1998 Harbor Benthic Monitoring Report

Massachusetts Water Resources Authority

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1998 HARBOR BENTHIC MONITORING REPORT

submitted to

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Executive Summary

MWRA began its studies of the infaunal communities and benthic habitats in Boston Harbor in 1991, just prior to the cessation of sludge dumping into the Harbor. The principal aim of the Harbor studies is documentation of continuing recovery of benthic communities in areas of Boston Harbor as improvements are made to the quality of wastewater discharges. Briefly, these can be listed as the

- cessation of sludge discharge into the Harbor—December 1991,
- operation of a new primary treatment facility at Deer Island—1995,
- initiation of secondary treatment (first battery)—1997,
- continuation of secondary treatment implementation (second battery)—1998,
- cessation of effluent discharge from Nut Island—July 1998, and
- completion of the implementation of secondary treatment—early 2000.

Recent reports have indicated that some observed infaunal community changes are consistent with those expected with habitat improvements that have resulted from the changes in discharges into the Harbor. Among the changes reported in these studies, the increase in abundance and geographic distribution of the tube-dwelling amphipod *Ampelisca* has been the most dramatic.

A major forthcoming change to discharges into the Harbor, the diversion of effluent to the new ocean outfall, is expected to result in further improvements in the Harbor's benthic habitats.

The Boston Harbor benthic monitoring program includes three components. <u>Sediment profile images</u> (SPI) are collected during the late summer to monitor the general condition of the soft-bottom benthic habitats in the Harbor. <u>Sediment geochemistry studies</u>, conducted via the collection of sediment grab samples from Traditional stations in April and August, consist of grain-size analysis and total organic carbon (TOC) content determination. The presence of a sewage tracer, *Clostridium perfringens*, also is quantified during these studies. 1998 studies included 16 grain-size, TOC, and *Clostridium* samples. <u>Infaunal communities</u> in Boston harbor are monitored via the collection of samples from eight Traditional stations. All stations were visited in 1998. This report also includes a programmatic evaluation of each of the components. Summaries of the 1998 results from these studies follow.

Sediment Profile Images

Typically, the distribution of sediment textures in the Harbor primarily results from a combination of sources, morphology, and hydrodynamics. The 1998 SPI data showed that surface features were dominated by biogenic activity. *Ampelisca* tube mats, feeding pits and mounds, and worm tubes were the dominant surface biogenic structures at all stations except R06, R19, R54, and T04. Subsurface biogenic structures and organisms were also common and widely distributed. Biogenic structures indicative of extreme environments were present at R06 (macroalgal bed on coarse sediments associated with physically dynamic environments) and T04 (bacterial mat on silty sediments associated with stagnant environments).

The predominance of biological activity at most stations, particularly those near the mouth of the Harbor, was indicative of a well-developed fauna that was generally characterized as being intermediate in successional stage. The organism sediment index (OSI) reflected this pattern, with values > 6 occurring toward the Harbor mouth and values < 6 in the inner areas of the Harbor. *Ampelisca* tube mats continue to be wide spread and are indicative of the intermediate step (stage II) in the macrobenthic community successional transition from the pioneering-dominated (stage I) inner harbor area to the equilibrium-dominated (stage III) Nearfield area in western Massachusetts Bay.

Overall, general benthic habitat quality within the study area was similar from August 1992 to 1998, with minor variations from year-to-year. For 1998, key indicators of benthic habitat quality were lower relative to previous year, however, the major changes in habitat quality appeared to have occurred in early 1992. Long-term data suggest that the current benthic communities appear to have developed in response to major physical disturbance events in 1991. These included the severe storm in late October and the December sludge discharge abatement. Interestingly, stations with the poorest habitat quality measured in the 1989/90 sampling continued to have poor quality habitat in 1998. Three stations (T04, R36, and R43) each had long-term average OSI values less than or equal to 3, indicative of poor habitat quality.

Sediment Geochemistry

Samples collected in April 1998 had highly variable grain size composition, ranging from coarse to very fine sediment texture. Samples collected in August 1998 clustered into sandy (> 75% sandy and gravel) and silty (> 60% fines) sediments. In general, stations T01 and T05A were comprised of coarser sediments (> 75% sand and gravel) and stations T02, T03, T04, and T07 were comprised of finer sediments (> 60% silt and clay) in April and August 1998.

Patterns in sediment composition were fairly consistent from 1991 to 1998 (April and August) at some stations, but variable at others. With few exceptions during the study years, sediments at stations T01, T05A, and T08 displayed very consistent texture, being comprised primarily of coarse-grained sediments. Sediment texture at station T04 was also fairly consistent over time, being comprised primarily of silty sediments. Patterns in sediment composition from 1991 to 1998 (April and August) were more variable at stations T03, T06, and T07.

TOC content was fairly variable in 1998 (April and August). The TOC content in sediments collected at station T04 in August 1998 was the highest measured during the study period. TOC content correlated well with grain size (% fines) in April ($r = 0.81$, $n = 8$, $p < 0.05$) and August 1998 ($r = 0.62$, $n = 8$, $p < 0.05$).

Patterns in TOC content were fairly consistent from 1991 to 1998 (April and August) at stations T01, T02, T03, and T07, but more variable at stations T05A and T08. Patterns in TOC content were more variable at stations T04 and T06 in April than in August. Station T04 consistently had the highest TOC concentrations, whereas the lowest levels were measured at stations T05A and T08. TOC and sediment grain size (% fines) generally correlated well at most stations over all sampling years (April and August).

The density of *Clostridium perfringens* spores was fairly consistent between April and August 1998 surveys at some stations (T01, T02, T06, and T07), but variable at others (T03, T04, T05A, and T08). The highest abundance of *Clostridium perfringens* spores were consistently measured at station T04. *Clostridium* density correlated well with sediment grain size (% fines) and TOC content. Fine sediments with high TOC content generally had higher densities of *Clostridium perfringens* spores.

Patterns in *Clostridium* densities were variable from 1991 to 1998 (April and August) at most stations (T02, T03, T04, T06, and T07). Patterns in *Clostridium* densities tended to be more consistent, with lower numbers (< 10,000 cfu), over time at stations (T01, T05A, and T08). There were no clear year-to-year trends in *Clostridium* densities between the April and August surveys. *Clostridium* densities have consistently correlated well with grain size and TOC in more recent sampling years (1996–1998) where *Clostridium* densities have consistently shown a trend of decreasing abundance.

Infaunal Communities

Multivariate analysis of the 1998 (April and August) Boston Harbor infaunal data segregated the samples into three dissimilar groups. One group consisted of all samples collected from station T04. The second major group consisted of all samples collected from stations T03, T06, T08 and the August samples from station T05A. The final major group was comprised of all samples collected from stations T01, T02, T07, and the April samples from T05A. The location within the Harbor from which samples were collected appeared to be one of the primary factors contributing to the cluster groups identified. Station T04, within Dorchester Bay, is the only station located at the western edge of the Harbor. The stations consistently comprising the second group (T03, T06, T08) are located relatively close to the mouth of the Harbor or in Hingham Bay. Stations appearing consistently within the third group (T01, T02, T07) are located in the northern Harbor or in Quincy Bay, well away from the Harbor mouth. Station T05A varied between the latter two groups, being associated with T01, T02, and T07 in April and with T03, T06, and T08 in August.

The annelid taxon *Capitella capitata* complex exerted the strongest influence on the distinction among station groups, clearly separating station T04 from the others. The separation between the second (stations T03, T06, T08) and third (stations T01, T02, T07) cluster groups described above was explained largely by the abundances of several crustaceans (*Ampelisca* spp., and/or *Phoxocephalus holbolli* and *Photis pollex*) at stations comprising the former group and annelid worms (*Streblospio benedicti* and/or *Chaetozone vivipara* and Oligochaeta spp.) comprising the latter group.

A station-level examination of the multivariate analysis of the complete 1991–1998 Harbor data set showed several features that very likely are a result of the improvements made in discharges into the Harbor, particularly the cessation of sludge discharge.

- The two stations that showed the most change since 1991, stations T05A and T03, are the two that were located closest to the sludge discharge point. The changes identified were best explained by increased influence of amphipods, *Ampelisca* spp.
- Station T04 has shown a relatively consistent and unique identity throughout the study period. This strong station identity, and the sporadic, very strong importance of *Streblospio benedicti* (1992, 1995) or *Capitella capitata* complex (1994, 1998) at the station, dominated the overall analyses, possibly inhibiting investigation of the recovery of the parts of the Harbor that were most likely influenced by sludge discharge.
- Station T06 showed the most consistent distribution of sample points among the Harbor stations. Station T06 is located near the point of the former Nut Island effluent discharge. Because of the relative consistency exhibited by the station's samples, any effect of termination of the effluent discharge, which occurred just prior to collection of the summer 1998 samples may be relatively easy to detect.
- 1996 appeared to be an unusual year at several stations, notably stations T01, T02, T05A, and T07. The differences were most evident among summer samples and appeared to be related to much lower abundances of *Polydora cornuta* and/or amphipods, including *Ampelisca* spp.

Conclusions

The observed changes in the structure of Harbor's infaunal communities, coupled with data from SPI studies, provide good evidence for improvement in the condition of benthic habitats in the Harbor since the cessation of sludge discharge in 1991. Most notable was the dramatic increase in abundance and geographic spread of the amphipod *Ampelisca* spp. Also important was the general increase in infaunal abundance and species numbers that occurred after 1991. The most substantial changes in the Harbor's benthos probably occurred within the first two to three years after sludge discharge ended. Most recently there has been some indication that the infaunal communities are in transition from those that appeared soon after release from the stress caused by the sludge to those more likely to be found in a less-polluted Harbor that is still prone to periodic natural disturbance.

1.0 INTRODUCTION

1.1 Program Background

MWRA began its studies of the infaunal communities and benthic habitats in Boston Harbor in 1991, just prior to the cessation of sludge dumping into the Harbor. The principal aim of the Harbor studies is documentation of continuing recovery of benthic communities in areas of Boston Harbor as improvements are made to the quality of wastewater discharges. Blake *et al.* (1998) and Werme and Hunt (2000) have summarized past and future changes in discharges into Boston Harbor. Briefly, these can be listed as the

- cessation of sludge discharge into the Harbor—December 1991,
- operation of a new primary treatment facility at Deer Island—1995,
- initiation of secondary treatment (first battery)—1997,
- continuation of secondary treatment implementation (second battery)—1998,
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Recent reports have indicated that some observed infaunal community changes are consistent with those expected with habitat improvements that have resulted from the changes in discharges into the Harbor (Kropp and Diaz 1995, Hilbig *et al.* 1996, Blake *et al.* 1998). Among the changes reported in these studies, the increase in abundance and geographic distribution of the tube-dwelling amphipod *Ampelisca* has been the most dramatic.

A major forthcoming change to discharges into the Harbor, the diversion of effluent to the new ocean outfall, is expected to result in further improvements in the Harbor's benthic habitats.

1.2 Overview of this Report

The Boston Harbor benthic monitoring program includes three components. <u>Sediment profile images</u> (SPI) are collected during the late summer to monitor the general condition of the soft-bottom benthic habitats in the Harbor. In this report, the analyses of the SPI that were collected from 62 Harbor Traditional and Reconnaissance stations are presented in Section 3. <u>Sediment geochemistry studies</u>, conducted via the collection of sediment grab samples from Traditional stations in April and August, consist of grain-size analysis and total organic carbon (TOC) content determination. The presence of a sewage tracer, *Clostridium perfringens*, also is quantified during these studies. 1998 studies included 16 grain-size, TOC, and *Clostridium* samples. These studies are presented in Section 4. <u>Infaunal communities</u> in Boston harbor are monitored via the collection of samples from eight Traditional stations. All stations were visited in 1998. Analyses of the infaunal communities are described in Section 5. This report also includes a programmatic evaluation of each of the components. This evaluation is presented in Section 6.

The raw data generated for all of these studies are available from MWRA.

2.0 FIELD OPERATIONS

by Roy K. Kropp and Jeanine D. Boyle

2.1 Sampling Design

The Harbor Benthic Surveys provide the benthic samples and other data required to document long-term improvement of sediment quality and resulting recovery of the benthic communities in Boston Harbor following the cessation of sludge and effluent discharge into the Harbor. Data from an extensive reconnaissance survey using sediment profile images (SPI) supplements and extends traditional infaunal data to provide a large-scale picture of benthic conditions in the Harbor. This expanded coverage is particularly important because conditions are expected to improve over a broader expanse of the Harbor as secondary treatment is implemented and effluent discharge is diverted to the new outfall.

2.1.1 Traditional

During the Harbor traditional surveys, conducted late April/early May and August 1998, soft-sediment grab samples were collected from eight sampling locations (Figure 2-1). These "traditional" stations were selected after consideration of historic sampling sites and Harbor circulation patterns (Kelly and Kropp 1992). Samples from these traditional stations were collected for analysis of selected physical sediment parameters and sewage tracers, and for benthic infaunal community parameters. The actual locations of all Boston Harbor grab samples collected in 1998 are listed in Appendix A-1.

2.1.2 Reconnaissance

To provide for greater geographic coverage of benthic community recovery, a Harbor reconnaissance survey was conducted during August 1998. Sediment profile images (SPI) were obtained at the 60 "reconnaissance" stations as described in Kropp and Boyle (1998); however an additional two stations (designated R54 and R55) were sampled at the direction of the Senior Scientist to examine smaller scale spatial variation (Figure 2-2). The actual locations of all Boston Harbor sediment profile images collected in 1998 are listed in Appendix A-2.

2.2 Surveys/Samples Collected

The dates of the Boston Harbor Traditional and Reconnaissance surveys and the numbers of samples collected on them are listed in Table 2-1.

Table 2-1. Survey dates and numbers of samples collected on Boston Harbor benthic surveys in 1998.

Survey	ID	Date(s)	Samples Collected				
			Inf	TOC	gs	Cp	SPI
April Harbor Benthic	HT981	30 April, 4 May 1998	24	8	8	8	–
August Harbor Benthic	HT982	12 August 1998	24	8	8	8	–
SPI	HR981	26–28 August 1998	–	–	–	–	360

Key:
Inf, Infauna
TOC, total organic carbon
Gs, grain size
Cp, *Clostridium perfringens*
SPI, sediment profile images (slides)

Figure 2-1. Target locations of the eight Boston Harbor Traditional stations.

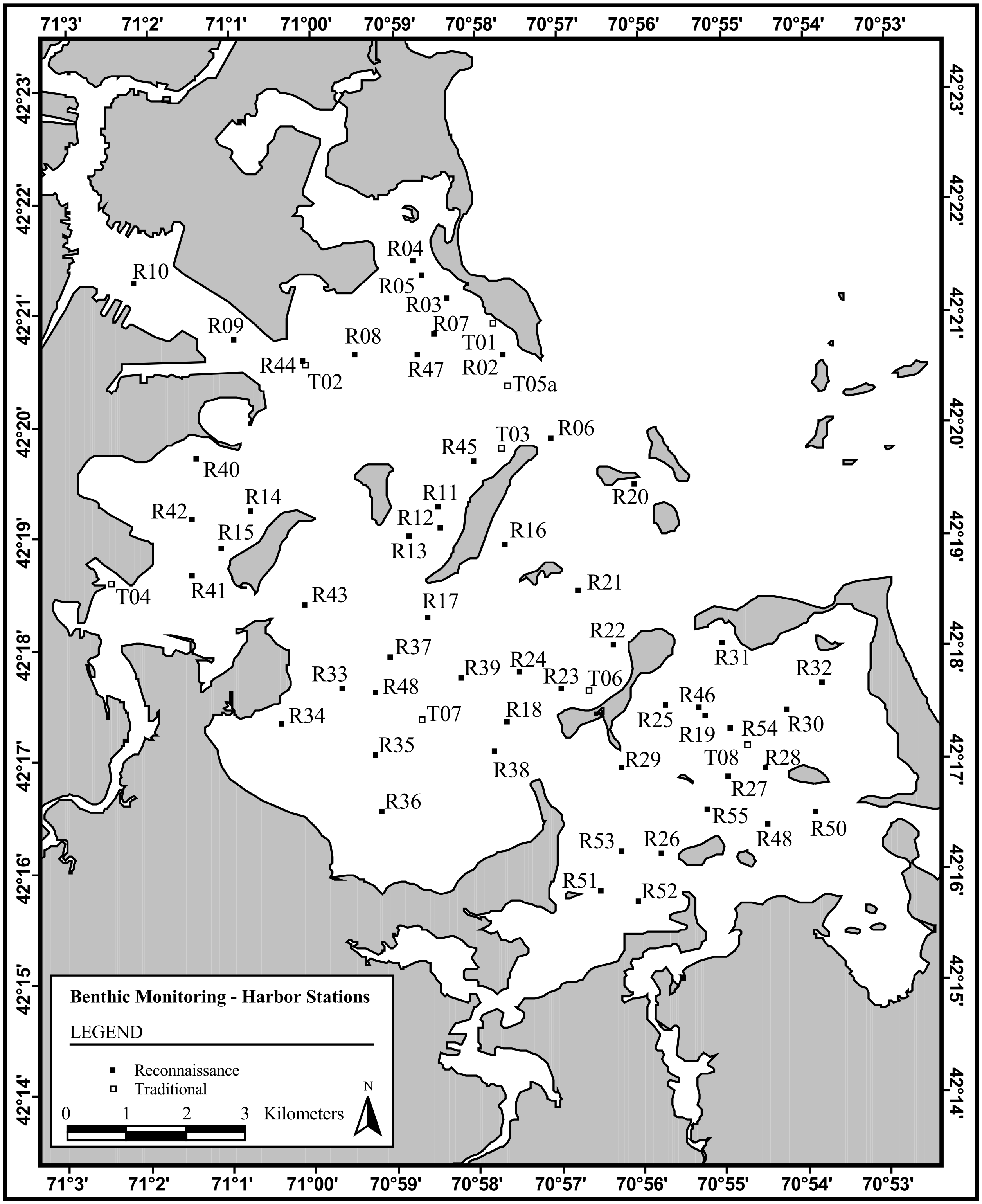


Figure 2-2. Locations of Boston Harbor Reconnaissance stations from which sediment profile images were collected in 1998.

2.3 Field Methods Overview

The following is a brief overview of the methods and protocols used on the benthic surveys. More detailed descriptions of the methods are contained in the CW/QAPP (Kropp and Boyle 1998).

2.3.1 Vessel/Navigation

Vessel positioning during benthic sample operations was accomplished with the BOSS Navigation system. This system consists of a Northstar differential global positioning system (DGPS) interfaced to the on-board BOSS computer. Data were recorded and reduced using NAVSAM data acquisition software. The GPS receiver has six dedicated channels and is capable of locking into six satellites at one time. The system was calibrated with coordinates obtained from USGS navigation charts at the beginning and end of each survey day.

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 ID to each sample when the sampling instrument hit bottom. The display on the BOSS computer screen was set to show a radius of 30 m around the target station coordinates (6, 5-m rings) for all Boston Harbor benthic surveys. A station radius of up to 30 m is considered acceptable for sediment sampling in Boston Harbor.

2.3.2 Grab Sampling

At all eight Traditional stations, a 0.04-m^2 modified van Veen grab sampler was used to collect three replicate samples for infaunal analysis and one sample was collected for *Clostridium perfringens*, sediment grain size, and total organic carbon (TOC) analyses. Infaunal samples were sieved onboard over a 300-μm-mesh sieve and fixed in buffered formalin. The “chemistry” grab sample was skimmed off the top 2 cm of the grab by using a Kynar-coated scoop, and was homogenized in a clean glass bowl before being distributed to appropriate storage containers. The TOC samples were frozen, whereas the *C. perfringens* and grain size samples were placed on ice in coolers.

2.3.3 SPI

At each station, a Hulcher Model Minnie sediment profile camera fitted with a digital video camera, to allow for real-time viewing of the sediment profiles, was deployed three times. The profile camera was set to take two pictures, using Fujichrome 100P slide film, on each deployment at 2 and 12 seconds after bottom contact. In the event that sediments were soft the two-picture sequence ensures that the sediment-water interface would be photographed before the prism window over penetrated. The combination of video and film cameras ensured accurate and reliable collection of sediment profile images. Any replicates that appeared to be disturbed during deployment were retaken. The videotape was recorded during each drop and was narrated in real time by Dr. Robert Diaz as the still photos were taken. The narration included the station, time, approximate prism penetration depth and a brief description of the substrate. In addition, Dr. Diaz estimated the Oxidation-Reduction Potential Discontinuity at each nearfield station. These measurements were hand entered in Dr. Diaz’s log, and the Battelle Survey logbook. Each touch down of the camera was marked as an event on the NAVSAM©.

3.0 SEDIMENT PROFILE CAMERA RECONNAISSANCE OF BENTHIC HABITATS IN BOSTON HARBOR, AUGUST 1998

by Robert J. Diaz

3.1 Methods

3.1.1 Image Analysis

Both the 2- and 12-second sediment profile images were analyzed visually by projecting the images and recording all features seen into a preformatted standardized spreadsheet file. The 12-second image was then digitized using a Polaroid Sprint Scan 35 Plus scanner and analyzed using the Adobe PhotoShop and NTIS Image programs. Steps in the computer analysis of each image were standardized and followed the basic procedures in Viles and Diaz (1991). Data from each image were sequentially saved to a spread sheet file for later analysis. Details of how these data were obtained can be found in Diaz and Schaffner (1988) and Rhoads and Germano (1986) and in the standardized image analysis procedures of Viles and Diaz (1991). A summary of major parameters measured follows:

Prism Penetration—was measured as the distance the sediment moved up the 23-cm length of the faceplate. The weight on the camera frame was kept constant at 75 lbs.

Surface Relief—(or boundary roughness) was measured as the difference between the maximum and minimum distance the prism penetrated.

Apparent Color Redox Potential Discontinuity (RPD) Layer—was defined as the area of all the pixels in the image discerned as being oxidized divided by the width of the digitized image. The area of the image with oxic sediment was obtained by digitally manipulating the image to enhance characteristics associated with oxic sediment (greenish-brown color tones). The enhanced area was then determined from a density slice of the image.

Sediment Grain Size—was determined by comparison of collected images with a set of standard images for which mean grain size had been determined in the laboratory. The sediment type descriptors used for image analysis followed the Wentworth classification as described in Folk (1974) and represent the major modal class for each image.

Surface Features—included a wide variety of features and were visually evaluated from each slide and compiled by type and frequency of occurrence.

Subsurface Features—included a wide variety of features and revealed much about physical and biological processes influencing the bottom. Surface features were visually evaluated from each slide and compiled by type and frequency of occurrence.

Successional Stage—was estimated by evaluating the following SPI parameters (– = not associated with, + = associated with, ++ = moderately associated with, +++ = strongly associated with):

Parameter	Successional Stage		
	I	II	III
Average RPD (cm)	<1	1-3	>2
Max depth RPD (cm)	<2	>2	>4
Small Tubes	+++	++	+
Large Tubes	–	++	+++
Burrows	–	++	+++
Feeding Voids	–	+	+++
Small Infauna	+++	++	+
Large Infauna	–	+	++
Epifauna	+	++	++

Organism-Sediment Index—was calculated by using the following parameter ranges and scores (taken from Rhoads and Germano 1986):

Depth of the apparent color RPD		Estimated successional stage	
(cm)	(score)	(stage)	(score)
0	0	Azoic	!4
>0-0.75	1	I	1
0.76-1.50	2	I-II	2
1.51-2.25	3	II	3
2.26-3.00	4	II-III	4
3.01-3.75	5	III	5
>3.75	6	I on III	5
		II on III	5
Other		**Score**	
Methane voids present		!2	
No/Low DO		!4	

3.2 Results and Discussion

3.2.1 August 1998 Harbor Image Data

Three replicate sediment profile film images and taped video were collected at 60 stations. One replicate was collected at two additional stations (R54, R55). A complete listing of sediment profile image (SPI) data can be found in Appendix B-1 and a station summary in Table 3-1.

Physical processes and sediments—Sediment grain size ranged from pebbles (R06) to soft, silty sediments (T04) (Table 3-1, Appendix B-1). The predominant sediment type throughout the study area was silty (modal phi 8 to 5) and occurred at 34 (55%) stations. Silty fine sands and fine sandy silts occurred at 19 (31%) stations, and fine sands to coarser sediments at 9 stations (15%) (Figure 3-1). Coarser sediments (medium sand to pebbles) occurred at four stations and fine sand sediments at six stations. Shell hash was a significant component of the sediments at eight stations scattered over the entire Harbor area. Shell beds (a mixture of clam, oyster, and mussel shells) occurred at stations R14 and R15 north of Thompson Island.

Table 3-1. Harbor area summary of SPI parameters for August 1998 reconnaissance stations. Data from all three replicates were averaged for quantitative parameters and summed for the qualitative parameters (for example, the presence of shell in one of the three replicates results in a + for the station). Key is at the end of the Table.

Stat.	Pen.	SR	RPD	Sediment	Shell	Bed-forms	Dominant Process	Comments	Am-pelisca	Worm Tubes	Stick Amphi.	Infauna	Bur-rows	Oxic Voids	Anaero. Voids	Gas Voids	Low DO	Median SS	Mean OSI
R02	15.8	1.2	1.0	SI	-	-	BIOG		MAT	-	+	+	+	+	+	-	NO	II/III	5.7
R03	13.7	1.0	2.2	SI	-	-	INTER		+	+	-	+	+	+	+	-	NO	II	6.7
R04	18.0	1.2	1.5	SI	-	-	INTER		-	MAT	-	+	+	+	+	-	NO	I/II	4.7
R05	15.0	1.2	1.8	SI	-	-	INTER		MAT	+	-	+	+	-	+	-	NO	II	5.7
R06	2.2	3.0	>2.2*	MSGRPB	-	-	PHY	Macroalgal-bed	-	-	-	-	-	-	-	-	NO	I	IND
R07	15.1	1.1	1.8	SI	-	-	BIOG		MAT	-	+	+	+	+	+	-	NO	II/III	6.7
R08	1.8	2.2	>1.8	FS	+	-	BIOG		-	+	-	-	-	-	-	-	NO	I	3.5
R09	18.7	1.4	1.0	SI	-	-	INTER		MAT	+	+	+	+	+	+	-	NO	II	4.7
R10	20.3	1.0	1.5	SI	-	-	PHY		-	+	-	+	+	+	+	-	NO	IonII	5.3
R11	19.4	0.8	7.1	SI	-	-	BIOG		MAT	-	+	+	+	+	+	-	NO	II	9.7
R12	18.1	2.3	5.9	SI	-	-	BIOG		MAT	-	+	+	+	+	+	-	NO	IIonIII	11.0
R13	3.4	1.7	1.0	FSPB	-	+	PHY	Pebbles on surface	-	+	-	-	+	-	-	-	NO	I	2.7
R14	8.8	1.4	1.9	FSSIGR	BED	-	BIOG		MAT	+	+	+	+	+	-	-	NO	I	5.3
R15	8.7	1.8	1.3	SI	BED	-	BIOG		-	-	-	+	-	-	+	-	NO	I	3.0
R16	11.3	1.6	1.1	SI	+	-	INTER	Senescent tube mat, Pebbles on surface	MAT	+	-	+	+	-	+	-	NO	I/II	4.0
R17	16.6	1.4	0.8	SI	-	-	INTER		MAT	+	-	+	+	+	-	-	NO	II	4.3
R18	17.4	0.9	4.9	SI	-	-	BIOG		MAT	+	+	+	+	+	+	-	NO	IIonIII	10.7
R19	1.1	0.6	>1.1	FSGR	+	-	PHY		-	-	-	-	-	-	-	-	NO	I	>3.0
R20	2.1	1.7	>1.9	FSMSGRPE	+	-	PHY		-	+	-	-	-	-	-	-	NO	I	>4.0
R21	11.0	1.1	3.8	SIFS	-	-	BIOG		MAT	-	+	+	+	+	-	-	NO	II/III	9.3
R22	11.6	0.7	2.9	SIFS	-	-	BIOG		MAT	-	+	+	+	+	-	-	NO	II	7.7
R23	3.8	1.1	0.8	FS	+	+	INTER	Senescent tube mat	+	+	-	+	+	-	-	-	NO	I/II	3.0
R24	13.0	0.7	2.1	SI	-	-	BIOG		MAT	-	+	+	+	+	-	-	NO	IIonIII	7.3
R25	16.5	1.2	4.3	SI	-	-	BIOG		MAT	-	+	+	+	+	+	-	NO	IIonIII	10.0
R26	17.5	1.2	0.6	SI	-	-	INTER		+	+	-	-	+	-	+	-	NO	I/II	3.0
R27	17.3	1.7	4.3	SI	-	-	BIOG		MAT	-	-	+	+	+	+	-	NO	IIonIII	10.3
R28	13.1	0.7	4.3	SIFS	-	-	BIOG		MAT	-	+	+	+	+	-	-	NO	II/III	9.7
R29	15.3	0.6	4.5	SIFS	-	-	BIOG		MAT	-	-	+	+	+	+	-	NO	IIonIII	10.0
R30	9.1	0.8	3.0	SIFS	-	-	BIOG		MAT	-	-	+	+	+	-	-	NO	II/III	8.3

* > At least one of the three station replicates had an RPD layer deeper than the prism penetration.

Table 3-1. (continued)

Stat.	Pen.	SR	RPD	Sediment	Shell	Bed-Forms	Dominant Process	Comments	Am-pelisca	Worm Tubes	Stick Amphi.	Infauna	Bur-rows	Oxic Voids	Anaero. Voids	Gas Voids	Low DO	Median SS	OSI
R31	14.8	1.3	4.3	SI	-	-	BIOG		MAT	-	+	+	+	+	-	-	NO	II/III	9.0
R32	12.9	1.5	0.8	SI	+	-	PHY		+	-	-	+	+	+	+	-	NO	I/II	3.7
R33	12.2	2.5	0.4	SI	+	-	INTER		-	+	-	-	+	+	+	-	NO	I	2.3
R34	18.0	0.9	0.3	SI	-	-	BIOG	Microalgal Mat	-	+	-	+	-	+	+	-	NO	I	2.3
R35	16.3	1.5	0.7	SI	-	-	INTER		-	+	-	+	+	+	+	-	NO	I	2.7
R36	4.7	0.7	0.9	FSSI	+	+	INTER	Pebbles on surface	-	+	-	-	-	-	-	-	NO	I	3.0
R37	13.6	0.8	0.9	SIFS	+	-	INTER		+	+	-	+	+	+	+	-	NO	I/II	4.0
R38	16.5	2.8	1.8	SI	-	-	BIOG		MAT	-	-	+	-	+	+	-	NO	IIonIII	6.7
R39	17.4	1.2	4.4	SI	-	-	BIOG		MAT	-	-	+	+	-	+	-	NO	II	9.0
R40	7.0	1.5	0.8	FSSI	+	+	INTER		+	+	-	+	+	-	+	-	NO	I	2.7
R41	5.8	0.9	1.3	FSSI	+	-	INTER		-	+	-	+	+	-	-	-	NO	II	4.7
R42	3.0	1.2	1.4	FS	+	+	PHY	Pebbles on surface	-	+	-	-	-	-	-	-	NO	I	>3.7
R43	18.0	0.7	0.4	SI	-	-	INTER		-	+	-	-	-	+	+	-	NO	I	2.0
R44	16.0	2.3	1.5	SI	-	-	BIOG		MAT	+	-	+	+	+	+	-	NO	II	5.7
R45	16.0	1.3	3.0	SI	-	-	BIOG		MAT	-	+	+	+	+	+	-	NO	II	7.7
R46	16.7	0.9	3.2	SI	-	-	BIOG		MAT	-	+	+	+	+	+	-	NO	IIonIII	9.0
R47	14.0	1.2	4.4	SI	-	-	BIOG		MAT	+	+	+	+	+	+	-	NO	II/III	9.3
R48	13.2	0.4	0.7	SIFS	+	-	INTER		+	-	-	+	+	+	-	-	NO	I/II	3.0
R49	11.6	1.1	1.1	SIFS	+	-	INTER		+	+	-	+	-	-	+	-	NO	I	3.0
R50	12.5	1.2	2.0	SIFS	-	-	INTER	Senescent tube mat	MAT	-	-	+	+	+	+	-	NO	IIonIII	7.7
R51	13.7	0.9	0.9	SIFS	+	-	INTER		+	+	-	+	+	+	+	-	NO	I	3.0
R52	10.3	0.8	1.0	SIFS	-	-	INTER		-	+	-	-	+	+	-	-	NO	I/II	3.5
R53	8.8	0.9	1.0	FSSI	+	+	INTER		-	+	-	-	+	-	-	-	NO	I	2.5
R54	0.3	1.2	.	PBGR	-	-	PHY	Shallow penetration	-	-	-	IND	IND	IND	IND	-	NO	IND	IND
R55	8.5	0.9	0.9	SIFS	-	-	INTER		+	-	-	+	+	+	-	-	NO	II	5.0
T01	8.0	1.3	1.6	SIFS	+	-	PHY	Pebbles on surface	-	+	-	+	+	-	-	-	NO	I	3.7
T02	14.1	2.9	0.9	SI	-	-	INTER		+	+	+	+	+	+	+	-	NO	I/II	3.7
T03	10.4	0.9	1.3	SI	-	-	BIOG		MAT	-	+	+	+	+	+	-	NO	II	5.7
T04	14.8	0.6	0.0	SI	-	-	PHY	Bacterial Mat	-	-	-	-	-	-	-	+	YES	0	-5.3
T05A	8.0	0.6	1.3	FS	-	-	INTER	High orgainic sand	-	+	+	+	+	+	+	-	NO	IonII	4.3
T06	13.1	0.8	3.1	SIFS	-	-	BIOG		MAT	-	+	+	+	+	-	-	NO	II	7.7
T07	15.9	0.9	0.5	SI	+	-	INTER		-	+	-	+	-	+	+	-	NO	I	2.7
T08	1.7	0.4	>1.7	FS	+	+	PHY		-	+	-	-	-	-	-	-	NO	I	>3.7

* > At least one of the three station replicates had an RPD layer deeper than the prism penetration.

Table 3-1. (continued)

Key:

Stat. = Station
Pen. = Average prism penetration depth (cm)
SR = Average surface relief or bed roughness across the 15 cm width of the prism face plate (cm)
RPD = Average depth of the apparent color RPD (cm)

Sediment:

		MS =	Medium-sand	GR =	Gravel	SIFS =	Silty Fine-sand
FS =	Fine-sand	FSSI =	Fine-sand-silt	PB =	Pebble	SI =	Silt

Shell:

-=	Not present	+=	Some shell present	BED=	Shell bed

Bedforms:

-=	Not present	+=	Present

Dominant Process:
BIOLG = Biological processes dominate surface sedimentary features
INTER = Both biological and physical processes shape surface features
PHY = Physical processes dominate surface sedimentary features
Ampelisca = *Ampelisca* spp. amphipod tubes
Worm Tube = Worm tubes
Stick Amphi. = Stick amphipod biogenic structures, likely the genus *Dyopedos*:
- -= Not present
- += Few to many tubes present
- MAT = Tube mat present

Burrows = Infaunal burrows:
Oxic Voids = Water filled inclusions in sediment that appear to have oxidized sediment in them
Anaero. Voids = Water filled inclusions in sediment that appear to have anerobic sediment in them

Gas Voids = Gas filled inclusions in sediment:
- -= Not present
- += Present

Low DO = Appearance that low dissolved oxygen condition were present when the image was taken.

SS = Estimated successional stage
- I = Pioneering sere
- II = Intermediate sere
- III = Equilibrium sere

OSI = Organism Sediment Index of Rhoads and Germano (1986)

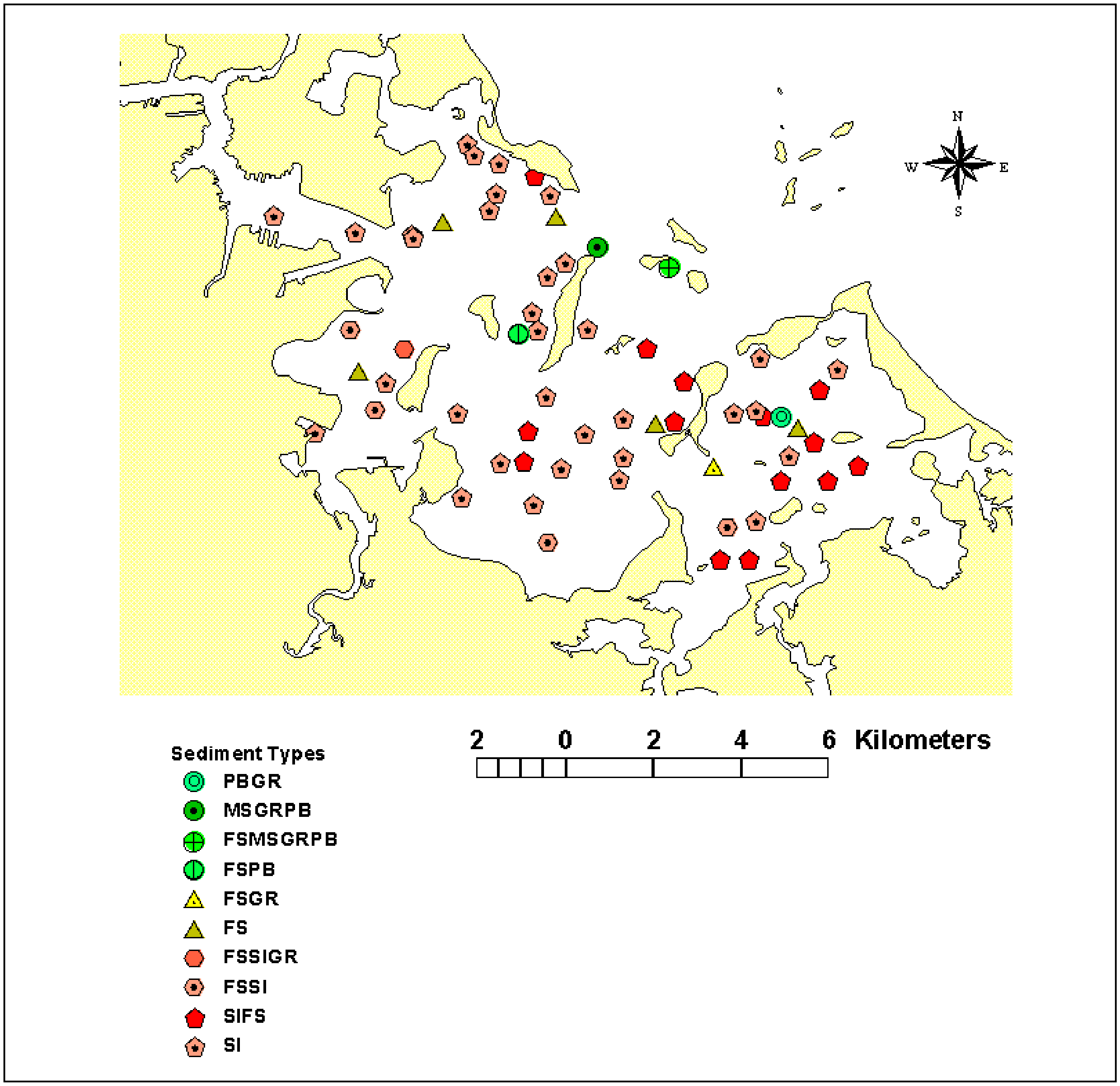


Figure 3-1. Distribution of sediment types at Harbor stations as determined from SPI, August 1998. Sediment type abbreviations are as listed in the key to Table 3.1.

The stations with the most spatial variability in sediment type were: R06, R14, and R20 where each replicate had a different sediment classification. At Station R14, the three image replicates graded from silty-fine sand to silty-fine sand, gravel, and shell over a distance of 33 m. Stations R06 and R20 on the outer edge of the Harbor had coarse, heterogeneous sediments. Pure sands and gravels, indicative of high kinetic energy bottoms, tended to occur toward the mouth of the Harbor (Figure 3-1). Bedforms, also an indicator of higher energy bottoms, were seen at seven stations, three of which had significant amounts of finer silts mixed in with the sand. Most stations were homogeneous finer sediments, fine-sand-silts to silts (Figure 3-1), with all three image replicates being similar. What appeared to be pebbles were on the surface of finer sediments at five stations (Table 3-1). This may be an indication that these stations are near transition points from finer to coarser sediment bottoms.

The broad range of sedimentary habitats within the Harbor is reflected in the range of average station prism penetration (0.3 to 20.3 cm). Prism penetration was related to sediment type, with the lowest penetration occurring in mixed coarser sediments with gravel and pebble, 1.6±0.5 cm (mean±std.er.) and in fine sand 3.7±1.2 cm (Table 3-2, Figure 3-2). Average penetration in silty-fine sand (FSSI) sediments was 7.0±0.8 cm, sandy-silt (SIFS) 11.8±0.6 cm, and low compaction silty sediments averaged 15.6±0.5 cm penetration with one replicate for station R16 being > 25 cm.

The bed roughness or surface relief in areas that appeared to be dominated by physical and biological processes was about the same magnitude (Table 3-2, Figure 3-3). Physically dominated bottoms tend to have coarser sediments, with bedforms in sands formed by water movement, and sediment surfaces lack evidence of biological activity. Biologically dominated bottoms tend to have mixed to finer sediments and surface sediments modified by biogenic activity (burrowing, feeding, and irrigating). The range of surface relief at the stations was 0.4 to 3.0 cm over the entire study area (Table 3-1). In physically dominated sandy habitats surface relief (bed roughness) was typically small sand ripples or bedforms (from 0.4 to 1.7 cm high). In muddy habitats surface relief was typically irregular surfaces, caused by biogenic activity of benthic organisms, primarily varying thickness of *Ampelisca* spp. tube mats and what appeared to be feeding pits or mounds.

The most prominent surface feature in the sediment profile images was *Ampelisca* spp. tube mats, which occurred at 28 (45%) stations (Table 3-1, Figure 3-4, Appendix B-2). The distribution of *Ampelisca* tubes appeared related to grain size with mats occurring only in silty fine sands (8 of 19 stations with SIFS and FSSI) and silts (20 of 33 stations with SI). It is possible that the tube-building and feeding activities of *Ampelisca* contribute to making the sediments finer by trapping particles among the tubes. Where *Ampelisca* mats occurred, the median RPD depth was 3 cm and the minimum ∃1 cm, except at Station R17, an indication of the importance of this amphipod in irrigation of surface sediments and advancing community succession. When mats were not present, RPD depths usually were < 2 cm (Figure 3-5). Worm tubes also were seen at mat densities at Station R04 (Table 3-1). The largest area without *Ampelisca* mats was Quincy Bay. Mats did occur at stations close to inner Boston Harbor (R09 and R44, Figure 3-4), however, only a few *Ampelisca* tubes were seen in one replicate image from Station T02, which was located 70 m from Station R44.

Apparent Color RPD Depth–The average apparent color redox potential discontinuity (RPD) layer depth ranged from 0.0 to 7.1 cm over the study area (Table 3-1, Figure 3-6). Silty fine sand and silty sediments with high levels of biogenic activity had the deepest apparent color RPD depths whereas the shallowest RPD depths were associated with stations that exhibited signs that physical processes structured surface sediments (Figure 3-7).

Table 3-2. Harbor area summary of SPI parameters for August 1998 by sediment category. Data from all three replicates were first averaged and then statistics calculated by sediment category. Sediment categories were assigned by major model sediment type, the first and second descriptor (*e.g.*, R14 with FSSIGR was placed in category FFSI). N is the number of stations with data in each category and SE is the standard error of the mean.

Parameter	Minimum	Maximum	Median	Mean	SE	N
Prism Penetration (cm)						
MS,GR,PB	0.3	3.4	1.5	1.8	0.5	5
FS	1.7	8.0	3.0	3.7	1.2	5
FSSI	4.7	8.8	7.0	7.0	0.8	5
SIFS	8.0	15.3	12.1	11.8	0.6	14
SI	8.7	20.3	16.0	15.6	0.5	33
Surface Relief (cm)						
MS,GR,PB	0.6	3.0	1.7	1.6	0.4	5
FS	0.4	2.2	1.1	1.1	0.3	5
FSSI	0.7	1.5	0.9	1.1	0.2	5
SIFS	0.4	1.3	0.8	0.9	0.1	14
SI	0.6	2.9	1.2	1.4	0.1	33
Depth of Apparent Color RPD (cm)						
MS,GR,PB	1.0	2.2	1.5*	1.6	0.3	4
FS	0.8	1.8	1.4	1.4	0.2	5
FSSI	0.8	1.9	1.0	1.2	0.2	5
SIFS	0.7	4.5	1.8	2.2	0.4	14
SI	0.0	7.1	1.5	2.2	0.3	33
Organism Sediment Index						
MS,GR,PB	2.7	4.0	3.0	3.2	0.4	3
FS	3.0	4.3	3.7	3.6	0.2	5
FSSI	2.5	5.3	3.0	3.6	0.6	5
SIFS	3.0	10.0	6.4	6.1	0.7	14
SI	-5.3	11.0	5.7	5.7	0.6	33
Infauna (number/image)						
MS,GR,PB	0.0	0.0	0.0	0.0	0.0	4
FS	0.0	0.7	0.0	0.2	0.1	5
FSSI	0.0	1.7	0.3	0.6	0.3	5
SIFS	0.0	4.7	2.0	1.9	0.4	14
SI	0.0	4.7	1.7	1.7	0.2	33
Burrows (number/image)						
MS,GR,PB	0.0	0.3	0.0	0.1	0.1	4
FS	0.0	1.3	0.0	0.3	0.3	5
FSSI	0.0	2.3	0.7	1.1	0.5	5
SIFS	0.0	4.7	2.5	2.4	0.4	14
SI	0.0	5.3	2.0	2.2	0.3	33
Oxic Voids (number/image)						
MS,GR,PB	0.0	0.0	0.0	0.0	0.0	4
FS	0.0	0.7	0.0	0.1	0.1	5
FSSI	0.0	0.3	0.0	0.1	0.1	5
SIFS	0.0	2.7	0.7	0.9	0.2	14
SI	0.0	3.7	0.7	0.7	0.1	33
Anaerobic Voids (number/image)						
MS,GR,PB	0.0	0.0	0.0	0.0	0.0	4
FS	0.0	1.0	0.0	0.2	0.2	5
FSSI	0.0	0.3	0.0	0.1	0.1	5
SIFS	0.0	1.7	0.0	0.3	0.2	14
SI	0.0	3.0	1.0	1.2	0.2	33

* > At least one of the three station replicates had an RPD layer deeper than the prism penetration.

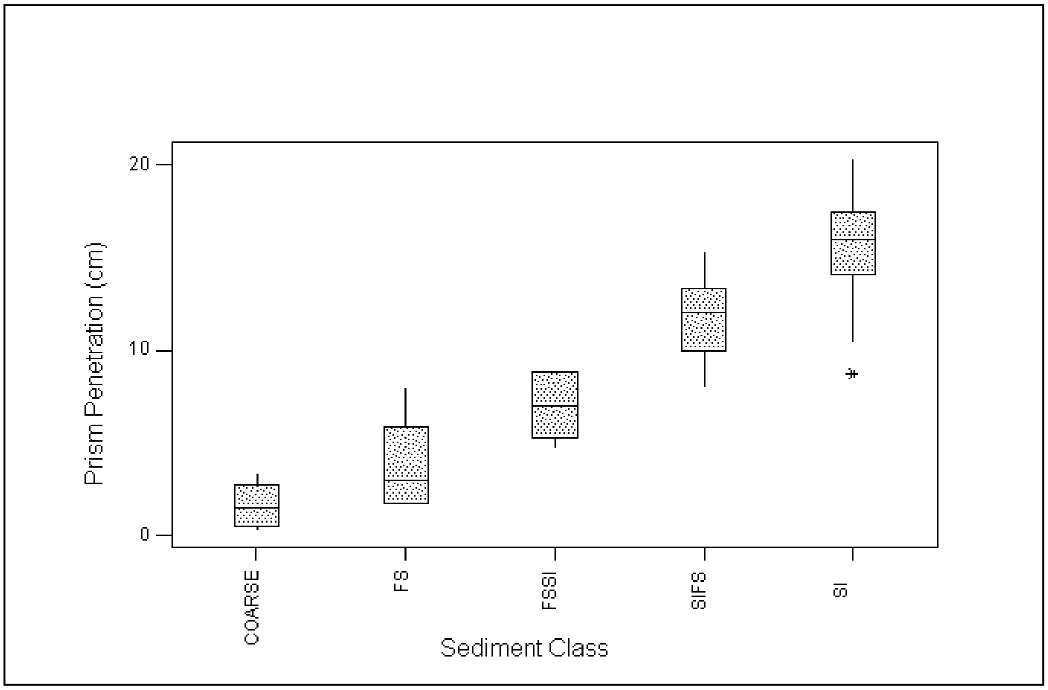


Figure 3-2. Boxplots of prism penetration (cm), a proxy for sediment compaction, by sediment type classes at Harbor stations, as determined from SPI, August 1998. The box represents the interquartile range (IQR, the center 50% of observations); whiskers are 1.5 times the IQR, * are outliers (> or < 1.5 IQR).

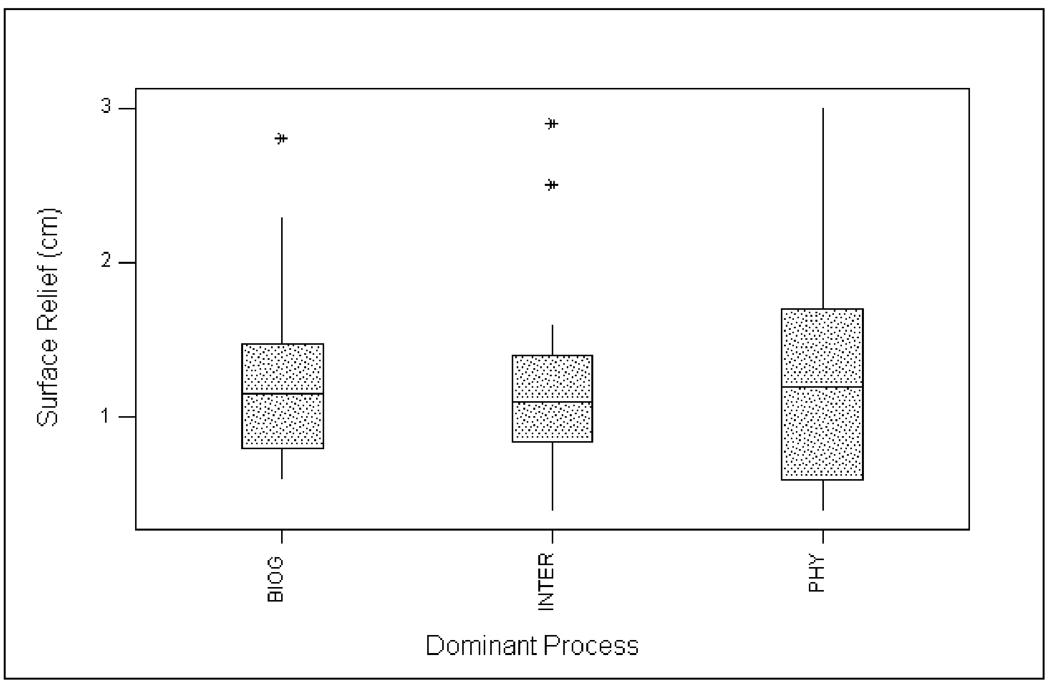


Figure 3-3. Boxplots of surface relief (cm), a measure of small scale bed roughness, by dominant processes that appeared to be at work shaping sediment surfaces at Harbor stations, as determined from SPI, August 1998. BIOG – Biological processes, PHY – Physical processes, INTER – both types of processes. Boxplot features as in Figure 3-2.

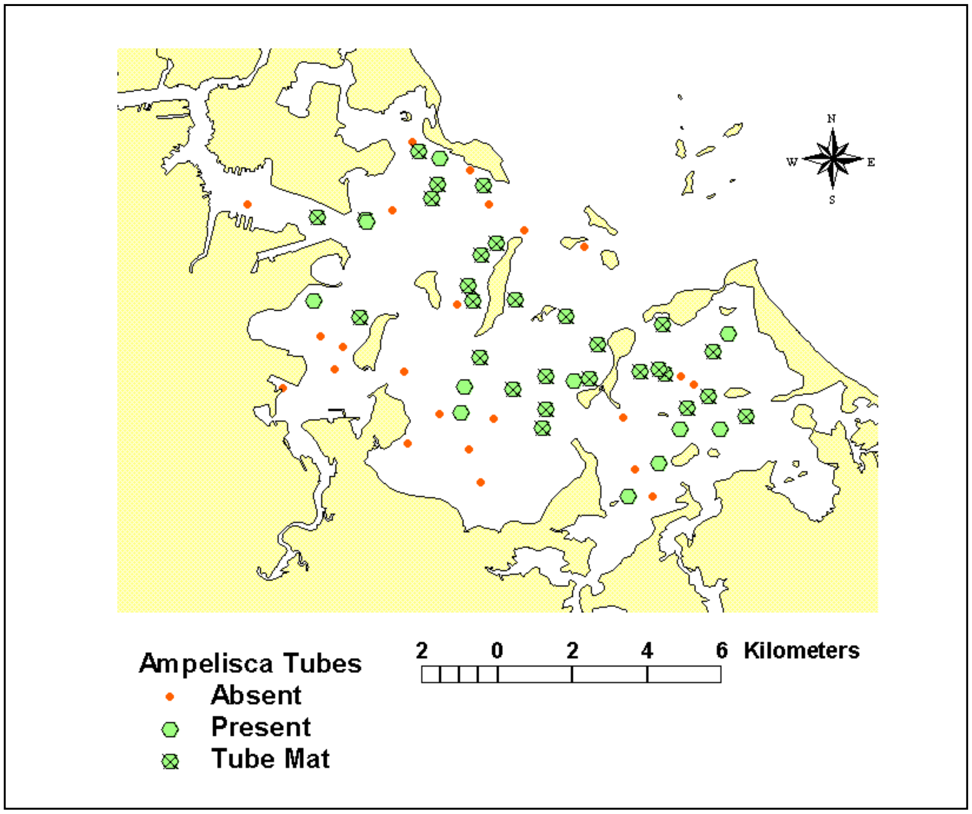


Figure 3-4. Distribution of *Ampelisca* spp. at Harbor stations as determined from SPI, August 1998.

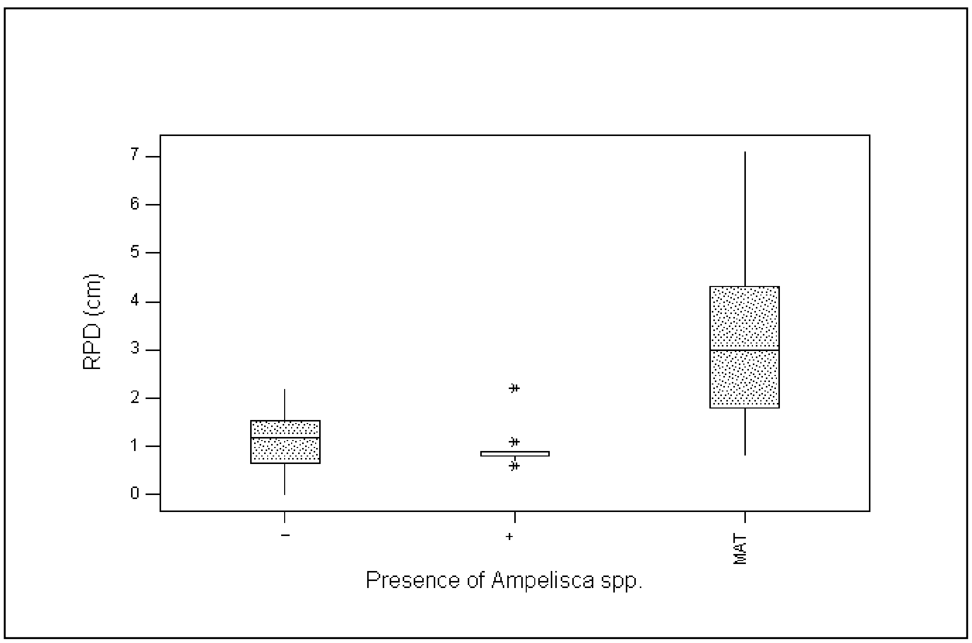


Figure 3-5. Boxplots of apparent color redox potential discontinuity layer (RPD) depth (cm), a measure of the thickness of oxidized sediments, by presence of *Ampelisca* spp. tubes at Harbor stations, as determined from SPI, August 1998. Boxplot features areas in Figure 3-2.

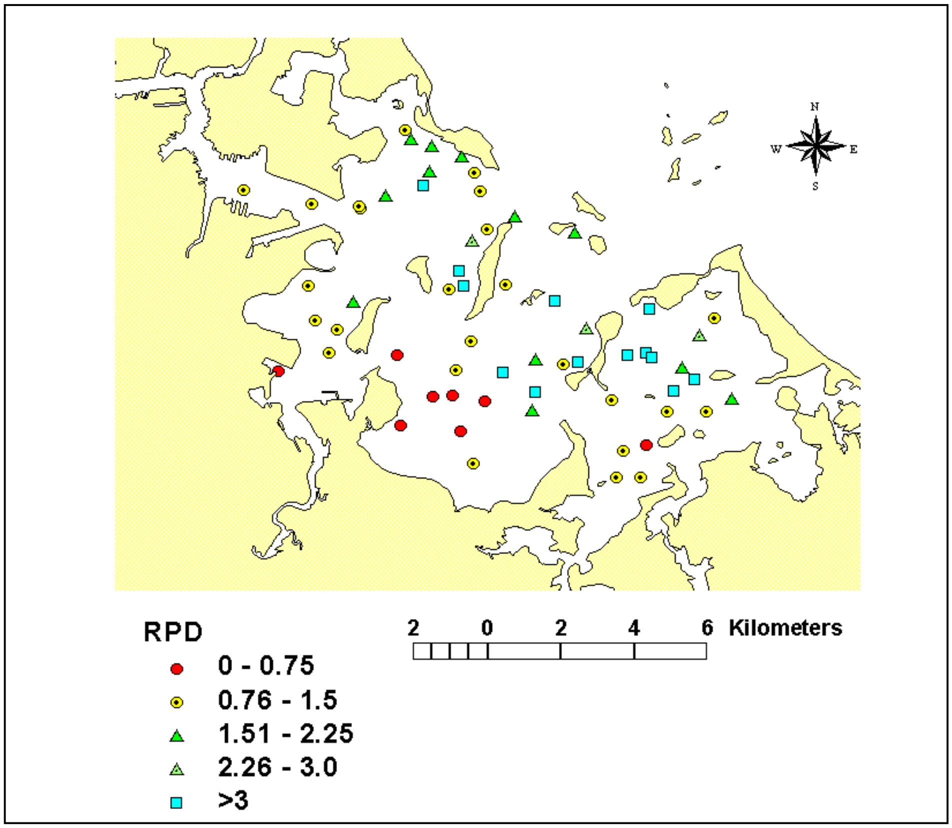


Figure 3-6. Distribution of the apparent color redox potential discontinuity layer (RPD) depth (cm) at Harbor stations as determined from SPI, August 1998.

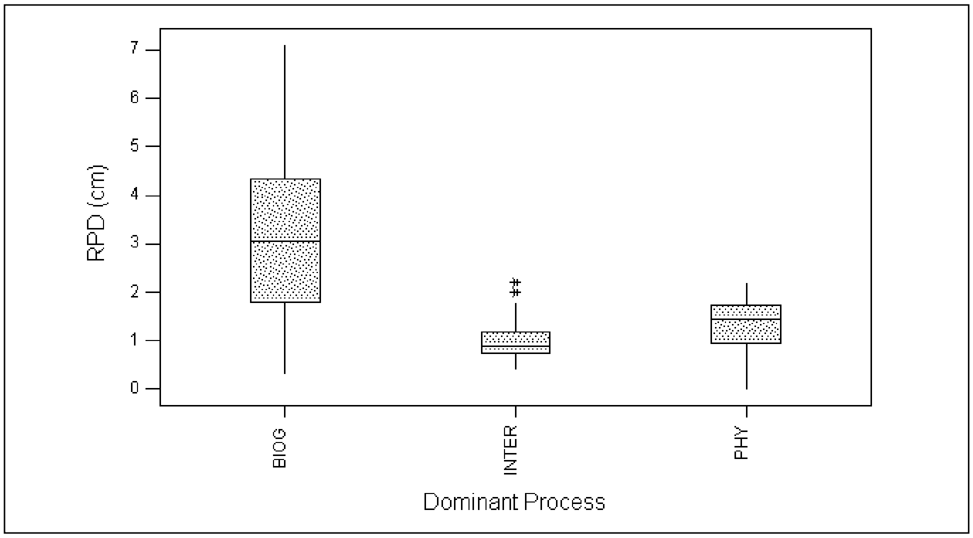


Figure 3-7. **Boxplots of apparent color redox potential discontinuity layer (RPD) depth (cm), a measure of the thickness of oxidized sediments, by dominant processes that appeared to be at work shaping sediment surfaces at Harbor stations, as determined from SPI, August 1998. BIOG – Biological processes, PHY – Physical processes, INTER – both types of processes. Boxplot features are as in Figure 3-2.**

The lowest RPD value of 0.0 cm occurred at Station T04, which appeared to be organically enriched and under hypoxic stress (Appendix B-2, Plate 2). As organic loading increases, the RPD layer becomes shallower in response to increased sediment oxygen demand and the elimination of deep bioturbating fauna (Pearson and Rosenberg 1978). The benthic community at Station T04 has consistently shown the signs of being the most stressed of all stations sampled (see Section 5).

The deepest RPD layers were associated with *Ampelisca* tube mats in silty fine sand and silty sediments. These occurred west of Long Island and Hull Bay, and in general toward the mouth of the Harbor (Figure 3-6). Biogenic activity in the form of infaunal burrows convoluted and extended the depth of the RPD layer. Oxic sediments associated with burrows were observed at many stations well below the average depth of the RPD layer. Maximum extent of oxic sediments exceeded 10 cm at R11, R28, and R47 (Appendix B-1, MAXRPD). Areas with shallow (< 1.0 cm) RPD depths tended to occur south-east of Hull Island, west of Deer Island, inner Quincy Bay, Dorchester Bay, and around the City of Boston (Figure 3-6). Stations in these areas exhibited less biogenic activity and a dominance of physical processes.

Biogenic Activity—The sediment surface at 42% (26 of 62) stations was dominated by biological processes as evidenced by wide spread biogenic activity associated with successional stage II and III fauna (Table 3-1). Evidence that a combination of biological and physical processes were active in structuring bed roughness occurred at 40% (25) of stations. Physical processes dominated the five coarse sediment stations (Table 3-1) and two of the five fine sand stations. However, biogenic surface features were present at some fine sand and gravel stations, R14 for example. The surface biogenic structures observed included; *Ampelisca* tube mats, biogenic mud whips or sticks made by amphipods likely in the genus *Dyopedos* (Mattson and Cedhagen 1989, Thiel 1997; see Appendix B-2, Plate 1), small and large worm tubes, epibenthic organisms, burrow openings, feeding pits and mounds, and shells.

The distribution of subsurface biogenic features (burrow structures, infaunal organisms, water and gas filled voids) was sediment related and tended to mirror patterns seen for surface biogenic features. Burrows were seen at about 75% of all stations with average number of burrows per image highest in finer silty-fine-sand and silt sediments (Table 3-2, Figure 3-8). Gas-filled voids and bacterial mats occurred only at Station T04 (Appendix B-2, Plate 2), which was in Dorchester Bay, had silty sediments, and appeared to be hypoxic at the time of sampling. When bacterial mats occur it is a good indication that dissolved oxygen has been low for some period of time. Bacterial mats are known to form over a narrow range of dissolved oxygen concentrations, typically < 0.5 ml/L, and are restricted to the narrow transition zone between oxic and anoxic environments where oxygen and H_2S are continuously supplied by diffusion along opposite gradients (Jørgensen 1977, Jørgensen and Revsbech 1983). Water-filled voids, oxic and anaerobic, occurred at 79% of all stations with an occurrence pattern that was similar to burrows (Table 3-1). Voids and burrows are biogenic structures that are indicative of infaunal activities. The number of water-filled voids was about equally distributed between oxic (46%, apparently filled with oxidized sediment indicating current or recent infaunal activity) and anoxic (54%, apparently relic voids from previous infaunal activity or created by some physical processes such as sediment cracking during profiling of the sediment). These percentages are based on the numbers of voids observed on the images (Appendix B-2). Infauna were more abundant in silty sediments than in sandy sediment types (Table 3-1). Infauna were seen in 79% of silty fine sand stations, in 88% of the silt and 40% of the sand stations with prism penetration deep enough to evaluate the presence of infauna.

Subsurface biogenic structures and actives were highest at stations where biological processes dominated surface features. For example, the number of infaunal organisms present per image declined from a median of 2.0 to 0.0 between biologically and physically dominated surfaces (Figure 3-9). Similar patterns of higher median values at biologically dominated stations were

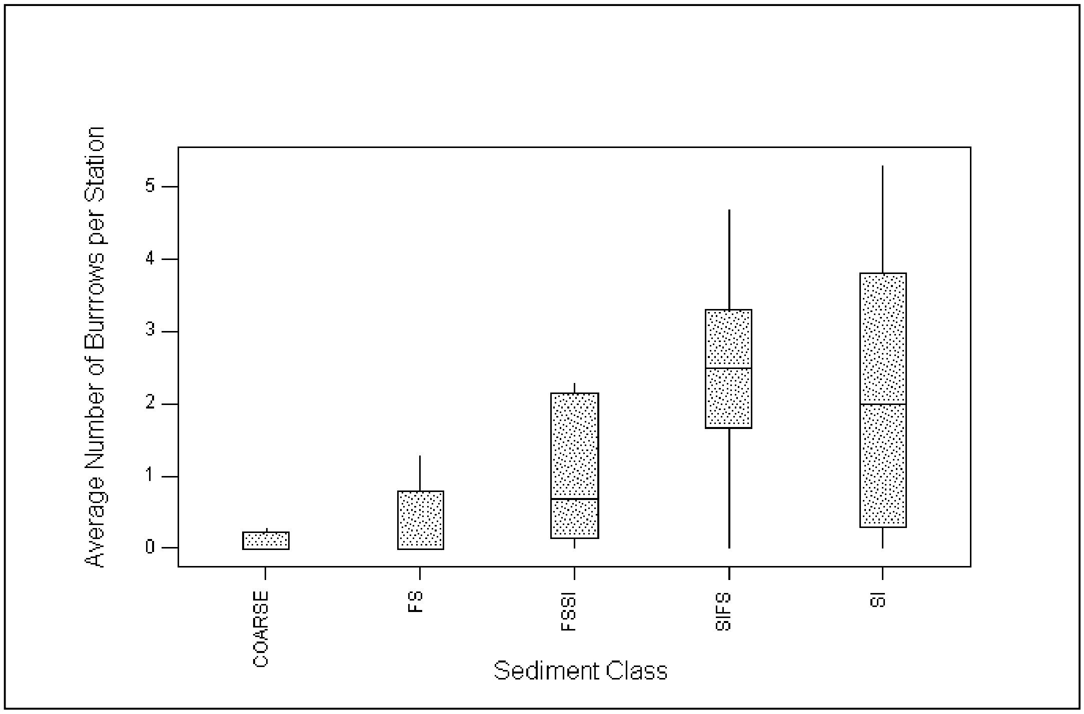


Figure 3-8. Boxplots of the average number of infaunal burrows, an indication of infaunal activity, by sediment type classes at Harbor stations, as determined from SPI, August 1998. Boxplot features are as in Figure 3-2.

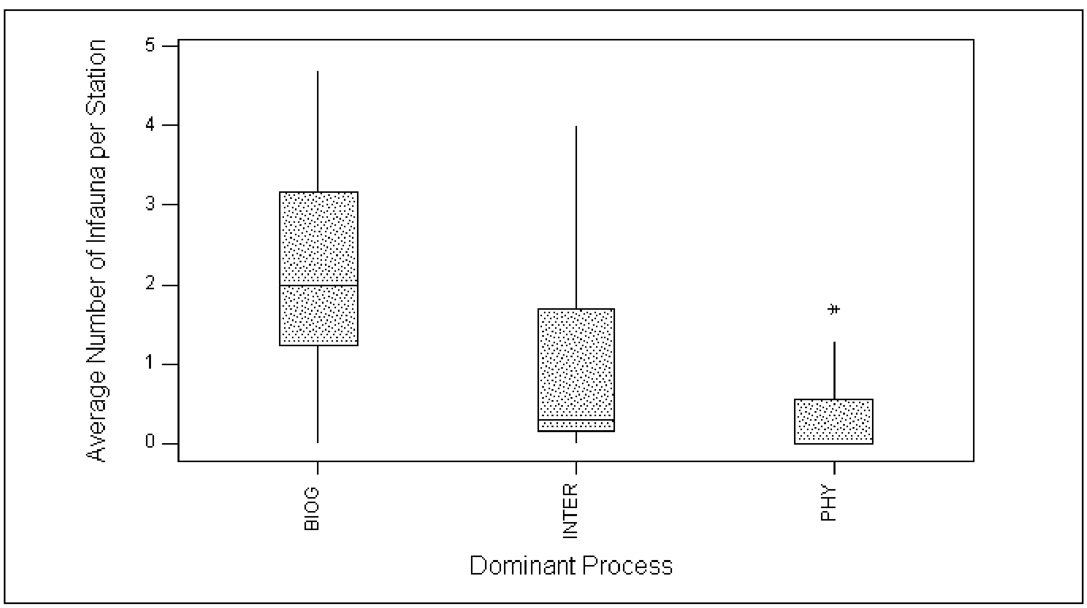


Figure 3-9. Boxplots of the average number of infaunal organisms, an indication of infaunal activity, by dominant processes that appear to be at work shaping sediment surfaces at Harbor stations, as determined from SPI, August 1998. BIOG – Biological processes, PHY – Physical processes, INTER – both types of processes. Boxplot features are as in Figure 3-2.

observed for number of burrows, oxic voids and anaerobic voids per image, and also the OSI. As many as eight free-burrowing worms were seen in individual replicates from Stations R07, R24, and R46 (Appendix B-1).

Successional Stage and Organism Sediment Index—The apparent successional stage of the benthos over the study area had a bimodal distribution with modes of stages I (20 stations) and stage II (13 stations, Figure 3-10), indicating that macrobenthic communities in the harbor area are split between pioneering and intermediate serial stages (see Section 5). The high degree of biogenic sediment reworking observed in many images was consistent with the stage II, and at times stage III, successional designation. Station T04 had the lowest successional stage designation (0 or azoic) with no indication of surface or subsurface biogenic activity (Table 3-1).

Some evidence of stage I communities occurred at about half (31 of 61) of the stations, whereas some evidence of stage II communities was found at about two-thirds (40 of 61) of the stations. Azoic conditions appeared to exist at Station T04 in Dorchester Bay (Figure 3-10) which also appeared to be affected by hypoxia. Silty fine sands and silts tended to have highest successional stages, with evidence of stage III communities at about a fourth (16 of 61) of the stations. *Ampelisca* tube mats were present at about two-thirds of all stations where the median successional stage of replicate images was estimated to be > stage I and at one replicate from Station R14 that had a median stage I designation. Station R14 appeared to be located on the edge of a transitional area between muddy bottom and a shell bed. It had heterogeneous sediments with one of three replicates being SIFS with the *Ampelisca* spp. tube mat present. The other two replicates did not have any *Ampelisca* tubes and graded to shelly sediments. A distance of 16 to 17 m separated the three replicate images.

The station average Organism Sediment Index (OSI) ranged from about –5 to 11 (Table 3-1). The single negative value occurred at Station T04 and resulted from a combination of the presence of gas-filled voids, low dissolved oxygen concentration (verified by the presence of bacterial mats), and what appeared to be azoic sediments. All these parameters are indicative of a poor quality benthic habitat. Positive, but low, OSI values characterized coarser sediments where the range was 2.7 to 5.3 (Table 3-2). For fine sand sediments, OSI values ranged from 3.0 to 4.3 (Table 3-2). OSI values for silty fine sand and silt sediment types were higher, averaging 5.7 to 6.1. The range of the OSI index in silt was greatest, from –5.3 to 11, with the negative value occurring at Station T04 (Figure 3-11). The highest OSI values were in silt and silty fine sand sediments (Figure 3-12), mostly west of Long Island and in Hull Bay.

The range of OSI values at Harbor stations was indicative of a wide range of macrobenthic communities, from severely stressed to well developed. Station T04 had the lowest OSI (–5.3) and level of community development of all stations sampled. The majority of Harbor stations had OSI values < 6 (65%, 39 of 60 stations), which indicates communities are under some form of moderate stress (Rhoads and Germano 1986). Most of these lower OSI stations were located in the inner bays and away from the Harbor mouth (Figure 3-11). Stations around the Harbor mouth had OSI > 6 and highest values of community structure. In the case of the harbor stations, both Traditional and Reconnaissance, the stress is most likely a combination of physical processes such as hydrodynamics and sediment transport at coarse sediment stations (for example R20) and high rates of sediment accumulation and organic enrichment at muddy stations (for example T04).

3.3 1998 Summary

While the distribution of sediment textures in the Harbor primarily results from a combination of sources, morphology, and hydrodynamics, 1998 SPI data showed that surface features were dominated by biogenic activity. *Ampelisca* tube mats, feeding pits and mounds, and worm tubes were the dominant surface biogenic structures occurring at all stations except R06, R19, R54, and T04. Subsurface biogenic structures and organisms were also common and widely distributed. Biogenic structures indicative of extreme environments were present at R06, macroalgal bed on coarse sediments associated with physically dynamic environments, and T04, bacterial mat on silty sediments associated with stagnant environments.

The predominance of biological activity at most stations, particularly those near the mouth of the Harbor, was indicative of a well-developed fauna that was generally characterized as being intermediate in successional stage. The organism sediment index (OSI) reflected this pattern, with values > 6 occurring toward the Harbor mouth and values < 6 in the inner areas of the Harbor. *Ampelisca* tube mats continue to be wide spread and indicative of the intermediate step (Stage II) in the macrobenthic community successional transition from the pioneering-dominated (Stage I) inner harbor area to the equilibrium-dominated (Stage III) Nearfield area in western Massachusetts Bay.

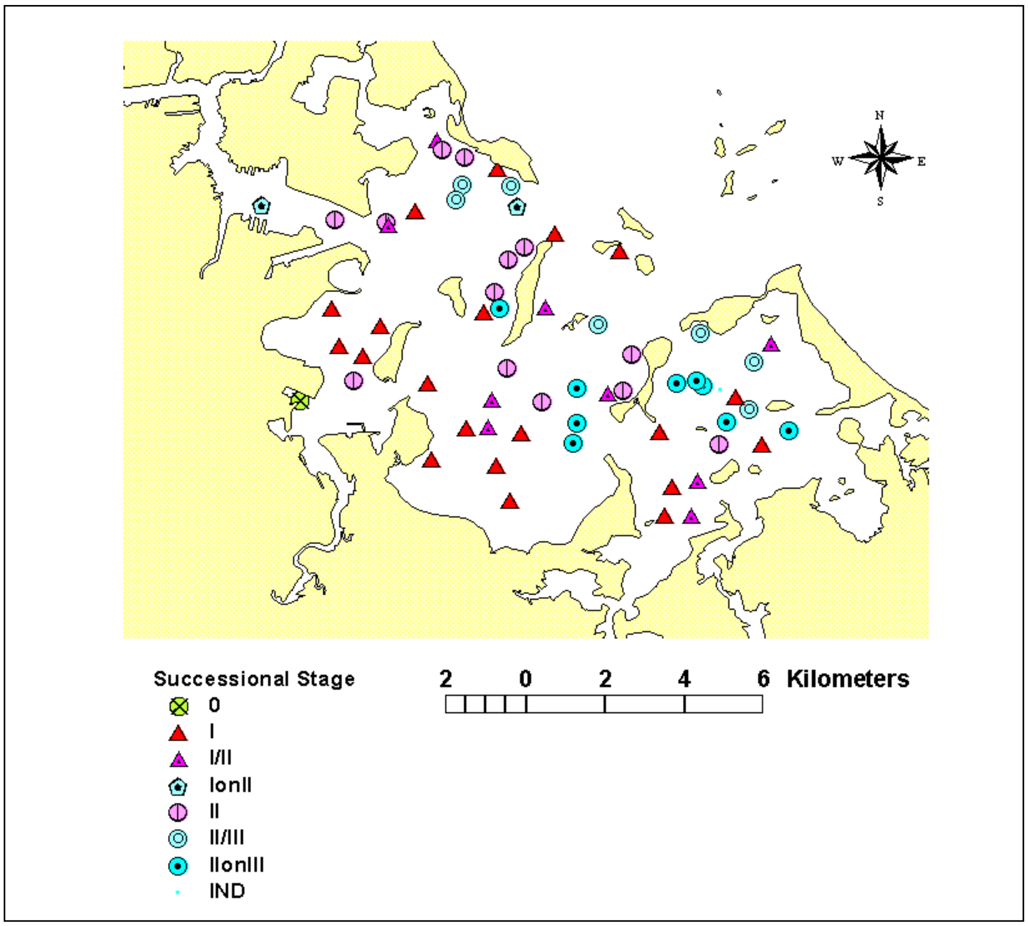


Figure 3-10. Distribution of apparent successional stages at Harbor stations as determined from SPI, August 1998. Roman numerals refer to successional stage, 0 refers to azoic sediments.

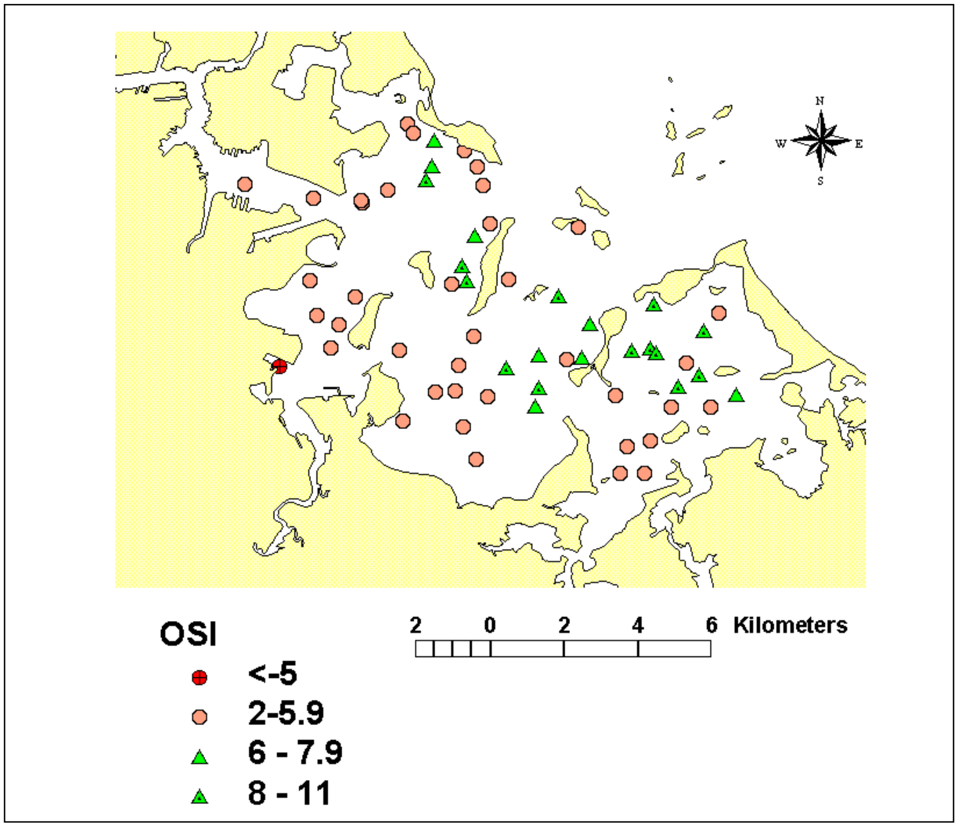


Figure 3-11. Distribution of the Organism Sediment Index (OSI) at Harbor stations as determined from SPI, August 1998.

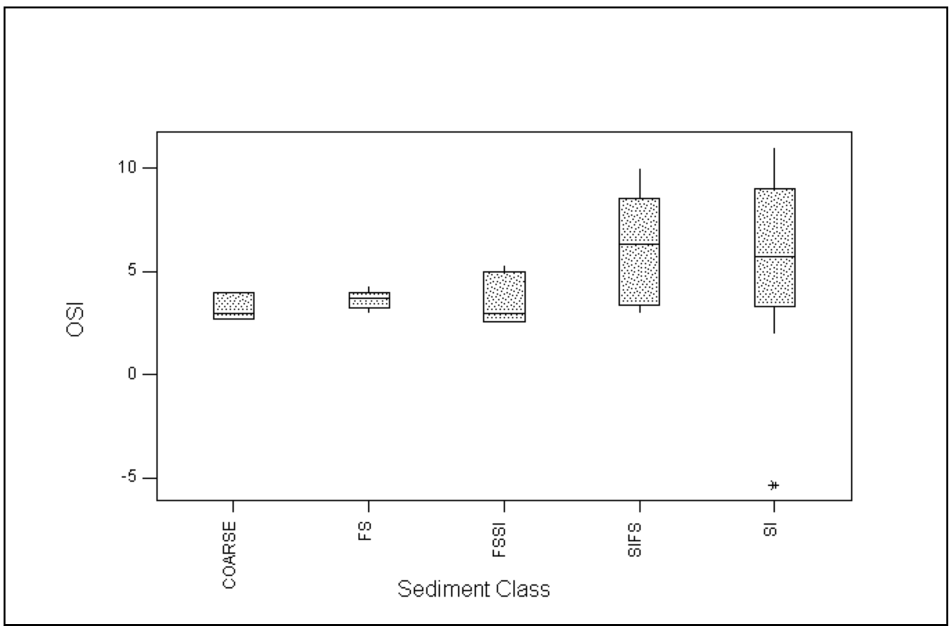


Figure 3-12. Boxplots of the Organism Sediment Index (OSI), an indicator of macrobenthic community development and activity, by sediment type classes at Harbor stations, as determined from SPI, August 1998. Sediment abbreviations are as listed in Table 3-1.

4.0 1998 SOFT-BOTTOM SEDIMENT CHEMISTRY

by Deirdre Dahlen

4.1 Methods

4.1.1 Laboratory Analyses for Ancillary Measurements

Laboratory procedures followed those outlined in the Benthic Monitoring CW/QAPP (Kropp and Boyle 1998). Concise summaries of the procedures are provided below.

Grain Size—Samples were analyzed for grain size by a sequence of wet sieving and dry sieving. Methodologies followed Folk (1974). The sand/gravel fraction was separated from the mud fraction. This sand/gravel fraction was transferred to a 200-mL beaker, decanted, and dried overnight at 95 ºC. The dried sand/gravel fraction was mixed by hand to disaggregate the material, and then dry-sieved on stacked -1-, 0-, 1-, 2-, 3-, and 4-phi sieves. Each size class was weighed to the nearest 0.1 mg on a top-loading balance. Particles smaller than 4 phi were analyzed using the pipette method. Data are reported in weight percent by size class. In addition, the gravel:sand:silt:clay ratio and a numerical approximation of mean size and sorting (standard deviation) was calculated. Grain size determinations were made by GeoPlan Associates.

TOC—TOC determinations were performed by Applied Marine Sciences, Inc. following SOP AMS – TOC94. A portion of the sample was dried at 70 ºC for 24–36 hours and ground to a fine powder. The sample was treated with 10% HCl to remove inorganic carbon and dried at 70 ºC for 24 hours. Between 10 and 500 mg of dry, finely ground, and homogenized sample were weighed to the nearest 0.1 mg and placed in a crucible that had been precombusted for 4 hours at 500 ºC. A Coulometric Carbon Analyzer was used to determine the TOC content of the samples. Data are reported as weight percent, dry weight.

***Clostridium perfringens*—**Sediment extraction methods for determination of *Clostridium perfringens* spores followed those developed by Emerson and Cabelli (1982) as modified by Saad (1992). The filters for enumeration of *Clostridium perfringens* spores were incubated anaerobically at 44.5 ºC for 24 hours. Following incubation, the filter was exposed to ammonium hydroxide for 15–30 seconds. Yellowish colonies that turn red to dark pink upon exposure were counted as *Clostridium perfringens*. Data are reported here as colony-forming units (cfu) per gram dry weight of sediment. This analysis was performed by MTH Environmental Associates.

4.1.2 Data Analyses

Sediment grain size results were evaluated by using ternary plots to visually display the distribution of sand, silt and clay in sediment collected from all stations during the April and August surveys. Results from sediment grain size, total organic carbon (TOC), and *Clostridium* analyses were compared from all stations using histogram plots. Linear regression analysis was performed on sediment grain size, TOC, and *Clostridium perfringens* data to examine the correlation between these parameters. Probability values were taken from Rohlf and Sokal (1969).

The numerical approximate mean phi, referred to simply as mean phi in the text, was calculated by weighting each class fraction measured and summing the weighted fractions (Table 4-1).

Table 4-1. An example of numerical approximate mean phi determination.

phi Class	Weight Factor[1]	% Fraction Measured (T01 August)	Weighted Fraction[2]
phi<-1	–2	1.11	–0.0222
-1<phi<0	–0.5	0.6	–0.0030
0<phi<1	0.5	0.64	0.0032
1<phi<2	1.5	4.52	0.0678
2<phi<3	2.5	20.93	0.5233
3<phi<4	3.5	49.54	1.7339
4<phi<8	6	14.6	0.8760
phi>8	9	8.1	0.7290
Sum of weighted fractions Numerical approximate mean phi[3]			3.91

[1] Weight Factor represents middle of the phi class range.
[2] Weighted Fraction = (Weight Factor)*(%Fraction Measure/100).
[3] Numerical approximate mean phi = Sum of weighted fractions.

4.2 Results and Discussion

Sediment samples collected in April and August 1998 from the eight Traditional stations were analyzed for grain size composition, total organic carbon (TOC), and *Clostridium perfringens* as described in Section 4.1.1. All 1998 grain-size, TOC, and *Clostridium* data are listed in Appendix C; summary data are presented in Table 4-2.

Table 4-2. Grain size, TOC, and *Clostridium perfringens* data from sediments collected at Traditional stations in April and August, 1998.

Station	T01	T02	T03	T04	T05A	T06	T07	T08
April 1998								
Gravel[1]	3.9	0	2.6	0	0.1	0.1	5.7	0.2
Sand[1]	74	16.4	34.9	2.8	79.1	51.4	22.7	62.6
Silt[1]	13.2	45.4	30.2	58.5	14.2	26.7	38.8	17.6
Clay[1]	8.8	38.2	32.3	38.7	6.6	21.8	32.8	19.5
Fines[2]	22	83.6	62.5	97.2	20.8	48.5	71.6	37.1
Mean phi[3]	3.75	6.7	5.55	7.07	3.93	5.2	5.74	4.44
TOC[1]	1.19	2.16	2.78	6.59	0.42	1.17	2.15	1.3
Clostridium perfringens[4]	4030	10500	16500	29800	2780	9050	8640	8430
August 1998								
Gravel	1.1	0.1	0.5	0	0	0.6	0.5	1
Sand	76.2	37.1	11.2	20.4	81.4	38.3	21.9	90.3
Silt	14.6	39.1	42.7	43.3	11.2	32	49.6	4.4
Clay	8.1	23.7	45.6	36.3	7.4	29.2	28	4.2
Fines	22.7	62.8	88.3	79.6	18.6	61.2	77.6	8.6
Mean phi	3.91	5.7	6.97	6.45	3.85	5.6	6.09	2.68
TOC	0.78	1.69	2.46	8.86	0.62	2.17	2.38	0.31
Clostridium perfringens	4450	8720	6840	15100	1400	7280	7650	1320

[1] Percent dry weight
[2] Fines is the sum of silt and clay.
[3] Numerical approximate mean phi (see Table 4-1).
[4] *Clostridium perfringens* reported in cfu per gram dry weight.

4.2.1 Grain Size

April 1998—Sediment grain size composition was highly variable (Table 4-2; Figure 4-1a). Two of the eight stations sampled (T01, T05A) were comprised of coarse sediments (> 75% sand and gravel; mean phi < 4); whereas more silty sediments (> 60% fines; mean phi > 5.5) were collected at stations T02, T03, T04, and T07. Sediment from station T04 contained the greatest amount of silt and clay (97% fines).

The phi analysis revealed that sediments generally were comprised of fine and very fine sands, silt and clay. Gravel, very coarse, coarse and medium sands were present only in small amounts. Very fine sand was the dominant sand fraction at stations T01, T05A, and T06; fine sand was dominant at station T08; and silt and clay fractions were dominant at stations T02, T03, T04, and T07 (Figure 4-2a).

Results from laboratory triplicate analyses for grain size composition that was performed on sediment from station T07 were similar, with coefficients of variation (CV) ranging from 1% to 8% for those fractions measured at levels greater than 10 × MDL.

August 1998—Sediment grain size composition generally clustered into two groups (Table 4-2; Figure 4-1b). Sediments collected from stations T01, T05A and T08 generally were comprised of coarse sediments (> 75% sand and gravel; mean phi < 4) and clustered in the upper apex of the ternary plot (Figure 4-1b). Siltier sediments (> 60% fines; mean phi > 5.5) were collected at stations T02, T03, T04, T06, and T07 and clustered in the middle region of the lower quadrants of the ternary plot (Figure 4-1b). Station T03 sediments contained the greatest amount of silt and clay (88% fines).

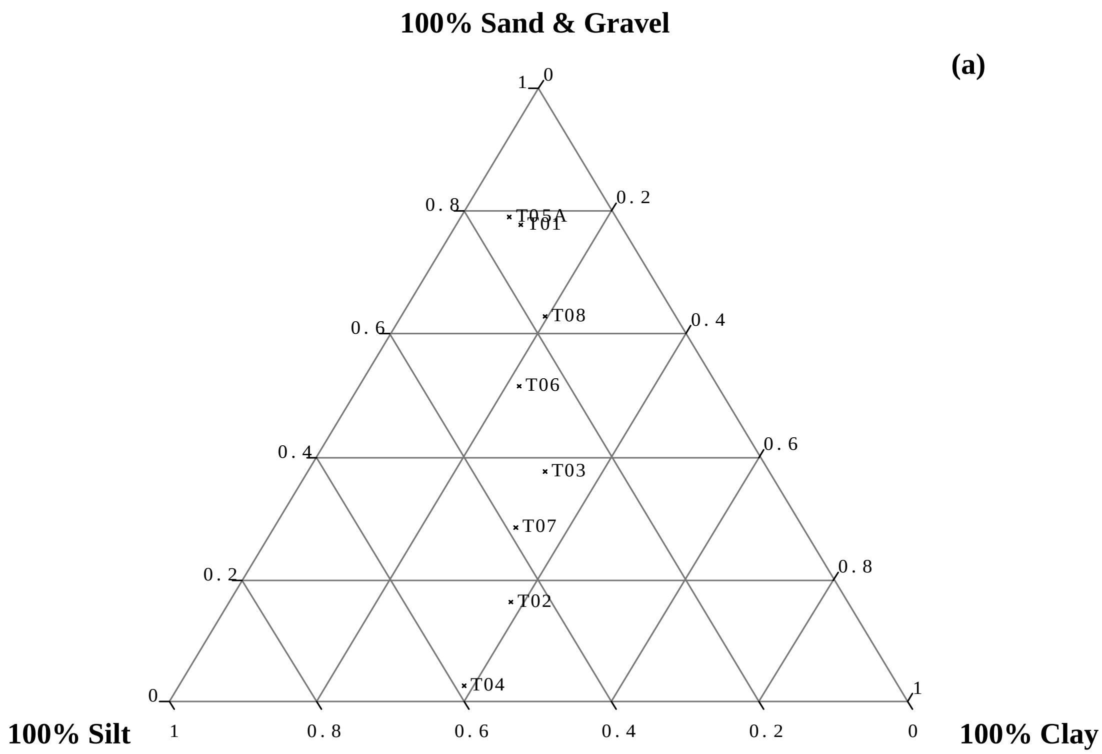
As was observed from the April survey results, sediments generally were comprised of fine and very fine sands, silt and clay. Gravel, very coarse, coarse and medium sands were present only in small amounts, except at station T08 where the medium sand fraction was slightly more than 20%. Very fine sand was the dominant sand fraction at stations T01 and T05A; fine sand was dominant at station T08. Silt and clay fractions were the dominant stations T02, T03, T04, T06, and T07 (Figure 4-2b).

Sediment composition at all stations was moderately variable between April and August surveys. Gravel content decreased at stations T01, T03 and T07; sand content more than doubled at stations T02 and T04 and decreased by a factor of 3 at station T03; and silt and clay content decreased by a factor of four at station T08.

4.2.2 Total Organic Carbon

April 1998—The TOC content of the samples collected in April was also quite variable (Table 4-2; Figure 4-3), ranging from 0.42 (T05A) to 6.59% dry weight (T04). Only one station had TOC levels less than 1% (T05A). Generally, the percentage of TOC increased in sediments that had higher percentage fines (i.e. mud, percent fines) (Figure 4-4). Elevated TOC content reflects areas where detrital organic matter accumulates during periods of low kinetic energy. Stations with low TOC content do not accumulate organic detritus due to frequent washing and sorting of the bottom by currents. The relationship between TOC and percent fines is illustrated in Figure 4-4. TOC correlated well with percent fines ($r = 0.81$, $n = 8$, $p < 0.05$) at all stations.

August 1998—The TOC content of the samples collected in August was also quite variable (Table 4-2; Figure 4-3), ranging from 0.31 (T08) to 8.86% dry weight (T04). As was observed from the April Survey results, the coarse sediments generally had a low TOC content, and the TOC content increased with percent fines (Figure 4-4). The relationship between TOC and percent fines is illustrated in Figure 4-4. TOC correlated well with percent fines ($r = 0.62$, $n = 8$, $p < 0.05$) at all stations. However, station T04 had much higher TOC content than would have been predicted by the TOC: grain size relationship demonstrated across the other seven stations. The correlation improved ($r = 0.98$, $n = 7$, $p < 0.01$) when T04 was excluded from the regression analysis.



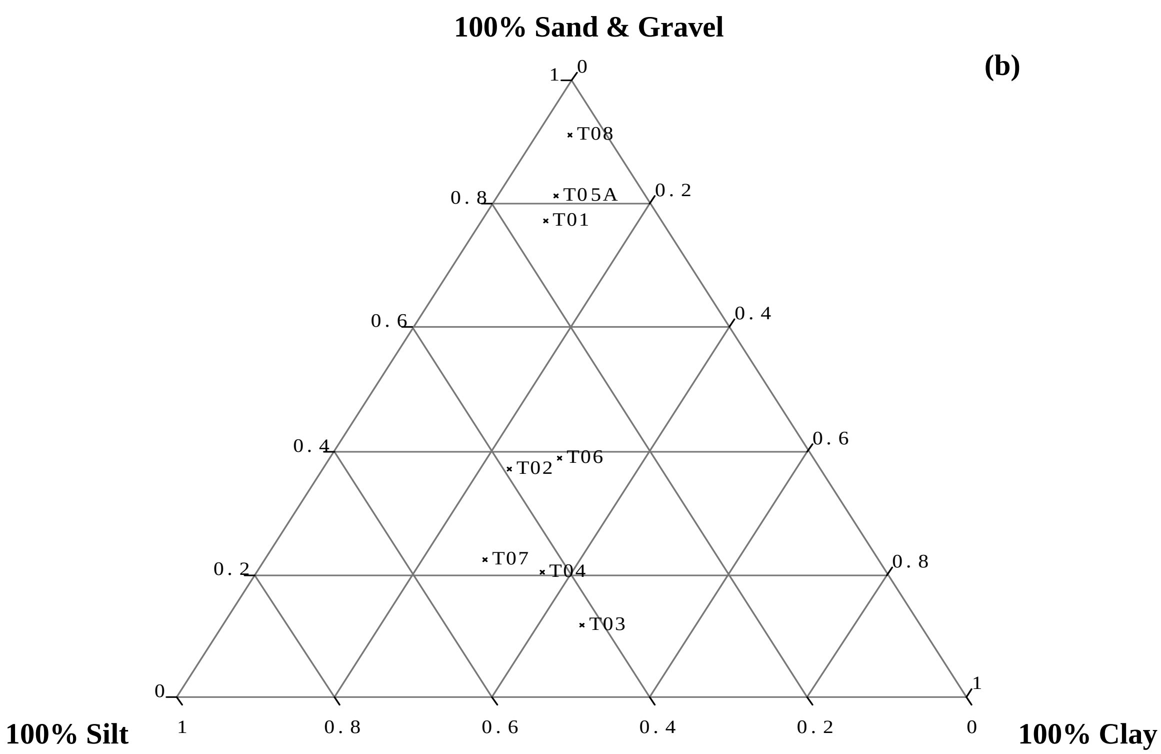
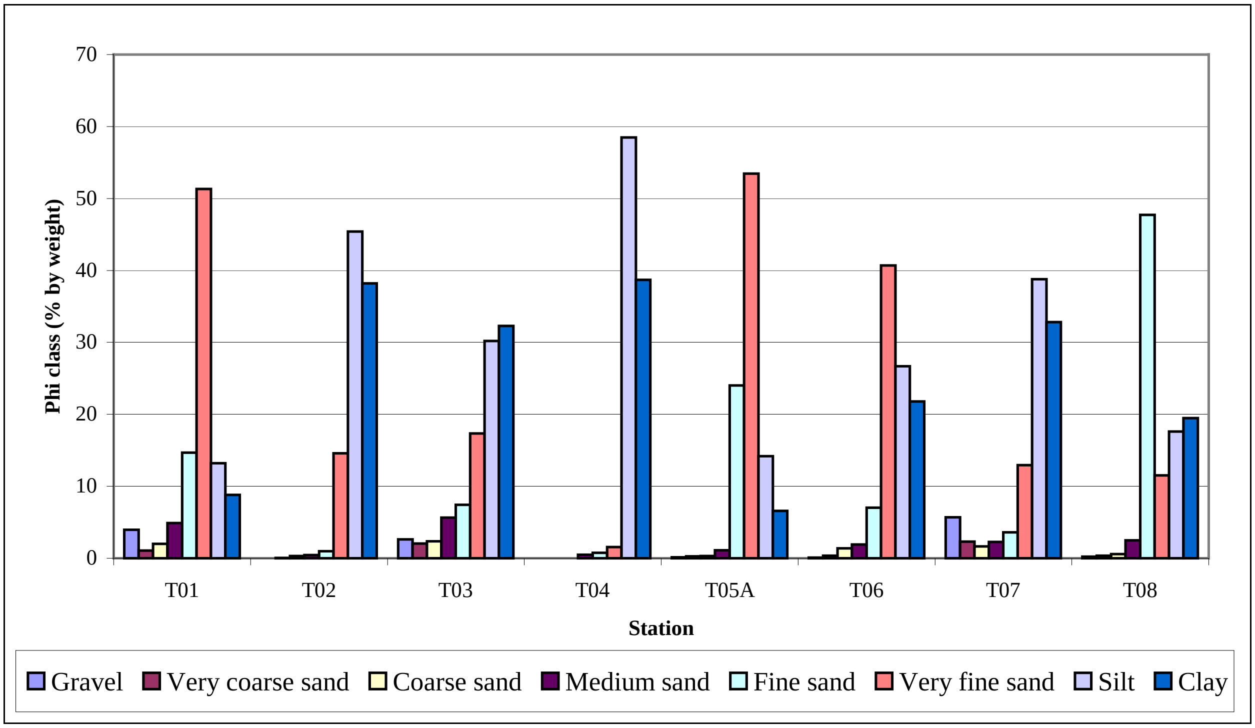


Figure 4-1. Grain size composition from sediments collected from Traditional stations in April (a) and August (b) 1998.

April (a)



August (b)

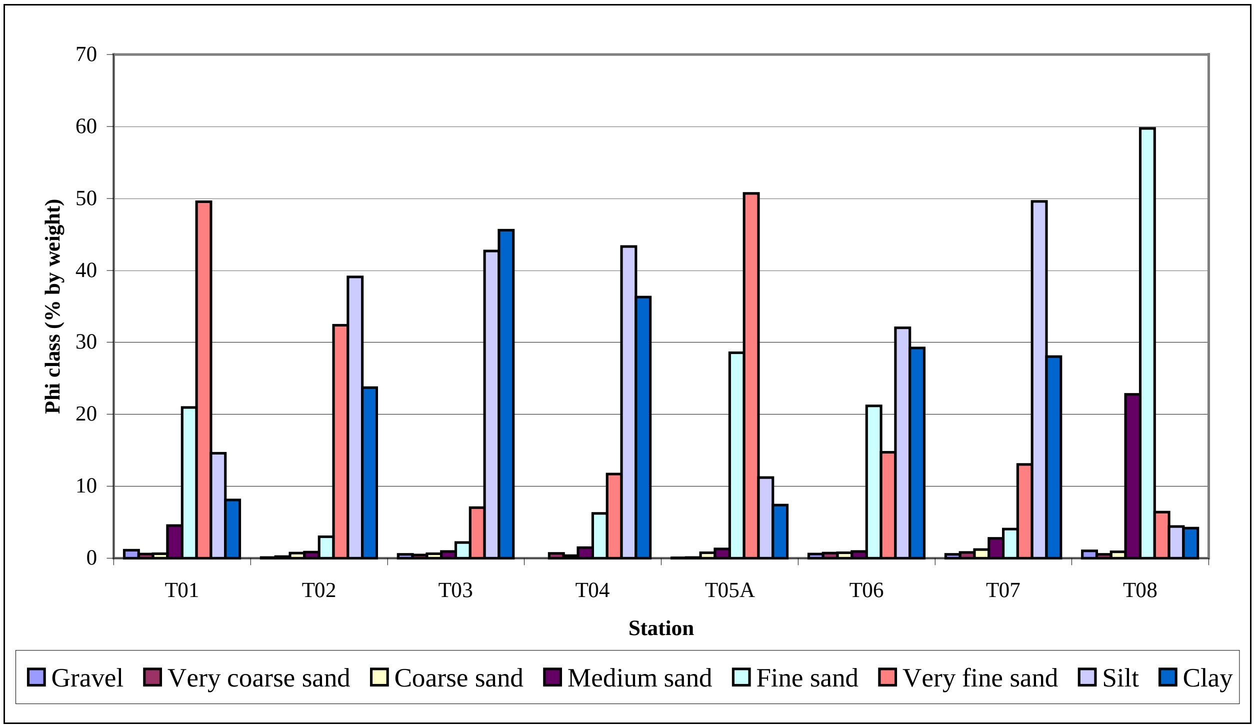


Figure 4-2. Phi class distribution in sediments collected from Traditional stations in April (a) and August (b) 1998.

Levels of TOC were fairly consistent (< 25% difference) between April and August surveys at all stations except T06 (2 fold increase) and T08 (four fold decrease).

4.2.3 Clostridium perfringens

April 1998—The density of *Clostridium perfringens* spores ranged from 2,780 cfu at station T05A to 29,800 cfu at station T04 (Table 4-2, Figure 4-5). In general, spore density was higher at stations with finer sediments ($r = 0.80$, $n = 8$, $p < 0.05$) (Figure 4-6),which had higher levels of TOC.

August 1998—The density of *Clostridium perfringens* spores at Traditional stations ranged from 1,320 cfu (T08) to 15,100 cfu (T04) (Figure 4-5). Spore density also correlate well with percent fines in sediments collected from stations in August ($r = 0.79$, $n = 8$, $p > 0.05$; Figure 4-6).

The density of *Clostridium perfringens* was fairly consistent between April and August surveys at stations T01, T02, T06, and T07. However, the density of *Clostridium perfringens* spores decreased at stations T03, T04, and T05A by approximately a factor of two and decreased at station T08 by a factor of six.

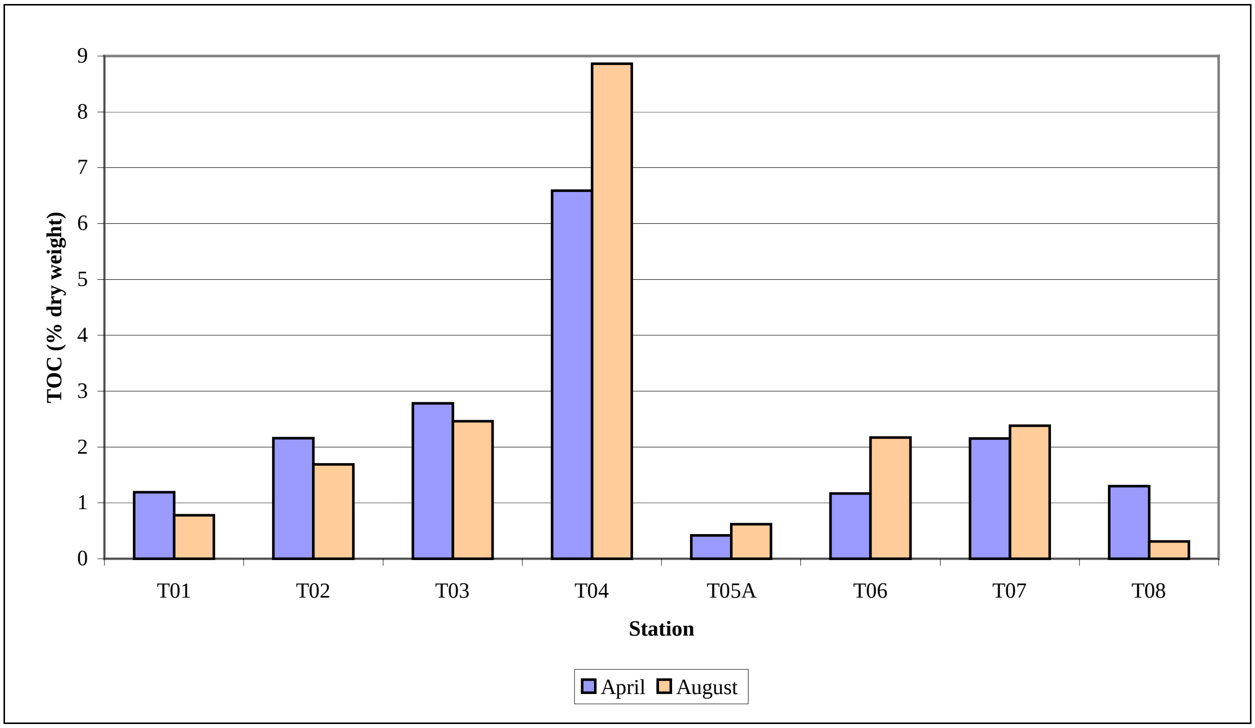


Figure 4-3. Total organic carbon content in sediments collected from Traditional stations in April and August 1998.

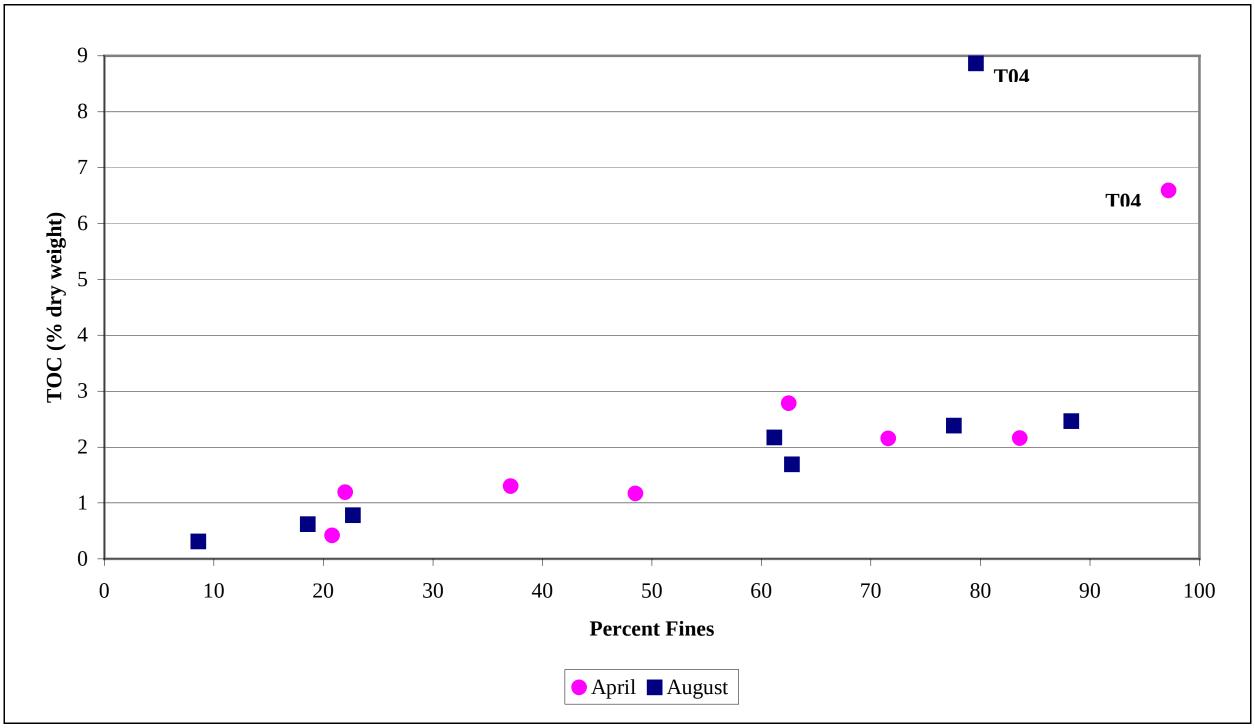


Figure 4-4. Total organic carbon plotted against percent fines in sediments collected from Traditional stations in April and August 1998.

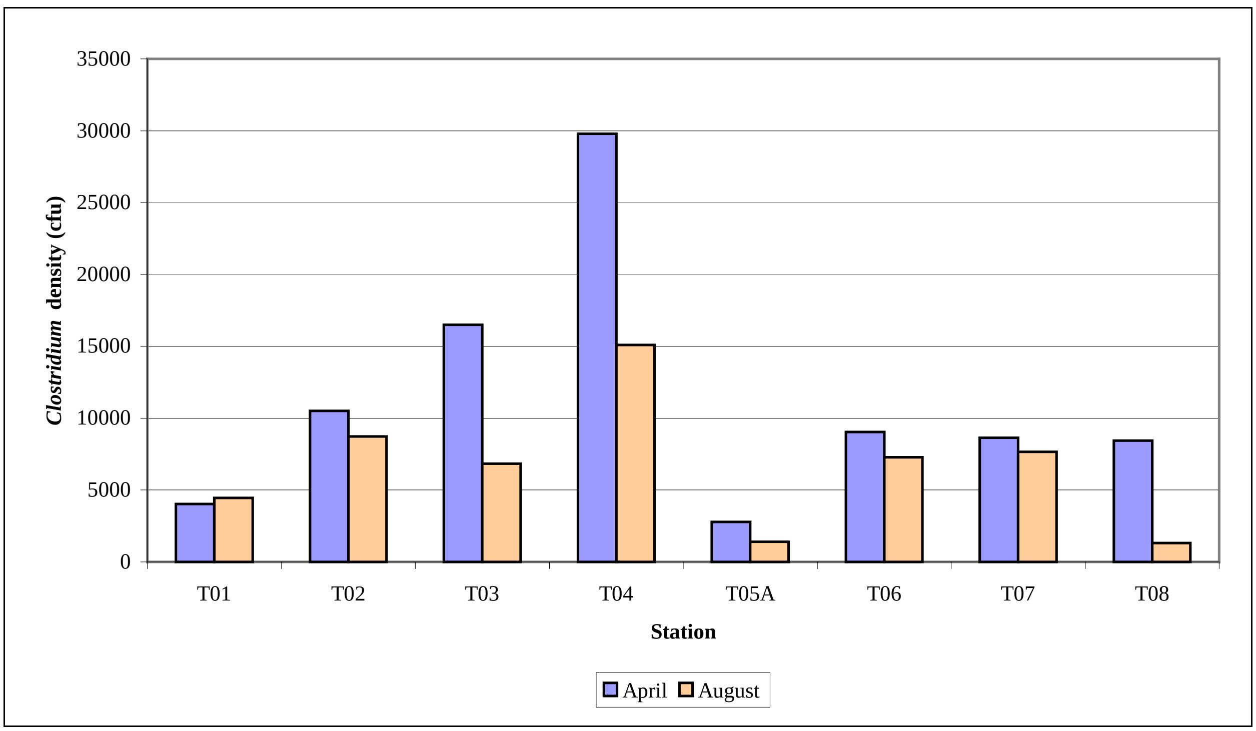


Figure 4-5. *Clostridium perfringens* density in sediment collected from Traditional stations in April and August 1998.

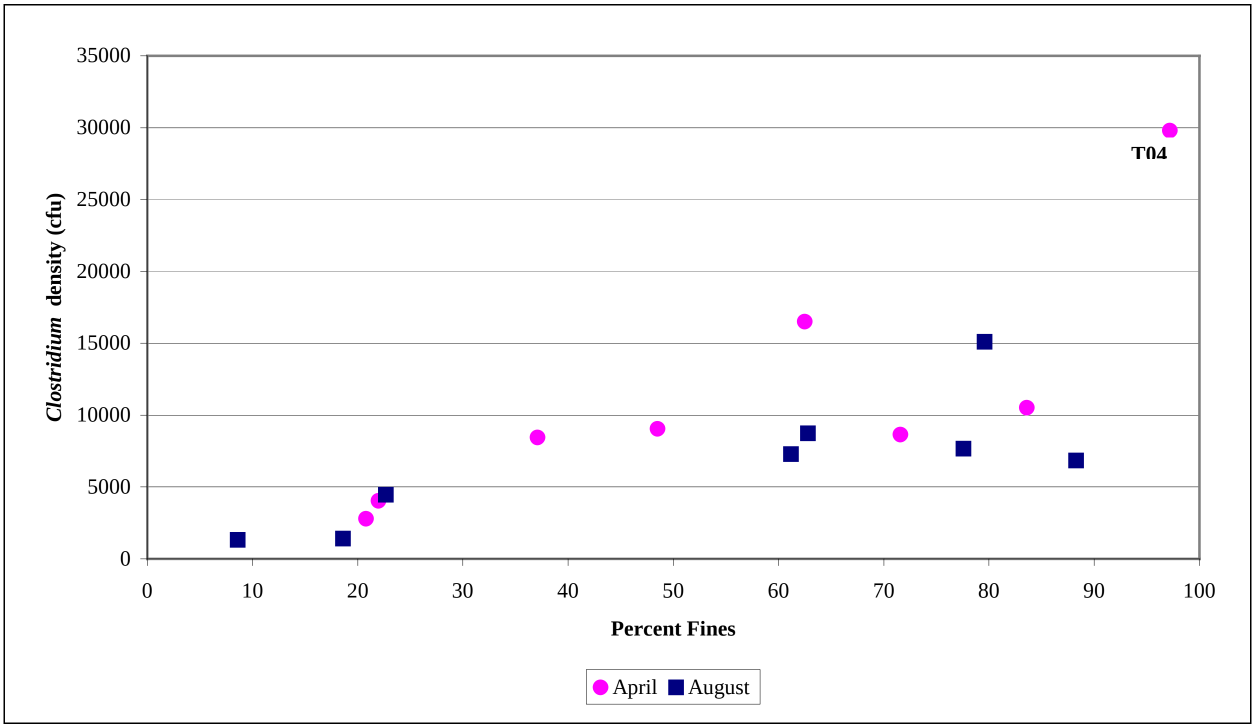


Figure 4-6. ***Clostridium perfringens*** **density versus percent fines in sediment collected from Traditional stations in April and August 1998.**

5.0 1998 SOFT-BOTTOM INFAUNAL COMMUNITIES

by Roy K. Kropp, Eugene D. Gallagher, and David H. Shull

5.1 Methods

5.1.1 Laboratory Analyses

Samples 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, small amounts of the sample were placed in glass dishes, and all organisms, including anterior fragments of polychaetes, were removed and sorted to major taxonomic categories such as polychaetes, arthropods, and mollusks. After samples were sorted, the organisms were sent to taxonomists for identification and enumeration. Identifications were made at the lowest practical taxonomic level, usually species. Taxonomic responsibilities for the 1998 Boston Harbor studies are listed in Appendix D-1.

5.1.2 Data Analyses

Preliminary Data Treatment—Prior to performing any of the analyses of the 1998 and 1992-1998 MWRA datasets, several modifications were made. Several non-infaunal taxa were excluded (listed in Appendix D-2). Data for several taxa were pooled. Usually this involved pooling data for a taxon identified to a level higher than species (e.g., genus) with those data for a species within the higher taxon. This pooling was done only when only a single species of the higher taxon was identified. For example, *Unciola irrorata* (an amphipod) was the only species of the genus found in the Harbor, so that any amphipods identified only to the genus (*Unciola* spp.) were treated as if they were *U.irrorata*. Because the identification of some taxa has been inconsistent through the duration of the project, data for some species were pooled to a higher-level taxon. For example, turbellarians were identified to species in 1993 and 1994, but have only been identified to phylum during the other years of the program. Therefore, data for Turbellaria sp. 1 were pooled with data for Turbellaria spp. All such changes are listed in Appendix D-2.

Several of the modifications made to the 1998 dataset prior to the analyses represented substantial departures from data treatments used in past analyses, e.g., 1996 and 1997. Two of the taxa excluded in 1998 were among the numerically predominant taxa (i.e., one of the 10 most abundant) at one or more stations in 1996 and/or 1997. The sevenspine bay shrimp, *Crangon septemspinosa*, was a top-10 species at station T04 in 1997 (Blake *et al.* 1998), but was excluded from the analyses in this report because it is a mobile epibenthic specie that is probably inadequately sampled by a grab sampler. Of larger importance is the exclusion of the blue mussel, *Mytilus edulis*, from the analyses in 1998. This species, which was among the predominant taxa at many stations in 1996 and 1997 (Blake *et al.* 1998), is not infaunal and the individuals obtained during the grab sample collection were typically very small, newly-settled individuals that most likely would not survive to adulthood. There were two important differences between the 1998 and previous analyses in the merging of taxa. For this report, all oligochaete species that were identified were merged into the combined category, Oligochaeta spp., because identifications of oligochaetes prior to 1992 were not made to the species level. Also, amphipods belonging to the genus *Ampelisca* were identified to species, but were treated as *Ampelisca* spp. in this report for a similar reason. Two species, *A. abdita* and *A. vadorum*, were reported in 1996/1997 (Blake *et al.* 1998) and were found in 1998. Blake *et al*. (1998) showed that *A. abdita* was much more abundant than *A. vadorm*, which is consistently found only at station T08. However, these species were not distinguished prior to 1995. These differences have implications only if the reader were to refer to previous reports while reading the results presented here. All analyses performed in this report that involve multi-year comparisons were performed on a unified dataset that was treated consistently. Therefore, all comparisons within this report are internally consistent.

Diversity Analysis— All of the diversity calculations were done with a MATLAB™ program written by Gallagher. Magurran (1988) describes all of the diversity indices used here. The rarefaction method was introduced by Sanders (1968), but Hurlbert (1971) provided the correct equations for calculating the index. Smith and Grassle (1977), the definitive reference on this statistic, proves that the Sanders-Hurlbert expected number of species is an unbiased estimator of diversity and that $E(S_2)$ is mathematically identical to Simpson's unbiased diversity. An unbiased statistic does not change in expected value as a function of sample size. Rosenzweig (1995) showed that several diversity estimators increase markedly with increasing sample size. He advocated using Simpson's diversity and log-series alpha, because neither exhibited much sample-size bias. May (1975) is the definitive reference on the log-series alpha. Log-series alpha is used here as an unbiased estimator of species richness. Log-series alpha is completely insensitive to the changes in species evenness.

The Sanders-Hurlbert $E(S_n)$ index can be used as either a species evenness index or a richness index. However, it isn't very good at estimating either component independently. At the lowest sample size, 2, $E(S_n)$ is Simpson's diversity, which is very sensitive to richness. In fact, Rosenzweig (1995) uses Simpson's index as a richness index. At a large sample size, the Sanders-Hurlbert $E(S_n)$ will become more sensitive to species richness. However, the upper limit of *n* in comparing a group of samples is set by the minimum in any one sample. In the present data set, that is about 100. At a sample size of 100, $E(S_n)$ is still very sensitive to the evenness component of diversity. So, despite its many strengths, *H'*, *J'*, and log-series alpha were chosen for most of the comparisons of diversity. Shannon's *H'* is sensitive to both the evenness and richness components of diversity.

H and *H'* can be calculated by using Napierien logarithms, $\log_{10}$ or $\log_2$. Here *H'* was calculated by using $\log_2$ because that is closest to Shannon's original intent. Previous MWRA reports have presented *H'* values calculated by using $\log_e$. *H'* values calculated by using different logarithms vary substantially. Therefore, the reader must not compare values calculated for this report with those presented in earlier MWRA reports. Pielou's *J'* is a measure of the evenness component of diversity, first described by Pielou (1966). It is simply the observed *H'*, divided by the maximum *H'*, which is simply $\log_2 s$.

Cluster & Ordination

Most analyses were performed with MATLAB™. The methods used for performing the principal components analysis of hypergeometric probabilities (PCA-H) analysis and cluster analysis are described in Trueblood *et al*. (1994). Cluster analysis was performed by using COMPAH96 (available on Eugene Gallagher's web page, http://www.es.umb.edu/edgwebp.htm). This program, originally written by Don Boesch (Boesch 1977), implements all of Williams' (1971) combinatorial clustering methods. The sample and species clusters presented here were generated by using unweighted pair-group mean average sorting (UPGMA; Sneath and Sokal 1973). With the PCA-H analysis, species habitat relationships were examined by *R*-mode cluster analysis. The clustering is based on Pearson's *r*. Pearson's *r* between columns of the hypergeometric matrix is cosine *2*, where *2* is the angle between the species shown in the covariance plots (Trueblood *et al.* 1994). UPGMA sorting of the cosine *2* similarities was used rather than the single-linkage clustering that Jardine and Sibson (1968) argued was the only method combinatorial with Pearson's *r*. However, Gallagher (unpublished) has since discovered major problems in interpretation that are introduced by using single-linkage clustering of variables. For example, with single-linkage clustering two highly correlated variables (*e.g.*, $r > 0.8$) may not cluster until a similarity level of near zero is reached. With UPGMA clustering, variables cluster at clustering levels approximating their original correlations.

All faunal similarities shown here were based on the chord normalized expected species shared, or CNESS (Trueblood *et al.* 1994). This is a metric version of Grassle and Smith's (1976) NESS faunal similarity that can be made more or less sensitive to the rare species in the samples by adjusting the random sample size (*m*).

Both indices are based on the ESS or the expected species shared. ESS represents the estimate of the number of species shared when *m* individuals are drawn at random from two samples.

By using the Kendall's correlation method described in Trueblood *et al.* (1994), a random sample size (*m*) of 15 was found to be appropriate for the 1998 Boston Harbor samples. A random sample size of 20 was determined to be appropriate for the 1992–1998 Harbor data.

There are three basic graphs produced by a PCA-H analysis. The first type is the metric scaling plot, which shows a planar view of the data representing the major variation in CNESS distances among stations. A sample point, called H_{max}, which indicates the position of a hypothetical sample containing equal abundances of every species in the dataset was included. Sample points that plot at increasing distances from this point have lower species diversities (Gallagher and Keay 1998). The results of cluster analyses were superimposed on the metric scaling as convex hulls. Samples occurring in the same cluster were surrounded by a convex hull. These clusters also were identified in the sample cluster analyses, and the convex hulls were used to surround the most disparate 8 to 10 groups (Gallagher and Keay 1998).

A second plot type is the Gabriel Euclidean distance biplot, based on Gabriel (1971). In this plot, stations from the metric scaling are shown as points and species are depicted as vectors (arrows). The relative abundance of species in a sample can be found by projecting the sample points at right angles on the species vectors. The Gabriel Euclidean biplot shows the species that are important in explaining CNESS variation. This contribution to CNESS can be calculated directly by using the contribution statistics developed originally for correspondence analysis and described in Greenacre (1984). The contribution of species to CNESS is directly proportional to the species loadings on the respective eigenvectors in the eigenvalue ordination of CNESS distances.

The third major plot type is the Gabriel covariance biplot. This plot, described by Gabriel (1971) and more recently by Legendre and Legendre (1998), plots species as vectors. Species vectors that plot with acute angles reflect species that tend to occur in the same samples. Species vectors oriented at right angles indicate no or weak associations. Species vectors oriented with obtuse angles indicate species that are negatively associated.

5.2 Results and Discussion

5.2.1 1998 Descriptive Community Measures

Abundance—Among individual Harbor samples collected in April 1998, infaunal abundance varied about 22-fold, ranging from 255 to 5,781 individuals/0.04 m^2 (6,375–144,525/m^2) at stations T07 (rep 2) and T08 (rep 2), respectively (Table 5-1). Mean (± 95% confidence intervals, CI) abundance per sample in April ranged from 307 (± 71) to 3,125 (± 2,622) individuals/0.04 m^2 at stations T07 and T08, respectively (Figure 5-1).

Annelid worms were the most abundant higher-level infaunal taxon among the April 1998 Harbor samples (Figure 5-2). Annelids accounted for more than 75% of the infauna at 5 of the Harbor stations sampled in April, with the highest percentage, 95%, at stations T01. Crustaceans were the second highest contributors to infaunal abundance at four stations. The highest proportions of crustaceans

Table 5-1. Descriptive ecological parameters for samples collected from Boston Harbor in April and August 1998.

		Total		Shannon		Brillouin	E(Sn), 0 if Sample Total < n							Log-Series
Site	**Repl.**	**Ind.**	**sp.**	***H'***	***J'***	***H***	**2**	**10**	**20**	**50**	**100**	**200**	**500**	**Alpha**
							April							
T01	1	1828	36	1.7	0.3	1.2	1.4	3.2	5.0	8.8	12.3	16.2	22.4	6.4
T01	2	729	15	2.2	0.6	1.5	1.7	4.0	5.3	7.2	9.1	11.4	14.3	2.7
T01	3	770	29	1.9	0.4	1.3	1.5	3.5	5.3	8.8	12.3	16.8	24.6	6.0
T02	1	428	18	2.5	0.6	1.7	1.8	4.6	6.2	8.6	10.9	13.9	0.0	3.8
T02	2	466	23	2.4	0.5	1.6	1.7	4.3	5.9	8.9	12.2	16.6	0.0	5.1
T02	3	478	24	2.3	0.5	1.5	1.6	4.1	6.0	9.4	12.7	16.8	0.0	5.3
T03	1	2456	30	2.7	0.6	1.9	1.8	4.8	6.5	9.1	11.3	13.7	18.0	4.8
T03	2	1774	25	2.4	0.5	1.6	1.7	4.3	5.6	7.9	10.2	12.8	17.2	4.1
T03	3	2815	30	2.6	0.5	1.8	1.8	4.7	6.4	8.8	10.9	13.4	18.1	4.7
T04	1	458	4	0.1	0.0	0.0	1.0	1.1	1.1	1.3	1.7	2.3	0.0	0.6
T04	2	641	5	0.2	0.1	0.1	1.0	1.2	1.4	1.9	2.6	3.5	4.7	0.7
T04	3	526	6	1.1	0.4	0.7	1.5	2.2	2.4	2.9	3.6	4.6	5.9	0.9
T05A	1	649	25	2.5	0.5	1.7	1.7	4.5	6.5	9.7	12.6	16.6	23.1	5.2
T05A	2	1178	27	2.1	0.4	1.4	1.6	3.6	4.9	7.7	10.6	14.3	20.4	4.9
T05A	3	557	33	3.3	0.7	2.2	1.8	5.8	8.3	13.0	18.0	23.9	32.0	7.7
T06	1	2193	21	2.7	0.6	1.9	1.8	4.9	6.5	9.2	11.5	14.0	17.3	3.2
T06	2	2424	23	2.3	0.5	1.6	1.7	4.1	5.3	7.2	9.1	11.5	15.3	3.5
T06	3	2289	24	2.2	0.5	1.5	1.6	4.0	5.4	7.8	10.1	12.8	16.6	3.7
T07	1	290	16	2.3	0.6	1.5	1.7	4.2	5.4	7.7	10.1	13.6	0.0	3.6
T07	2	255	13	2.2	0.6	1.5	1.7	3.9	4.9	7.0	9.3	11.9	0.0	2.9
T07	3	376	14	2.2	0.6	1.4	1.7	3.8	4.9	6.9	9.0	11.4	0.0	2.9
T08	1	1512	51	3.4	0.6	2.3	1.8	5.7	8.5	13.7	18.7	24.9	35.0	10.2
T08	2	5781	49	2.9	0.5	2.0	1.8	5.0	6.8	10.0	13.4	17.8	25.1	7.3
T08	3	2083	43	3.3	0.6	2.2	1.8	5.6	8.4	13.2	17.6	22.5	29.5	7.7
							August							
T01	1	3675	52	3.3	0.6	2.3	1.8	5.7	8.1	12.4	17.0	22.9	31.6	8.6
T01	2	2108	38	3.1	0.6	2.1	1.8	5.4	7.7	11.5	15.4	20.7	28.7	6.6
T01	3	3297	38	2.7	0.5	1.9	1.8	4.7	6.6	10.2	13.9	18.3	24.6	6.0
T02	1	2840	43	3.0	0.5	2.0	1.8	5.1	7.3	10.9	14.2	18.1	24.7	7.2
T02	2	1207	39	3.3	0.6	2.2	1.8	5.7	8.0	12.0	16.3	21.5	29.6	7.7
T02	3	1563	40	3.4	0.6	2.3	1.8	5.9	8.6	13.2	17.3	22.3	30.1	7.5
T03	1	17416	53	2.1	0.4	1.5	1.7	3.7	4.9	6.9	8.7	11.0	15.5	6.7
T03	2	11575	41	2.1	0.4	1.5	1.6	3.8	5.1	7.2	9.1	11.5	15.8	5.3
T03	3	20111	50	2.1	0.4	1.4	1.6	3.7	4.9	7.0	8.7	10.6	14.3	6.2
T04	1	3826	5	0.0	0.0	0.0	1.0	1.0	1.1	1.1	1.3	1.5	2.1	0.6
T04	2	5664	6	0.0	0.0	0.0	1.0	1.0	1.1	1.2	1.4	1.7	2.7	0.7
T04	3	2163	3	0.0	0.0	0.0	1.0	1.0	1.0	1.1	1.2	1.3	1.8	0.3
T05A	1	6091	38	2.0	0.4	1.4	1.5	3.7	5.6	9.3	12.4	15.5	19.9	5.4
T05A	2	5602	46	1.9	0.3	1.3	1.5	3.4	5.4	9.4	13.2	17.2	23.4	6.9
T05A	3	6892	48	2.3	0.4	1.6	1.6	4.0	6.2	10.3	14.0	18.1	24.3	7.0
T06	1	9454	43	2.6	0.5	1.8	1.7	4.7	6.5	9.1	11.3	14.1	18.9	5.8
T06	2	6660	38	2.3	0.4	1.6	1.6	4.3	6.1	8.7	11.0	13.8	18.6	5.3
T06	3	8843	43	2.6	0.5	1.8	1.7	4.6	6.4	9.0	11.4	14.3	19.0	5.9
T07	1	1140	30	3.3	0.7	2.2	1.9	5.9	8.1	11.5	14.8	18.8	25.0	5.6
T07	2	1729	27	2.5	0.5	1.7	1.7	4.4	6.1	8.5	11.1	14.6	19.7	4.5
T07	3	1179	26	3.1	0.6	2.1	1.8	5.5	7.3	10.1	12.8	16.1	20.8	4.7
T08	1	5846	50	2.4	0.4	1.7	1.7	4.1	5.9	9.8	13.7	18.3	24.7	7.5
T08	2	3983	57	3.5	0.6	2.4	1.8	5.9	8.6	13.8	19.0	25.1	34.3	9.4
T08	3	8707	61	3.1	0.5	2.1	1.8	5.3	7.6	11.6	15.6	20.4	28.2	8.9

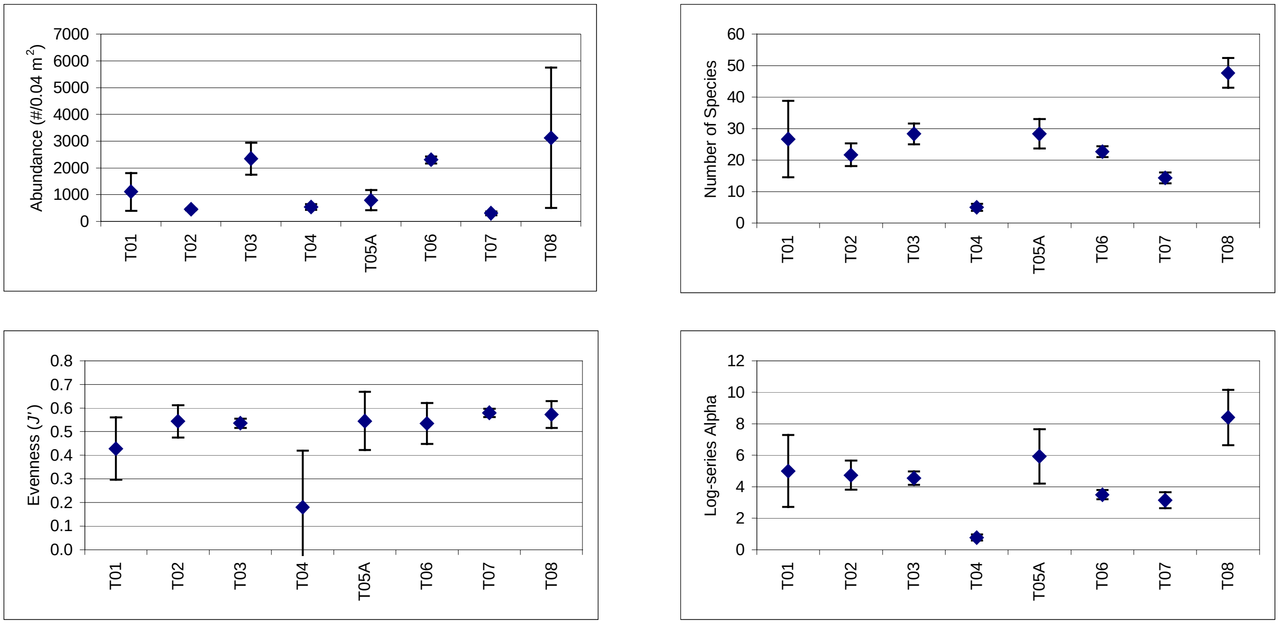


Figure 5-1. Infaunal abundance, numbers of species, evenness, and log-series alpha values for Boston Harbor samples collected in April 1998. The mean and 95% confidence intervals are shown.

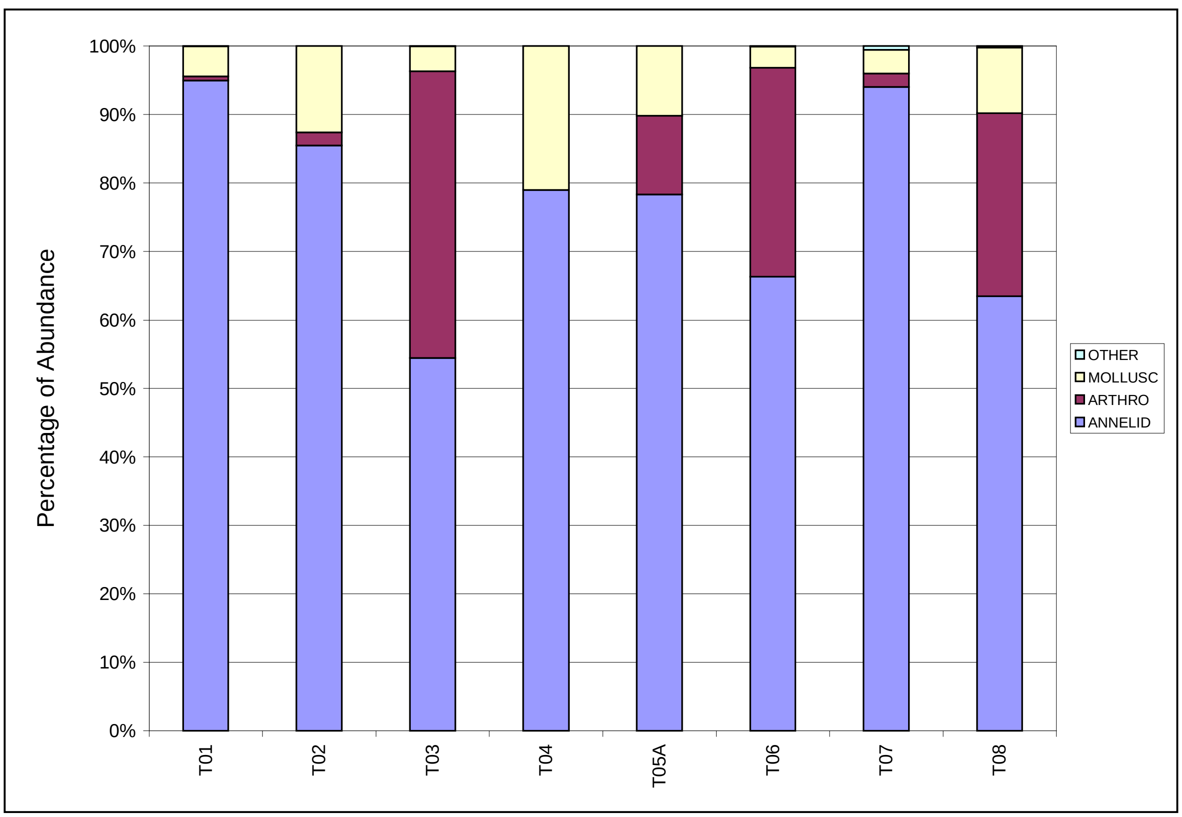


Figure 5-2. Relative contribution of higher-level taxa to infaunal abundance among Boston Harbor samples collected in April 1998.

occurred at stations T03 (42%) and T06 (31%). Molluscs were relatively important contributors to infaunal abundance at two stations; T02 (13%) and T04 (21%). At a slightly finer taxonomic scale, oligochaete worms were the most abundant annelids at four stations, comprising 70% of the total infaunal abundance at station T01 (Figure 5-3). Polychaetes were significant contributors at four stations, accounting for 79% of the infaunal abundance at station T04. Amphipods, the most numerous crustaceans, were the largest of the lower-level taxa at stations T03, accounting for 42% of the total infaunal abundance there. Gastropods were the only taxon other than polychaetes at station T04, contributing 21% of the total infaunal abundance there.

Among the August samples, infaunal abundance varied about 18-fold, ranging from 1,140 to 20,111 individuals/0.04 m^2 (28,500–502,775/m^2) at stations T07 (rep 1) and T03 (rep 3), respectively (Table 5-1). Mean (± 95% confidence intervals, CI) abundance per sample in August ranged from 1,349 (± 373) to 16,367 (± 4,938) individuals/0.04 m^2 at stations T07 and T03, respectively (Figure 5-4).

Annelids were the most significant contributors to infaunal abundance at five of the Harbor stations sampled in August (Figure 5-5). Annelids accounted for all but three of the infaunal organisms found at station T04 in August and contributed more than 75% of the infauna at four other stations. Crustaceans were the most numerous major taxon at two stations sampled in August, T03 (61%) and T06 (73%). Molluscs were relatively unimportant contributors to infaunal abundance in August. In contrast to April, polychaetes were more abundant than oligochaetes in all August samples (Figure 5-6). Amphipods were again the most abundant crustaceans and were the most abundant minor taxon at three stations; T03 (61% of the total infaunal abundance), T06 (73%), and T08 (46%).

Numbers of Species—The total numbers of species per individual Harbor sample collected in April 1998 varied about 13-fold, ranging from 4 to 51 at stations T04 (rep 1) and T08 (rep 1), respectively (Table 5-1). In April, mean (± 95% CI) numbers of species per sample ranged from 5 (± 1.1) to 48 (± 4.7) species at stations T04 and T08, respectively (Figure 5-1). In April, Boston Harbor infaunal species numbers were correlated with abundance (r = 0.625, n = 24, p > 0.01).

Among the higher-level taxa collected in April, annelid worms contributed the highest percentage of species, accounting for about 38–71% of the species collected at each Harbor station (Figure 5-7). Crustaceans and molluscs accounted for up to 35% and about 14–33% of the species collected at each Harbor station, respectively. Within each of their respective major taxa, polychaetes, amphipods, and bivalves typically provided the greatest contribution to species numbers (Figure 5-8).

The total numbers of species per individual Harbor sample collected in August 1998 varied about 20-fold, ranging from 3 to 61 at stations T04 (rep 3) and T08 (rep 3), respectively (Table 5-1). In August, mean (± 95% CI) numbers of species per sample ranged from 5 (± 1.7) to 56 (± 6.3) species at stations T04 and T08, respectively (Figure 5-4). In August, Boston Harbor infaunal species numbers were slightly correlated with abundance (r = 0.408, n = 24, p = 0.05).

Among the samples collected in August, the proportional contributions of the three higher-level taxa were similar to those for the April samples (Figure 5-9). Annelid worms contributed the highest percentage of species at all 8 stations, accounting for about 41-71% of the species collected. Crustaceans and molluscs accounted for about 7-22% and about 7–21% of the species collected at each Harbor station, respectively. Within each of their respective major taxa, polychaetes, amphipods, and bivalves provided the greatest contribution to species numbers (Figure 5-10).

Diversity—As measured by the traditional Shannon index (H'), diversity among individual Boston Harbor samples collected in April 1998 varied from about 0.1 at station T04 (rep 1) to about 3.4 at station T08 (rep 1; Table 5-1). Evenness (J') among most Harbor samples ranged from 0.5 to 0.6. Within-station

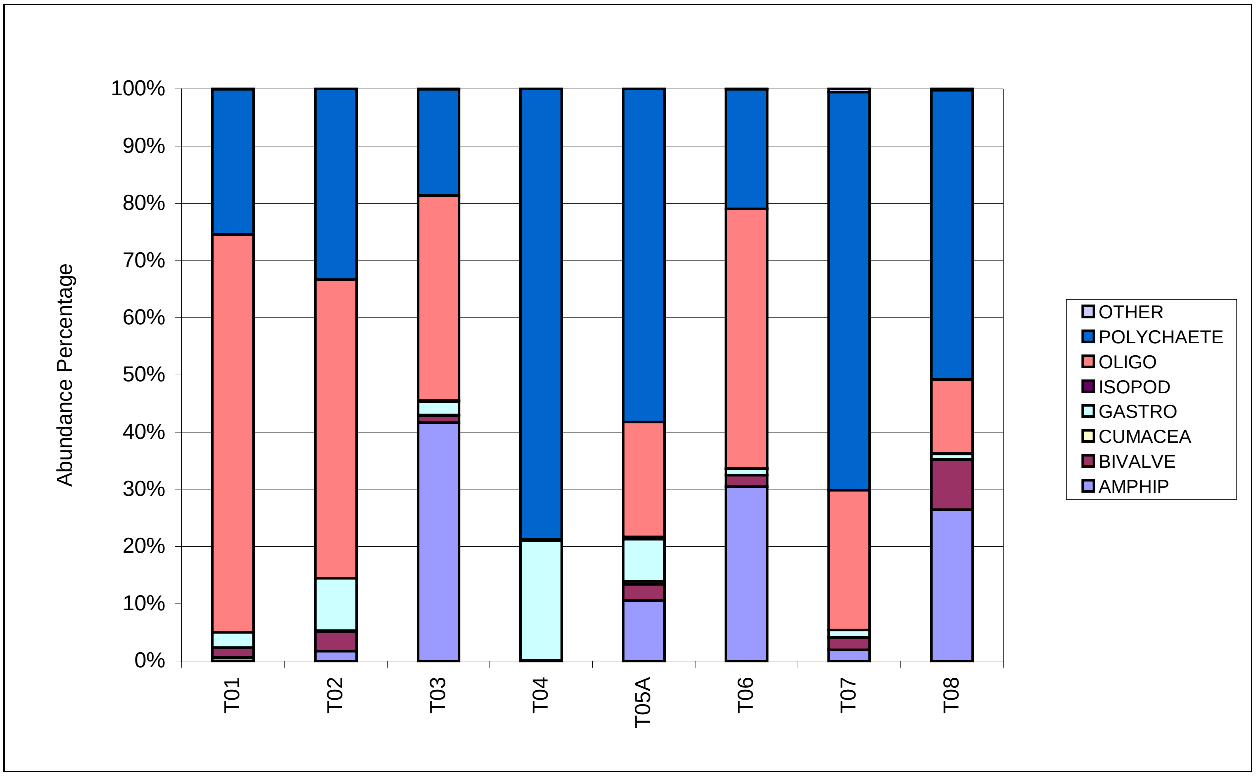


Figure 5-3. Relative contribution of lower-level taxa to infaunal abundance among Boston Harbor samples collected in April 1998.

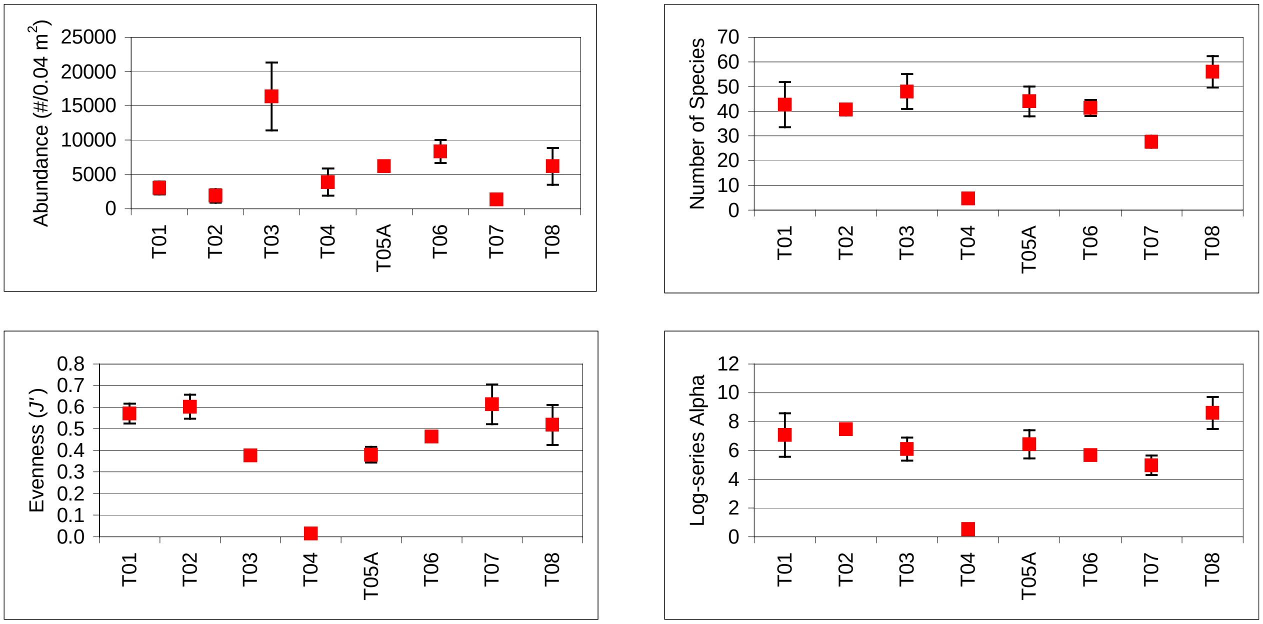


Figure 5-4. Infaunal abundance, numbers of species, evenness, and log-series alpha values for Boston Harbor samples collected in August 1998. The mean and 95% confidence intervals are shown.

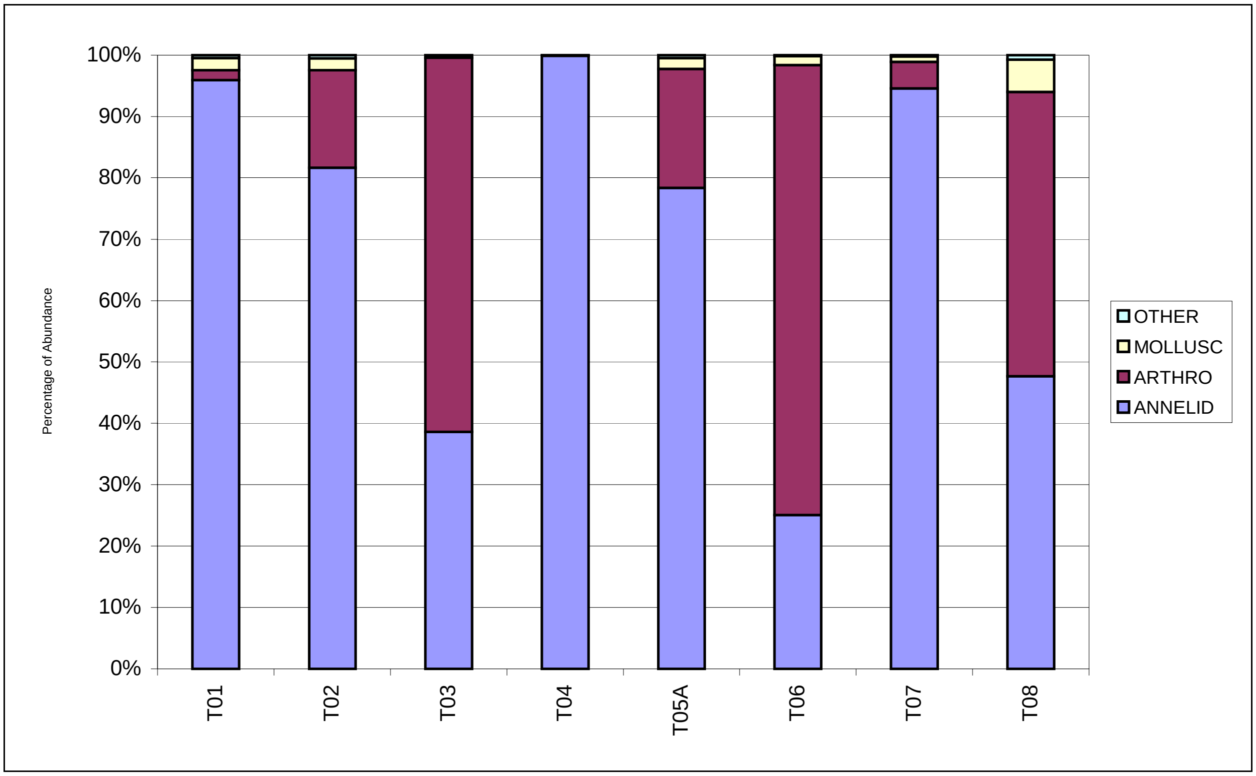


Figure 5-5. Relative contribution of higher-level taxa to infaunal abundance among Boston Harbor samples collected in August 1998.

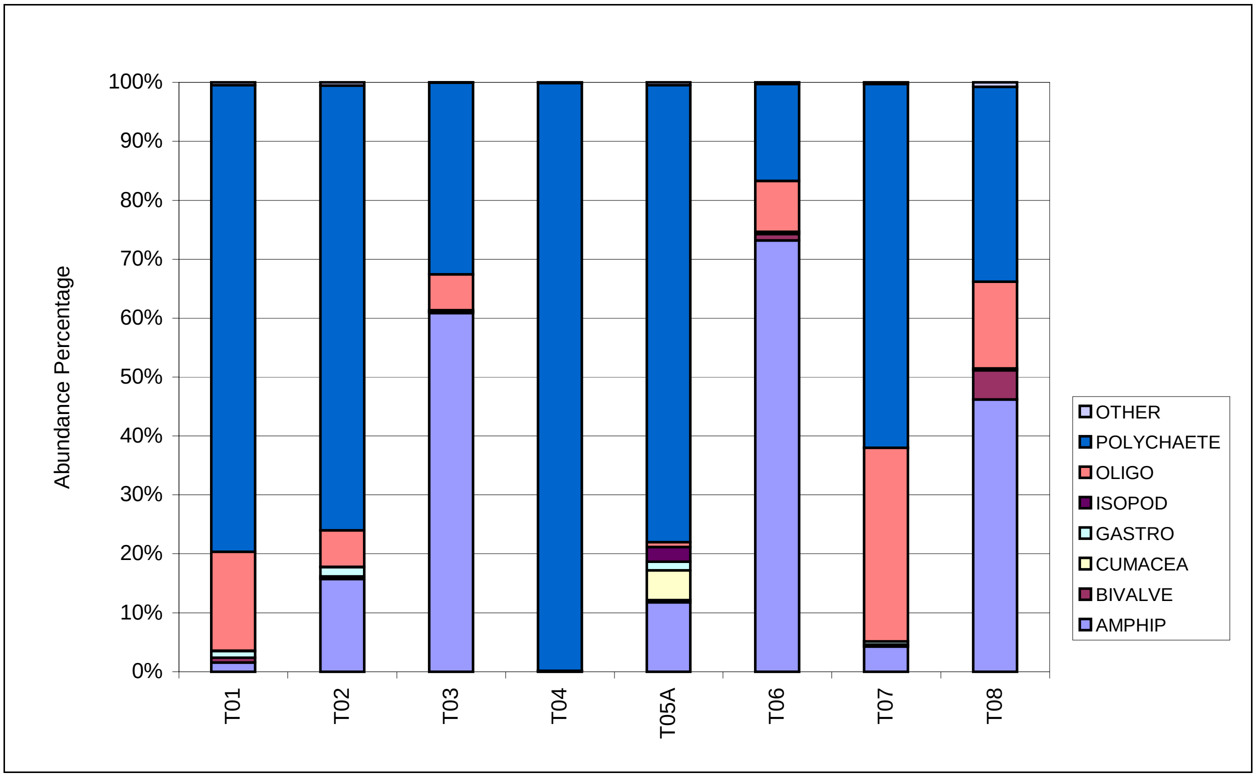


Figure 5-6. Relative contribution of lower-level taxa to infaunal abundance among Boston Harbor samples collected in August 1998.

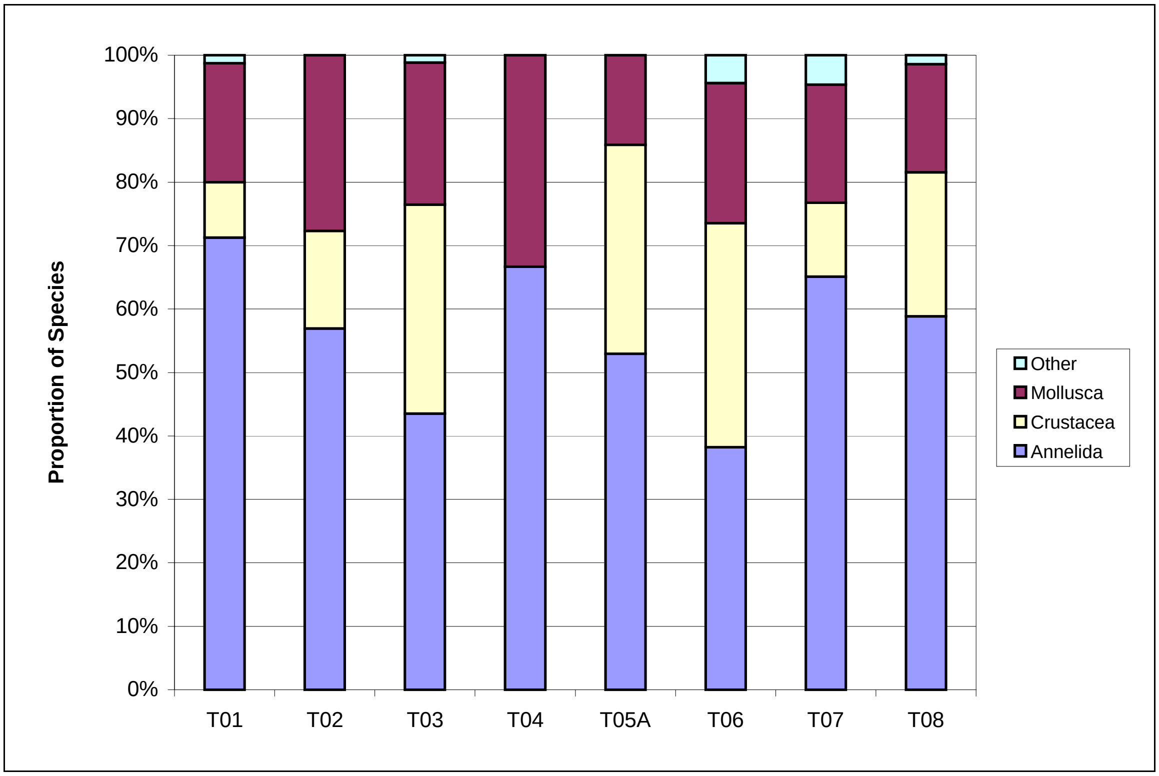


Figure 5-7. Relative contribution of higher-level taxa to numbers of infaunal species among Boston Harbor samples collected in April 1998.

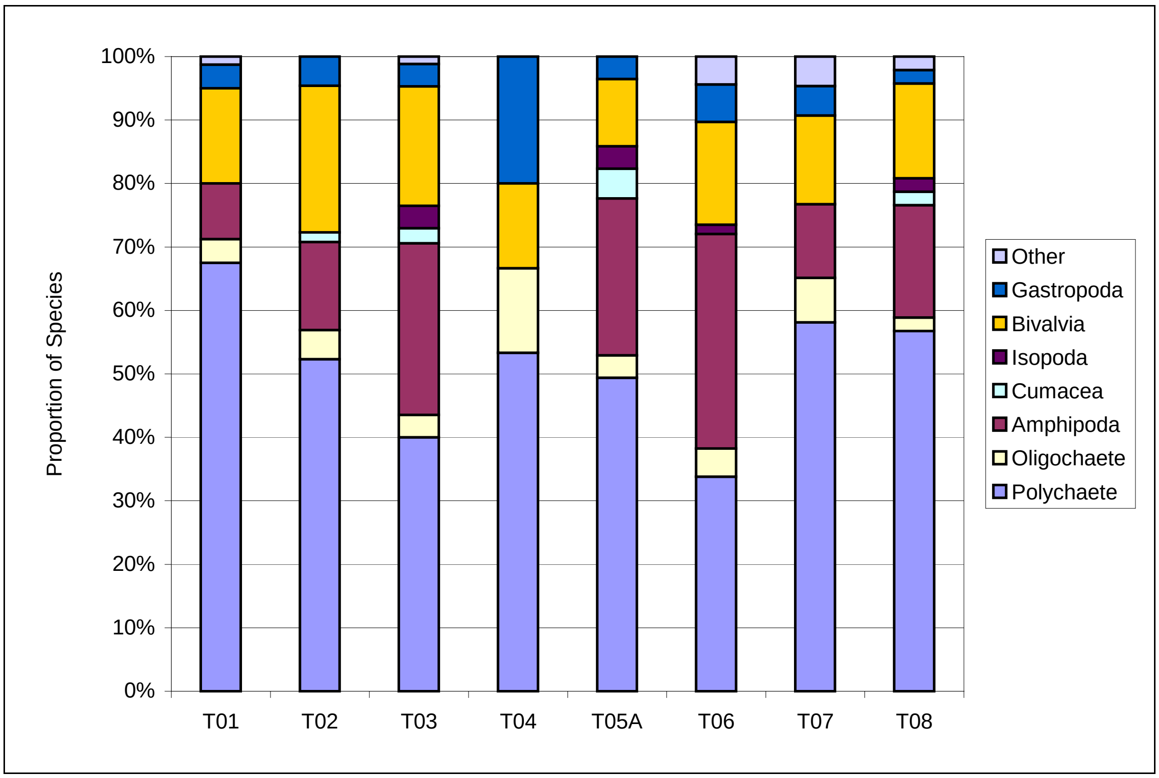


Figure 5-8. Relative contribution of lower-level taxa to numbers of infaunal species among Boston Harbor samples collected in April 1998.

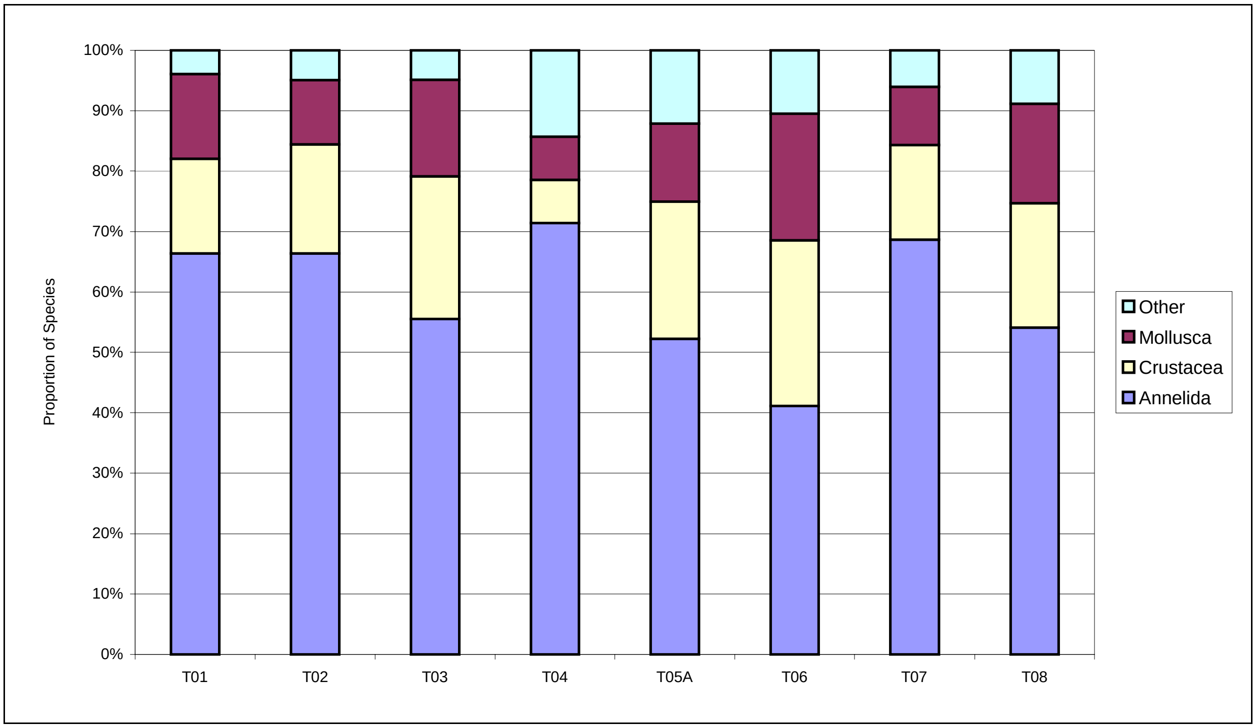


Figure 5-9. Relative contribution of higher-level taxa to numbers of infaunal species among Boston Harbor samples collected in August 1998.

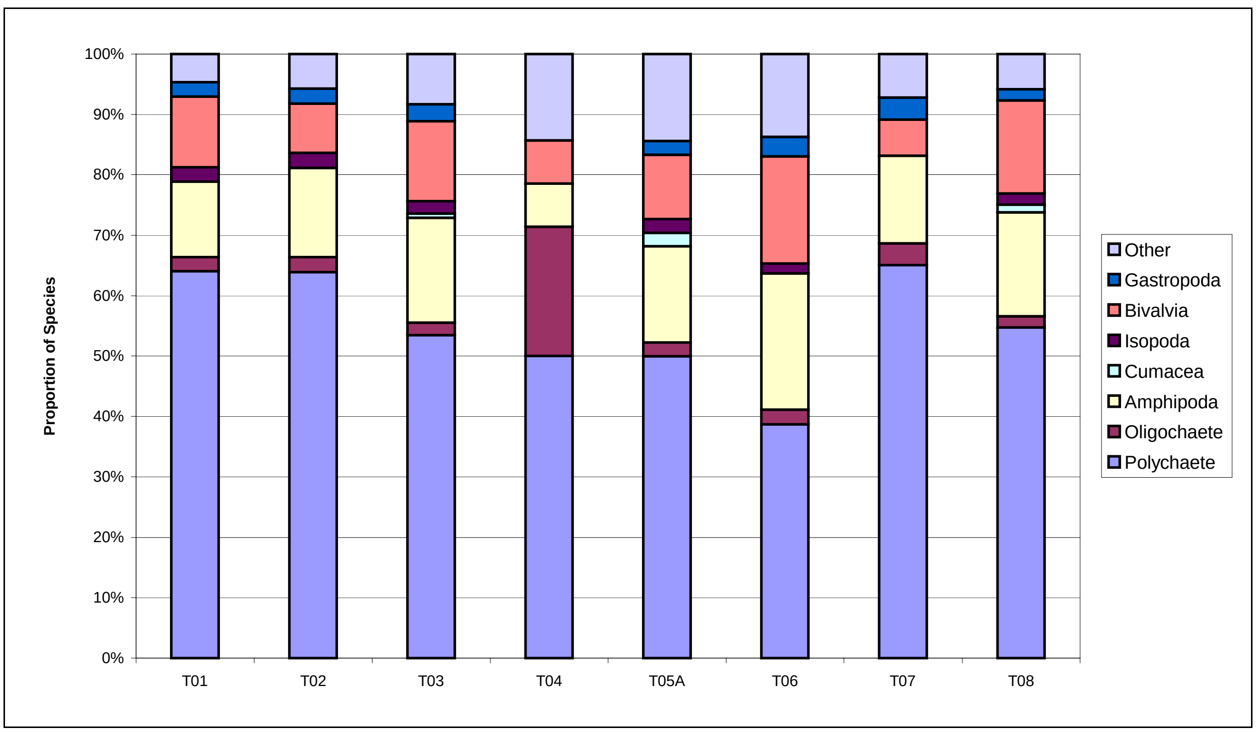


Figure 5-10. Relative contribution of lower-level taxa to numbers of infaunal species among Boston Harbor samples collected in August 1998.

variation was low at all stations except T01 and T04 (Figure 5-1). Log-series alpha varied considerably among Harbor stations, ranging from 0.6 at station T04 (rep 1) to 10.2 at station T08 (rep 1). Within-station variation in log-series alpha among the Harbor stations was relatively high at stations T01, T05A, and T08 (Figure 5-1).

Diversity (*H'*) among individual Boston Harbor samples collected in August 1998 varied from < 0.1 at station T04 (all reps) to about 3.5 at station T08 (rep 2; Table 5-1). In August, evenness among most Harbor samples ranged from 0.4 to 0.6. Within-station variation was relatively low at all stations except T07 and T08 (Figure 5-4). Log-series alpha varied considerably among August samples, ranging from 0.3 at station T04 (rep 3) to 9.4 at station T08 (rep 2). Within-station variation in log-series alpha among the August samples was highest at stations T01 and T08 (Figure 5-4).

Most Abundant Species—The 12 most abundant species found at each Harbor station in April and August 1998 are listed in Appendix D-3. Oligochaeta spp., a composite of several species (see methods), was the predominant taxon in Boston Harbor in April. The category was the most abundant at four of the eight Harbor stations and ranked among the top three taxa at all of the other stations. At station T01, oligochaetes comprised 70% of the total infaunal abundance. At five of the remaining seven stations, oligochaetes accounted for at least 20% of the total infaunal abundance. At station T04, the polychaete *Capitella capitata* complex (78%) and the gastropod *Ilyanassa trivittata* (21%) accounted for 99% of the total infaunal abundance (Appendix D-3). The cirratulid polychaete *Chaetozone vivipara* and the paraonid polychaete *Aricidea catherinae* were the most abundant species at stations T05A and T08, respectively. *Streblospio benedicti*, a spionid polychaete, was the most abundant species at station T07. In April, the 12 most abundant taxa accounted for about 92–100% of the infaunal abundance at each station.

Compared to April 1998, the relative numerical importance of oligochaetes was reduced in August. Oligochaetes were the most numerous taxon at only station T07. However, oligochaetes were still among the five most abundant taxon at the other Harbor stations except station T05A (12^{th}). The amphipod *Ampelisca* spp. was the most abundant taxon at stations T03, T06, and T08. It ranked third in abundance at stations T02 and T05A. A spionid polychaete, *Polydora cornuta*, was the most abundant species at stations T02 and T05A and ranked among the three most abundant species at four other stations (T01, T03, T06, and T07. In August, the 12 most abundant taxa accounted for about 93–100% of the infaunal abundance at each station. As in April, station T04 was completely dominated by *Capitella capitata* complex, which comprised virtually 100% of the total infaunal abundance at the station. *Streblospio benedicti* was the most abundant species at station T01 in August.

5.2.2 1998 Multivariate Analyses

Cluster analysis of the 1998 (April and August) Boston Harbor infaunal data segregated the samples into three dissimilar groups (Figure 5-11). One group, which clustered with the remaining stations at a CNESS value of 1.37, consisted of all samples collected from station T04. The two remaining major groups of samples were relatively dissimilar, linking at a CNESS value of about 1.10. The second major group consisted of all samples collected from stations T03, T06, T08 and the August samples from station T05A. The final major group was comprised of all samples collected from stations T01, T02, T07, and the April samples from T05A. Location within the Harbor from which samples were collected appeared to be one of the primary factors contributing to the cluster groups identified. Station T04, within Dorchester Bay, is the only station located at the western edge of the Harbor (Figure 2-1). The stations consistently comprising the second group (T03, T06, T08) are located relatively close to the mouth of the Harbor or in Hingham Bay (Figure 2-1). Stations consistently within the third group (T01, T02, T07) are located in the northern Harbor or in Quincy Bay, well away from the Harbor mouth (Figure 2-1). Station T05A varied between the latter two groups and is discussed further below.

Comparisons of the linkages of individual samples (i.e., replicates) collected from each station provided an indication of the relative strength of station and/or seasonal signatures (see Figure 5-11). For example, station T04 exhibited a strong station signature regardless of the season of sample collection. Station T07 showed a strong station signature as all six replicates clustered together, but also showed a seasonal component as the three April replicates clustered together as did the three August replicates. Stations T01 and T02 showed a combined station signature. Replicates from each station clustered together and demonstrated a relatively strong seasonal signature. The April (May on Figure 5-11) samples clustered together as did the August samples although one August replicate cluster among April samples. Stations T03 and T06 comprised another station pair, always clustering together (by season). However, replicates from each station showed strong stations affinity by clustering together. Station T08 showed mixed affinities. Replicates from T08 were always more similar to each other than they were to those from other stations, but did not show strong seasonal affinity.

The basic clustering pattern shown in the dendogram (Figure 5-11) also is reflected clearly in the metric scaling plot that compares PCA-H axes 1 versus 2 (Figure 5-12). The contribution of the samples collected from station T04 is distinctly indicated. Those samples accounted for 25% of the total CNESS variation in the 1998 Boston Harbor dataset (Table 5-2). Samples collected from stations T03 and T01 contributed the least (8% and 9%, respectively) towards CNESS variation in 1998. Each season accounted for about 50% of the total CNESS variation in the 1998 dataset (Table 5-2).

The 24 most important species contributing to CNESS variation within the 1998 dataset are listed in Table 5-3. The Gabriel Euclidean Distance biplot that compares PCA-H axes 1 versus 2 (Figure 5-13) indicates those infaunal taxa that were the most important contributors to the CNESS variation expressed along the two axes. Clearly, the annelid taxon *Capitella capitata* complex exerted the strongest influence on the distinction among station groups, separating station T04 from the others primarily along PCA-H axis 1. The separation between the second (stations T03, T06, T08) and third (stations T01, T02, T07) cluster groups described above was explained primarily along PCA-H axis 2, largely by the abundances of several crustaceans (*Ampelisca* spp. and/or *Phoxocephalus holbolli* and *Photis pollex*) at stations comprising the former group (positive direction along the axis) and annelid worms (*Streblospio benedicti* and/or *Chaetozone vivipara* and Oligochaeta spp.) comprising the latter group (negative direction along the axis). However, this particular biplot does not adequately explain the separation of the samples collected during April and August at station T05A. Examination of taxa that were important contributors to PCA-H axis 3 (Table 5-3) and the two plots that compare PCA-H axes 1 versus 3 (Figures 5-14 and 5-15) helps provide an explanation. Separation along PCA-H axis 3 appeared to be primarily seasonal as most of the samples on the positive side of the axis were collected in April, whereas most of those on the negative side of the axis were collected in August. Primary factors contributing to this general separation were differences in the <u>relative</u> abundances of the annelids Oligochaeta spp. and *Aricidea catherinae* in April and the <u>actual</u> abundances of *Polydora cornuta* and, to a certain degree, the amphipod *Unciola irrorata* in August. Among the seven stations best separated along PCA-H axis 3 (i.e., all except station T04), Oligochaeta spp. was the most abundant at four and second or third most abundant at the remaining ones (Appendix D-3). *Aricidea catherinae* ranked among the top three taxa at three of the stations. Although the actual abundances of each taxon probably did not differ between April and August (Figure 5-16; Appendix D-3), the relative importance of each did. Oligochaeta spp. was the most abundant taxon at only one station (station T07) in August and *Aricidea catherinae* ranked no higher than the third most abundant (station T08). One of the major reason for the reduction in relative abundance of these two taxa was the substantial increase in abundance of the polychaete *Polydora cornuta* in August. *Polydora cornuta* was particularly abundant at station T05A in August (4,249 individuals/0.04 m^2; Figure 5-15; Appendix D-3), but was not found there in April. It was this difference in abundance of *Polydora cornuta* that was the primary factor separating the samples collected from T05A during the different seasons.

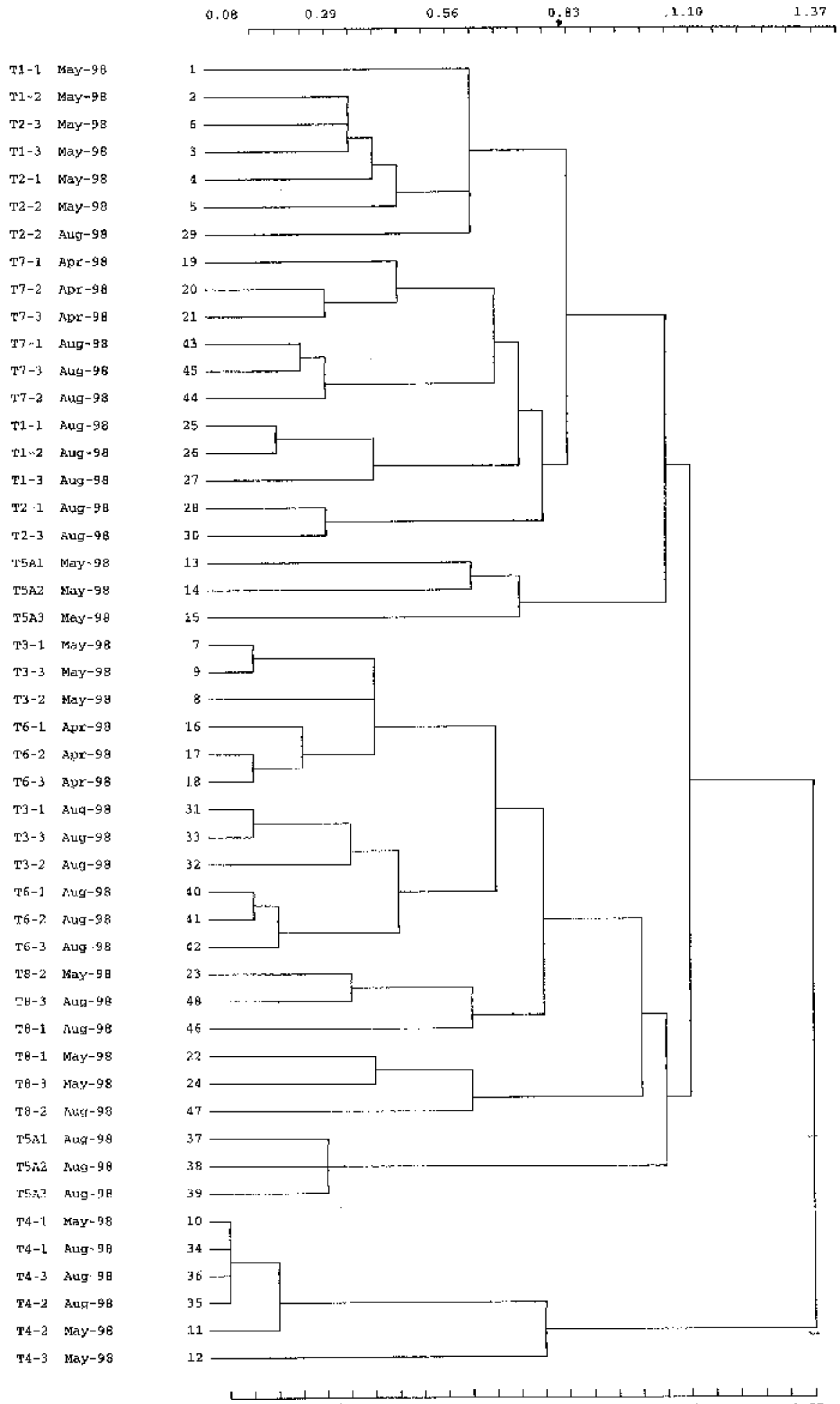


Figure 5-11. Dendrogram resulting from CNESS cluster analysis of all Boston Harbor samples collected in 1998.

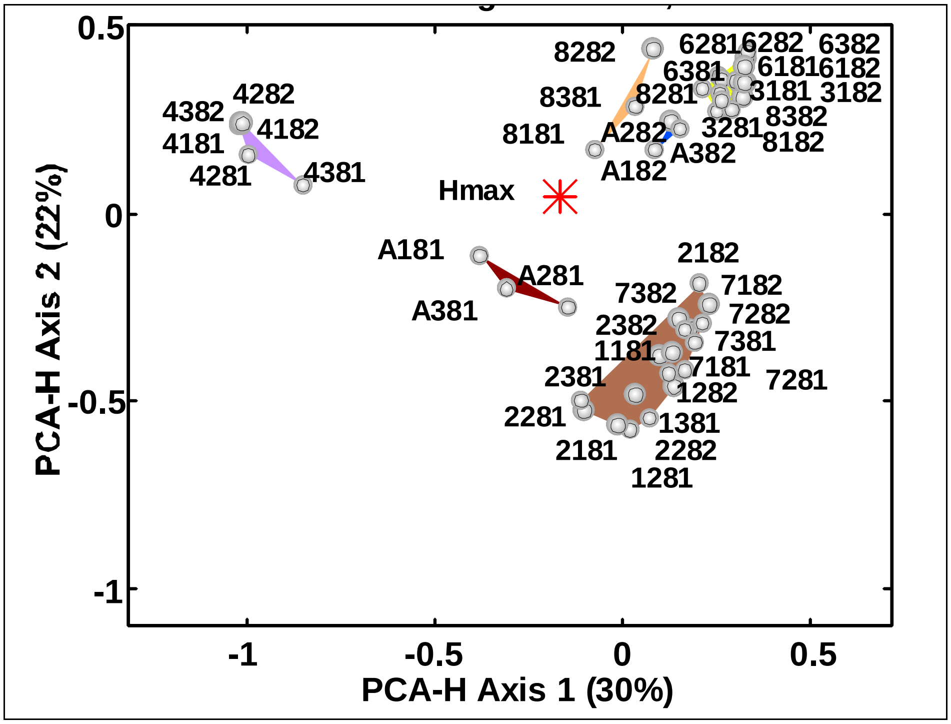


Figure 5-12. Metric scaling plot of CNESS distances, axes 1 versus 2, among all Boston Harbor samples collected in 1998. Results of the CNESS cluster analysis are shown as convex hulls. Station codes are: 1st digit = station number, 2nd digit = replicate, 3rd digit = year, 4th digit = replicate; A = TO5A.

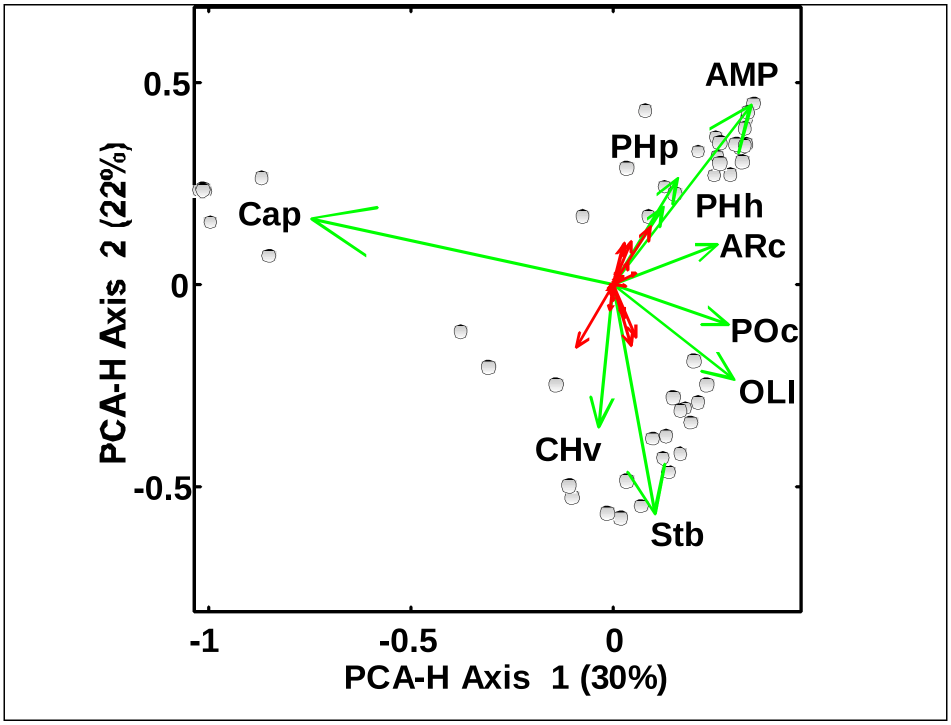


Figure 5-13. Gabriel Euclidean distance biplot, axes 1 versus 2, for the 1998 Boston Harbor data showing those species that control the orientation of samples shown in Figure 5-12. Species codes are as listed in Table 5-2. Open circles represent the spatial pattern of samples shown in Figure 5-12.

Table 5-2. The relative contribution of individual samples to CNESS distances in the 1998 Boston Harbor data. "Cont." is the contribution to overall CNESS distances, "Total Cont." is the cumulative amount of CNESS variation explained by the samples. The final columns indicate the contribution of each sample to each of the first seven PCA-H axes.

				Total	PCA- H Axis						
Rank	**Sample**	**Season**	**Cont.**	**Cont.**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1	T04-1	Sum	4	4	13	1	0	1	1	0	1
1	T04-1	Spr	4	9	13	1	0	1	1	0	1
1	T04-3	Sum	4	13	13	1	0	1	1	0	1
1	T04-2	Sum	4	17	13	1	0	1	1	0	1
1	T04-2	Spr	4	22	13	0	0	1	1	0	0
1	T04-3	Spr	4	25	9	0	0	1	0	4	16
7	T08-1	Spr	3	28	0	0	5	0	19	4	1
7	T05A-1	Sum	3	31	0	0	10	1	6	10	0
7	T08-2	Sum	3	33	0	3	0	1	18	4	1
7	T05A-3	Spr	3	36	1	1	1	11	1	0	2
7	T05A-2	Sum	3	38	0	1	11	0	5	7	0
12	T05A-1	Spr	2	41	2	0	1	13	0	0	3
12	T05A-2	Spr	2	43	0	1	2	9	0	4	4
12	T08-3	Spr	2	45	0	1	5	0	15	0	0
12	T05A-3	Sum	2	48	0	1	10	1	3	2	1
12	T02-2	Spr	2	50	0	5	0	5	0	0	3
12	T01-3	Sum	2	52	0	3	2	3	0	0	5
12	T07-1	Spr	2	53	0	2	3	5	0	2	3
12	T08-2	Spr	2	55	1	2	4	0	3	6	0
12	T01-2	Spr	2	57	0	6	0	1	0	0	3
12	T02-1	Sum	2	59	1	1	4	2	0	9	9
12	T02-2	Sum	2	60	0	5	1	0	0	3	0
12	T02-1	Spr	2	62	0	6	0	2	0	0	0
12	T03-2	Sum	2	64	1	2	3	0	1	0	0
12	T07-3	Sum	2	66	0	2	0	7	0	0	2
12	T06-2	Spr	2	67	1	2	4	0	2	0	0
12	T08-3	Sum	2	69	1	2	2	1	1	8	0
12	T07-3	Spr	2	70	0	1	4	2	0	3	1
12	T07-2	Spr	2	72	0	2	3	4	0	2	0
12	T06-1	Spr	2	74	1	2	3	0	2	0	1
12	T06-3	Spr	2	75	1	2	4	0	2	0	0
12	T06-2	Sum	2	77	1	3	0	0	3	0	0
12	T06-3	Sum	2	78	1	3	1	0	3	0	1
12	T06-1	Sum	2	80	1	3	1	0	2	0	0
12	T03-3	Sum	2	81	1	2	3	0	1	0	0
12	T07-2	Sum	2	83	1	2	0	5	1	1	1
12	T01-1	Sum	2	85	0	3	0	3	0	1	7
12	T02-3	Spr	2	86	0	4	0	3	0	1	1
12	T02-3	Sum	2	88	0	2	3	0	0	10	8
40	T01-2	Sum	1	89	0	4	0	2	0	1	5
40	T03-1	Sum	1	91	1	2	3	0	1	0	1
40	T03-2	Spr	1	92	1	1	4	0	2	1	2
40	T01-1	Spr	1	93	0	3	1	1	0	1	8
40	T08-1	Sum	1	95	1	1	0	0	0	12	1
40	T07-1	Sum	1	96	1	1	0	6	0	0	3
40	T01-3	Spr	1	98	0	4	0	2	0	0	2
40	T03-1	Spr	1	99	1	2	1	0	3	1	0
40	T03-3	Spr	1	100	1	2	0	0	3	1	0

Table 5-3. The 24 most important contributors to CNESS distances in the 1998 Boston Harbor data. "Cont." is the contribution to overall CNESS distances, "Total Cont." is the cumulative amount of CNESS variation explained by species (96% by the top 24 species). The final columns indicate the contribution of each species to each of the first six PCA-H axes.

Rank	Species	Spp. Code	Cont.	Total Cont.	PCA-H Axis 1	2	3	4	5	6
1	*Capitella capitata* complex	Cap	18	18	55	3	0	2	4	1
2	*Polydora cornuta*	POc	9	27	8	1	45	1	0	1
2	*Streblospio benedicti*	Stb	9	36	1	32	0	11	1	0
2	*Ampelisca* spp.	AMP	9	45	12	20	1	1	1	19
5	*Oligochaeta* spp.	OLI	7	53	9	6	12	4	6	1
5	*Aricidea catherinae*	ARc	7	60	7	1	23	10	0	11
7	*Chaetozone vivipara*	CHv	6	66	0	13	0	30	1	8
8	*Ilyanassa trivittata*	ILt	4	70	1	2	0	15	1	8
8	*Photis pollex*	PHp	4	74	3	7	0	2	7	4
10	*Spiophanes bombyx*	SPB	3	76	0	1	1	0	29	1
10	*Nephtys caeca*	nec	3	79	0	2	0	8	0	0
12	*Phoxocephalus holbolli*	PHh	2	82	2	4	0	0	7	1
12	*Polygordius* sp. A	poa	2	83	0	1	0	0	20	1
12	*Unciola irrorata*	UNC	2	85	1	2	5	1	0	3
12	*Microphthalmus aberrans*	Mia	2	87	0	2	0	3	0	1
16	*Clymenella torquata*	Clt	1	88	0	1	0	1	0	0
16	*Nucula delphinodonta*	NUd	1	90	0	1	2	0	4	7
16	*Diastylis polita*	DIp	1	91	0	0	3	1	3	8
16	*Dyopedos monacanthus*	DYO	1	92	0	0	1	4	1	0
16	*Tellina agilis*	TEL	1	93	0	0	2	1	3	1
16	*Leptocheirus pinguis*	LEp	1	94	0	0	0	1	0	13
16	*Pholoe minuta*	Phm	1	95	0	1	1	1	0	5
16	*Exogone hebes*	EXh	1	96	0	0	1	0	5	0
16	*Pontogeneia inermis*	PON	1	96	0	0	0	1	0	0

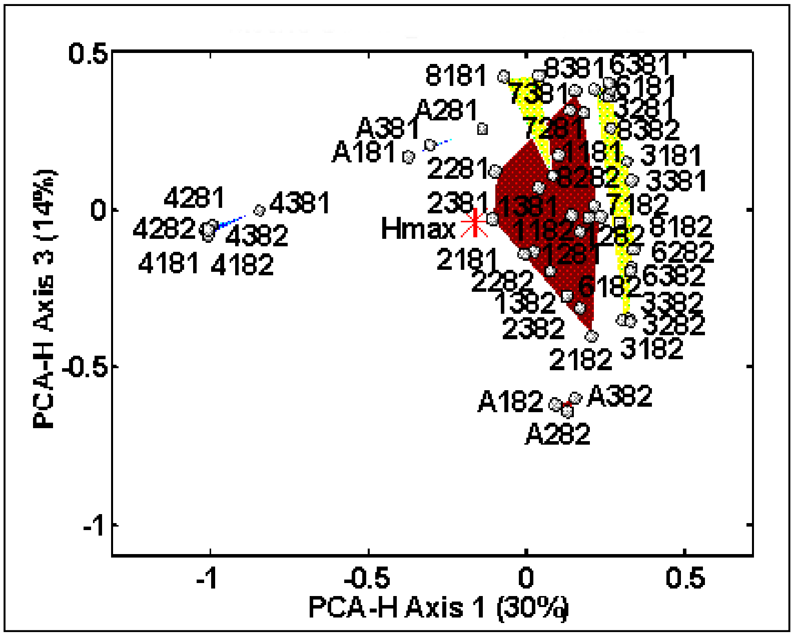


Figure 5-14. Metric scaling plot of CNESS distances, axes 1 versus 3, among all Boston Harbor samples collected in 1998. Results of the CNESS cluster analysis are shown as convex hulls. Station codes are as in Figure 5-12.

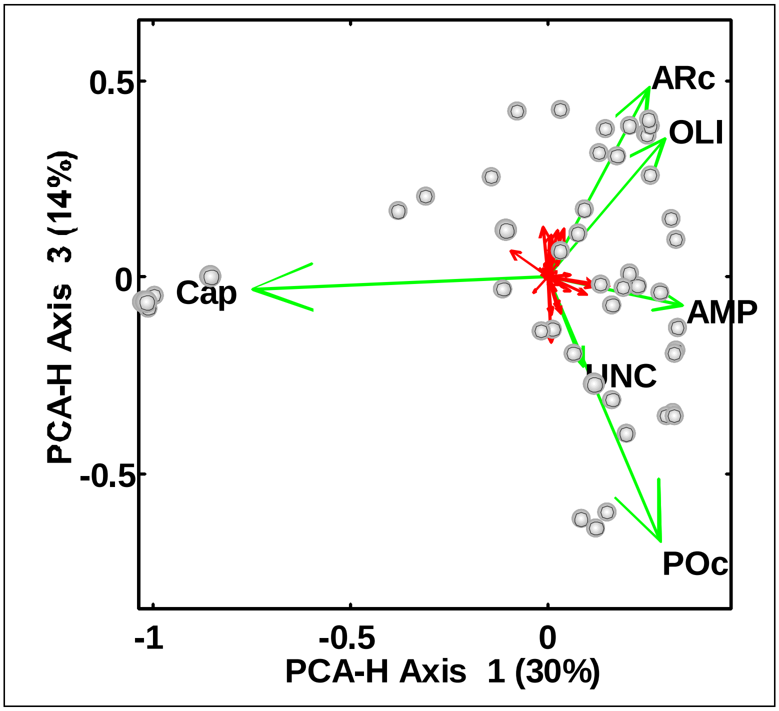


Figure 5-15. Gabriel Euclidean distance biplot, axes 1 versus 3, for the 1998 Boston Harbor data showing those species that control the orientation of samples shown in Figure 5-14. Species codes are as listed in Table 5-2. Open circles represent the spatial pattern of samples shown in Figure 5-14.

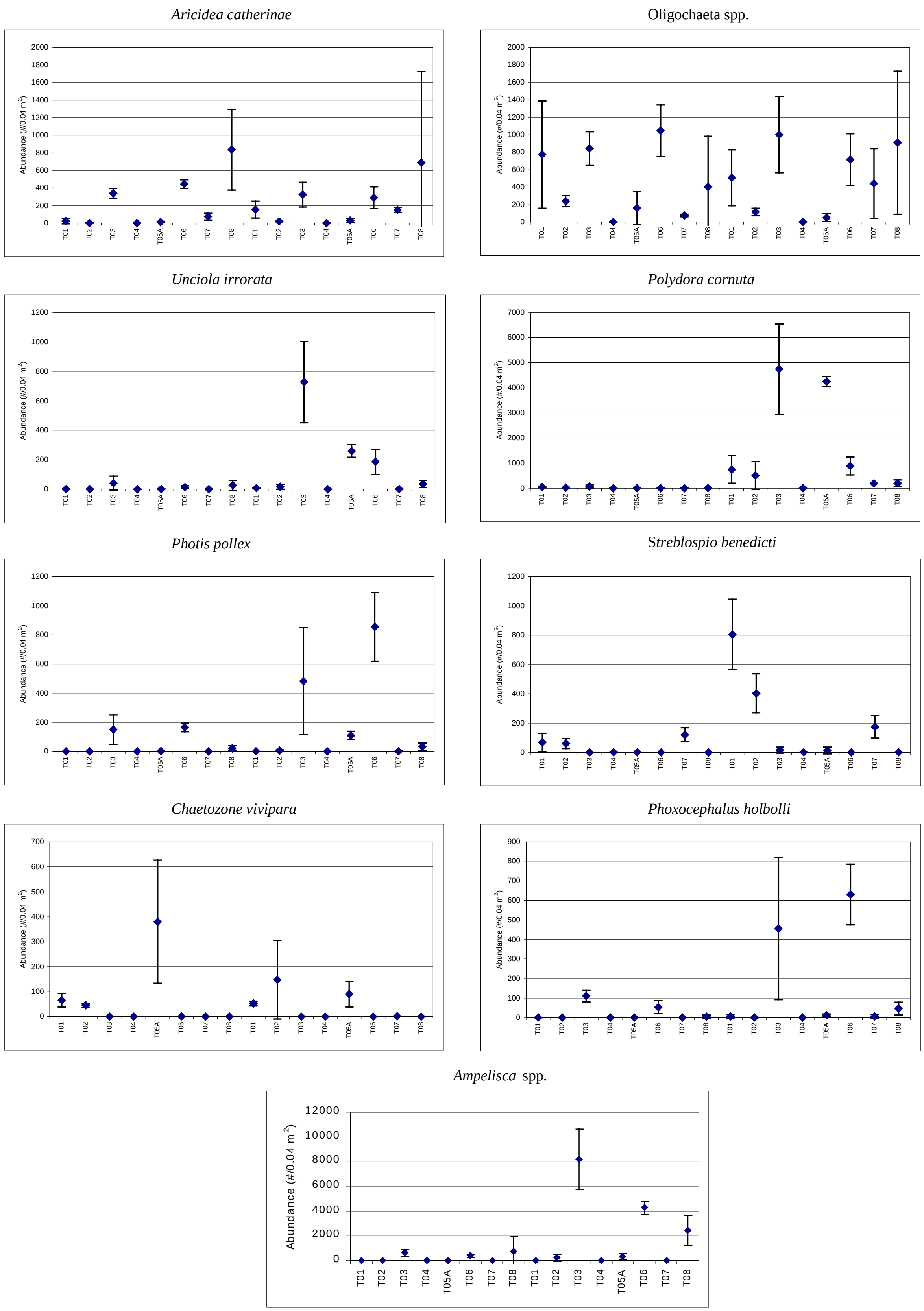


Figure 5-16. Abundance of selected infaunal taxa collected from Boston Harbor in April and August 1998. Mean and 95% confidence intervals are shown.

One of the most noticeable differences between the Boston Harbor infaunal communities described here for 1998 and those described by Blake *et al.* (1998) for 1997 was the relative importance of location (1998) or "season" (1997) in explaining faunal affinities among samples collected during the respective years. Blake *et al.*, although errors in labeling of the dendogram shown in their Figure 36 and incorrect shading of the convex hulls in their Figure 37 make the interpretation more difficult, seemed to find that season likely had more importance in determining cluster group affinity than what was determined in this report for 1998. At least part of the reason for the differences between the two years could have resulted from the differences in data treatment between the two years (as described in Section 5.1.2). Several key 1997 taxa, which may have shown relatively strong seasonal signals in 1997, were not included in the 1998 analyses. *Mytilus edulis*, reported in 1997 had much greater relative abundance in April than in August and seemed to explain the cluster of stations T01, T02, and T05A collected in April 1997 (see Blake *et al.* Figures 37 and 38). Also, two species that showed somewhat opposing distributions (*Tubificoides apectinatus* and *T.* nr. *pseudogaster*, see Blake *et al.* Figure 39) were merged in 1998 as Oligochaeta spp. (along with several other oligochaete species). *Tubificoides apectinatus* seemed to have somewhat greater relative abundance at several stations in August 1997 than it did in April (Blake *et al.* 1998, their Appendix F).

5.2.3 Infaunal Associations

The Gabriel covariance biplot (Figure 5-17) and cluster analysis were used to explore possible associations among the Boston Harbor infauna in 1998. The covariance biplot showed four reasonably well-defined groups of taxa. One assemblage, at about 10 o'clock in Figure 5-17, was comprised of several amphipods, *Ampelisca* spp., *Photis pollex*, *Phoxocephalus holbolli*, and *Unciola irrorata*. None of these taxa was associated with any particular sediment type of sediment TOC content (Table 5-4). They were typically most abundant at stations T03, T06, and T08. An assemblage of annelid worms is shown at about 2 o'clock in the covariance biplot. These species, *Streblospio benedicti*, *Microphthalmus aberrans*, *Phyllodoce mucosa*, and *Nephtys cornuta*, were not significantly associated with sediment type or TOC content (Table 5-4). Generally, these species, except *P. musoca*, were most abundant at stations T01, T02, and T07. The third assemblage, comprised of the nut clam *Nucula delphinodonta*, and the polychaetes *Polygordius* sp. A, *Spiophanes bombyx*, and *Exogone hebes*, is shown at about 7 o'clock in Figure 5-17. All of these species were negatively correlated with sediment mean phi (Table 5-4), indicating a marked association with relatively coarsely-grained sediments. The fourth species group occurs at about 5 o'clock in the covariance biplot. This group, which appeared rather weakly defined, was comprised of the polychaetes *Capitella capitata* complex and *Chaetozone vivipara*, the amphipod *Pontogenia inermis*, the snail *Ilyanassa trivitatta*, and the clam *Tellina agilis*.

As described by Trueblood *et al.* (1994), Pearson's *r* similarity among the 24 most important taxa contributing to CNESS distances in 1998 was determined by using the normalized hypergeometric probability matrix (m = 15). The resultant similarity values then were clustered by using the UPGMA method. The resulting dendogram (Figure 5-18) allowed further examination of possible species associations. The dendrogram revealed the same four main infaunal groups shown in the covariance biplot. However, the cluster patterns in the dendrogram allowed some of the associations among taxa that were not clearly resolved in the covariance biplot to be identified. For example, the covariance biplot (Figure 5-17) did not show *Polydora cornuta* (near 12 o'clock in the plot) to be clearly associated with any particular group. However, the dendrogram shows that this polychaete was more closely, albeit weakly, associated with the crustaceans occurring at about 10 o'clock in the covariance biplot rather than to the polychaete assemblage found at two o'clock. The association of the maldanid polychaete *Clymenella torquata* also was clarified by the cluster analysis, which revealed that the species was more closely associated with the polychaetes found at about 2 o'clock in Figure 5-17 rather than with *Chaetozone vivipara* or the other taxa near 5 o'clock in the covariance biplot.

Table 5-4. Pearson correlation coefficients (*r*) between selected infaunal taxa and sedimentary mean phi and TOC content. Critical values of *r* (*n* = 16): *p* < 0.05 (*), *r* = 0.497; *p* < 0.01 (**), *r* = 0.623; from Rohlf and Sokal (1969).

Taxon	Mean Phi	TOC
Ampelisca spp.	0.205	–0.077
Polydora cornuta	0.055	–0.166
Oligochaeta spp.	–0.218	–0.393
Capitella capitata complex	0.284	0.818**
Aricidea catherinae	–0.341	–0.328
Photis pollex	0.205	–0.057
Streblospio benedicti	–0.156	–0.217
Phoxocephalus holbolli	0.250	–0.026
Unciola irrorata	0.236	–0.075
Spiophanes bombyx	–0.536*	–0.293
Chaetozone vivipara	–0.330	–0.334
Ilyanassa trivittata	0.023	0.036
Nucula delphinodonta	–0.510*	–0.282
Polygordius sp. A	–0.632**	–0.344
Leptocheirus pinguis	–0.472	–0.283
Phyllodoce mucosa	–0.156	–0.239
Diastylis polita	–0.282	–0.201
Clymenella torquata	–0.348	–0.223
Nephtys cornuta	0.184	–0.034
Microphthalmus aberrans	–0.206	–0.241
Prionospio steenstrupi	–0.480	–0.324
Pholoe minuta	–0.129	–0.225
Dyopedos monacanthus	–0.135	–0.263
Edotia triloba	–0.285	–0.223
Exogone hebes	–0.556*	–0.305
Tellina agilis	–0.380	–0.366
Scoletoma hebes	–0.565*	–0.339
Orchomenella minuta	–0.065	–0.164
Mediomastus californiensis	–0.564*	–0.490
Pygospio elegans	–0.371	–0.259
Nephtys caeca	–0.450	–0.333
Dipolydora socialis	–0.494	–0.351
Spio thulini	0.170	–0.115
Polycirrus cf. *haemotodes*	0.046	–0.103
Crassicorophium bonelli	0.252	–0.010

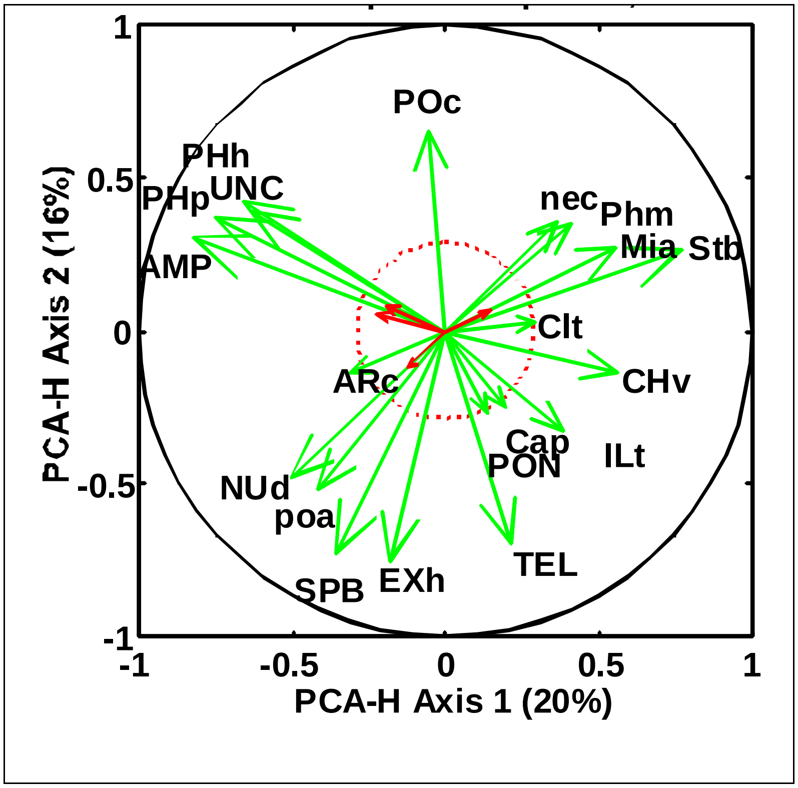


Figure 5-17. Gabriel covariance biplot, axes 1 versus 2, for the 1998 Boston Harbor data.

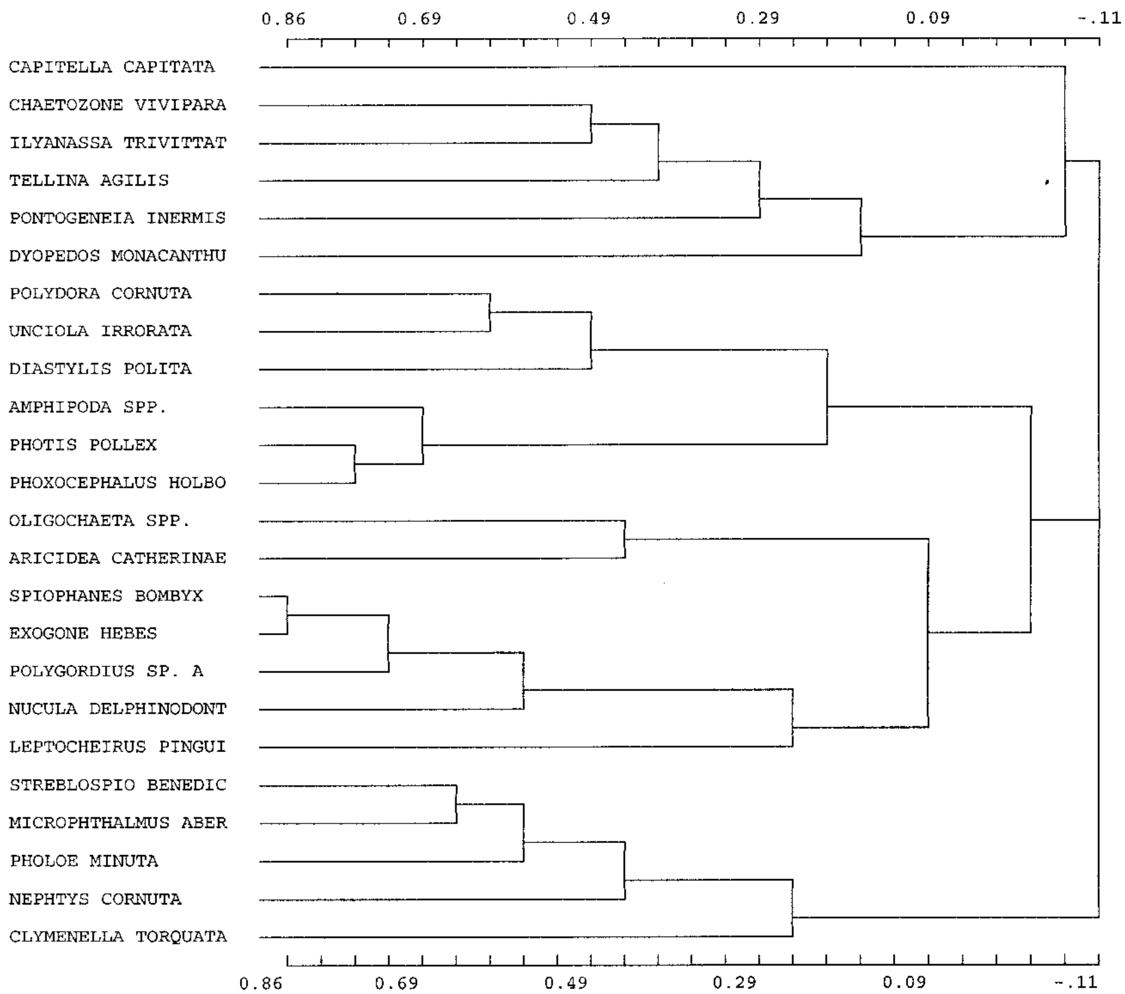


Figure 5-18. Dendrogram resulting from cluster analysis of the 24 most significant contributors to CNESS variation in the Boston Harbor 1998 dataset. The scale is Pearson's *r* = cos*2* (see text).

6.0 PROGRAMMATIC EVALUATION (1992–1998)

6.1 Spatio-temporal Trend in Sediment Profiles

by Robert J. Diaz

Blake *et al*. (1998) evaluated the long-term trends at Boston Harbor benthic monitoring stations from 1990 to 1997. Data for 1998 indicated a slight downward shift in the primary indicators of benthic habitat condition, the Organism Sediment Index (OSI) and the depth of the apparent color RPD layer. Median values for both the apparent color RPD depth and OSI were lower in 1998 relative to previous years (Figures 6.1-1 and 6.1-2). Mean and median values summarized by year are presented below.

	92	93	94	95	96	97	98
OSI Median	6.8	5.3	5.3	7.0	6.0	6.3	4.7
OSI Mean	6.4	5.6	5.2	6.5	6.4	6.4	5.3
OSI SE	0.2	0.4	0.4	0.4	0.3	0.4	0.4

	92	93	94	95	96	97	98
RPD Median	1.8	1.7	1.6	2.1	2.0	2.0	1.5
RPD Mean	1.8	2.4	1.8	2.9	2.7	2.7	2.0
RPD SE	0.1	0.3	0.2	0.3	0.2	0.2	0.2

The yearly differences among OSI values were significant (Kruskal-Wallis Test, $H = 23.12$, $p = 0.001$, and ANOVA, $F = 2.61$, $p = 0.017$). Multiple comparison tests based on the median showed that the yearly median OSI for 1998 was lower than those for all other years. Multiple comparison tests based on the median showed that 1994 and 1998 OSI values were lower, and 1995 and 1996 OSI values were higher than those for all other years. Multiple comparison based on the mean showed that yearly average OSI values for 1994 and 1998 to be lower than those for other years.

The yearly differences in apparent color RPD depth were significant (Kruskal-Wallis Test, $H = 16.07$, $p = 0.013$, and ANOVA, $F = 4.32$, $p = < 0.000$). Multiple comparison tests based on the median showed that 1994 and 1998 had lower, and 1995 and 1996 had higher overall median RPD depths than those for all other years. Multiple comparison based on the mean showed yearly average RPD depths for 1992, 1994, and 1998 to be lower than those for other years, and 1995, 1996, and 1997 values to be higher.

The decline in these two parameters in 1998 appears to be related to the continued predominance of successional stage I seres at many of the nearshore and inner harbor stations (Figure 3-10). Much of the benthic habitat quality in the Boston Harbor area is determined by the distribution of stage I and stage II seres (Blake *et al*. 1998). As one or the other increases, a shift is seen in the OSI, which is an overall measure of benthic habitat quality. In 1998, data from the 60 long-term benthic stations showed that there was a decline in the area of the Harbor where *Ampelisca* tubes and tube mats occurred (Figure 3-4, and Figure 58 in Blake *et al*. 1998). This decline in the intermediate successional stage seres may represent a negative rebound of the *Ampelisca* populations that had monotonically increased in aerial coverage of the bottom (percentage of stations) from 1992 to 1996. In 1997 there was a slight decline in the coverage by *Ampelisca* mats that continued into 1998 with a 17% decline in a number of stations with mats (Figure 6.1-3).

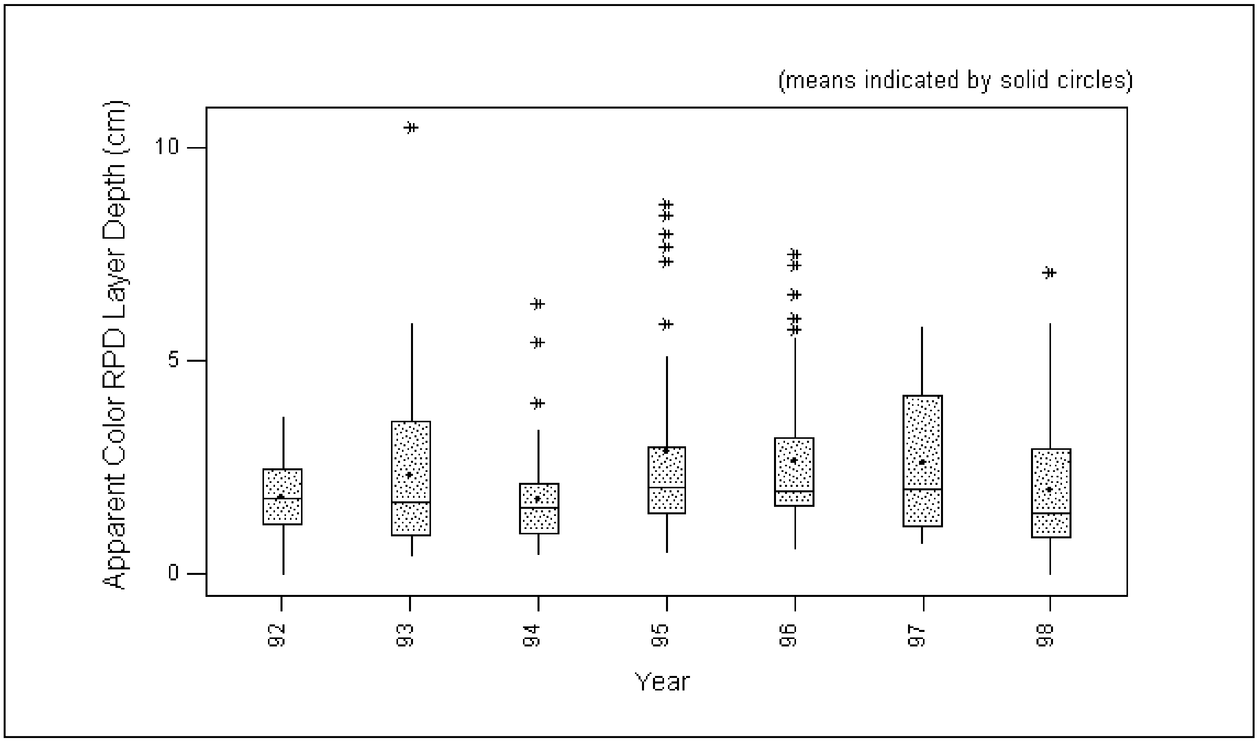


Figure 6.1-1. Boxplots of long-term trends in the apparent color redox potential discontinuity layer depth (cm), a measure of the thickness of oxidized sediments, for Boston Harbor stations.

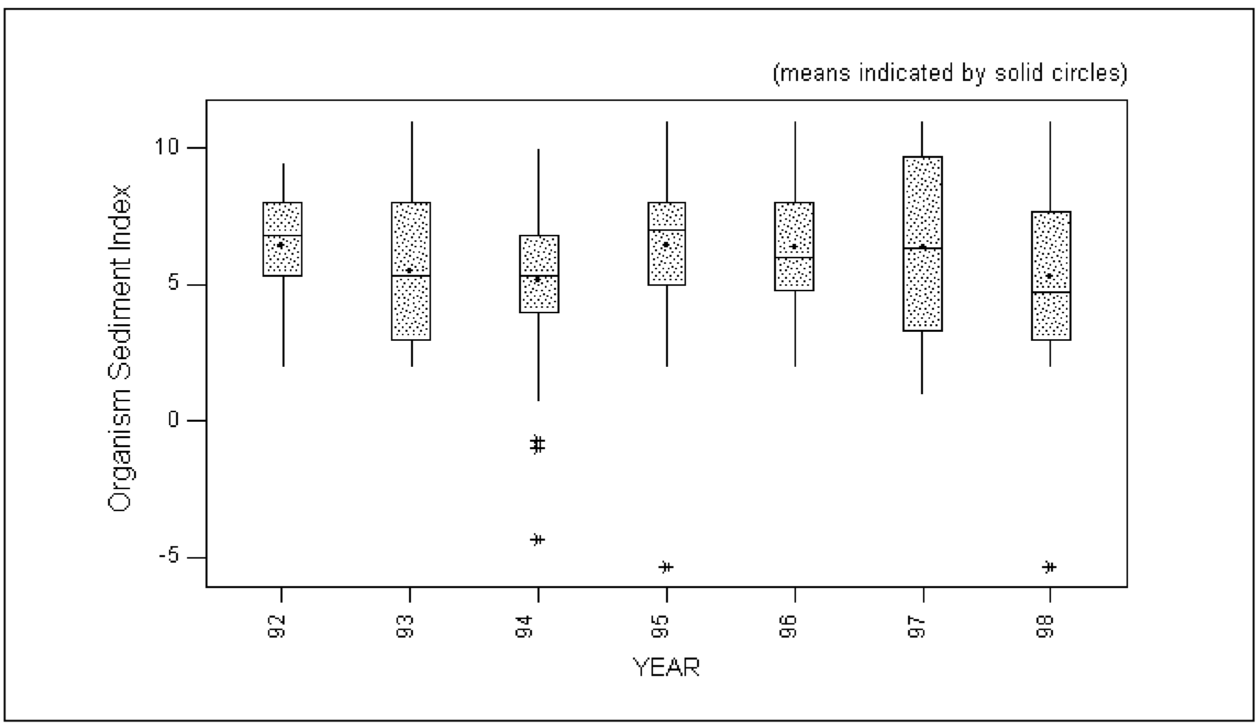


Figure 6.1-2. Boxplots of long-term trends in the Organism Sediment Index, an indicator of macrobenthic community development and activity, for Boston Harbor stations.

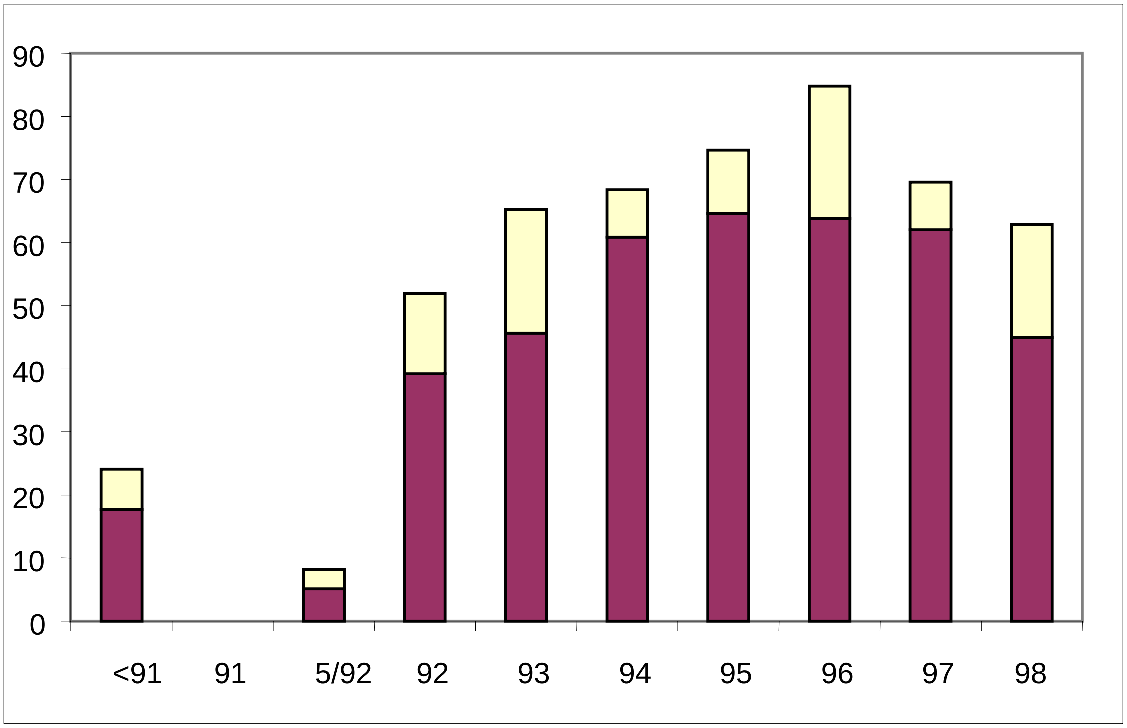


Figure 6.1-3. Percentage of benthic monitoring stations with Boston Harbor with *Ampelisca* spp. tubes (open bars) and mats (solid bars) from 1989 to 1998. Based in part on Blake *et al*. (1998).

Overall, general benthic habitat quality within the study area was similar from August 1992 to 1998, with minor variations from year-to-year (Blake *et al*. 1998, this report Section 3). For 1998, key indicators of benthic habitat quality were lower relative to previous year, however, the major changes in habitat quality appeared to have occurred in early 1992. Current benthic communities appear to have developed in response to major disturbance events in 1991, the October severe storm and the December sewage discharge abatement (Blake *et al*. 1998). Interestingly, stations with the poorest habitat quality in the 1989/90 sampling (Blake *et al*. 1993) continued to have poor quality habitat in 1998. Three stations (T04, R36, and R43) all had long-term average OSI values less than or equal to 3.

6.2 Spatio-temporal Trends in Sedimentary Parameters

by Deirdre Dahlen

6.2.1 Sediment Texture

April Surveys—Patterns in sediment composition for sediments collected in April over the course of the study period (1993 through 1998) were consistent at some stations and variable at others. For example, sediments collected at stations T01 and T04 displayed very consistent grain size composition over time and sediments from stations T05A and T08 showed somewhat consistent patterns of sediment composition over time. However, sediments collected at stations T02, T03, T06, and T07 displayed fairly variable grain size composition over time. Sediments from station T01 were comprised primarily of coarse-grained sediments and clustered in the upper apex of the ternary plot (Figure 6.2-1a). Sediments from station T02 displayed variable sediment composition over time with sediment texture ranging from sandy (70% sand and gravel in 1994) to very silty (84% fines in 1998) (Figure 6.2-1b). Sediments from station T03 also displayed variable sediment composition over time, ranging from sandy (52% in 1994) to very silty (90% fines in 1995) (Figure 6.2-1c). Sediments from station T04 were comprised primarily of very silty sediments and clustered in the lower quadrants of the ternary plot (Figure 6.2-1d). Sediments collected from stations T05A and T08 generally were comprised of more coarse-grained sediments (> 60% gravel and sand) and clustered in the upper quadrants of the ternary plot (Figure 6.2-2a and Figure 6.2-2d). One exception was observed in 1997, when sediments collected at station T08 were more silty (63% fines) in sediment texture compared to all other sampling years. Sediments collected at station T06 displayed variable patterns of sediment composition with sediment texture ranging from sandy in 1995 (65% sand and gravel) to silty in 1996 (77% fines) (Figure 6.2-2b). Similarly, sediments from station T07 also had variable sediment composition over time, ranging from very sandy in 1997 (92% sand and gravel) to very silty in 1993 (80% fines) (Figure 6.2-2c).

August Surveys—Sediments collected during August at most Traditional stations displayed fairly consistent grain size composition over the course of the study period (1991 through 1998). Sediments from station T01 displayed very consistent patterns in sediment texture during all sampling years except 1995, and was comprised primarily of coarse-grained sediments (Figure 6.2-3a). Sediments collected at station T01 in 1995 were very silty (58%) by comparison. Sediments from station T02 displayed fairly consistent patterns in sediment composition over time, with sandy sediment texture in 1991 through 1994 (> 60% sand and gravel) and slightly more silty in 1995, 1997, and 1998 (56–63% fines) (Figure 6.2-3b). Sediments from station T03 displayed fairly variable sediment composition over time and clustered into two groups on the ternary plot (Figure 6.2-3c). Sediments collected from 1995 through 1998 at station T03 were silty and clustered in the lower quadrants of the ternary plot; whereas sediment collected in 1991 through 1994 was more sandy with less silt and clay (Figure 6.2-3c). Sediments from station T04 displayed fairly consistent sediment texture over time and were primarily comprised of silty sediments (68–97% fines), clustering in the lower, middle quadrants of the ternary plot (Figure 6.2-3d). Sediments collected from station T05A displayed the most consistent patterns in sediment composition over time, and were comprised of very sandy sediments clustering in the upper apex of the ternary plot (Figure 6.2-4a). Sediments collected at station T06 displayed fairly variable patterns in sediment composition from year-to-year and clustered into two distinct groups on the ternary plot (Figure 6.2-4b). Sediments collected in 1995, 1996 and 1998 contained considerably higher amounts of silt and clay (61–77% fines) compared to those collected in 1991 through 1994 and 1997, which were sandier. Sediments collected from station T07 had fairly variable sediment texture over time, ranging from sandy (59% sand and gravel) in 1991 to silty in 1998 (61% fines) (Figure 6.2-4c). Sediments collected from station T08 displayed very consistent patterns in sediment composition during all sampling years except 1991, and were comprised of very sandy sediments (> 80% sand and gravel) clustering in the upper apex of the ternary plot (Figure 6.2-4d). Sediments collected at this station in 1991 contained high amounts of silt and clay by comparison (88% fines).

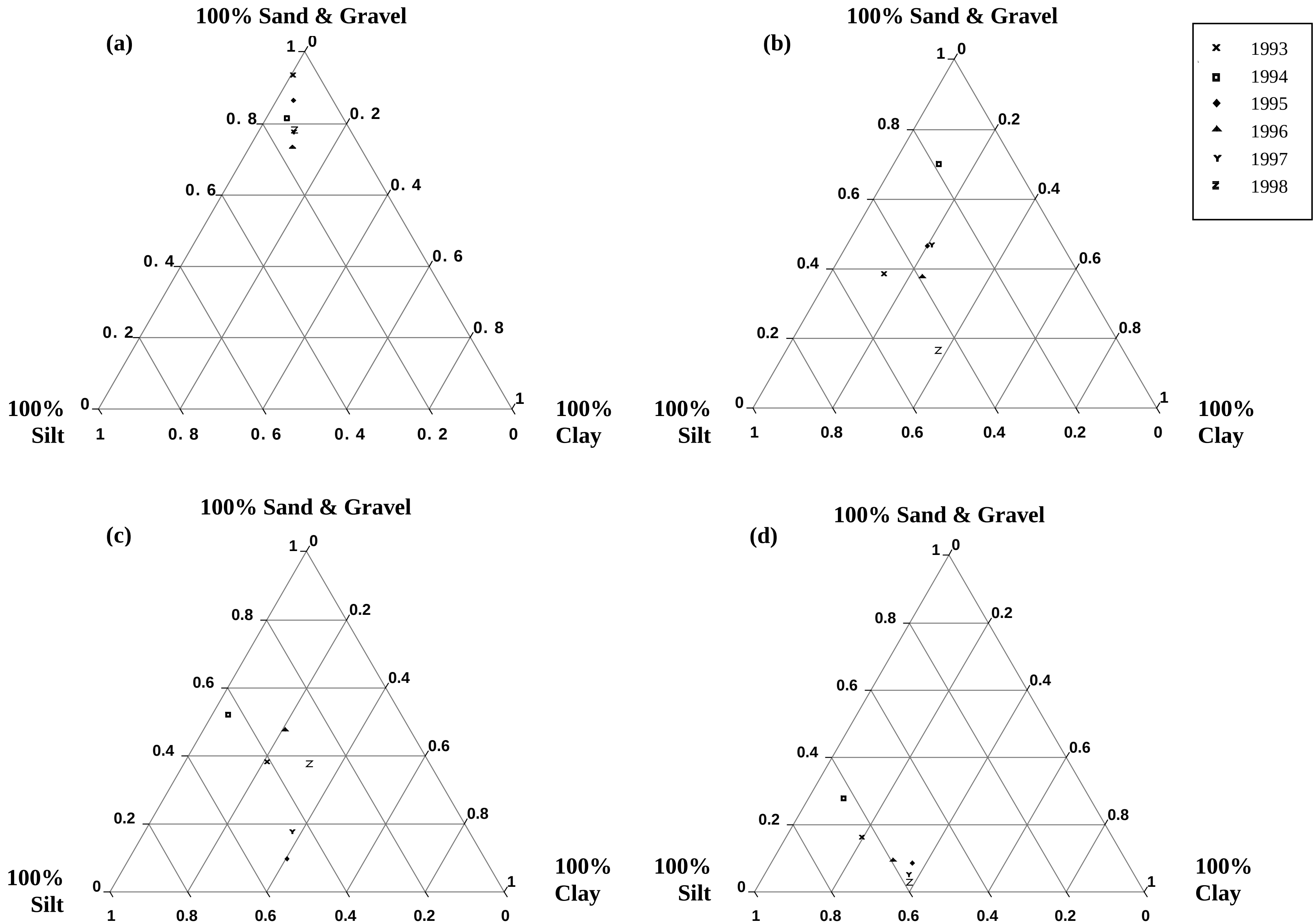


Figure 6.2-1. Grain size composition from sediments collected at station T01 (a), T02 (b), T03 (c), and T04 (d) in April 1993 through 1998.

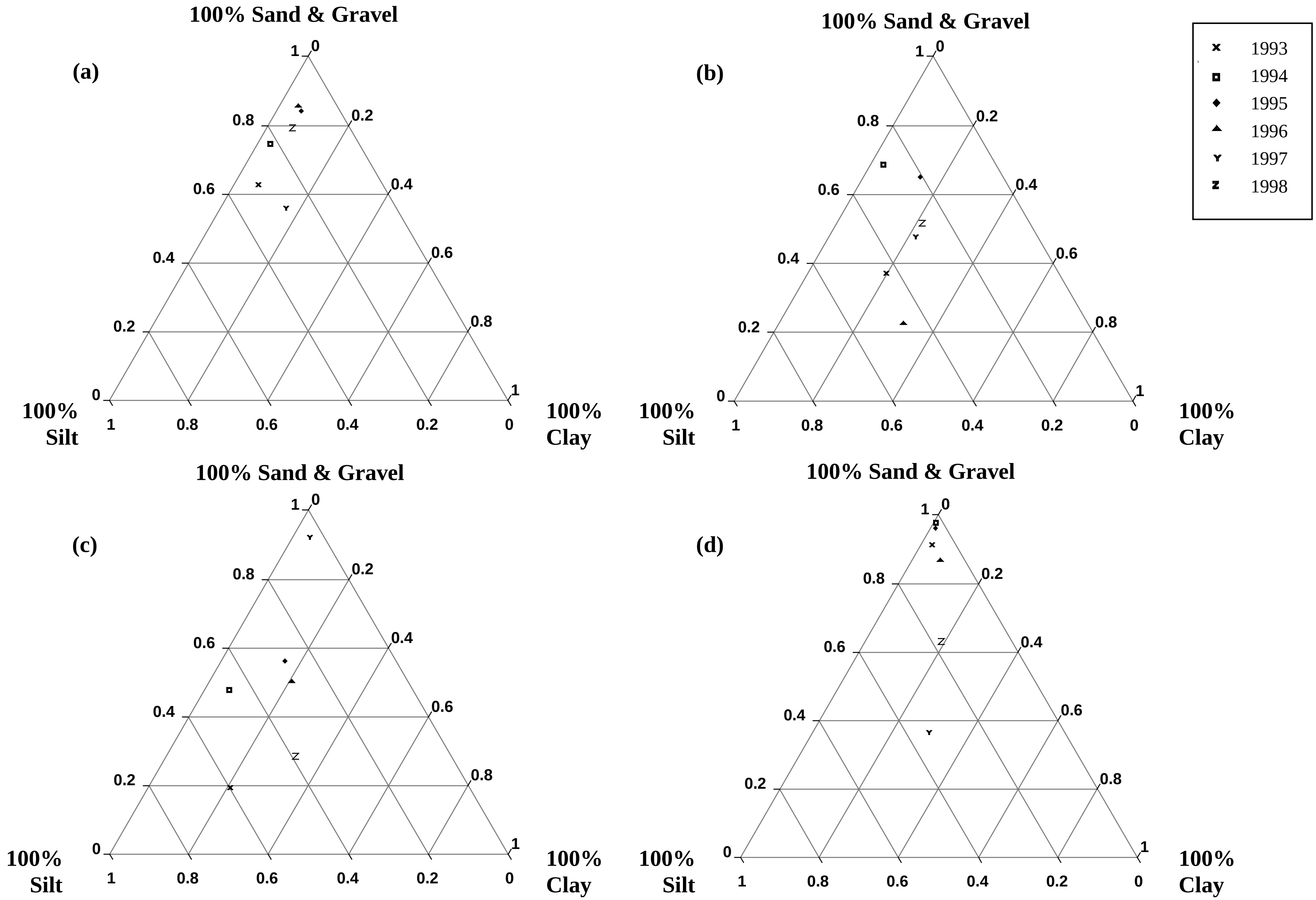
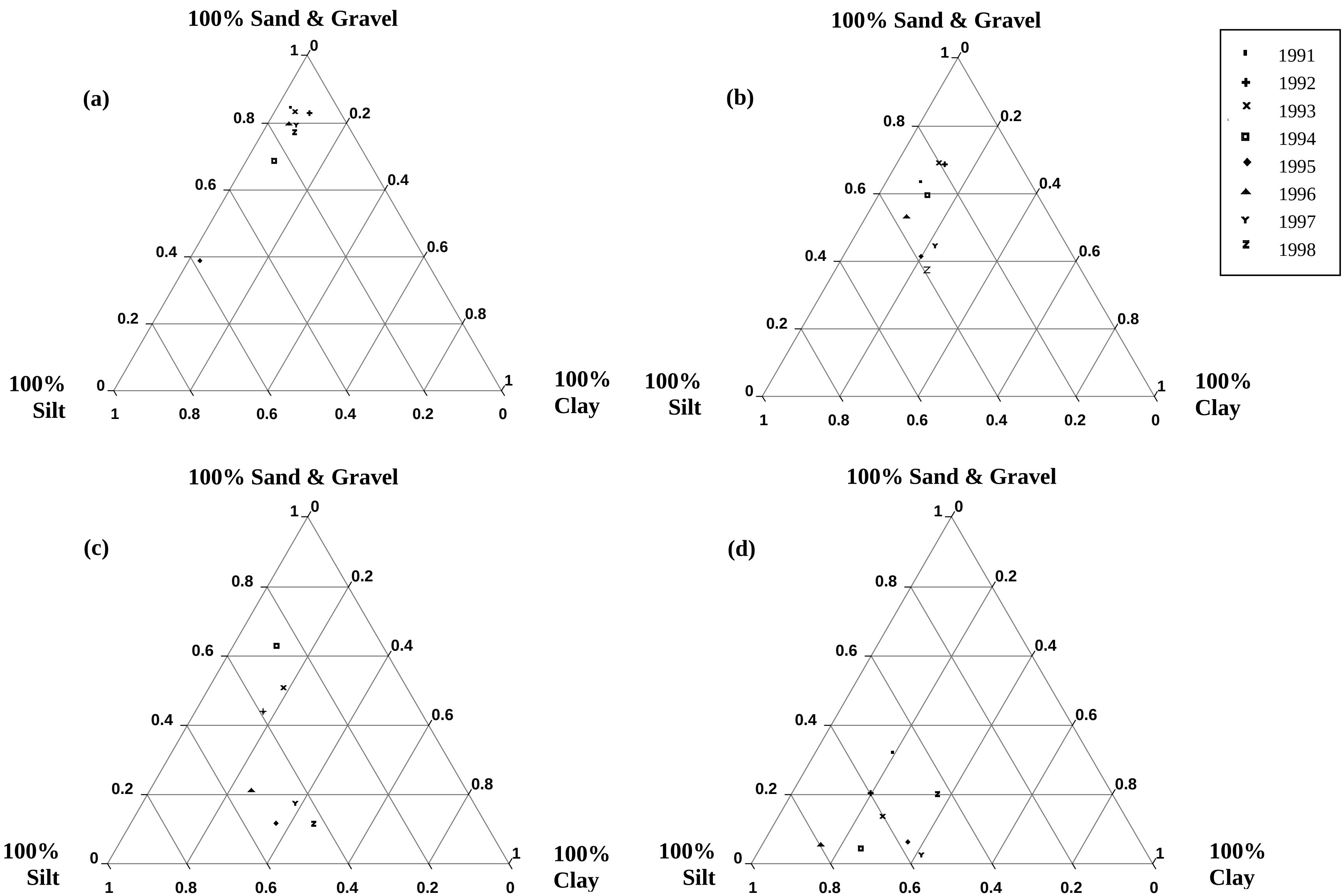


Figure 6.2-2. Grain size composition from sediments collected at station T05A (a), T06 (b), T07 (c), and T08 (d) in April 1993 through 1998.



igure 6.2-3. Grain size composition from sediments collected at station T01 (a), T02 (b), T03 (c), and T04 (d) in August 1991 through 1998.

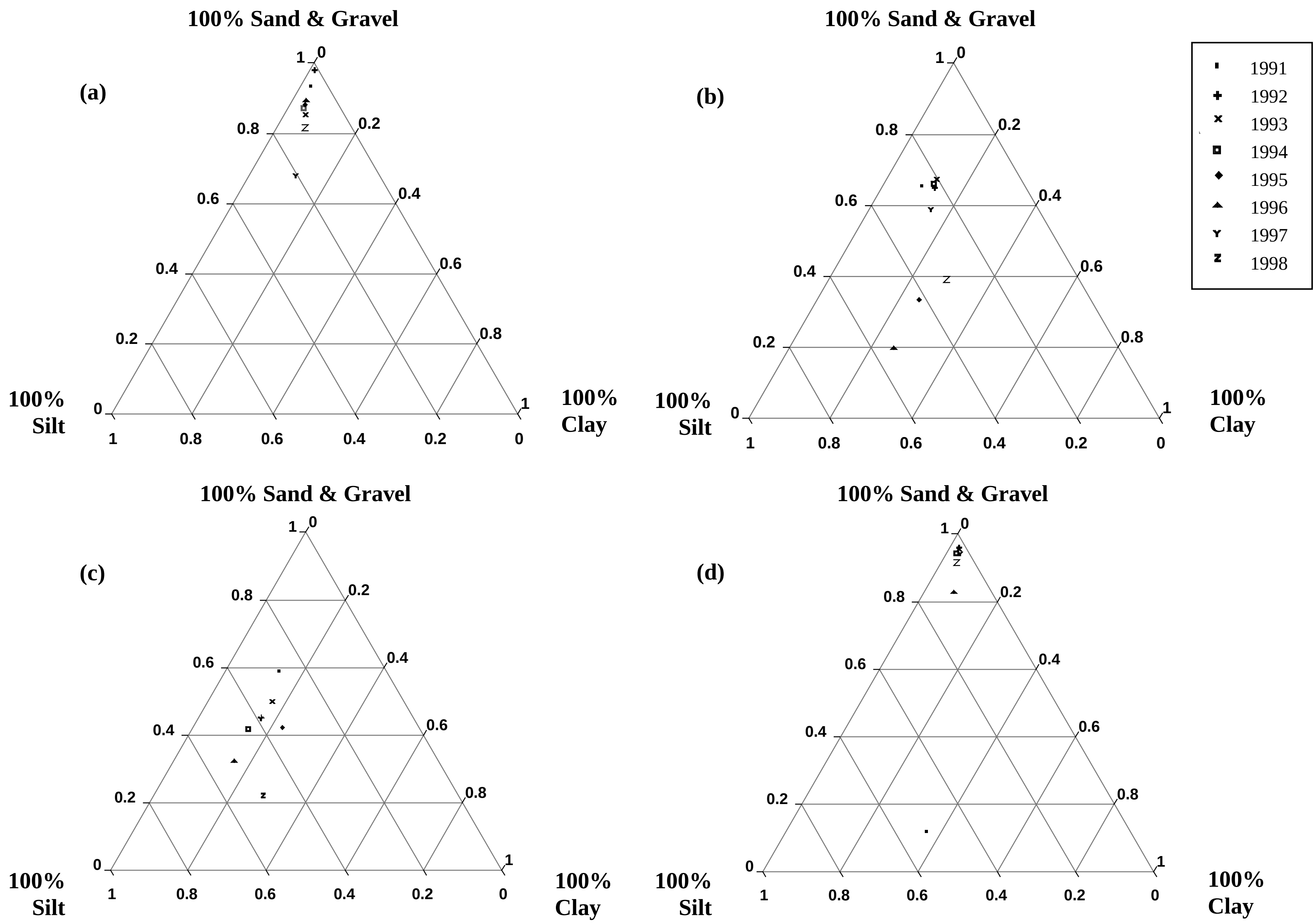


Figure 6.2-4. Grain size composition from sediments collected at station T05A (a), T06 (b), T07 (c), and T08 (d) in August 1991 through 1998.

6.2.2 Total Organic Carbon Content

The TOC content measured during April surveys is representative of natural contributions such as the spring plankton bloom in addition to spring run-off and anthropogenic loadings (Blake *et al*. 1998). However, the TOC content measured during August surveys is in large part representative of the net inventory of organic matter following respiration of the spring input of carbon substrates (Blake *et al*. 1998). TOC is generally expected to be higher in April than in August (Blake *et al*. 1998). This relationship held true only at some stations, while most stations had higher levels of TOC in August compared to April inventories. These findings are consistent with previous studies (Blake *et al*. 1998) and are discussed in greater detail below.

April Surveys—The TOC content in sediments collected at Traditional stations from 1993 through 1998 is presented in Figure 6.2-5. The expected relationship between April and August TOC values did not consistently hold true (Figure 6.2-6). Rather, April TOC values were higher than August values only 40% of the time. For example, TOC content was higher in April 1993 compared to August values at all stations except T01 and T03. In addition, station T02 consistently had higher TOC values in April than in August during all sampling years with the sole exception of 1995. Conversely, higher TOC values were observed at stations T01 and T03 in August during all sampling years except 1998.

Patterns in TOC content were fairly consistent over time at stations T01, T02, T03, and T07; whereas TOC content was more variable at stations T04, T05A, T06, and T08 (Figure 6.2-5). Sediments collected from station T04 consistently had the highest levels of TOC over time, whereas the lowest levels were found at stations T05A and T08. The relationship between TOC and percent fines is illustrated in Figure 6.3-7 ($r = 0.76$, $n = 48$, $p < 0.01$). TOC correlated well with percent fines at all stations over all sampling years with the exception of 1997 where $r = 0.35$ ($n = 8$, $p < 0.05$).

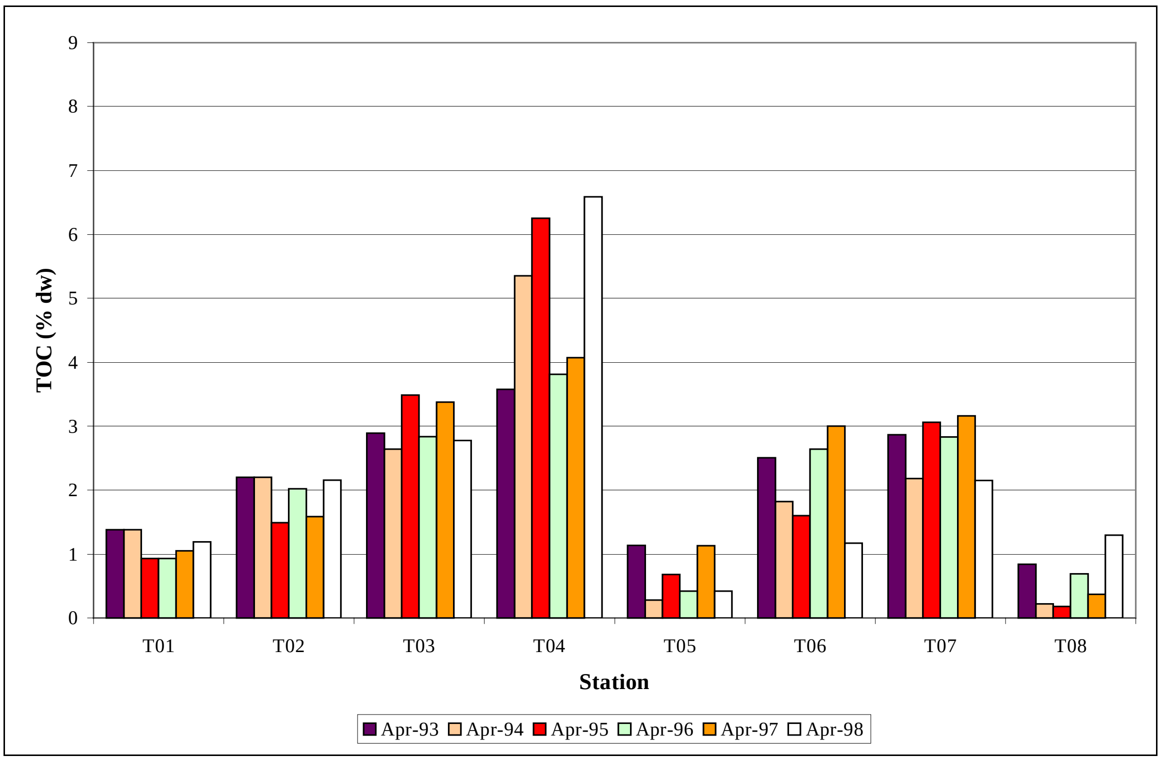


Figure 6.2-5. Total organic carbon content in sediments collected at Traditional stations in April 1993 through 1998.

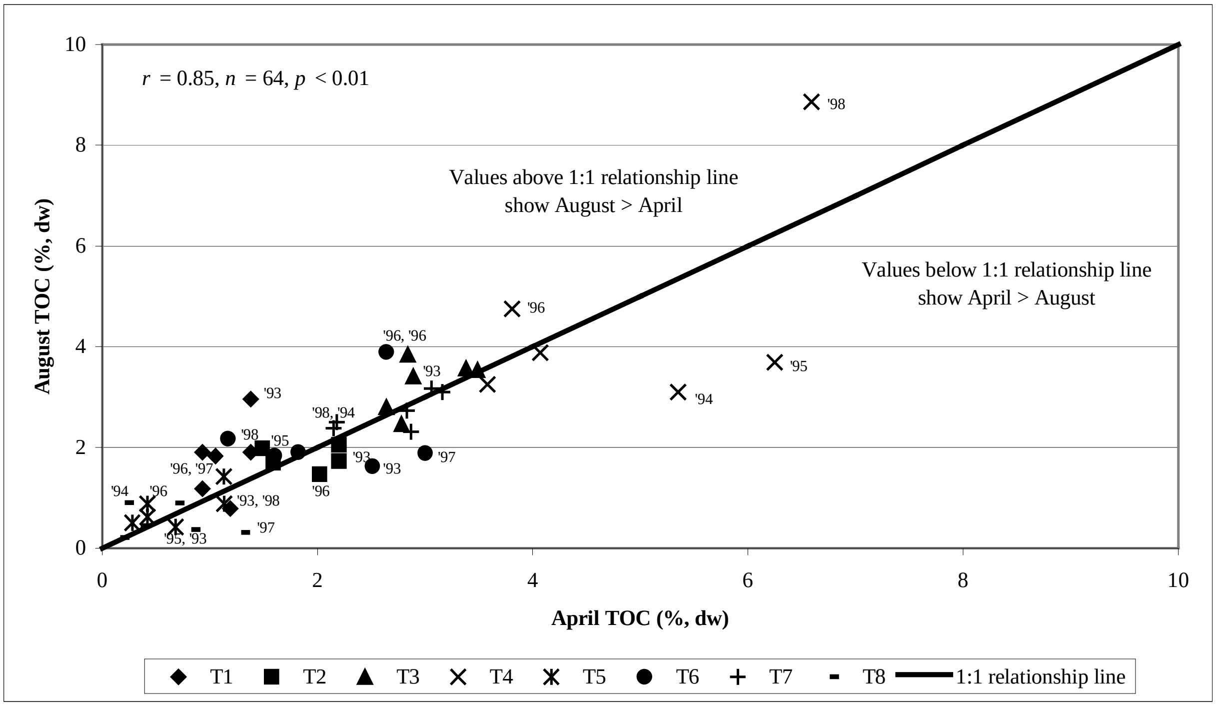


Figure 6.2-6. A comparison of April and August total organic carbon content in sediments collected from Traditional stations, 1993–1998. There are no values for April 1991 and 1992.

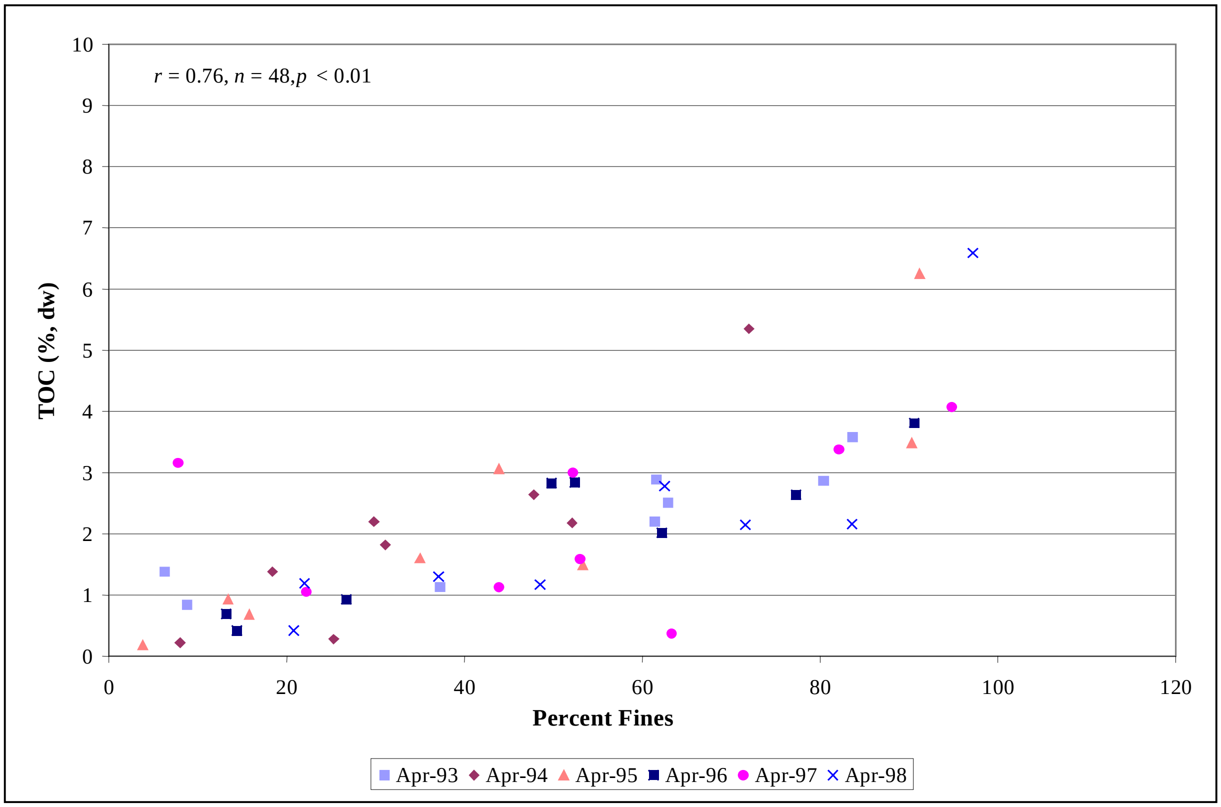


Figure 6.2-7. Total organic carbon content plotted versus percent fines in sediments collected at Traditional stations in April 1993 through 1998.

August Surveys—Patterns in TOC content were fairly consistent over time at all Traditional stations except T05A and T08 (Figure 6.2-8). In addition, the TOC content in sediments collected at station T04 in 1998 was the highest measured (2–3× compared to other values) among in all sampling years. Similarly, the TOC content in sediments collected at station T06 in 1996 was also quit high (2×) compared to values measured in all other sampling years. Sediments collected from station T04 consistently had the highest levels of TOC over time, whereas the lowest levels were found at stations T05A and T08. The relationship between TOC and percent fines is illustrated in Figure 6.2-9 ($r = 0.68$, $n = 64$, $p < 0.01$). TOC correlated well with percent fines at most stations over all sampling years with the exception of 1991 ($r = 0.09$, $n = 8$, $p < 0.05$) and 1998 ($r = 0.62$, $n = 8$, $p < 0.05$). TOC content at station T04 in 1998 was unusually high in relation to grain size and the correlation between TOC and percent fines in 1998 improved considerably by excluding this station from the regression analysis ($r = 0.98$, $n = 7$, $p < 0.01$).

6.2.3 *Clostridium perfringens*

April Surveys—*Clostridium* densities for samples collected in April ranged from 600 cfu in 1996 (station T01) to 75,000 cfu in 1995 (station T03) (Figure 6.2-10). Sediment collected at stations T01, T05A and T08 generally had the lowest *Clostridium* densities (< 10,000 cfu) compared to values measured at all other Traditional stations. Patterns in *Clostridium* densities at stations T02, T03, T04, T06, and T07 were variable over time (1993–1998) and showed several peaks in 1995 and 1997 returning to more intermediate levels in the next sampling year (Figure 6.2-10). There were no clear year-to-year trends in *Clostridium* densities when compared between April and August surveys. For example, April *Clostridium* densities were generally higher in 1994, 1995, 1997, and 1998; whereas August values were higher in 1996.

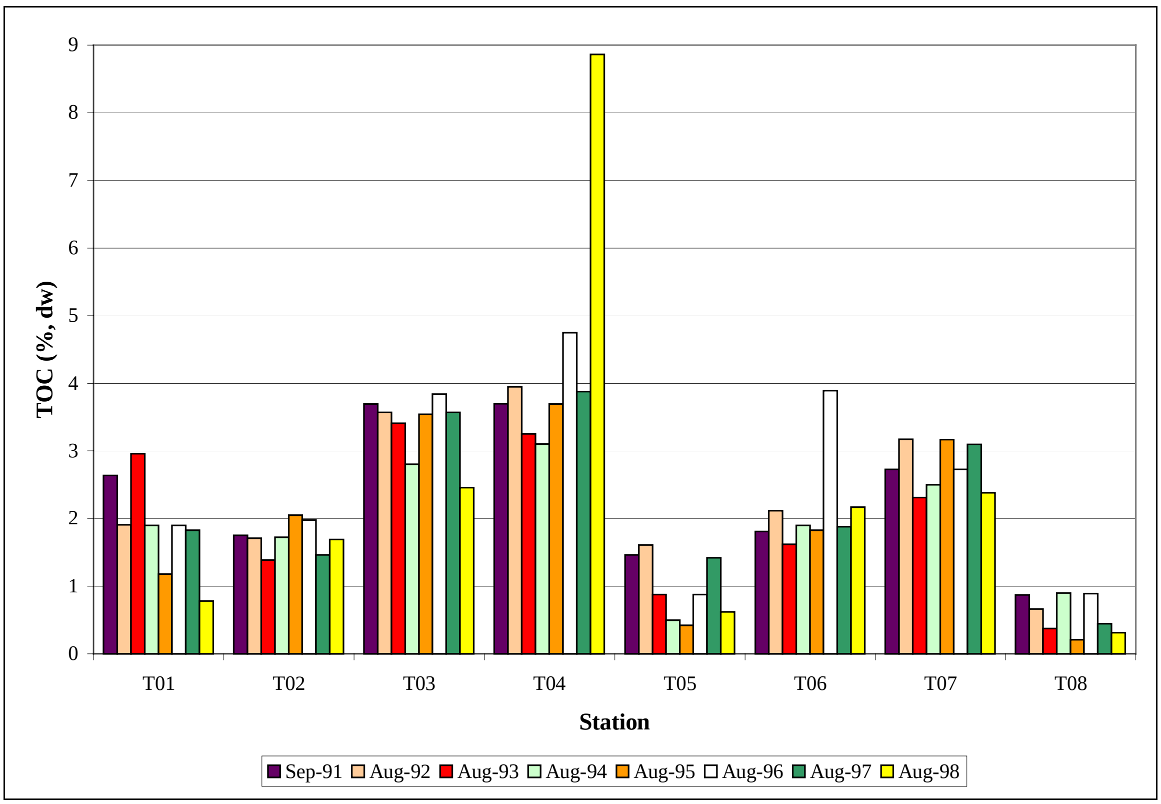


Figure 6.2-8. Total organic carbon content in sediments collected at Traditional stations in August 1991 through 1998.

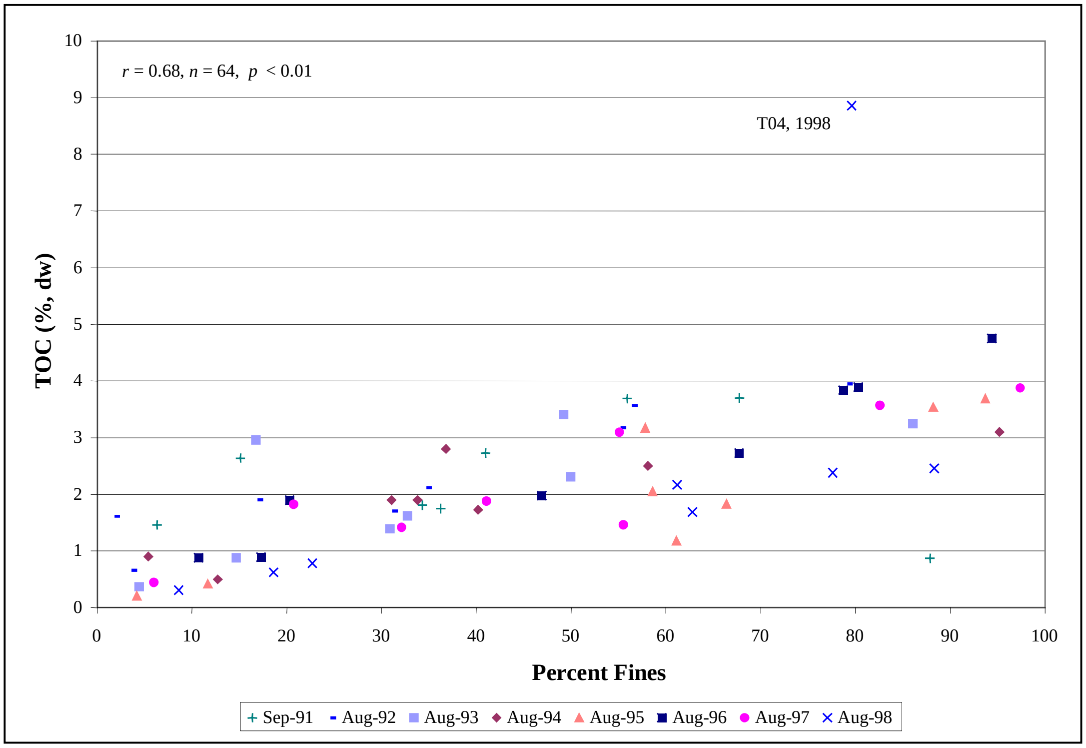


Figure 6.2-9. Total organic carbon content plotted against percent fines in sediments collected at Traditional stations in August 1991 through 1998.

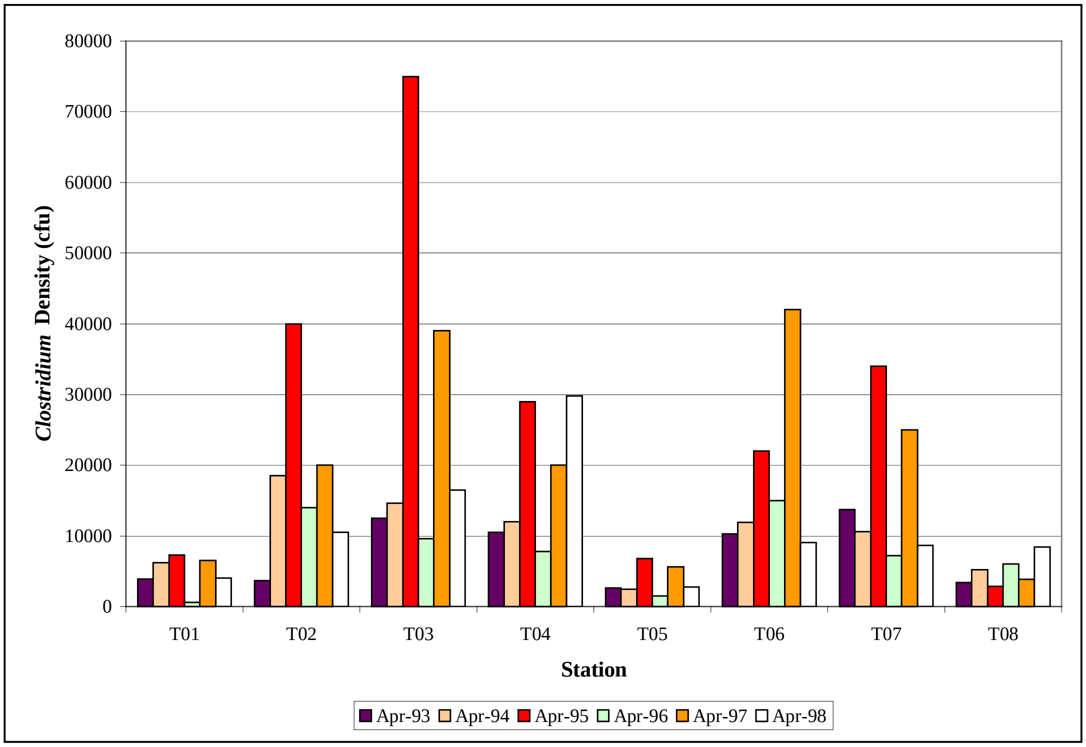
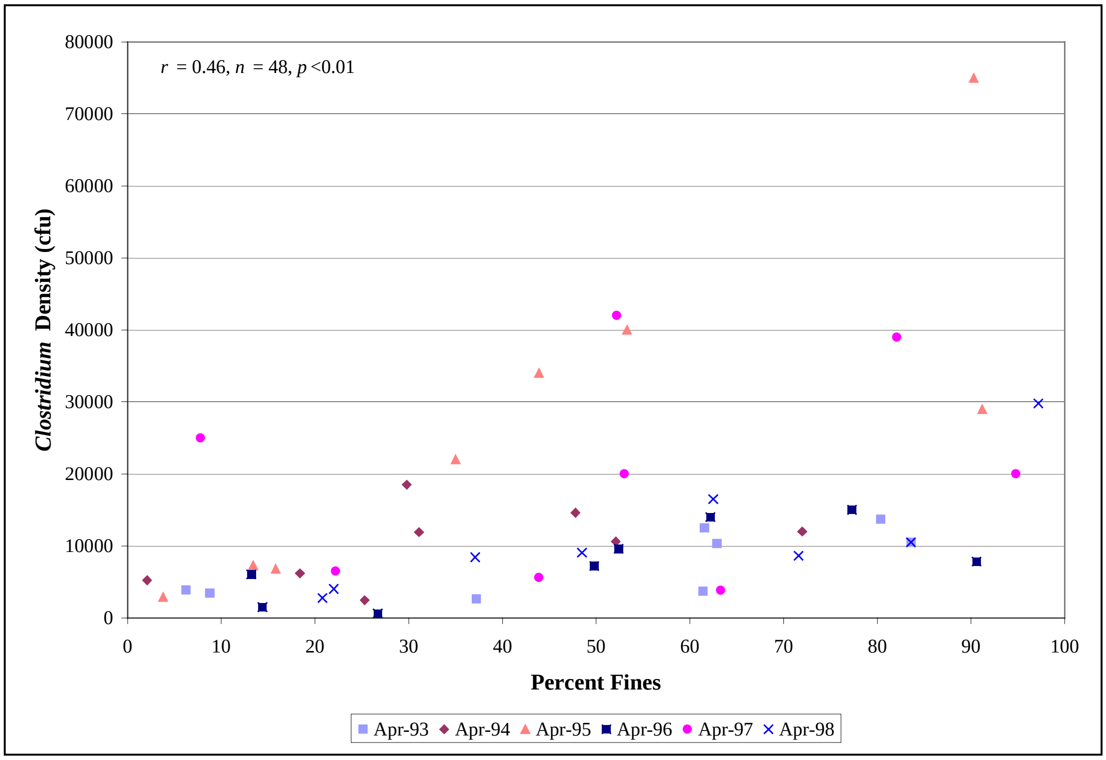


Figure 6.2-10. Distribution of *Clostridium* densities (cfu) in sediments collected at Traditional stations in April 1993 through 1998.

Clostridium densities correlated well with grain size or TOC for some years of the study, but not others (Figure 6.2-10a and b). For example, *Clostridium* densities did correlate well with percent fines in 1993 ($r = 0.76$, $n = 8$, $p < 0.05$), 1995 ($r = 0.83$, $n = 8$, $p < 0.01$), 1996 ($r = 0.71$, $n = 8$, $p < 0.05$), and 1998 ($r = 0.80$, $n = 8$, $p < 0.05$). Similarly, *Clostridium* densities correlated well with TOC content in 1993 ($r = 0.84$, $n = 8$, $p < 0.01$), 1997 ($r = 0.76$, $n = 8$, $p < 0.05$) and 1998 ($r = 0.97$, $n = 8$, $p < 0.01$).

August Surveys—*Clostridium* densities for samples collected in August ranged from slightly less than 1,000 cfu (stations T03 in 1992 and station T08 in 1995) to 207,000 cfu in 1991 (station T03) (Figure 6.2-12). Consistent with April trends, sediments collected at stations T01, T05A and T08 generally had the lowest *Clostridium* densities (< 10,000 cfu), with the exception of the 1991 and 1992 densities for station T05A. Patterns in *Clostridium* densities were fairly variable at most Traditional stations (Figure 6.3-12). In addition, *Clostridium* densities peaked in 1996 at stations T04, T06 and T07 before returning to more intermediate levels in the next sampling year. *Clostridium* density was very high (207,000 cfu) at station T03 in 1991, dropped to less than 1,000 cfu in 1992 and returned to more consistent values in 1993 (20,000 to 30,000 cfu).

Clostridium densities did not correlate well with either grain size or TOC content over the course of the study period (1991–1998) (Figure 6.2-13a and b). However, *Clostridium* densities have consistently correlated well with grain size and TOC for the more recent sampling years (1996–1998), during which C*lostridium* densities have shown a decreasing trend. For example, *Clostridium* densities did correlate well with percent fines in 1996 ($r = 0.92$, $n = 8$, $p < 0.01$), 1997 ($r = 0.79$, $n = 8$, $p < 0.05$) and 1998 ($r = 0.79$, $n = 8$, $p < 0.05$). Similarly, *Clostridium* densities correlated well with TOC content in 1995 ($r = 0.76$, $n = 8$, $p < 0.05$), 1996 ($r = 0.92$, $n = 8$, $p < 0.01$) and 1997 ($r = 0.71$, $n = 8$, $p < 0.05$) and 1998 ($r = 0.91$, $n = 8$, $p < 0.01$).



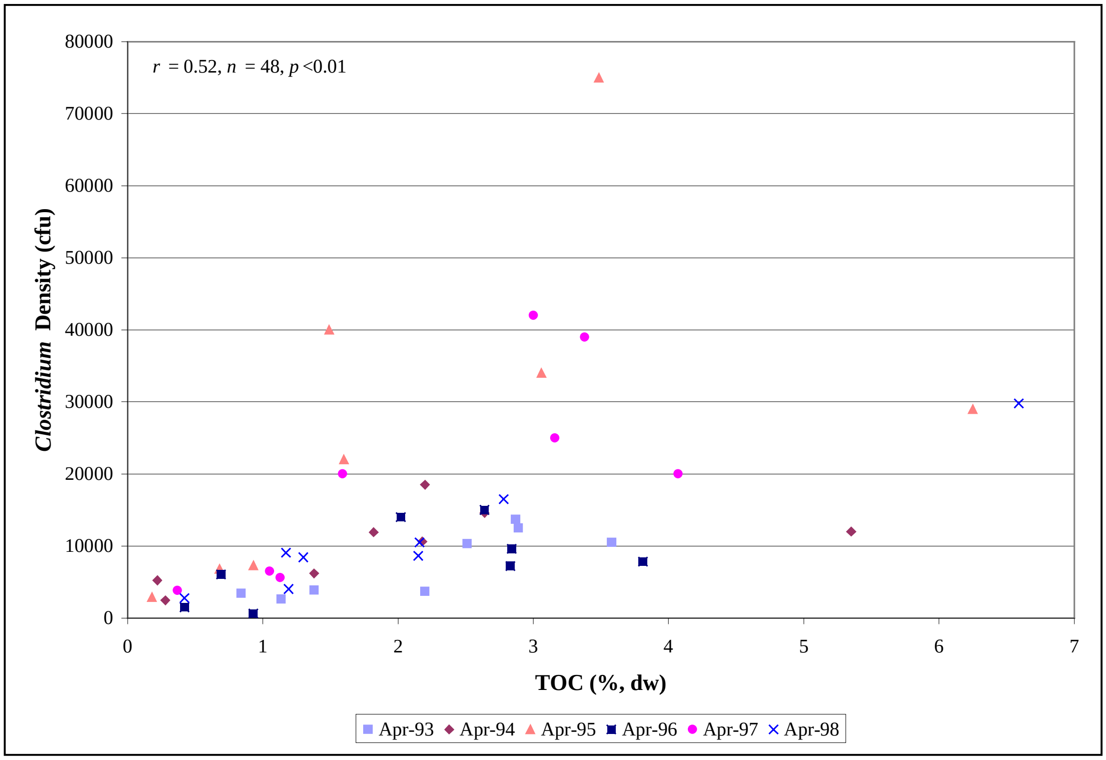


Figure 6.2-11. *Clostridium* density (cfu) plotted versus percent fines (a) and TOC content (b) in sediments collected at Traditional stations in April 1993 through 1998.

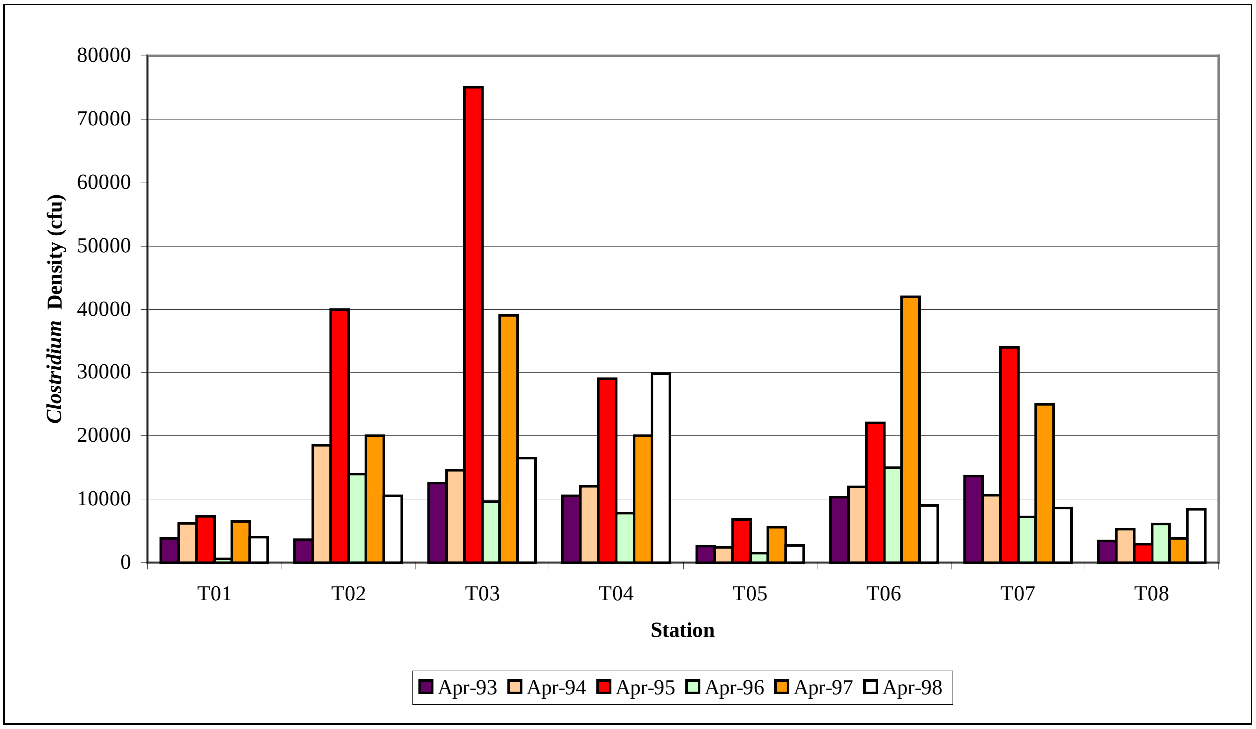
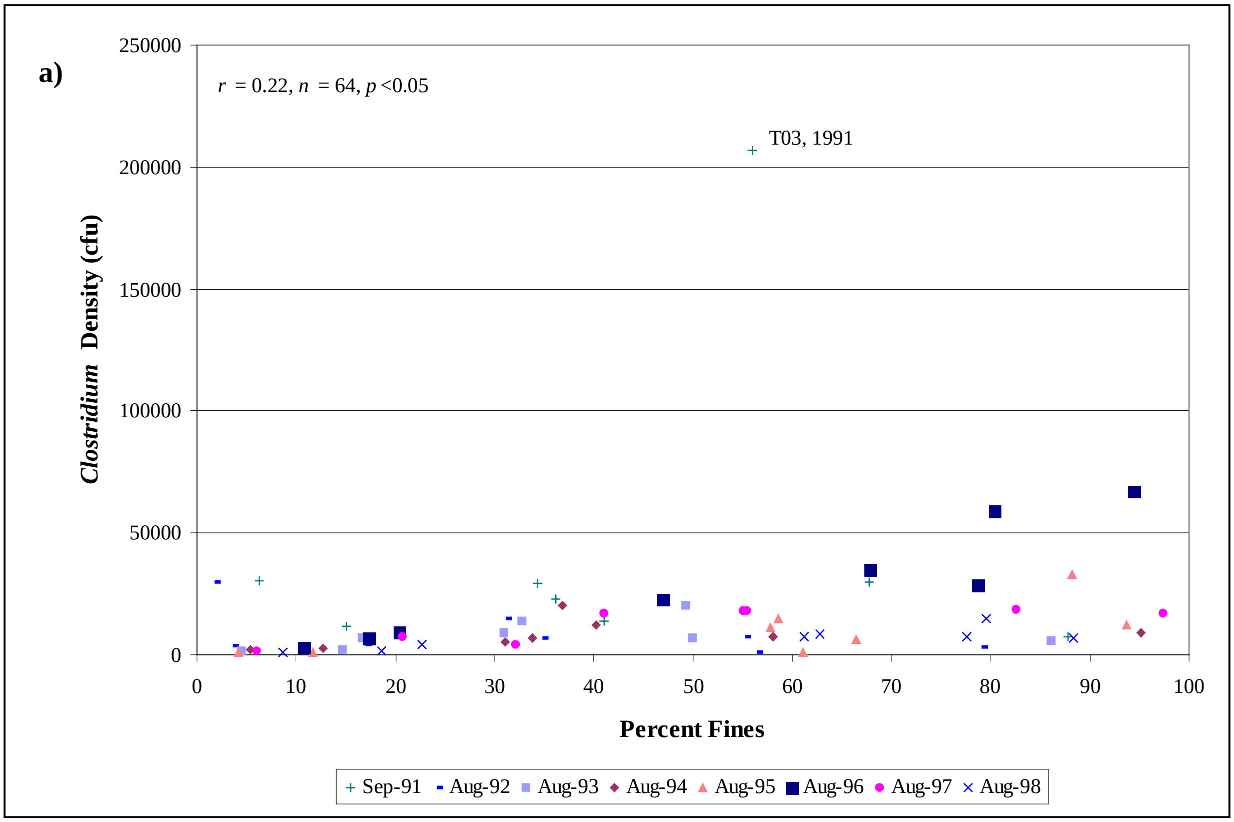


Figure 6.2-12. *Clostridium* Density distribution between September 1991 and August 1998 at Traditional harbor stations in Boston Harbor.



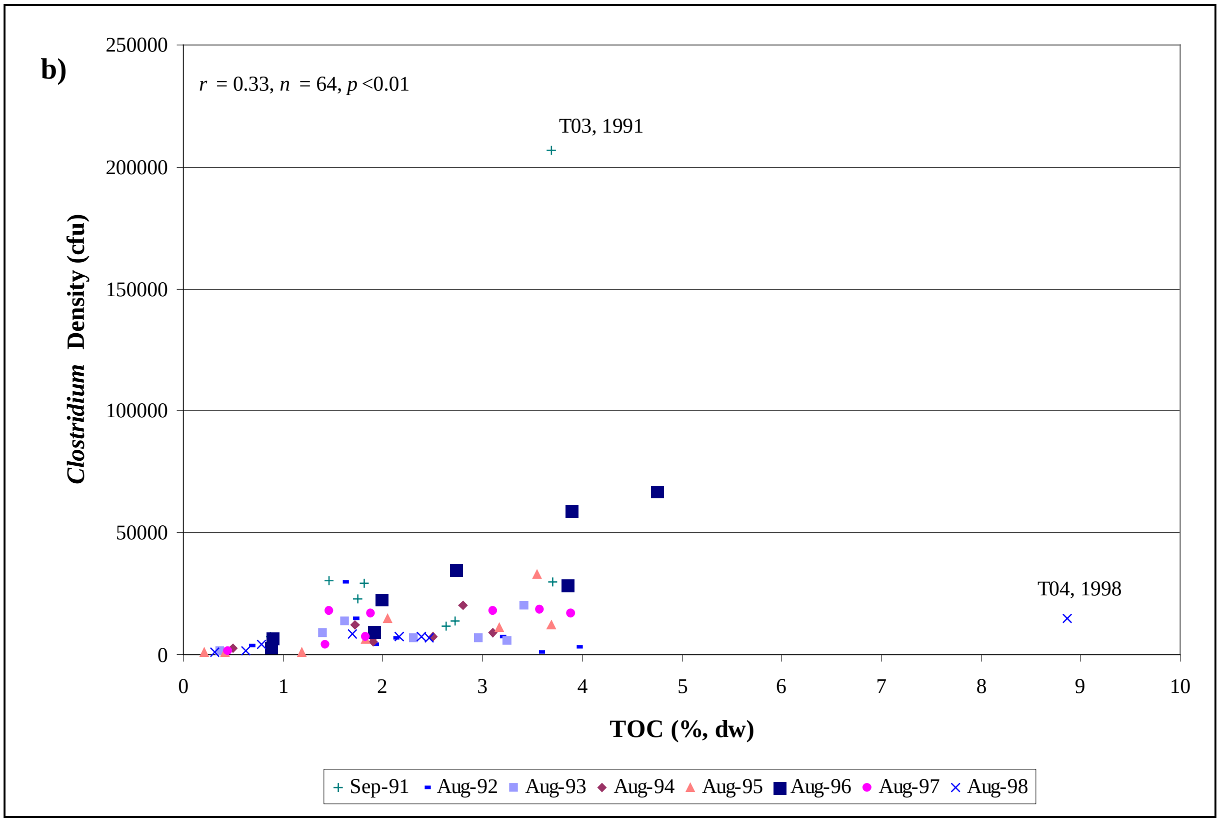


Figure 6.2-13. Correspondence between Clostridium Density and fine sediment fraction (a) and total organic carbon (b) in Boston Harbor sediments between 1991 and 1998.

6.3 Spatio-temporal Trends in Infaunal Communities

by Roy K. Kropp, Eugene D. Gallagher, and David H. Shull

6.3.1 Descriptive Community Measures, Combined 1992–1998 Data Set

In this section, a general consideration of the variability in infaunal abundance, numbers of species, and diversity among the Boston Harbor samples is presented. Data for all ecological metrics calculated for 1991–1998 are included in Appendix E-1.

Abundance—As mentioned in previous reports (e.g., Blake *et al.* 1998), some of the largest differences in descriptive community parameters occurred between September 1991 and April or August 1992. For infaunal abundance, the largest of these changes occurred at three stations (T01, T02, and T05A) in the northern part of the Harbor and at station T04 (Figure 6.3-1). However, note that although the changes may have been large relative changes (e.g., > 1,000 % increase from 1991 to August 1992), they have not been the largest absolute changes, even at three of these four stations (T02, T04, T05A). Also part of the explanation for the large percent change at some of the stations is that abundances in 1991 were very low (e.g., T02 and T05A with less than 100 individuals/0.04 m^2 at each station). None of the changes was permanent as abundances at each station have dropped well below the 1992 peaks for one or more of the years sampled since. Many of the stations in the Harbor have shown very large absolute increases in abundance from one summer to the next (Figure 6.3-1). As for relative change, none of the large absolute changes has been lasting. For example, abundance at station T05A increased by more than 20,500 individuals/0.04 m^2 between the summers of 1996 and 1997 (Figure 6.3-1). The increase is even more spectacular if one considers that the April 1997 samples were relatively depauperate (~279 individuals/0.04 m^2), which means that the dramatic increase abundance at station T05A occurred within the approximately four-month span between sampling periods (Figure 6.3-1). The amphipod *Ampelisca* spp. and the polychaete *Polydora cornuta* together accounted for more than 17,000 individuals/0.04 m^2 in August 1997. By April 1998, abundance at station T05A had decreased substantially and increased only to about 6,000 individuals/0.04 m^2 by August. Similarly, a large increase in abundance occurred at station T02 between August 1993 and August 1994 (~11,000 individuals/0.04 m^2), but abundance decreased steadily over the next two summers and has remained at < 2,000 individuals/0.04 m^2 (Figure 6.3-1). A second pattern of more gradual, but consistent change in abundance was observed at stations T03 and T08 (Figure 6.3-1). At both stations, abundance in summer increased relatively gradually until 1993 (T03) or 1994 (T08), decreased by 1995, then has gradually increased since.

Numbers of Species—As noted previously, the numbers of species found at most stations have increased during the study (Figure 6.3-2). With the exception of station T04, species numbers in August 1998 were more than 29% greater than they were in 1991. The greatest changes have occurred at stations T02 and T05A, at which species numbers increased from 4 and 7 to 41 and 44, respectively between 1991 and 1998. Note, however, that the 1998 numbers were not the highest recorded at either station (Figure 6.3-2). At station T04, species numbers increased between 1991 and 1994–1996, but have decreased since and in 1998 were about what they were in 1991 (Figure 6.3-2). Species numbers at station T08 generally have increased since 1991, but have fluctuated during that period and have shown relatively high within-station variation (Figure 6.3-2).

Diversity—With the exceptions of stations T04 and T08, species diversity, as measured by log-series alpha, has increased since 1991, although the change has been relatively small at stations T06 and T07 (Figure 6.3-3). It appeared that the greatest degree of change (relative and probably absolute) occurred between 1991 and August 1992 (Figure 6.3-3), with change, if any, since then being relatively small. As for species numbers, the greatest changes in diversity between 1991 and 1998 have occurred at stations T02 and T05A. Log-series alpha increased from about 1.2 to 7.5 at station T02, and from about 1.7 to 6.4

at station T05A. Excluding the perennially degraded station T04, the range of diversity values found among the Harbor stations has decreased since 1991. In 1991 log-series alpha values ranged from about 1.2 (T02) to 7.5 (T08), whereas in 1998 (excluding station T04) they ranged from about 5.0 (T07) to 8.6 (T08).

6.3.2 Boston Harbor Multivariate Analyses, Combined 1992–1998 Data Set

Normal, Q-mode cluster analysis (Boesch, 1977) was performed on the complete 1991–1998 Boston Harbor data set, using CNESS as the similarity measure. The results, as shown in the dendrogram (Appendix E-2) and associated metric scaling plot (Figure 6.3-4) showed a large-scale pattern of three major, dissimilar groups of stations. Examination of the Gabriel Euclidean Distance biplot comparing PCA-H axes 1 versus 2 (Figure 6.3-5), in conjunction with the appropriate metric scaling plot, permits evaluation of the taxa most likely to explain group affinities. The most important contributors to CNESS distances among the 1991–1998 Boston Harbor samples are listed in Table 6.3-1.

The first distinctive group consisted of samples from station T04 that were collected in April 1994 (two replicates) and 1998 (both seasons) and samples from station T05A collected in 1991 and 1992 and in the spring 1996–1998. As indicated by the Gabriel Euclidean Distance biplot, abundances of the opportunistic polychaete *Capitella capitata* complex helped explain the linkage of most of these samples.

Location in Boston Harbor from where samples were collected was a contributing factor in determining the next two cluster groups. The second major cluster group was comprised of samples collected from stations T03, T06, T08, and those from station T05A collected in 1993, 1994, and the summers of 1996–1998. The final cluster group consisted of all samples from stations T01, T02, T07, and the remaining T04 samples.

Some other patterns shown in the dendrogram are noteworthy. Most of the samples from stations T01 and T02 (80 of 90 samples) formed a cluster that did not include samples from any other station. Similarly, samples from stations T03 (except spring 1992) and T06 most often clustered together, but were joined by some samples from T08. Station T07 had a strong station signature as all 45 samples comprised the same group that included only one sample from another station (T01, spring 1997). Finally, station T08 had a reasonably characteristic identity as 34 of 45 samples clustered uniquely together. Most of the T08 samples not included in this group were collected in the spring of various years.

As mentioned previously, the basic features of the dendrogram are shown in the metric scaling plot comparing PCA-H axis1 versus 2 (Figure 6.3-4) and the taxa contributing the most information explaining the distribution of the sample points in PCA-H space are shown in the Gabriel Euclidean Distance biplot (Figure 6.3-5). Examination of these plots showed that one factor that helped explain the position of samples along PCA-H axis 1 was location in the Harbor from which samples were collected. Generally, samples on the positive side of the axis were collected from “southeast” part of the Harbor (T03, T06, T08), whereas those on the negative side of the axis were collected from the Harbor’s north to west areas (T01, T02, T04, T07). Station T05A showed allegiance to both sides. Primary taxa contributing to the spread of samples along the axis included *Streblospio benedicti*, *Ampelisca* spp., and *Aricidea catherinae*. The distribution of points along PCA-H axis 2 seemed best explained by the season in which the samples were collected. Generally, samples with higher positive values along the axis typically were collected in summer, whereas those with greater negative values were collected in spring. The taxon that contributed the most towards the explanation of variation along this axis was the polychaete *Polydora cornuta*. Additional, much smaller, contributions were made by *Ampelisca* spp., *Capitella capitata* complex, and *Streblospio benedicti*. However, as might be expected because there are more than 350 data points in each figure, detailed interpretation of the figures is difficult at best. One useful approach is to dissect information regarding individual stations from the main figure and examine it separately. Among the features of interest are the taxa best explaining the distribution of sample points, the presence or absence of any overall seasonal separation of the sample points, and the degree of relative change in sample point position through out the study period, if there has been any. With respect to season, the observation generally will focus on whether or not there has been any overall separation in PCA-H space of the sample points that was best explained by the season in which the samples were collected rather than a comparison of samples from individual years. The observation concerned with change in position during the study period will involve a general comparison of each year's samples to the 1991 (before sludge discharge ceased) to determine whether or not there may have been any change that may be related to the cessation of sludge discharge. It should be remembered that in the metric scaling plots, each year's sample points are displayed in the context of the entire 1991–1998 dataset and that most discussion of taxon abundances are of relative numbers at a station (data available in Appendix E-3). Also, all of the observations were made by qualitative examination of the plots.

Table 6.3-1. The 30 most important contributors to CNESS distances in the 1998 Boston Harbor data. "Cont." is the contribution to overall CNESS distances, "Total Cont." is the cumulative amount of CNESS variation explained by species (94% by the top 30 species). The final columns indicate the contribution of each species to each of the first six PCA-H axes.

Rank	Species	Spp. Code	Cont.	Total Cont.	PCA-H Axis 1	2	3	4	5	6
1	Streblospio benedicti	Stb	14	14	45	8	8	13	1	1
2	*Ampelisca* spp.	AMP	9	23	20	11	1	1	0	21
3	Aricidea catherinae	ARc	8	31	16	1	24	2	3	3
3	Polydora cornuta	POc	8	39	1	35	10	0	6	17
5	*Capitella capitata* complex	Cap	7	46	3	9	17	11	18	1
6	Oligochaeta spp.	OLI	6	52	0	0	21	32	1	8
7	Tharyx acutus	THa	5	57	1	1	2	3	35	27
8	Ilyanassa trivittata	ILt	3	60	0	7	0	0	8	2
8	Microphthalmus aberrans	Mia	3	63	1	0	2	1	3	4
8	Phoxocephalus holbolli	PHh	3	65	4	1	0	3	2	0
11	Spiophanes bombyx	SPB	2	68	1	4	1	9	2	1
11	Chaetozone vivipara	CHv	2	70	0	1	1	0	4	2
11	Nucula delphinodonta	NUd	2	72	2	3	0	6	0	1
11	Leptocheirus pinguis	LEp	2	74	1	2	0	1	0	0
11	*Polycirrus* sp. A (Blake 1992)	poa	2	77	1	5	1	6	2	2
11	Unciola irrorata	UNC	2	79	2	1	5	0	0	0
11	Crassicorophium bonelli	CRb	2	80	0	1	1	1	0	0
11	Photis pollex	PHp	2	82	1	1	1	1	0	1
11	Exogone hebes	EXh	2	83	0	4	0	6	1	1
11	Nephtys cornuta	nec	2	85	0	0	2	1	0	0
11	Turbellaria spp.	TUS	2	86	0	0	0	0	0	0
22	Tellina agilis	TEL	1	88	0	3	0	0	4	1
22	Edotia triloba	EDO	1	89	0	0	1	0	2	1
22	Clymenella torquata	Clt	1	90	0	0	0	0	1	1
22	Spio limicola	SPl	1	91	0	0	0	0	0	2
22	Dipolydora socialis	DiS	1	91	0	0	0	0	1	0
22	Mya arenaria	MYA	1	92	0	0	0	0	0	1
22	Scoletoma hebes	SCh	1	93	0	0	1	0	0	0
22	Nephtys caeca	Nec	1	93	0	0	0	0	2	0
22	Phyllodoce mucosa	phm	1	94	0	0	0	0	0	0

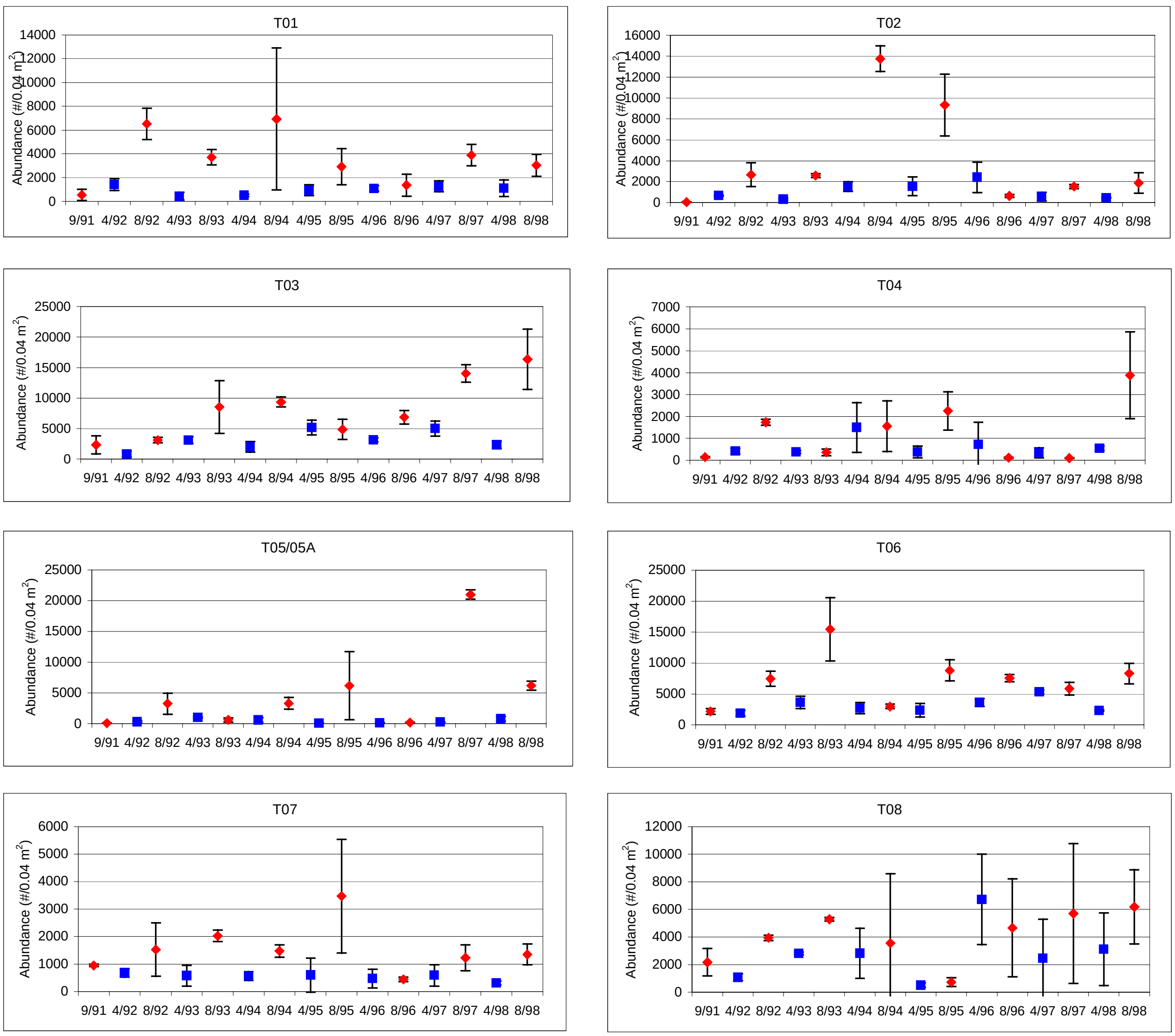


Figure 6.3-1. Mean infaunal abundance per sample (0.04 m^{-2}) for Boston Harbor stations sampled from 1991 to 1998. The vertical bars are the 95% confidence intervals. Note that scales for the Y axes differ.

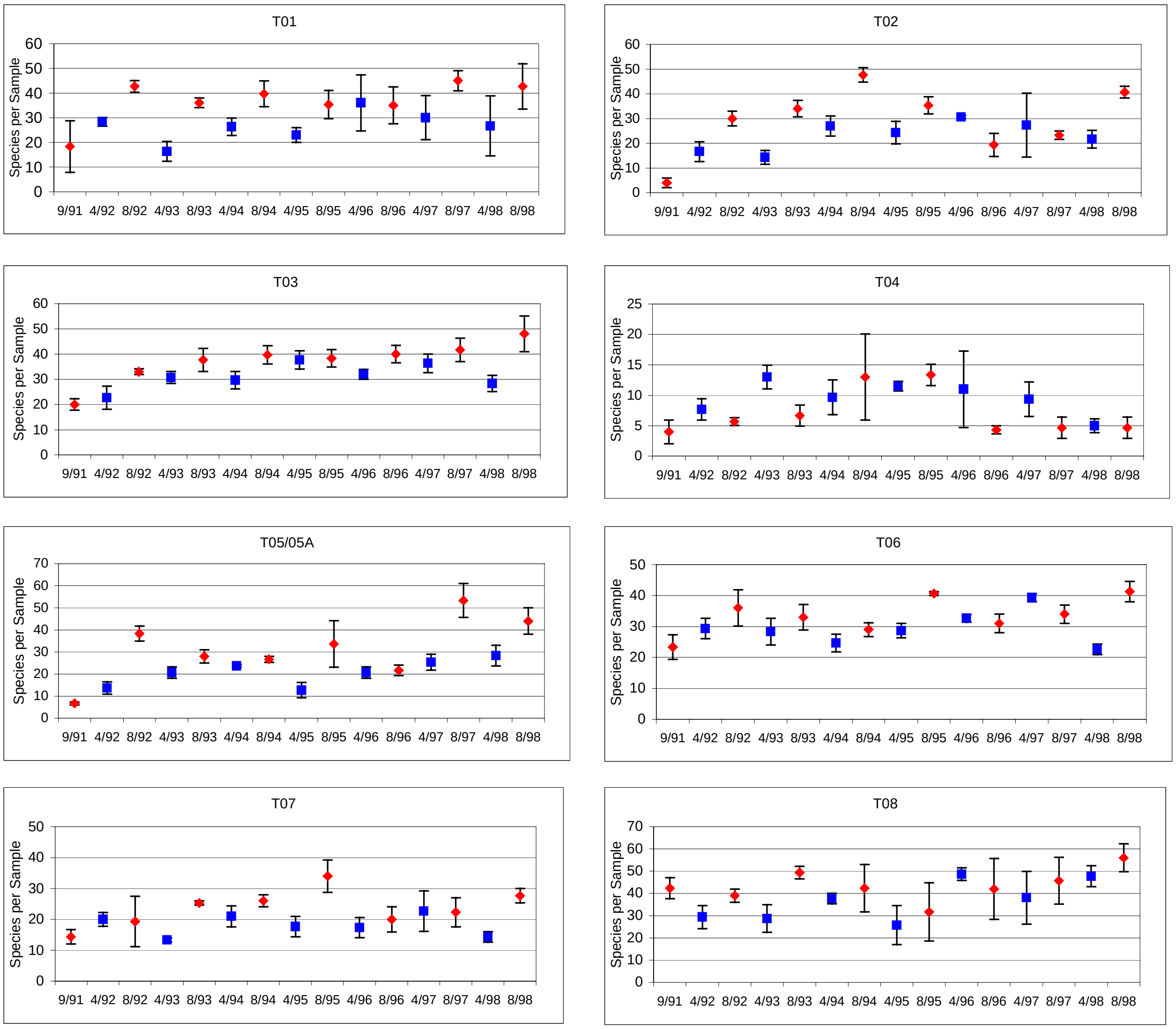


Figure 6.3-2. Mean number of species per sample for Boston Harbor stations sampled from 1991 to 1998. The vertical bars are the 95% confidence intervals. Note that scales for the Y axes differ.

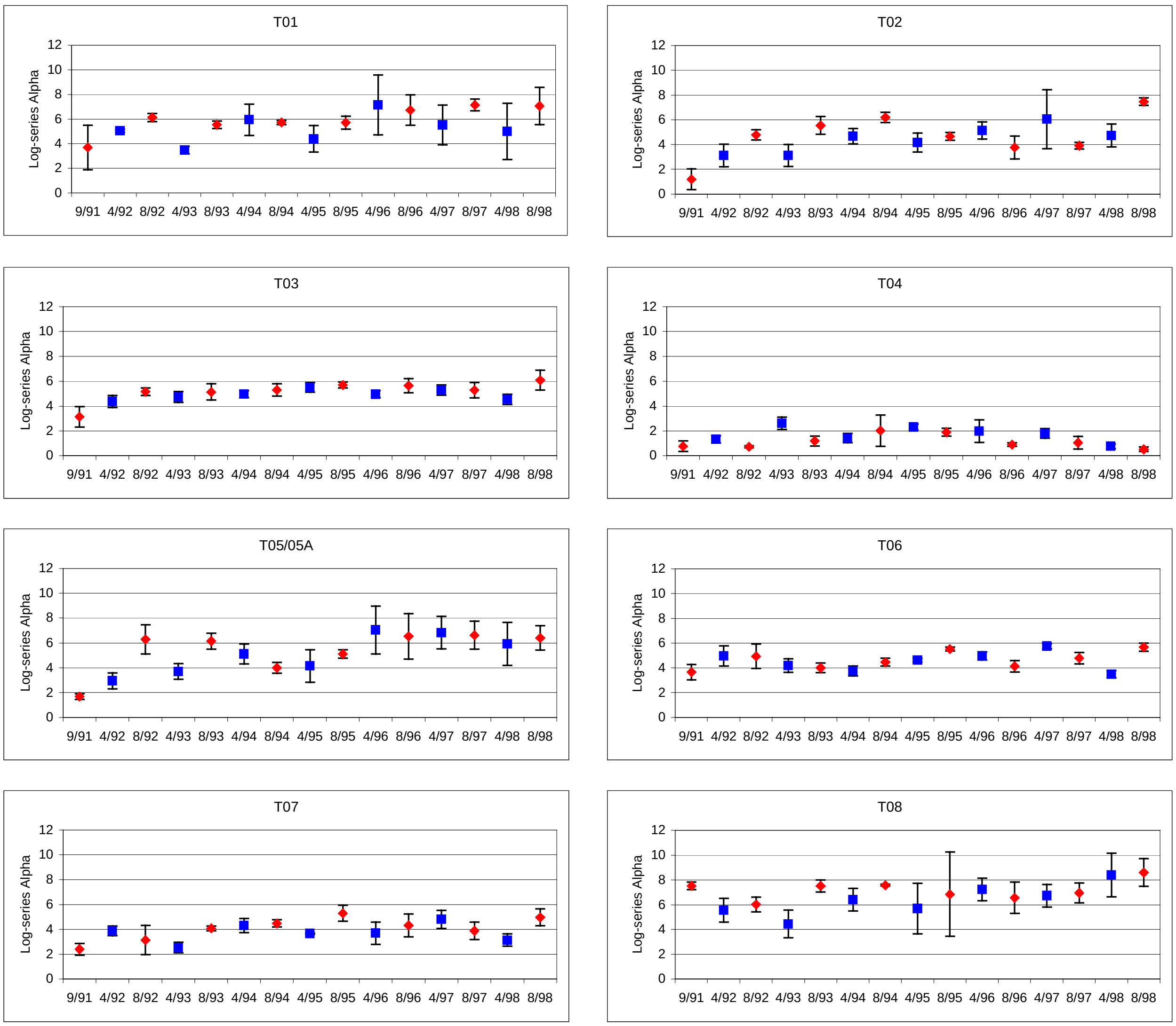


Figure 6.3-3. Mean log-series alpha for Boston Harbor stations sampled from 1991 to 1998. The vertical bars are the 95% confidence intervals.

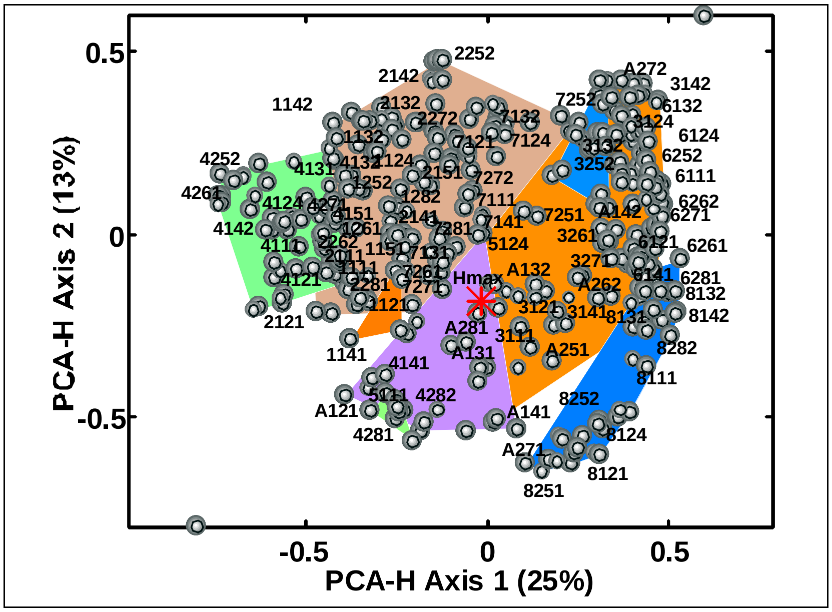


Figure 6.3-4. Metric scaling plot of CNESS distances, axes 1 versus 2, among Boston Harbor stations sampled from 1991 to 1998. Results of the CNESS cluster analysis are shown as convex hulls. All stations are not labeled; some labels have been placed outside their respective clusters. Station labels are as in Figure 5-12.

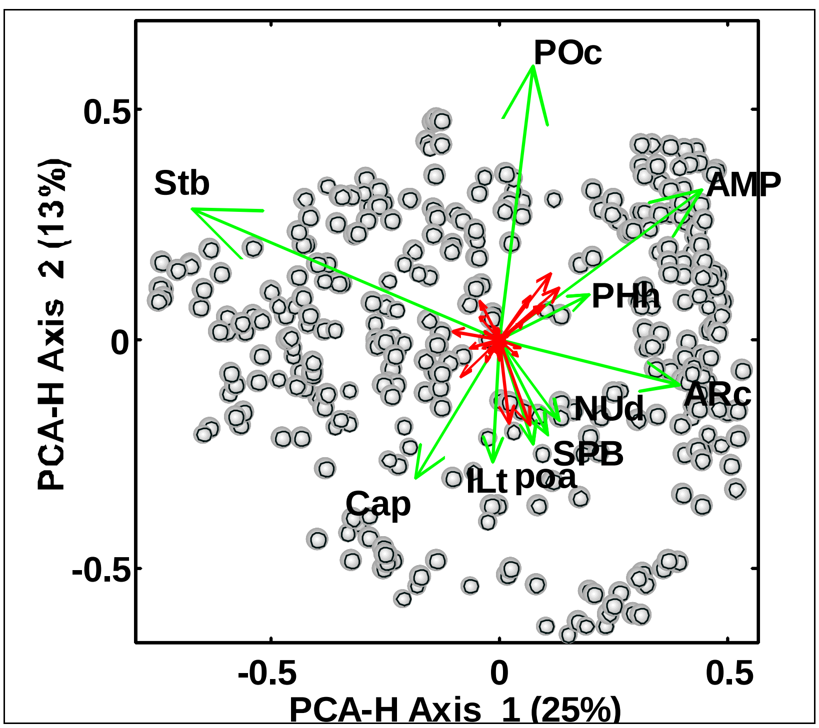


Figure 6.3-5. Gabriel Euclidean distance biplot, axes 1 versus 2, for the 1991–1998 Boston Harbor data showing those species that control the orientation of samples shown in Figure 6.3-4. Species codes are as listed in Table 6.3-1. Open circles represent the spatial pattern of samples shown in Figure 6.3-4.

Station T01—The main features of the metric scaling plot showing station T01 (Figure 6.3-6) show that there has been a relatively strong overall season separation of the samples collected there. In particular, there has been a shift of the summer samples collected after 1992 away from those collected in 1991. This shift appeared to be related to increased abundances of *Polydora cornuta* that began in the summer of 1992 and occurred every summer thereafter, with the exception of 1996. *Streblospio benedicti* also has had some influence on the position of station T01 samples. The separation of the summer 1997 samples from the other summer samples may have been related to relatively high numbers of *Ampelisca* spp. that year as compared to other years. Samples from station T01 have shown occasional influence by taxa that were not among the major contributors to PCA-H axes 1 or 2. Examples include Oligochaeta spp., an important contributor to PCA-H axis 3, *Tharyx acutus*, *Chaetozone vivipara,* and *Clymenella torquata*.

Station T02—Since 1993, except for 1996, samples from station T02 have shown very distinct overall seasonal separation (Figure 6.3-6). This separation of the summer samples reflected a reduction in the influence of *Streblospio benedicti* and increased importance of *Polydora cornuta* and in 1994–1995 by high abundances of *Ampelisca* spp. These changes occurred despite the parallel, but less dramatic, increases in abundance of *Streblospio*. Samples collected in spring have shown more variability than those from summer (since 1993), probably related in part to some fluctuation in *Ampelisca* spp. (1995) and *Streblospio benedicti*.

Station T03—Samples collected from station T03 have shown considerable change in composition since 1991 and spring 1992 (Figure 6.3-6). However, most of this general change was along PCA-H axis 2, with shift in a positive direction along the axis primarily representing increased influence of the polychaete *Polydora cornuta* (summer samples) and the amphipod *Ampelisca* spp. and polychaete *Aricidea catherinae* (both often affecting both seasons). There has been some general separation of summer from spring samples that was mostly a result of the high summer abundance of *Polydora cornuta*. The greatest degree of change occurred after the spring 1992 samples were collected. Since then samples have shown reasonably consistent within-season composition. Samples from 1996 did not stand dramatically apart from those collected in other years.

Station T04—The most striking observations about the samples collected from station T04 (Figure 6.3-6) was the overall consistency in position of those collected from most years and the radical departure of samples collected in 1998 and spring 1994 (two replicates). Samples from most years were strongly dominated by high relative abundances of *Streblospio benedicti*. Seasonal differences have not been very large, although some spring samples (e.g., 1992, 1997) have shown reduced importance of *Streblospio*. The strong separation of the 1998 and spring 1994 samples was primarily a result of high abundances of the polychaete *Capitella capitata* complex, accompanied by reduced numbers of *Streblospio benedicti*. Station T04 was included in the original study design to represent an area of the Harbor that is perennially degraded. Because the degradation was not related to the MWRA sludge or effluent discharges, station T04 was selected to serve as a “polluted” reference station for the Harbor. Except for the changes in relative importance of *Streblospio* and *Capitella*, the station has changed little during the study.

Station T05/05A—Samples collected from station T05A after 1992 probably have shown the greatest change from the 1991 samples among all Harbor stations (Figure 6.3-7). The differences among samples were not related to the shift in location of station T05 that occurred early in the program. In spring 1992 samples were collected from the new location, station T05A, yet were similar to those collected in summer 1991 at the former location. Summer 1992 samples were collected from the station T05 location, but differed somewhat from those collected about one year earlier. Dramatic changes at station T05A began with the spring 1993 samples. Change in position on the metric scaling plot after 1991 have been primarily in a positive direction along PCA-H axis 1, indicating the dramatic increase in importance of high numbers of *Ampelisca* spp. Some summer samples (especially 1995, 1997, and 1998) also have shown substantial change in the positive direction along PCA-H axis 2, primarily reflecting high numbers of *Polydora cornuta*. There appeared to be a strong overall and within-year seasonal signal at the station, again each reflected fluctuations in abundances of *Ampelisca* spp. and *Polydora cornuta*. As was the case at other station, samples collected from station T05A in 1996 differed appreciably from the other years. Here, the differences appeared related to very low abundances of *Ampelisca* spp. and *Polydora cornuta*. *Capitella capitata* complex had a strong influence on the samples collected in 1992.

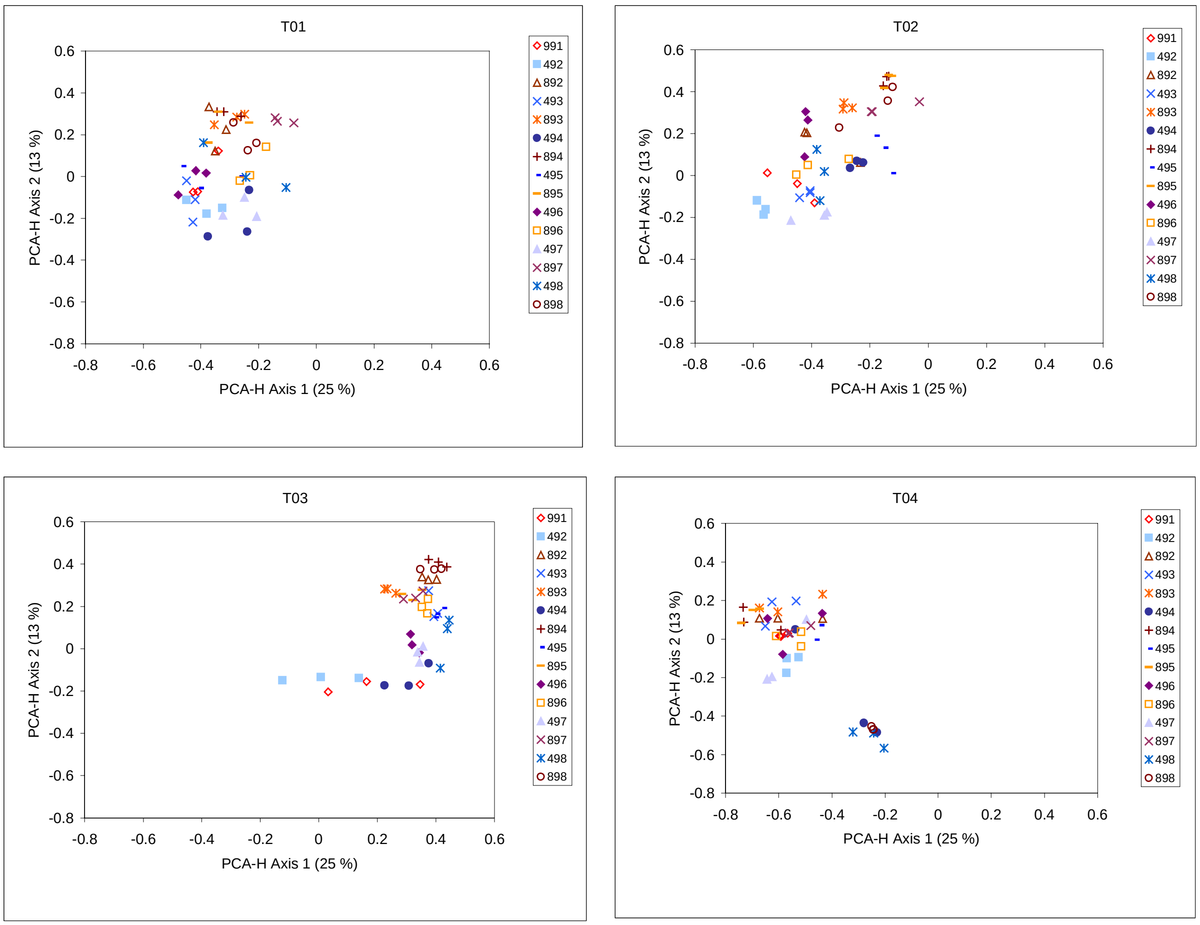


Figure 6.3-6. Metric scaling plot of CNESS distances, axes 1 versus 2, among Boston Harbor stations T01, T02, T03, and T04 sampled from 1991 to 1998. Symbols represent the spatial pattern of samples shown in Figure 6.3-4.

Station T06—In sharp contrast to the pattern at station T05A, samples collected at station T06 have shown not only the least overall change from the 1991 samples, but also probably the least amount of overall change (Figure 6.3-7). Samples from T06 have shown considerable consistency in position along PCA-H axis 1, which largely has been a result of consistent relative abundances of *Aricidea catherinae* and, to a certain extent, *Ampelisca* spp. However, there has been some degree of seasonal variation that was expressed along PCA-H axis 2, most of which occurred because of seasonal fluctuations in *Polydora cornuta*.

Station T07—With the exception of a few samples (spring 1997 and three summer samples from 1992 or 1995), the general location of most samples at station T07 in the PCA-H metric scaling plot has been relatively consistent (Figure 6.3-7). The general overall seasonal signal at this station has been moderately weak. The positions of most sample points along PCA-H axis 1 was near zero, which reflected the opposing influence of *Streblospio benedicti* versus *Ampelisca* spp. (up to 1995) and *Aricidea catherinae*. *Polydora cornuta* has shown some relative importance during the summer, which was demonstrated by the presence of most summer samples on the positive side of PCA-H axis 2. Oligochaetes have been relatively numerous at station T07, but their influence was not expressed along either of the first two PCA-H axes.

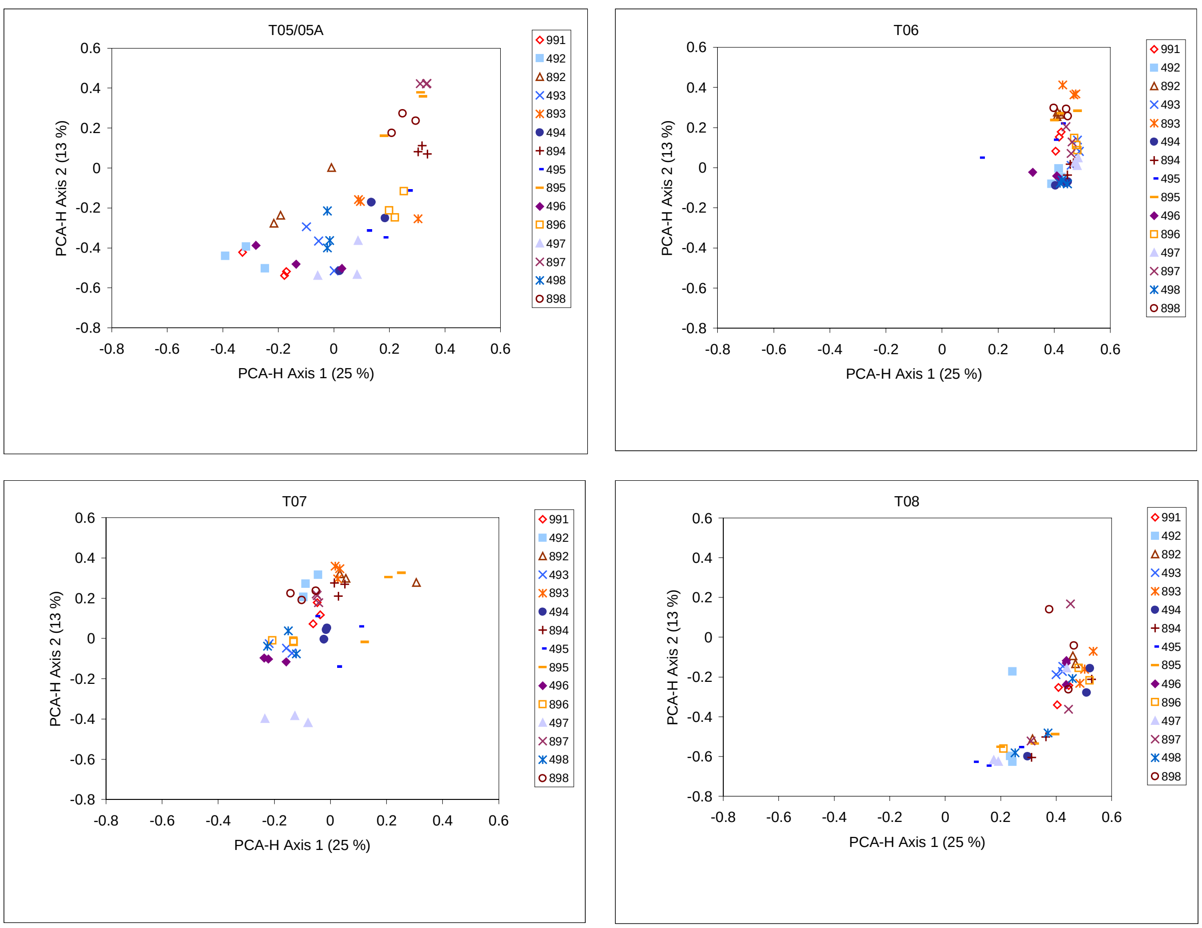


Figure 6.3-7. Metric scaling plot of CNESS distances, axes 1 versus 2, among Boston Harbor stations T05/T05A, T06, T07, and T08 sampled from 1991 to 1998. Symbols represent the spatial pattern of samples shown in Figure 6.3-4.

Station T08—The locations of station T08 sample points on the metric scaling plot have varied, but have not shown a strong overall seasonal difference (Figure 6.3-7). The positions of samples along PCA-H axis 1 resulted from consistent high abundances of *Aricidea catherinae* and *Ampelisca* spp. in conjunction with the virtual absence of *Streblospio benedicti*. The orientation of most samples on the negative side of PCA-H axis 2 may be related to the combined relative influence of several taxa that individually show little effect on the axis. Included, among others were the nut clam *Nucula delphinodonta*, the polychaetes *Spiophanes bombyx* and *Polygordius* sp. A, and the gastropod *Ilyanassa trivittata*. Samples collected in 1996 did not depart substantially from those collected in most other years.

Summary—A station-level examination of the multivariate analysis of the complete 1991–1998 Harbor data set showed several features that very likely resulted from the improvements made in discharges into the Harbor, particularly the cessation of sludge discharge.

- The two stations that showed the most change since 1991, stations T05A and T03, are the two that were located closest to the sludge discharge point. The changes identified were best explained by increased influence of amphipods, *Ampelisca* spp.

- Station T04 has shown a relatively consistent and unique identity throughout the study period. This strong station identity, and the sporadic, very strong importance of *Streblospio benedicti* (1992, 1995) or *Capitella capitata* (1994, 1998) at the station has dominated the overall analyses, possibly inhibiting investigation of the recovery of the parts of the Harbor that were most likely influenced by sludge discharge.

- Station T06 showed the most consistent distribution of sample points among the Harbor stations. Station T06 is located near the point of the former Nut Island effluent discharge. Because of the relative consistency exhibited by the stations samples, any effect of termination of the effluent discharge, which occurred just prior to collection of the summer 1998 samples, may be relatively easy to detect.

- 1996 appeared to be an unusual year at several stations, notably stations T01, T02, T05A, and T07. The differences were most evident among summer samples and appeared to be related to much lower abundances of *Polydora cornuta* and/or amphipods, including *Ampelisca* spp.

Conclusions

The observed changes in the structure of Harbor's infaunal communities, coupled with data from SPI studies, provide good evidence for improvement in the condition of benthic habitats in the Harbor since the cessation of sludge discharge in 1991. Most notable was the dramatic increase in abundance and geographic spread of the amphipod *Ampelisca* spp. Also important was the general increase in infaunal abundance and species numbers that occurred after 1991 and their gradual decline since. The most substantial changes in the Harbor's benthos probably occurred within the first two to three years after sludge discharge ended. Most recently there has been some indication that the infaunal communities are in transition from those that appeared soon after release from the stress caused by the sludge to those more likely to be found in a less-polluted Harbor that is still prone to periodic natural disturbance.

7.0 LITERATURE CITED

Blake JA, Rhoads DC, Williams IP. 1993. Boston Harbor sludge abatement monitoring program, soft bottom benthic biology and sedimentology, 1991-1992 monitoring surveys. Boston: Massachusetts Water Resources Authority. Report ENQUAD 93-11. 65 p.

Blake JA, Maciolek NJ, Rhoads DC, Gallagher E, Williams IP. 1998. Boston Harbor soft-bottom benthic monitoring program. Boston: Massachusetts Water Resources Authority. Report ENQUAD 98-15. 96 p.

Bonsdorff E, Diaz RJ, Rosenberg R, Norkko A, Cutter GR. 1996. Characterization of soft-bottom benthic habitats of the Åland Islands, northern Baltic Sea. *Marine Ecology Progress Series* 142:235-245.

Boesch DF. 1977. Application of numerical classification in ecological investigations of water pollution. Report prepared for US EPA Ecological Research Series (EPA-600/3-77-033). Available as PB269 604 from: National Technical Information Service. U.S. Department of Commerce. Springfield VA 22161.

Day ME, Schaffner LC, Diaz RJ. 1988. Long Island Sound sediment quality survey and analyses. Tetra Tech Report to NOAA, NOS, OMA, Rockville, MD. 113 pp.

Diaz RJ, Schaffner LC. 1988. Comparison of sediment landscapes in the Chesapeake Bay as seen by surface and profile imaging. p. 222-240. In: Lynch MP, Krome EC, eds. Understanding the estuary; Advances in Chesapeake Bay Research. Chesapeake Research Consortium Publication 129, CBP/TRS 24/88.

Emerson DJ, Cabelli VJ. 1982. Extraction of *Clostridium perfringens* spores from bottom sediment samples. *Applied Environmental Microbiology* 44:1144-1149.

Fenchel T. 1969. The ecology of marine microbenthos. IV. Structure and function of the benthic ecosystem, its chemical and physical factors and microfauna communities with special reference to the ciliated Protozoa. *Ophelia* 6:1-182.

Folk RL 1974. Petrology of sedimentary rocks. Austin, Texas, Hemphill's. 170 pp.

Gabriel KR. 1971. The biplot graphic display of matrices with application to principal component analysis. *Biometrika* 58:453-467.

Gallagher ED, Keay KK. 1998. Organism-sediment-contaminant interactions in Boston Harbor. Pp. 89-132. In: Stolzenbach KD, Adams EE, eds., Contaminated sediments in Boston Harbor. MIT Sea Grant Publication 98-1. 170p.

Grassle JF, Smith W. 1976. A similarity measure sensitive to the contribution of rare species and its use in investigation of variation in marine benthic communities. *Oecologia* 25:13-22.

Greenacre MJ. 1984. Theory and Application of Correspondence Analysis. Academic Press, Orlando FL.

Hurlbert SH. 1971. The non-concept of species diversity: a critique and alternative parameters. *Ecology* 52:577-586.

Jardine N, Sibson R. 1968. The construction of hierarchic and nonhierarchic classifications. *Computer Journal* 11:177-184.

Jørgensen BB. 1977. Distribution of colorless sulfur bacteria (*Beggiatoa* spp.) in a coastal marine sediment. *Marine Biology* 41:19-28.

Jørgensen BB, Revsbech NP. 1983. Colorless sulfur bacteria, *Beggiatoa* spp. and *Thiovulum* spp. in O_2 and H_2S microgradients. *Applied Environmental Microbiology* 45:1261-1270.

Kelly JR, Kropp RK. 1992. Benthic recovery following sludge abatement to Boston Harbor. Boston: Massachusetts Water Resources Authority. Report ENQUAD 92-07. 149 p.

Kropp RK, Boyle JD. 1998. Combined work/quality assurance plan for benthic monitoring: 1998-2000. Boston: Massachusetts Water Resources Authority. Report ENQUAD ms-50. 72 p.

Kropp RK, Diaz RJ. 1994. 1993 Annual soft-bottom benthic monitoring report: Boston Harbor studies. Boston: Massachusetts Water Resources Authority. Report ENQUAD 94-10. 117 p.

Legendre P, Legendre L. 1998. Numerical Ecology Second English edition. Elsevier, Amsterdam.

Magurran AE. 1988. Ecological Diversity and its Measurement. Princeton University Press, Princeton.

Mattson S, Cedhagen T. 1989. Aspects of the behaviour and ecology of *Dyopedos monacanthus* (Metzger) and *D. porrectus* Bate, with comparative notes on *Dulichia tuberculata* Boeck (Crustacea: Amphipoda: Podoceridae). *Journal of Experimental Marine Biology and Ecology* 127:253-272.

Odum EP. 1969. The strategy of ecosystem development. *Science* 164:262-270.

Pearson TH, Rosenberg R. 1978. Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. *Oceanography and Marine Biology Annual Review* 16:229-311.

Pielou EC. 1966. Species diversity and pattern diversity in the study of ecological succession. *Journal of Theoretical Biology* 10:370-383.

Revelas EC, Rhoads DC, Germano JD. 1987. San Francisco Bay sediment quality survey and analysis. NOAA Technical Memorandum. NOS OMA 35. Rockville, MD. 127 pp.

Rhoads DC. 1974. Organism sediment relations on the muddy sea floor. *Oceanography and Marine Biology Annual Review* 12:263-300.

Rhoads DC, Germano JD. 1982. Characterization of organism-sediment relations using sediment profile imaging: an efficient method of remote ecological monitoring of the seafloor (REMOTS system). *Marine Ecology Progress Series* 8:115-128.

Rhoads DC, Germano JD. 1986. Interpreting long-term changes in benthic community structure: a new protocol. *Hydrobiologia* 142:291-308.

Rohlf FJ, Sokal RR. 1969. Statistical Tables. San Francisco, CA: W.H. Freeman and Company. 253 p.

Rosenzweig ML. 1995. Species Diversity in Space and Time. Cambridge University Press, Cambridge. 436 p.

Saad DL. 1992. Simplified method for extraction of *Clostridium perfringens* spores and indicator bacteria from marine sediments. In: *Seasonal Disinfection with Respect to Marine Waters*. Ph.D. Dissertation, University of Rhode Island, Kingston, RI.

Sanders HL. 1968. Marine benthic diversity: A comparative study. *American Naturalist* 102:243-282.

Smith W, Grassle JF. 1977. Sampling properties of a family of diversity measures. *Biometrics* 33:283-292.

Sneath PHA, Sokal RR. 1973. Numerical Taxonomy. San Francisco: WH Freeman & Co., San Francisco.

Thiel M. 1997. Reproductive biology of an epibenthic amphipod (*Dyopedos monacanthus*) with extended parental care. *Journal of the Marine Biological Association of the United Kingdom* 77(4):1059-1072.

Trueblood DD, Gallagher ED, Gould DM. 1994. The three stages of seasonal succession on the Savin Hill Cove mudflat, Boston Harbor. *Limnology and Oceanography* 39:1440-1454.

Valente RM, Rhoads DC, Germano JD, Cabelli VJ. 1992. Mapping of benthic enrichment patterns in Narragansett Bay, Rhode Island. *Estuaries* 15:1-17.

Viles C, Diaz RJ. 1991. Bencore, an image analysis system for measuring sediment profile camera slides. School of Marine Science, Virginia Institute of Marine Science, College of William and Mary, Gloucester Pt. VA. 13 pp.

Vismann B. 1991. Sulfide tolerance: Physiological mechanisms and ecological implications. *Ophelia* 34:1-27.

Werme C, Hunt CD. 2000. 1998 Outfall monitoring overview. Boston: Massachusetts Water Resources Authority. Report ENQUAD 00-04. 66 p.

Williams WT. 1971. Principles of clustering. *Annual Review of Ecology and Systematics* 2:303-326.

APPENDICES

Appendix A-1: Actual Locations of Grab Samples, April and August 1998
Appendix A-2: Actual Locations of Sediment Profile Image Camera Drops, August 1998
Appendix B-1: Data from Detailed Analysis of Sediment Profile Images for August 1998 Sampling of MWRA Harbor Stations MWRA Harbor Stations
Appendix B-2: Selected Sediment Profile Images, August 1998
Appendix C: 1998 Sediment Chemistry Data
Appendix D-1: Taxonomic Responsibilities for 1998 Boston Harbor Identifications
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Appendix E: Programmatic Evaluation
Appendix E-1: Ecological Variables Calculated for 1991–1998 Boston Harbor Samples
Appendix E-2: Dendrogram Resulting from CNESS Cluster Analysis of 1991–1998 Boston Harbor Samples
Appendix E-3: Mean and 95% Confidence Interval Abundance of Selected Boston Harbor Taxa, 1991–1998
Appendix E-4: List of Taxa included in the Analyses of 1991–1998 Boston Harbor Data

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