Boston Harbor Benthic Monitoring Report: 2017 Results

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EXECUTIVE SUMMARY

Boston Harbor was once considered among the most degraded urban estuaries 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 9.5 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.

Conditions in the sediments and the associated benthic infaunal community reflect cumulative water quality exposures. 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 2017. 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. These reductions have enabled processes that enhance bioturbation or the mixing of sediment by organisms to predominate. At one time, the sediment organic matter in Boston Harbor was derived primarily from sewage but once changes in wastewater treatment and disposal were initiated, marine-derived organic material has become 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 2017 exhibited minor changes from recent years but were consistent with longer-term trends (Pembroke et al. 2017). Concentrations of both total organic carbon (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. As municipal wastewater and sludge discharges were eliminated from the harbor, total abundance has trended downward, particularly for opportunistic species such as *Capitella capitata*, reaching a fairly stable level for about the last decade. 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., *Aricidea catherinae,* 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 2017 survey are consistent with the recovery of benthic habitats from decades of inadequately treated sewage discharges.

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1. INTRODUCTION

Boston Harbor was once considered among the most degraded urban estuaries 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. In 2015, MWRA and its member communities completed a series of 35 projects intended to eliminate or minimize the impacts of Combined Sewer Overflows (CSOs) to Boston Harbor and its tributaries (Kubiak et al. 2016).

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 2017. These include sediment conditions, benthic infauna, and sediment profile imagery.

2. METHODS

Benthic monitoring in Boston Harbor continued at the same stations that have been surveyed since 1991. 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. (2017) for previous monitoring years. Detailed descriptions of the methods are contained in the Quality Assurance Project Plan (QAPP) for Benthic Monitoring (Rutecki et al. 2017). 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 2017 (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 3, 2017.

SPI samples were collected in triplicate at 61 stations on August 6-8, 2017 (Figure 1).

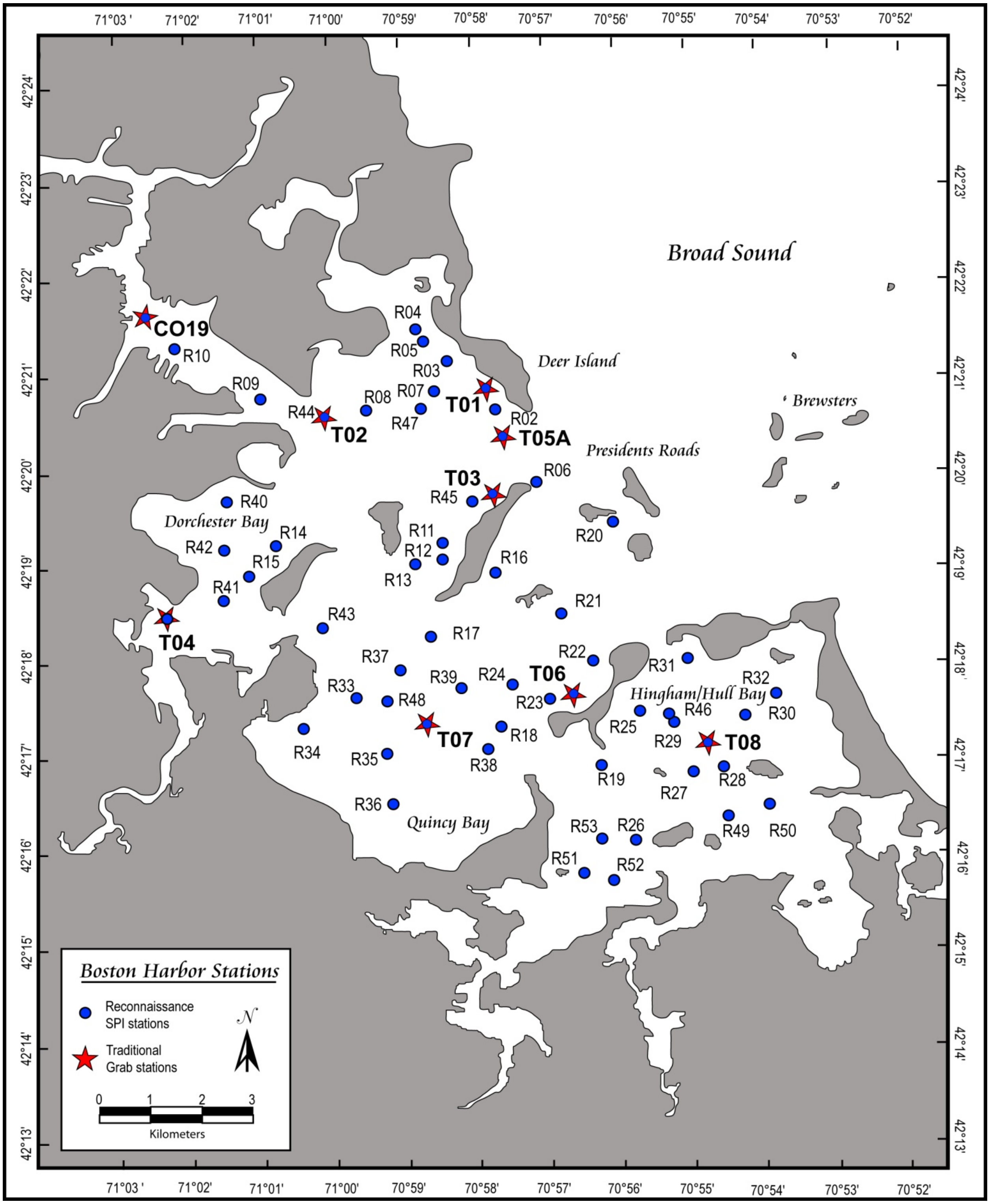


Figure 1. Locations of soft-bottom sampling and sediment profile imaging stations for 2017.

2.2 Laboratory Methods

Laboratory methods for benthic infauna and SPI image analyses were consistent with the QAPP (Rutecki et al. 2017). 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 9.3), as described in the QAPP (Rutecki et al. 2017) 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. These evaluations generally focused on Stations T01 to T08 (traditional stations, Periods I-IV) and excluded data from Station C019 which are only available since 2004 (Period IV).

3. RESULTS AND DISCUSSION

3.1 Sediment Conditions

Sediment conditions in Boston Harbor were characterized in 2017 by measuring three parameters 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 2017 included a wide range of sediment types (Table 1, Figure 2). Grain size profiles ranged from predominantly sand (e.g., T08, T05A) to almost entirely silt and clay (i.e., C019 and T04). Most stations had mixed sediments. The outer harbor stations (T01, T05A, T06, and T08) generally had more than 50% sand with varying fractions of silt-clay. Outer harbor stations T02 and T07 had nearly equal proportions of sand and silt-clay. Grain size has been variable at Station T03, in the lee of Long Island, having more fines than sand in 2015 and 2017 but more sand in 2016. The grain size composition at each station in 2017 generally remained within the ranges reported in prior years although several stations (T01, T03, T04 and T07) exhibited a change in percent fines of about 10% compared to 2016. 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 (Figure 3).

Total Organic Carbon. Concentrations of total organic carbon (TOC) in 2017 were generally similar to 2016, remaining within the ranges reported in prior years (Figure 4). Concentrations of TOC tend to track closely to percent fine sediments (silt + clay), with higher TOC values generally associated with higher percent fines (Figures 3 and 4). During 2017, Stations T03, T04, and C019 had among the highest concentrations of TOC and also had among the highest proportions of fines (Table 1). T04 and C019 have typically had the highest TOC. TOC levels at T03 have been below 3% since 2005 and below 2.5% since 2011; levels in 2017 are consistent with this trend. This pattern has paralleled the proportion of fine grained sediments. As in prior years, the lowest TOC concentrations for 2017 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 2017 were highest at Stations T02 and T08 with the lowest value found at Station T05A (Table 1). *C. perfringens* concentrations in 2017 were lower than, or comparable to, the previous year at all stations. In the Outer Harbor, abundances have exhibited the highest variability among years at T04, a depositional site in Savin Hill Cove. After a period of decline from 2008-2012, followed by an increase in 2013 and 2014, *C. perfringens* counts decreased again in 2015, remained steady in 2016, and declined in 2017. *C. perfringens* counts at Station T08 were considerably higher in 2016 than in the present year and most recent years; this was largely an artifact of normalizing the counts by percent fine sediments. Percent fine sediments were extremely low at T08 in 2016. *C. perfringens* counts at other Harbor stations have remained consistently below historical averages since around 1999 (Figure 5).

Table 1. 2017 monitoring results for sediment condition parameters.

Parameter		C019	T01	T02	T03	T04	T05A	T06	T07	T08
Grain Size	**Gravel (%)**	**0**	**4.3**	**0**	**1.6**	**0.4**	**0**	**0.7**	**0**	**13.8**
	Sand (%)	**3.8**	**78.4**	**46.7**	**39.2**	**18.2**	**88.1**	**65.3**	**45.2**	**83.8**
	Silt (%)	**64.2**	**12.5**	**34.8**	**36.1**	**63.7**	**10.5**	**21.8**	**33.3**	**1.1**
	Clay (%)	**32.1**	**4.8**	**18.5**	**23.2**	**17.7**	**1.4**	**12.2**	**21.5**	**1.3**
	Percent Fines (Silt + Clay)	**96.2**	**17.3**	**53.3**	**59.3**	**81.4**	**11.9**	**34.0**	**54.9**	**2.4**
Total Organic Carbon	**TOC (%)**	**2.6**	**0.5**	**1.4**	**2.4**	**4.5**	**0.5**	**1.2**	**1.9**	**0.2**
Clostridium perfringens	**Not Normalized**	**409**	**295**	**3050**	**371**	**817**	**40**	**756**	**311**	**127**
	Normalized (cfu/g dry/%fines)	**4.3**	**17.1**	**57.2**	**6.3**	**10.0**	**3.4**	**22.2**	**5.7**	**54.0**

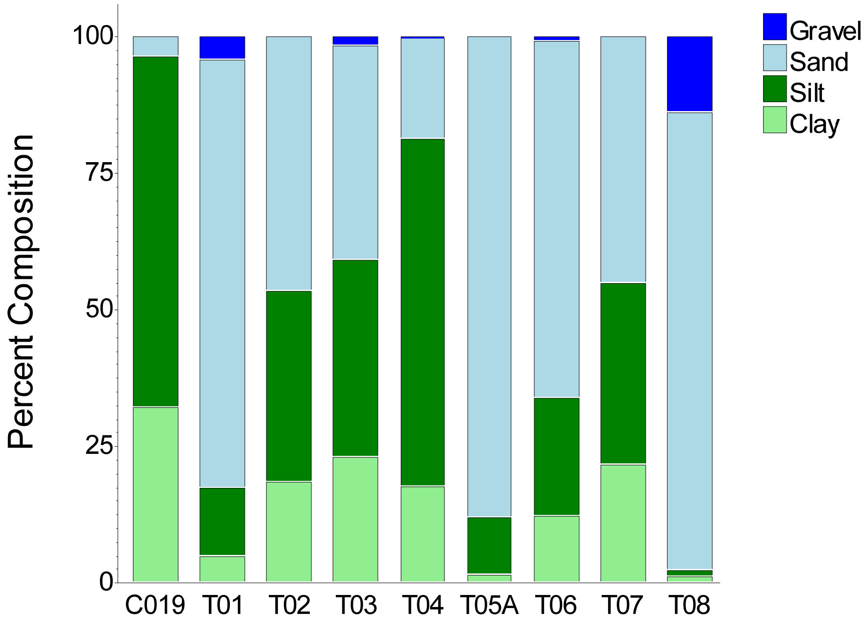


Figure 2. 2017 monitoring results for sediment grain size in Boston Harbor.

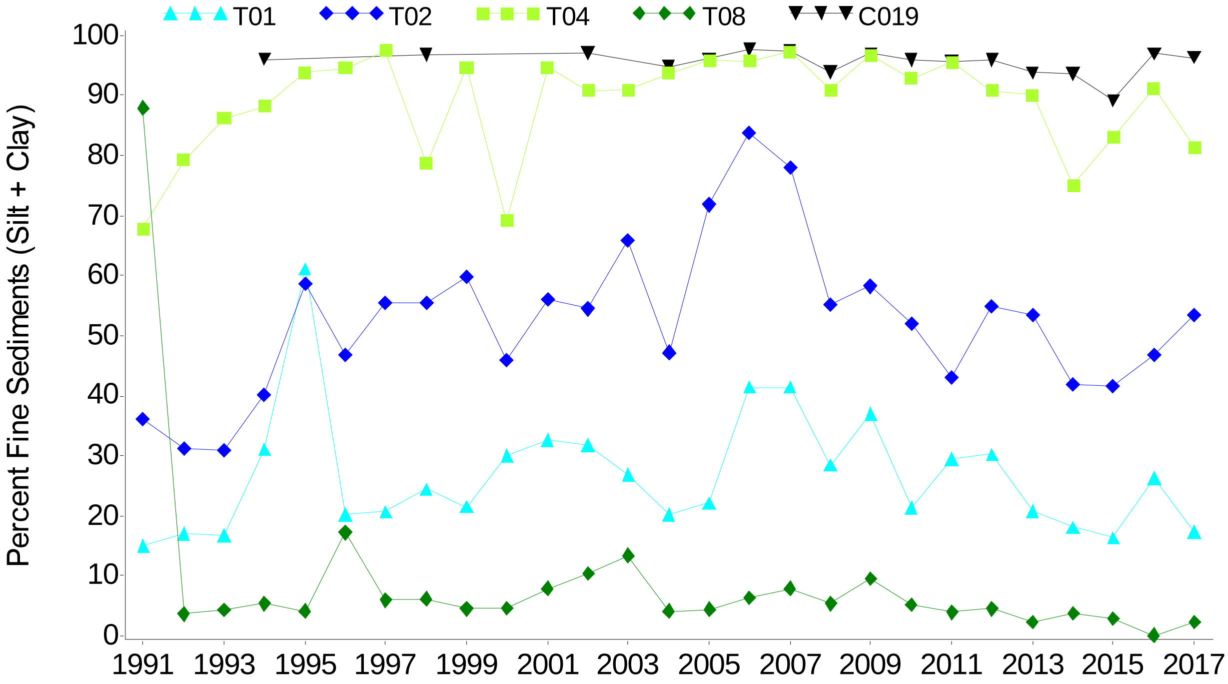


Figure 3. **Mean percent fine sediments at five stations in Boston Harbor, 1991 to 2017.**

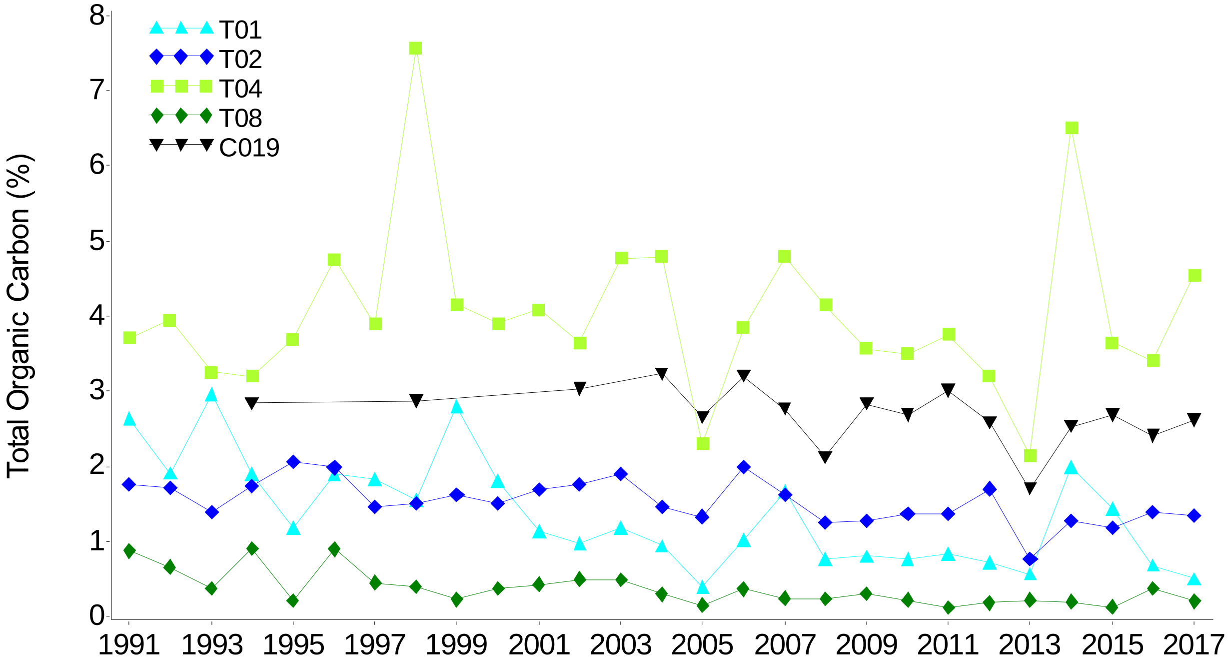


Figure 4. **Mean concentrations of TOC at five stations in Boston Harbor, 1991 to 2017.**

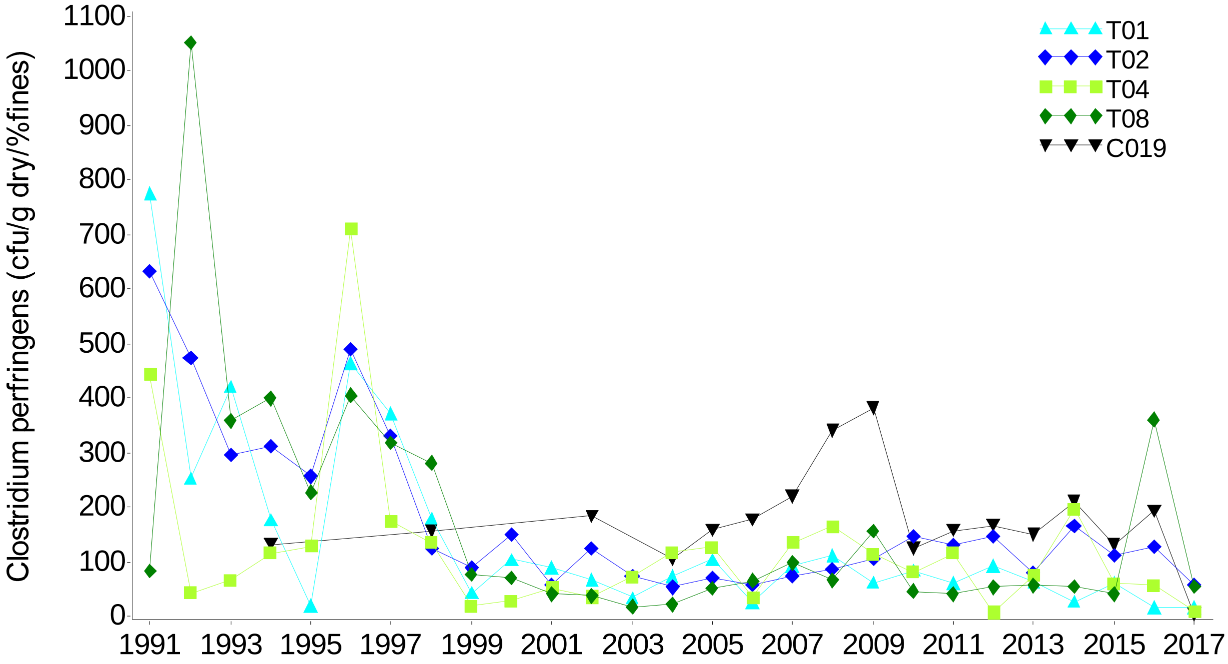


Figure 5. Mean normalized concentrations of *Clostridium perfringens* at five stations in Boston Harbor, 1991 to 2017.

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).

Results during 2017 for grain size, TOC, and *C. perfringens* in Boston Harbor sediments, are consistent with monitoring results from previous post-outfall implementation years (Maciolek et al. 2008, 2011; Pembroke et al. 2017). 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). In Figures 6 and 7, Period IV has been divided into five-year segments to show potential changes of TOC and *C. perfringens* concentrations over time in this period. These findings are consistent with other changes documented in the Harbor following improvements to the collection, treatment and disposal of wastewater as part of the Boston Harbor Project (Taylor 2006, Maciolek et al. 2008).

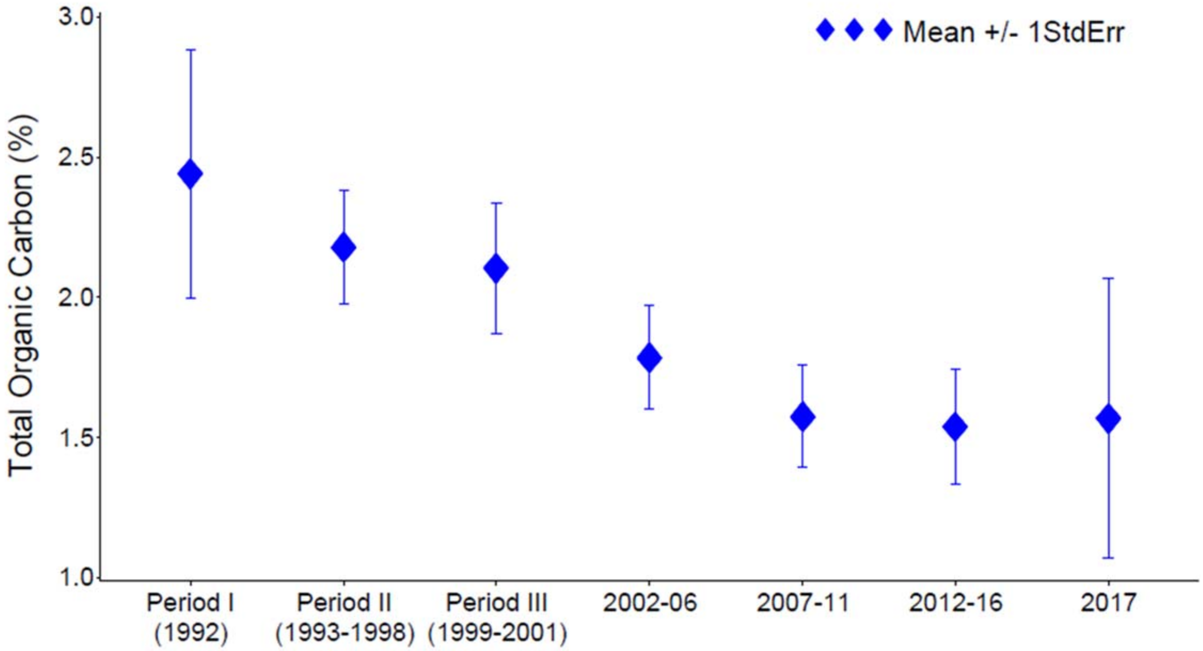


Figure 6. **Comparison of TOC across time periods (offset by one year) at Boston Harbor stations (T01-T08) from 1992 to 2017 (1991 excluded).**

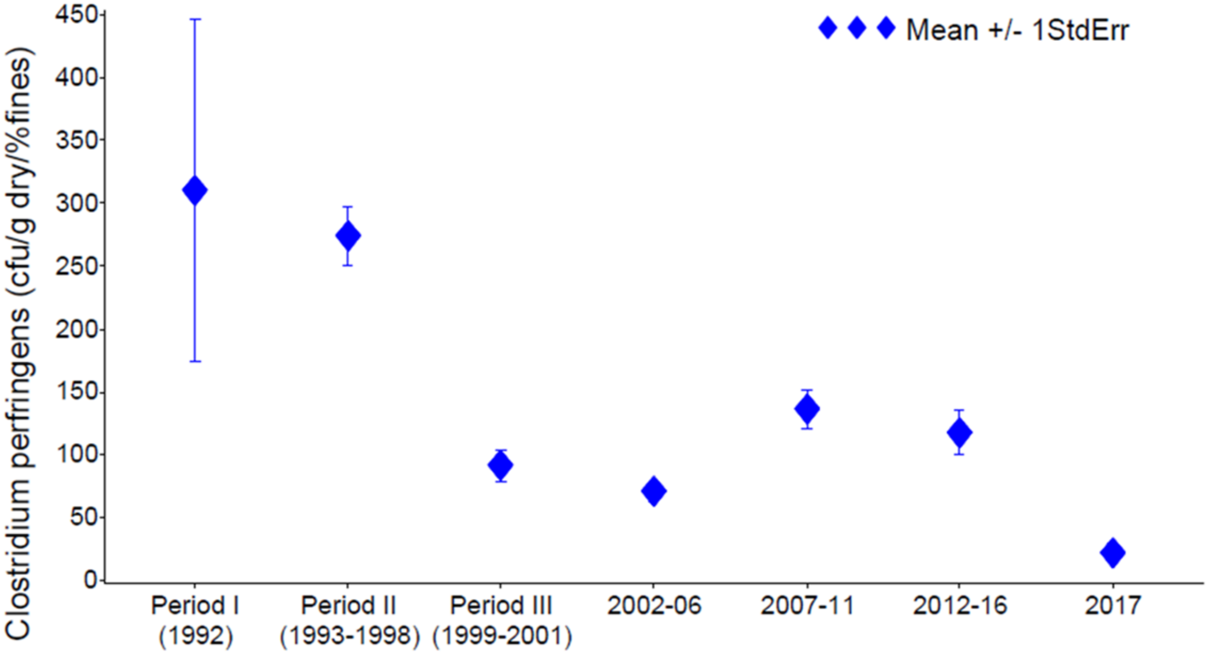


Figure 7. **Comparison of *Clostridium perfringens* across time periods (offset by one year) at Boston Harbor stations (T01-T08) from 1992 to 2017 (1991 excluded).**

3.2 Benthic Infauna

3.2.1 Community Parameters

A total of 37,135 infaunal organisms were counted from the 18 samples in 2017. Organisms were classified into 146 discrete taxa, 129 of which were species-level identifications. More than 99% of the individuals were identified to species; all remaining individuals were identified to genus or family. 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). Data are presented in figures as means (averages per station) unless otherwise noted.

Table 2. 2017 mean infaunal community parameters by station.

Station	Total Abundance	Number of Species	Pielou's Evenness (J')	Shannon-Wiener Diversity (H')	Log-series alpha
C019	1009.5	15.5	0.57	2.21	2.60
T01	3259.5	63.5	0.59	3.53	11.27
T02	3048.5	51.5	0.57	3.23	8.81
T03	4089.5	59.0	0.50	2.92	9.91
T04	1676.5	12.5	0.18	0.68	1.84
T05A	1218.0	45.0	0.70	3.81	9.21
T06	3062.5	39.5	0.56	2.97	6.41
T07	571.5	23.5	0.61	2.78	4.95
T08	679.5	41.0	0.60	3.18	10.01

At most stations mean total abundance values reported for 2017 were higher than values in 2016. Increases in mean abundance were observed at six stations (C019, T01, T02, T03, T04, and T08) and ranged from 7 to 66% (Pembroke et al. 2017). Stations T05A, T06, and T07 exhibited decreases in mean abundance that ranged from 14 to 30%. Station T07 typically has low infaunal abundance. Abundances in 2017 were within the range observed during the post-offshore diversion period but relatively low compared to pre-diversion values (Figure 8). Ten species each contributed at least 2.5% and together they contributed nearly 81% of the total abundance across the eight traditional benthic stations. Most of the species that dominated the infauna at these stations in the past several years continued to do so in 2017 (Table 3) although the rank order changed. The tube-dwelling amphipod *Ampelisca* spp. that rebounded in 2015, increased in 2017 due to the high abundances at T03. Six species of polychaetes and three species of oligochaetes were among the most abundant taxa in 2017. Abundances of two species that achieved dominance status in 2015 based on elevated numbers at a single station, *Clymenella torquata* and Naidinae sp. 1, dropped below the 2.5% threshold in 2016, then returned to dominance status in 2017. The top five dominant taxa in 2017 have

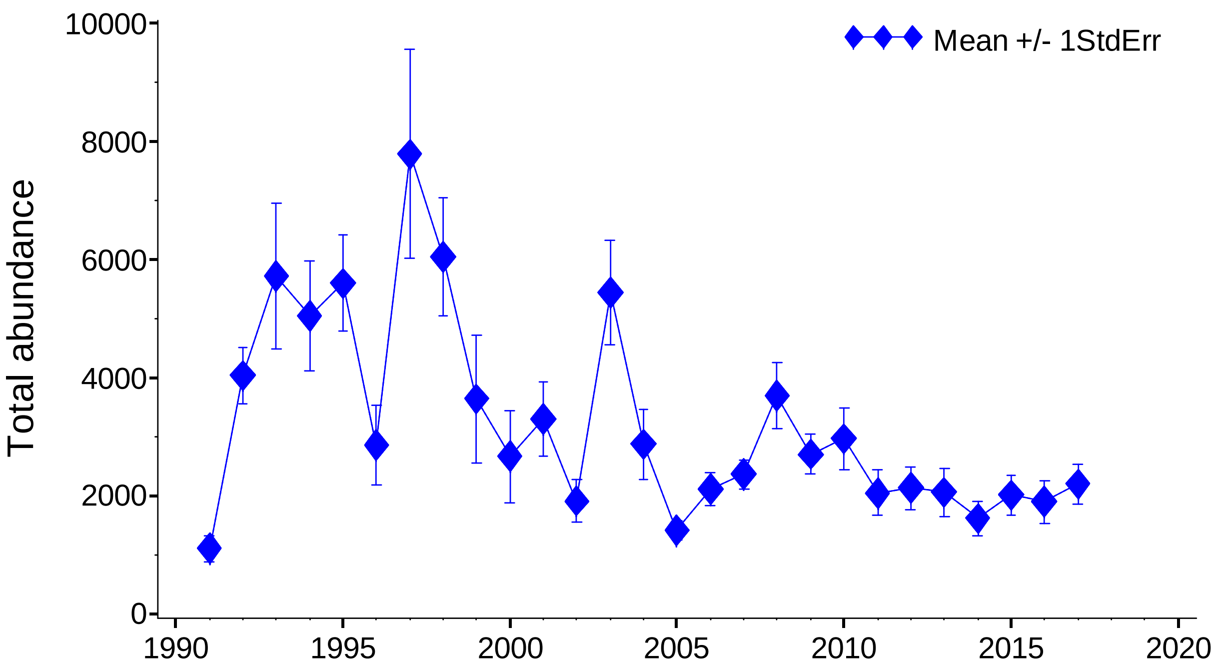


Figure 8. Mean abundance of benthic infauna at eight Boston Harbor stations (T01-T08), 1991-2017.

Table 3. Dominant taxa at eight grab stations (T01-T08) in Boston Harbor in August 2017.

Taxon	**Total 2017 Abundance (compared with 2016)[a]**
Streblospio benedicti	5,727 (increase)
Aricidea catherinae	5,351 (similar)
Ampelisca spp.	4,157 (increase)
Polydora cornuta	2,756 (decrease)
Limnodriloides medioporus	2,686 (decrease)
Clymenella torquata	2,242 (increase)
Scoletoma hebes	2,213 (increase)
Tubificoides intermedius[b]	1,728 (similar)
Naidinae sp. 1	955 (increase)
Bipalponephtys neotena	935 (increase)

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

[b] previously identified as *T. apectinatus*

frequently been among the most abundant in the harbor during previous years. Certain spatial patterns of abundance also appeared to be consistent with previous years; T04, T07 and C019 continued to support low infaunal abundances (Table 2). As previously observed, Station T03 supported among the highest abundances among the harbor stations.

Temporally, benthic infaunal abundance in the harbor has been controlled by a limited number of species (Table 4). Although these dominants have varied somewhat over the course of the surveys, four taxa (*Ampelisca* spp., *Aricidea catherinae, Limnodriloides medioporus*, and *Polydora cornuta*) have been among the most abundant organisms during the baseline and subsequent periods. 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). It is noteworthy that abundances of the oligochaete *Tubificoides intermedius* have steadily increased. While it dropped from its high abundance observed in 2015, it was evenly distributed across the Harbor stations in 2016 and 2017, and has remained higher than during Period I.

Table 4. Mean abundance per sample of dominant taxa during four discharge periods at eight Boston Harbor stations (T01-T08), 1992-2017.

Phylum	Higher taxon	Family	Species[a]	Period I	Period II	Period III	Period IV	2017
Annelida	Polychaeta	Capitellidae	*Capitella capitata* complex	65.2	88.8	3.4	6.1	3.3
		Lumbrineridae	*Scoletoma hebes*	3.4	10.5	4.2	72.9	138.3
		Maldanidae	*Clymenella torquata*	34.7	17.6	10.6	20.4	140.1
		Nephtyidae	*Bipalponephtys neotena*[b]	-	11.4	10.3	180.3	58.4
		Paraonidae	*Aricidea catherinae*	325.0	237.4	204.3	233.0	334.4
		Spionidae	*Polydora cornuta*	525.8	1053.0	269.6	253.6	172.3
			Streblospio benedicti	236.0	298.6	27.7	81.7	357.9
	Oligochaeta	Tubificidae	*Limnodriloides medioporus*	484.7	297.9	315.2	239.6	167.9
			Tubificoides intermedius	42.6	101.4	231.2	247.6	108.0
Arthropoda	Amphipoda	Ampeliscidae	*Ampelisca* spp.	354.3	1698.3	1205.9	549.0	259.8
		Corophiidae	Corophiidae spp.	16.1	336.2	23.0	1.4	0.4
			Crassicorophium bonellii	7.9	217.3	37.3	7.3	0.8
			Leptocheirus pinguis	29.0	117.4	66.0	75.8	1.5
		Photidae	*Photis pollex*	11.4	77.0	86.8	30.4	0.3
		Phoxocephalidae	*Phoxocephalus holbolli*	28.0	116.9	125.9	6.2	0.9

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

[b] previously identified as *Nepthys cornuta.*

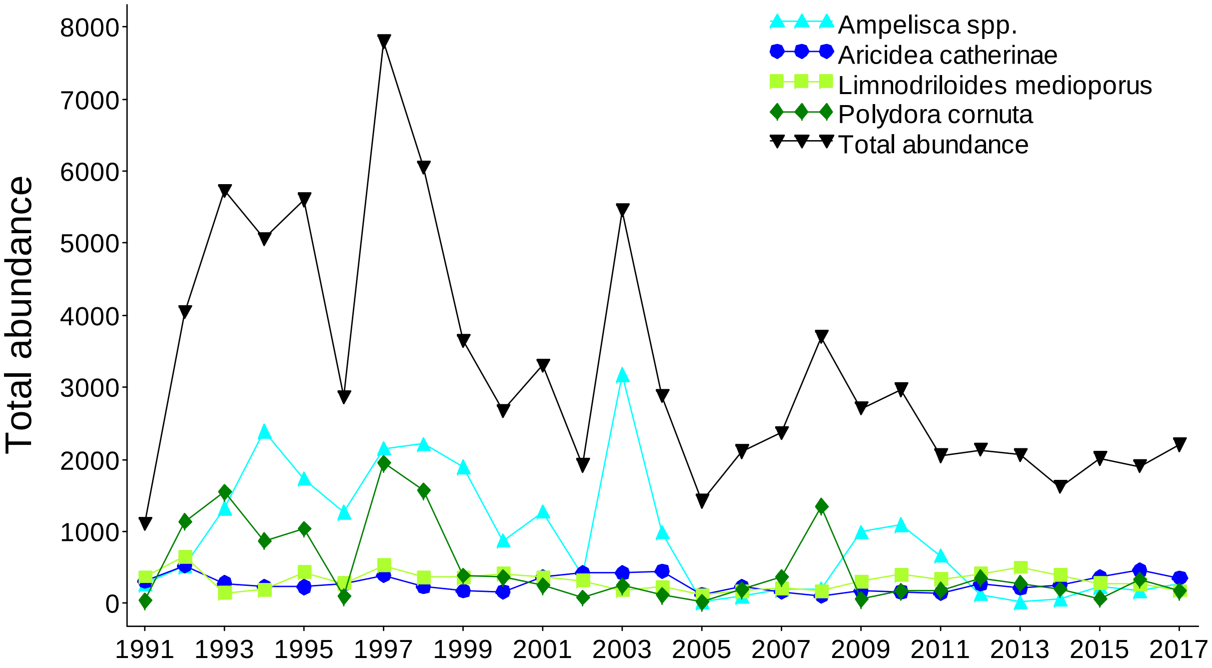


Figure 9. Total abundance of four dominant taxa at eight Boston Harbor stations (T01-T08), 1991-2017.

Patterns of abundance of *Ampelisca* spp. have been of particular interest throughout the history of the program due to the numerical dominance of this taxon in Harbor assemblages. 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 2012-2014 to levels comparable to those seen in 2005-2008, and increasing slightly in 2015 and 2017 (Figure 10). *Ampelisca* was more widespread in 2015 (seven stations) compared to 2014 (five stations) although in both years more than 90% of the population was 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. Abundances at Stations T03 and T05A increased in 2017 compared to 2016. As observed in the past three years, Station T03 supported the largest population of this species.

The numbers of species reported for 2017 ranged from 12.5 to 63.5 per station and averaged 39 species per sample. These values were 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). Mean species richness was slightly higher in 2017 than in 2016, increasing at all stations except C019, T05A, and T08. Stations T02, T03, and T08 were among the most species-rich stations from 2011 through 2016 (Pembroke et al. 2017); in 2017 species richness at all three stations was above the average for the Harbor. Station T04 has consistently supported the lowest species richness in this time frame. Species richness at T07 in Quincy Bay, which reached unusual peaks in 2013 and 2016, exhibited typical species richness in 2017 (Pembroke et al 2014, 2017).

When averaged across the eight outer harbor stations, two measures of community structure, Pielou's evenness and Shannon-Weiner diversity, decreased in 2017 as they did in 2016 (Figures 13 and 14, Table 2, and Pembroke et al. 2017). 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 2016 and 2017 were typically small and, in general, spatial patterns in these 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, decreased in 2017 compared to 2016 (Pembroke et al. 2017). Although the value in 2017 was below the relatively high value seen in 2012 it was well above pre-diversion values (1991-2000; Figure 15). Highest log-series alpha diversity occurred at T01 where this measure has typically been one of the highest in the harbor. Consistent with recent patterns, log-series alpha diversity was lowest at T04 in 2017 (Table 2; Pembroke et al. 2017). The largest change in log-series alpha compared to 2016 was the decrease at T07.

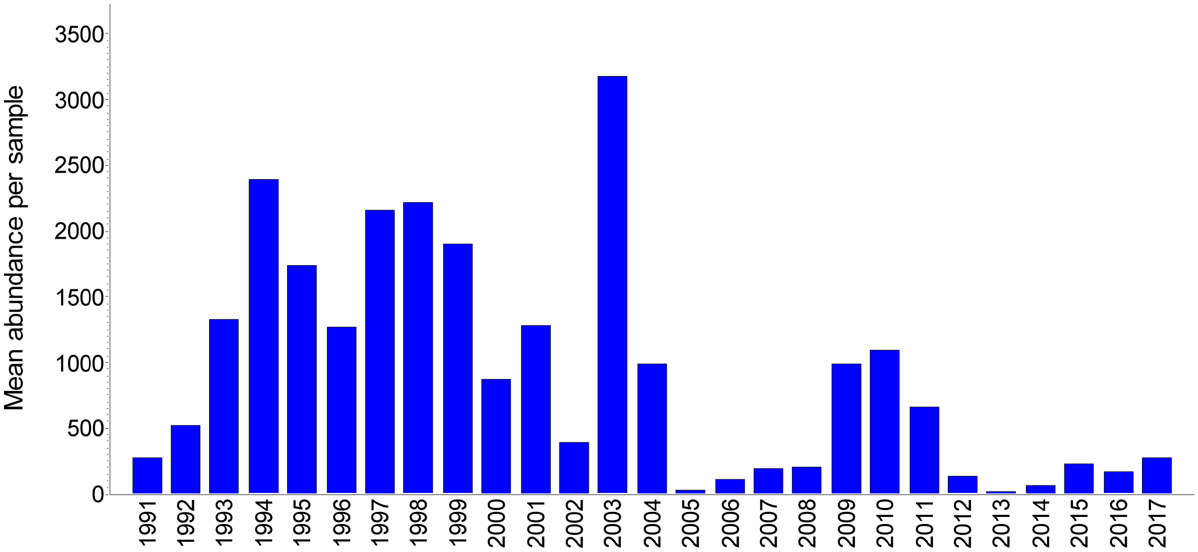


Figure 10. Mean annual abundance of *Ampelisca* spp. averaged over eight Boston Harbor stations (T01-T08), 1991-2017.

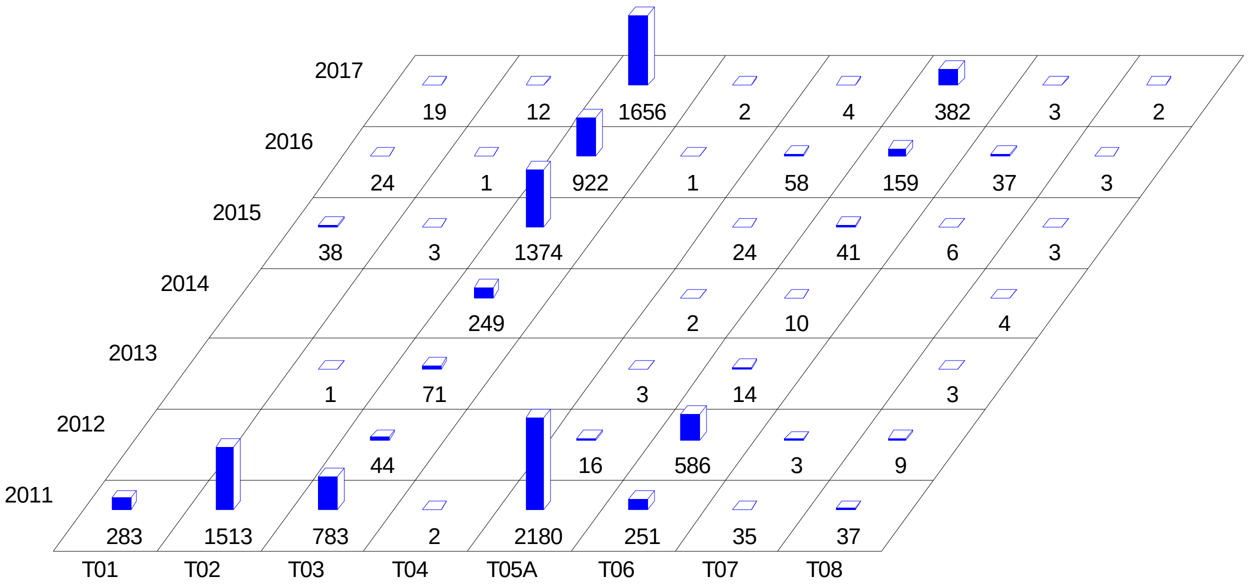


Figure 11. Spatial distribution of *Ampelisca* spp. at eight Boston Harbor stations (T01-T08), 2011-2017.

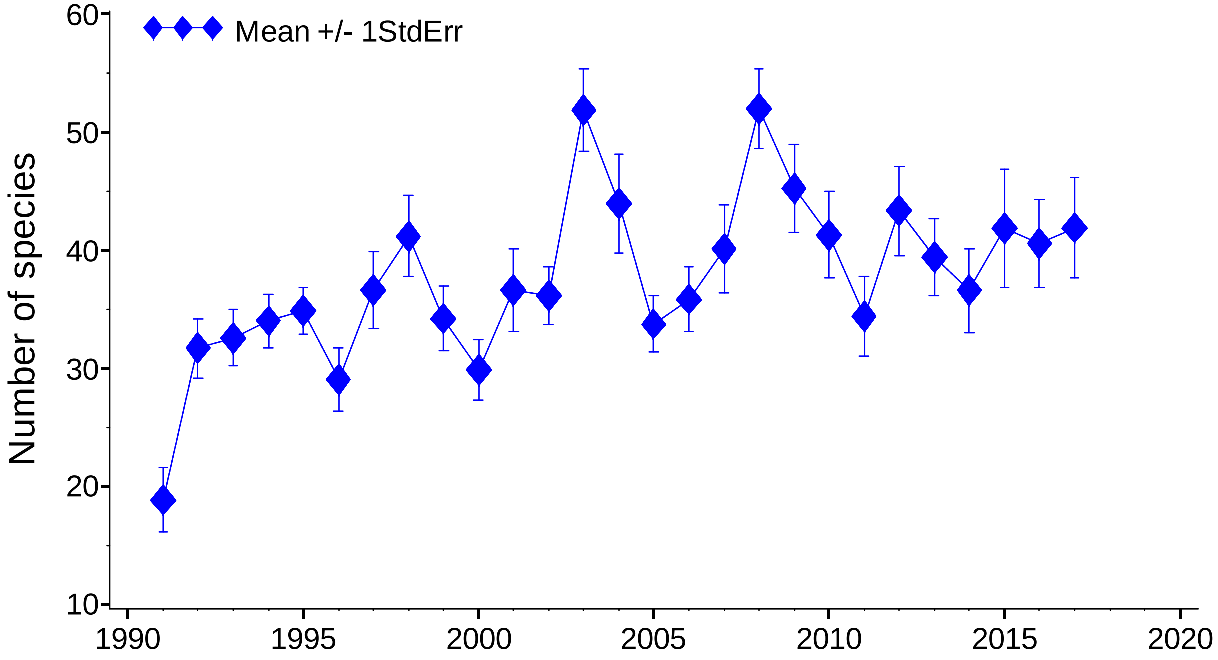


Figure 12. Mean species richness at eight Boston harbor stations (T01-T08), 1991-2017.

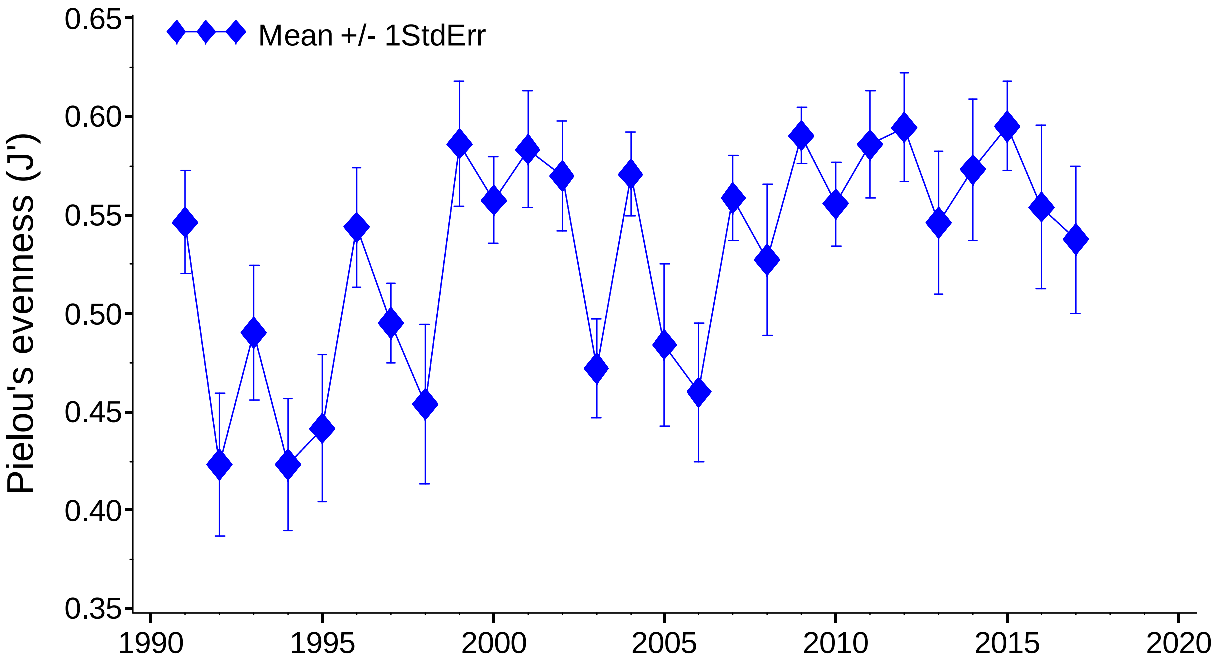


Figure 13. Mean community evenness at eight Boston Harbor stations (T01-T08), 1991-2017.

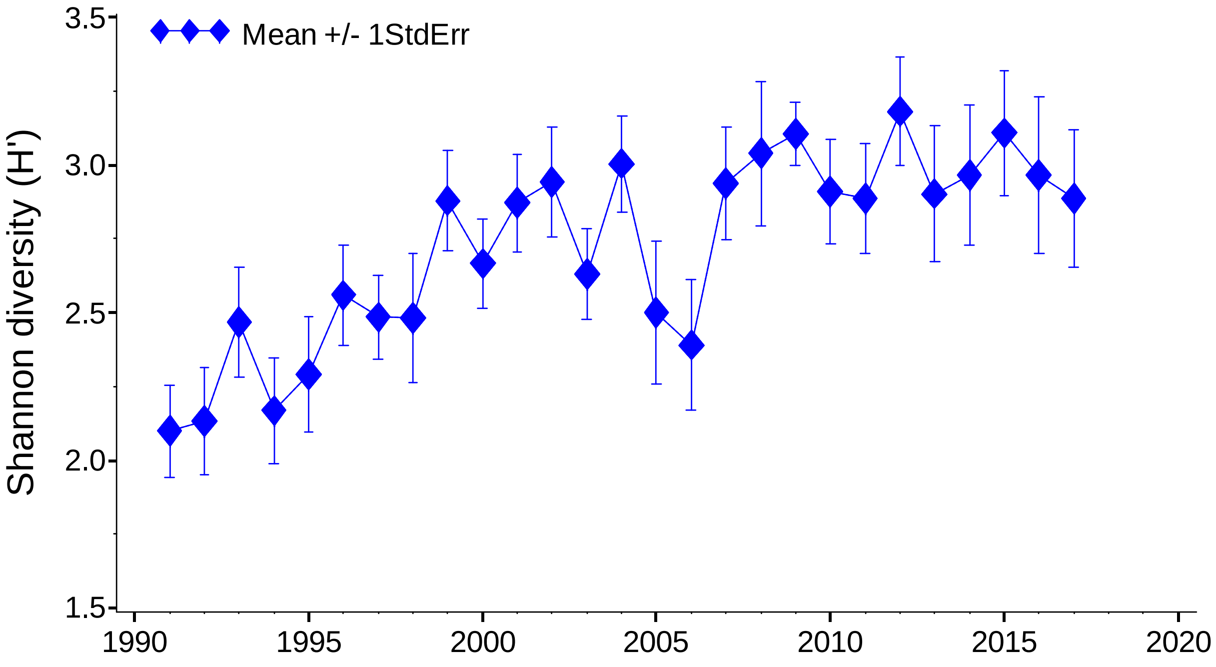


Figure 14. Mean Shannon-Weiner diversity at eight Boston harbor stations (T01-T08), 1991-2017.

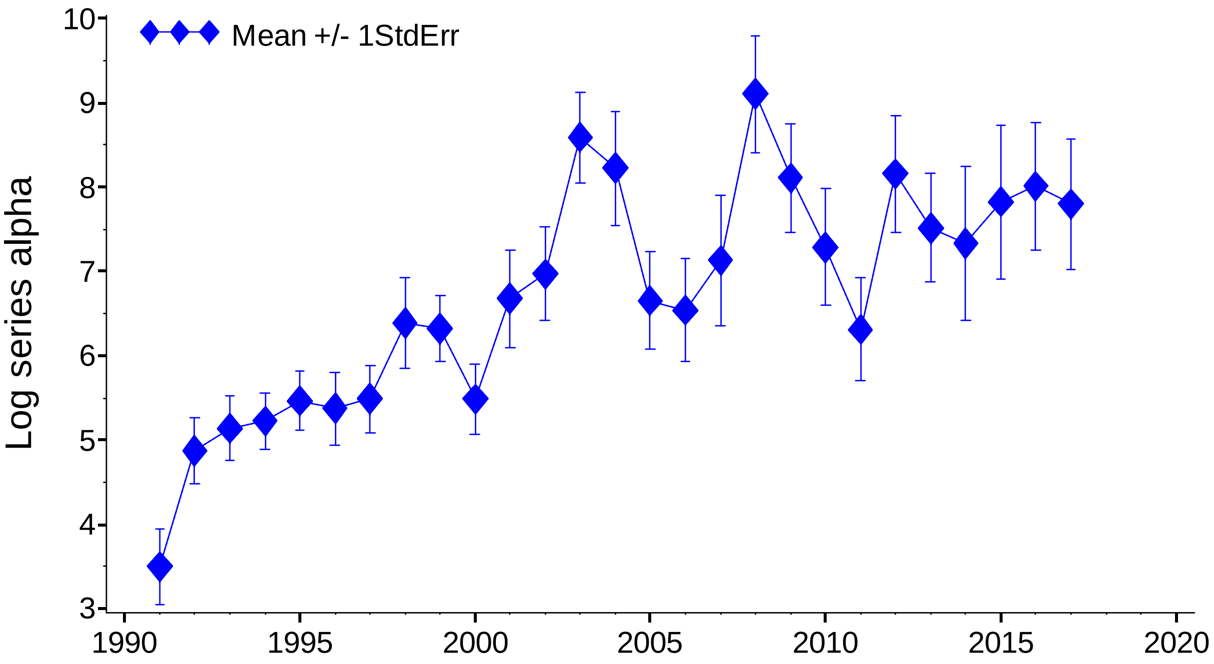


Figure 15. Mean log-series alpha diversity at eight Boston Harbor stations (T01-T08), 1991-2017.

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 and grouped together. Four main assemblages were identified in a cluster analysis of the 18 samples from 2017 (Figure 16). Patterns identified through cluster analysis were confirmed in the MDS ordination plot for the 2017 Harbor samples (Figure 16). All assemblages were dominated by polychaetes or oligochaetes. Spatial patterns in the faunal assemblages of Boston Harbor reflect a habitat gradient from species poor stations C019, T04, and T07, to more diverse stations in the mid to outer Harbor. The Group IA assemblage was found at outer Harbor Stations T08 and T05A; the Group IB assemblage was found at outer Harbor to mid-Harbor stations (T01, T02, T03, and T06); the Group IIA assemblage was found at Stations T07 (Quincy Bay) and C019 (Inner Harbor); and the Group IIB assemblage was found at Station T04, at the mouth of Savin Hill Cove, in Dorchester Bay. The assemblage at Station T04 is typically the most different from all of the others. This gradient was also observed in the community parameters (Section 3.2.1) and likely reflects differences in tidal flushing in the Outer Harbor compared to the Inner Harbor along with differing proximity to sources of organic inputs, nutrients, and other possible contaminants.

Main Group I encompassed six stations (T01, T02, T03, T05A, T06, and T08) and abundances averaged 2559.5 individuals across 50 species. Eight species (*Aricidea catherinae*, *Ameplisca* spp., *Polydora cornuta*, *Limnodriloides medioporus*, *Streblospio benedicti*, *Clymenella torquata, Scoletoma hebes,* and *Tubificoides intermedius*,) contributed 81% of the total abundance (Table 5). The deeper-dwelling polychaete *C. torquata* is considered an indicator of a stable community. Within Group I, Stations T05A and T08 were distinct enough to form Subgroup IA dominated by *Ameritella agilis, Tharyx acutus,* and *Polygordius jouinae* and characterized by moderately high species richness (averaging 43 species per collection). Subgroup IB was comprised of Stations T01, T02, T03, and T06 characterized by high abundance and species richness (averaging 53 species per collection). Dominants included *A. catherinae*, *Ameplisca* spp., *L. medioporus*, and *S. benedicti.* The main Group II consisted of Stations C019, T04, and T07 dominated by three species (*S. benedicti, Bipalponephtys neotena,* and *Cossura* sp. 1) which contributed 79% of the total abundance (Table 5). Stations C019 and T07 formed Subgroup IIA and were dominated by the three species that dominated the main Group II. This subgroup was characterized by low abundance and species richness (averaging 19.5 species per collection). Station T04 was distinct enough to form Subgroup IIB dominated by *S. benedicti* and *Tubificoides* sp. 2, total abundance was moderate and species richness was low. Sediment conditions, particularly percent fines and TOC were likely factors in distinguishing the benthic communities among the Boston Harbor stations. Subgroup IA (T05A and T08) was predominantly sand and very low TOC. Sediments at stations in Subgroup IB ranged from about 39 to 78% sand and moderate to low TOC (0.5 to 2.4%). Sediments at stations C019 and T07 (Subgroup IIA) and T04 (Subgroup IIB) were predominantly fines and TOC was higher than at other locations (Table 1).

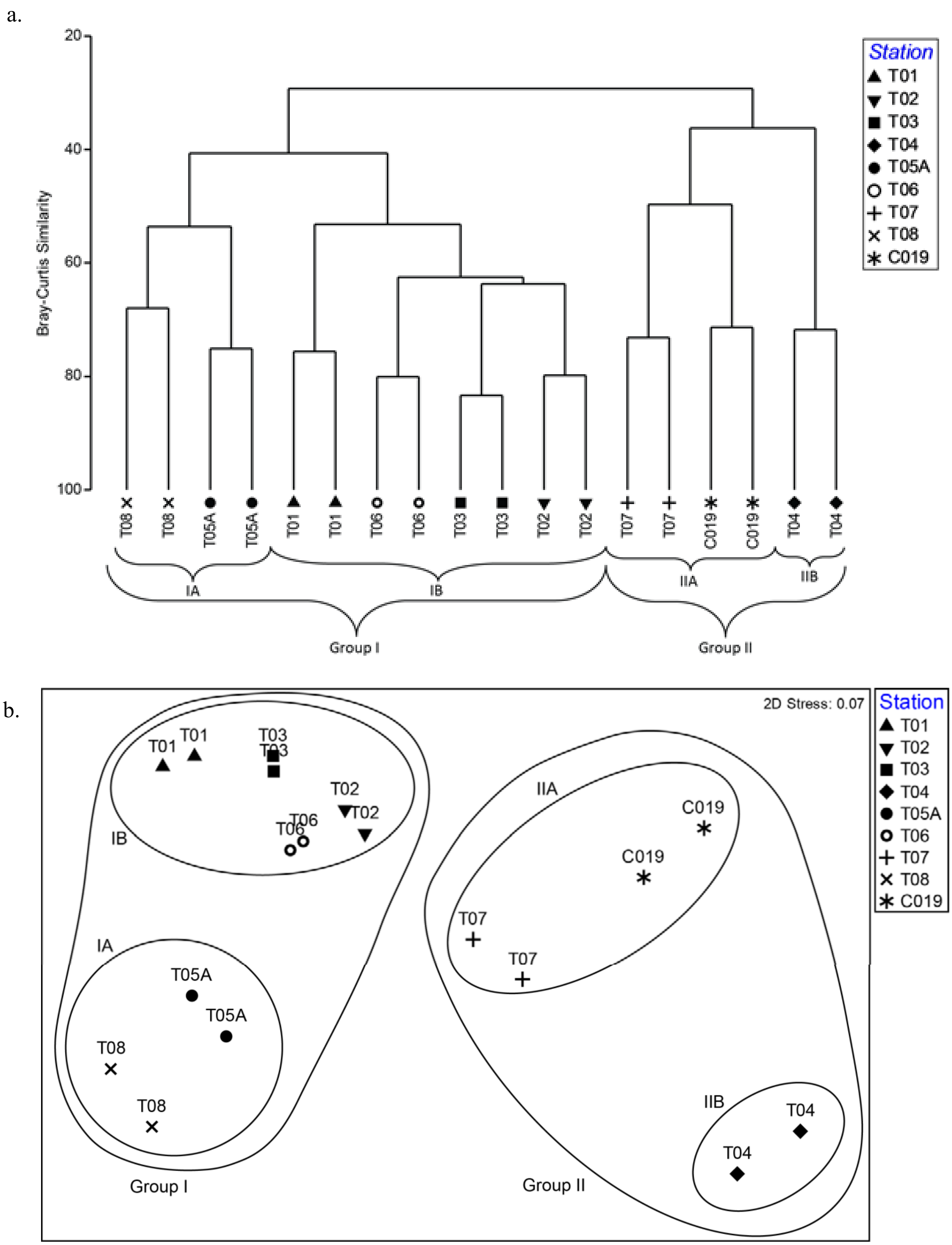


Figure 16. Results of (a) cluster analysis and (b) multidimensional scaling analysis of the 2017 infauna samples.

Table 5. Mean abundance of dominant taxa in 2017 Boston Harbor station groups defined by cluster analysis.

Major Taxon	Family	Species	I	IA[a]	IB[a]	II	IIA[b]	IIB[b]
Bivalvia	Lyonsiidae	*Lyonsia arenosa*	**13.8**	-	-	**0.2**	-	-
	Tellinidae	*Ameritella agilis*	**60.0**	146.3	16.9	**2.5**	2.8	2.0
Polychaeta	Capitellidae	*Mediomastus ambiseta*	**0.5**	-	-	**0.7**	-	-
		Mediomastus californiensis	**14.9**	-	-	**0.3**	-	-
	Cirratulidae	*Tharyx acutus*	**60.2**	145.0	17.8	**5.8**	5.8	6.0
	Cossuridae	*Cossura* sp. 1	**0.3**	-	0.5	**106.5**	159.8	-
	Hesionidae	*Microphthalmus pettiboneae*	**21.4**	2.0	31.1	**2.8**	4.3	-
	Lumbrineridae	*Scoletoma hebes*	**179.3**	4.0	267.0	**10.3**	15.5	-
	Maldanidae	*Clymenella torquata*	**186.6**	58.0	250.9	**0.5**	0.8	-
	Nephtyidae	*Bipalponephtys neotena*	**43.3**	-	65.0	**110.8**	159.8	13.0
		Nephtys incisa	**0.6**	-	-	**2.2**	-	-
	Orbiniidae	*Leitoscoloplos robustus*	**3.8**	-	-	**2.5**	-	-
	Paraonidae	*Aricidea catherinae*	**444.3**	3.8	664.6	**4.2**	6.0	0.5
	Phyllodocidae	*Hypereteone heteropoda*	**-**	0.3	-	**-**	-	1.5
		Phyllodoce mucosa	**26.1**	-	-	**-**	-	-
	Polygordiidae	*Polygordius jouinae*	**37.6**	112.3	0.3	**0.2**	0.3	-
	Spionidae	*Polydora cornuta*	**219.0**	88.8	284.1	**39.2**	53.5	10.5
		Pygospio elegans	**26.3**	-	-	**-**	-	-
		Spiophanes bombyx	**32.8**	97.0	0.8	**-**	-	-
		Streblospio benedicti	**210.8**	5.8	313.4	**634.0**	209.3	1483.5
	Terebellidae	*Polycirrus phosphoreus*	**10.4**	-	-	**1.5**	-	-
Oligochaeta	Tubificidae	*Limnodriloides medioporus*	**218.3**	4.5	325.3	**13.3**	19.3	1.5
		Naidinae sp. 1	**78.8**	70.8	82.9	**1.5**	2.3	-
		Tubificoides benedeni	**1.5**	4.5	-	**1.0**	-	3.0
		Tubificoides intermedius	**128.5**	39.3	173.1	**86.3**	129.5	-
		Tubificoides sp. 2	**-**	-	-	**49.8**	-	149.5
Amphipoda	Ampeliscidae	*Ampelisca* spp.	**345.7**	2.5	517.3	**1.5**	1.5	1.5
	Unciolidae	*Unciola irrorata*	**11.5**	-	-	**-**	-	-
	Idoteidae	*Edotia triloba*	**-**	15.8	0.6	**-**	-	-
	Diastylidae	*Diastylis polita*	**-**	20.8	-	**-**	-	-

[a] distinct subgroup of Group I

[b] distinct subgroup of Group II

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 2017, species richness was the highest of the harbor stations, evenness was average, and Shannon-Weiner diversity and log-series alpha was high at T01. All of these community parameters increased compared to 2016 (Pembroke et al. 2017). Mean abundance in 2017 increased compared to 2016 and was similar to the peak observed 2015 (Figure 17). Species richness and log-series alpha were on the high end of the range observed since the diversion (Figures 18 and 19) while Shannon-Weiner diversity and Pielou's evenness were about average for that period (Figures 20 and 21). Although mean log-series alpha was below the peak seen in 2015, it was one of the highest values observed since the diversion to the offshore outfall (Figure 19). In 2017, all of these community parameters except Pielou's evenness remained above 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*). Mean abundance declined from its 2013 peak in 2014 and 2015, but increased to average levels in 2016 and 2017 (Figure 17). Species richness also peaked in 2013 and decreased in both 2014 and 2015, reached average levels in 2016, and then declined again in 2017 (Figure 18). Log series alpha and Shannon-Weiner diversity reached their peak values in 2014, declining from 2015 through 2017 (Figures 19 and 20). Pielou's evenness reached its peak value in 2014, declined in 2015 and 2016, and then increased in 2017 (Figure 21). Despite decreasing values in some recent years, all diversity measures remained among the highest levels observed to date. The polychaete *Bipalponephtys neotena* (formerly called *Nepthys cornuta*) had represented the majority of the infauna found at Station C019 from 2004-2011 (Figure 22) but the relative abundance of this species has been substantially lower since 2012 (Pembroke et al. 2013). The community structure has varied since then with *C. anasimus* dominating in 2013 (Pembroke et al. 2014), no numerical dominant in 2014 (Pembroke et al. 2015), the oligochaete *Tubificoides intermedius* dominating in 2015, and *Polydora cornuta* in 2016. In 2017, *Cossura* sp 1 and *S. benedicti* dominated the infaunal community (Figure 22).

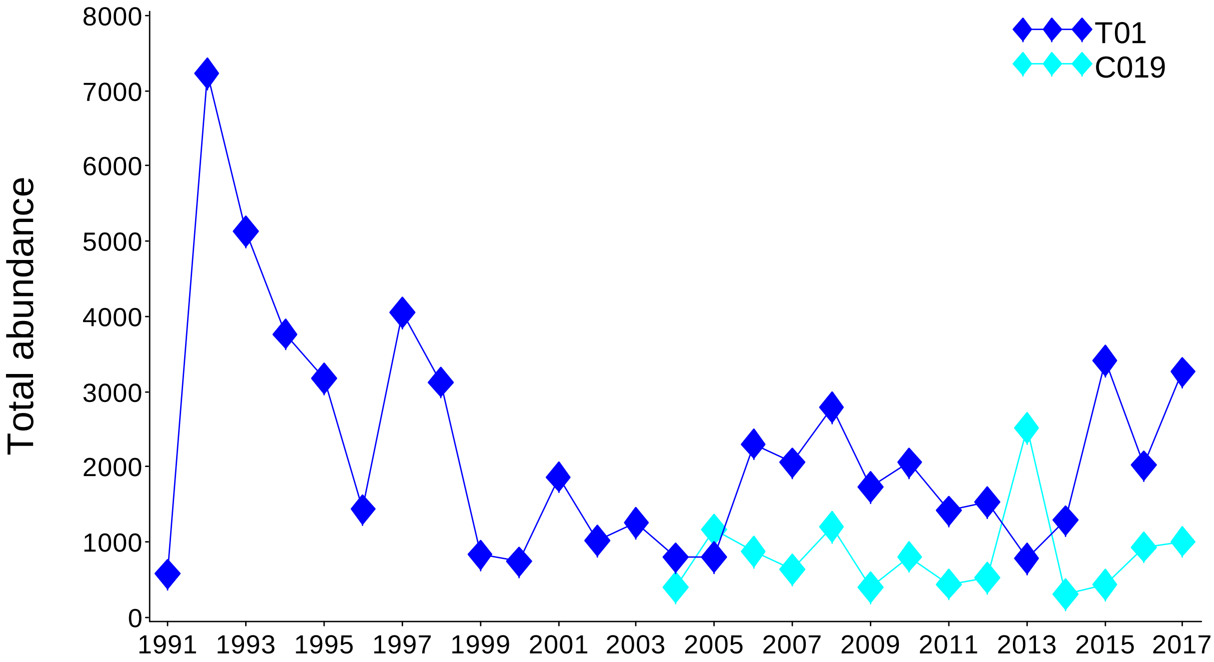


Figure 17. Mean total abundance at Boston Harbor Stations T01 and C019, 1991-2017.

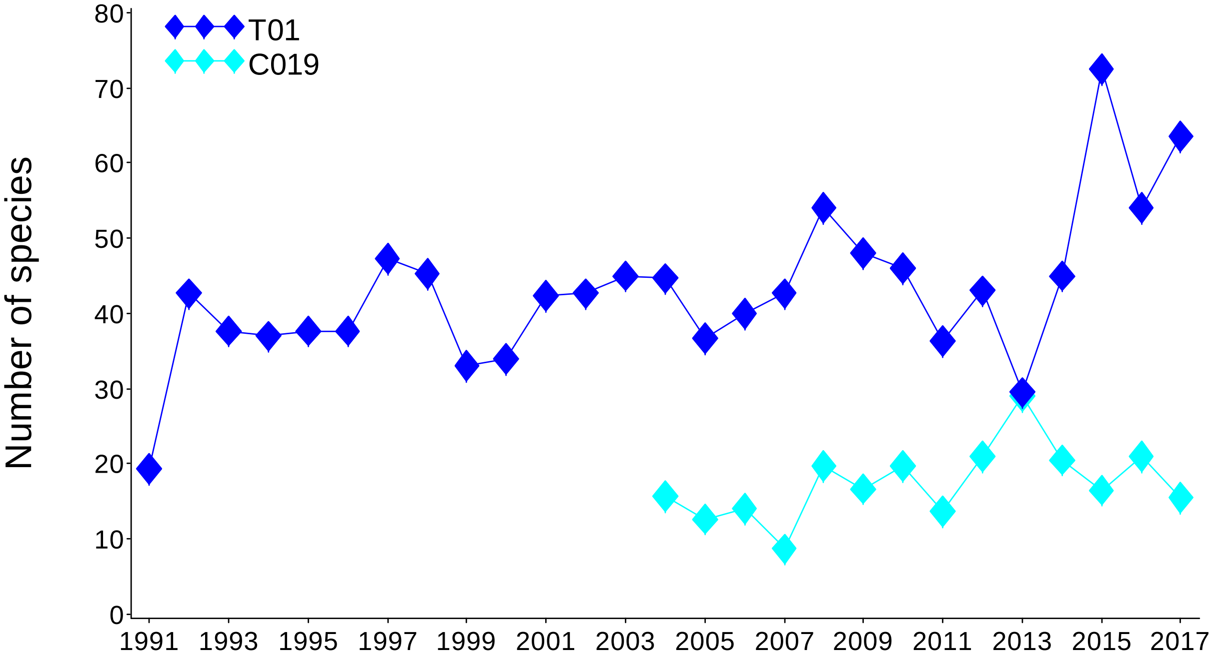


Figure 18. Mean species richness at Boston Harbor Stations T01 and C019, 1991-2017.

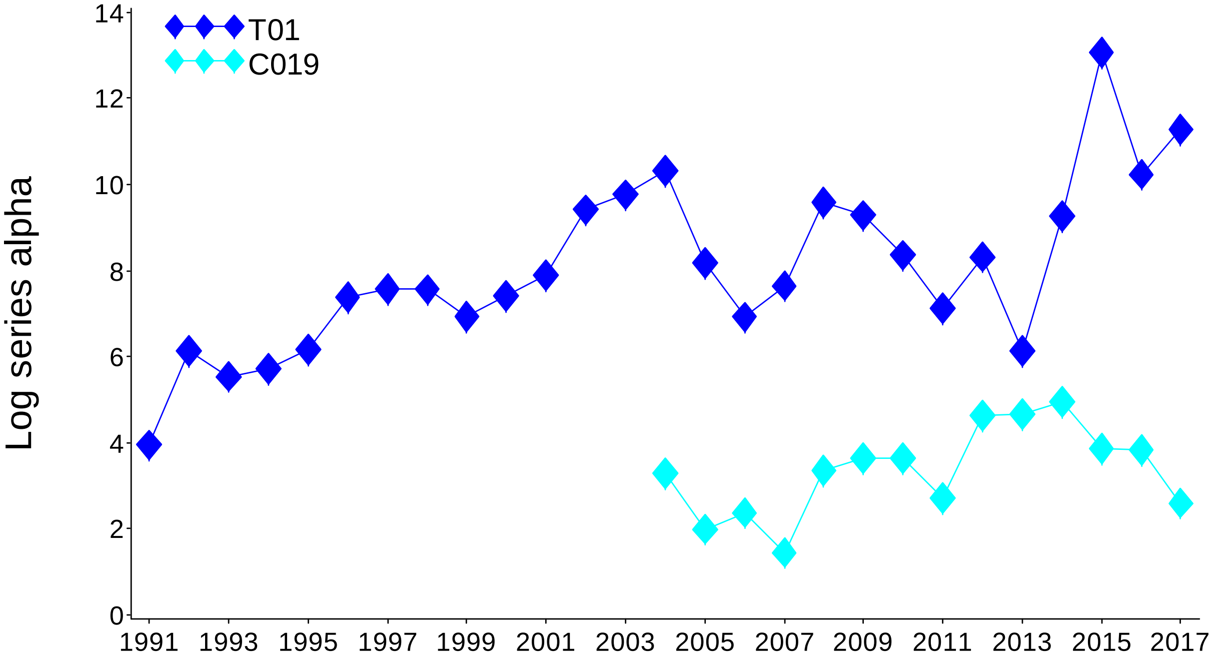


Figure 19. Mean log-series alpha diversity at Boston Harbor Stations T01 and C019, 1991-2017.

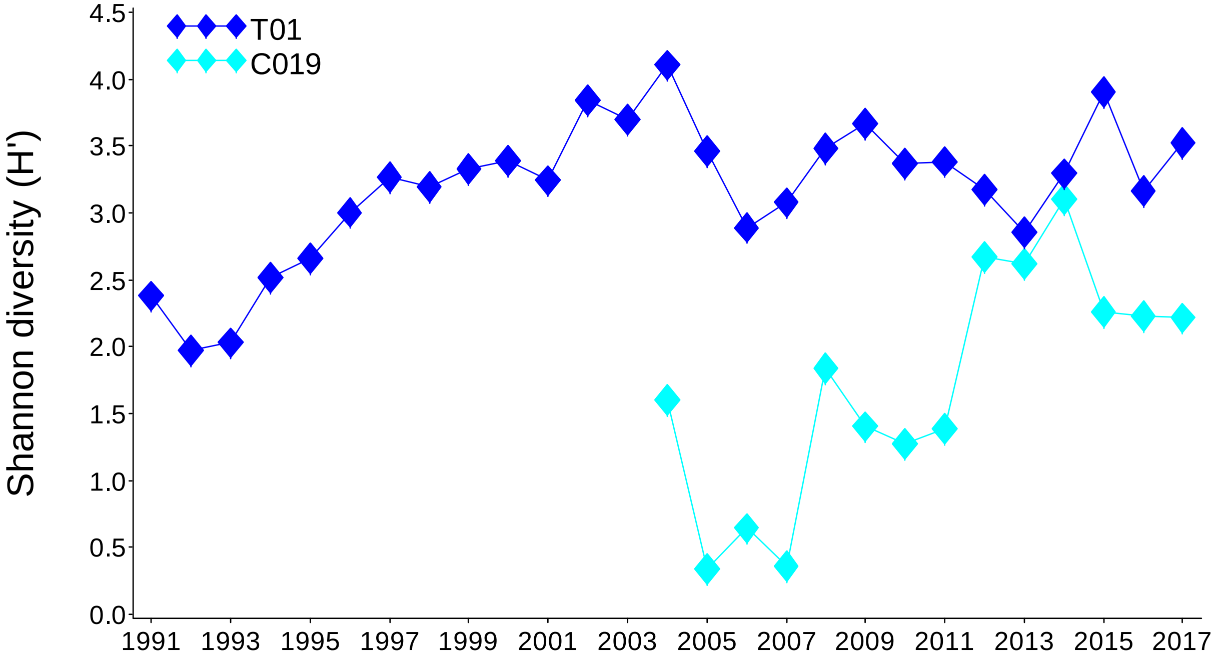


Figure 20. Mean Shannon-Weiner diversity at Boston Harbor Stations T01 and C019, 1991-2017.

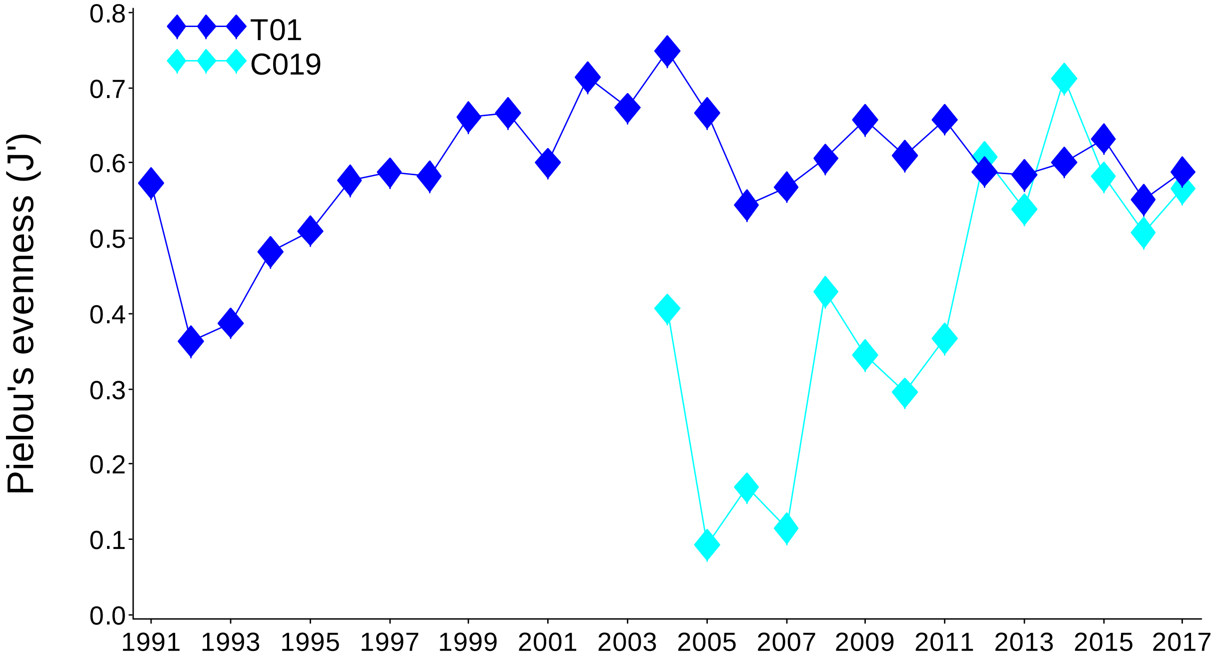


Figure 21. Mean evenness at Boston Harbor stations T01 and C019, 1991-2017.

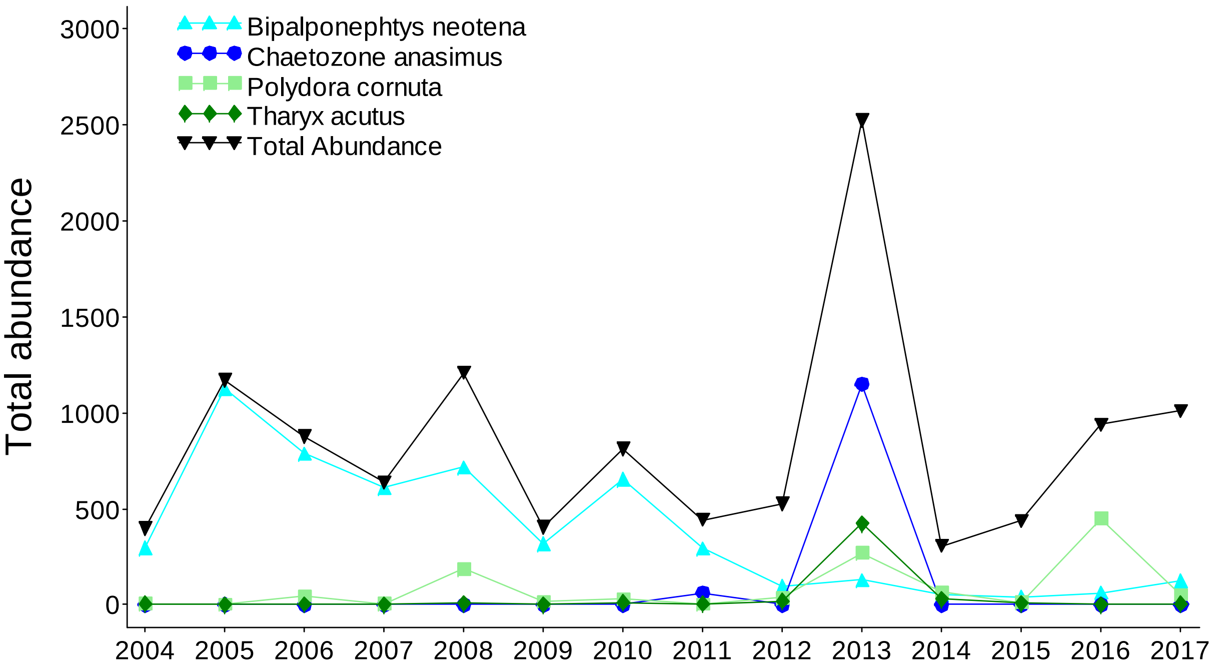


Figure 22. Mean abundance of *Bipalponephtys neotena* and other dominants and total community abundance at Station C019, 2004-2017.

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 for 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 2001-2017 were virtually the same as for 2001-2016 (Pembroke et al. 2017) 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 (prior to Dec. 1991)		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	2,537	125
Log-series alpha	4.2	0.3	5.5	0.2	6.2	0.3	7.6	0.2
Shannon-Wiener Diversity (H')	2.1	0.1	2.4	0.1	2.8	0.1	2.9	0.5
Pielou's Evenness (J')	0.48	0.02	0.47	0.01	0.58	0.02	0.55	0.01
Number of Species	25.5	2.1	34.7	1.1	33.6	1.7	41.2	0.9
Years included (with one year offset)	1991-1992		1993-1998		1999-2001		2002-2017	

3.3 Sediment Profile Imaging

Whole Harbor Patterns

Improvements in sewage treatment and relocation of outfalls within Boston Harbor in the 1990s with a diversion of all sewage in 2000 to an ocean outfall set the stage for recovery of pelagic and benthic habitats within the Harbor (Gallagher and Keay 1998, Oviatt et al. 2007, Diaz et al. 2008, Taylor 2010, Tucker et al. 2014). By the late 2000s much of the recovery in soft bottom benthic habitat quality in terms of benthos and sediment fluxes had taken place (Diaz et al. 2008, Tucker et al. 2014). From the early 2010s to 2017 there was year-to-year variation in patterns of benthic habitat quality and benthic communities with the general long-term trend of improvement for the whole Harbor (Pembroke et al. 2017).

Since 2003 the yearly average Organism Sediment Index (OSI), a measure of benthic habitat quality (Rhoads and Germano 1986), has remained above 6 (Figure 23). For soft sediment benthic habitats within northeastern estuarine and coastal ecosystems, such as portions of Boston Harbor, values of 6 and greater were associated with higher quality habitats with well-developed macrofaunal communities. An OSI <6 would indicate some form of stress was lowering benthic habitat quality (Rhoads and Germano 1986, Valente et al. 1992, Diaz et al. 2003). From the start of SPI monitoring to diversion OSI was variable and remained below the grand mean OSI of 6.5 for all stations and years. Much of the variability in OSI was related to the sequence of treatment upgrades prior to diversion as described by Taylor (2010). During post sludge disposal from 1992 to 1994 (Period IIA), OSI averaged <6. With implementation of full primary treatment 1995 to 1997 (Period IIB), OSI was slightly lower than the grand mean. With implementation of secondary treatment (Period III), OSI again declined to <6. After offshore diversion (Period IV), OSI started an upward trend that lasted through 2014 (Break Point Linear Regression, R^2 = 0.44, p = 0.007, N = 15). In 2015 and 2016, OSI declined below the grand mean which was a departure from the long-term trend of increasing OSI values but still represented improved benthic habitat quality over the early and late 1990s (Figure 23). In 2017, the annual average OSI increased to 7.4 primarily driven by increased aRPD (apparent color Redox Potential Discontinuity) layer thickness, which averaged

1.9 cm (SD = 1.04 cm) in 2016 and 2.4 cm (SD = 1.67 cm) in 2017 (Figure 24).

On a Harbor wide basis there were two significant runs of shallowing aRPD from 1992 to 2017 (Figure 24). The first occurred from 1995 to 2000 (Break Point Linear Regression, $R^2 = 0.91$, $p = 0.003$, $N = 6$) after the aRPD increased by 1.0 cm from 1.8 cm (SD = 1.22 cm) in 1994 to 2.8 cm (SD = 1.70 cm) in 1995. By 2000 the aRPD had declined to 1.9 cm (SD = 1.34 cm). The second run was from 2007 to 2017 (Break Point Linear Regression, $R^2 = 0.49$, $p = 0.015$, $N = 11$), and started with a 1.2 cm increase in aRPD layer thickness between 2006 and 2008. A similar but nonsignificant trend in aRPD occurred between 2001 and 2006 when the aRPD layer increased by 1.5 cm between 2000 and 2001 to the deepest annual mean for all monitoring years (3.4 cm, SD = 2.10 cm). Had the aRPD layer not shallowed by 1.5 cm in 2002, the 2001 to 2006 would have also been a significant declining run (Figure 24).

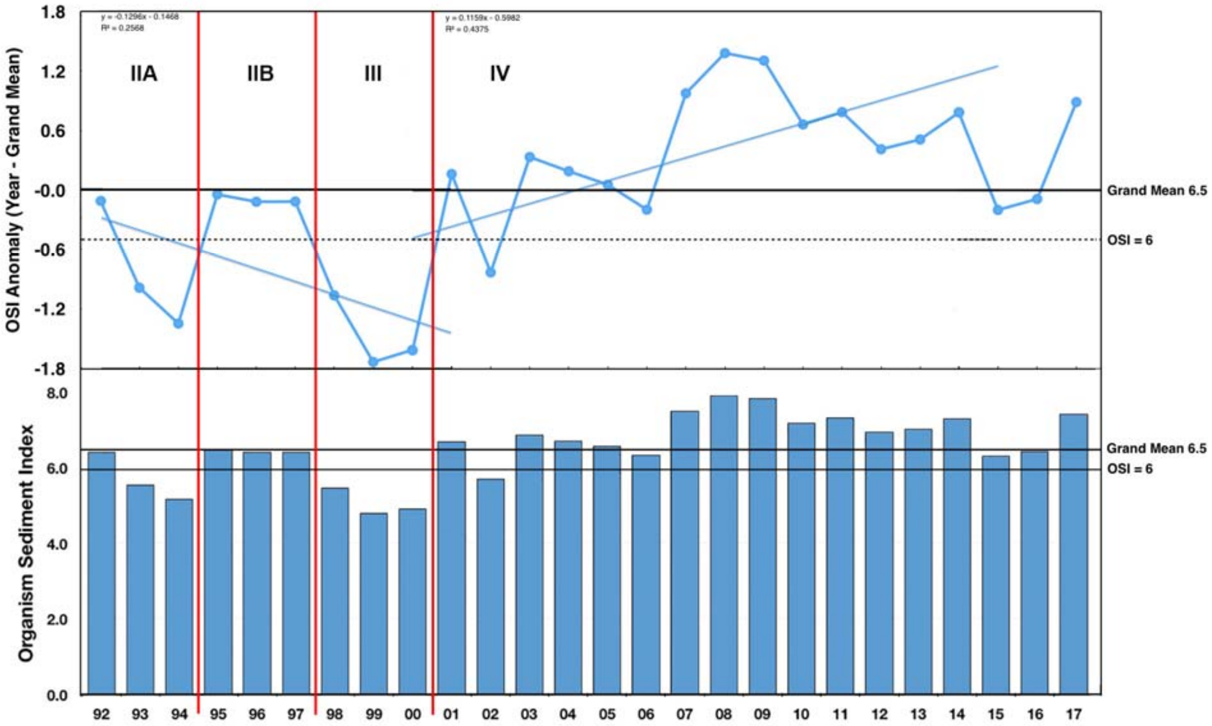


Figure 23. OSI anomaly (yearly - grand mean OSI) and annual means for all SPI stations in Boston Harbor over the 26 years of monitoring. Higher OSI years are positive and lower are negative values. Vertical lines separate periods of change in wastewater treatment based on Taylor (2010). IIA is post sludge disposal, IIB is full primary treatment, III is full secondary treatment, and IV is offshore diversion. OSI less than 6 indicates stressed benthic habitat.

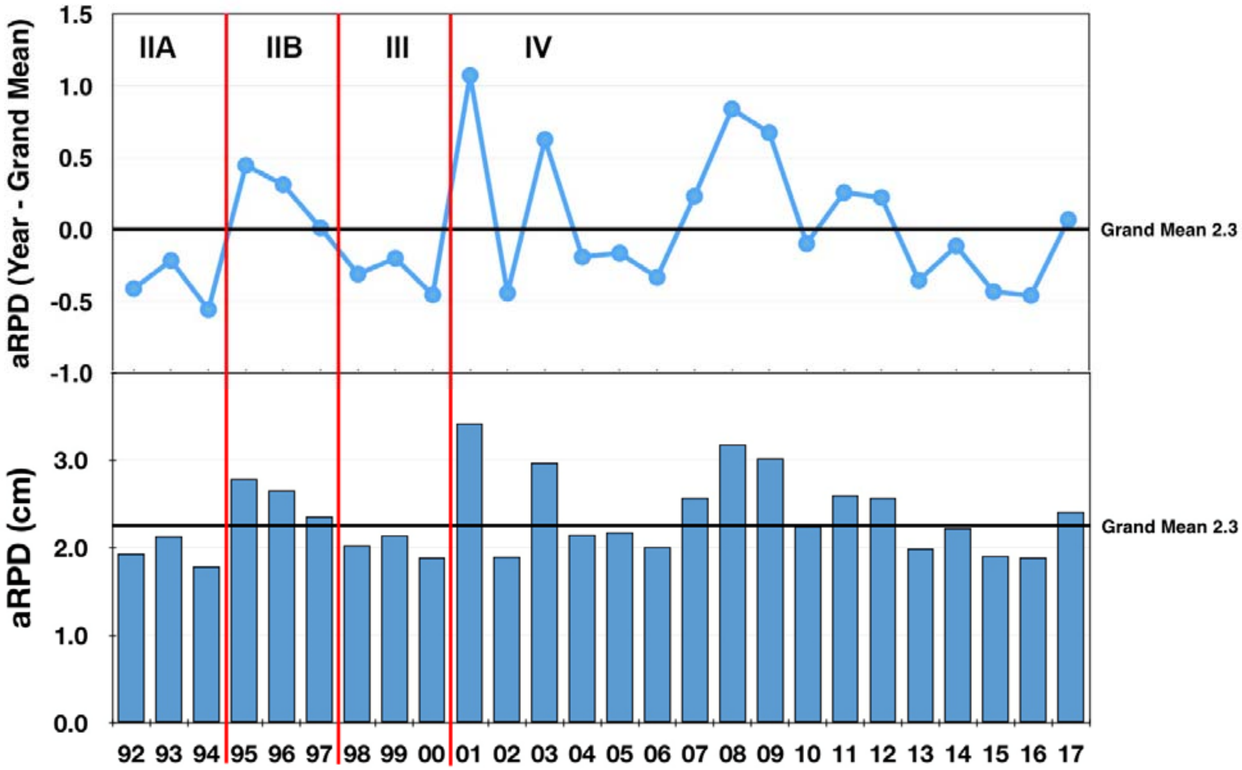


Figure 24. aRPD anomaly (yearly - grand mean aRPD) and annual means for all SPI stations in Boston Harbor over the 26 years of monitoring. Higher aRPD layer depth years are positive and lower are negative values. Vertical lines separate periods of change in wastewater treatment based on Taylor (2010). IIA is post sludge disposal, IIB is full primary treatment, III is full secondary treatment, and IV is offshore diversion.

This oscillating pattern in aRPD appeared loosely linked to biogenic activity and infaunal trophic groups. The depth of the aRPD layer increased as the number of oxic voids increased (r = 0.67, p = 0.001, N = 23). Most oxic voids were formed by feeding of larger head-down subsurface deposit feeders (for example the polychaete *Clymenella torquata*) or burrowing species that ventilate their burrows (for example the amphipod *Leptocheirus pinguis*). To assess effects of other trophic groups, infaunal species were assigned one of six groups based on Blake et al. (2008). From 1991 to 2001 the dominant trophic groups were the functionally related interface and suspension feeders. The numerical dominant taxa in each of these groups was the polychaete *Polydora cornuta* and the amphipod *Ampelisca* spp., respectively. The proportion of these groups gradually declined through to 2005 as the proportion of small subsurface deposit feeders (examples would be the oligochaete *Tubificoides intermedius* and polychaete *Aricidea catherinae*) increased (Figure 25). In 2007 the proportion of interface and suspension feeders again increased and then gradually declined through 2015 as subsurface deposit feeders increased. Both of these trophic cycles followed the aRPD layer cycles. The proportion of surface deposit feeders (for example the polychaete *Tharyx acutus*), omnivores/scavengers (for example the amphipod *Phoxocephalus holbolli*), and predators (for example the polychaete *Bipalponephtys neotena*) was usually under 10% of the fauna. The exception was for predators that were 23% to 41% of the fauna from 2005 to 2007 (Figure 25).

In addition to being a numerically dominant suspension feeder, *Ampelisca* spp. is also a key bioturbator as is the amphipod interface feeder *L. pinguis*. Both species tended to increase the depth of the aRPD when present in large numbers. The decline in these species from 1995 to 2000 was a large factor in the shallowing of the aRPD layer over this period. The numbers of *Ampelisca* spp. oscillated twice between 2007 and 2017 but its effect on the aRPD was not as clear as *L. pinguis*. In 2007 *L. pinguis* abundance started to increase and peaked at over 75,000 individuals per m^2 (ind m^{-2}) in 2008, then crashed in 2009 to 11,500 ind m^{-2}, and gradually declined through to 2017 to 300 ind m^{-2}. *L. pinguis* abundance and aRPD layer depth were strongly correlated over the entire monitoring period (r = 0.70, p = <0.001, N = 23). The same was not the case for *Ampelisca* spp. abundance (r = 0.17, p = 0.438, N = 23) even though its population peaked for a second time at over 185,000 ind m^{-2} between 2009 and 2011 and then declined (Figure 26).

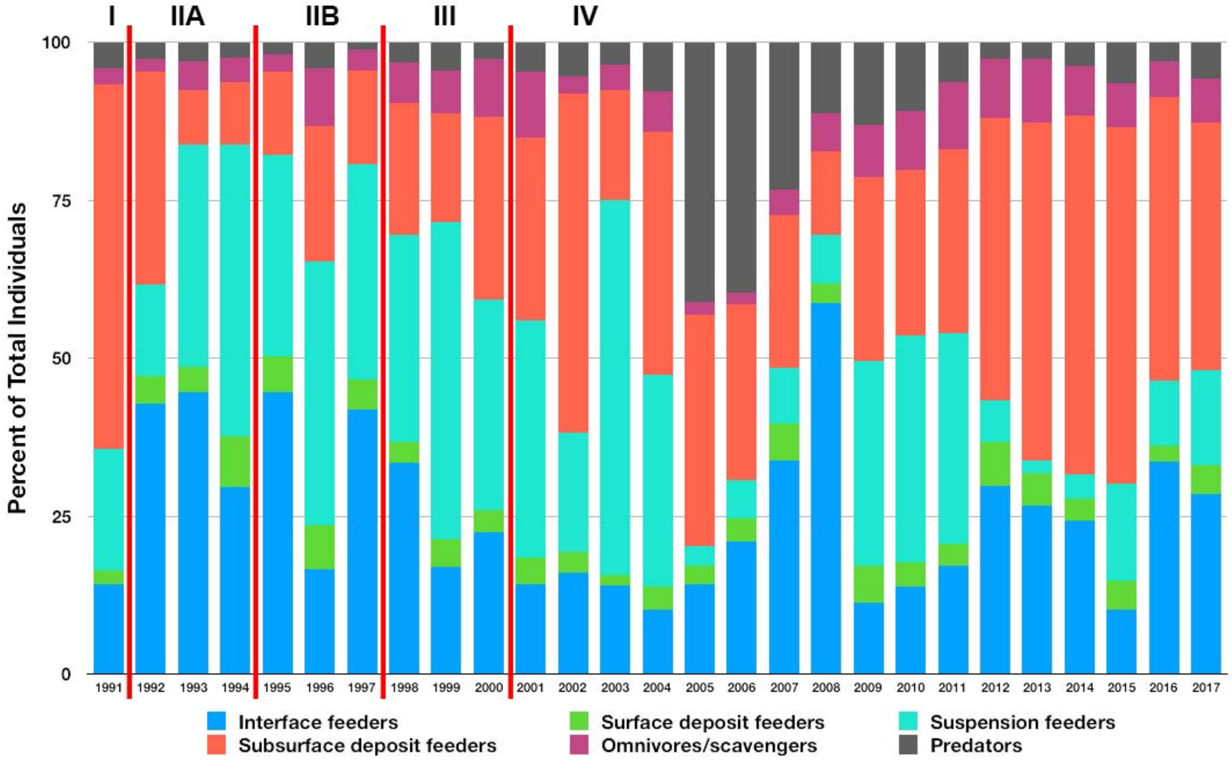


Figure 25. Percentage of trophic groups for all benthic stations in Boston Harbor (Based on Blake et al. 2008). Vertical lines separate periods of change in wastewater treatment based on Taylor (2010). I is digested sludge discharge, IIA is post sludge discharge, IIB is full primary treatment, III is full secondary treatment, and IV is offshore diversion.

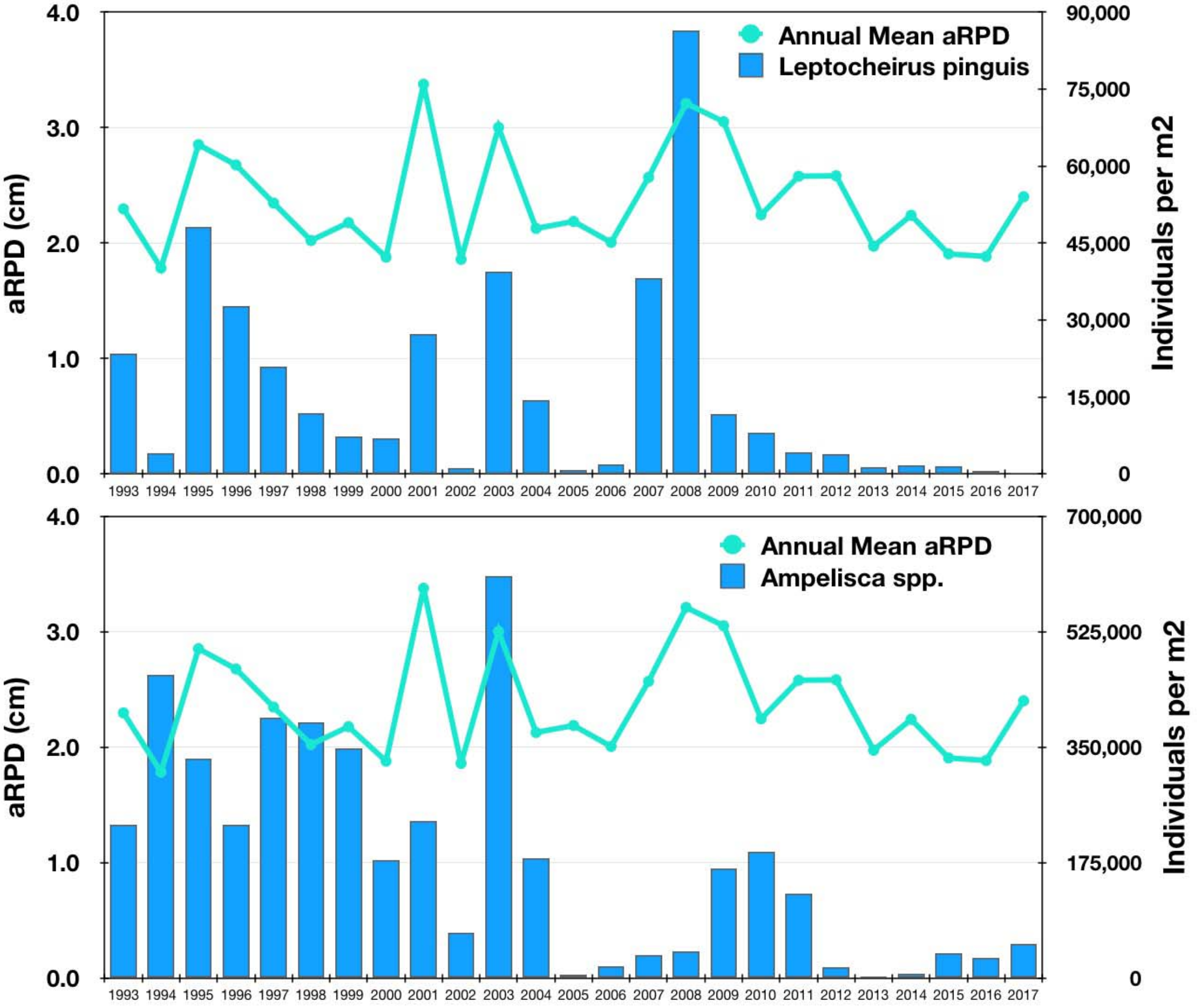


Figure 26. Abundance of *Leptocheirus pinguis* and *Ampelisca* spp. relative to the mean annual aRPD layer depth.

Improvements in wastewater treatment and moving the outfall offshore did result in improvements in benthic habitats within Boston Harbor by favoring processes that enhance bioturbation or the mixing of sediment by organisms, which has led to more aerobic sediment conditions, particularly for outer Harbor regions (Taylor 2010, Tucker et al. 2014). Superimposed on effects of wastewater treatment on benthic habitat conditions was the effect of major storm events. Butman et al. (2008) ranked storms occurring in Massachusetts Bay from 1990 to 2006 by wind stress and wave-generated bottom stress. A storm was defined based on bottom-wave stress at a water depth of 30 m as a period when the bottom stress caused by waves was greater than 0.1 Pascal (Pa) for at least 6 h. Their integrated excess bottom stress caused by waves (IWAVE) calculations for 30 m depth were summarized and compared to processes structuring surficial sediments derived from SPI for the period 1992 to 2006 (Nestler et al. 2018).

Particulate organic carbon (POC) and total nitrogen (TN) loading to the harbor were highly correlated (data from 1992 to 2006: $r = 0.92$, $p = <0.001$, $N = 15$) and declined through time (Taylor 2010; Table 7). When processes structuring surficial sediments were compared with POC and IWAVE (from 1998 to 2006, the period all three parameters were measured), the odds of a station being physically dominated increased with declining POC (logistic regression, ChiSq = 21.8, $p = <0.001$, df = 1) and increased storm strength (higher IWAVE; logistic regression, ChiSq = 6.6, $p = 0.010$, df = 1). The opposite of physical process dominance would be dominance by biological processes (Figure 27). For 2005, the highest IWAVE year, the odds of a station being physically dominated was also the highest at 1.65 (Figure 28). Lowest odds of physical dominance occurred in 1999, which had the lowest IWAVE, when almost all of Harbor stations were biologically dominated (59 of 60 stations). From 1998 to 2017 the highest odds for physical dominance of surface sediments was 60 and occurred in 2015 when 60 of 61 stations were physically dominated. This dramatic increase in odds was consistent with the stormy winter of 2014-2015 (R. Geyer, personal communication). Strong northeasters in October and February, a northwester in March, and a late northeaster in June all mixed the water column to depths greater than all of Boston Harbor. The last of these storms occurred two months prior to August 2015 sampling and likely affected surficial sediments by redistributing fine-grained sediments and destroying biogenic structures.

Amphipod Patterns

Much of the recovery in benthic habitat quality can be seen in the dynamics of the tube building amphipod *Ampelisca* spp., the most abundant taxa (Figure 29), and the burrowing amphipod *L. pinguis*, the ninth most abundant (Figure 30). Over the 26 years of SPI monitoring, biogenic activity associated with the presence of *Ampelisca* spp. had the most influence on benthic habitat quality followed by *L. pinguis* (Diaz et al. 2008, Tucker et al. 2014). *Ampelisca* spp. construct tubes about 2 to 3 cm long and 2-3 mm wide at the mouth end, flattened laterally, and composed of a grey, non-chitinous, parchment-like material and fine sand grains (Mills 1967). Tubes can extend up to a cm above the sediment surface with the flat sides oriented perpendicular to the current. At high densities this orientation enhances feeding and also increases sediment deposition around the tubes to counteract their tendency to wash-out. *Ampelisca* spp. suspension feed from the top of their tubes (Mills 1967). *L. pinguis* construct low stability U-shaped burrows in muddy sediments, which can extend up to 10 cm below the sediment surface (Thiel 1999). It pumps water through its burrow to feed on suspended particles (Thiel 1997, Shull et al. 2009).

Sometime between 1990 and 1992, when the SPI monitoring started, there was an increase in the occurrence of *Ampelisca* spp. tube mats (Figure 31). 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 likely in response to a combination of factors, relocation of Nut Island outfalls to Deer Island, implementation of full primary treatment, and lower storm intensity (Figure 32). It is possible that prior to outfall relocation and other improvements in treatment levels, either organic or pollutant loading was too high for *Ampelisca* spp. to thrive. *Ampelisca* spp. do have a life history that reflects a combination of opportunism in responding to organic matter (McCall 1977) and sensitivity to pollutants (Wolfe et al. 1996). *L. pinguis* is also considered a contaminant sensitive species (Chang et al. 1992). As the organic and pollutant loading declined with implementation of full secondary treatment and diversion of sewage offshore, primary production within the Harbor declined (Oviatt et al. 2007, Taylor

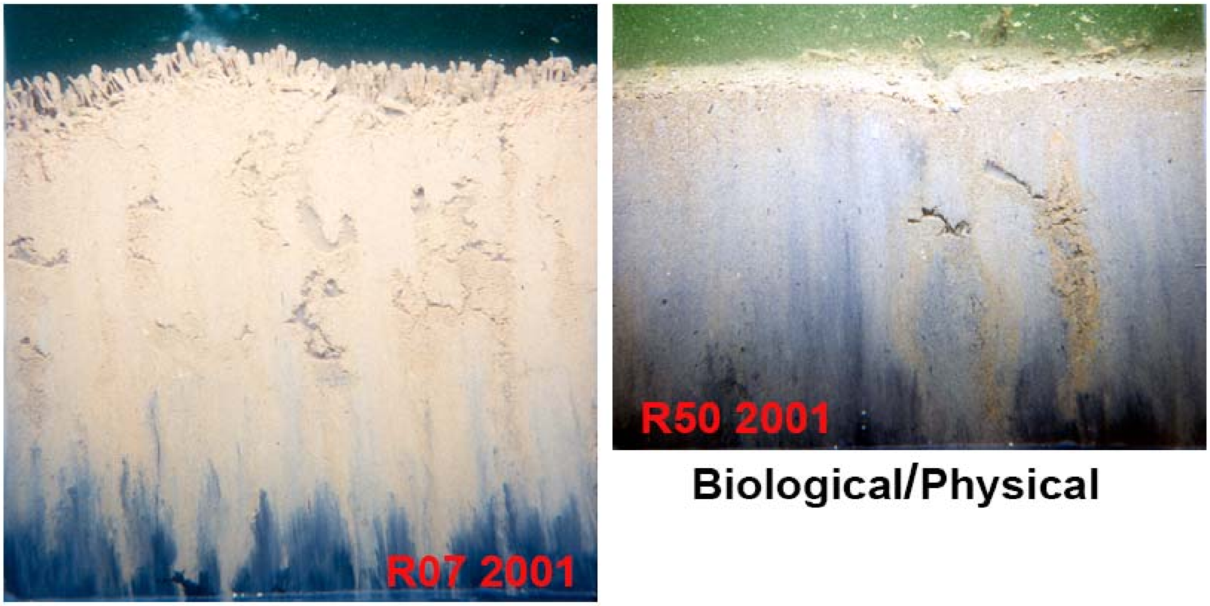
Table 7. Loading and storm data compared to odds of a Harbor station having a sediment surface that was physically dominated and the odds of an *Ampelisca* spp. tube mat occurring.

August Sample Year	Loading Period*	POC Loading* (Ton/d)	Total N Loading* (Ton/d)	Phytoplankton Biomass* (Chl-a ug/l)	IWAVE** Oct-Jan (Pa h)	IWAVE** Feb-Apr (Pa h)	IWAVE** May (Pa h)	IWAVE ** Sum (Pa h)	Odds of Physical Dominated Surface	Odds of *Ampelisca* Mat
1991	I	90	23							
1992	IIA	57	21		116	0	0	118		0.38
1993	IIA	60	23		160	0	0	162		0.85
1994	IIA	63	24		63	86	0	151		1.50
1995	IIB	45	24	7.6	39	0	0	41		1.61
1996	IIB	59	30	5.5	36	0	0	38		1.61
1997	IIB	47	25	7.4	52	94	0	148		1.07
1998	III	37	25	7.0	120	69	0	192	0.20	0.94
1999	III	17	18	6.8	0	0	0	3	0.02	0.71
2000	III	15	14	6.0	0	32	0	35	0.30	0.71
2001	IV	6	4	3.3	0	109	0	113	0.35	1.00
2002	IV	6	3	6.0	0	0	0	4	0.67	0.30
2003	IV	6	5	4.2	49	0	0	53	0.62	0.43
2004	IV	8	5	4.2	114	0	0	118	0.45	0.15
2005	IV	6	5	3.0	159	27	76	266	1.03	0.00
2006	IV	6	3	3.0	53	0	0	57	0.53	0.03
2007	IV	5	5	3.5					1.65	0.05
2008	IV			0.3					3.36	0.20
2009	IV			3.6					2.21	0.11
2010	IV			3.0					3.07	0.36
2011	IV			3.3					1.90	0.53
2012	IV			3.6					2.39	0.53
2013	IV			5.5					14.25	0.02
2014	IV			5.0					14.25	0.07
2015	IV								60.00	0.03
2016	IV								2.81	0.42
2017	IV								2.81	0.49

* Data from Taylor 2010

* * Data from Butman et al. 2008

2010) as did mat densities of *Ampelisca* spp. in SPI. The odds of a station having a tube mat declined with declining POC (logistic regression, ChiSq = 78.4, p = <0.001, df = 1). Abundance of both amphipod taxa also declined in benthic samples (Figure 26). The decline in mats started in 1998 and by 2005 no tube mats were observed. Amphipod abundance followed a similar pattern with declines starting a few years earlier.



Biological/Physical

Biological

Physical

Figure 27. Examples of stations at which various degrees of biological and physical processes dominated sediment surfaces.

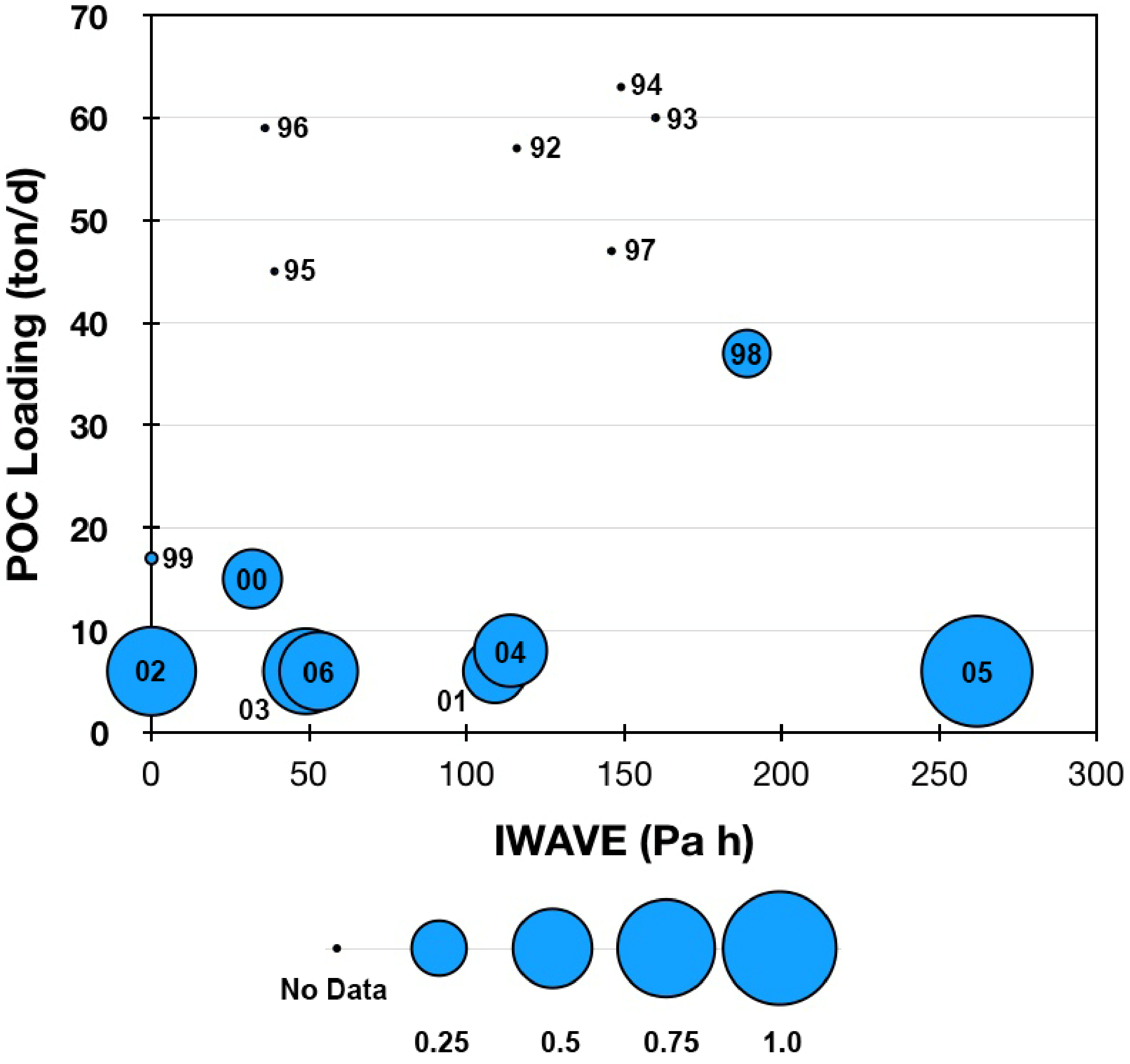


Figure 28. Odds of a station having surface sediments dominated by physical processes relative to particulate organic carbon (POC, from Taylor 2010) loading to Boston Harbor and cumulative storm strength (IWAVE, from Butman et al. 2008) from 1998 to 2006. Dots are years with no data for odds from 1992 to 1997.

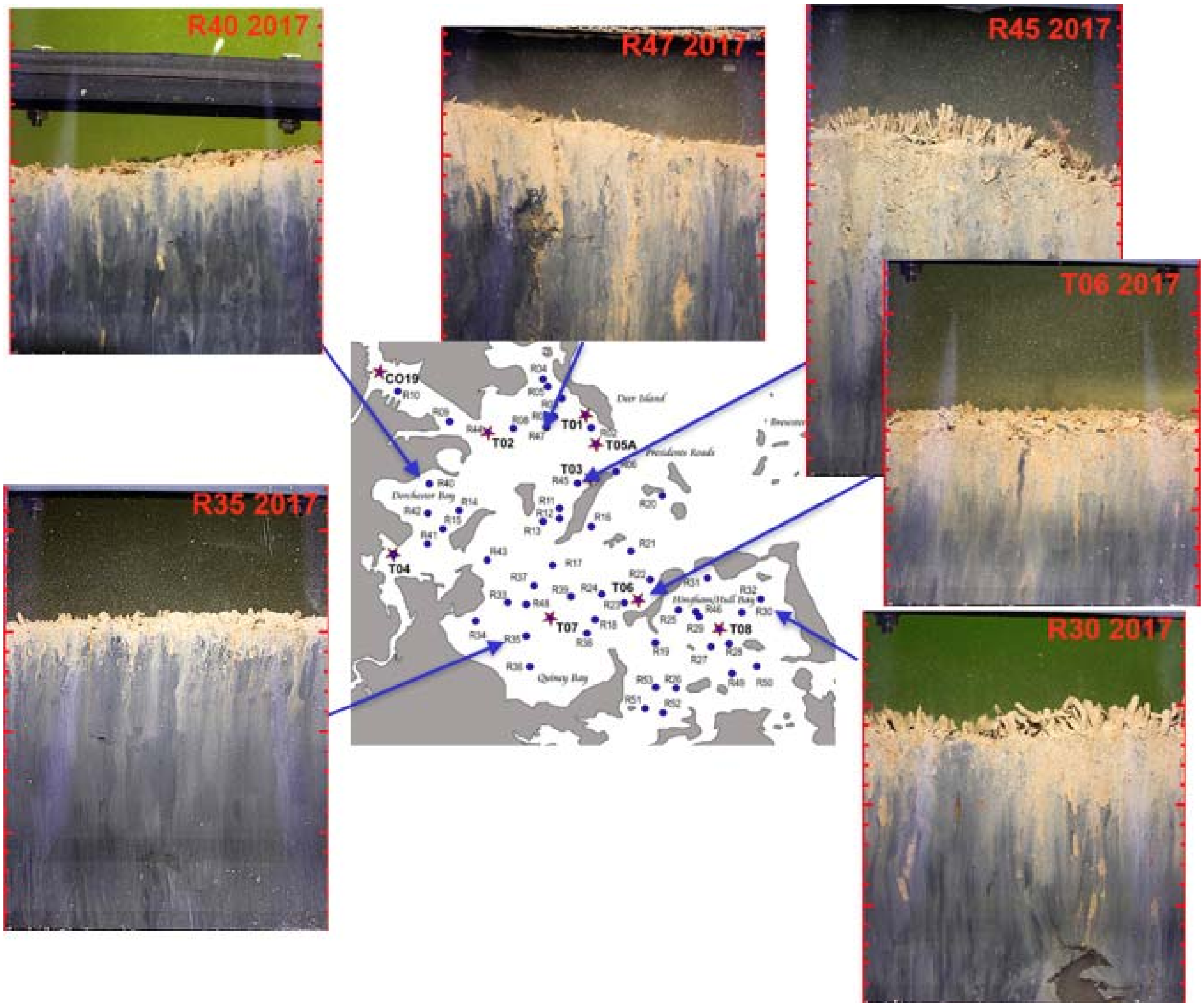


Figure 29. Examples of *Ampelisca* spp. tube mat for 2017. Longer tubes occurred at outer Harbor stations. Scale on side of image is in cm.

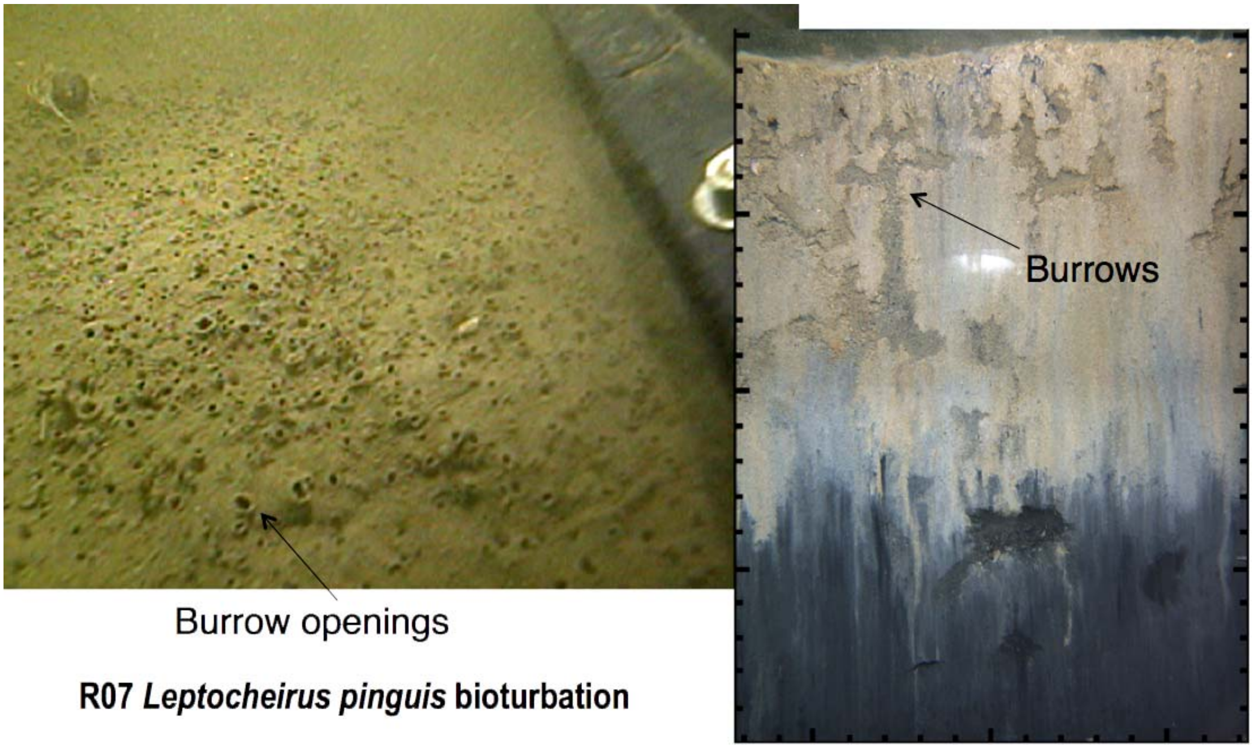


Figure 30. Highly bioturbated sediments at Station R07 in 2008 caused by high densities of the burrowing amphipod *Leptocheirus pinguis*.

The loss of tube mats in 2005 was associated with bottom-wave stress from a series of strong storms that occurred in winter 2004-5 and spring 2005, the last occurring in May less than three months before the August sampling. Cumulatively these storms had the highest IWAVE (266 Pa h total) between 1992 and 2006 (Butman et al. 2008; Table 7). The odds of a station having a tube mat declined with increasing IWAVE (logistic regression, ChiSq = 5.3, p = 0.022, df = 1). Another factor contributing to the decline in amphipod mats and amphipods in 2005 was the lowest primary production measured between 1992 and 2005 (Oviatt et al. 2007). *Ampelisca* spp. tube mats reappeared 2006 and increased to levels seen in the late 1990s by 2011 and 2012. In 2013 no tube mats were observed for the second time in the 26-year monitoring record as the abundance of both amphipods again declined. In 2014 tube mats reappeared at four stations, two stations in 2015, 18 stations in 2016, and were present at 20 stations in 2017. The size of the tubes, and by implication the size of the amphipods, did vary by Harbor region with largest, longest tubes found in the outer Harbor (Figure 29).

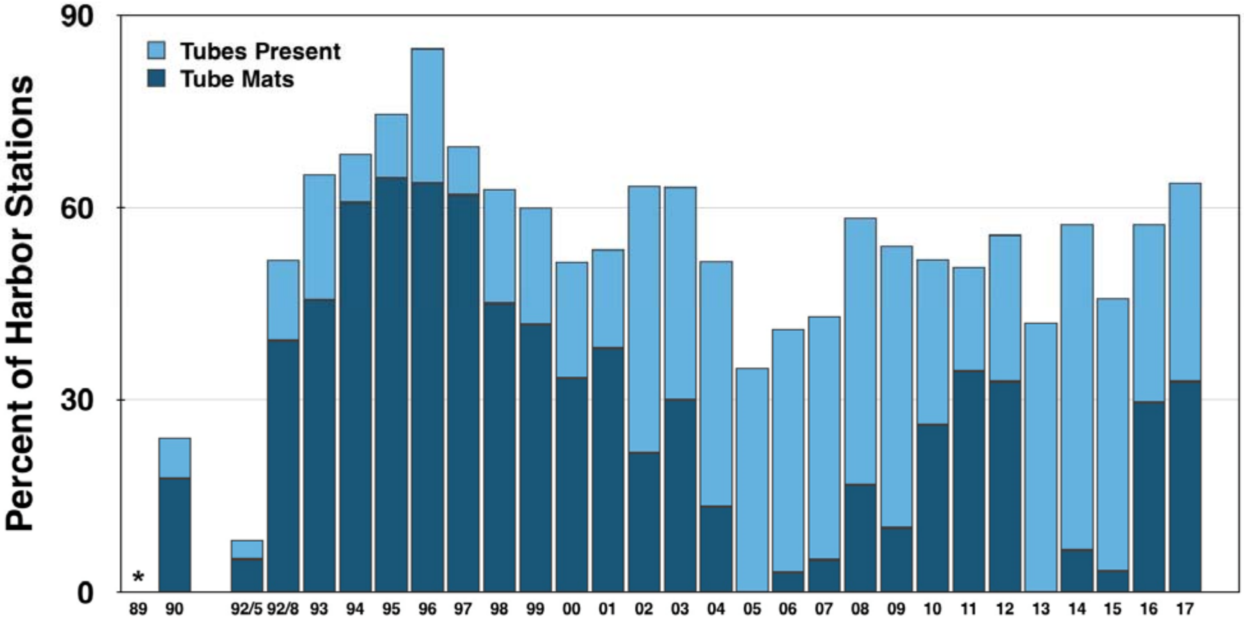


Figure 31. Histogram of *Ampelisca* spp. tubes present at Harbor stations. Mat densities of tubes are the bottom part of the bar in dark blue. There are no data from 1989 or 1991. There were two sample periods in 1992, spring and summer (92/8). *SPI collected in 1989 did not appear to have *Ampelisca* tubes, but live mussel beds and high densities of long thin polychaete tubes at many stations (SAIC 1990).

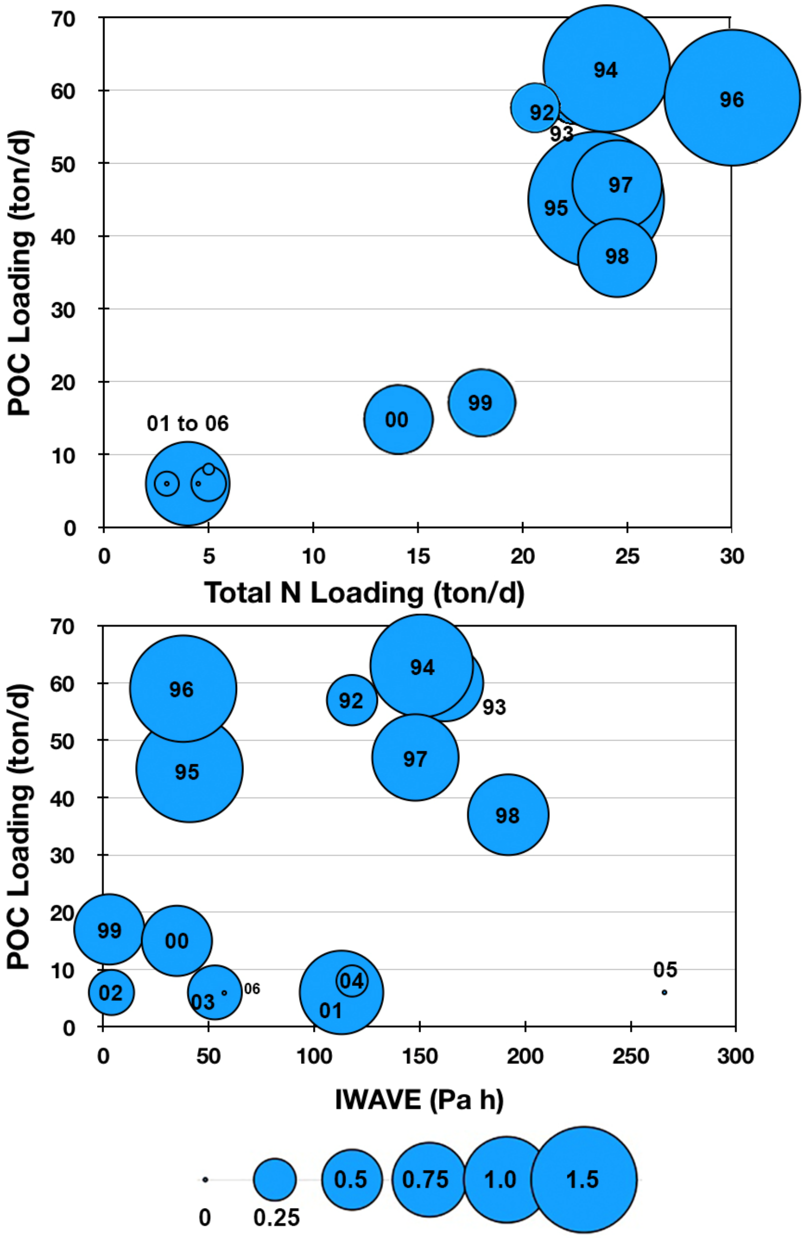


Figure 32. Odds of a station having an *Ampelisca* spp. tube mat relative to particulate organic carbon (POC) and total nitrogen (Total N, both from Taylor 2010) loading to Boston Harbor, and cumulative storm strength (IWAVE, from Butman et al. 2008) from 1992 to 2006.

3.4 Regional Harbor Patterns

Gradients of benthic habitat quality in Boston Harbor continue to exist, driven primarily by distance from the Harbor mouth. Dividing the Harbor into nine regions, lowest benthic habitat quality was along the inner western side of the Harbor and highest along the eastern outer side (Table 8, Figures 33 and 34). For seven of nine regions, lowest habitat quality occurred prior to diversion. Lowest habitat quality at stations off Long Island occurred in 2005 and was likely related to strong storms that occurred in winter 2004-5 and spring 2005 (Butman et al. 2008). Stations in Nantasket Roads had lowest habitat quality in 2006 and was likely related to longer-term improvements in water quality. Discussion of long-term patterns for all regions follows.

Table 8. OSI summarized by Boston Harbor region from 1993 to 2017. Regions are arranged from lowest to highest OSI. OSI value below six indicates stressed benthic habitat.

Harbor Region	Minimum of All Years		Maximum of All Years		Grand Mean All Years	2016	2017	Delta (2017-2016)	N
Dorchester Bay	2.1	1998	7.2	2005	4.9	4.2	6.5	2.3	7
Inner Harbor	3.0	1995	8.1	2014	5.5	6.2	6.2	0.0	3
Hingham Bay	2.8	1999	7.9	2007	5.5	6.5	7.1	0.6	7
Quincy Bay	3.3	1994	8.4	2008	5.9	5.6	6.6	0.9	10
President Roads	2.9	1999	9.3	2007	6.6	7.3	7.8	0.4	3
Deer Island Flats	3.6	1993	9.0	1997	6.9	6.9	7.3	0.4	8
Off Long Island	6.2	2005	9.4	2009	7.4	6.7	7.5	0.8	8
Hull Bay	5.9	1999	8.8	2017	7.5	7.7	8.9	1.2	9
Nantasket Roads	5.8	2006	9.8	2008	7.8	8.1	8.8	0.7	6

Stressed benthic habitat conditions continued to dominate the seven stations in Dorchester Bay for 2017 (Table 8, Figure 35). From 1992 to 2017 the grand mean OSI for Dorchester Bay was 4.9 (SD = 1.38) with Periods IIA and III being the lowest. By 2005, five years after diversion, benthic habitats improved with annual OSIs above 6 where it basically remained until 2012 when OSI again declined. Much of the pattern in OSI could be attributed to variation in aRPD layer depth around the grand mean of 1.5 cm (SD = 0.57 cm) with the thinnest layers in Periods II and III and increases into Period IV. Advancement of estimated successional stage toward equilibrium Stage III from 2005 to 2009 produced the highest benthic habitat quality for Dorchester Bay. Estimated successional stage tended to decline after 2010. Poorest habitat quality was consistently found at Station T04 which always appeared to have Stage I pioneering communities except for 1996 when Stage II amphipod tubes were present (Figure 35). Using CT scans of sediment cores Shull et al. (2009) found burrow density at Station T04 to be 184 burrows m^{-2} in 2003 and 79 burrows m^{-2} in 2007. They attributed the low burrow numbers in 2007 to an anoxic event as they could not identify any infauna large enough to belong to these burrows. It is likely that most of these burrows were gas track created when methane bubbles percolate through the sediment. Gas voids were a common feature in SPI from Station T04 (Figure 35). But improvements in habitat quality did occur as OSI for T04 was positively correlated with community structure variables of evenness (r = 0.56, p = 0.004, N = 24) and Shannon-Wiener diversity (r = 0.56, p = 0.004, N = 24), and negatively correlated with total abundance (r = -0.69, p = <0.001, N =24). After diversion, Stations R14, R40 and R41 exhibited the most improvement in Period IV relative to Periods II and III.

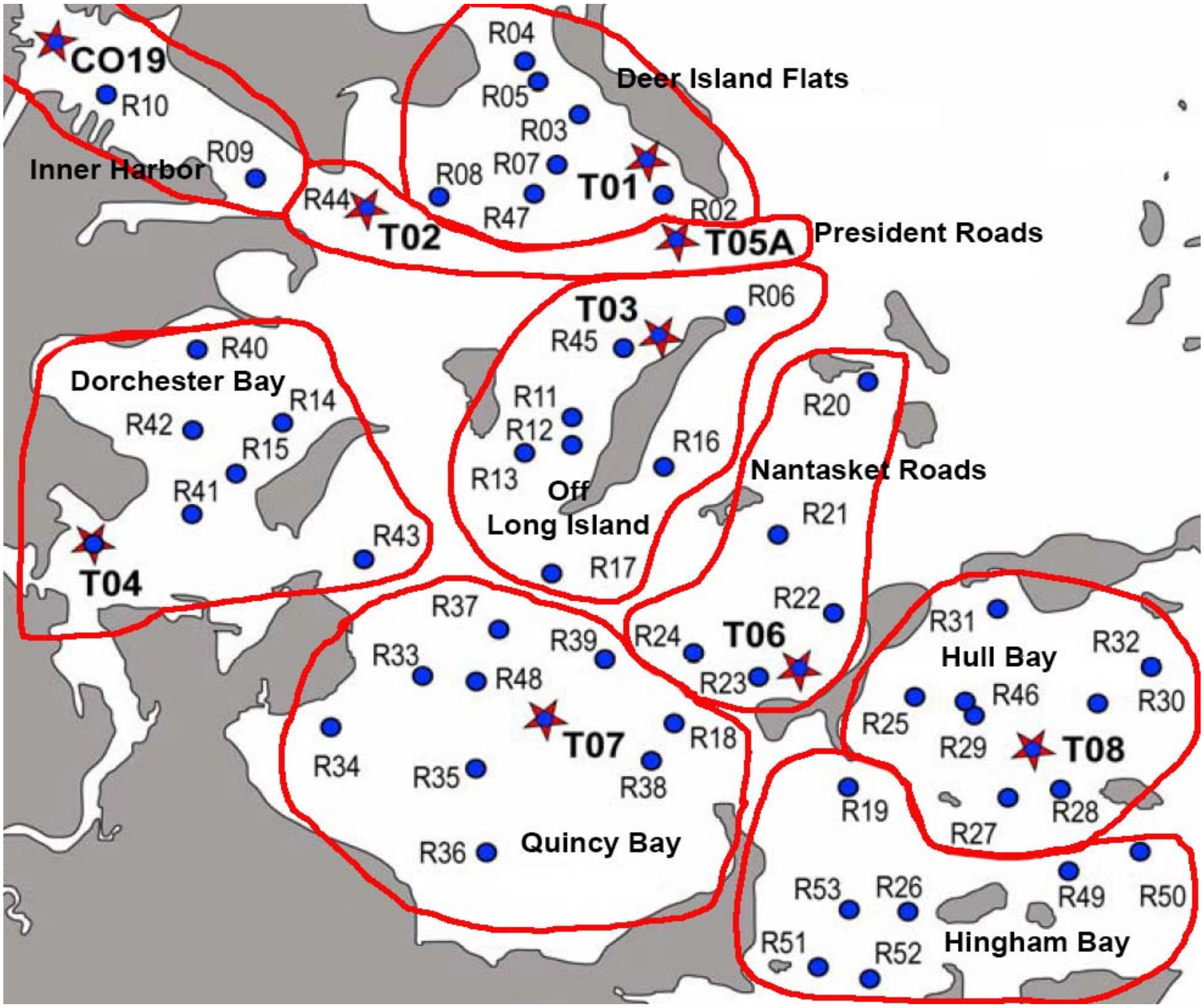


Figure 33. SPI (circles) and grab (stars) stations in defined Boston Harbor regions.

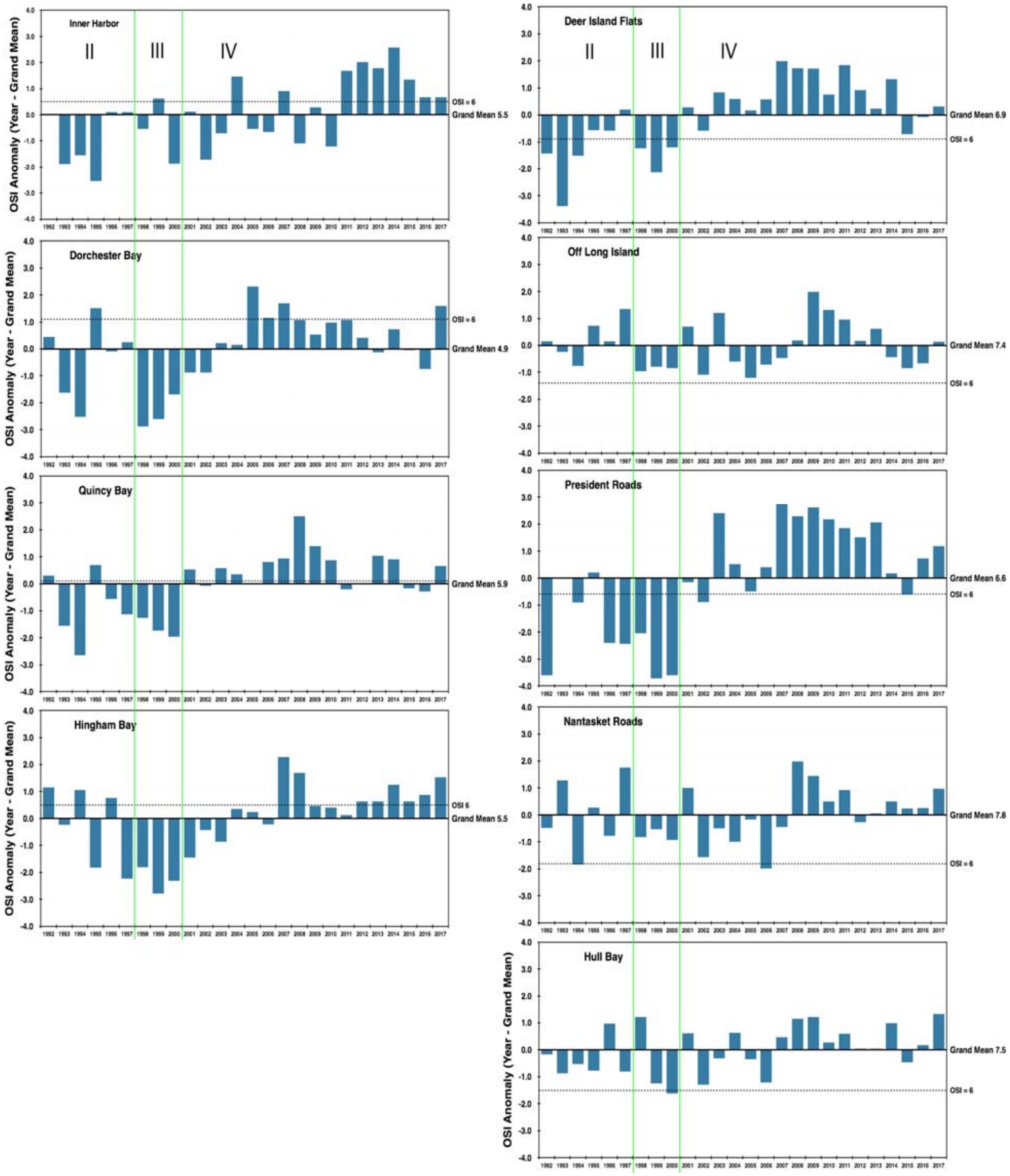


Figure 34. Organism Sediment Index anomaly (yearly mean - grand mean OSI) for Boston Harbor regions over the 26 years of SPI monitoring. Higher OSI years are positive and lower are negative values. OSI values below 6 indicate poorer benthic habitat quality. Vertical lines separate periods of change in wastewater treatment based on Taylor (2010). Period II is post sludge disposal to full primary treatment, III is full secondary treatment, and IV is offshore diversion.

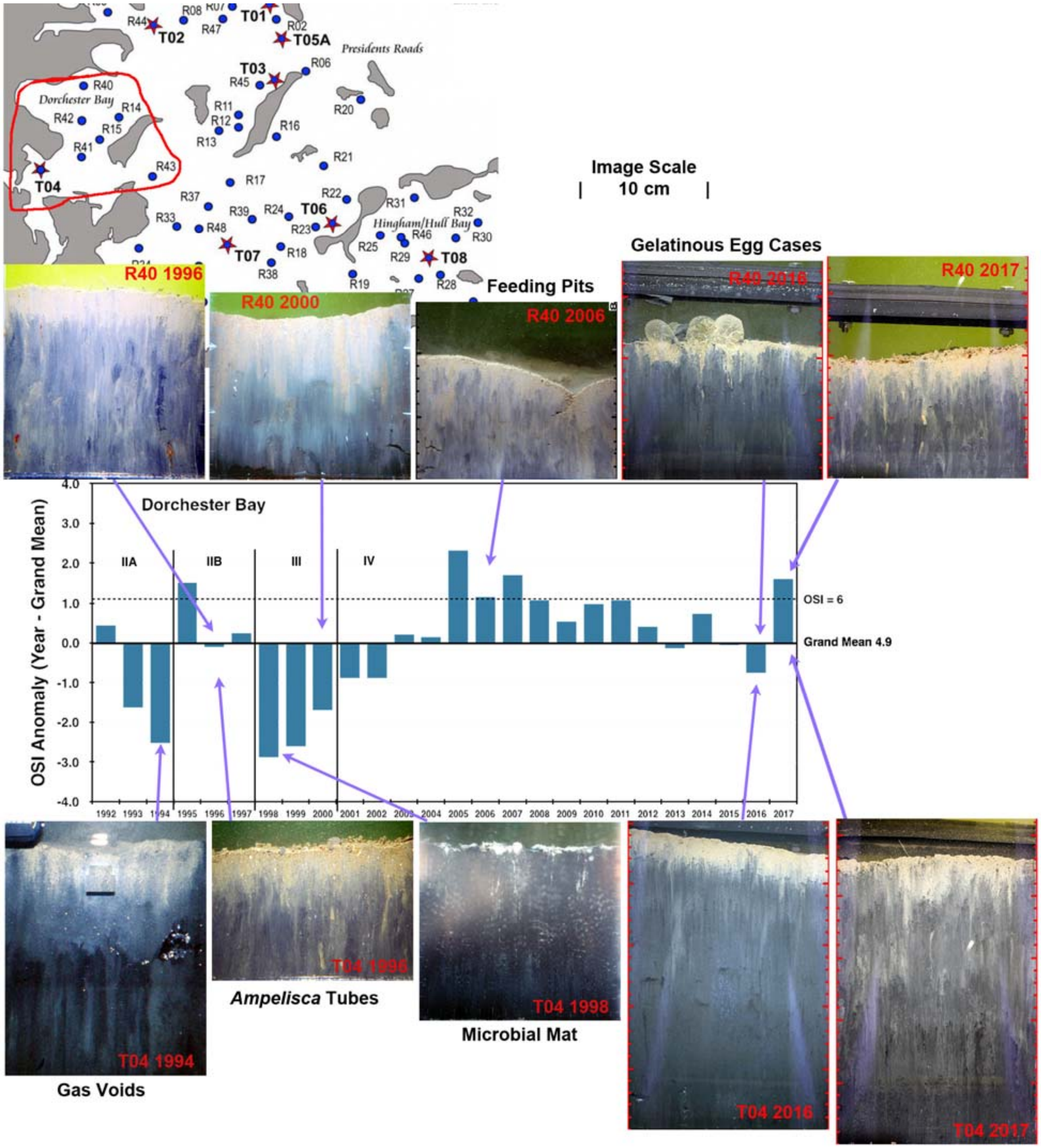


Figure 35. OSI anomaly (yearly - grand mean OSI) for Dorchester Bay stations. Station R40 is typical of Dorchester Bay and Station T04 is the lowest in Dorchester Bay. Higher OSI years are positive and lower are negative values. Map insert shows stations within region. Vertical lines separate periods of change in wastewater treatment based on Taylor (2010). Period IIA is post sludge disposal, IIB is full primary treatment, III is full secondary treatment, and IV is offshore diversion. OSI less than 6 indicates stressed benthic habitat.

Benthic habitat conditions at the ten stations in Quincy Bay followed a similar pattern as Dorchester Bay, but had a higher grand mean OSI of 5.9 (SD = 1.16; Table 8, Figure 36). Periods II and III had the lowest OSI values. After diversion benthic habitats improved for several years before declining in 2015 and 2016. Much of the decline in OSI was associated with a declining trend in aRPD layer depth from 2010 to 2016. For these years the aRPD was below the grand mean of 1.9 cm (SD = 0.57 cm). In 2017, OSI increased primarily from increased estimated successional stage. Advancement of estimated successional stage toward equilibrium Stage III starting in Period IV lead to the highest benthic habitat quality for Quincy Bay in 2008. This appeared to be related to increased bioturbation from high abundance of the burrowing amphipod *L. pinguis* (Figures 26 and 36). In 2003, when *L. pinguis* was numerically dominant at Station T07 burrow density reached 962 burrows m^{-2} (SD = 300). Burrows declined to 197 burrows m^{-2} (SD = 167) in 2007 when *L. pinguis* was at low densities (Shull et al. 2009). OSI for Station T07 was positively correlated with abundance of *L. pinguis* up to 2016 (r = 0.42, p = 0.038, N = 24). In 2017 no *L. pinguis* occurred making the correlation insignificant (r = 0.39, p = 0.054, N = 25). Poorest habitat quality was consistently found at Station R36 which always appeared to have Stage I pioneering communities except for 2000 and 2002 when Stage II amphipod tubes were present.

Stations within the Inner Harbor and Hingham Bay also tended to have lower benthic habitat quality with Inner Harbor having a grand mean OSI of 5.5 (SD = 1.38) and Hingham Bay 5.6 (SD = 1.35; Table 8, Figures 37 and 38). For the three Inner Harbor stations habitat quality remained low through Periods II and III, and well into IV. From 2011 on, habitat quality was good, primarily related to advances in estimated successional stage from Stage I to Stages II and III. For example, from 2011 to 2017 surface and subsurface biogenic features increased at CO19, which was first sampled in 2004, coincided with the appearance of both *Ampelisca* spp. and *L. pinguis.* The number of biogenic features was correlated with total amphipod abundance (r = 0.66, p = 0.010, N = 14). Total amphipod abundance increased at CO19 from 2004 to 2013, peaked in 2012 at about 1,900 ind m^{-2}, and then declined to zero from 2014 to 2017. OSI was positively correlated with Shannon-Wiener diversity (r = 0.76, p = 0.002, N = 14). aRPD layer depth at the three Inner Harbor stations tended to increase from 2011 to 2015. For these years the aRPD was above the grand mean of 1.8 cm (SD = 0.45 cm). In 2016, the aRPD layer depth declined by almost 1 cm and increased to again to 1.9 cm in 2007.

For the seven Hingham Bay stations the patterns for OSI were different then the Inner Harbor. Overall Hingham Bay habitat quality declined from Period IIA, which was moderately good to poor in Periods IIB and III, and remained lower until 2007 (Figure 38). After Period IIA, Hingham Bay did not consistently stay above the grand mean OSI of 5.6 (SD = 1.35) until 2007. Much of the improvement in Hingham Bay was related to advancement in estimated successional stages from Stage I to Stage III with increased biogenic activity. Coarse sediment Station R19 was an exception and remained at Stage I for most monitoring years. With the start of Period IV, aRPD layer depths tended to be above the long-term mean of 1.7 cm (SD = 0.46 cm), which tended to drive OSI values higher.

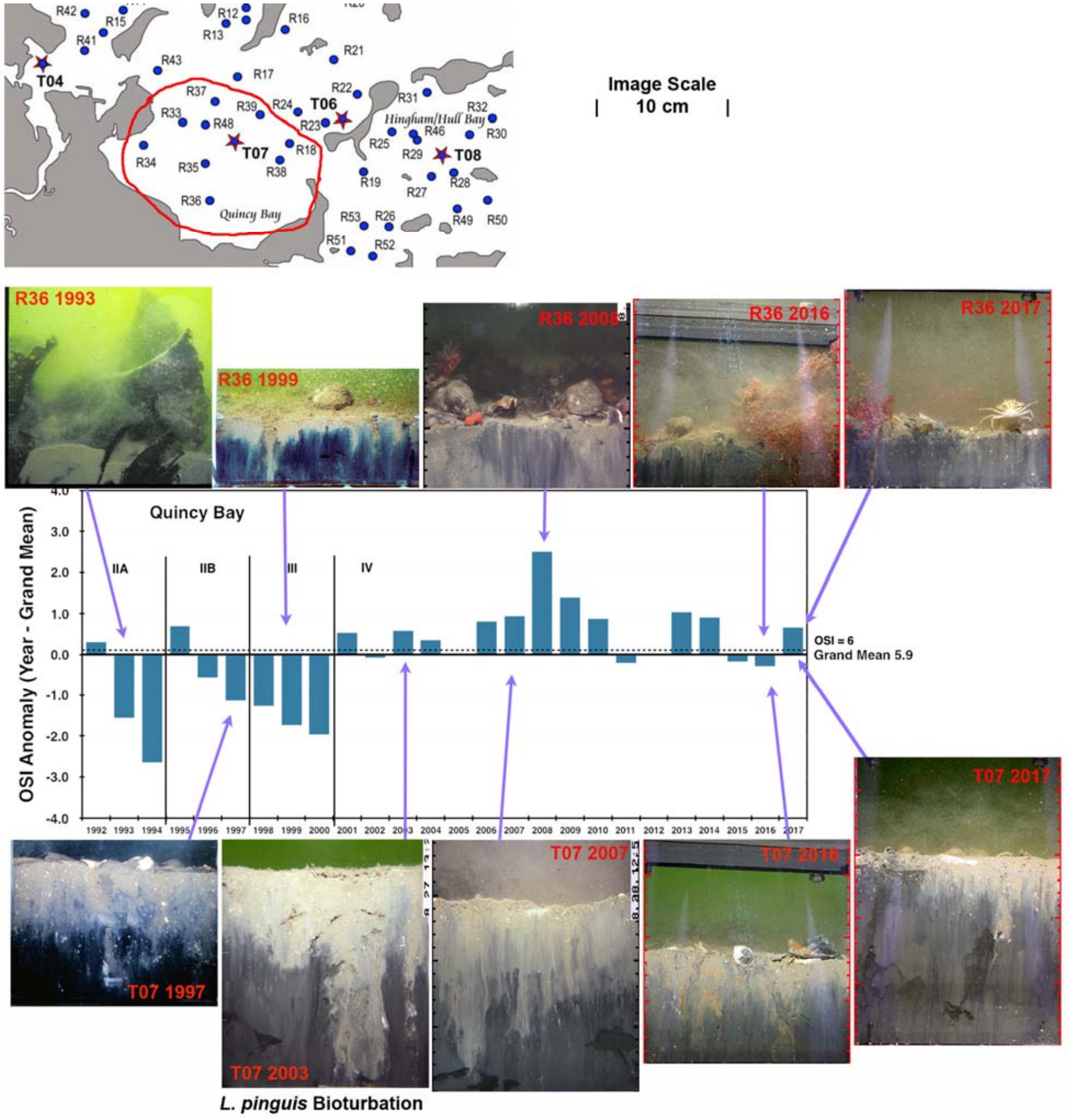


Figure 36. OSI anomaly (yearly - grand mean OSI) for Quincy Bay stations. Stations R36 and T07 are typical for Quincy Bay. Higher OSI years are positive and lower are negative values. Map insert shows stations within region. Vertical lines separate periods of change in wastewater treatment based on Taylor (2010). Period IIA is post sludge disposal, IIB is full primary treatment, III is full secondary treatment, and IV is offshore diversion. OSI less than 6 indicates stressed benthic habitat.

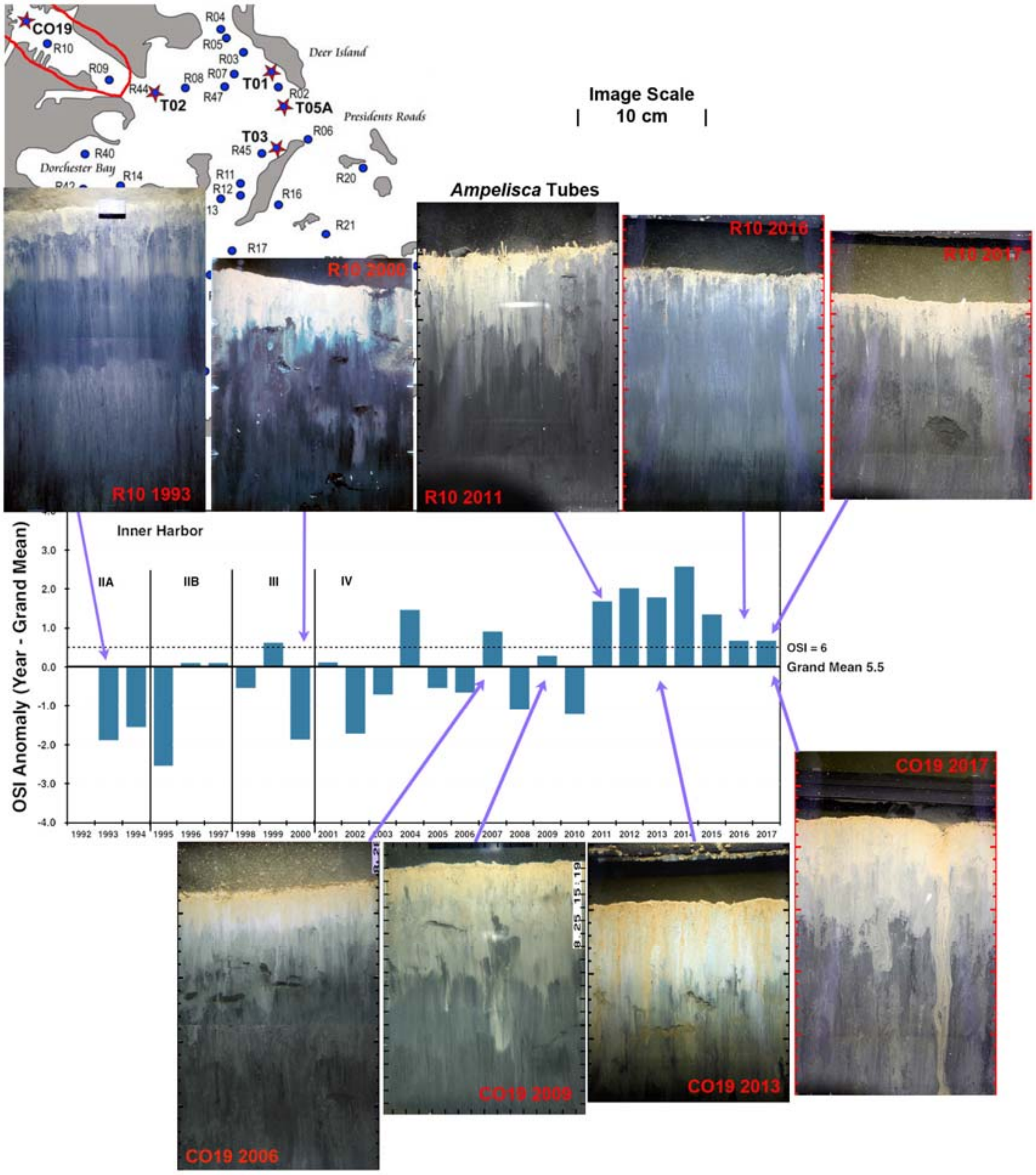


Figure 37. OSI anomaly (yearly - grand mean OSI) for Inner Harbor stations. Stations R10 and CO19 are typical for Inner Harbor. Higher OSI years are positive and lower are negative values. Map insert shows stations within region. Vertical lines separate periods of change in wastewater treatment based on Taylor (2010). Period IIA is post sludge disposal, IIB is full primary treatment, III is full secondary treatment, and IV is offshore diversion. OSI less than 6 indicates stressed benthic habitat.

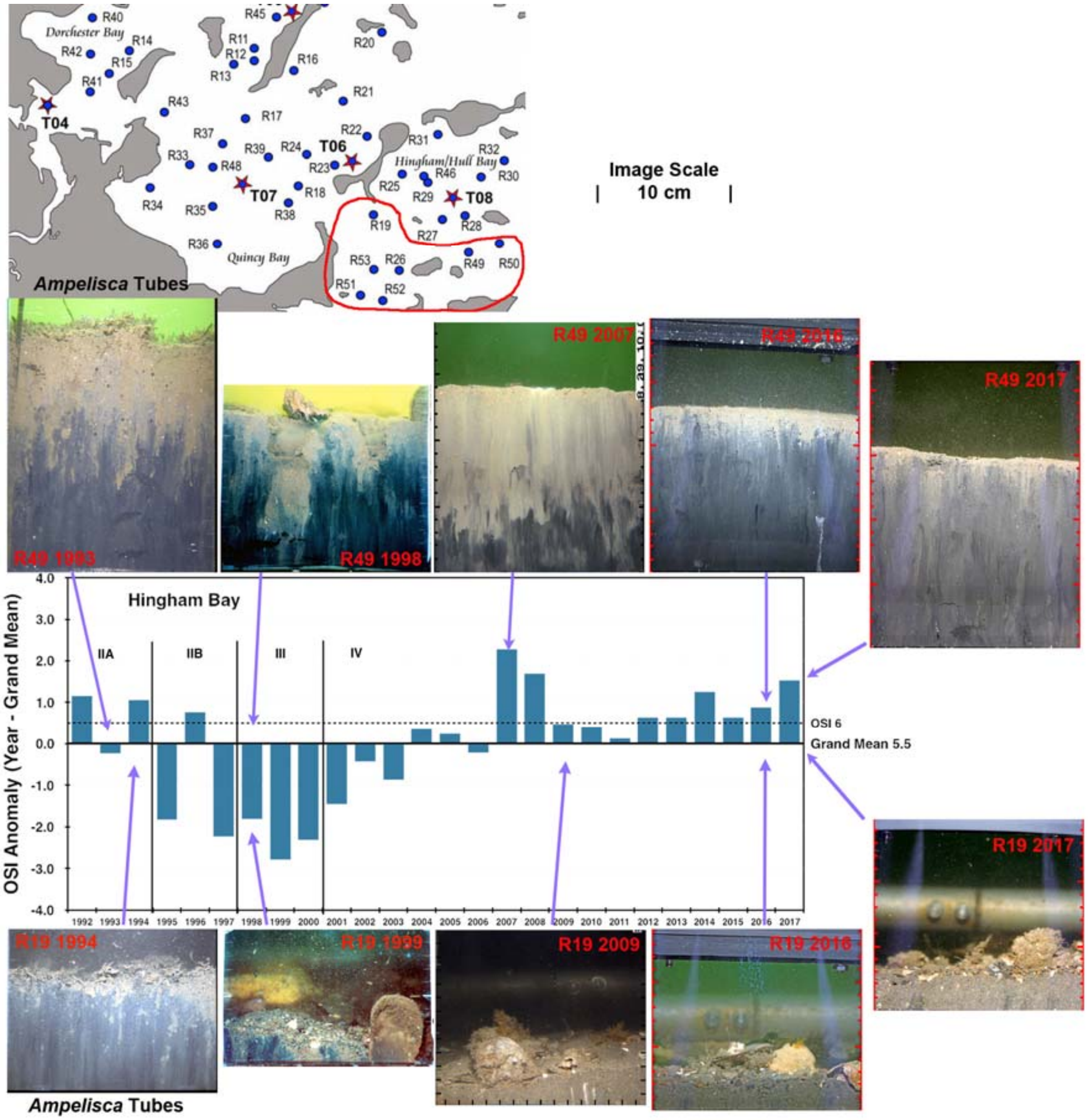


Figure 38. **OSI anomaly (yearly - grand mean OSI) for Hingham Bay stations. Stations R49 and R19 are typical for Hingham Bay. Station R19 was coarse sediments with lower OSI. Higher OSI years are positive and lower are negative values. Map insert shows stations within region. Vertical lines separate periods of change in wastewater treatment based on Taylor (2010). Period IIA is post sludge disposal, IIB is full primary treatment, III is full secondary treatment, and IV is offshore diversion. OSI less than 6 indicates stressed benthic habitat.**

Better habitat conditions characterized mid and outer harbor areas of President Roads and Deer Island Flats relative to the Inner Harbor and Hingham Bay (Table 8, Figures 39 and 40). Several years after diversion the three President Roads stations exhibited large improvements in benthic habitat quality that were sufficient to bring the grand mean OSI to 6.6 (SD = 2.04), above the <6 OSI threshold for stressed benthic habitat. The increase in OSI appeared to be related to increased bioturbation from high abundance of the burrowing amphipod *L. pinguis* (Figure 39). In 2007, *L. pinguis* was a numerical dominant at Station T02 and burrow density reached 2,870 burrows m^{-2} (SD = 488; Shull et al. 2009). In 2008, *L. pinguis* reached about 42,000 ind m^{-2} at T02 and about 600 ind m^{-2} at T05A. OSI at Station T02 was positively correlated with total species (r = 0.54, p = 0.010), but not with *Ampelisca* spp. or *L. pinguis*. At T02 *Ampelisca* spp. were abundant and formed tube mats in Period IIB and again in Period IV from 2010 to 2012. While tube mats were present during Period IIB, the aRPD layer depth associated with them was shallow ranging from 0.8 cm to 1.7 cm. The mats that appeared in Period IV were coincident with deeper aRPD layers from 2.0 cm to 4.2 cm. From 2013 to 2017, *Ampelisca* spp. tube mats occurred only in 2016 at only T02. Advancement of estimated successional stage toward equilibrium Stage III starting early in Period IV led to the high benthic habitat quality in President Roads until 2014 and 2105 when OSI declined. The decline was related to thinner aRPD layers at both Stations T02 and T05A, and to a decline in estimated successional stage for Station T05A. In 2016 and 2017 OSI again increased from higher estimated successional stages.

The eight stations on Deer Island Flats (Figure 40), the shallow area north of President Roads, followed a similar pattern to President Roads with the long-term OSI grand mean of 7.0 (SD = 1.31). Periods IIA and III were the only time OSI was <6 for the eight stations. Period IIB was above 6 for all three years. After diversion the OSI gradually increased to a peak between 2007 and 2008. Much of the pattern in OSI could be attributed to a general deepening of the aRPD layer depth that started in Period III and continued till 2013 when aRPD declined to below the grand mean of 2.7 cm (SD = 0.85 cm). The thinnest aRPD layers occurred in Periods IIA. By the start of Period IIB in 1995, estimated successional stage had advanced toward equilibrium Stage III and stayed at that level through to 2017. This increase in successional stage was likely related to increased infaunal bioturbation by *L. pinguis* at the start of Period IV. OSI for Station T01 was correlated with *L. pinguis* abundance (r = 0.39, p = 0.054, N = 25) and Fisher alpha (r = 0.41, p = 0.042, N = 25). Station R08 was an exception with estimated successional stage staying at Stage I all years but with some Stage II amphipods present in 1996 and 1997. Station T01 followed a similar pattern to R08 but did have Stage III equilibrium communities present in 2008 and 2009. An eelgrass (*Zostera marina*) bed appeared at Station R08 in 2008 and has persisted to 2017. Starting in 2015 large amounts of macroalgae appeared within the bed. Macroalgae was also common in the 1900s (Figure 41). The presence of eelgrass at Station R08 was a result of successful restoration efforts by MA Division of Marine Fisheries in the Deer Island Flats (Governors Island Flats) area (Evans et al. 2018).

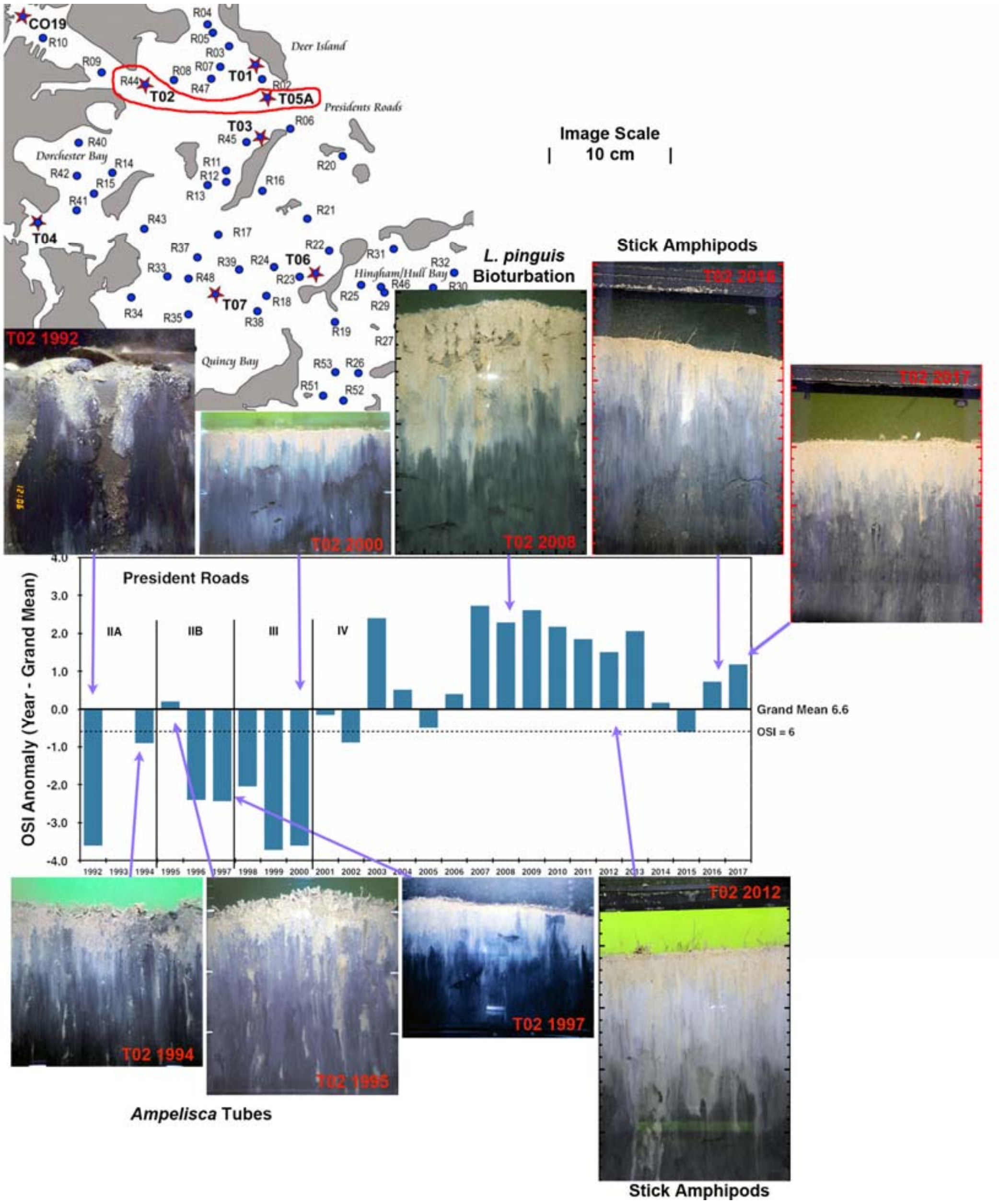


Figure 39. OSI anomaly (yearly - grand mean OSI) for President Roads stations. Station T02 improved greatly several years after diversion. Higher OSI years are positive and lower are negative values. Map insert shows stations within region. Vertical lines separate periods of change in wastewater treatment based on Taylor (2010). Period IIA is post sludge disposal, IIB is full primary treatment, III is full secondary treatment, and IV is offshore diversion. OSI less than 6 indicates stressed benthic habitat.

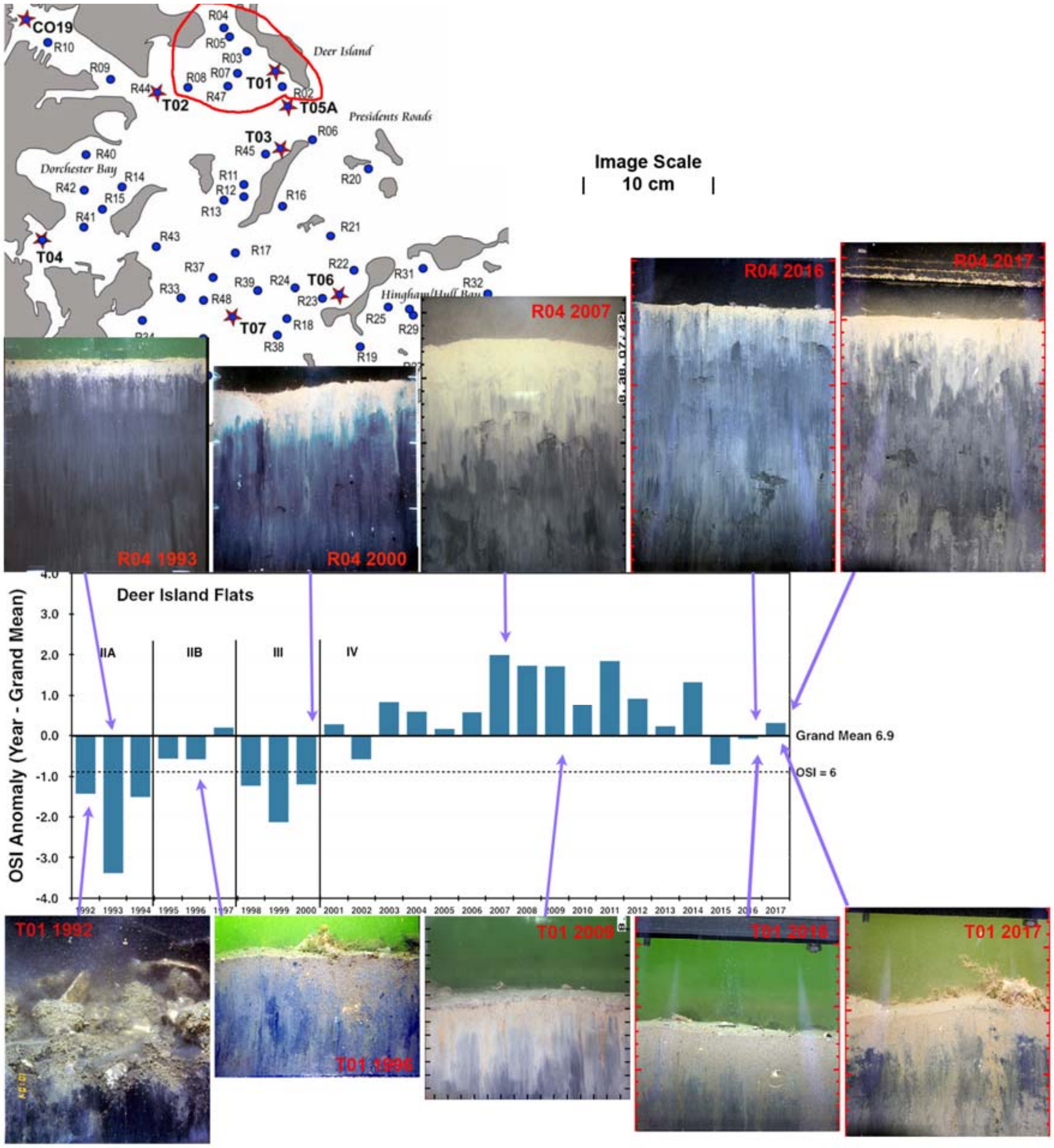
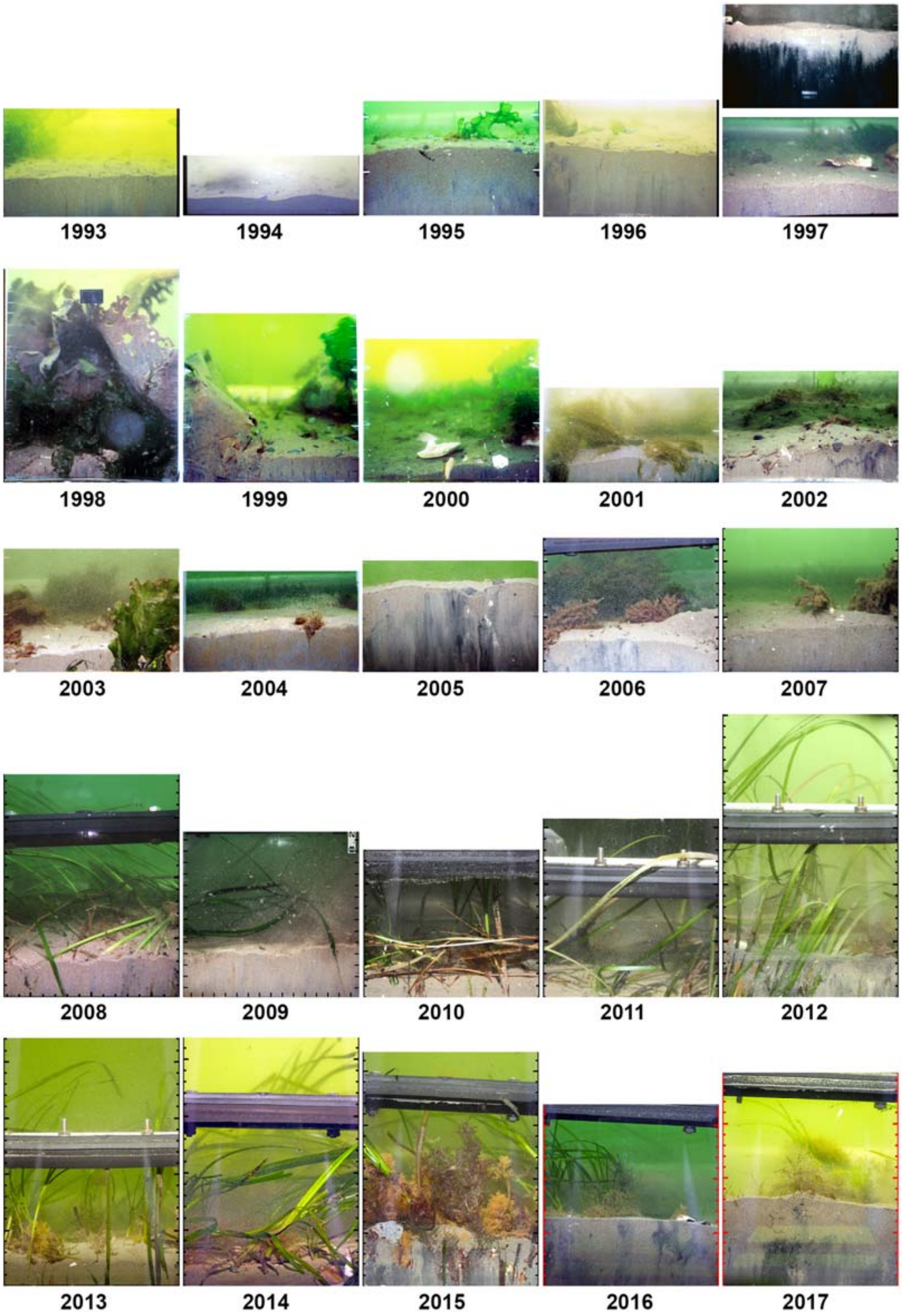


Figure 40. OSI anomaly (yearly - grand mean OSI) for Deer Island Flats stations. Station R04 is a typical finer sediment station and T01 is a coarser sediment station. Higher OSI years are positive and lower are negative values. Map insert shows stations within region. Vertical lines separate periods of change in wastewater treatment based on Taylor (2010). Period IIA is post sludge disposal, IIB is full primary treatment, III is full secondary treatment, and IV is offshore diversion. OSI less than 6 indicates stressed benthic habitat.



1993 1994 1995 1996 1997

1998 1999 2000 2001 2002

2003 2004 2005 2006 2007

2008 2009 2010 2011 2012

2013 2014 2015 2016 2017

Figure 41. Eelgrass bed at Station R08 on Deer Island Flats. The bed first appeared in SPI in 2008. Prior to 2008, sediments were fine-sand with macroalgae. Scale on sediment profile image is in cm.

The highest OSI regions were in the outer Harbor areas off Long Island, Nantasket Roads, and Hull Bay (Figures 42, 43, and 44). Over the entire Boston Harbor SPI monitoring period, stations in these three regions consistently had good benthic habitat quality. For the eight stations off Long Island the annual OSI mean never dipped below 6 with a grand mean of 7.4 (SD = 0.88; Table 8) despite the individual means for Stations R06, R13, and R16 being 5.1 to 5.9. Stations R06 and R16 had coarser sediments that tend to score lower for OSI because of physical stress associated with naturally dynamic sandy sediments. Station R13 had finer sediment with thicker aRPD layers when *Ampelisca* spp. tube mats were present (1994, 2001, and 2009) and non-mat years had thinner aRPD layers (Figure 42). If these three station are removed, the grand mean OSI for the other five Long Island stations was 8.4. The overall high benthic habitat quality around Long Island was due to a combination of deep aRPD layers and predominance of estimated successional Stage II and III. The grand mean aRPD layer depth for all eight stations was 3.1 cm (SD = 0.91 cm), the deepest for all Harbor regions. Bioturbation and biogenic structures from high densities of tube building *Ampelisca* spp. and burrowing *L. pinguis* appeared to be responsible for the high habitat quality at Station T03. In 2003, burrow density at Station T03 was 269 burrows m^{-2} (SD = 40; Shull et al. 2009) when *Ampelisca* spp. was numerically dominant, but *L. pinguis* was not abundant. From 1994 to 2003 these amphipods averaged over 90,000 ind m^{-2} with a range of 32,000 ind m^{-2} to 240,000 ind m^{-2} (Pembroke et al. 2016), but the correlations of OSI with amphipod abundance were not significant. OSI at Station T03 was positively correlated with only TOC (r = 0.41, p = 0.042, N = 25).

The six Nantasket Roads stations consistently had the highest benthic habitat quality of all Boston Harbor regions (Figure 43). The OSI grand mean was 7.8 (SD = 1.06), and ranged from 5.8 in 2006 to 9.8 in 2008 (Table 8). The lowest OSI in 2006 appeared related to shallowing of the aRPD at Stations R20, R21, R24, and T06. The aRPD at these stations deepened during the highest OSI years of 1993, 1997, 2001, 2008 and 2009. For individual Nantasket Roads stations the average OSI ranged from 6.8 at R23 to 8.8 at R21. This range in OSI was in part due to differences in modal grain-size. Coarser sediments at Station R23, primarily fine-medium sands, tended to have deeper aRPD layers when prism penetration was sufficient to measure aRPD and lower estimated successional stage. OSI at Stations R23 was calculated only 16 of 26 years due to low prism penetration. At Station R21 sediments were fine-sand-silt with both deep aRPD layers and higher estimated successional stage. Similar to Long Island stations, the overall high benthic habitat quality in Nantasket Roads was due to a combination of deep aRPD layers and predominance of estimated successional Stage II and III. Bioturbation and biogenic structures from high densities of tube building *Ampelisca* spp. and burrowing *L. pinguis* drove these variables at Station T06. From 1993 to 2004 these amphipods averaged over 62,000 ind m^{-2} with a range of 6,500 ind m^{-2} to 114,000 ind m^{-2} (Pembroke et al. 2016). The OSI for Station T06 was positively correlated with *L. pinguis* abundance (r = 0.56, p = 0.004, N = 25) but not with *Ampelisca* spp. OSI at Station T06 was also positively correlated with community structure variables Pielou's evenness (r = 0.47, p = 0.018, N = 25) and Shannon-Wiener diversity (r = 0.57, p = 0.003, N = 25) and negatively correlated with percent fine sediments (silt+clay, r = -0.45, p = 0.024, N = 25). The negative correlation of OSI with percent fines appeared to be related to an independent long-term decline in fine sediments at T06 that started during Period IIB around 1996 (Linear Regression, $R^2 = 0.49$, p = 0.024, N = 21). The decline in percent silt+clay sediment fraction may have been related to the closure of the nearby Nut Island outfall, located within a km of Station T06, which discharged significant quantities of solids until 1998 (Taylor 2010).

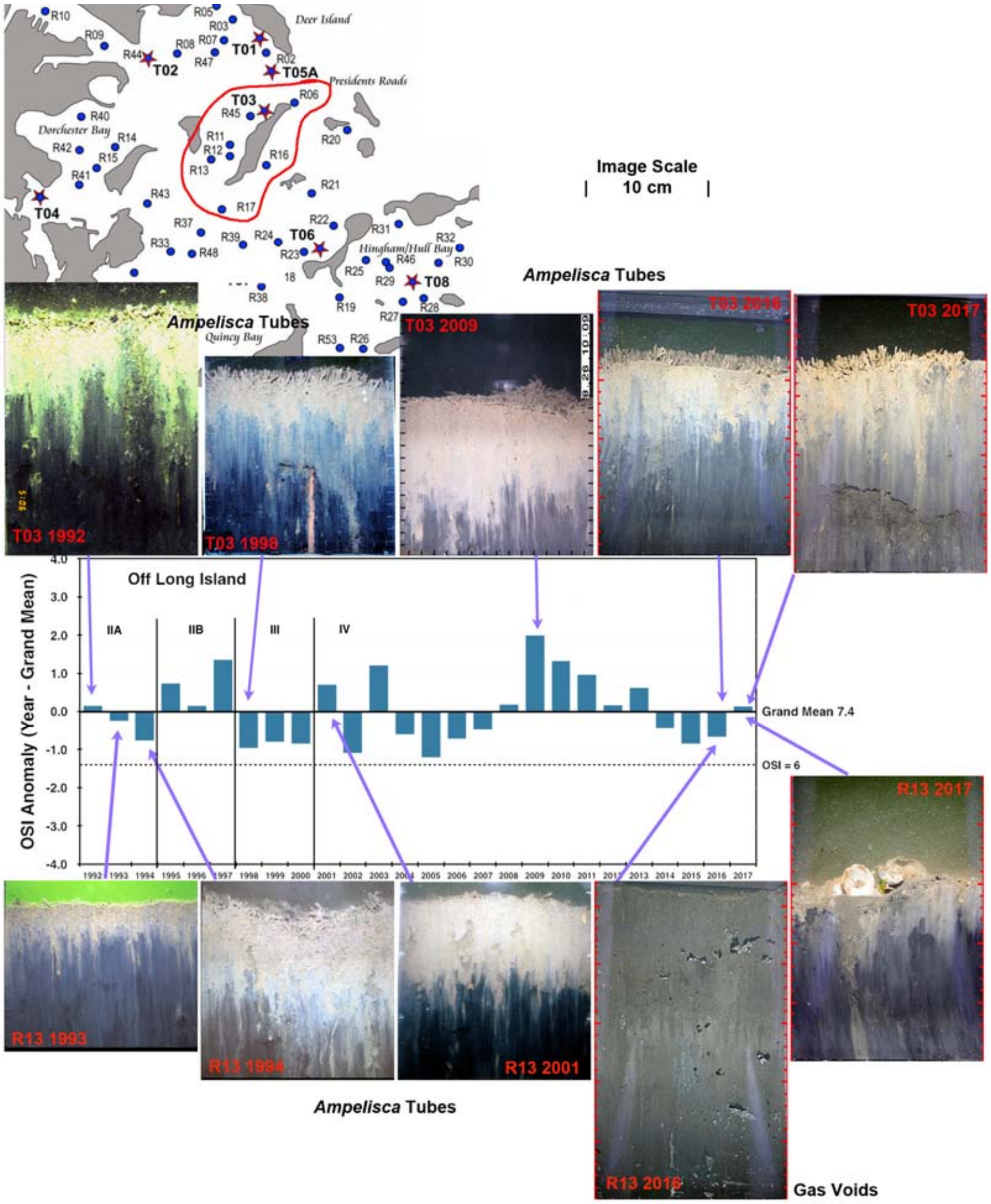


Figure 42. OSI anomaly (yearly - grand mean OSI) for stations off Long Island. Station T03 consistently had high habitat quality. Station R13 had variable habitat quality. Higher OSI years are positive and lower are negative values. Map insert shows stations within region. Vertical lines separate periods of change in wastewater treatment based on Taylor (2010). Period IIA is post sludge disposal, IIB is full primary treatment, III is full secondary treatment, and IV is offshore diversion. OSI less than 6 indicates stressed benthic habitat.

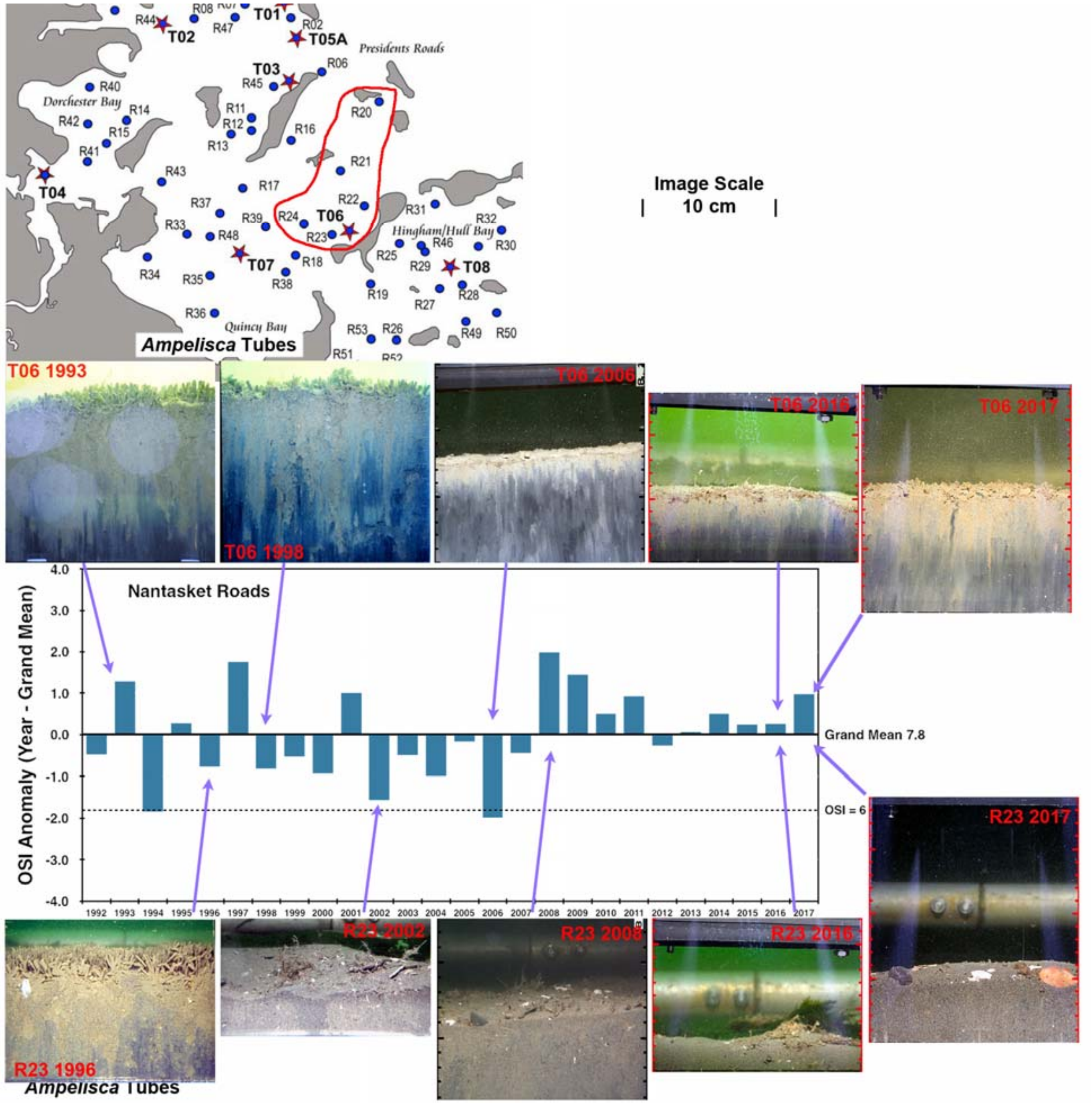


Figure 43. OSI anomaly (yearly - grand mean OSI) for Nantasket Roads stations with example images from Stations T06 and R23. Higher OSI years are positive and lower are negative values. Map insert shows stations within region. Vertical lines separate periods of change in wastewater treatment based on Taylor (2010). Period IIA is post sludge disposal, IIB is full primary treatment, III is full secondary treatment, and IV is offshore diversion. OSI less than 6 indicates stressed benthic habitat.

The nine Hull Bay stations consistently had high benthic habitat quality. The OSI grand mean was 7.5 (SD = 0.88), and ranged from 5.9 in 2000 to 8.9 in 2017 (Table 8). The <6 mean OSI in 2000 was due to Stations R25 and R32 having aRPD layer depths that were <1.0 cm and lower estimated successional stages. For individual Hull Bay stations the average OSI ranged from 6.5 at R32 to 8.7 at R31. Similar to Long Island and Nantasket Roads stations, the overall high benthic habitat quality in Hull Bay was due to a combination of deep aRPD layers and predominance of estimated successional Stage II and III. Bioturbation and biogenic structures from high densities of tube building *Ampelisca* spp. drove these variables at Station T08. From Period IIA through to diversion and into Period IV to 2003 these amphipods averaged over 26,000 ind m^{-2} with a range of 120 ind m^{-2} in 1999 to 60,000 ind m^{-2} in 1993 (Pembroke et al. 2016). While the benthic habitat quality in Hull Bay tended to always be high, there was a pattern of increasing OSI through time with only one year (2015) below grand mean after 2006 (Figure 44). OSI for Station T08 was correlated with Fisher alpha (r = 0.48, p = 0.015, N = 25).

Summary

Improvements in wastewater treatment and moving the outfall offshore have led to improvements in benthic habitats within Boston Harbor from 1992 to 2017 by favoring processes that enhance bioturbation or the mixing of sediment by organisms. These have led to more aerobic sediment conditions, particularly for the outer eastern Harbor regions. The shift from a more anaerobic sediment state to a more aerobic state was caused by drastically lowered organic carbon and nutrient loading associated with improvements in wastewater treatment and cessation of sewage discharge within the Harbor (Taylor 2010, Tucker et al. 2014). There were also corresponding decreases in primary production due to reduced nutrient loadings (Oviatt et al. 2007).

Soft bottom benthic habitat conditions in Boston Harbor for 2017 improved slightly over 2016, as measured by the Organism Sediment Index (OSI) of Rhoads and Germano (1986), in all harbor regions except the Inner Harbor (Stations CO19, R09, and R10). Stressed benthic habitat conditions, represented by an OSI of <6, continued to predominate in harbor areas of Dorchester and Quincy Bays followed by the Inner Harbor and Hingham Bay (Table 8). Better habitat conditions continued to characterize mid and outer harbor areas of Deer Island Flats and President Roads with the highest OSI regions being off Long Island, Nantasket Roads, and Hull Bay. Over the 26 years of Harbor SPI monitoring, stations off Long Island, Nantasket Roads, and Hull Bay consistently had good benthic habitat conditions. All of the other Harbor regions showed improving trends through time. Much if not all of the improvement in benthic habitat quality over the 26 years can be attributed to upgrades in wastewater treatment and removal of the outfall from within the Harbor (Diaz et al. 2008, Taylor 2010, Taylor et al. 2010).

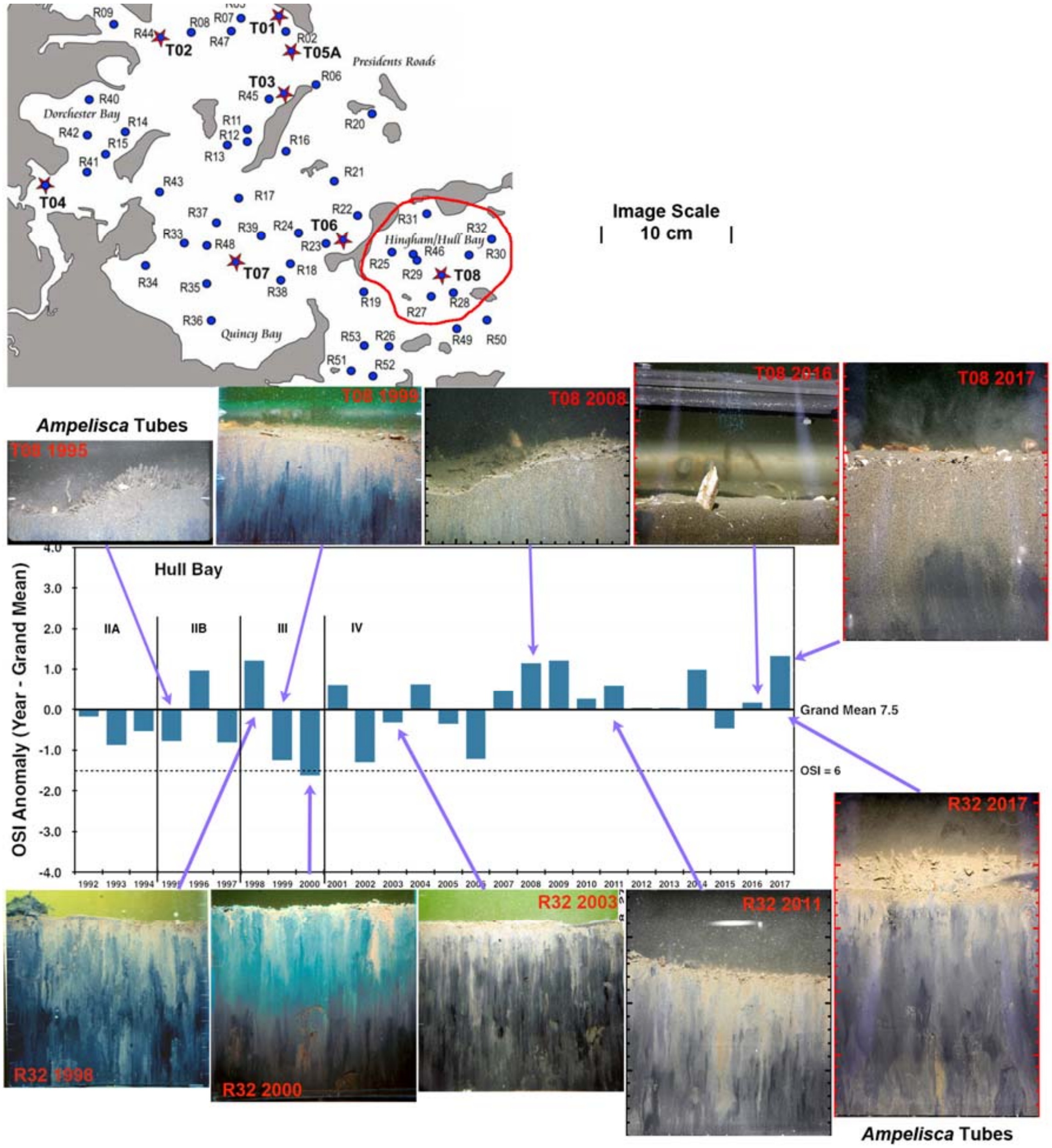


Figure 44. OSI anomaly (yearly - grand mean OSI) for Hull Bay stations with example images from Stations T08 and R32. Higher OSI years are positive and lower are negative values. Map insert shows stations within region. Vertical lines separate periods of change in wastewater treatment based on Taylor (2010). Period IIA is post sludge disposal, IIB is full primary treatment, III is full secondary treatment, and IV is offshore diversion. OSI less than 6 indicates stressed benthic habitat.

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 predominant origin of sediment organic matter in Boston Harbor has shifted from sewage to marine derived. Recovery of benthic communities has enhanced bioturbation rates by infaunal and epibenthic species and has led to more aerobic and 'healthier' sediment conditions by enhancing remineralization of legacy organics and nutrients stored in the sediments from years of sewage disposal. Physical and biological properties of the soft substrate in Boston Harbor in 2017 exhibited minor changes from recent years but were consistent with longer-term trends (Pembroke et al. 2017). Concentrations of both TOC and *Clostridium perfringens*, indicators of organic enrichment and deposition from municipal wastewater discharge, have remained low at most stations 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 with all measures appearing to reach static levels in recent years. Although abundances of individual taxa, such as the dominants *Ampelisca* spp., *Aricidea catherinae,* 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 persisted in the 2017 survey, are consistent with the recovery of benthic habitats from decades of inadequately treated sewage discharges.

5. REFERENCES

Blake JA, Diaz RJ, Doner SA, Maciolek NJ. 2008. Evaluation of functional group or trophic level classification for benthic infauna and sediment profile imaging results from Boston Harbor and Massachusetts Bay. 35 p. plus appendices.

Butman B, Sherwood CR, Dalyander PS. 2008. Northeast storms ranked by wind stress and wave-generated bottom stress observed in Massachusetts Bay, 1990–2006. Continental Shelf Research 28:1231-1245.

Chang S, Steimle FW, Reid RN, Fromm SA, Zdanowicz VS, Pikanowski RA. 1992. Association of benthic macrofauna with habitat types and quality in the New York Bight. Marine Ecology Progress Series 89:237-251.

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

Clarke KR, Green RH. 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, Cutter GR Jr., Dauer DM. 2003. A comparison of two methods for estimating the status of benthic habitat quality in the Virginia Chesapeake Bay. Journal of Experimental Marine Biology and Ecology 285-286:371-381.

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

Evans T, Carr J, Frew K, Rousseau M, Ford K, Boeri A. 2018. Massachusetts Division of Marine Fisheries 2010 to 2016 HubLine eelgrass restoration. Final Report. Submitted to: Massachusetts Department of Environmental Protection. 25 p. plus appendices.

Gallagher ED, Keay KE. 1998. Organisms-Sediment-Contaminant Interactions in Boston Harbor. p. 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.

Kubiak DA, Smoske NS, Coughlin K, Rando L, Wu D, Whittaker E. 2016. Combined Sewer Overflow Control Plan Annual Progress Report 2015. 2015 csoar-r4. 58 p.

Maciolek NJ, Dahlen DT, Diaz RJ. 2011. 2010 Boston Harbor Benthic Monitoring Report. Boston: Massachusetts Water Resources Authority. Report 2011-18. 20 p. plus appendices.

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

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

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

Mills EL. 1967. The biology of an ampeliscid amphipod crustacean sibling species pair. Journal of the Fisheries Research Board of Canada 24:305−355.

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, Diaz RJ, Hecker B. 2018. Outfall benthic monitoring report: 2017 results. Boston: Massachusetts Water Resources Authority. Report 2018-xx. 57 p. plus appendices

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

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

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

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

Pembroke AE, Diaz RJ, Nestler EC. 2016. Boston Harbor Benthic Monitoring Report: 2015 Results. Boston: Massachusetts Water Resources Authority. Report 2016-14. 38 p.

Pembroke AE, Diaz RJ, Nestler EC. 2017. Boston Harbor Benthic Monitoring Report: 2016 Results. Boston: Massachusetts Water Resources Authority. Report 2017-10. 45 p.

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

Rutecki D, Nestler E, Hasevlat R. 2017. Quality Assurance Project Plan for Benthic Monitoring 2017–2020. Boston: Massachusetts Water Resources Authority. Report 2017-06. 92 p. plus Appendices.

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 p.

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 p.

Shull DH, Benoit JM, Wojcik C, Senning JR, 2009. Infaunal burrow ventilation and pore-water transport in muddy sediments. Estuarine, Coastal and Shelf Science 83:277-286.

Taylor DI. 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. 77p.

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.

Taylor DI, Oviatt CA, Borkman DG. 2010. Non-linear responses of a coastal aquatic ecosystem to large decreases in nutrient and organic loadings. Estuaries and Coasts 34:745–757.

Thiel M. 1997. Reproductive biology of a filter-feeding amphipod, *Leptocheirus pinguis*, with extended parental care. Marine Biology 130:249-258.

Thiel M. 1999. Extended parental care in marine amphipods II. Maternal protection of juveniles from predation. Journal of Experimental Marine Biology and Ecology 234:235-253.

Tucker J, Giblin AE, Hopkinson CS, Kelsey SW, Howes BL. 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.

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

Warwick RM. 1993. Environmental impact studies on marine communities: pragmatical considerations. Aust. J. Ecol., 18:63-80.

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

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