Harbor Benthic Monitoring Report: 2011 Results

Massachusetts Water Resources Authority

Environmental Quality Department
Report 2012-14

Citation:

Pembroke, AE, RJ Diaz, and EC Nestler. 2012. ***Harbor Benthic Monitoring Report: 2011 Results.*** Boston: Massachusetts Water Resources Authority. Report 2012-14. 28 pages.

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Submitted to

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December 2012
Report No. 2012-14

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1. INTRODUCTION

1.1 Background

Boston Harbor was once considered among the most degraded harbors in the country. Direct discharge of wastewater with limited treatment into the harbor had affected both water quality and biological conditions. Both the EPA and the Federal Court prevailed upon the Commonwealth of Massachusetts to take actions to improve these conditions substantially and the Massachusetts Water Resources Authority (MWRA) was created in response. In 1985, MWRA initiated a multi-faceted plan to meet these mandates, most significantly including an upgrade to secondary treatment, elimination of sludge disposal into the harbor, and relocation of wastewater discharge through an offshore diffuser located 9.3 mi off Deer Island in Massachusetts Bay. Subsequently, improvements have been made to numerous Combined Sewer Overflows (CSOs).

MWRA has conducted monitoring in Boston Harbor since 1991 in order to evaluate changes to the ecosystem, in particular the benthic community, as contaminated discharges have been reduced over time. This report provides a summary of the results of the benthic surveys that were conducted in 2011. These include sediment conditions, benthic infauna, and sediment profile imagery. A quantitative evaluation of the long-term sediment monitoring data collected since 1991 is provided in the 2007 harbor benthic monitoring report (Maciolek et al. 2008).

2. METHODS

Benthic monitoring in Boston Harbor continued at the same stations that have been surveyed since 1991. No changes were made to this program in the 2010 revision to the Ambient Monitoring Plan (MWRA 2010). This survey comprises three components: sediment conditions (grain size, total organic carbon, and *Clostridium perfringens*), benthic infauna, and sediment profile imaging (SPI).

Methods used to collect, analyze, and evaluate all sample types remain largely consistent with those reported by Maciolek et al. (2010 and 2011) for previous monitoring years. Detailed descriptions of the methods are contained in the Quality Assurance Project Plan (QAPP) for Benthic Monitoring 2011–2014 (Nestler et al. 2011). A brief overview of methods, focused on information that is not included in the QAPP, is provided in Sections 2.1 to 2.3.

2.1 Field Methods

Sediment and infauna sampling was conducted at 9 stations on August 20 and 22, 2011 (Figure 1). Soft-bottom stations were sampled for grain size composition, total organic carbon (TOC), the sewage tracer *Clostridium perfringens*, and benthic infauna.

SPI samples were collected in triplicate at 61 stations on August 16-18, 2011 (Figure 1).

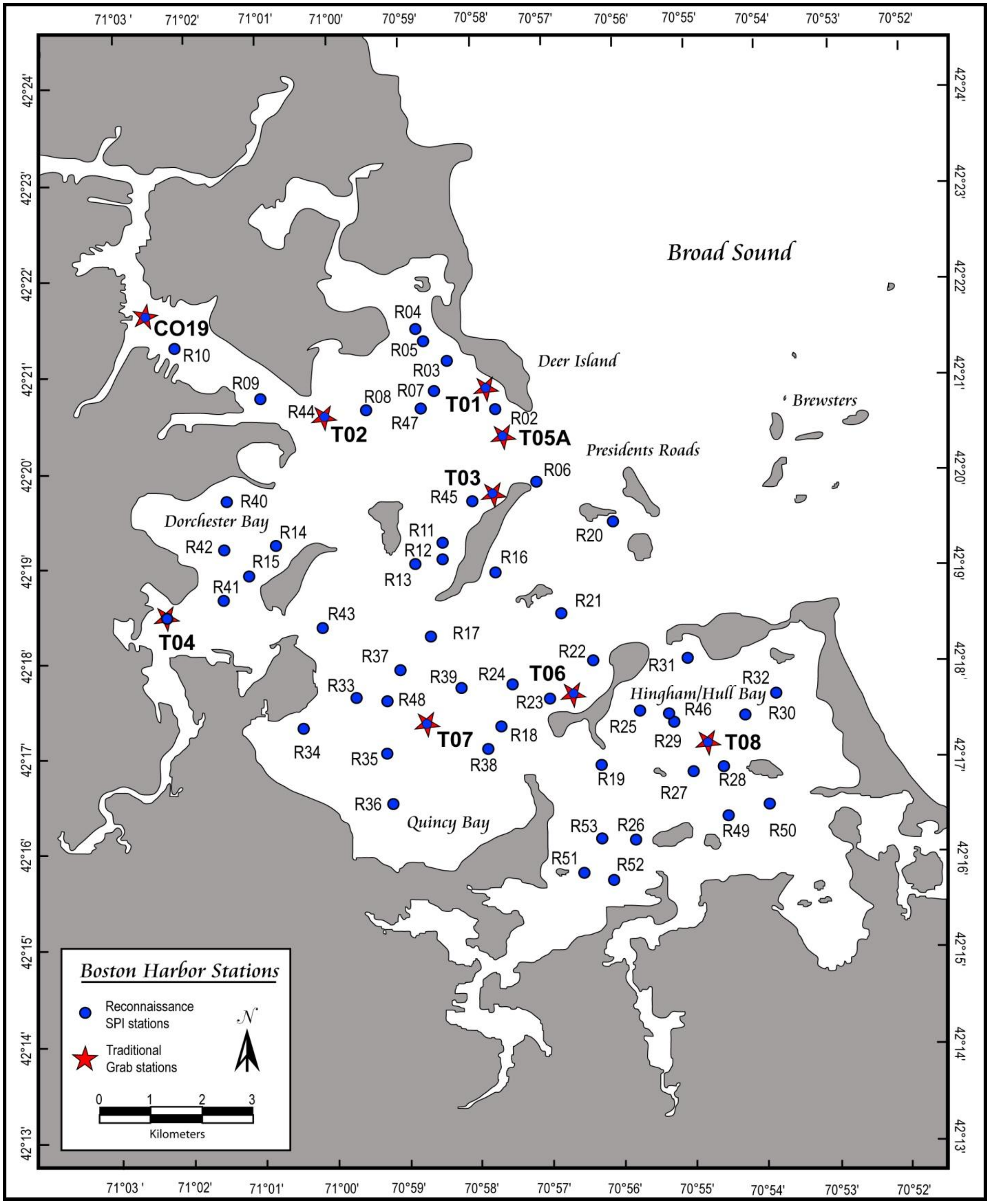


Figure 1. Locations of soft-bottom sampling and sediment profile imaging stations for 2011.

2.2 Laboratory Methods

Laboratory methods for benthic infauna and SPI image analyses were consistent with the QAPP (Nestler et al. 2011) except that all three replicates were analyzed for benthic infauna from each station. Analytical methods for grain size, TOC, and *Clostridium perfringens* are described in (Lao et al. 2012).

2.3 Data Handling, Reduction, and Analysis

All benthic data were extracted directly from the HOM database and imported into Excel. Data handling, reduction, and graphical presentations were performed in Excel or SAS (version 9.2), as described in the QAPP (Nestler et al. 2011) or in Maciolek et al. (2008). Data are presented graphically as means (averages per sample) unless otherwise noted. Multivariate analyses were performed using PRIMER v6 (Plymouth Routines in Multivariate Ecological Research) software to examine spatial patterns in the overall similarity of benthic assemblages in the survey area (Clarke 1993, Warwick 1993, Clarke and Green 1988). These analyses included classification (cluster analysis) by hierarchical agglomerative clustering with group average linking and ordination by non-metric multidimensional scaling (MDS). Bray-Curtis similarity was used as the basis for both classification and ordination. Prior to analyses, infaunal abundance data were fourth-root transformed to ensure that all taxa, not just the numerical dominants, would contribute to similarity measures.

Cluster analysis produces a dendrogram that represents discrete groupings of samples along a scale of similarity. This representation is most useful when delineating among sites with distinct community structure. MDS ordination produces a plot or “map” in which the distance between samples represents their rank ordered similarities, with closer proximity in the plot representing higher similarity. Ordination provides a more useful representation of patterns in community structure when assemblages vary along a steady gradation of differences among sites. Stress provides a measure of adequacy of the representation of similarities in the MDS ordination plot (Clarke 1993). Stress levels less than 0.05 indicate an excellent representation of relative similarities among samples with no prospect of misinterpretation. Stress less than 0.1 corresponds to a good ordination with no real prospect of a misleading interpretation. Stress less than 0.2 still provides a potentially useful two-dimensional picture, while stress greater than 0.3 indicates that points on the plot are close to being arbitrarily placed. Together, cluster analysis and MDS ordination provide a highly informative representation of patterns of community-level similarity among samples. The “similarity profile test” (SIMPROF) was used to provide statistical support for the identification of faunal assemblages (i.e., selection of cluster groups). SIMPROF is a permutation test of the null hypothesis that the groups identified by cluster analysis (samples included under each node in the dendrogram) do not differ from each other in multivariate structure.

3. RESULTS AND DISCUSSION

3.1 Sediment Conditions

Sediment conditions in Boston Harbor were characterized by three parameters measured during 2011 at each of the nine sampling stations: (1) grain size (gravel, sand, silt, and clay), (2) total organic carbon, and (3) *Clostridium perfringens* (Table 1).

Grain Size. Surface sediments at the nine stations sampled during 2011 included a wide range of sediment types (Table 1, Figure 2). Grain size profiles ranged from predominantly sand (i.e., T08) to almost entirely silt and clay (i.e., C019 and T04); with most stations having mixed sediments ranging from silty-sand (i.e., T01, T05A) to sandy-silt (i.e., T03, T07). The grain size composition of the sediments in 2011 remained consistent with results reported in prior years (Figure 3).

Total Organic Carbon. Concentrations of total organic carbon (TOC) in 2011 also remained similar to values reported in prior years (Figure 4). Concentrations of TOC track closely to percent fine sediments (i.e., silt + clay), with higher TOC values generally associated with higher percent fines (Maciolek et al. 2008). A comparison of Figures 3 and 4 illustrates this association. During 2011, the highest concentrations of TOC were once again reported at stations T04 and C019, two stations with the highest percent fine sediments. Nonetheless, although these stations have very similar grain size compositions, TOC concentrations remain higher at T04 than at C019 (Table 1, Figure 4). This station (T04) is located in a depositional area where contaminants entering Boston Harbor are known to accumulate (Wallace et al. 1991; Stolzenbach and Adams 1998). As in prior years, the lowest TOC concentrations for 2011 were reported at station T08.

***Clostridium perfringens*.** Spores of *Clostridium perfringens*, an anaerobic bacterium found in the intestinal tract of mammals, provide a sensitive tracer of effluent solids. Abundances of *C. perfringens* (normalized to percent fines) during 2011 were highest at station C019 and lowest at station T08 (Table 1, Figure 5). *C. perfringens* concentrations at C019 during 2011 were comparable to those reported in 2010, and below the elevated levels at this station in 2008 and 2009. *C. perfringens* counts at other Harbor stations have remained consistently below historical averages since around 1999 (Figure 5).

Taylor (2006) defined time periods related to various changes in MWRA's management of wastewater and sludge treatment and discharges. Significant events that had a likelihood of affecting the harbor benthic community included ending the discharge of sludge in 1991 (end of Period I); opening of the new primary treatment plant at Deer Island (1995) and its upgrade to secondary treatment between 1997 and 2001 (Period II); implementation of the transfer of wastewater from Nut Island to Deer Island, ending the Nut Island discharge in 1998 (onset of Period III); and implementation of the offshore outfall in 2000 (onset of Period IV).

Results during 2011 for grain size, TOC, and *C. perfringens* in Boston Harbor sediments, are consistent with prior year monitoring results (Maciolek et al. 2008, 2011). Concentrations of both TOC and *C. perfringens* at the traditional harbor stations (T01 to T08) have remained lower during the past decade, than those reported during the 1990s (Figures 6 and 7). These findings are consistent with changes documented in the Harbor following improvements to the collection, treatment and disposal of wastewater as part of the Boston Harbor Project (Maciolek et al. 2008, Taylor 2006).

Table 1. 2011 monitoring results for sediment condition parameters.

Parameter	C019	T01	T02	T03	T04	T05A	T06	T07	T08
Clostridium perfringens **(cfu/g dry/%fines)**	157	61	130	121	115	57	149	141	41
Total Organic Carbon (%)	3.01	0.84	1.37	2.45	3.75	0.72	1.02	2.11	0.12
Gravel (%)	0	1.6	1.2	1.9	0	1.6	0.8	4.5	0.8
Sand (%)	4.5	68.8	55.8	26.9	4.5	74.0	67.0	30.4	95.3
Silt (%)	60.6	19.6	29.6	47.0	66.0	18.4	21.6	43.3	2.5
Clay (%)	34.9	9.9	13.4	24.2	29.6	6.0	10.6	21.9	1.5
Percent Fines (Silt + Clay)	95.5	29.5	43.0	71.2	95.5	24.4	32.3	65.2	4.0

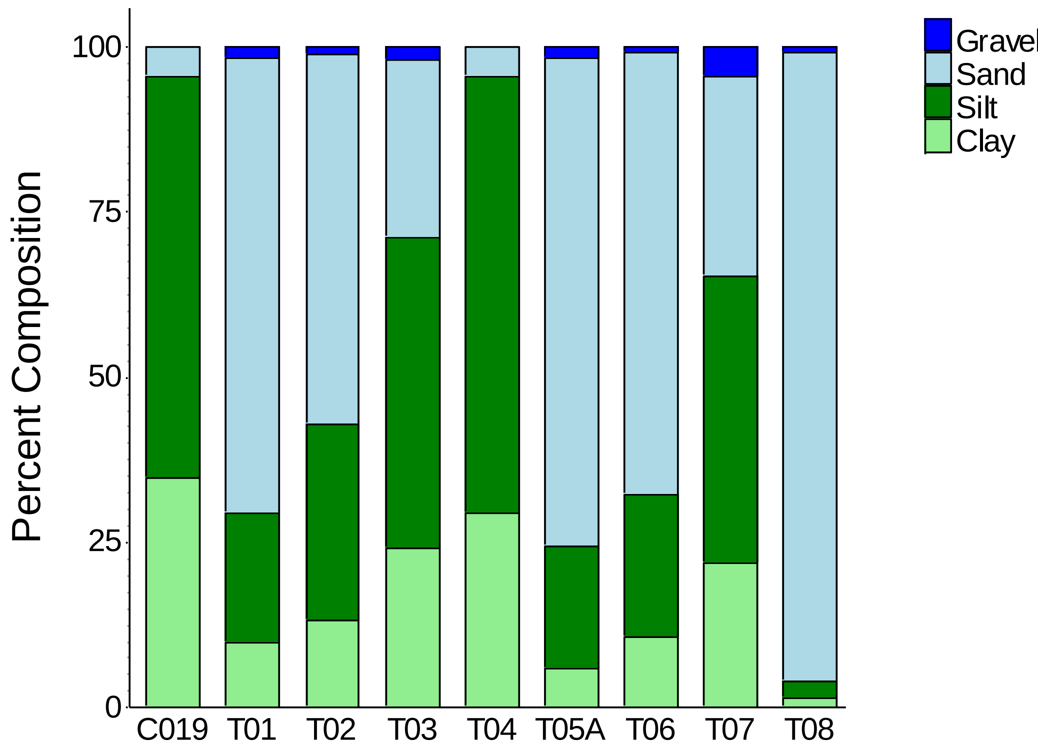


Figure 2. 2011 monitoring results for sediment grain size.

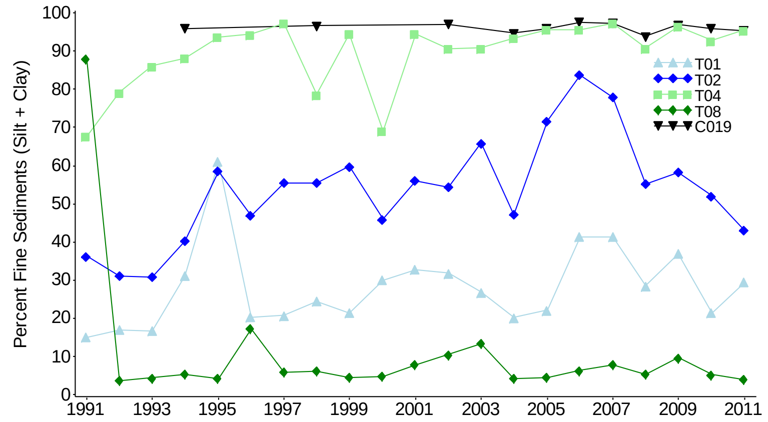


Figure 3. Mean percent fine sediments at five stations in Boston Harbor, 1991 to 2011.

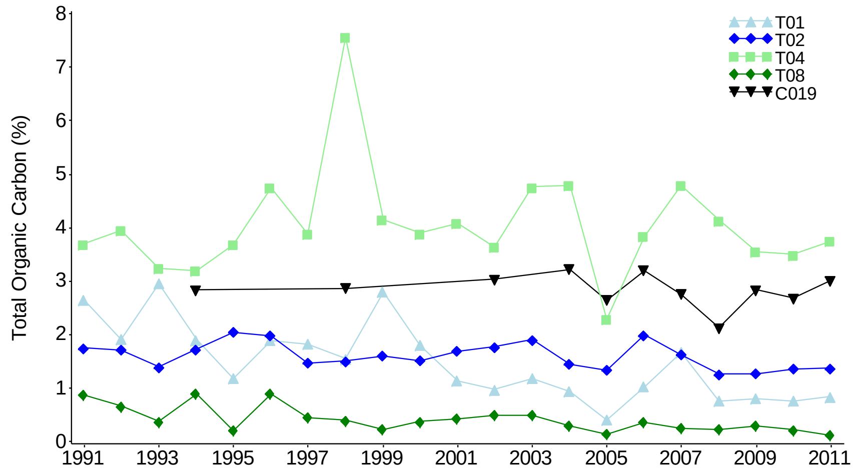


Figure 4. Mean concentrations of TOC at five stations in Boston Harbor, 1991 to 2011.

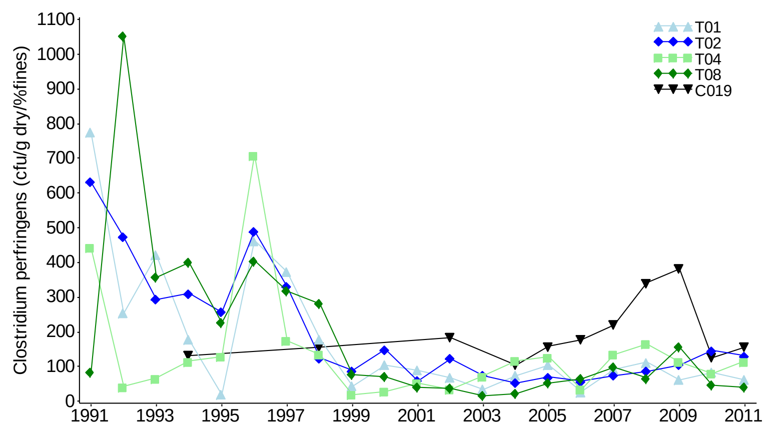


Figure 5. Mean concentrations of *Clostridium perfringens* at five stations in Boston Harbor, 1991 to 2011.

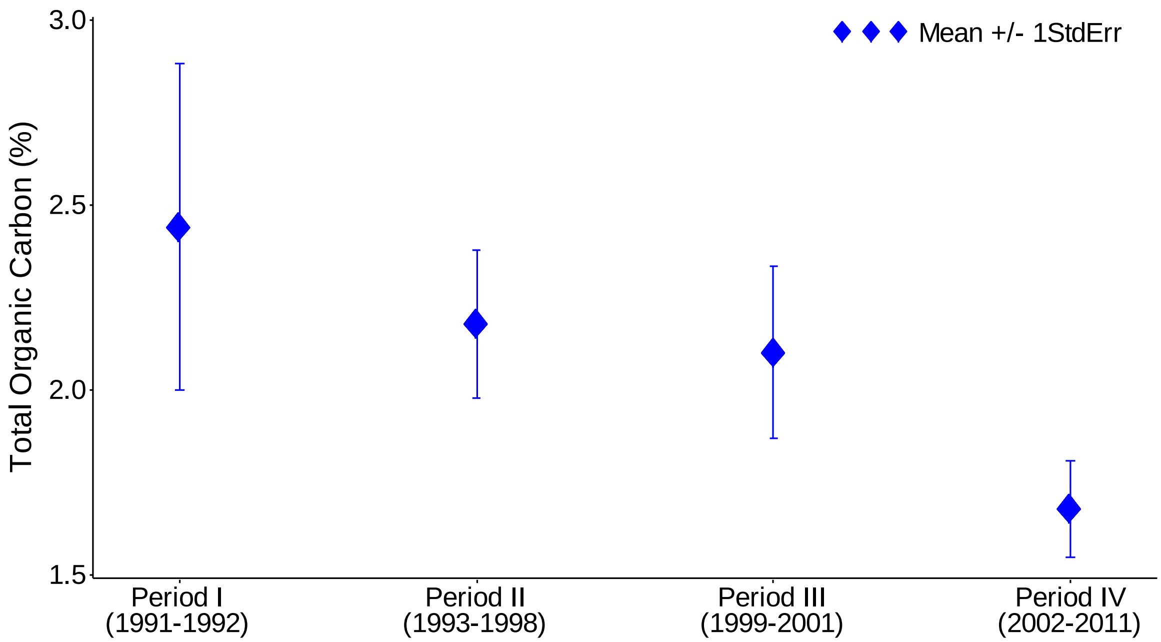


Figure 6. Comparison of TOC across four discharge periods at Boston Harbor stations (T01-T08) from 1992 to 2011 (1991 excluded).

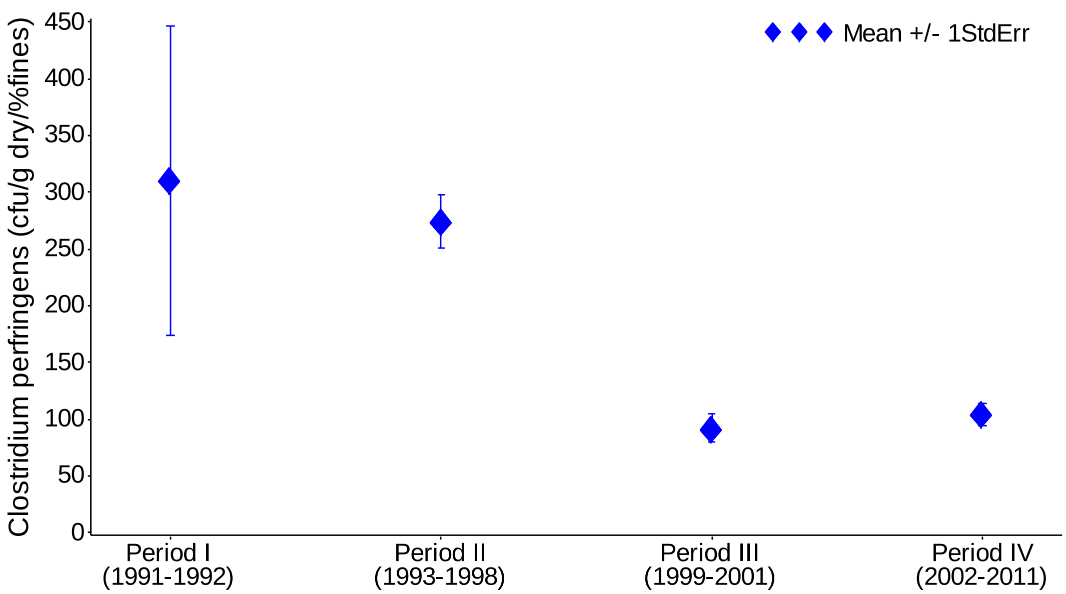


Figure 7. Comparison of *Clostridium perfringens* across four discharge periods at Boston Harbor stations (T01-T08) from 1992 to 2011 (1991 excluded).

3.2 Benthic Infauna

3.2.1 Community Parameters

A total of 50,566 infaunal organisms were counted from the 27 samples in 2011. Organisms were classified into 165 discrete taxa; 134 of those taxa were species-level identifications, and these species richness values are consistent with values observed in the harbor in recent years. Abundance values reported herein reflect the total counts from both species and higher taxonomic groups, while diversity measures are based on the species-level identifications only (Table 2).

Table 2. 2011 mean infaunal community parameters by station

Station	Total Abundance	Number of Species	Pielou's Evenness (J')	Shannon-Wiener Diversity (H')	Log-series alpha
C019	442.3	13.7	0.37	1.39	2.71
T01	1416.7	36.3	0.66	3.38	7.13
T02	3817.0	43.0	0.55	2.96	6.82
T03	3465.3	41.0	0.60	3.18	6.59
T04	84.7	5.3	0.35	0.83	1.27
T05A	4794.0	57.0	0.54	3.17	9.34
T06	1462.0	32.3	0.61	3.08	5.89
T07	520.3	16.0	0.66	2.58	3.16
T08	853.0	45.3	0.71	3.91	10.44

Abundance values reported for 2011 were generally lower than in 2010 and were among the lowest reported since 1991 but were still within the range of abundances observed historically (Figure 8). Most of the species that dominated the infauna at these stations in 2010 continued to do so in 2011 but at lower abundances (Table 3). In particular, ampeliscid amphipods and two oligochaete species remained the most abundant taxa. One change from 2010 was the order-of-magnitude decline in abundance of the polychaete *Phyllodoce mucosa* (total abundance of 343 in 2011, compared to 2,142 in 2010). Spatial patterns of abundance appeared to be consistent with 2010, however, as Stations T02, T03, and T05A continued to support the highest abundances and T04, T07, and C019 continued to support the lowest abundances.

Temporally, benthic infauna abundance in the harbor has been controlled by a handful of species (Table 4). Although these dominants have varied somewhat over the course of the surveys, four taxa have consistently been among the most abundant organisms. Annual abundances of these species are presented in Figure 9. *Aricidea catherinae* and *Limnodriloides medioporus* have exhibited little interannual variation in abundance whereas both *Polydora cornuta* and *Ampelisca* spp. have exhibited fluctuations of one to two orders of magnitude. Both of these species reside in the upper substrate layer so variability could be related to many factors, including changes in organic enrichment, physical forces such as storm events, and reproductive success in a given year as was described in previous reports (Maciolek et al. 2006, 2011).

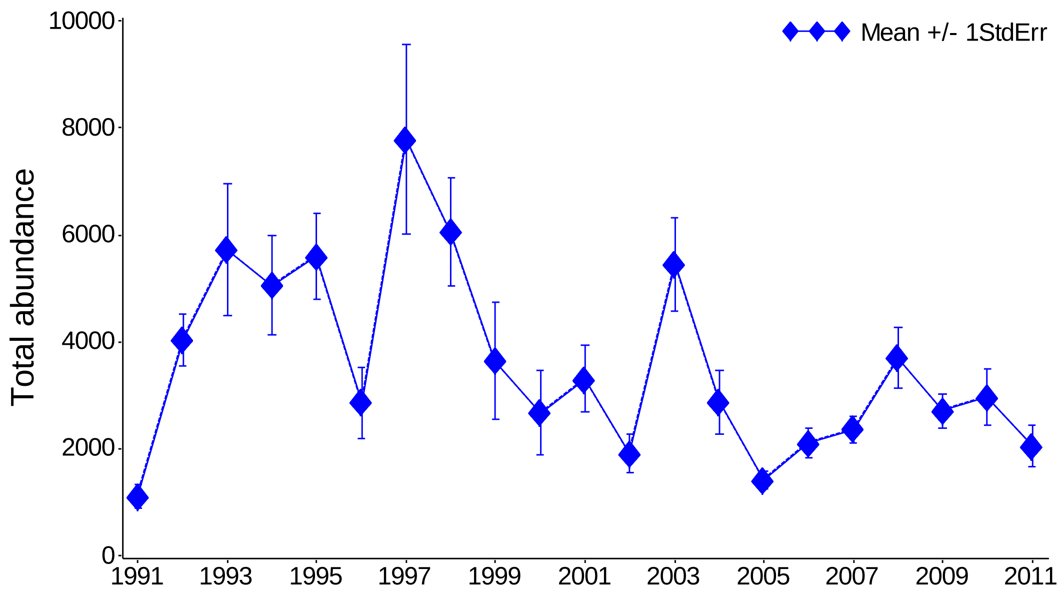


Figure 8. Mean abundance of benthic infauna at eight Boston Harbor stations, 1991-2011.

Table 3. Dominant taxa at eight grab stations in Boston Harbor in August 2011.

Taxon	**Total 2011 Abundance (compared with 2010)**
Ampelisca spp.	15,251 (decrease)
Limnodriloides medioporus	5,717 (decrease)
Tubificoides intermedius[a]	4,621 (decrease)
Polydora cornuta	3,913 (decrease)
Aricidea catherinae	2,777 (decrease)
Scoletoma hebes	1,954 (decrease)
Nepthys cornuta	1,927 (large decrease)
Tharyx spp.	1,116 (decrease)
Scolelepis bousfieldi	906 (increase)
Streblospio benedicti	872 (slight decrease)
Orchomenella minuta	832 (decrease)
Photis pollex	772 (decrease)

[a] previously identified as *T. apectinatus*

Table 4. Mean abundance per sample of dominant[a] taxa during four discharge periods at eight Boston Harbor stations (T01-T08), 1992-2011.

Phylum	Higher Taxon	Family	Species	Period I	Period II	Period III	Period IV	2011
Annelida	Polychaeta	Capitellidae	*Capitella capitata* complex	**65.2**	88.8	3.4	6.3	7.0
		Cirratulidae	*Tharyx acutus*	50.6	111.8	52.4	**61.9**	**46.4**
		Lumbrineridae	*Scoletoma hebes*	3.4	10.5	4.2	47.5	**81.4**
		Nephtyidae	*Nephtys cornuta*	-	11.4	10.3	**244.8**	**80.3**
		Paraonidae	*Aricidea catherinae*	**325.0**	**237.4**	**204.3**	**210.6**	**115.7**
		Spionidae	*Polydora cornuta*	**525.8**	**1053.0**	**269.6**	**261.8**	**163.0**
			Streblospio benedicti	**236.0**	**298.6**	27.7	**53.0**	36.3
Annelida	Oligochaeta	Tubificidae	*Limnodriloides medioporus*	**484.7**	**297.9**	**315.2**	**208.8**	**238.2**
			Tubificoides intermedius	42.6	101.4	**231.2**	**255.0**	**192.5**
Arthropoda	Amphipoda	Ampeliscidae	*Ampelisca* spp.	**354.3**	**1698.3**	**1205.9**	**720.4**	**635.5**
		Aoridae	*Leptocheirus pinguis*	29.0	117.4	66.0	**103.1**	21.5
		Corophiidae	Corophiidae spp.	16.1	**336.2**	23.0	1.7	1.3
			Crassicorophium bonellii	7.9	**217.3**	37.3	9.9	1.1
		Isaeidae	*Photis pollex*	11.4	77.0	**86.8**	42.5	32.2
		Phoxocephalidae	*Phoxocephalus holbolli*	28.0	116.9	**125.9**	7.9	25.8

[a]Dominants identified as taxa composing 75% of total abundance in each period.

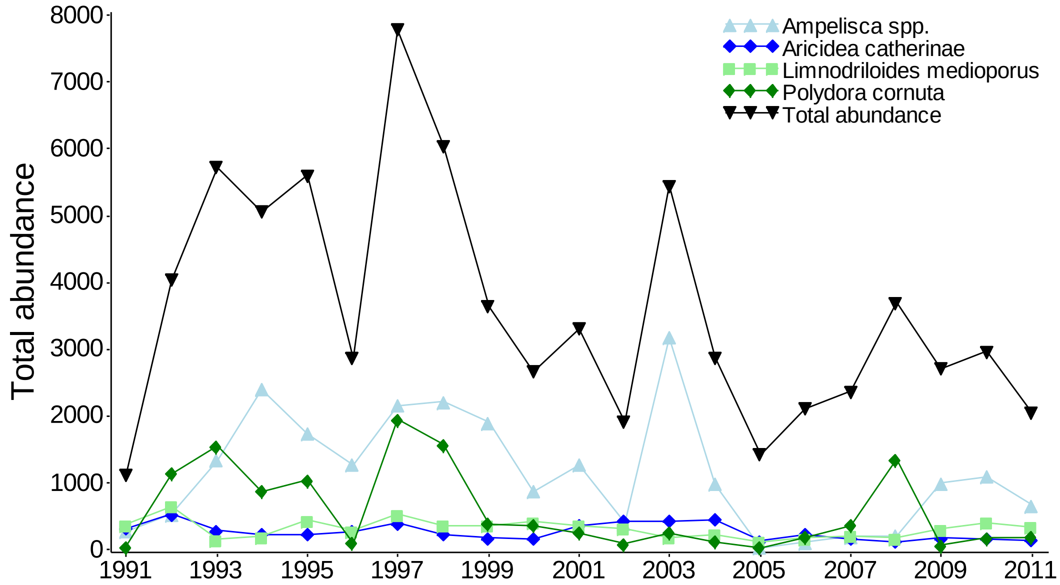


Figure 9. Total abundance of four dominant taxa at eight Boston Harbor stations, 1991-2011.

Patterns of abundance of *Ampelisca* spp. have been of particular interest throughout the past 21 years that Stations T01-T08 have been studied. Previous annual reports on the harbor surveys have related changes in the spatial extent of *Ampelisca* beds and abundances of individual amphipods to changes in organic loading (the period from 1991 through about 1999) and storm events and subsequent recruitment (around 2005 through 2009; Maciolek et al. 2006, 2011). Following a period of low abundances, *Ampelisca* abundances increased again in 2009 and have remained at moderately high levels since (Figure 10). Several stations have not exhibited a substantial increase in *Ampelisca* abundance (Figure 11), however, and only three stations (T02, T03, and T05A) accounted for most of the change consistently in the last three years. Each of these stations is located in the vicinity of the main shipping channel.

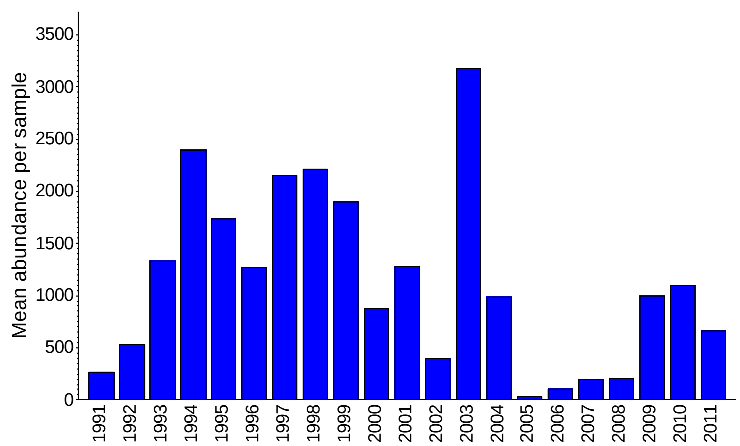


Figure 10. Mean annual abundance of *Ampelisca* spp. averaged over eight Boston Harbor stations, 1991-2011.

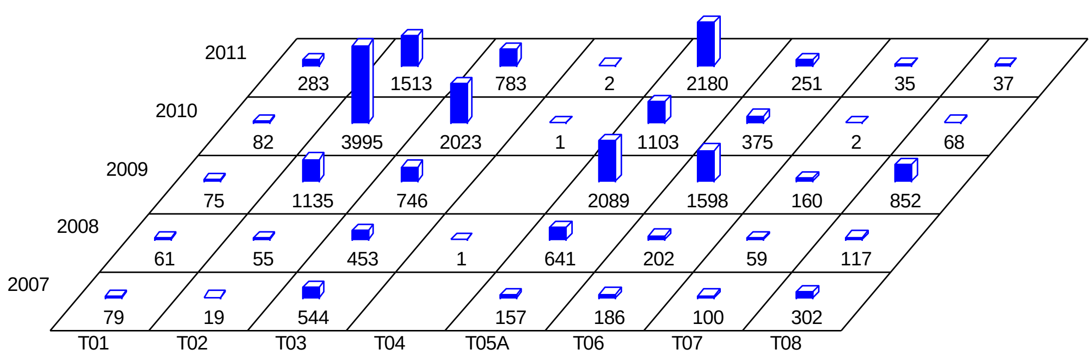


Figure 11. Spatial distribution of *Ampelisca* spp. at eight Boston Harbor stations, 2007-2011.

The numbers of species reported for 2011 ranged from 5 to 57 per station and averaged around 32 species per sample, consistent with numbers reported in the mid-1990s and for several years between 1999 and 2007 (Figure 12). The decrease in species richness from the 2008 peak continued a trend that was observed in 2009 and 2010 (Maciolek et al. 2011). As with abundance, species richness followed the same spatial patterns observed previously. Stations T05A, T08, and T02 exhibited the highest species richness and Stations C019, T07, and T04 supported the lowest species richness in both 2010 (Maciolek et al. 2011) and 2011.

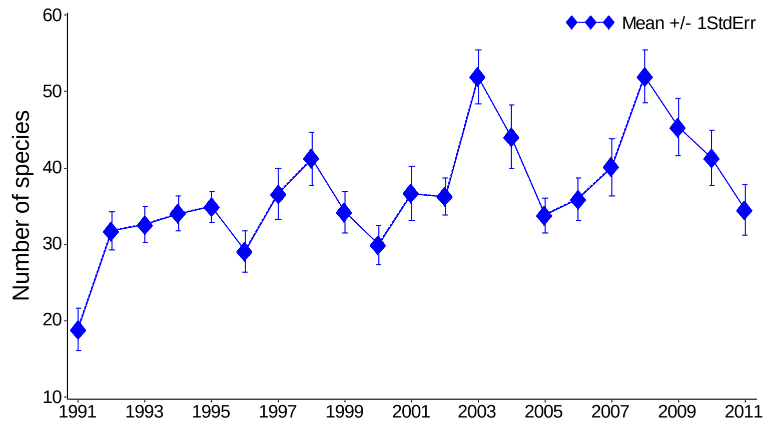


Figure 12. Mean species richness at eight Boston harbor stations, 1991-2011.

Measures of community structure including Pielou's evenness and Shannon-Weiner diversity were similar in 2011 compared to 2010 when averaged across the harbor stations (Figures 13 and 14). In general, spatial patterns for these parameters were similar between the two years suggesting that the integrity of the benthic infaunal community had not changed despite decreases in abundance and species richness. Although there was a drop in average diversity as measured by log-series alpha between 2010 and 2011 (Figure 15), the spatial pattern observed in 2011 was consistent with that seen in 2010.

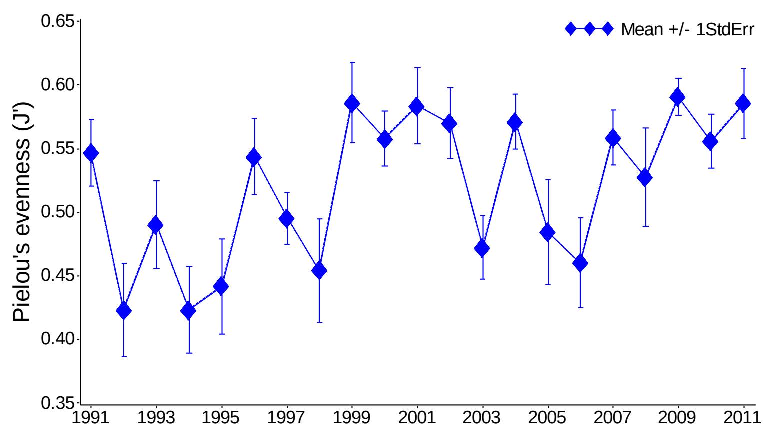


Figure 13. Mean community evenness at eight Boston Harbor stations, 1991-2011.

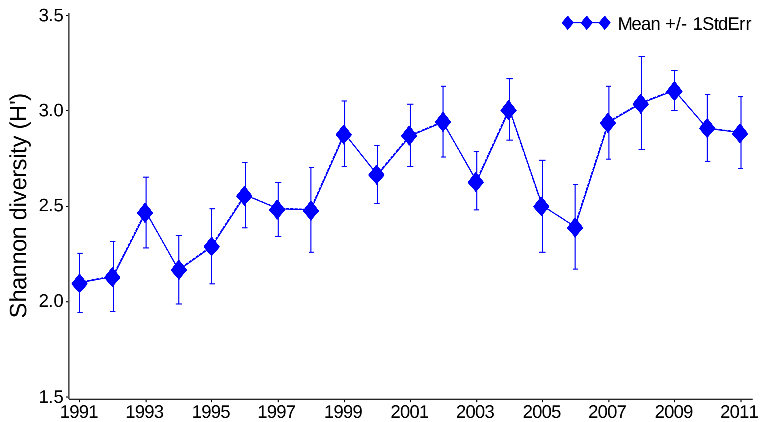


Figure 14. Mean Shannon-Weiner diversity at eight Boston harbor stations, 1991-2011.

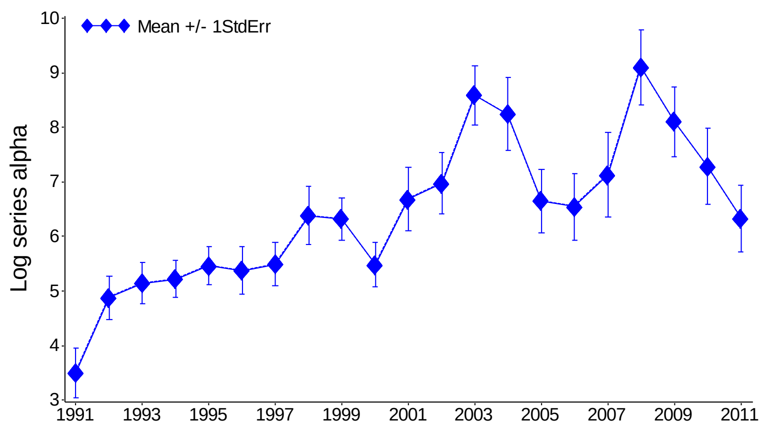


Figure 15. Mean log-series alpha diversity at eight Boston Harbor stations, 1991-2011.

3.2.2 Infaunal Assemblages

Multivariate analyses were used to assess spatial and temporal patterns in the faunal assemblages at the Boston Harbor sampling stations. Replicates within each station exhibited high similarities in community structure. One main assemblage was identified in a cluster analysis of the 27 samples from 2011 and included all replicates from each of 6 stations (T01, T02, T03, T05A, T06, and T08); three stations each formed their own discrete groups (Figure 16). Average community parameters, including total abundance, number of species, Shannon-Weiner and log-series alpha diversity, were all notably higher at stations in the main group than at T04, T07, or C019 (Table 2). The amphipod *Ampelisca* spp. (comprising *A. abdita* and *A. vadorum*) dominated in the main group, averaging more than double the abundance of the next most common species and was an important differentiator among the groups (Table 5). *Ampelisca* spp. also occurred at Stations T04, T07, and C019 but at more than an order of magnitude lower abundance than in the main group. Low abundances of *Ampelisca* spp. at these harbor stations are consistent with recent patterns (Maciolek et al. 2011). Three species of oligochaetes were among the top dominants but the majority of the other dominants were polychaetes that have been common among the dominant taxa in recent years in the harbor. Stations T04 (Dorchester Bay) and C019 a.

b.

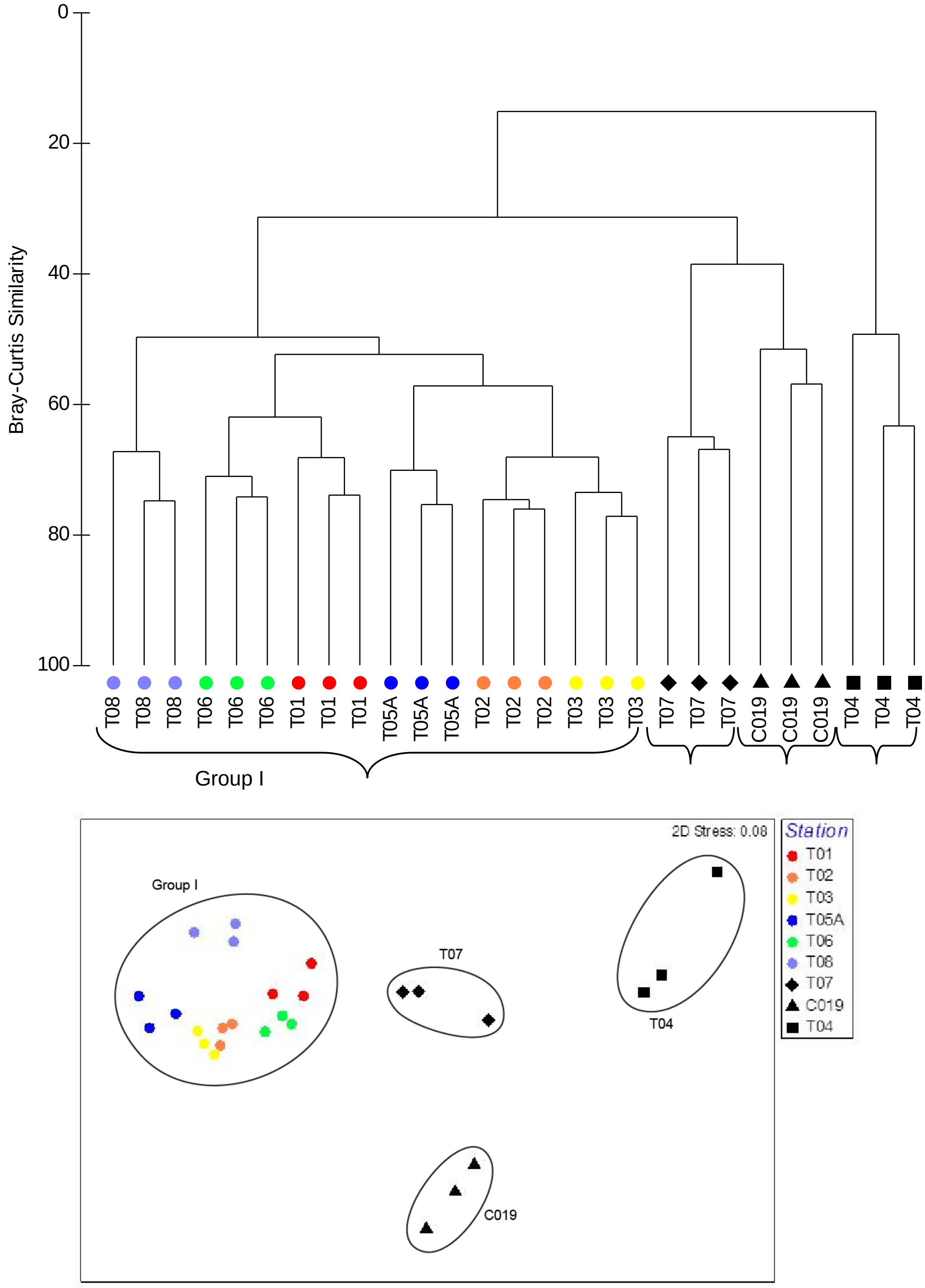


Figure 16. Results of (a) cluster analysis and (b) multidimensional scaling analysis of the 2011 infauna samples.

Table 5. Mean abundance of dominant taxa in 2011 Boston Harbor station groups defined by cluster analysis.

Phylum	Major Taxon	Family	Species	Group I	T07	C019	T04
Platyhelminthes	Turbellaria		*Turbellaria* spp.	0.9	-	-	0.7
Mollusca	Bivalvia	Tellinidae	*Angulus agilis*	13.2	2.7	1.7	0.3
		Yoldiidae	*Yoldia limatula*	0.1	-	1.7	-
Annelida	Polychaeta	Cirratulidae	*Chaetozone anasimus*	-	-	61.7	-
			Chaetozone cf. *vivipara*	0.1	-	9.7	-
			Tharyx acutus	61.2	3.7	5.3	0.3
			Tharyx sp. b	-	-	-	1.0
		Lumbrineridae	*Scoletoma hebes*	107.6	5.7	-	-
		Nephtyidae	*Nephtys cornuta*	82.2	142.3	294.0	6.7
		Paraonidae	*Aricidea catherinae*	154.2	0.7	-	-
		Phyllodocidae	*Eteone heteropoda*	0.8	-	-	0.3
		Spionidae	*Polydora cornuta*	212.2	31.0	2.7	-
			Scolelepis bousfieldi	50.3	-	0.7	-
			Streblospio benedicti	19.0	106.0	-	70.7
Annelida	Oligochaeta	Tubificidae	*Limnodriloides medioporus*	304.1	81.3	-	-
			Tubificoides intermedius	247.8	53.3	1.3	-
			Tubificoides sp. 2	4.4	44.7	0.3	3.0
Arthropoda	Amphipoda	Ampeliscidae	*Ampelisca* spp.	841.2	35.0	13.3	1.3
		Aoridae	*Leptocheirus pinguis*	28.6	-	40.3	-
		Lysianassidae	*Orchomenella minuta*	46.2	-	2.7	-
Arthropoda	Decapoda	Crangonidae	*Crangon septemspinosa*	1.1	-	0.7	0.3

(Inner Harbor) have long had the highest percentage of fine sediments of all harbor stations (see Section 3.1), and differences in the infaunal assemblages at these stations as compared to other harbor stations were identified and discussed by Maciolek et al. (2008). Maciolek et al. (2011) reported an abrupt decline in the numbers of taxa at Station T07 (Quincy Bay) from 2009 (32 species) to 2010 (12.7 species) that could be related to a substantial reduction in the percent fines. Number of taxa remained relatively low in 2011, averaging 16 species per sample although percent fines increased to levels found previously at this station.

3.2.3 Selected Stations

Station T01. Infaunal community conditions at Station T01, located near Deer Island Flats north of President Roads, have exemplified conditions at most stations in the Harbor throughout the survey period. Community parameters in 2011 were generally equal to or higher than the means for Stations T01-T08, but most of these parameters decreased in 2011 compared to 2010. Mean abundance was slightly lower in 2011 than from 2006 through 2010, but remained higher than 1999-2000 and 2002-2005 (Figure 17). Species richness declined to a level below that seen in most years since 1991 (Figure 18), but Shannon-Weiner diversity (Figure 19) and Pielou’s evenness (Figure 20) remained at or above levels observed since the mid-1990s, indicating that the substrate at this station continued to support a benthic community with a varied species composition with relatively even distribution of abundances. Mean log-series alpha continued to decline at T01, reaching a similar level to that observed in 2006 and years preceding the divergence.

Station C019. Station C019 was initially included in the Harbor sampling program as part of the Sediment-Water Exchange (SWEX) study (Gallagher and Keay 1998). When first sampled in 1989, the benthic infauna consisted of only a few taxa and was overwhelming dominated by two polychaete species, *Streblospio benedicti* and *Chaetozone setosa*. There has been a substantial increase in species richness during recent years (Figure 18), although the number of taxa present in 2011 declined compared to the peak in 2010. Mean abundance was also lower in 2011 compared to 2010 (figure 17). Measures of diversity, however, were all similar to the past several years (Figures 19, 20, and 21). As in 2004 through 2010, *Nepthys cornuta* continued to represent the majority of the infauna found at Station C019 (Figure 22), accounting for 66.5% of the total abundance. The decrease in the relative contribution of a single species to the total abundance explains the increase in the evenness and Shannon-Weiner indices.

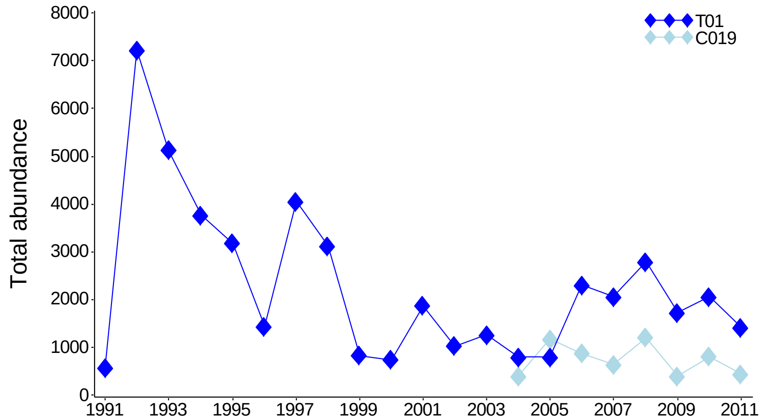


Figure 17. Mean total abundance at Boston Harbor Stations T01 and C019, 1991-2011.

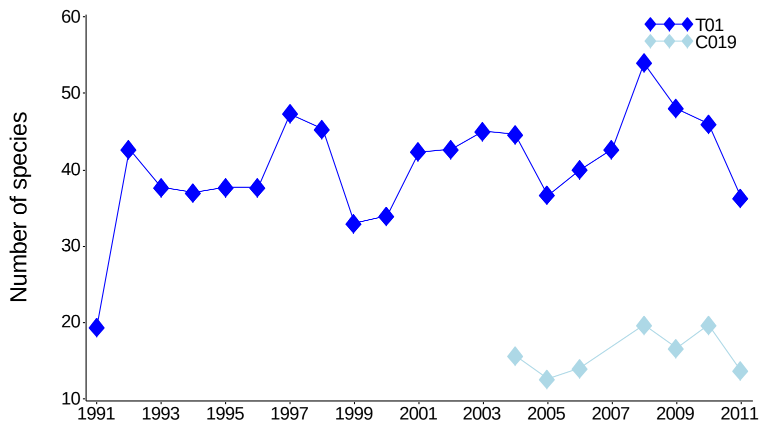


Figure 18. Mean species richness at Boston Harbor Stations T01 and C019, 1991-2011.

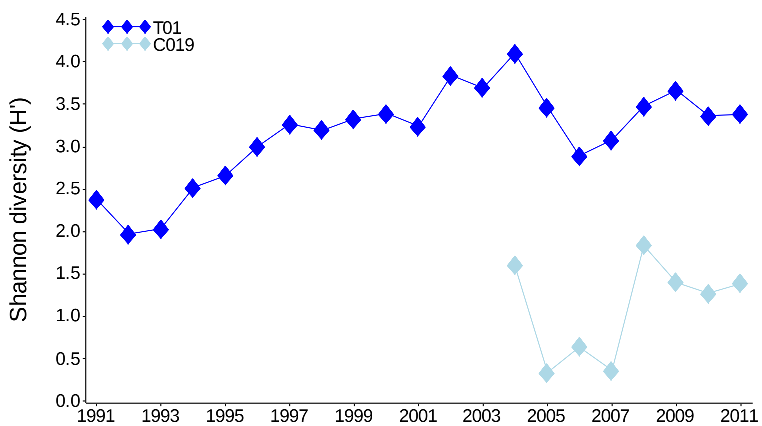


Figure 19. Mean Shannon-Weiner diversity at Boston Harbor Stations T01 and C019, 1991-2011.

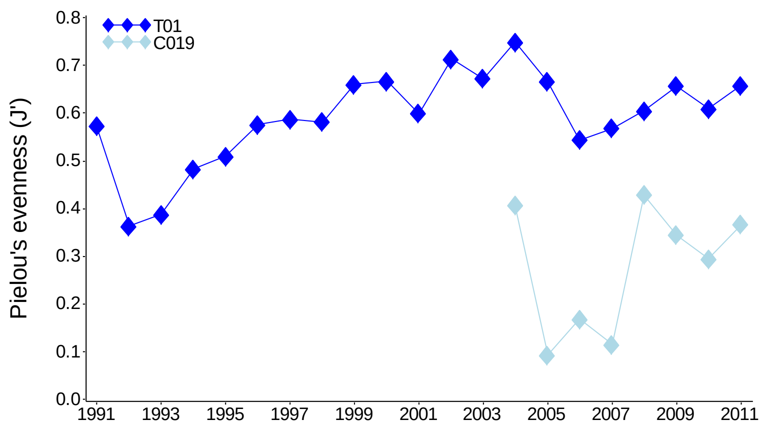


Figure 20. Mean evenness at Boston Harbor Stations T01 and C019, 1991-2011.

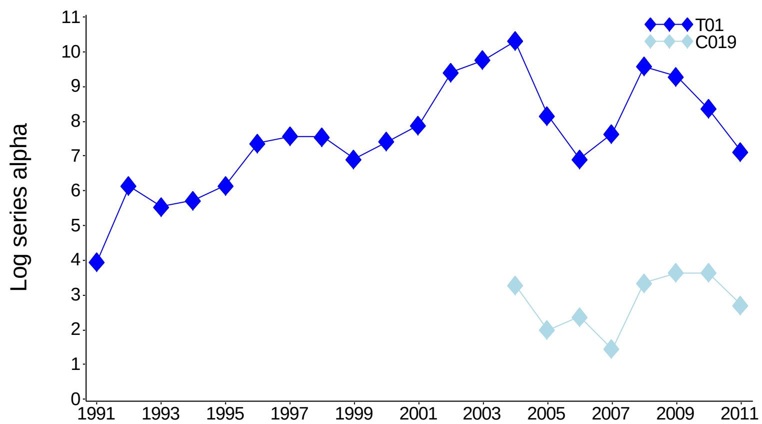


Figure 21. Mean log series alpha diversity at Boston Harbor stations T01 and C019, 1991-2011.

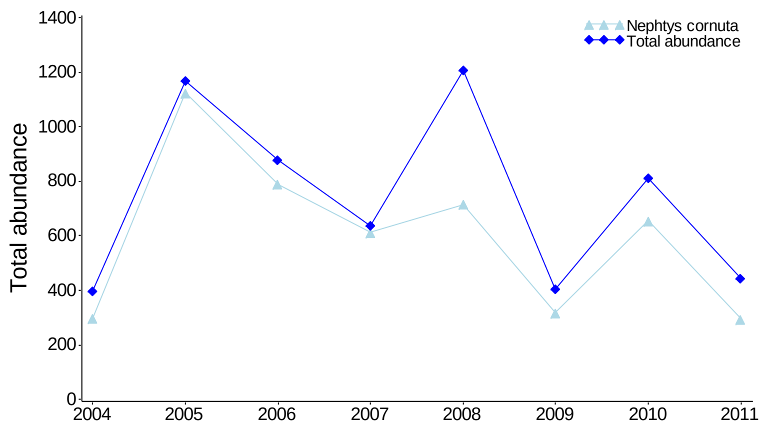


Figure 22. Mean abundance of *Nephtys cornuta* and total community abundance at Station C019, 2004-2011.

3.2.4 Trends Over Time

Benthic community parameters for the harbor have exhibited changes since 1991 that correspond well to the management changes defined by Taylor (2006) and described in Section 3.1 (Table 6). While mean total abundance has not changed dramatically through these periods, increases in species richness, evenness, and diversity between Periods I and IV have been notable and the trend in all of these parameters suggests a response to the reduction in pollutant loading into the harbor. Mean Period IV values for number of species, Shannon-Weiner diversity, and log-series alpha diversity for 2001-2011 were virtually the same as for 2001-2010 (Maciolek et al. 2011) so it is apparent that this trend has continued.

Table 6. Benthic community parameters for stations T01-T08, summarized by time periods defined by Taylor (2006)

Parameter	Period I (1991-1992) n=47		Period II (1993-1998) n=144		Period III (1999-2001) n=70		Period IV (2001-2011) n=240	
	Mean	Std Err	Mean	Std Err	Mean	Std Err	Mean	Std Err
Total Abundance	2606.4	343.64	5513.4	469	3213.5	492.66	2756.5	163.54
Log-series alpha	4.2	0.31	5.51	0.17	6.16	0.27	7.5	0.21
Shannon-Wiener Diversity (H')	2.12	0.12	2.41	0.07	2.81	0.09	2.84	0.06
Pielou's Evenness (J')	0.48	0.02	0.47	0.01	0.58	0.02	0.54	0.01
Number of Species	25.45	2.06	34.74	1.14	33.61	1.7	41.51	1.12

3.3 Sediment Profile Imaging

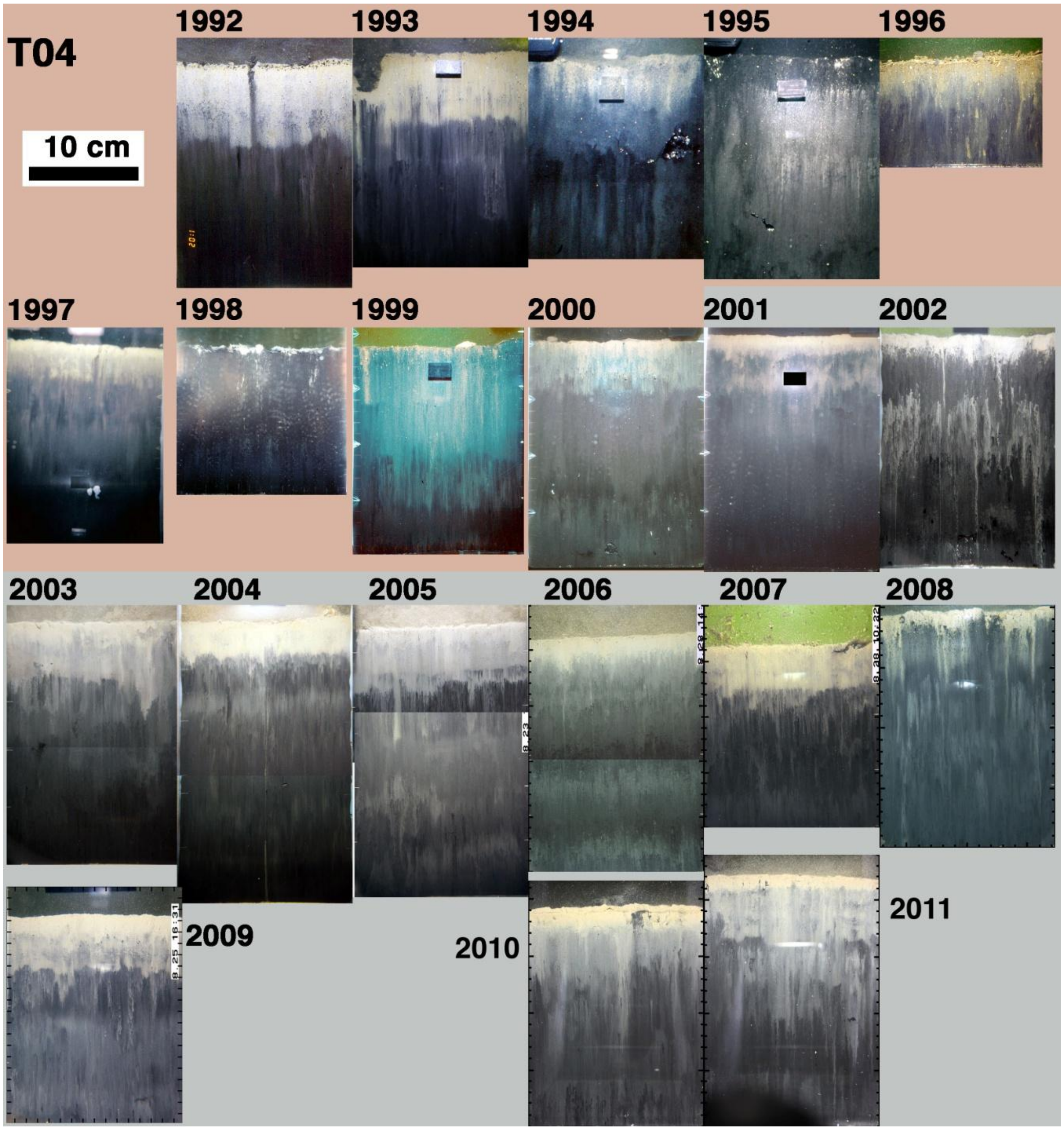
In 2011, soft bottom benthic habitat in Boston Harbor continued to show signs of improvement. Much if not all of the improvement in benthic habitat quality over the last 20 years can be attributed to upgrades in wastewater treatment and removal of outfall discharge from within the Harbor (Diaz et al. 2008, Taylor 2010). Improvements continue to be observed at inner Harbor stations, such as those in Dorchester Bay, for example T04 (Figure 23). Of the eight long-term benthic stations within the Harbor, T04 was the most impacted by poor benthic habitat conditions. In 1995 and 1998 it appeared that T04 was severely hypoxic with traces of bacterial mats at the sediment-water-interface in August when the SPI images were collected (Figure 23). Benthic diversity (H') for these years was 0.19 in 1995 and 0.03 in 1998. By the early 2000s T04 had substantially recovered with no signs of hypoxia and H' diversity consistently >1, but it continues to have lowest diversity and a species composition that sets it apart from the other benthic stations (Figure 16). Species known to be favored by high levels of TOC, such as *Streblospio benedicti*, are still the dominants at T04 but species indicative of improving sediment conditions, such as *Ampelisca* spp., are starting to appear.

The general recovery pattern of inner and mid Harbor stations has closely followed the classic Pearson-Rosenberg (1978) organic gradient model, which relates community structure and bioturbation rates to the concentration of organic matter in the sediments. A good example of this recovery sequence is seen at station T02 in President Roads, near Deer Island Flats (Figure 24). Through the 1990s, the aRPD was shallow with a mean of about 1 cm. In the early 2000s the aRPD deepened to about 1.5 cm and by the late 2000s and early 2010s the aRPD was >4 cm. Sediments appeared lighter in color during the mid-2000s and the presence of deep-dwelling infauna and biogenic structures increased. As a result, much of the improvement in benthic habitat quality at T02 was related to increased bioturbation, which burns off sediment organic matter. Through time there was a decline in TOC at three of the four harbor flux stations (T03, T07, and T08) from 1995 to 2008 (Tucker et al. 2009). At the fourth flux station, T02, TOC remained about the same over the same period.

Outer Harbor stations that are more strongly influenced by hydrodynamic factors have always had higher habitat quality, but also improved after the operation of the ocean outfall. From 1992 to the present there is strong evidence that benthic habitats within Boston Harbor shifted from a more anaerobic state to a more aerobic state and that these changes are directly related to changes in carbon loading associated with outfall placement and improvements in wastewater treatment. There were also corresponding decreases in primary production due to reduced nutrient loadings (Oviatt et al. 2007).

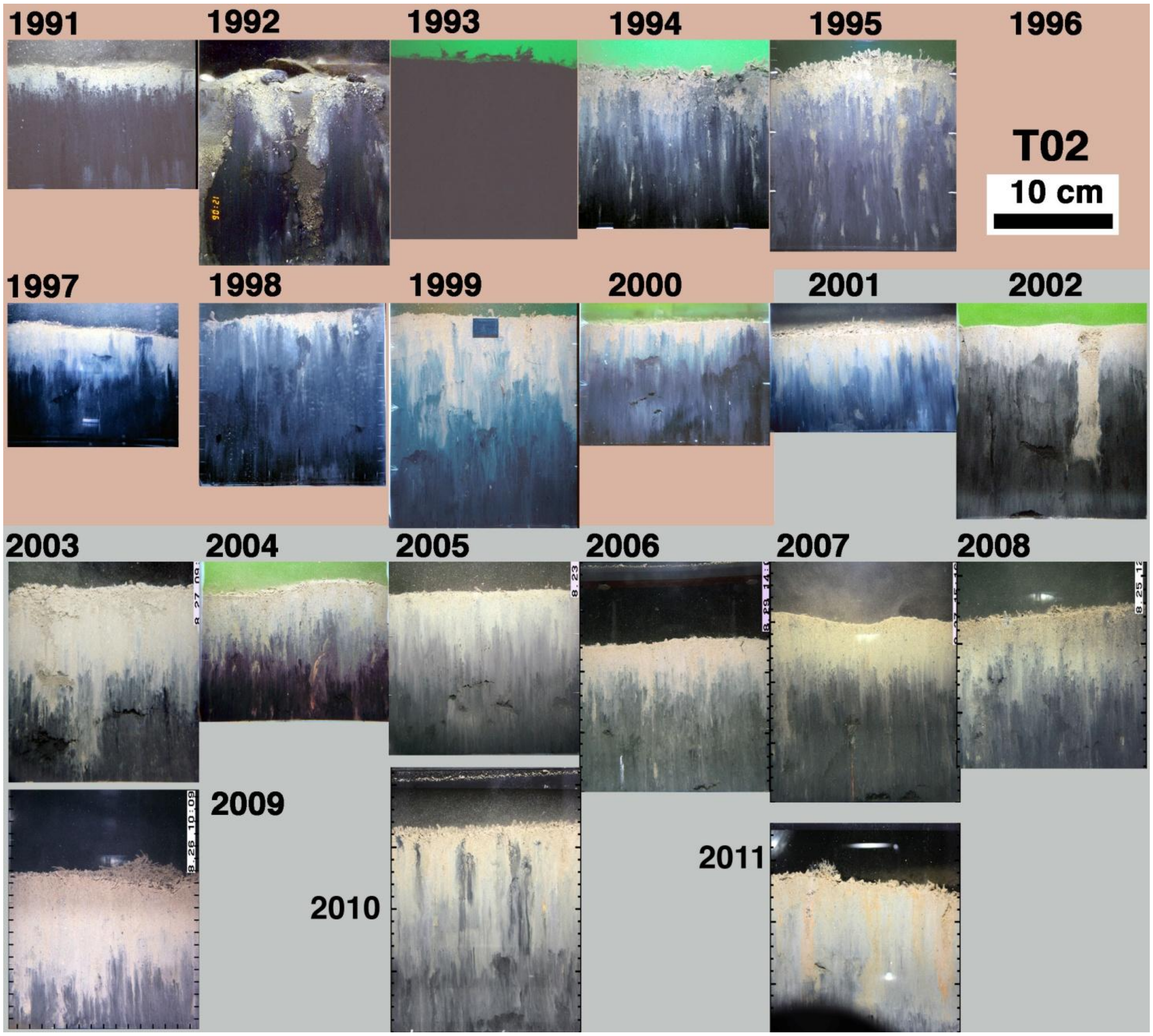
Much of the recovery in benthic habitat quality can be seen in the dynamics of the tube building amphipod *Ampelisca* spp. which can reach very high densities and form thick tube mats (Figure 25). Over the 20 years of SPI monitoring, biogenic activity associated with the presence of *Ampelisca* spp. had the most influence habitat quality. At some time between 1990 and 1992, when the SPI monitoring started, there was an increase in the occurrence of *Ampelisca* spp. tube mats (Figure 26). Prior to the dominance of *Ampelisca* spp. it appeared that blue mussels and polychaete tube mats were widely distributed (SAIC 1990, 1992). Amphipod tube mats peaked from 1994 to 1997 potentially in response to a combination of sediment disturbance from a significant storm event in October 1991 (the “perfect storm”), cessation of sludge discharge in December 1991, and the onset of new primary treatment plants at Deer Island in 1995. It is possible that prior to these events either organic or pollutant loading was too high for *Ampelisca* spp. to thrive. Life history of *Ampelisca* spp. reflects a combination of opportunism in responding to organic matter (McCall 1977) and sensitivity to pollutants (Wolfe et al. 1996). As the organic and pollutant loading, and also primary production within the Harbor continued to decline, mat densities of *Ampelisca* spp. also declined. This started in 1998 and by 2005 no tube mats were observed. The loss of tube mats in 2005 may also have been associated with a strong storm in late 2004 that disrupted tube mats. *Ampelisca* spp. tube mats reappeared 2006 and have increased to levels seen in the late 1990s (Figure 26). The reappearance of tube mats was at stations with highest occurrences in the past (Figure 27).

Overall, the improvements in wastewater treatment and moving the outfall offshore have led to improvements in benthic habitats within Boston Harbor by favoring processes that enhance bioturbation or the mixing of sediment by organisms. For example, in 2008 and 2009, high levels of bioturbation from large numbers of the amphipod *Leptocheirus pinguis* was observed at many stations (Figure 28). An eelgrass bed has persisted at Station R08 since 2008 (Figure 29).



(vertical scale on each image = 1 cm increments)

Figure 23. Thumbnail SPI images from station T04 located in Dorchester Bay, for baseline (1992-2000) and post-baseline (2001-present) years.

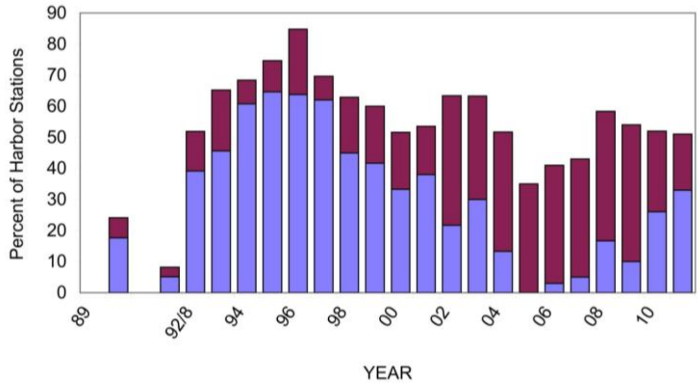


(vertical scale on each image = 1 cm increments)

Figure 24. Thumbnail SPI images from station T02 located in President Roads, for baseline (1991-2000) and post-baseline (2001-present) years.

(note: vertical scale on image = 1 cm increments)

Figure 25. *Ampelisca* spp. tube mat at Station R20 in 2011.



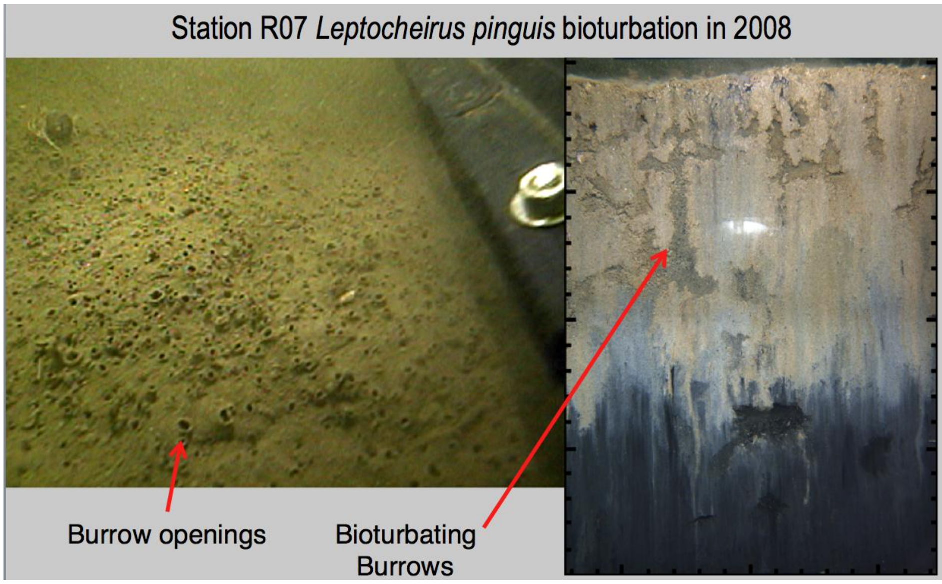
(Note: no data 1989 and 1991; 1992 represented by two sampling periods in 1992, spring [low occurrence] and summer [92/8])

Figure 26. Proportion of SPI stations in Boston Harbor with *Ampelisca* spp. tubes present at mat densities (bottom of bar in blue) or as scattered tubes (top of bar in brown) during baseline (through 2000) and post-baseline (2001-present) surveys.

		1990	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
CHARLES	CO19	.	.	.	.	.	.	.	.	.	.	.	.	.	-	-	-	-	-	-	-	-
RIVER	R09	-	.	-	MAT	-	MAT	MAT	MAT	MAT	+	MAT	+	+	+	-	-	-	-	-	-	MAT
	R10	-	.	-	-	-	-	+	-	MAT	-	-	-	-	-	-	-	-	-	-	MAT	MAT
DORCHESTER	R14	.	.	-	MAT	MAT	MAT	MAT	MAT	-	-	MAT	-	+	-	-	+	-	-	+	MAT	MAT
BAY	R15	.	.	+	-	MAT	+	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-
	R40	-	.	-	-	+	+	-	+	-	-	+	+	-	+	+	-	-	+	-	+	-
	R41	-	.	-	MAT	MAT	MAT	MAT	+	-	+	+	MAT	+	+	-	-	-	+	-	+	-
	R42	-	.	-	-	-	-	-	-	-	-	-	+	-	+	+	+	-	-	-	-	-
	R43	-	.	+	-	+	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-
	T04	.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
QUINCY	R18	.	.	MAT	MAT	-	MAT	MAT	MAT	MAT	MAT	MAT	+	MAT	+	+	+	+	MAT	+	MAT	MAT
BAY	R33	-	.	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	+	-	-	-
	R34	-	.	-	-	-	+	-	-	-	-	.	-	-	-	-	-	-	-	-	-	-
	R35	-	.	-	-	MAT	-	-	-	-	-	.	-	-	-	+	-	-	-	-	-	-
	R36	-	.	-	-	-	-	-	-	-	-	.	-	-	-	-	-	-	-	-	-	-
	R37	+	.	+	-	MAT	-	+	+	+	-	-	+	+	+	-	-	-	+	-	-	-
	R38	+	.	MAT	MAT	MAT	MAT	MAT	MAT	MAT	+	MAT	+	MAT	+	-	+	+	+	+	+	+
	R39	-	.	MAT	MAT	MAT	MAT	+	MAT	+	MAT	+	MAT	-	-	-	+	-	+	+	+	+
	R48	-	.	.	.	-	-	-	+	-	+	+	+	+	+	-	-	-	-	-	-	-
	T07	.	+	+	-	MAT	MAT	-	-	-	-	+	-	+	-	-	+	-	+	+	-	-
DEER ISLAND	R02	.	.	MAT	MAT	+	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	-	+	+	MAT	MAT	MAT	+	MAT
FLATS	R03	.	.	+	MAT	MAT	MAT	MAT	MAT	+	+	+	+	MAT	-	-	-	+	+	+	MAT	MAT
	R04	.	.	-	MAT	MAT	+	-	-	-	-	MAT	-	-	-	-	-	-	-	+	-	-
	R05	.	.	-	MAT	MAT	+	-	MAT	+	+	+	+	+	+	-	-	-	+	+	+	-
	R07	.	.	-	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	+	+	-	-	+	+	-	+	MAT
	R47	.	.	.	.	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	+	-	+	+	MAT	+	MAT	MAT
	T01	.	-	-	-	-	+	-	-	-	-	-	+	-	-	+	-	-	-	-	+	-
	R08	-	.	-	-	-	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-
OFF LONG	R11	.	.	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	-	-	-	+	+	+	MAT	MAT
ISLAND	R12	.	.	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	+	-	-	-	-	+	+	MAT	MAT
	R13	.	.	+	MAT	+	+	-	-	-	-	MAT	-	-	-	-	-	-	-	MAT	-	+
	R16	+	.	MAT	+	MAT	MAT	MAT	MAT	MAT	MAT	+	-	+	-	+	-	+	+	-	-	-
	R17	+	.	MAT	MAT	MAT	+	MAT	MAT	MAT	MAT	-	+	-	-	+	-	+	-	-	-	+
	R45	.	.	.	.	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	+	+	+	+	+	MAT	MAT	MAT	MAT
	T03	+	MAT	-	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	+	+	+	MAT	MAT	MAT	MAT
	R06	.	.	MAT	+	-	-	-	-	-	-	+	-	+	+	-	-	-	-	-	-	-
PRESIDENT	R44	.	.	.	.	MAT	-	-	MAT	-	+	MAT	+	+	-	-	-	-	-	-	MAT	MAT
ROADS	T02	-	-	+	MAT	MAT	+	MAT	+	+	MAT	+	-	+	+	-	-	+	+	+	MAT	MAT
	T05a	.	-	.	-	MAT	MAT	MAT	-	-	-	MAT	-	MAT	MAT	+	-	+	+	+	MAT	MAT
NANTASKET	R21	+	.	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	+	MAT	MAT	MAT	+	+	MAT
ROADS	R22	-	.	MAT	MAT	MAT	+	MAT	MAT	MAT	MAT	MAT	+	+	-	+	+	-	-	+	-	-
	R23	-	.	MAT	MAT	MAT	MAT	MAT	+	+	MAT	MAT	+	+	+	+	-	+	+	+	-	+
	R24	+	.	MAT	MAT	MAT	MAT	+	MAT	MAT	MAT	MAT	+	+	-	-	+	+	MAT	+	MAT	MAT
	T06	.	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	+	MAT	MAT	-	-	+	+	MAT	+	+
	R20	+	.	MAT	MAT	MAT	MAT	MAT	-	MAT	MAT	MAT	MAT	MAT	MAT	+	+	MAT	MAT	MAT	MAT	MAT
HINGHAM	R19	.	.	+	+	-	MAT	-	-	+	-	-	-	+	+	-	-	-	-	-	-	-
BAY	R25	.	.	MAT	MAT	MAT	MAT	MAT	MAT	MAT	+	-	-	MAT	-	-	-	-	-	-	+	-
	R26	-	.	MAT	-	+	MAT	+	+	+	-	-	-	-	-	-	-	-	+	+	-	+
	R27	-	-	+	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	+	MAT	+	-	+	+	+	+	-	+
	R28	-	.	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	+	MAT	MAT	+	+	+	+	+	-	-
	R29	-	.	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	+	+	+	+	+	+	+
	R30	.	+	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	+	MAT	+	+	MAT	+	MAT	-	+	MAT
	R31	+	.	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	+	-	+	-	+	+	MAT	MAT
	R32	.	+	+	MAT	-	MAT	-	+	+	-	MAT	-	-	+	-	-	-	+	+	+	MAT
	R46	+	.	.	.	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	MAT	+	+	+	+	+	MAT	+
	R49	.	.	.	.	-	MAT	-	+	-	-	-	+	-	+	-	+	-	-	-	-	-
	R50	+	.	.	.	MAT	MAT	MAT	MAT	+	MAT	-	+	+	-	+	+	+	+	+	-	-
	R51	-	.	.	.	+	MAT	-	+	+	-	-	-	-	-	-	+	+	-	+	-	-
	R52	+	.	.	.	-	MAT	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	R53	-	.	.	.	+	MAT	-	-	-	+	-	+	-	-	-	-	-	-	-	-	-
	T08	.	MAT	MAT	+	MAT	-	MAT	-	+	-	MAT	+	+	+	+	+	+	MAT	+	+	-

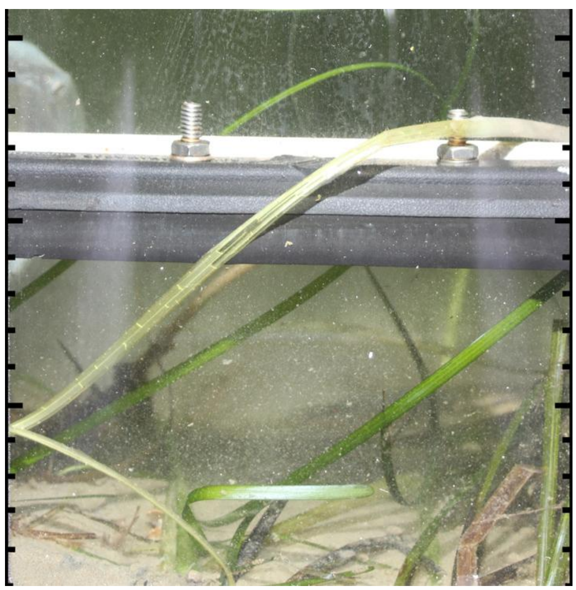
(Note: mat [dark green] is tube mat densities, + [light green] is tubes present, - [pink] is no amphipod tubes present, blank cell is no data)

Figure 27. Temporal and spatial distribution of *Ampelisca* spp. tubes at Boston Harbor SPI stations during baseline (1990-2000) and post-baseline (2001-2011) years.



(Note: vertical scale on image = 1 cm increments)

Figure 28. High level of bioturbation from the amphipod *Leptocheirus pinguis* at Station R07 in 2008.



(Note: vertical scale on image = 1 cm increments)

Figure 29. Eelgrass bed at Station R08 in 2011.

4. CONCLUSION

Physical and biological properties of the soft substrate in Boston Harbor in 2011 were consistent with trends observed in previous years (Maciolek et al. 2011). Concentrations of both TOC and *C. perfringens*, indicators of organic enrichment and deposition from municipal wastewater discharge, have remained low compared to the levels occurring prior to the offshore diversion. Although abundances of individual taxa, such as the dominants *Ampelisca* spp. and *Polydora cornuta* have varied over time, the infaunal community structure and evidence from sediment profile imaging suggest that these changes relate more to normal physical disturbances than organic stress in the years since wastewater impacts to the Harbor have been reduced. The trends observed in previous years, including reduction of indicators of organic enrichment and increases in species diversity that continued in the 2011 survey are consistent with the recovery of benthic habitats from decades of inadequately treated sewage discharges.

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