ident.)						(27)

- = not among the numerical dominants