Boston Harbor Benthic Monitoring Report: 2014 Results

Massachusetts Water Resources Authority

Environmental Quality Department

Report 2015-10

Citation:

Pembroke AE, Diaz RJ, Nestler EC. 2015. ***Boston Harbor Benthic Monitoring Report: 2014 Results.*** Boston: Massachusetts Water Resources Authority. Report 2015-10. 37 p.

Boston Harbor Benthic Monitoring Report: 2014 Results

Submitted to

Massachusetts Water Resources Authority
Environmental Quality Department
100 First Avenue
Charleston Navy Yard
Boston, MA 02129
(617) 242-6000

prepared by

Ann E. Pembroke[1]
Robert J. Diaz[2]
Eric C. Nestler[1]

[1]Normandeau Associates, Inc.
25 Nashua Road
Bedford, NH 30110

[2]Diaz and Daughters
6198 Driftwood Lane
Ware Neck, VA 23178

September 2015
Report No. 2015-10

EXECUTIVE SUMMARY

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 miles off Deer Island in Massachusetts Bay. Subsequently, improvements have been made to numerous Combined Sewer Overflows (CSOs) reducing another source of water quality concern.

Sediments and associated benthic infauna reflect cumulative water quality conditions. In order to evaluate changes to the ecosystem, particularly the benthic community, resulting from reductions in contaminated discharges over time, MWRA has conducted benthic monitoring in Boston Harbor on an ongoing basis since 1991. This report provides a summary of the results of the benthic surveys that were conducted in 2014. These include sediment conditions, benthic infauna, and sediment profile imagery.

Overall, the improvements in wastewater treatment and moving the outfall offshore have led to improvements in water quality and benthic habitat quality within Boston Harbor by reducing organic and nutrient loading and favoring processes that enhance bioturbation or the mixing of sediment by organisms. At one time, the sediment organic matter in Boston Harbor was derived primarily from sewage but since changes in wastewater treatment and disposal were initiated, marine-derived organic material has been prevalent in the sediment. The infaunal community has responded to this change and subsequent biological activity has led to more aerobic and 'healthy' sediment conditions. Physical and biological properties of the soft substrate in Boston Harbor in 2014 exhibited minor changes from recent years but were consistent with longer-term trends (Pembroke et al. 2014). Concentrations of both TOC and *Clostridium perfringens*, indicators of organic enrichment and deposition from municipal wastewater discharge, have remained low compared to the levels occurring prior to the offshore diversion.

Community structure measures also continue to point to improving benthic conditions. Since municipal wastewater and sludge discharges have been eliminated from the harbor, total abundance has trended downward, particularly for opportunistic species such as *Capitella capitata*. Species richness, while variable, has trended upward as did evenness (J'), Shannon diversity (H'), and log series alpha diversity. 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 2014 survey are consistent with the recovery of benthic habitats from decades of inadequately treated sewage discharges.

TABLE OF CONTENTS

1. INTRODUCTION 1

2. METHODS 1

2.1 FIELD METHODS 1
2.2 LABORATORY METHODS 3
2.3 DATA HANDLING, REDUCTION, AND ANALYSIS 3

3. RESULTS AND DISCUSSION 4

3.1 SEDIMENT CONDITIONS 4
3.2 BENTHIC INFAUNA 8
3.3 SEDIMENT PROFILE IMAGING 23

4. CONCLUSION 35

5. REFERENCES 36

LIST OF FIGURES

Figure 1. Locations of soft-bottom sampling and sediment profile imaging stations for 2014......................2
Figure 2. 2014 monitoring results for sediment grain size...5
Figure 3. Mean percent fine sediments at five stations in Boston Harbor, 1991 to 2013...............................6
Figure 4. Mean concentrations of TOC at five stations in Boston Harbor, 1991 to 2014. 6
Figure 5. Mean concentrations of *Clostridium perfringens* at five stations in Boston Harbor, 1991 to 2014. 7
Figure 6. Comparison of TOC across four discharge periods (offset by one year) at Boston Harbor stations (T01-T08) from 1992 to 2014 (1991 excluded)...7
Figure 7. Comparison of *Clostridium perfringens* across four discharge periods (offset by one year) at Boston Harbor stations (T01-T08) from 1992 to 2014 (1991 excluded). 8
Figure 8. Mean abundance of benthic infauna at eight Boston Harbor stations, 1991-2014. 10
Figure 9. Total abundance of four dominant taxa at eight Boston Harbor stations, 1991-2014. 11
Figure 10. Mean annual abundance of *Ampelisca* spp. averaged over eight Boston Harbor stations, 1991-2014. 12
Figure 11. Spatial distribution of *Ampelisca* spp. at eight Boston Harbor stations, 2007-2014....................12
Figure 12. Mean species richness at eight Boston harbor stations, 1991-2014. 13
Figure 13. Mean community evenness at eight Boston Harbor stations, 1991-2014. 14
Figure 14. Mean Shannon-Weiner diversity at eight Boston harbor stations, 1991-2014. 14
Figure 15. Mean log-series alpha diversity at eight Boston Harbor stations, 1991-2014. 15
Figure 16. Results of (a) cluster analysis and (b) multidimensional scaling analysis of the 2014 infauna samples. 17
Figure 17. Mean total abundance at Boston Harbor Stations T01 and C019, 1991-2014. 19
Figure 18. Mean species richness at Boston Harbor Stations T01 and C019, 1991-2014. 19
Figure 19. Mean Shannon-Weiner diversity at Boston Harbor Stations T01 and C019, 1991-2014. 20
Figure 20. Mean evenness at Boston Harbor Stations T01 and C019, 1991-2014..20
Figure 21. Mean log series alpha diversity at Boston Harbor stations T01 and C019, 1991-2014. 21
Figure 22. Mean abundance of *Bipalponephtys neotena* and total community abundance at Station C019, 2004-2014. 22
Figure 23. Matrix of successional stage estimated from SPI images. 0 - azoic, Stage I - pioneering, Stage II - intermediate, Stage III - equilibrium. Successional stage is a continuum with evidence of a mixture of stages being present at the same time. For example, I-II would indicate the presence of pioneering and intermediate species characteristics (Table 1) in the same image. 24
Figure 24. Histogram of *Ampelisca* spp. tubes present at harbor stations. Total bar represents percent of stations with tubes present. Mat densities of tubes are the bottom part of the bar in blue. There are no data from 1989 or 1991, but in 1989 there were mat densities of polychaete tubes present at some of the benthic grab stations. There were two sample periods in 1992, spring and summer (92/8). Baseline years are up to 2000. Post-baseline years are from 2001. The change in tube density between 2012 and 2013 can be seen at R31. 25
Figure 25. Mosaic of SPI from station T02 in President Roads, near Deer Island Flats, for all years. Improvements in benthic habitat quality occurred from the 1990s to the late 2000s and has remained high into the 2010s. Scale along the side of each image is in cm. 26
Figure 26. Mosaic of SPI from station T03 in President Roads, off Long Island, for all years. Improvements in benthic habitat quality occurred from the 1990s to the late 2000s and has remained high into the 2010s. Scale along the side of each image is in cm. 27

Figure 27. Relationship of summer SOD to depth of the aRPD at station T02 (BH02). Symbols indicate visual assessments of amphipod densities as observed in sediment cores for June and July of each year. (High density - amphipod tube mats or numerous tubes or holes noted; low density - few to no tubes or holes). From Tucker et al. (2014). 28
Figure 28. Relationship of summer SOD to depth of the aRPD at station T03 (BH03). Symbols indicate visual assessments of amphipod densities as observed in sediment cores for June and July of each year. (High density - amphipod tube mats or numerous tubes or holes noted; low density -few to no tubes or holes). From Tucker et al. (2014). 29
Figure 29. Matrix of *Ampelisca* spp. tube occurrence through time in SPI images. Mat is mat densities of tubes, + is tubes present, - no tube observed. 31
Figure 30. Mosaic of SPI from Dorchester Bay station T04 for all years. Some improvement in benthic habitat quality occurred by the early 2000s. In the mid-2000s signs of deeper bioturbation appear, but there has not been much change in benthic habitat conditions in the 2010s. Scale along the side of each image is in cm. 32
Figure 31. Eelgrass bed at station R08 on Deer Island Flats. The bed first appeared in SPI in 2008 and has persisted. Prior to 2008, R08 was always fine-sand with macroalgae. Scale on sediment profile image is in cm. 33
Figure 32. Changes in sedimentary processes in Boston Harbor relative to improvements in water quality and benthic habitat quality from 1990 to 2010. SOD - sediment oxygen demand, DIN - dissolved inorganic nitrogen, aRPD - apparent color redox potential discontinuity. From Tucker et al. (2014). 34

LIST OF TABLES

Table 1. 2014 monitoring results for sediment condition parameters. 4
Table 2. 2014 mean infaunal community parameters by station. 9
Table 3. Dominant taxa at eight grab stations in Boston Harbor in August 2014. 10
Table 4. Mean abundance per sample of dominant taxa during four discharge periods at eight Boston Harbor stations (T01-T08), 1992-2014. 11
Table 5. Mean abundance of dominant taxa in 2014 Boston Harbor station groups defined by cluster analysis. 16
Table 6. Benthic community parameters for stations T01-T08, summarized by time periods defined by Taylor (2006). 22
Table 7. General weight given to SPI data used to estimate successional stage. These biogenic parameters are broad relative indicators of association between successional stage and benthic physical and biological parameters based on models developed by Odum (1969), Pearson and Rosenberg (1978), and Rhoads and Germano (1986). 23

1. INTRODUCTION

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 benthic monitoring in Boston Harbor on an ongoing basis since 1991 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 2014. These include sediment conditions, benthic infauna, and sediment profile imagery. A quantitative evaluation of the long-term sediment monitoring data collected through 2007 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 Pembroke et al. (2014) for previous monitoring years. Detailed descriptions of the methods are contained in the Quality Assurance Project Plan (QAPP) for Benthic Monitoring (Nestler et al. 2014). 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 in August 2014 (Figure 1). Soft-bottom stations were sampled for grain size composition, total organic carbon (TOC), the sewage tracer *Clostridium perfringens*, and benthic infauna. One sediment sample and triplicate infauna samples were collected at each station on August 6 and 8, 2014.

SPI samples were collected in triplicate at 61 stations on August 10-12, 2014 (Figure 1).

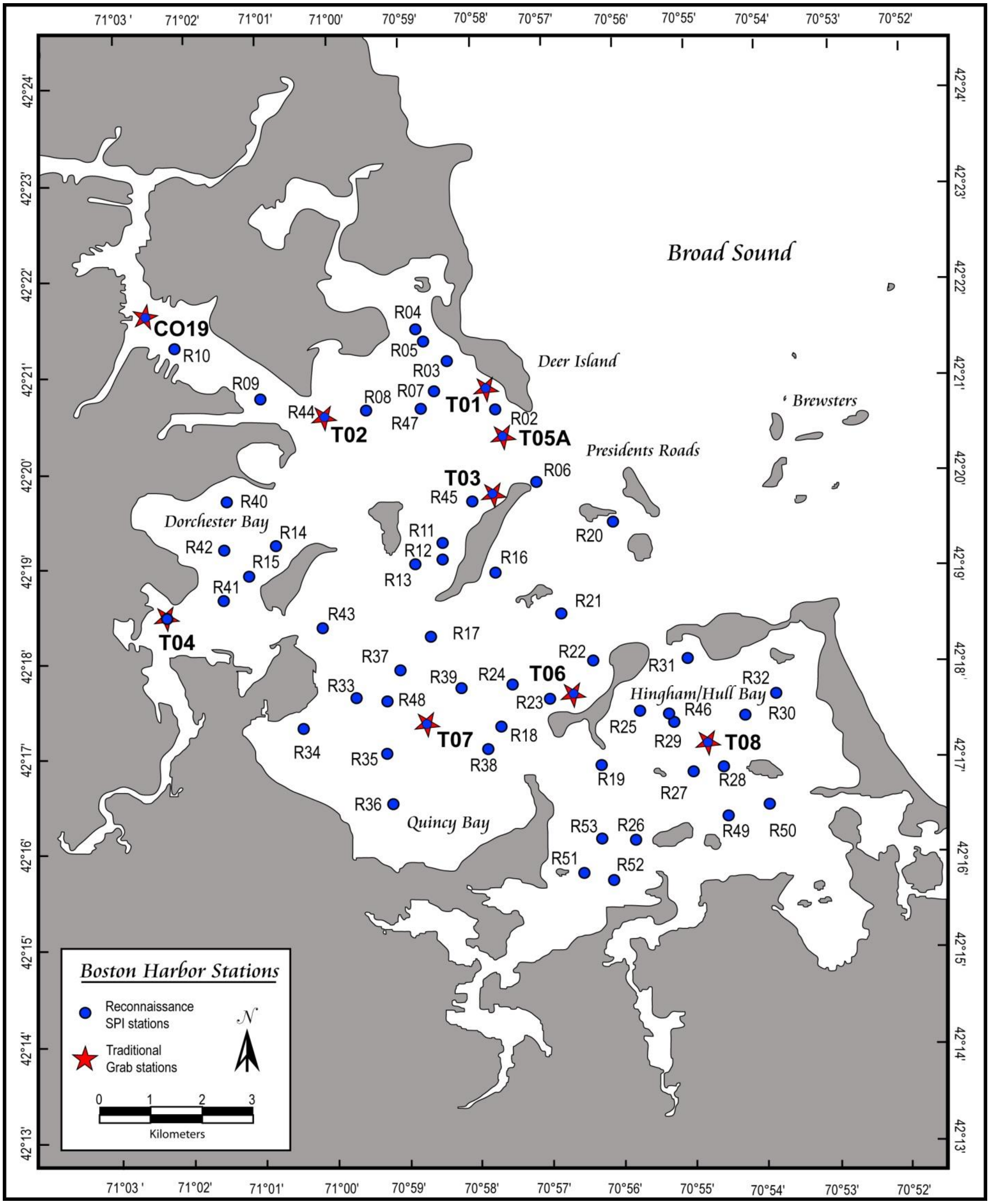


Figure 1. Locations of soft-bottom sampling and sediment profile imaging stations for 2014.

2.2 Laboratory Methods

Laboratory methods for benthic infauna and SPI image analyses were consistent with the QAPP (Nestler et al. 2014). Two of the infauna samples were randomly selected for processing, while the third was archived. Analytical methods for grain size, TOC, and *Clostridium perfringens* are described in (Constantino et al. 2014).

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. 2014) or in Maciolek et al. (2008). Data are presented graphically as means (averages per station) unless otherwise noted. Shannon-Weiner (H') was calculated using log base 2. 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.

Temporal patterns in the infaunal community and sediment chemistry were evaluated in the context of the four discharge periods described by Taylor (2006) offset by one year to allow for a lag in response time.

3. RESULTS AND DISCUSSION

3.1 Sediment Conditions

Sediment conditions in Boston Harbor were characterized by three parameters measured during 2014 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 2014 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., T07). Characterization of the grain size composition of the sediments at each station in 2014 generally remained consistent with results reported in prior years. Percent fines decreased by more than 10% at Stations T02, T03, T04, T05A, and T06 compared to 2013. T01 (just west of Deer Island) and T02 (at the mouth of the Inner Harbor) have exhibited the largest fluctuations in fine sediments over the years and T04 has occasionally exhibited fairly large drops in percent fines, as occurred in 2014 (Figure 3).

Table 1. 2014 monitoring results for sediment condition parameters.

Parameter	C019	T01	T02	T03	T04	T05A	T06	T07	T08
***Clostridium perfringens*, not normalized**	19,600	492	6,870	11,400	14,700	42	2,170	20,600	203
***Clostridium perfringens* (cfu/g dry/%fines)**	209.6	27.2	164.4	238.2	196.0	3.3	92.4	333.6	54.1
Total Organic Carbon (%)	2.5	2.0	1.3	1.8	6.5	0.4	1.1	2.9	0.2
Gravel (%)	0	11.7	0.1	0.9	0	0	3.0	0	2.3
Sand (%)	6.5	70.2	58.1	51.3	25.0	87.4	73.5	38.2	94.0
Silt (%)	51.2	12.2	26.5	30.6	61.3	8.2	15.0	34.9	1.9
Clay (%)	42.3	5.9	15.3	17.2	13.7	4.4	8.5	26.9	1.8
Percent Fines (Silt + Clay)	93.5	18.1	41.8	47.9	75.0	12.7	23.5	61.8	3.8

Total Organic Carbon. Concentrations of total organic carbon (TOC) in 2014 also generally increased but remained within the ranges reported in prior years, although T01, T02, T04, and C019 have exhibited slight declines over the last few years (Figure 4). An unusually high concentration at T04 may be attributable to the presence of vegetative debris in the sample. Concentrations of TOC tend to track closely to percent fine sediments (silt + clay), with higher TOC values generally associated with higher percent fines although that relationship was not as clear in 2014 (Figures 3 and 4). During 2014, Stations T04, T07, and C019 had among the highest concentrations of TOC (Table 1). T04 and C019 have typically had the highest TOC. Values increased at all three stations, particularly T04 where TOC reached the second highest level in the time series (Table 1; Figure 4). 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) and there was a notable amount of vegetative debris in the sample in 2014. TOC at Station T01 (with percent fines of 18%) was also somewhat elevated although within previously reported values (Table 1, Figure 4). As in prior years, the lowest TOC concentrations for 2014 were reported at Station T08.

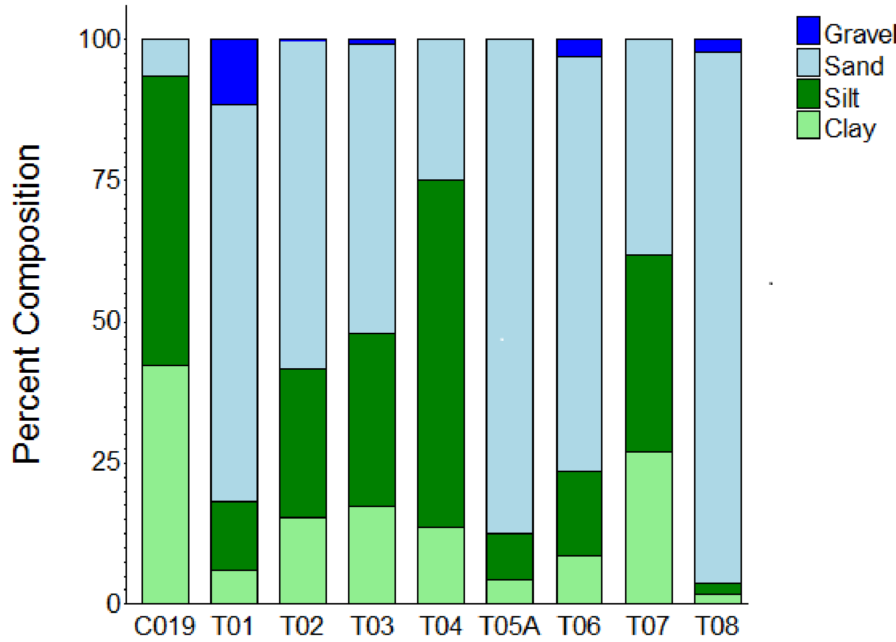


Figure 2. 2014 monitoring results for sediment grain size.

***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 2014 were highest at Station T07 in the Outer Harbor. Station C019 in the Inner Harbor had the third highest value. Lowest values were found at station T05A (Table 1). Abundances at T04, a depositional site in Savin Hill Cove, had declined for several years (2008-2012) but increased again in 2014. Abundances were the third highest measured in the period from 1991 through 2014, although much lower than the peaks seen in 1991 and 1996 (Figure 5). *C. perfringens* counts at other Harbor stations have remained consistently below historical averages since around 1999 (Figure 5).

Association with wastewater treatment improvements. 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).

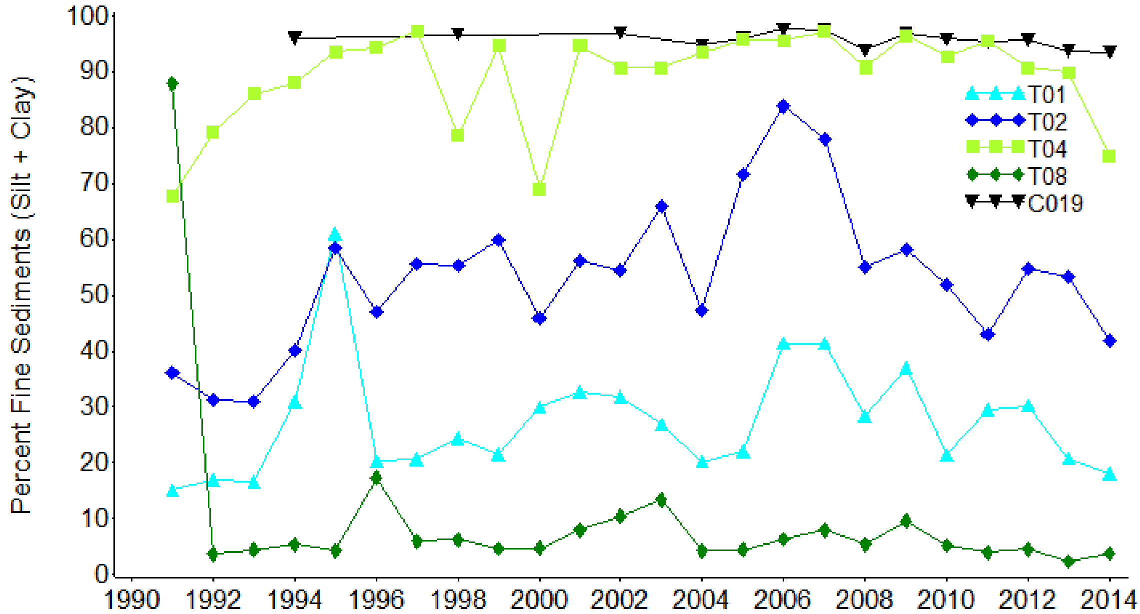


Figure 3. Mean percent fine sediments at five stations in Boston Harbor, 1991 to 2014.

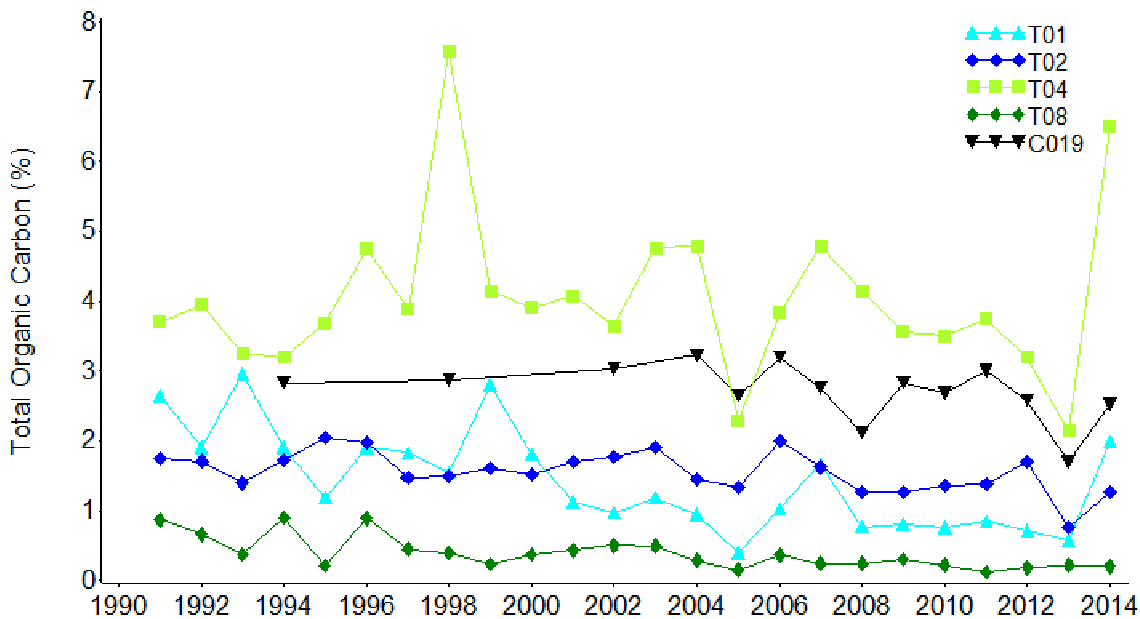


Figure 4. Mean concentrations of TOC at five stations in Boston Harbor, 1991 to 2014.

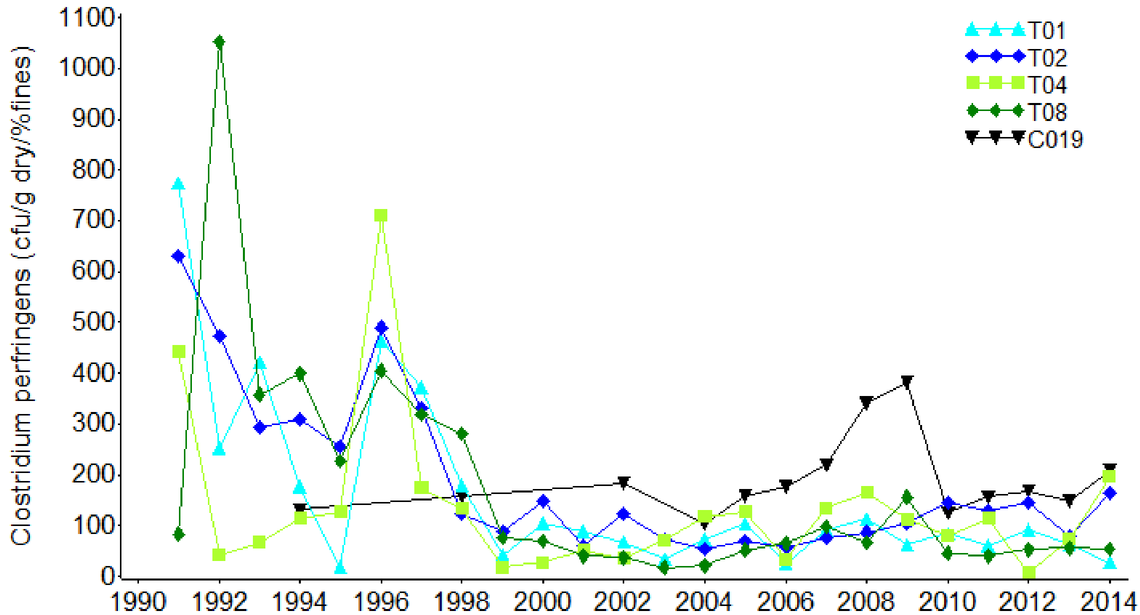


Figure 5. Mean concentrations of *Clostridium perfringens* at five stations in Boston Harbor, 1991 to 2014.

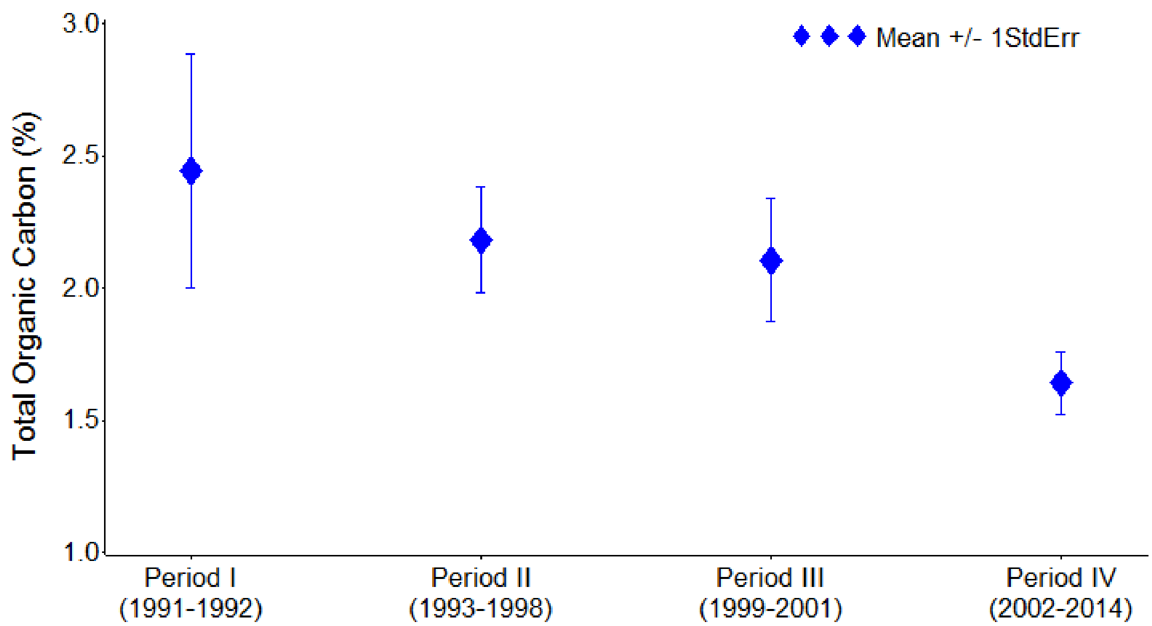


Figure 6. Comparison of TOC across four discharge periods (offset by one year) at Boston Harbor stations (T01-T08) from 1992 to 2014 (1991 excluded).

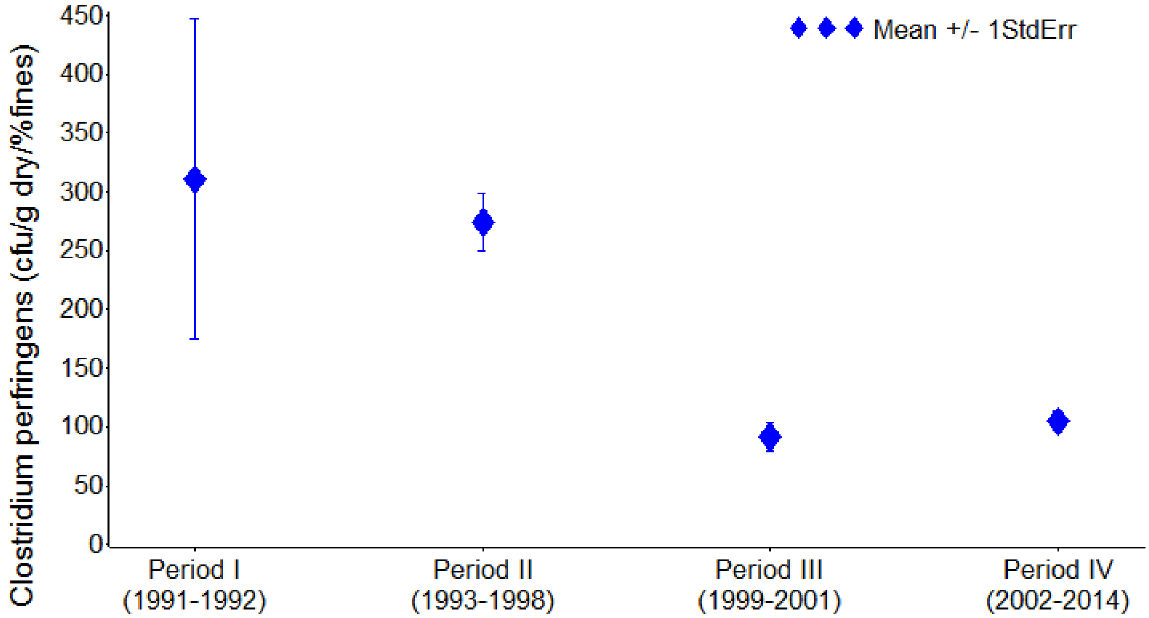


Figure 7. Comparison of *Clostridium perfringens* across four discharge periods (offset by one year) at Boston Harbor stations (T01-T08) from 1992 to 2014 (1991 excluded).

Results during 2014 for grain size, TOC, and *C. perfringens* in Boston Harbor sediments, are consistent with monitoring results from prior Period IV years (Maciolek et al. 2008, 2011; Pembroke et al. 2012, 2013, 2014). 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).

3.2 Benthic Infauna

3.2.1 Community Parameters

A total of 26,477 infaunal organisms were counted from the 18 samples in 2014. Organisms were classified into 134 discrete taxa; 119 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. 2014 mean infaunal community parameters by station.

Station	Total Abundance	Number of Species	Pielou's Evenness (J')	Shannon-Wiener Diversity (H')	Log-series alpha
C019	306.5	20.5	0.71	3.10	4.96
T01	1,290.0	45	0.60	3.29	9.26
T02	3,840.5	41.5	0.49	2.62	6.66
T03	2,344.0	48	0.57	3.18	8.56
T04	1,116.5	9.5	0.26	0.84	1.43
T05A	1,120.0	35	0.68	3.48	6.87
T06	2,171.0	38	0.60	3.13	6.55
T07	432.0	23.5	0.67	3.03	5.37
T08	618.0	52.5	0.72	4.14	13.96

Mean abundance values reported for 2014 varied from values in 2013 by 70% or more at five stations, including Stations T01, T02, T03, T04, T07, and T08 (Pembroke et al. 2013). Abundances in 2014 were within the range observed during the post-offshore diversion period but relatively low compared to pre-diversion values (Figure 8). Most of the species that dominated (contributing $\geq$ 2.5% of the total abundance) the infauna at these stations in the past several years continued to do so in 2014 (Table 3) although the rank order changed. Abundances of three taxa (*Ampelisca* spp., *Mediomastus californiensis*, and *Tharyx* spp.) that had been numerical dominants prior to 2013 remained below the 2.5% threshold. Two species of oligochaetes and four species of polychaetes were among the most abundant taxa in 2014. Abundance of amphipods in the genus *Ampelisca* remained low, appearing in appreciable numbers only at Station T03. All dominant taxa in 2014 have previously been among the most abundant in the harbor. Certain spatial patterns of abundance appeared to be consistent with previous years; T04, T07, and C019 continued to support low abundances (Table 2). As previously observed, Stations T02 and T03 supported the highest abundances among the harbor stations. Abundances at Station T05A continued to increase from the low in 2012. Abundances at Station T06 were similar to those observed in 2013.

Temporally, benthic infaunal 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 and abundances of both species are currently low. 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).

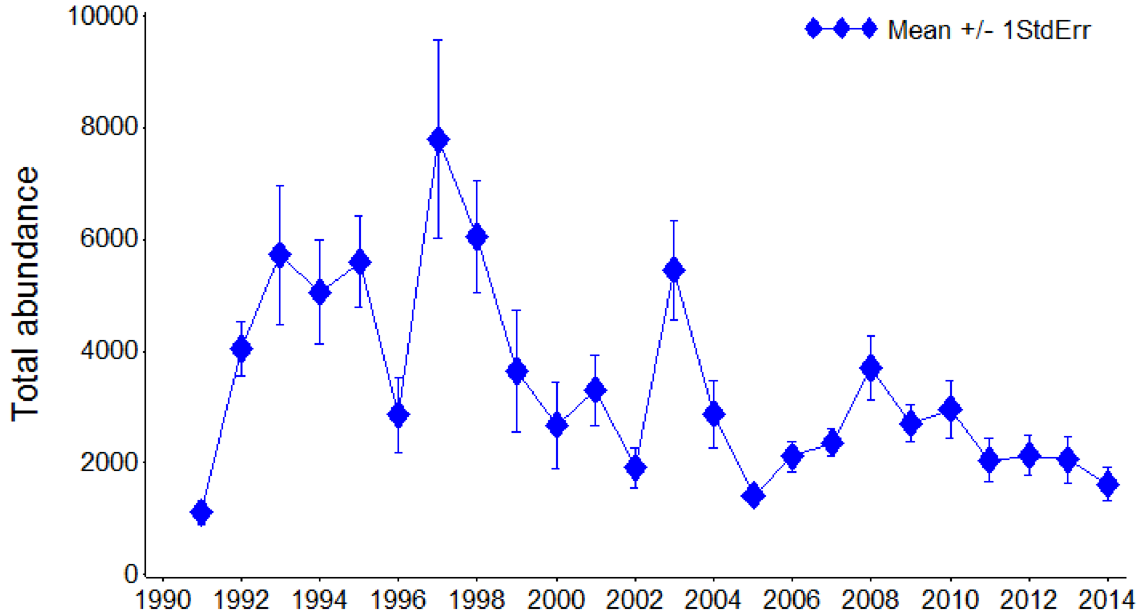


Figure 8. Mean abundance of benthic infauna at eight Boston Harbor stations, 1991-2014.

Table 3. Dominant taxa at eight grab stations in Boston Harbor in August 2014.

Taxon	**Total 2014 Abundance (compared with 2013)[a]**
Limnodriloides medioporus	5,546 (increase)
Tubificoides intermedius[b]	3,822 (decrease)
Aricidea catherinae	3,663 (similar)
Polydora cornuta	3,206 (decrease)
Streblospio benedicti	2,042 (increase)
Scoletoma hebes	1,866 (decrease)
Scolelepis bousfieldi	46 (decrease to 3%)

[a] increase or decrease indicates ≥25% change from previous year

[b] previously identified as *T. apectinatus*

Table 4. Mean abundance per sample of dominant taxa during four discharge periods at eight Boston Harbor stations (T01-T08), 1992-2014.

Phylum	Higher Taxon	Family	Species	Period I	Period II	Period III	Period IV	2014
Annelida	Polychaeta	Capitellidae	*Capitella capitata* complex	65.2	88.8	3.4	6.0	7.8
		Lumbrineridae	*Scoletoma hebes*	3.4	10.5	4.2	65.7	116.6
		Nephtyidae	*Bipalnephtys neotena*[b]	-	11.4	10.3	205.1	11.5
		Paraonidae	*Aricidea catherinae*	325.0	237.4	204.3	213.1	228.9
		Spionidae	*Polydora cornuta*	525.8	1,053.0	269.6	264.5	200.4
			Streblospio benedicti	236.0	298.6	27.7	59.3	127.6
Annelida	Oligochaeta	Tubificidae	*Limnodriloides medioporus*	484.7	297.9	315.2	241.4	346.6
			Tubificoides intermedius	42.6	101.4	231.2	256.3	238.9
Arthropoda	Amphipoda	Ampeliscidae	*Ampelisca* spp.	354.3	1,698.3	1,205.9	607.3	33.1
		Corophiidae	*Corophiidae* spp.	16.1	336.2	23.0	1.5	0.4
			Crassicorophium bonellii	7.9	217.3	37.3	8.3	0.3
			Leptocheirus pinguis	29.0	117.4	66.0	87.8	8.2
		Isaeidae	*Photis pollex*	11.4	77.0	86.8	35.4	0.1
		Phoxocephalidae	*Phoxocephalus holbolli*	28.0	116.9	125.9	7.0	1.1

[a]Dominants identified as taxa composing 75% of total abundance in each period.
[b]previously identified as *Nepthys cornuta*.

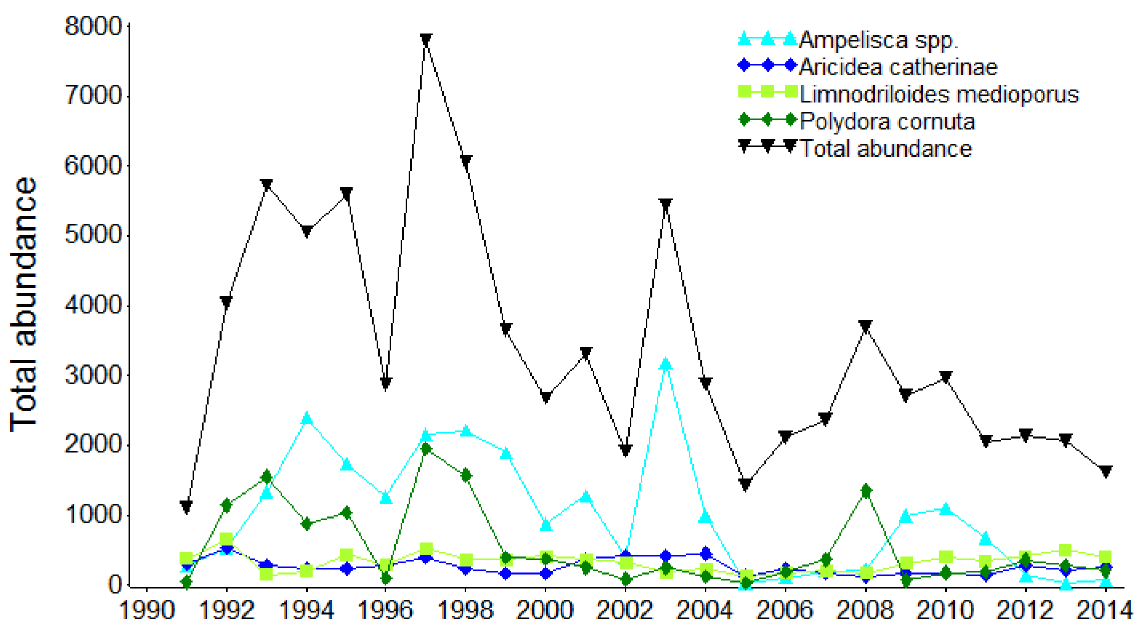


Figure 9. Total abundance of four dominant taxa at eight Boston Harbor stations, 1991-2014.

Patterns of abundance of *Ampelisca* spp. have been of particular interest throughout the past 24 years that Stations T01-T08 have been studied. Previous annual reports on the harbor surveys have related changes in the spatial extent of *Ampelisca* spp. 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 (2005-2008), average abundances of *Ampelisca* at these stations reached moderately high levels from 2009 through 2011, declining in 2012 to levels comparable to those seen in 2005-2008, and remaining low through 2014 (Figure 10). In 2014, *Ampelisca* was present at only four stations with 94% of the population found at Station T03 in the vicinity of the Main Ship Channel (Figure 11). Severe winter storms in 2004-2005 and 2012-2013 have been suggested as a major factor in disturbing *Ampelisca* mats. Maintenance dredging conducted in the nearby President Roads Anchorage and Main Ship Channel in 2004-2005 could also have resulted in disturbances (sedimentation or substrate contact from anchored vessels) to stations T03 and T05A.

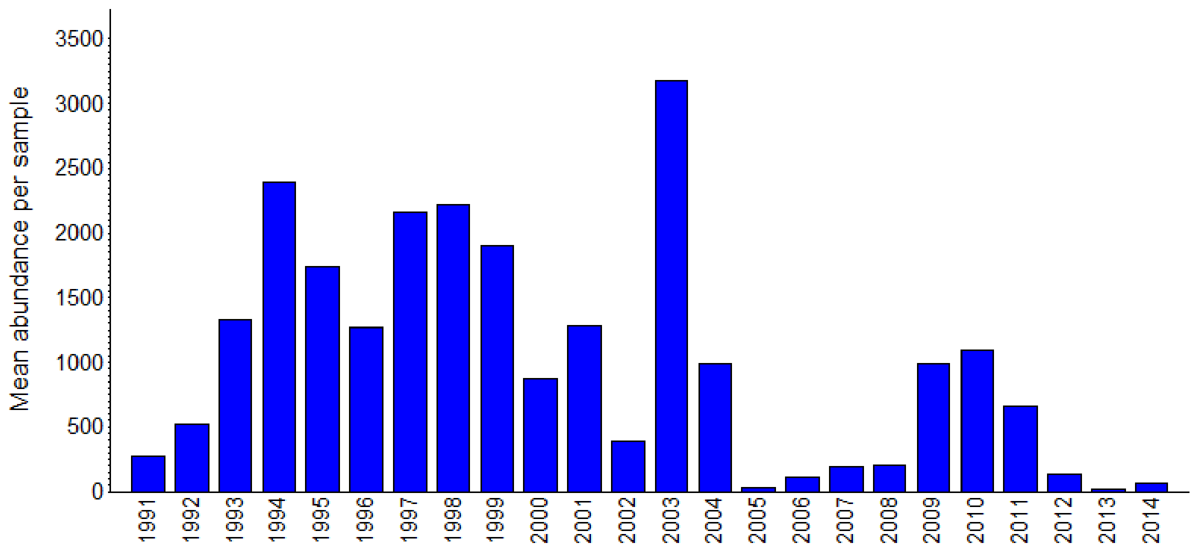


Figure 10. Mean annual abundance of *Ampelisca* spp. averaged over eight Boston Harbor stations, 1991-2014.

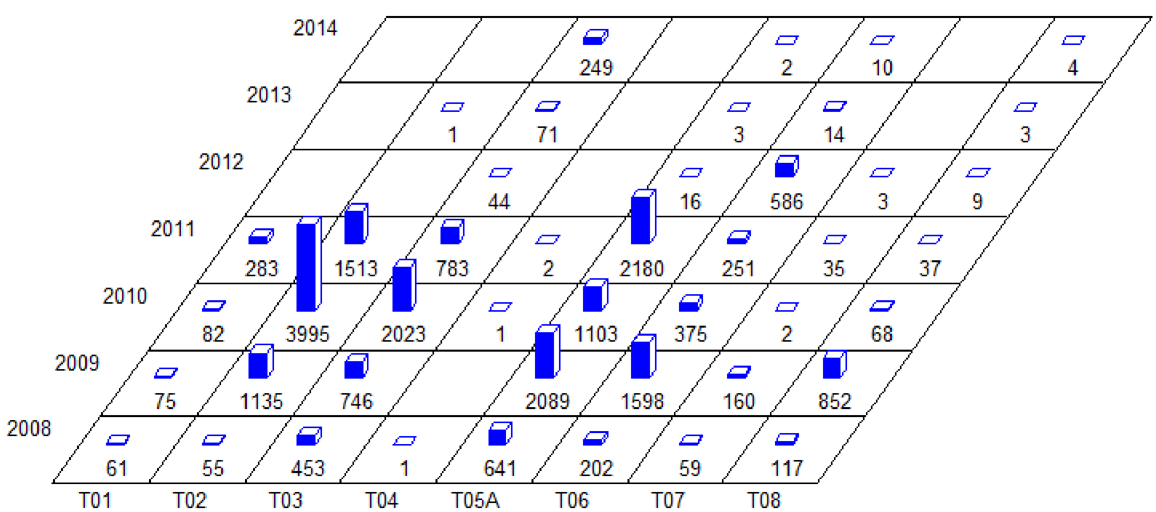


Figure 11. Spatial distribution of *Ampelisca* spp. at eight Boston Harbor stations, 2007-2014.

The numbers of species reported for 2014 ranged from 10 to 53 per station and averaged around 37 species per sample, higher than numbers reported in most years in the 1990s and about average for the 2000s, when species richness exhibited inter-annual variation (Table 2, Figure 12). Species richness was slightly lower in 2014 than in 2013. As with abundance, species richness followed spatial patterns generally similar to those observed previously. Stations T02, T03, and T08, among the most species-rich stations from 2011 through 2014, continued to support the highest numbers of species (Pembroke et al. 2013, 2014). Station T04 has consistently supported the lowest species richness in this time frame. Species richness at T07 in Quincy Bay, which reached an unusual peak in 2013, was closer to its historical pattern in 2014 (Pembroke et al. 2013, 2014).

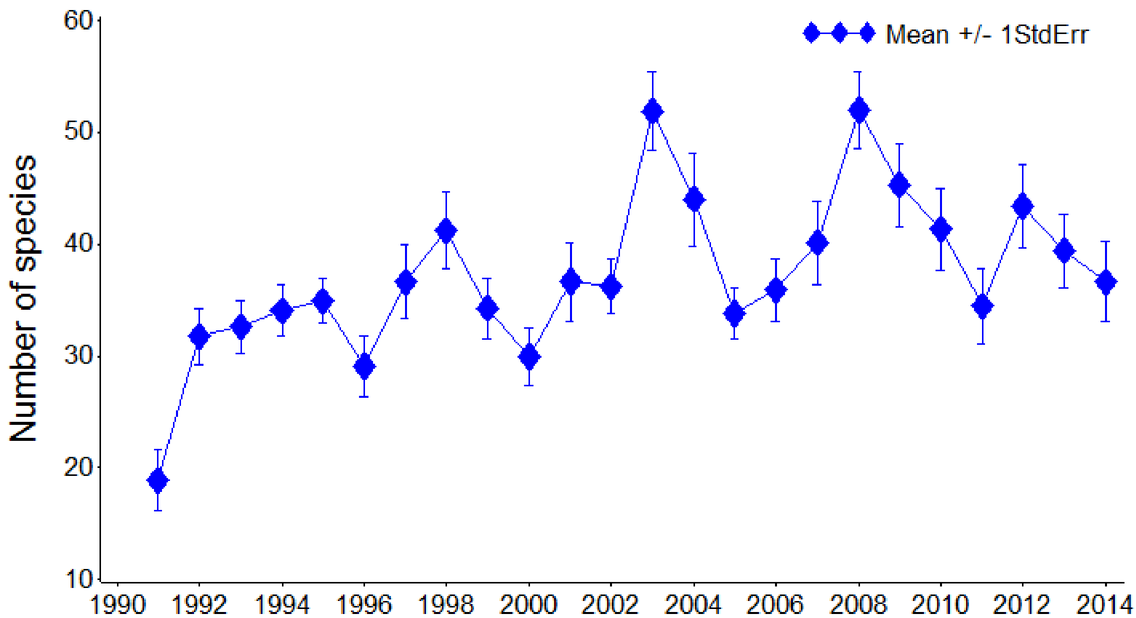


Figure 12. Mean species richness at eight Boston harbor stations, 1991-2014.

When averaged across the eight outer harbor stations, two measures of community structure, Pielou's evenness and Shannon-Weiner diversity, increased in 2014 compared to 2013 (Figures 13 and 14). Across the eight stations in the outer harbor, values for these metrics remained within the high range of post-diversion values. Within each station, differences in these metrics between 2013 and 2014 were small and, in general, spatial patterns parameters were similar between the two years suggesting that the integrity of the benthic infaunal community had not changed. Average diversity for the harbor stations, as measured by log-series alpha, dropped in 2014 below the relatively high value seen in 2012 and 2013 but still remained well above pre-diversion values (1991-2000; Figure 15). Highest log-series alpha diversity occurred at T08 and lowest occurred at T04, consistent with 2013 (Table 2; Pembroke et al. 2014). The largest changes in log-series alpha compared to 2013 were a decrease at T07 and increases at T08 and T01.

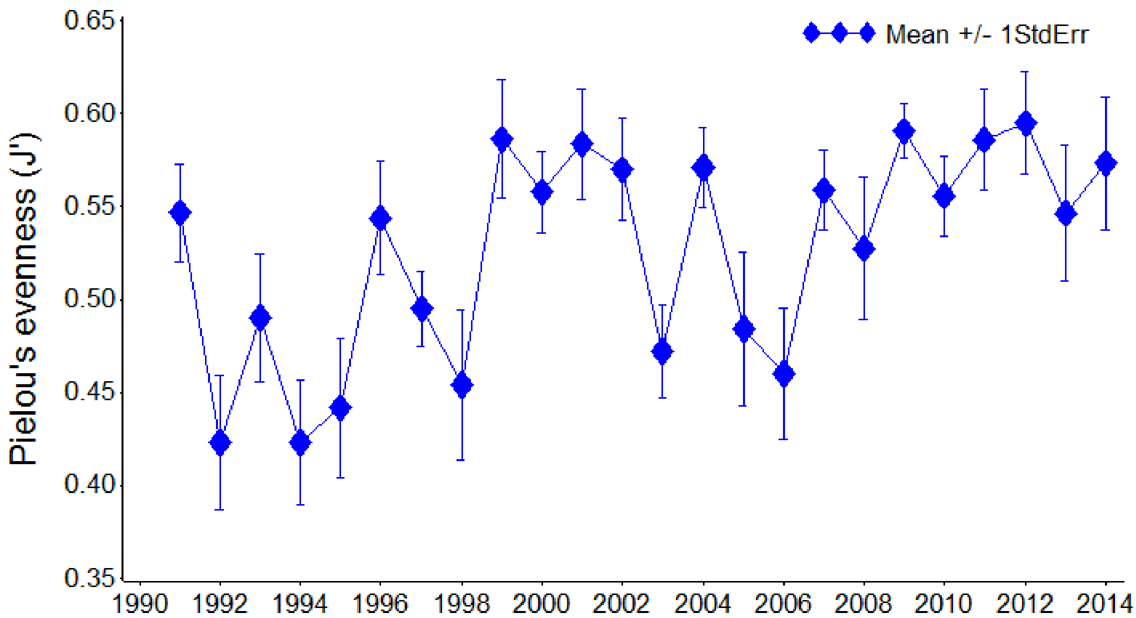


Figure 13. Mean community evenness at eight Boston Harbor stations, 1991-2014.

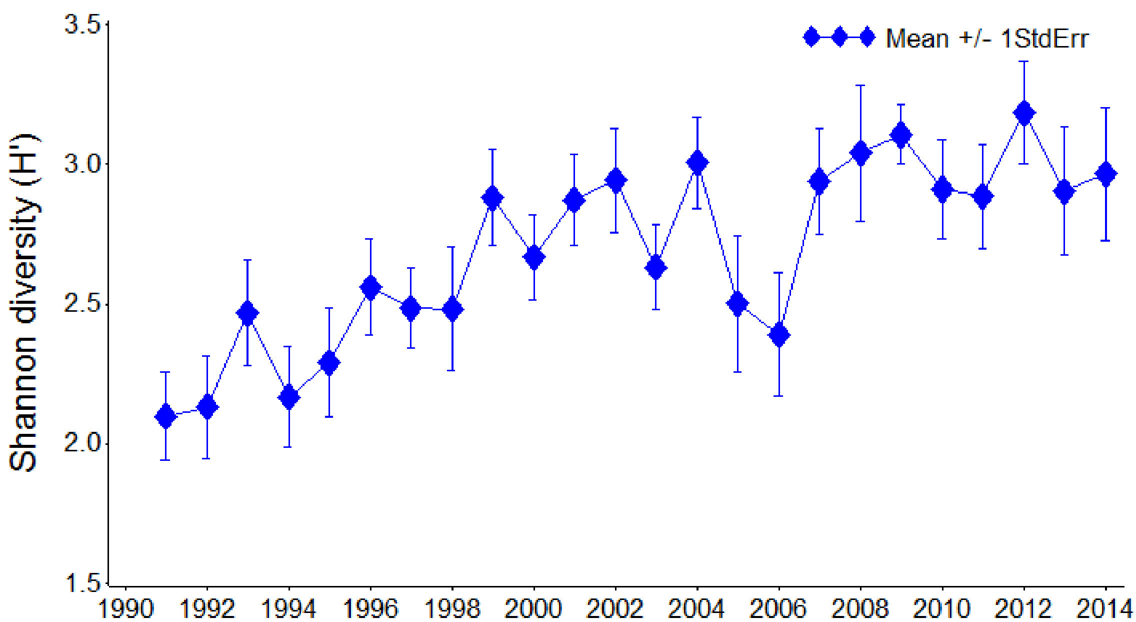


Figure 14. Mean Shannon-Weiner diversity at eight Boston harbor stations, 1991-2014.

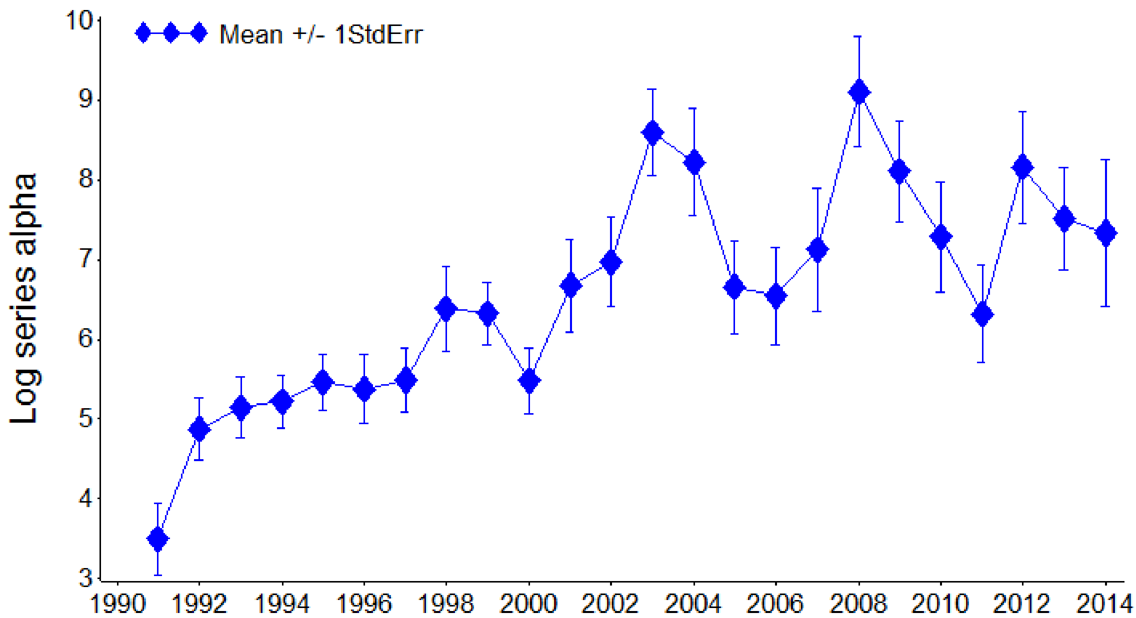


Figure 15. Mean log-series alpha diversity at eight Boston Harbor stations, 1991-2014.

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. Two main assemblages were identified in a cluster analysis of the 18 samples from 2014. Group I included both replicates of six stations (T01, T02, T03, T05A, T06, and T08), although species composition at T08 differed sufficiently from the other stations to be separated as a subgroup. Replicates from two other stations (T07 and C019) also formed their own discrete group (Group II, Figure 16). Together with T04, these stations had formed a discrete group in 2011, 2012, and 2013 (Pembroke et al. 2012, 2013, 2014). In 2014, the community observed at T04 bore little resemblance to the other harbor stations resulting in its separation at a similarity value of less than 20% (Figure 16).

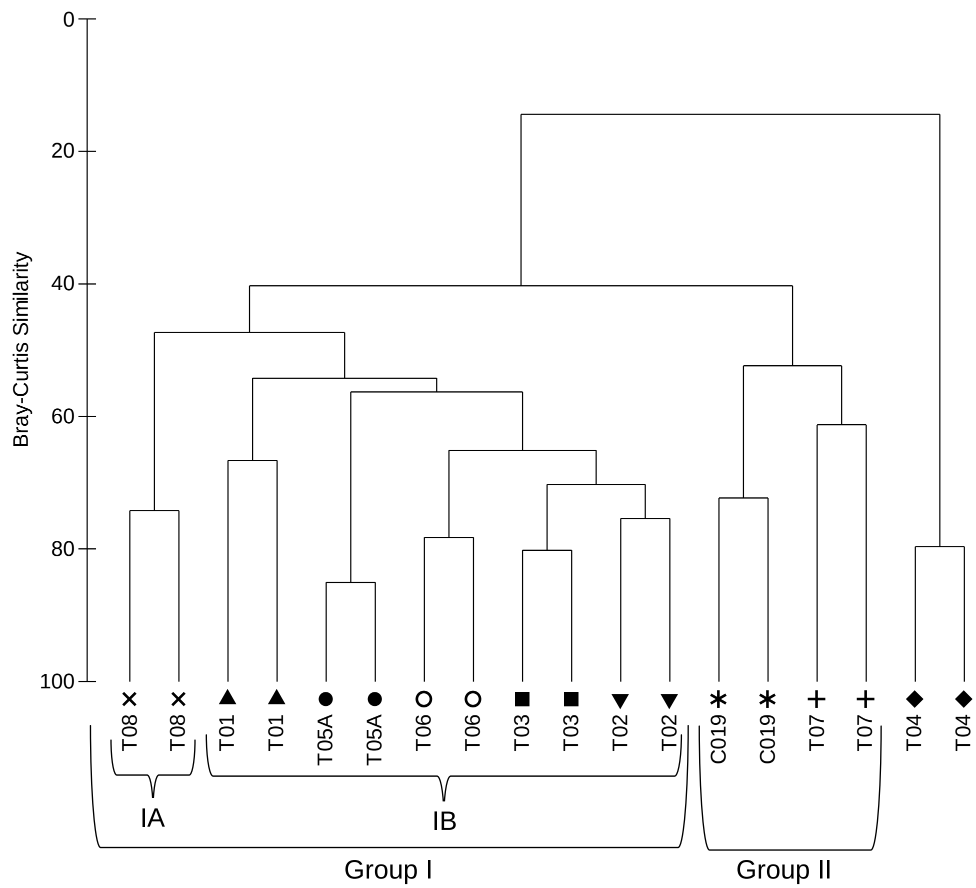
Main Group I was characterized by a relatively high species richness (averaging 43 species per collection). Five species (*Limnodriliiloides medioporus*, *Aricidea catherinae*, *Tubificoides intermedius*, *Polydora cornuta*, and *Scoletoma hebes*) had relatively high abundances (Table 5). Species composition, species richness, and total abundance differed between the two subgroups however. Species richness was high at Station T08 (Subgroup IA), but total abundances were low and the community was dominated by three species (*Polygordius jouniae*, *Tharyx acutus*, and *Clymenella torquata*) that were not among the most abundant in the other Group I collections. Oligochaete abundances were notably low at Station T08. Subgroup IB included five stations (T01, T02, T03, T05A, and T06). Total abundance was high in this subgroup, species richness was relatively high (42 species), and the dominant species were the same as in the main group. Three of the four stations where *Ampelisca* spp. occurred in 2014 were included in Group IB.

Table 5. Mean abundance of dominant taxa in 2014 Boston Harbor station groups defined by cluster analysis.

Phylum	Major Taxon	Family	Species	I	IA[a]	IB[a]	II	T04
Platyhelminthes	Turbellaria		*Turbellaria* spp.	**-**	-	-	**-**	**2.0**
Mollusca	Bivalvia	Tellinidae	*Angulus agilis*	**5.7**	22.5	2.3	**2.0**	**-**
Annelida	Polychaeta	Capitellidae	*Capitella capitata* complex	**4.4**	3.5	4.6	**0.8**	**36.0**
			Mediomastus californiensis	**29.5**	0.5	35.3	**6.5**	**-**
		Cirratulidae	*Monticellina baptisteae*	**7.5**	28.5	3.3	**-**	**-**
			Tharyx acutus	**22.7**	70.5	13.1	**23.5**	**0.5**
		Cossuridae	*Cossura longocirrata*	**0.1**	-	0.1	**12.8**	**-**
		Hesionidae	*Microphthalmus pettiboneae*	**3.2**	-	3.8	**16.5**	**-**
		Lumbrineridae	*Scoletoma hebes*	**150.8**	8.0	179.4	**14.5**	**-**
		Maldanidae	*Clymenella torquata*	**35.3**	56.5	31.1	**0.5**	**-**
		Nephtyidae	*Bipalponephtys neotena*	**5.7**	-	6.8	**54.5**	**-**
		Nereididae	*Neanthes virens*	**0.3**	1.0	0.1	**0.5**	**4.5**
		Paraonidae	*Aricidea catherinae*	**304.4**	12.5	362.8	**3.5**	**-**
		Phyllodocidae	*Eteone longa*	**3.3**	15.0	1.0	**-**	**0.5**
			Phyllodoce mucosa	**25.5**	4.0	29.8	**-**	**-**
		Polygordiidae	*Polygordius jouinae*	**29.2**	162.5	2.5	**-**	**-**
		Spionidae	*Polydora cornuta*	**248.9**	24.5	293.8	**79.0**	**18.0**
			Spiophanes bombyx	**29.1**	43.0	26.3	**-**	**-**
			Streblospio benedicti	**7.0**	0.5	8.3	**8.5**	**965.0**
Annelida	Oligochaeta	Tubificidae	*Limnodriloides medioporus*	**453.4**	3.5	543.4	**26.8**	**-**
			Naidinae sp. 1	**41.1**	13.5	46.6	**1.0**	**-**
			Tubificoides benedeni	**0.4**	-	0.5	**-**	**6.0**
			Tubificoides intermedius	**298.3**	3.5	357.3	**91.8**	**-**
			Tubificoides sp. 2	**-**	-	-	**-**	**81.5**
Arthropoda	Amphipoda	Ampeliscidae	*Ampelisca* spp.	**44.1**	3.5	52.2	**-**	**-**
		Corophiidae	*Monocorophium acherusicum*	**-**	-	-	**0.3**	**1.5**
Total Abundance				***1897***	***618***	***2153***	***369***	***1117***
Number of Species				***43***	***53***	***42***	***22***	***10***

[a] distinct subgroup of Group I

a.



b.

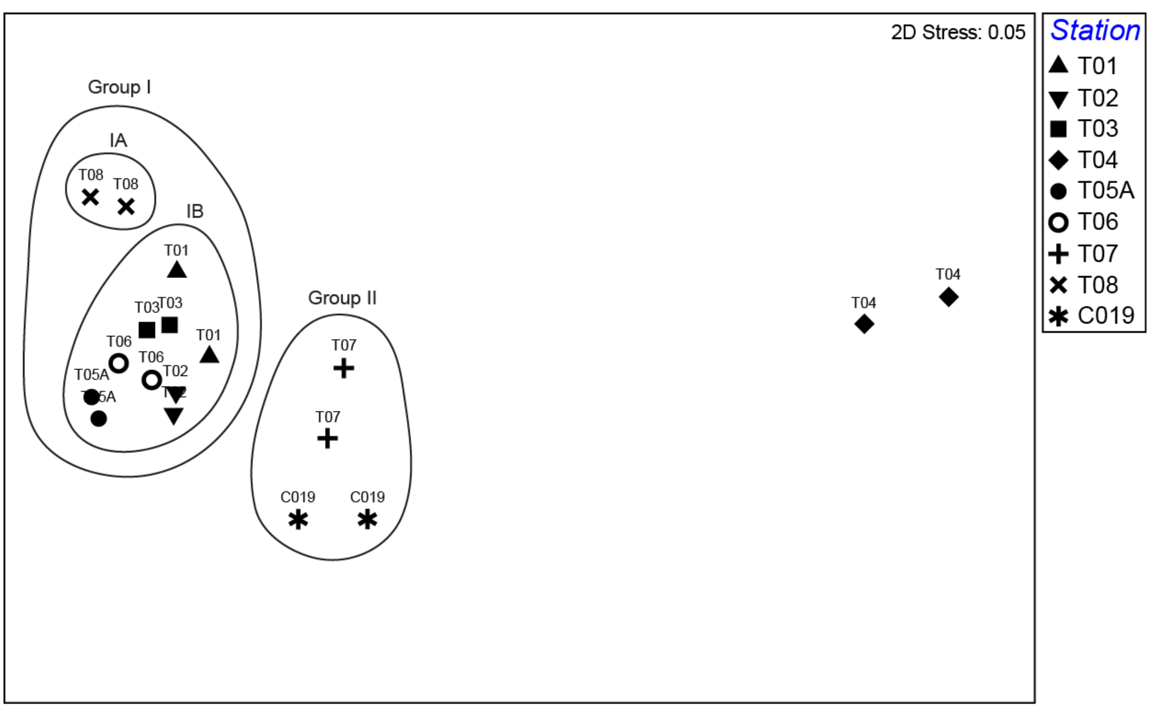


Figure 16. Results of (a) cluster analysis and (b) multidimensional scaling analysis of the 2014 infauna samples.

Group II collections were characterized by low total abundance and relatively low species richness. Three taxa (*Tubificoides intermedius, Polydora cornuta*, and *Bipalponephtys neotena*) were numerical dominants. Domination of T04 collections by *Streblospio benedicti* (Table 5) influenced its average community parameters, including number of species, Shannon-Weiner and log-series alpha diversity, and Pielou's evenness which were all notably lowest at T04 (Table 2).

Sediment conditions, particularly percent fines and TOC were likely factors in distinguishing the benthic communities among the Boston Harbor stations. Group I stations tended to have relatively low (<50%) silt-clay components and Station T08 had extremely low fines (3.8%; Table 2). Group II stations had relatively high percent fines but moderate levels of TOC whereas Station T04 had relatively high percent fines and high TOC (Table 2).

3.2.3 Selected Stations

Station T01. Infaunal community conditions at Station T01, located near Deer Island Flats north of President Roads, have typically exemplified conditions at most stations in the Harbor throughout the survey period. In 2014, species richness and diversity measures were among the highest of the harbor stations and evenness was relatively high at T01. These community parameters (except evenness) were higher than the values in 2013 (Pembroke et al. 2014). Mean abundance, species richness, Shannon-Weiner diversity, and Pielou's evenness in 2014 were all about average for the period following diversion to the offshore outfall (Figures 17, 18, 19, and 20). Mean log-series alpha has fluctuated substantially since the diversion to the offshore outfall and in 2014 reached one of the highest values observed since the diversion (Figure 21). In 2014, all of these community parameters increased from the relatively low values observed in 2013 (Figures 17 through 21).

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 overwhelmingly dominated by two polychaete species, *Streblospio benedicti* and *Chaetozone anasimus* (previously called *C. setosa*). Species richness exhibited a net increase in 2014 compared to the mid-2000s although it fell below the peak seen in 2013 (Figure 18). Although mean abundance peaked in 2013, total numbers in 2014 were again very low (Figure 17). Shannon-Weiner diversity, Pielou's evenness, and log-series alpha all reached their peak values in 2014 (Figures 19, 20, and 21). The polychaete *Bipalponephtys neotena* (formerly called *Nepthys cornuta*) had represented the majority of the infauna found at Station C019 from 2004-2011

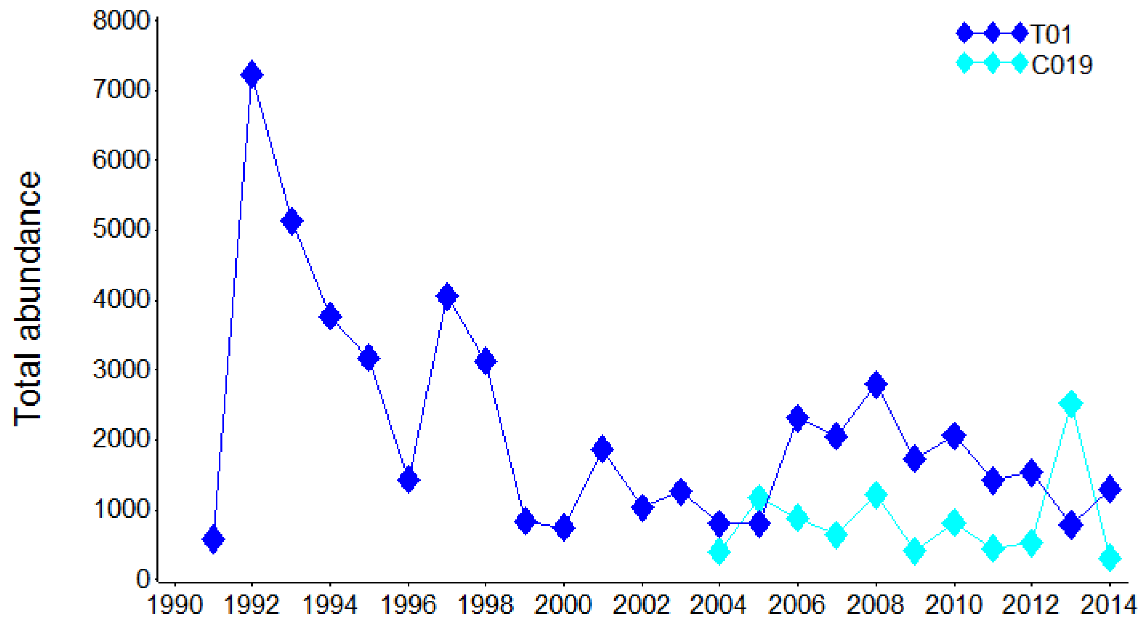


Figure 17. Mean total abundance at Boston Harbor Stations T01 and C019, 1991-2014.

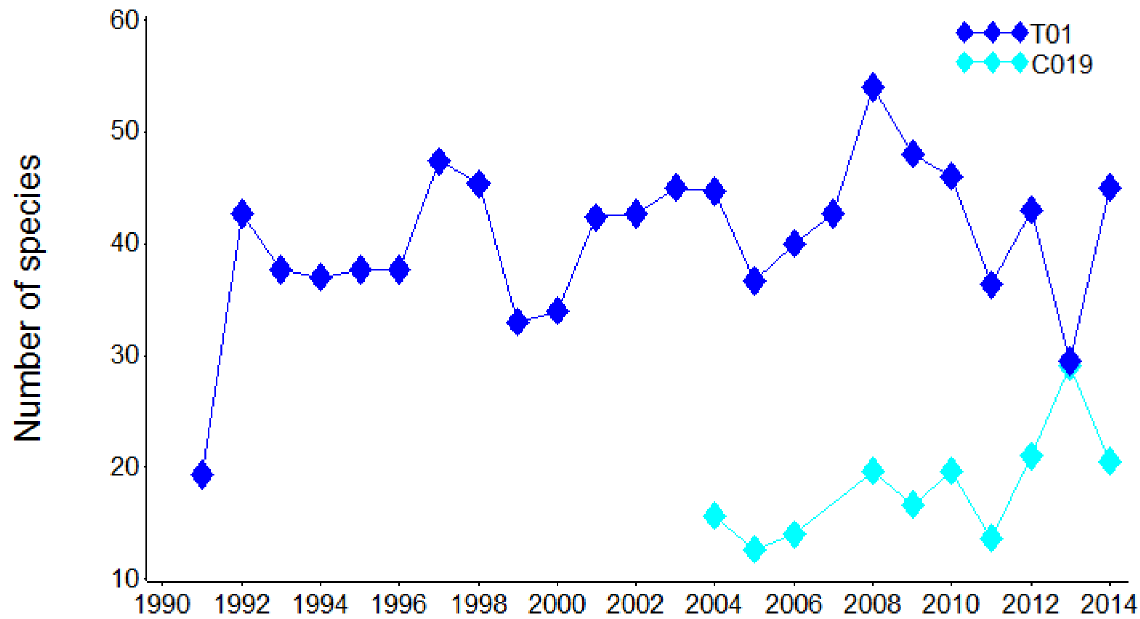


Figure 18. Mean species richness at Boston Harbor Stations T01 and C019, 1991-2014.

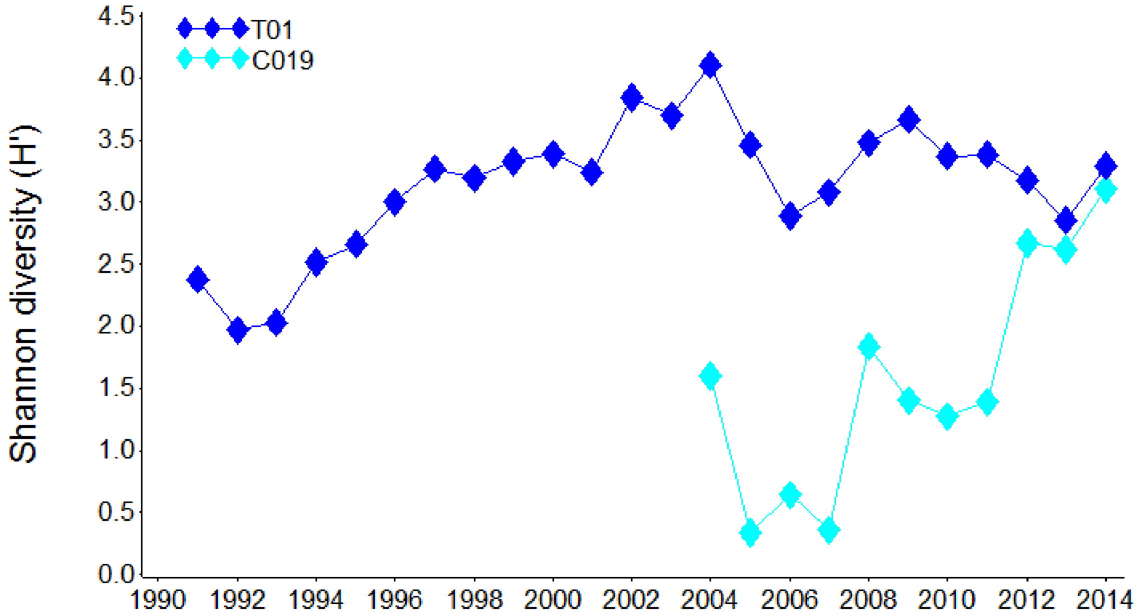


Figure 19. Mean Shannon-Weiner diversity at Boston Harbor Stations T01 and C019, 1991-2014.

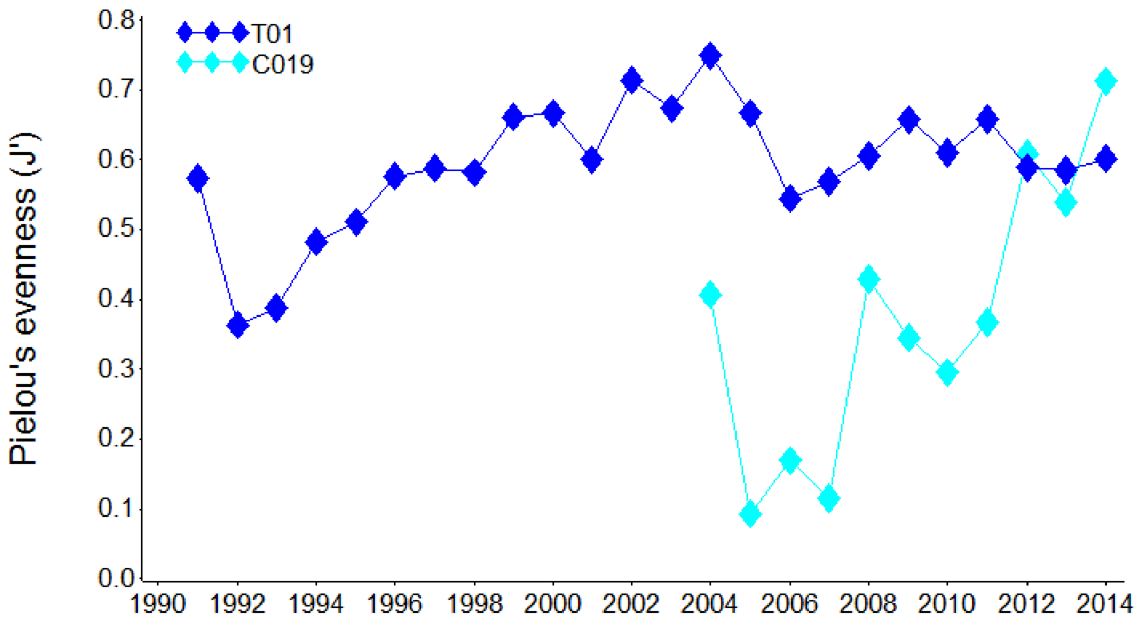


Figure 20. Mean evenness at Boston Harbor Stations T01 and C019, 1991-2014.

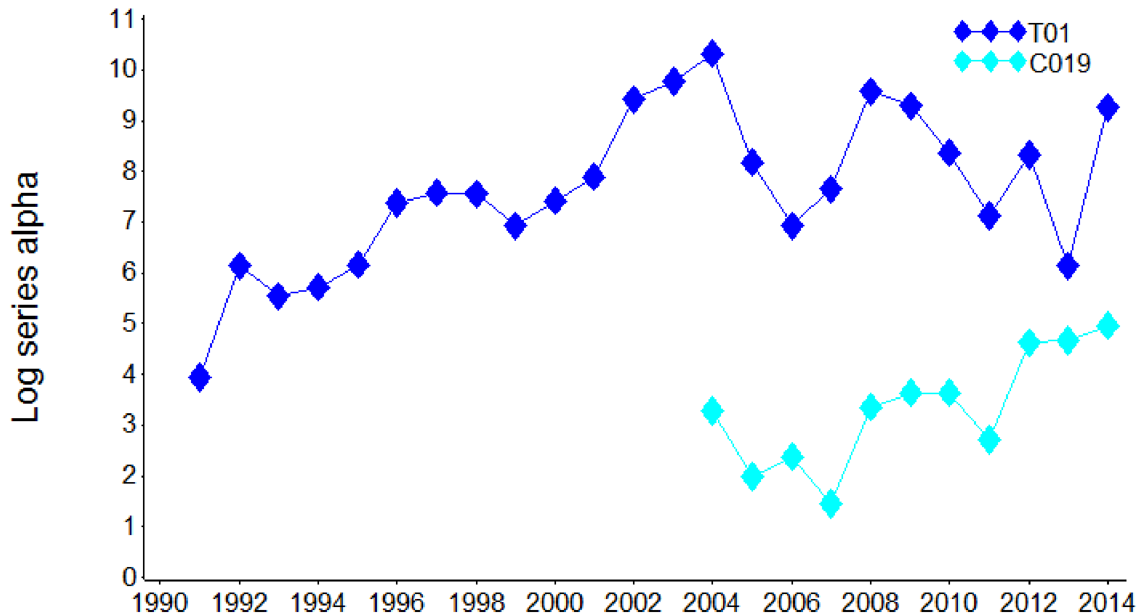


Figure 21. Mean log series alpha diversity at Boston Harbor stations T01 and C019, 1991-2014.

(Figure 22) but the relative abundance of this species has been substantially lower since 2012 (Pembroke et al. 2013). In 2013 *C. anasimus* again dominated the infauna community (Pembroke et al. 2014), coincident with a sharp decrease in TOC (Figure 4). The decrease in the relative contribution of a single species to the total abundance, coupled with low total abundance, explains the relatively high evenness, Shannon-Weiner, and log-series alpha values.

3.2.4 Temporal Trends

Benthic community parameters for the harbor have exhibited changes since 1991 that correspond well to the management changes defined by Taylor (2006) when a one-year offset is included to account a lag in benthic community response (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 total abundance, number of species, evenness, Shannon-Weiner diversity, and log-series alpha diversity for 2001-2014 were virtually the same as for 2001-2013 (Pembroke et al. 2014) so it is apparent that this trend has continued.

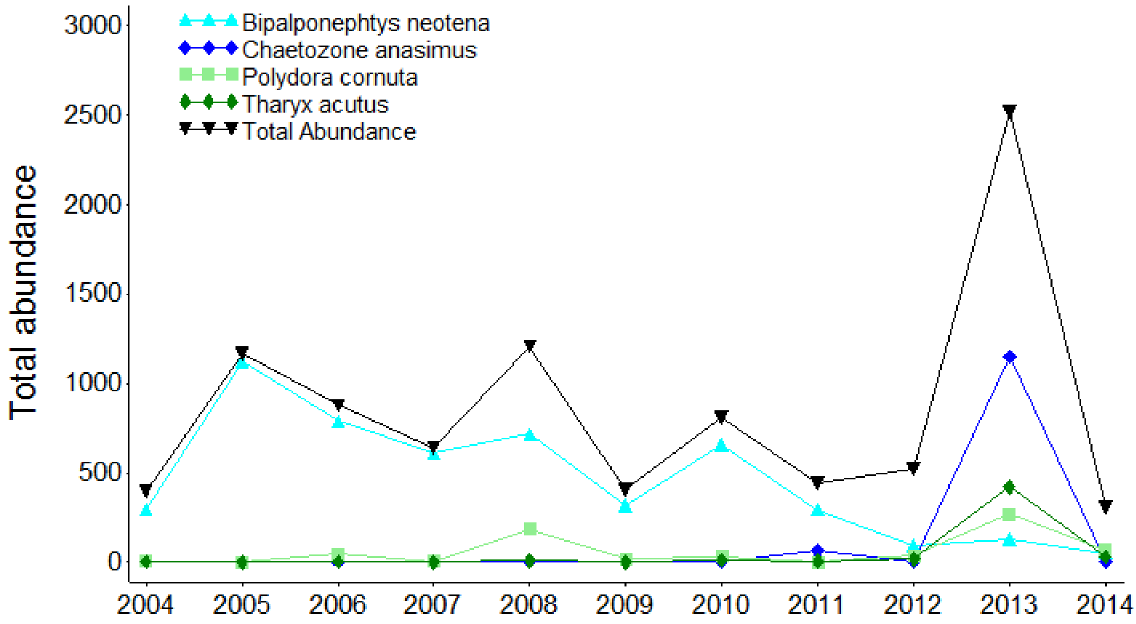


Figure 22. Mean abundance of *Bipalponephtys neotena* and other dominants and total community abundance at Station C019, 2004-2014.

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

Parameter	Period I (prior to Dec. 1991)[a]		Period II (Dec. 1991-mid 1998)		Period III (mid-1998-Sept. 2000)		Period IV (after Sept. 2000)	
	Mean	Std Err	Mean	Std Err	Mean	Std Err	Mean	Std Err
Total Abundance	2,606	344	5,513	469	3,213	493	2,620	142
Log-series alpha	4.2	0.3	5.5	0.2	6.2	0.3	7.5	0.2
Shannon-Wiener Diversity (H')	2.12	0.1	2.4	0.1	2.8	0.1	2.9	0.1
Pielou's Evenness (J')	0.48	0.02	0.47	0.01	0.58	0.02	0.54	0.01
Number of Species	25.5	2.1	34.7	1.1	33.6	1.7	41.2	1.0
Years included (with one year offset)	1991-1992		1993-1998		1999-2001		2002-2014	

[a]Years included in analysis (with one year offset): Period I 1991-1992; Period II 1993-1998; Period III 1999-2001; Period IV 2001-2014

3.3 Sediment Profile Imaging

In 2014, soft bottom benthic habitat conditions in Boston Harbor appeared to be similar to the last few years with continuation of improved conditions over the early 1990s (Blake et al. 1993, Pembroke et al. 2014). Much if not all of the improvement in benthic habitat quality over the last 24 years can be attributed to upgrades in wastewater treatment and relocation of outfalls from within the Harbor to the current ocean outfall (Diaz et al. 2008, Taylor 2010). Using estimated infaunal successional stage from sediment profile images as a proxy for benthic habitat quality (Table 7), the pattern of improvement started in the mid-1990s with cessation of sludge discharge (Figure 23). With the implementation of full primary and secondary treatment benthic habitats continued improvement from 1995 to 2000. After operation of the ocean outfall in 2001, the continued improvement in benthic habitats was driven primarily by expanding evidence of advanced successional stage fauna as the extent of *Ampelisca* spp. tube mats declined (Figure 24). By 2005, *Ampelisca* spp. tube mats disappeared and advanced successional stage fauna tended to dominate until 2010, when tube mats returned. Although *Ampelisca* spp. mats were absent in 2013 and rare in 2014, overall, benthic habitat conditions at individual stations from 2001 to the present were relatively consistent (Figure 23) with much of the variation due to variation in sediment grain size.

Table 7. General weight given to SPI data used to estimate successional stage. These biogenic parameters are broad relative indicators of association between successional stage and benthic physical and biological parameters based on models developed by Odum (1969), Pearson and Rosenberg (1978), and Rhoads and Germano (1986).

		Successional Stage		
Parameter	**0 - Azoic**	**I - Pioneering**	**II - Intermediate**	**III - Equlibrium**
aRPD Layer Depth (cm)	Near 0	<1	1-3	>2-3
Maximum aRPD Depth (cm)	<<1	<2	>2	>3-4
Small Tubes (<1 mm dia.)	-	+++	++	+
Large Tubes (>2 mm dia.)	-	-	++	+++
Burrows	-	-	++	+++
Feeding Voids	-	-	++	+++
Small Infauna	-	+++	++	+
Large Infauna	-	-	+	++
Epifauna	-	+	++	++
	- = Not Associated With	+ = Associated With	++ = Moderately Associated With	+++ = Strongly Associated With

		90	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14
CHARLES	CO19														I-III	I	I	I	I	I	I	I-III	I-III	I-III	I-III
RIVER	R09			II-III	II	I-III	II-III	II-III	II-III	II	I-II	II-III	I-II	I-II	I-II	I	I	III	I	I	I	II-III	II-III	I	I-III
	R10			I	I	I	I	I-III	I-III	I	I-II	I	I-II	I	I-III	II-III	I	III	I-II	I-II	II-III	II-III	II-III	II-III	I-III
DORCHESTER	R14			II	II	I-III	I-II	I-III	I-III	I	I-II	II-III	I	I-II	I	III	II-III	III	III	III	II-III	II-III	II-III	I-III	II-III
BAY	R15			I	I-II	I-III	I-III	I	I	I	I-II	I	I	I	I-II	III	III	I-III	I-III	I-III	I	I	I	I	II-III
	R40	I-III		I	I	I-III	I-III	I-III	I-II	I-II	I-II	I-II	II-III	II-III	II-III	III	III	III	II-III	II-III	II-III	I-III	I-III	II-III	II
	R41	I-III		I	I-II	I-III	I-III	I-II	I-II	I	I-II	I-II	II-III	II-III	I-III	III	III	III	II-III	II-III	I-II	I-III	I-III	I-III	II-III
	R42	I-III		I		I-III	I	I	I	I-II	I-II	I	I-II	I-II	I-II	III	III	III	III	III	I	I	I	I	I
	R43	I		I	I	I-III	I	I	I	I	I	I	I	I-II	I-III	III	III	III	III	III	I-III	I-III	I-III	I-III	I-III
	T04		I	I	0	0-I	II	I	0	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I
QUINCY	R18			II-III	II	II	II-III	II-III	II-III	II	II	II-III	II-III	II-III	II-III	III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III
BAY	R33	I-III		I	0-I	I-III	I	I	I-II	I-II	I-II	I	I	I-II	I-III	III	III	III	II-III	II-III	I	I-III	I-III	II-III	I-II
	R34	I-III		I	0-I	I-III	I-III	I	I-II	I-II	I		I-II	I-II	I-III	III	III	III	III	III	I-III	I	I	I	I
	R35	I-III		I	0-I	II-III	I-III	I	I-II	I-II	I-II		II-III	I-II	I	II-III	III	I	III	III	I-III	I	I	I-III	I-III
	R36					I		I	I	I	I-II		I-II	I	I	I	I	I	I	I	I	I	I	I	I
	R37	I-III		I	II	II-III	I	I-II	I-II	I-II	I-II	I	II-III	II-III	I-III	I	III	III	II-III	II-III	I-III	I-III	I-III	II-III	II-III
	R38	II-III		II	II	II-III	II	II-III	II-III	II	I-II	II-III	II-III	II-III	II-III	III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III
	R39	II-III		II	III	II	II-III	I-III	II	I-II	I-II	II-III	II-III	I-II	I-II	I	I-II	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III
	R48					I-III	I-III	I	I-II	I-II	I-II	I-II	II-III	I-II	II-III	I	III	III	III	III	I-III	I-III	I-III	I-III	I-III
	T07		0-III	I	I-II	I-III	I-III	I	I	I-II	I-II	I-II	I	I-II	I-III	III	III	I-III	II-III	II-III	I	I	I	I-III	I-III
DEER ISLAND	R02			0-II	II	II	II	II-III	II-III	II-III	II	II-III	II	II	II-III	I	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III
FLATS	R03			I-II	II-III	I-III	II-III	II-III	II-III	I-II	I-II	II-III	II-III	II-III	I-III	III	III	III	II-III	II-III	II-III	II-III	II-III	II	II-III
	R04			I-II	I-II	II-III	I-III	I	I-II	I-II	I	II-III	I-II	I-II	I-III	I	I	I-III	I-III	I-III	I-III	I-III	I-III	I-III	I-III
	R05			I-II	II	II-III	I-III	I-III	II	I-II	I-II	I-II	II	II	I-III	II-III	I-II	I-III	II-III	II-III	II-III	I-III	I-III	I-III	II-III
	R07			I-II	II	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	III	III	III	III	III	II-III	II-III	II-III	I-III	II-III
	R47					II-III	II-III	II-III	II-III	II	II-III	II	II-III	II-III	II-III	III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III
	T01		I	I	II	I-III	I-II	I	I	I-II	I-II	I-II	II-III	II-III	I-II	II-III	I	I	III	III	I-II	I-III	I-III	I	I
	R08						I-II	I-II	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I
OFF LONG	R11			II-III	II	II-III	II	II-III	II-III	II	II-III	II-III	II-III	II-III	I-III	I	I	II-III	II-III	II-III	II-III	II-III	II-III	I-III	I-III
ISLAND	R12			I-II	II-III	II-III	II-III	II-III	II-III	II	II-III	II-III	II-III	II-III	I-III	III	III	III	II-III	II-III	II-III	II-III	II-III	I-III	II-III
	R13			I-II	II-III	I-III	I-III	I	I	I	I	II-III	I-II	I-II	I	I	II-III	I	I	I	I	II-III	II-III	I-III	I
	R16			II	I-II	I-III	II-III	I-III	I-II	II	I-II	II	I	I-II	I	II-III	I	II-III	II-III	II-III	I	I	I	I	I
	R17			II	I-II	II-III	I-II	I-II	I-II	II-III	II	I	II-III	II-III	II-III	II-III	III	II-III	III	III	I-III	II-III	II-III	I-III	II-III
	R45					II-III	II-III	II-III	II-III	II	II	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II	II	II-III	II-III	II-III	II-III	II-III
	T03		II-III	III	II	II-III	II-III	II-III	II	II	II	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III
	R06			II	I-II	I	I	I	I	I	I	I-II	I	I-II	I-II	I	I	I	I	I	I	I	I	I	I
PRESIDENT	R44					I-III	I	I	I-III	I-II	I	II	II-III	II-III	I-III	I	III	III	II-III	II-III	I-II	II-III	II-III	II-III	I-III
ROADS	T02		I		II	II-III	I-III	II	I-II	I	I-II	I-II	II-III	II-III	I-III	III	III	III	II-III	II-III	II-III	II-III	II-III	II-III	II-III
	T05a					II	I-II	II	I-II	I	I	II	I	II	II-III	II-III	I	II-III	II	II	II-III	II	II	II-III	I
NANTASKET	R21			II	II	II	II-III	II-III	II-III	II	II-III	II-III	II-III	II-III	II-III	II-III	I-II	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II
ROADS	R22			II	II	I-II	I-II	II-III	II-III	I-II	II-III	II-III	II-III	II-III	I	II-III	I-II	I	I	I	I	I	I	I-II	I-II
	R23			II	II	II	II	I-II	I-II	I	I-II	I-II	I-II	I-II	I-II	I-II	I	I-II	II	II	I	I-II	I-II	I	I
	R24			II	II	II-III	II-III	I-II	II-III	II-III	II-III	II-III	II-III	II-III	I-III	III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III
	T06		II-III	II-III	I-II	II-III	II-III	II	II	II	II	II	II-III	II-III	II-III	III	I-II	II-III	II-III	II-III	II-III	II	II	II-III	II
	R20			II-III	II	II-III	II	II-III	I	I-II	II	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II	II-III	II-III	II-III	II-III
HINGHAM	R19			I-II	I-II	I	II		I	I	I	I	I	I-II	I-II	I	I	I	I	I	I	I	I	I	I
BAY	R25			II-III	II-III	II-III	II-III	I-III	II-III	II	I-II	I-II	II-III	II	I-III	III	I	I-III	I-III	I-III	II-III	I-III	I-III	I-III	I-III
	R26	I-III		II	III	I-III	II	I-II	I-II	I-II	I-II	I	II-III	I-II	I-III	III	III	III	II-III	II-III	I-III	I-II	I-II	I-III	II-III
	R27		I-III	I-II	II-III	I-III	II	II-III	II-III	II	II	II-III	II-III	II	II-III	III	II-III	II-III	II-III	II-III	I-III	II-III	II-III	I-III	II-III
	R28	II-III		II	III	II	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	III	II-III	I-II	II-III	II-III	I	I	I	I	I
	R29	II-III		II	II-III	II-III	II-III	II	II-III	II	II	II-III	II-III	II-III	II-III	I-II	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III
	R30		II-III	II	II	II-III	II	II	II-III	II	II	II	I-II	II	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	I-III	II-III
	R31	I-III		II-III	III	II	II-III	II-III	II-III	II-III	II	II-III	II-III	II-III	II-III	III	II	I-III	II-III	II-III	II-III	II-III	II-III	I-III	II-III
	R32		I-III	I-II	II	I-III	I-III	I	I-II	I-II	I-II	II	I-II	I-II	II-III	III	III	III	II-III	II-III	II-III	I-III	I-III	I-III	I-III
	R46					II-III	II-III	II	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	II-III	I-II	II-III
	R49					I	II	I	I	I-II	I-II	I-II	II-III	I-II	I-III	I	II-III	III	III	III	I-III	I-III	I-III	I-III	I-III
	R50					II-III	II-III	II	II-III	I-II	I-II	I-II	I-II	I-II	I-II	II-III	II-III	II-III	II-III	II-III	I	I	I	I-III	I-III
	R51					I-II	I-III	I-III	I-II	I-II	I-II	I-II	I-II	I-II	I-III	III	I-II	II-III	I-III	I-III	I	I	I	I	I-III
	R52					I	I-II	I	I-II	I-II	I-II	I	I	I-II	I-II	III	III	III	III	III	I-III	I-III	I-III	I	I
	R53					I-II	II	I	I	I	I-II	I-II	I	I	I-III	III	I	III	III	III	I	I	I	I	I
	T08		II	I-II	I-II	II		II	I	I	I	I-II	I-II	I-II	I-II	I-II	I-II	I-II	II	II	II	I	I	I	I

Figure 23. Matrix of successional stage estimated from SPI images. 0 - azoic, Stage I - pioneering, Stage II - intermediate, Stage III - equilibrium. Successional stage is a continuum with evidence of a mixture of stages being present at the same time. For example, I-II would indicate the presence of pioneering and intermediate species characteristics (Table 7) in the same image.

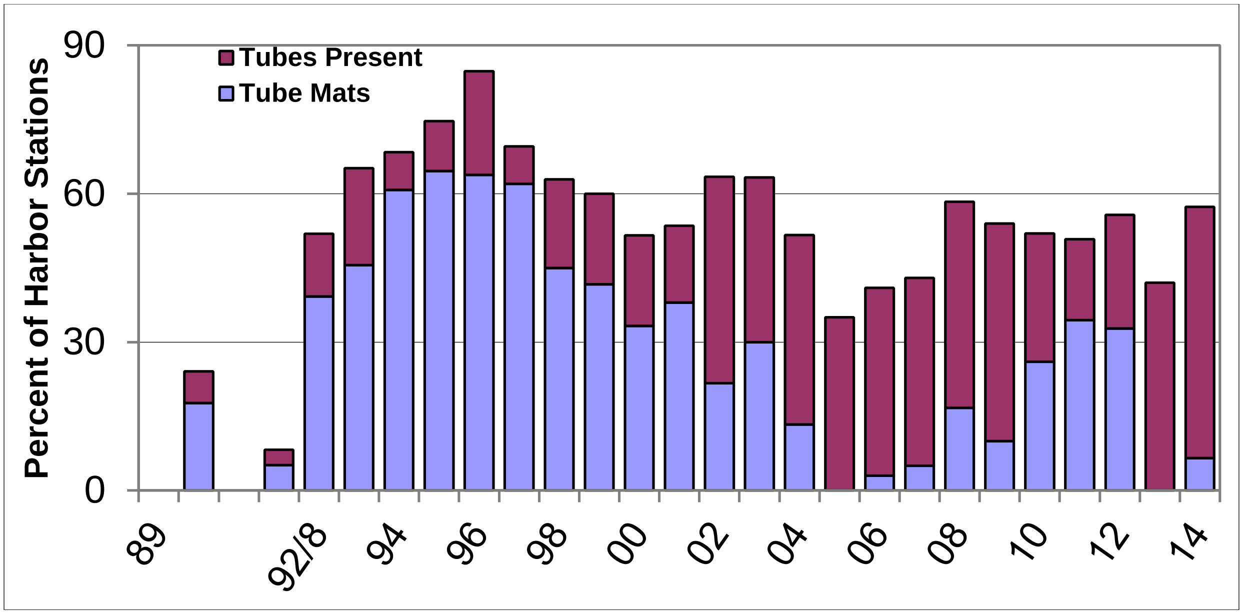


Figure 24. Histogram of *Ampelisca* spp. tubes present at harbor stations. Total bar represents percent of stations with tubes present. Mat densities of tubes are the bottom part of the bar in blue. There are no data from 1989 or 1991, but in 1989 there were mat densities of polychaete tubes present at some of the benthic grab stations. There were two sample periods in 1992, spring and summer (92/8). Baseline years are up to 2000. Post-baseline years are from 2001. The change in tube density between 2012 and 2013 can be seen at R31.

Improvements were observed at inner Harbor stations, such as those in Dorchester Bay and Quincy Bay in the mid-1990s and remained good after outfall diversion in 2001 (Figure 23). Recovery of some inner and most mid-Harbor stations has closely followed the classic Pearson-Rosenberg (1978) organic gradient model. A good example of this recovery is seen at stations T02, in President Roads near Deer Island Flats, and T03 also in President Roads on the north side of Long Island near the Harbor mouth (Figures 25 and 26). Tucker et al. (2014) found sediment oxygen demand (SOD) and nutrient effluxes at these two stations initially increased in the early 1990s due to bioturbation by macrofauna as sediments were rapidly colonized by tube-building *Ampelisca* spp. amphipods that dominated a dense macrofaunal tube mat community (Figures 27 and 28). As reductions in loading to the harbor progressed, mean rates in oxygen uptake and release of ammonium, nitrate, and phosphate all decreased. By the time of outfall diversion in 2001, rates and variability of sediment fluxes had decreased substantially. By 2010, average oxygen uptake had decreased from 74 to 41 mmol m^2 d^{-1} and spatial and temporal variability had decreased (Tucker et al. 2014). Similarly, nutrient fluxes declined by a factor of two from 1992 to 2010 and were also less variable. Other evidence of improved benthic habitat conditions included a decrease in the carbon content of sediments (Pembroke et al. 2014, see Section 3.2) and higher sediment redox potential (Eh) values, which indicates less reducing sedimentary conditions (Tucker et al. 2014). Higher Eh values can be seen in SPI images that showed a deepening of the apparent redox potential discontinuity (aRPD) when high densities of amphipods were present (Figures 27 and 28).

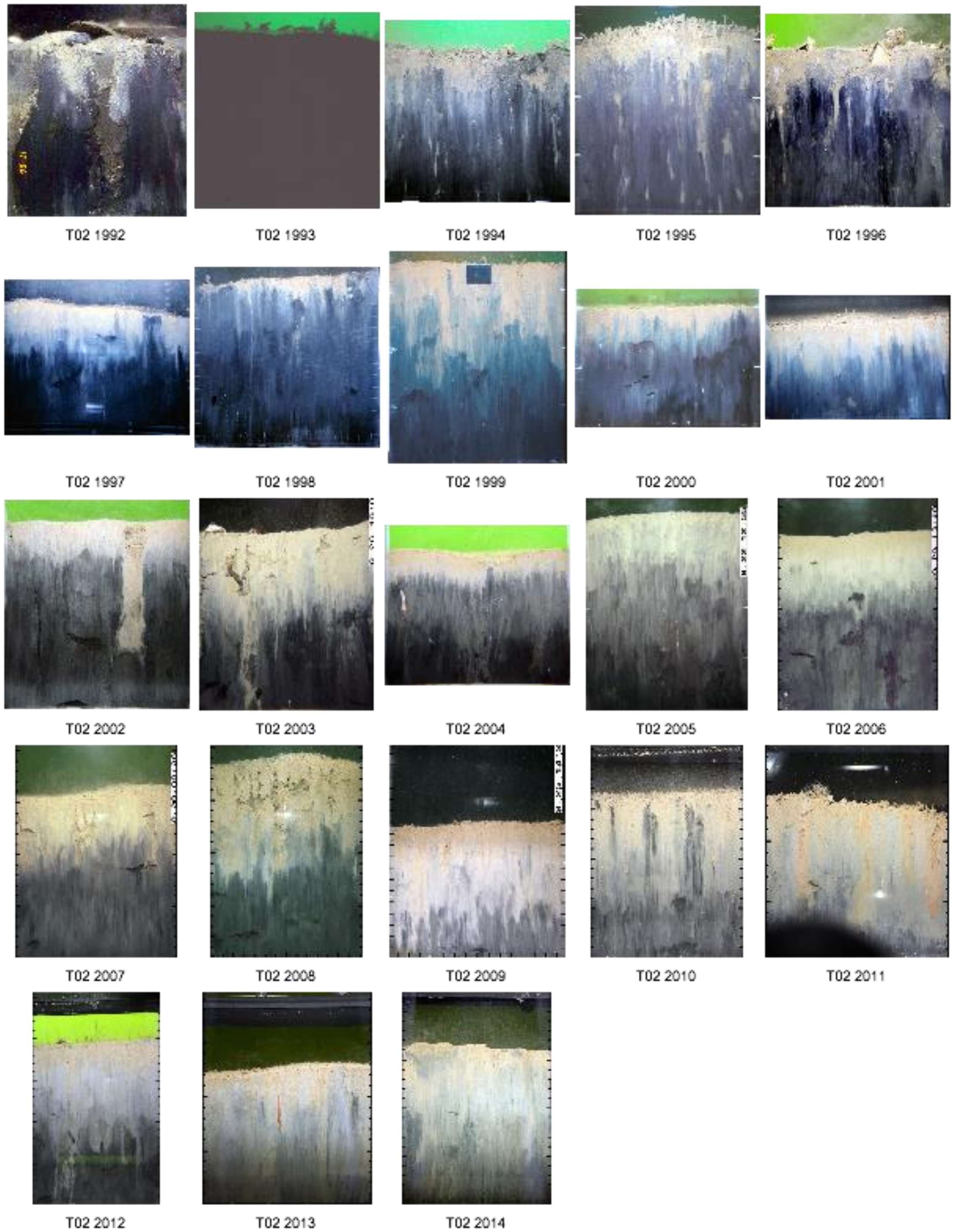


Figure 25. Mosaic of SPI from Station T02 in President Roads, near Deer Island Flats, for all years. Improvements in benthic habitat quality occurred from the 1990s to the late 2000s and has remained high into the 2010s. Scale along the side of each image is in cm.

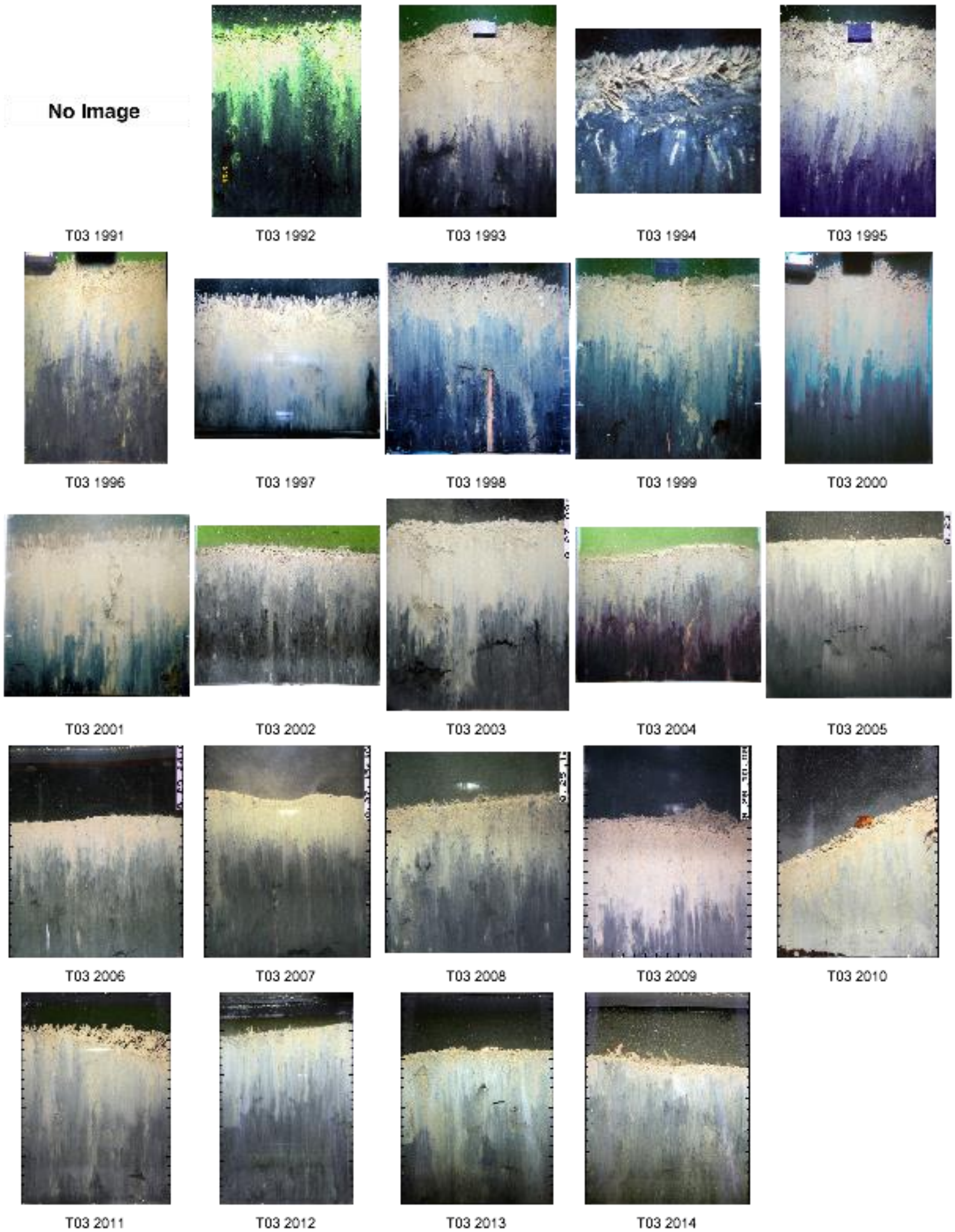


Figure 26. Mosaic of SPI from Station T03 in President Roads, off Long Island, for all years. Improvements in benthic habitat quality occurred from the 1990s to the late 2000s and has remained high into the 2010s. Scale along the side of each image is in cm.

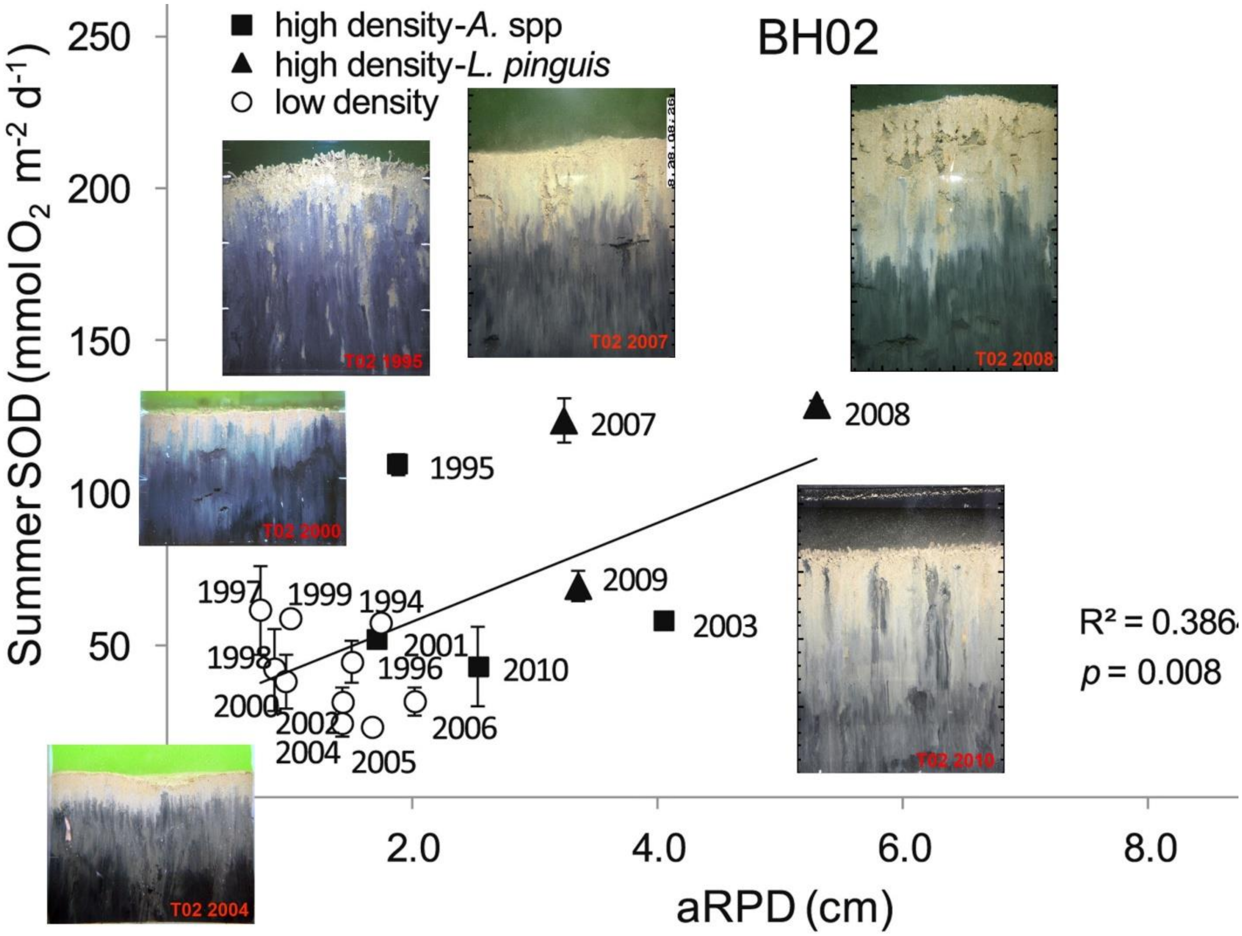


Figure 27. Relationship of summer SOD to depth of the aRPD at Station T02 (BH02). Symbols indicate visual assessments of amphipod densities as observed in sediment cores for June and July of each year. (High density - amphipod tube mats or numerous tubes or holes noted; low density - few to no tubes or holes). From Tucker et al. (2014).

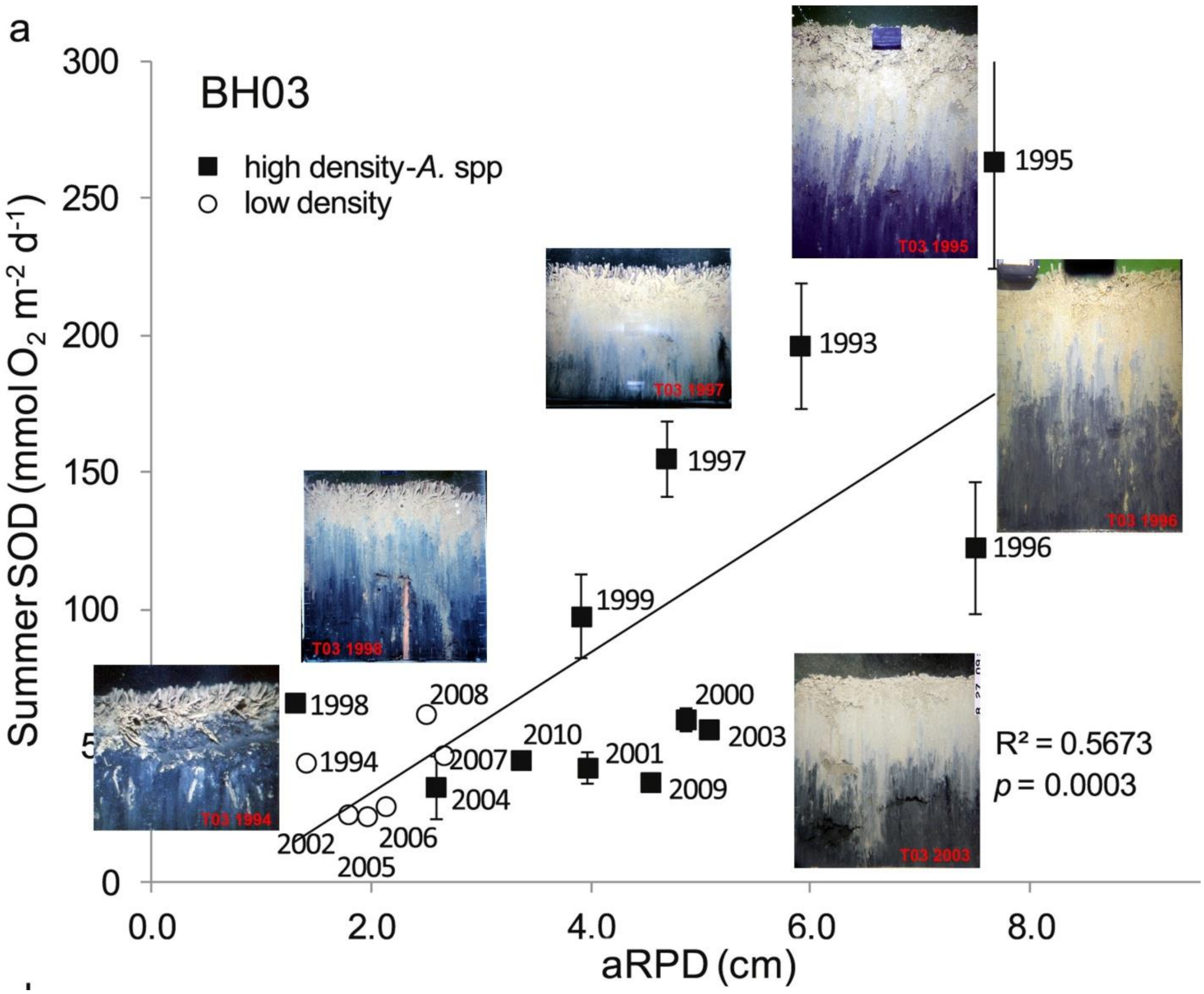


Figure 28. Relationship of summer SOD to depth of the aRPD at Station T03 (BH03). Symbols indicate visual assessments of amphipod densities as observed in sediment cores for June and July of each year. (High density - amphipod tube mats or numerous tubes or holes noted; low density -few to no tubes or holes). From Tucker et al. (2014).

Much of the recovery in benthic habitat quality can be seen dynamics of the tube building amphipod *Ampelisca* spp. Over the 24 years of SPI monitoring, biogenic activity associated with the presence of *Ampelisca* spp. had the most influence on habitat quality (Diaz et al. 2008, Tucker et al. 2014). 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 24). 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 coverage increased from about 5% to 65% of harbor stations from 1992 to 1997. This was likely in response to cessation of sludge disposal that resulted in large reductions in nutrient and organic loading (Taylor 2010). Amphipod tube mats peaked in 1996 with about 65% coverage. *Ampelisca* spp. have life histories that reflect a combination of opportunism in responding to organic matter (McCall 1977) and sensitivity to pollutants (Wolfe et al. 1996). It is possible that sludge disposal had contributed either organic or pollutant loading that was too high for *Ampelisca* spp. to thrive. 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 increased to levels seen in the late 1990s in 2011 and 2012. In 2013, no tube mats were observed for the second time in the 24-year monitoring record, but amphipod tubes were observed at 26 of 61 stations. In 2014 tube mats reappeared at four stations that had *Ampelisca* spp. tubes present almost all years (Figure 29). While the occurrence of *Ampelisca* spp. tubes shifted from year to year, likely driven by physical factors such as storms and quality of organic matter, 2005 and 2013 were the only years of SPI monitoring with no tube mats. In both of these years, strong winter storms occurred that could seriously disturb *Ampelisca* spp. populations. The 2013 storms likely disturbed surficial sediments to water depths of 50 m (R. Geyer, personal communication).

Stations in President Roads and Nantucket Roads in the outer harbor are more strongly influenced by hydrodynamic factors and have always had higher habitat quality than inner Harbor stations. The outer harbor stations have also improved in habitat quality after the operation of the ocean outfall (Figure 23). 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 (Taylor 2010, Tucker et al. 2014). There were also corresponding decreases in primary production due to reduced nutrient loadings (Oviatt et al. 2007).

Station T04 was an exception to the trend to a more aerobic state through time and still remains the station with the lowest quality benthic habitat. The biggest change at station T04 appeared to be due to improved oxygen conditions by the late 1990s. The last year that bacterial mats were observed on the sediment surface at T04 was 1998 (Figure 30). Since 1999, Station T04 has consistently been characterized by Stage I pioneering species likely due to its high organic content soft silt-clay sediments (see Section 3.2). Further evidence of improvement in benthic habitat quality in the outer harbor is the eelgrass bed that has persisted at Station R08 since 2008 (Figure 31). Beds of eelgrass have also been reported in and around Nahant and Lynn Harbor, inside the northernmost breakwater in Winthrop, western and southwestern sides of Calf Island, off Long Island, and Whitehead Flats in Hull (P. Colarusso personal communication to K. Keay).

The improvements in wastewater treatment and moving the outfall offshore have led to improvements in benthic habitats within Boston Harbor by favoring sedimentary processes that enhance bioturbation or the mixing of sediment by organisms, and has led to more aerobic sediment conditions (Figure 32). These changes in sediment processes documented by benthic metabolism and nutrient fluxes (Tucker et al., 2014) lead to the improvements in benthic habitat quality as documented by SPI (Diaz et al., 2008), which in turn led to improvements in benthic infaunal community structure and diversity (see Section 3.2).

		90	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14
CHARLES	C019	.	.	.	.	.	.	.	.	.	.	.	.	.	-	-	-	-	-	-	-	-	-	-	-
RIVER	R09	-	.	-	MAT	-	MAT	MAT	MAT	MAT	+	MAT	+	+	+	-	-	-	-	-	-	MAT	+	-	+
	R10	-	.	-	-	-	-	+	-	MAT	-	-	-	-	-	-	-	-	-	-	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	+	-	+	+	+	+	+	+	+	+	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	MAT	+	+
FLATS	R03	.	.	+	MAT	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	MAT	-	+
	R47	.	.	.	.	MAT	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	MAT	-	-
ISLAND	R12	.	.	MAT	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	MAT	+	+
	T03	+	MAT	-	MAT	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	MAT	+	-
ROADS	T02	-	-	+	MAT	MAT	+	MAT	+	+	MAT	+	-	+	+	-	-	+	+	+	MAT	MAT	MAT	+	+
	T05a	.	-	.	-	MAT	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	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	MAT	+	MAT
	T06	.	MAT	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	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	+	-	+	+	+	+	-	+	MAT	+	+
	R28	-	.	MAT	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	MAT	-	+
	R31	+	.	MAT	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	+	MAT	+	+
	R49	.	.	.	.	-	MAT	-	+	-	-	-	+	-	+	-	+	-	-	-	-	-	-	-	-
	R50	+	.	.	.	MAT	MAT	MAT	MAT	+	MAT	-	+	+	-	+	+	+	+	+	-	-	-	-	+
	R51	-	.	.	.	+	MAT	-	+	+	-	-	-	-	-	-	+	+	-	+	-	-	-	-	-
	R52	+	.	.	.	-	MAT	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	R53	-	.	.	.	+	MAT	-	-	-	+	-	+	-	-	-	-	-	-	-	-	-	-	-	-
	T08	.	MAT	MAT	+	MAT	-	MAT	-	+	-	MAT	+	+	+	+	+	+	MAT	+	+	-	-	+	-

Figure 29. Matrix of *Ampelisca* spp. tube occurrence through time in SPI images. Mat is mat densities of tubes, + is tubes present, - no tube observed.

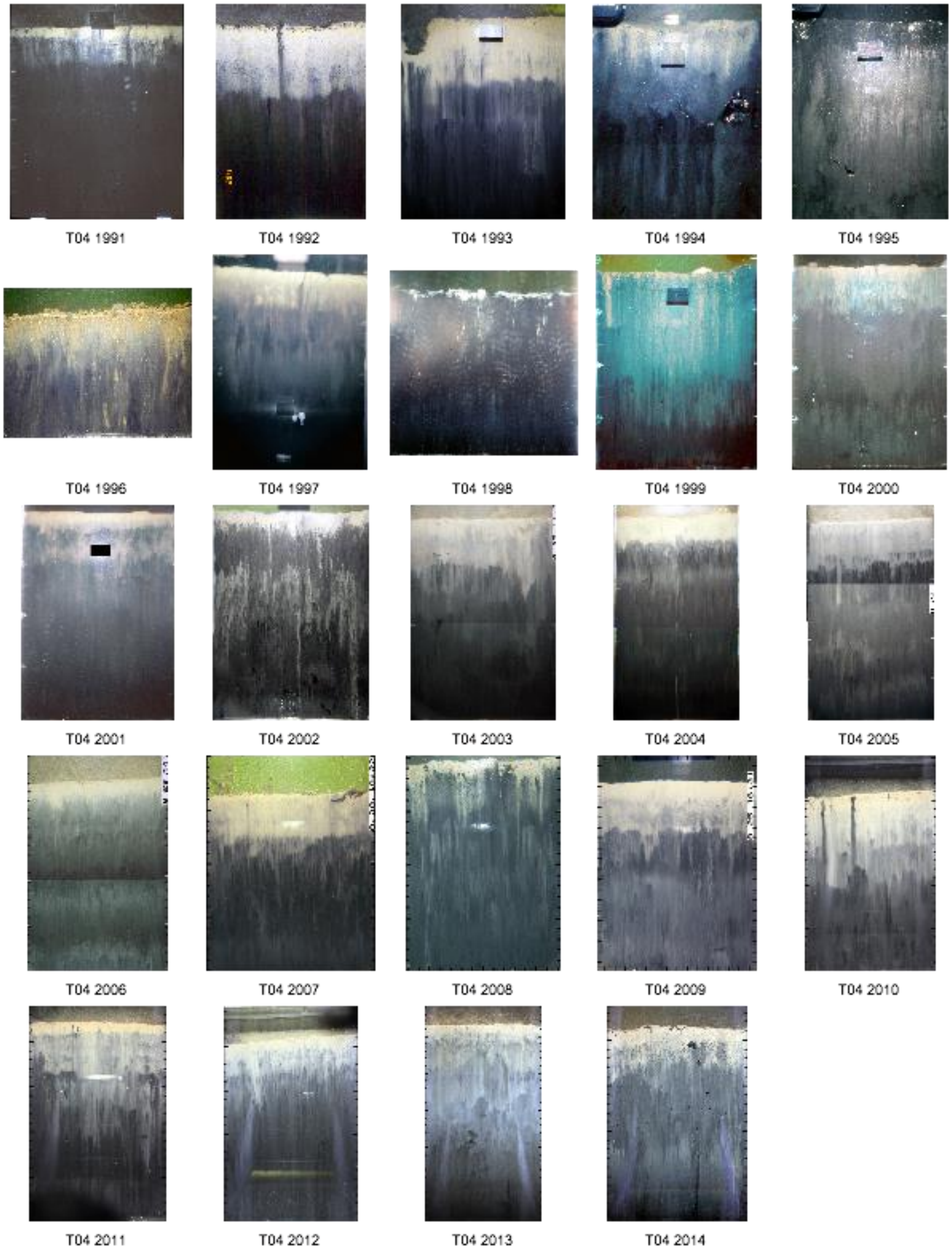


Figure 30. Mosaic of SPI from Dorchester Bay Station T04 for all years. Some improvement in benthic habitat quality occurred by the early 2000s. In the mid-2000s signs of deeper bioturbation appear, but there has not been much change in benthic habitat conditions in the 2010s. Scale along the side of each image is in cm.

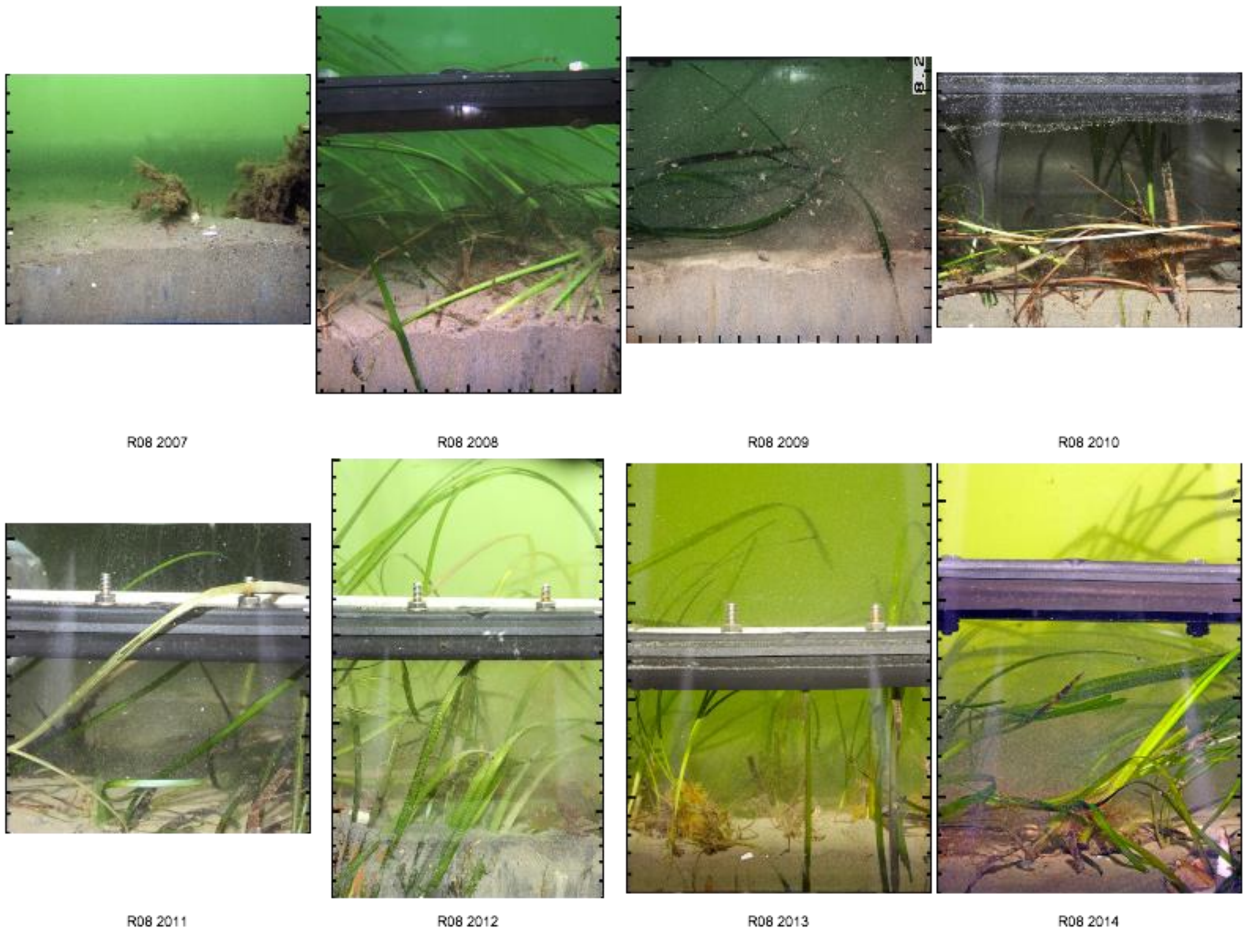


Figure 31. Eelgrass bed at station R08 on Deer Island Flats. The bed first appeared in SPI in 2008 and has persisted. Prior to 2008, R08 was always fine-sand with macroalgae. Scale on sediment profile image is in cm.

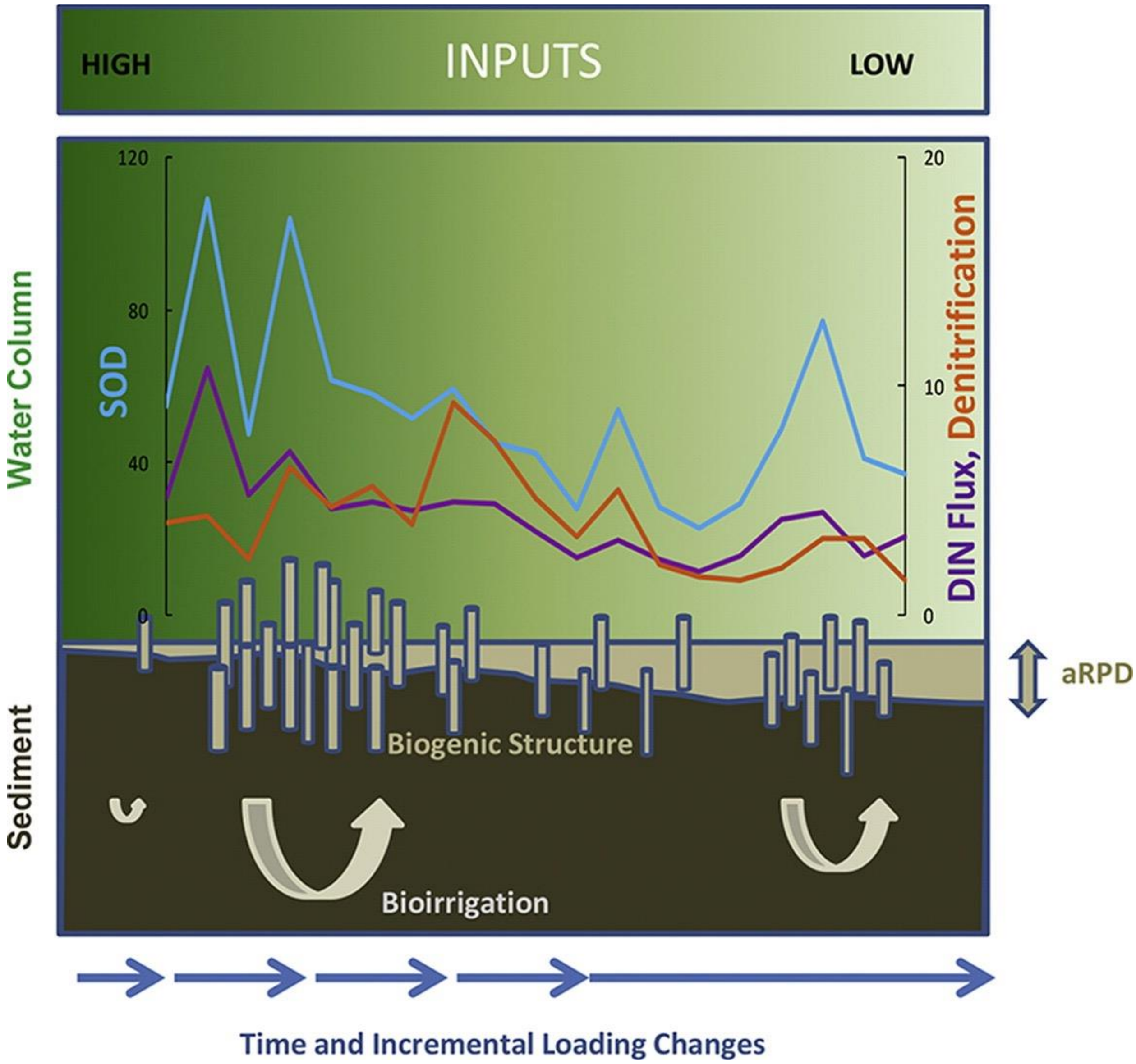


Figure 32. Changes in sedimentary processes in Boston Harbor relative to improvements in water quality and benthic habitat quality from 1990 to 2010. SOD - sediment oxygen demand, DIN - dissolved inorganic nitrogen, aRPD - apparent color redox potential discontinuity. From Tucker et al. (2014).

4. CONCLUSION

Overall, the improvements in wastewater treatment and moving the outfall offshore have led to improvements in water quality and benthic habitat quality within Boston Harbor by reducing organic and nutrient loading and favoring processes that enhance bioturbation or the mixing of sediment by organisms. From 1990 to the present, the sediment organic matter in Boston Harbor has shifted from sewage to marine derived and infaunal activity has led to more aerobic and 'healthy' sediment conditions. Physical and biological properties of the soft substrate in Boston Harbor in 2014 exhibited minor changes from recent years but were consistent with longer-term trends (Pembroke et al. 2014). Concentrations of both TOC and *Clostridium perfringens*, indicators of organic enrichment and deposition from municipal wastewater discharge, have remained low compared to the levels occurring prior to the offshore diversion.

Community structure measures also continue to point to improving benthic conditions. Since municipal wastewater and sludge discharges have been eliminated from the harbor, total abundance has trended downward, particularly for opportunistic species such as *Capitella capitata*. Species richness, while variable, has trended upward as did evenness (J'), Shannon diversity (H'), and log series alpha diversity. 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 2014 survey are consistent with the recovery of benthic habitats from decades of inadequately treated sewage discharges.

5. REFERENCES

Blake, JA, DC Rhoads, and IP Williams. 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 pp.

Clarke, K.R. (1993). Non-parametric multivariate analyses of changes in community structure. Aust. J. Ecol., 18: 117-143.

Clarke, K.R. and R.H. Green (1988). Statistical design and analysis for a 'biological effects' study. Mar. Ecol. Prog. Ser., 46: 213-226.

Constantino J, Leo W, Delaney MF, Epelman P, Rhode S. 2014. Quality Assurance Project Plan (QAPP) for Sediment Chemistry Analyses for Harbor and Outfall Monitoring, Revision 4 (February 2014). Boston: Massachusetts Water Resources Authority. Report 2014-02. 53 p.

Diaz, RJ, Rhoads, DC, Blake, JA, Kropp, RK, and Keay, KE. 2008. Long-term trends in benthic habitats related to reduction in wastewater discharges to Boston Harbor. Estuaries and Coasts 31:1184–1197.

Gallagher, E.D. and K.E. Keay. 1998. Organisms-Sediment-Contaminant Interactions in Boston Harbor. Pp. 89-132 In: *Contaminated Sediments in Boston Harbor*. K.D. Stolzenbach and EE. Adams (eds.) Marine Center for Coastal Processes, MIT Sea Grant College Program. Cambridge, MA 02139.

McCall, PL 1977. Community patterns and adaptive strategies of the infaunal benthos of Long Island Sound. Journal of Marine Research 35:221–266.

Maciolek, NJ, DT Dahlen, and RJ Diaz. 2011. 2010 Boston Harbor Benthic Monitoring Report. Boston: Massachusetts Water Resources Authority. Report 2011-18. 20 pages + appendix.

Maciolek, NJ, RJ Diaz, DT Dahlen, and IP Williams. 2006. 2005 Boston Harbor Benthic Monitoring Report. Boston: Massachusetts Water Resources Authority. Report ENQUAD 2006-24. 87 pages + appendices.

Maciolek, NJ, RJ Diaz, DT Dahlen, and SA Doner. 2008. 2007 Boston Harbor Benthic Monitoring Report. Boston: Massachusetts Water Resources Authority. Report ENQUAD 2008-22. 77 pages + appendices.

MWRA. 2010. Ambient monitoring plan for the Massachusetts Water Resources Authority effluent outfall revision 2. July 2010. Boston: Massachusetts Water Resources Authority. Report 2010-04. 107 p.

Nestler, EC, AE Pembroke, and RC Hasevlat. 2014. Quality Assurance Project Plan for Benthic Monitoring 2014–2017. Boston: Massachusetts Water Resources Authority. Report 2014-03, 92 pp. plus Appendices.

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

Oviatt, CA, Hyde, KJW, and Keller, AA. 2007. Production patterns in Massachusetts Bay with outfall relocation. Estuaries and Coasts 30:35–46.

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

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

Pembroke, AE, RJ Diaz, and EC Nestler. 2013. Harbor Benthic Monitoring Report: 2012 Results. Boston: Massachusetts Water Resources Authority. Report 2013-13. 41 pp.

Pembroke, AE, RJ Diaz, and EC Nestler. 2014. Harbor Benthic Monitoring Report: 2013 Results. Boston: Massachusetts Water Resources Authority. Report 2014-12. 43 pp.

Rhoads, DC. 1967. Biogenic reworking of intertidal and subtidal sediments in Barnstable Harbor and Buzzards Bay, Massachusetts. Journal of Geology 75:461-476.

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

SAIC. 1990. REMOTS® sediment-profile photography surveys of Boston Harbor, Dorchester, Quincy, Hingham, and Hull Bays: June 1989 and May 1990. SAIC Report No. SAIC-90/7578&236. Science Applications International Corporation, Woods Hole, MA 45 pp.

SAIC. 1992. REMOTS® sediment-profile photography survey of Boston Harbor, Dorchester, Quincy, Hingham, and Hull Bays: May 1992. SAIC Report No. 266. Science Applications International Corporation, Newport, RI. 20 pp.

Stolzenbach, K.D. and E.E. Adams. 1998. Contaminated Sediments in Boston Harbor. MIT Sea Grant Publication 98 1, MIT Sea Grant College Program. Cambridge, MA. 170 pp.

Taylor, D.I. 2006. Update of patterns of wastewater, river, and non-point source loadings to Boston Harbor (1990-2005). Boston: Massachusetts Water Resources Authority. Report 2006-22. 77pp.

Taylor, DI. 2010. The Boston Harbor Project, and large decreases in loadings of eutrophication-related materials to Boston Harbor. Marine Pollution Bulletin 60:609–619.

Tucker, J, AE Giblin, CS Hopkinson, SW Kelsey and BL Howes. 2014. Response of benthic metabolism and nutrient cycling to reductions in wastewater loading to Boston Harbor, USA. Estuarine, Coastal and Shelf Science 151: 54-68.

Wallace, G.T., C. Krahfrost, L. Pitts, M. Studer, and C. Bollinger. 1991. Assessment of the chemical composition of the Fox Point CSO effluent and associated subtidal and intertidal environments: Analysis of CSO effluent and surficial sediments for trace metals prior to CSO modification. Final report to the Massachusetts Department of Environmental Protection, Office of Research and Standards.

Wang, X-U, Y-X Zhang and RF Chen. 2001. Distribution and partitioning of polycyclic aromatic hydrocarbons (PAHs) in different size fractions in sediments from Boston Harbor, United States. Marine Pollution Bulletin 42:1139-1149.

Wolfe, DA, ER Long, and GB Thursby. 1996. Sediment toxicity in the Hudson-Raritan Estuary: Distribution and correlations with chemical contamination. Estuaries 19:901–912.

Massachusetts Water Resources Authority
Charlestown Navy Yard
100 First Avenue
Boston, MA 02129
(617) 242-6000
www.mwra.com