Boston Harbor Benthic Monitoring Report:

2015 Results

Massachusetts Water Resources Authority

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2015 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 9.3 miles off Deer Island in Massachusetts Bay. Subsequently, improvements have been made to numerous Combined Sewer Overflows (CSOs) reducing another source of water quality concern.

Sediments and associated benthic infauna reflect cumulative water quality conditions. In order to evaluate changes to the ecosystem, particularly the benthic community, resulting from reductions in contaminated discharges over time, MWRA has conducted benthic monitoring in Boston Harbor on an ongoing basis since 1991. This report provides a summary of the results of the benthic surveys that were conducted in 2015. 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 2015 exhibited minor changes from recent years but were consistent with longer-term trends (Pembroke et al. 2015). Concentrations of both TOC and *Clostridium perfringens*, indicators of organic enrichment and deposition from municipal wastewater discharge, have remained low compared to the levels occurring prior to the offshore diversion.

Community structure measures also continue to point to improving benthic conditions. 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 2015 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 2015. 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. No changes were made to this program in the 2010 revision to the Ambient Monitoring Plan (MWRA 2010). This survey comprises three components: sediment conditions (grain size, total organic carbon, and *Clostridium perfringens*), benthic infauna, and sediment profile imaging (SPI).

Methods used to collect, analyze, and evaluate all sample types remain largely consistent with those reported by Pembroke et al. (2015) for previous monitoring years. Detailed descriptions of the methods are contained in the Quality Assurance Project Plan (QAPP) for Benthic Monitoring (Nestler et al. 2014). A brief overview of methods, focused on information that is not included in the QAPP, is provided in Sections 2.1 to 2.3.

2.1 Field Methods

Sediment and infauna sampling was conducted at 9 stations in August 2015 (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 13, 2015.

SPI samples were collected in triplicate at 61 stations on August 2-4, 2015 (Figure 1).

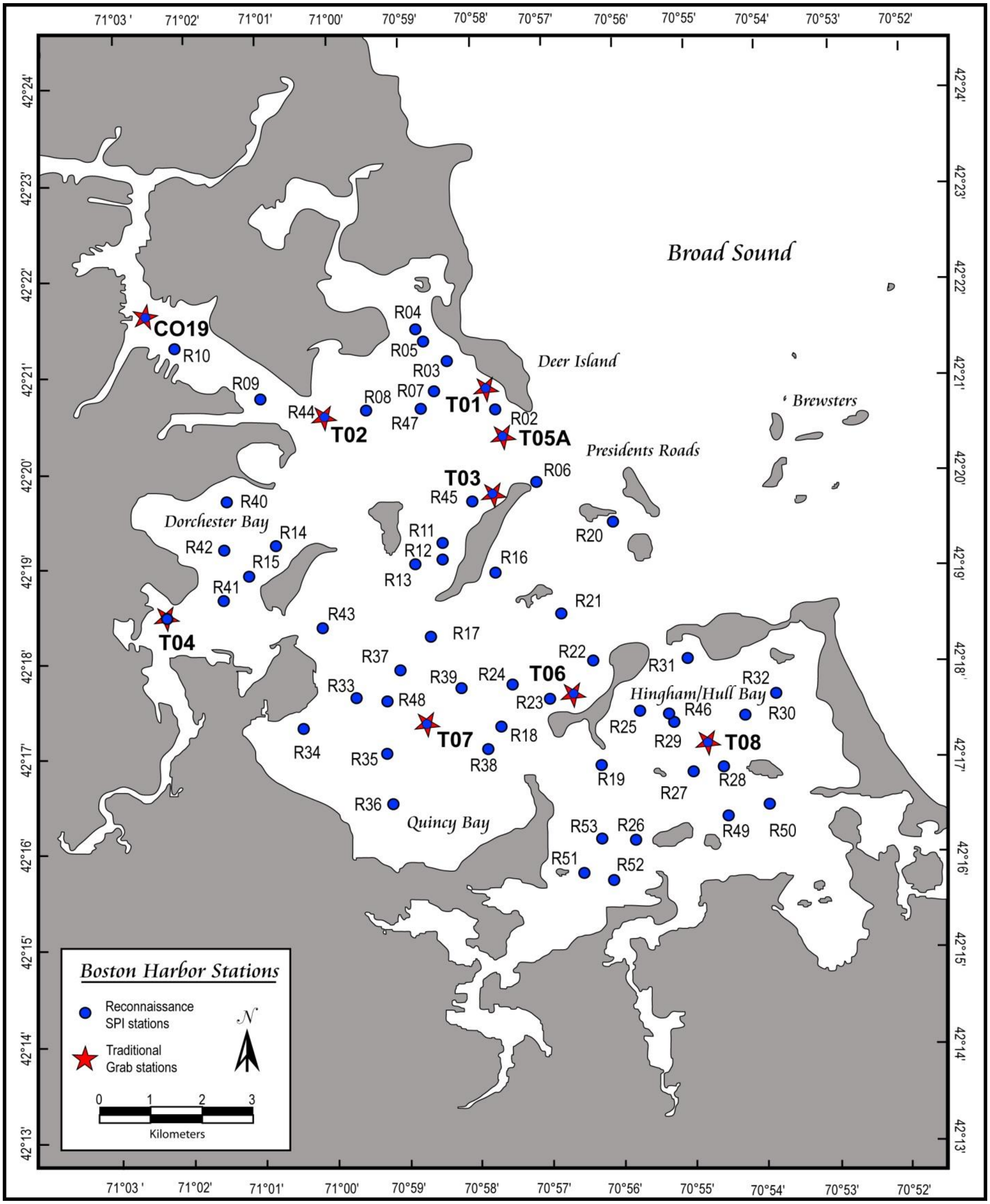


Figure 1. Locations of soft-bottom sampling and sediment profile imaging stations for 2015.

2.2 Laboratory Methods

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

2.3 Data Handling, Reduction, and Analysis

All benthic data were extracted directly from the HOM database and imported into Excel. Data handling, reduction, and graphical presentations were performed in Excel or SAS (version 9.3), as described in the QAPP (Nestler et al. 2014) or in Maciolek et al. (2008). Data are presented graphically as means (averages per station) unless otherwise noted. Shannon-Weiner (H') was calculated using log base 2. Multivariate analyses were performed using PRIMER v6 (Plymouth Routines in Multivariate Ecological Research) software to examine spatial patterns in the overall similarity of benthic assemblages in the survey area (Clarke 1993, Warwick 1993, Clarke and Green 1988). These analyses included classification (cluster analysis) by hierarchical agglomerative clustering with group average linking and ordination by non-metric multidimensional scaling (MDS). Bray-Curtis similarity was used as the basis for both classification and ordination. Prior to analyses, infaunal abundance data were fourth-root transformed to ensure that all taxa, not just the numerical dominants, would contribute to similarity measures.

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

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

3. RESULTS AND DISCUSSION

3.1 Sediment Conditions

Sediment conditions in Boston Harbor were characterized by three parameters measured during 2015 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 2015 included a wide range of sediment types (Table 1, Figure 2). Grain size profiles ranged from predominantly sand (i.e., T08) to almost entirely silt and clay (i.e., C019 and T04). Most stations had mixed sediments. The outer harbor stations (T01, T02, T05A, T06, and T08) generally had more than 50% sand with varying fractions of silt-clay. Outer harbor station T07 had nearly equal proportions of sand and silt-clay whereas Station T03, in the lee of Long Island had more fines than sand. The grain size composition at each station in 2015 generally remained consistent with results reported in prior years with a decrease in percent fines of more than 10% compared to 2014 only at Station T07. 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).

Table 1. 2015 monitoring results for sediment condition parameters.

Parameter		C019	T01	T02	T03	T04	T05A	T06	T07	T08
Grain Size	**Gravel (%)**	0.3	13.8	0.1	4.0	0.0	0.3	0.9	2.2	2.4
	Sand (%)	10.6	69.8	58.3	43.2	17.1	83.5	81.0	49.3	94.7
	Silt (%)	59.6	10.8	26.7	30.6	69.3	11.4	10.5	29.3	0.8
	Clay (%)	29.5	5.6	15.0	22.3	13.6	4.8	7.6	19.3	2.2
	Percent Fines (Silt + Clay)	89.1	16.4	41.7	52.8	82.9	16.2	18.1	48.6	2.9
Total Organic Carbon	**TOC (%)**	2.7	1.4	1.2	2.4	3.6	0.6	0.7	3.8	0.1
Clostridium perfringens	**not normalized**	11,700	993	4,640	19,700	5,010	711	1,620	22,700	120
	normalized (cfu/g dry/%fines)	131.3	60.6	111.4	373.0	60.5	43.9	89.4	467.6	41.0

Total Organic Carbon. Concentrations of total organic carbon (TOC) in 2015 were generally similar to 2014, remaining within the ranges reported in prior years, although T04 exhibited a sharp decline from the unusually high value observed in 2014 when there was vegetative debris in the sample (Figure 4). Concentrations of TOC tend to track closely to percent fine sediments (silt + clay), with higher TOC

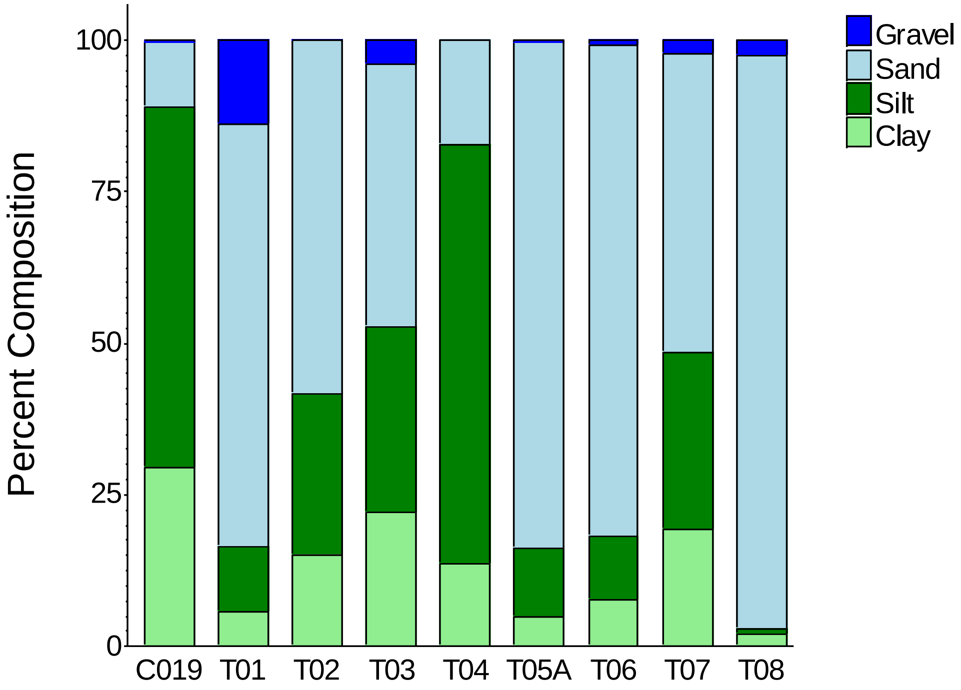


Figure 2. **2015 monitoring results for sediment grain size.**

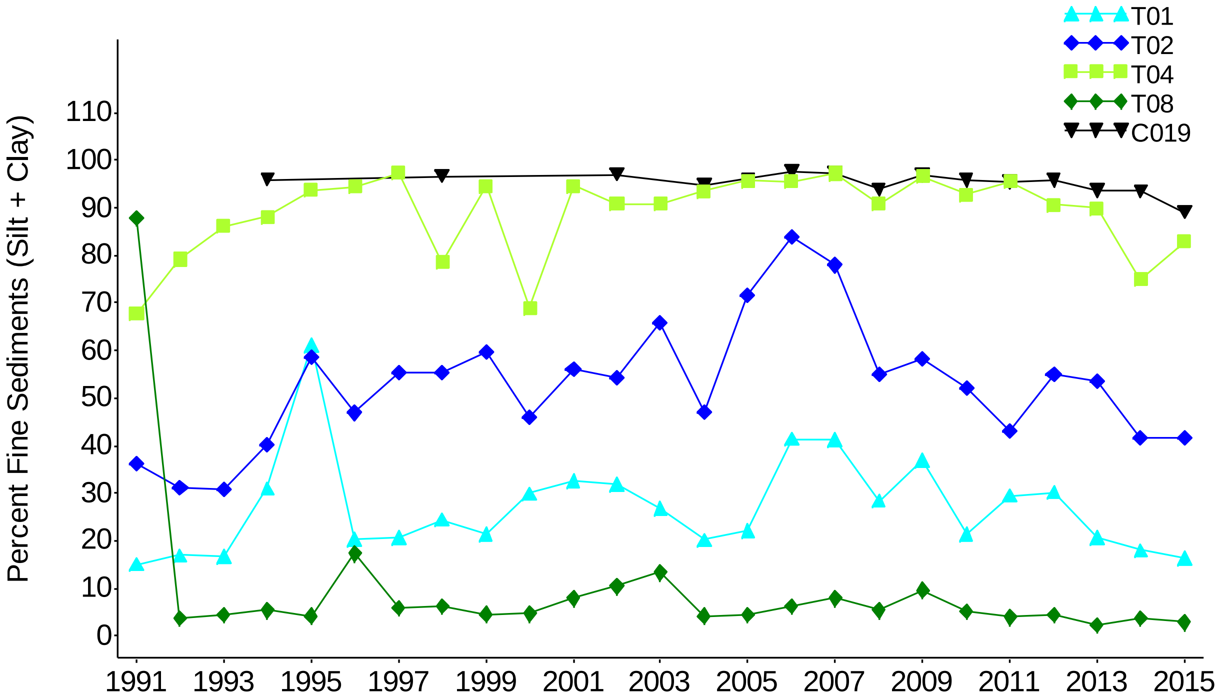


Figure 3. **Mean percent fine sediments at five stations in Boston Harbor, 1991 to 2015.**

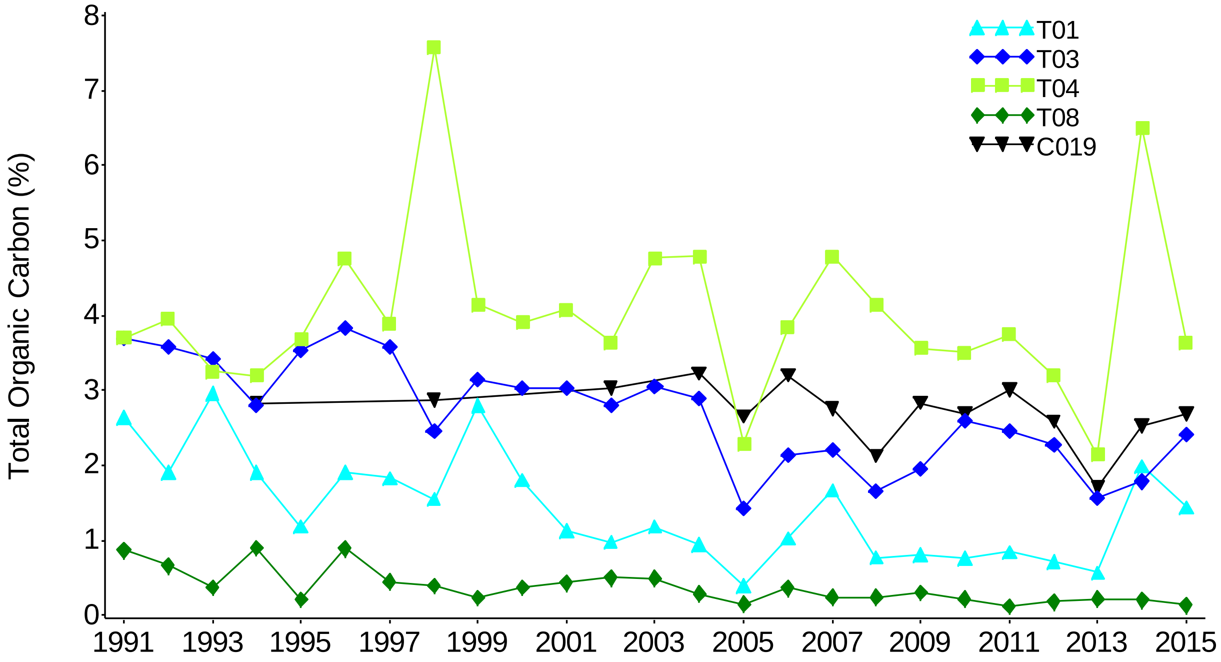


Figure 4. Mean concentrations of TOC at five stations in Boston Harbor, 1991 to 2015.

values generally associated with higher percent fines (Figures 3 and 4). During 2015, Stations T03, T04, T07, and C019 had among the highest concentrations of TOC and also had the highest proportions of fines (Table 1). Although T04 and C019 have typically had the highest TOC, values were highest at T07 in 2015 (compared to 2.9% in 2014) despite a decrease in percent fines from 61.8 to 48.6%. TOC values also increased slightly at C019 and T03 (Table 1; Figure 4). As in prior years, the lowest TOC concentrations for 2015 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 2015 were highest at Stations T07 and T03 in the Outer Harbor. Station C019 in the Inner Harbor had the third highest value. Lowest values were found at station T08 (Table 1). 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. *C. perfringens* counts at other Harbor stations have remained consistently below historical averages since around 1999 (Figure 5).

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

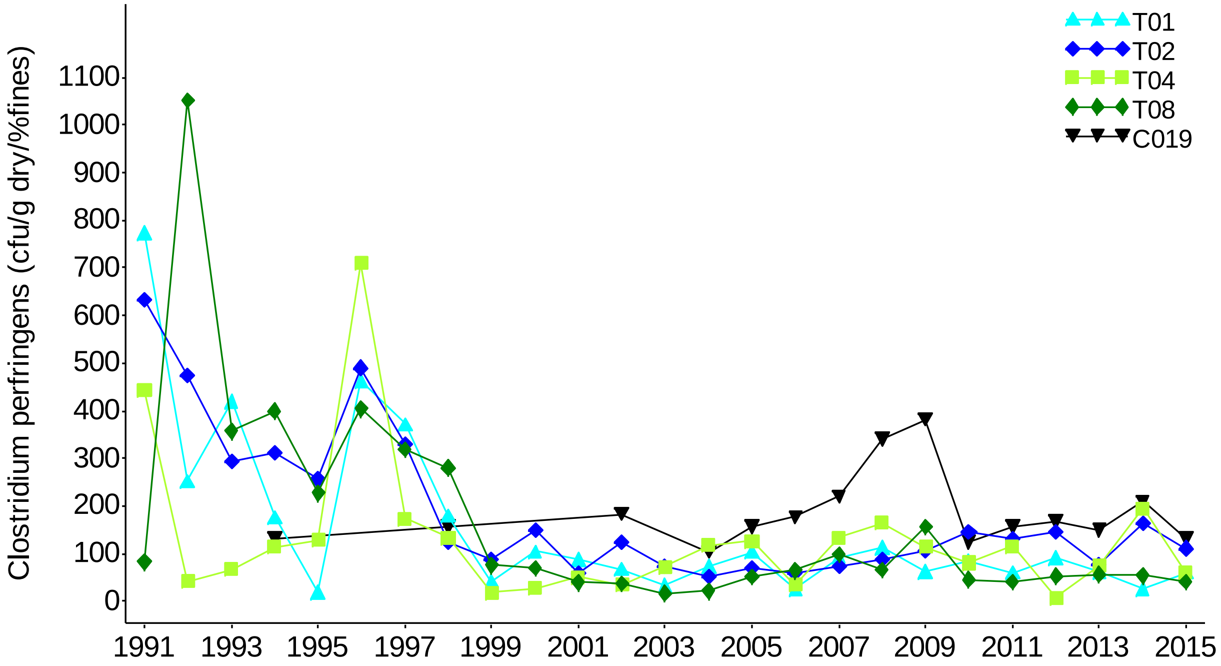


Figure 5. Mean concentrations of *Clostridium perfringens* at five stations in Boston Harbor, 1991 to 2015.

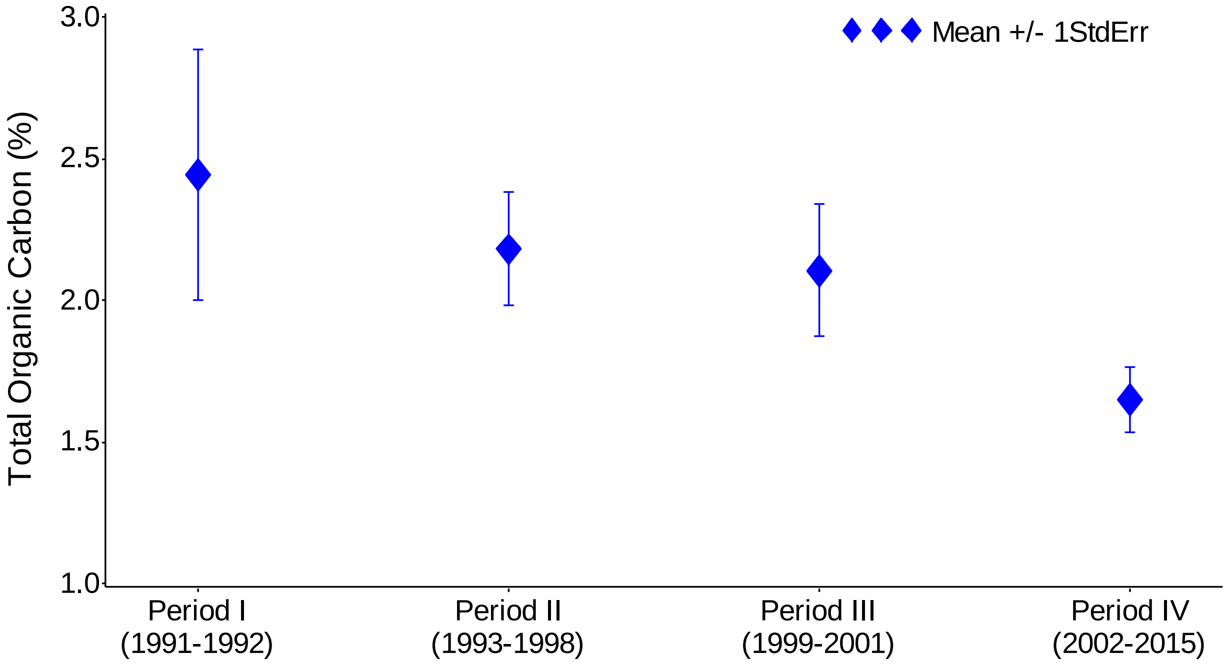


Figure 6. Comparison of TOC across four discharge periods (offset by one year) at Boston Harbor stations (T01-T08) from 1992 to 2015 (1991 excluded).

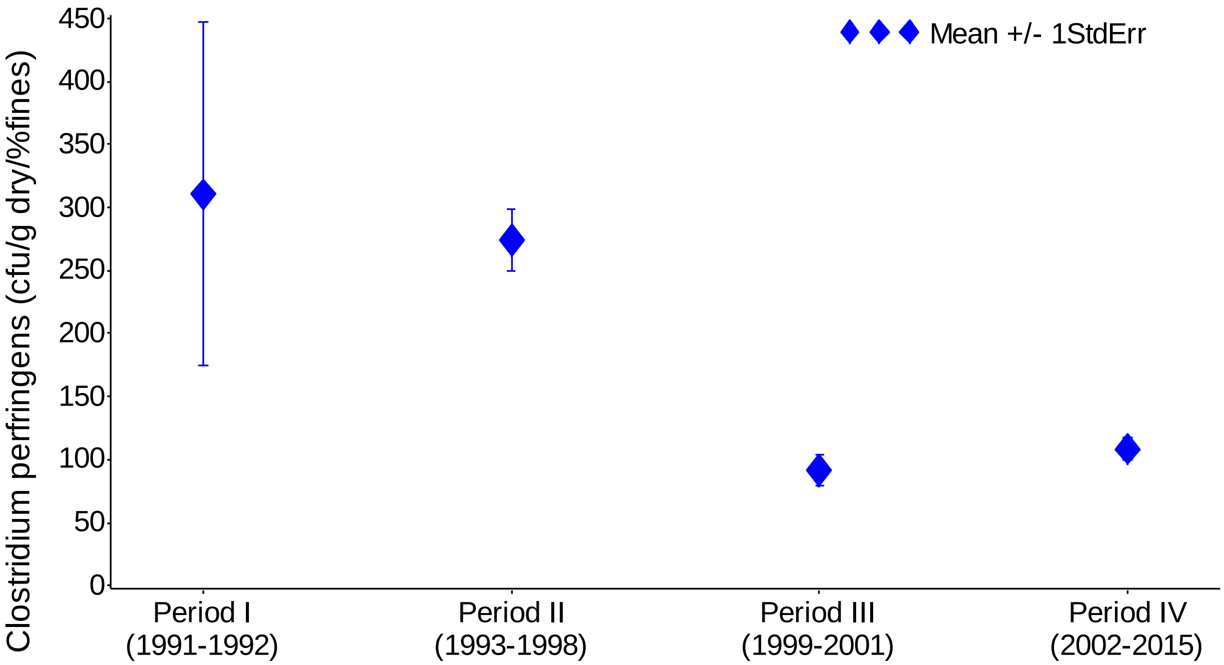


Figure 7. Comparison of *Clostridium perfringens* across four discharge periods (offset by one year) at Boston Harbor stations (T01-T08) from 1992 to 2015 (1991 excluded).

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 2015 for grain size, TOC, and *C. perfringens* in Boston Harbor sediments, are consistent with monitoring results from prior Period IV years (Maciolek et al. 2008, 2011; Pembroke et al. 2012, 2013, 2014, 2015). Concentrations of both TOC and *C. perfringens* at the traditional harbor stations (T01 to T08) have remained lower during the past decade than those reported during the 1990s (Figures 6 and 7). These findings are consistent with other changes documented in the Harbor following improvements to the collection, treatment and disposal of wastewater as part of the Boston Harbor Project (Maciolek et al. 2008, Taylor 2006).

3.2 Benthic Infauna

3.2.1 Community Parameters

A total of 33,058 infaunal organisms were counted from the 18 samples in 2015. Organisms were classified into 142 discrete taxa; 129 of those taxa were species-level identifications, and these species richness values are consistent with values observed in the harbor in recent years. Abundance values reported herein reflect the total counts from both species and higher taxonomic groups, while diversity measures are based on the species-level identifications only (Table 2). Data are presented in figures as means (averages per station) unless otherwise noted.

Table 2. 2015 mean infaunal community parameters by station.

Station	Total Abundance	Number of Species	Pielou's Evenness (J')	Shannon-Wiener Diversity (H')	Log-series alpha
C019	437	17	0.58	2.26	3.86
T01	3416	73	0.63	3.90	13.07
T02	2616	35	0.57	2.93	5.65
T03	3775	61	0.53	3.12	10.37
T04	370	7	0.44	1.25	1.25
T05A	1929	47	0.70	3.88	8.78
T06	2774	43	0.55	2.99	7.24
T07	483	26	0.64	2.98	5.76
T08	731	45	0.70	3.82	10.51

At most stations mean total abundance values reported for 2015 were higher than values in 2014. Increases in mean abundance exceeded 60% at Stations T01, T03, and T05A whereas mean abundance at T04 decreased by more than 60% (Pembroke et al. 2014). Abundances in 2015 were within the range observed during the post-offshore diversion period but relatively low compared to pre-diversion values (Figure 8). Most of the species that dominated (contributing $\geq$ 2.5% of the total abundance) the infauna at these stations in the past several years continued to do so in 2015 (Table 3) although the rank order changed. Abundances of two taxa (*Mediomastus californiensis* and *Tharyx* spp.) that had been numerical

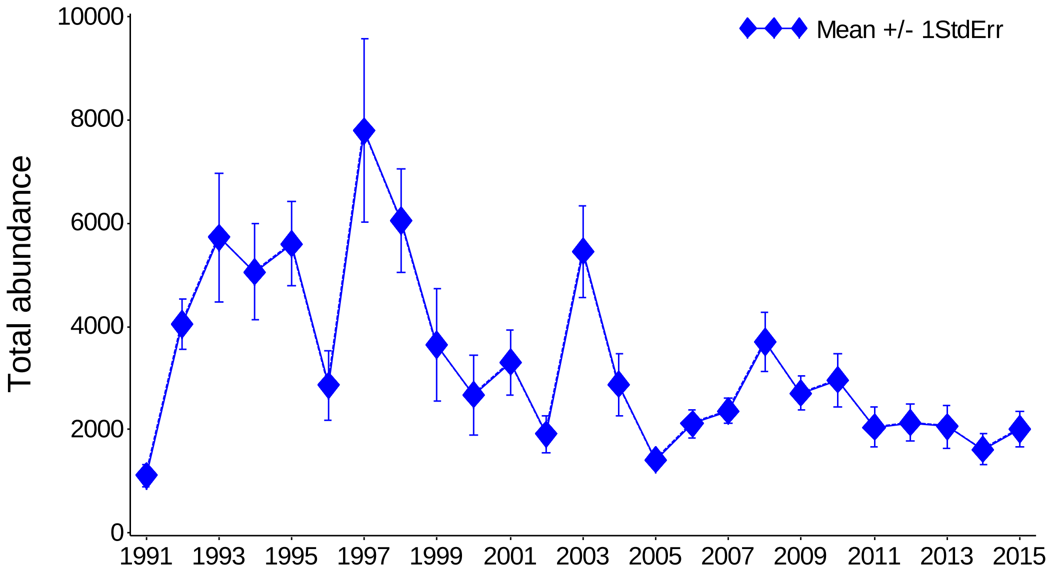


Figure 8. Mean abundance of benthic infauna at eight Boston Harbor stations, 1991-2015.

Table 3. Dominant taxa at eight grab stations in Boston Harbor in August 2015.

Taxon	Total 2015 Abundance (compared with 2014)[a]
Tubificoides intermedius[b]	5,616 (increase)
Aricidea catherinae	5,099 (increase)
Limnodriloides medioporus	4,490 (decrease)
Ampelisca spp.	2,972 (increase)
Scoletoma hebes	1,851 (similar)
Naidinae sp. 1	1,277 (increase)
Clymenella torquata	993 (increase)
Polydora cornuta	979 (decrease)
Streblospio benedicti	936 (decrease)

[a] increase or decrease indicates $\geq$25% change from previous year

[b] previously identified as *T. apectinatus*

dominants prior to 2013 remained below the 2.5% threshold but the tube-dwelling amphipod *Ampelisca* spp. rebounded in 2015 because of high abundances at T03. Three species of oligochaetes and five species of polychaetes were among the most abundant taxa in 2015. With the exception of *Clymenella torquata* and Naidinae sp. 1, all dominant taxa in 2015 have 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 the highest abundances among the harbor stations. Abundances at Station T05A continued to increase from the low in 2012. Abundances at Station T06 were similar to those observed in 2013 and 2014.

Temporally, benthic infaunal abundance in the harbor has been controlled by a handful of species (Table 4). Although these dominants have varied somewhat over the course of the surveys, four taxa (*Ampelisca* spp., *Aricidea catherinae, Limnodriloides medioporus*, and *Polydora cornuta*) have typically been among the most abundant organisms. Annual abundances of these species are presented in Figure 9. *Aricidea catherinae* and *Limnodriloides medioporus* have exhibited little interannual variation in abundance whereas both *Polydora cornuta* and *Ampelisca* spp. have exhibited fluctuations of one to two orders of magnitude and abundances of both species are currently low. Both of these species reside in the upper substrate layer so variability could be related to many factors, including changes in organic enrichment, physical forces such as storm events, and reproductive success in a given year as was described in previous reports (Maciolek et al. 2006, 2011). It is noteworthy that abundances of the oligochaete *Tubificoides intermedius* have steadily increased. In 2015, it was the most abundant species in the Harbor, nearly an order of magnitude higher than during Period I.

Patterns of abundance of *Ampelisca* spp. have been of particular interest throughout the past 24 years that Stations T01-T08 have been studied. Previous annual reports on the harbor surveys have related changes in the spatial extent of *Ampelisca* spp. beds and abundances of individual amphipods to changes in organic loading (the period from 1991 through about 1999) and storm events and subsequent recruitment (around 2005 through 2009; Maciolek et al. 2006, 2011). Following a period of low abundances (2005-

Table 4. Mean abundance per sample of dominant taxa during four discharge periods at eight Boston Harbor stations (T01-T08), 1992-2015.

Phylum	Higher taxon	Family	Species[a]	Period I	Period II	Period III	Period IV	2015
Annelida	Polychaeta	Capitellidae	*Capitella capitata* complex	65.2	88.8	3.4	6.3	11.1
		Lumbrineridae	*Scoletoma hebes*	3.4	10.5	4.2	68.3	115.7
		Maldanidae	*Clymenella torquata*	34.7	17.6	10.6	13.6	62.1
		Nephtyidae	*Bipalponephtys neotena*[b]	-	11.4	10.3	195.4	21.0
		Paraonidae	*Aricidea catherinae*	325.0	237.4	204.3	218.6	318.7
		Spionidae	*Polydora cornuta*	525.8	1053.0	269.6	253.8	61.2
			Streblospio benedicti	236.0	298.6	27.7	59.3	58.5
Annelida	Oligochaeta	Tubificidae	*Limnodriloides medioporus*	484.7	297.9	315.2	243.4	280.6
			Naidinae sp. 1	-	0.0	0.0	12.3	79.8
			Tubificoides intermedius	42.6	101.4	231.2	261.3	351.0
Arthropoda	Amphipoda	Ampeliscidae	*Ampelisca* spp.	354.3	1698.3	1205.9	585.2	185.8
		Corophiidae	Corophiidae spp.	16.1	336.2	23.0	1.4	-
			Crassicorophium bonellii	7.9	217.3	37.3	8.0	4.3
			Leptocheirus pinguis	29.0	117.4	66.0	83.6	7.3
		Photidae	*Photis pollex*	11.4	77.0	86.8	33.6	0.5
		Phoxocephalidae	*Phoxocephalus holbolli*	28	116.9	125.9	6.8	1.4

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

[b] previously identified as *Nepthys cornuta*.

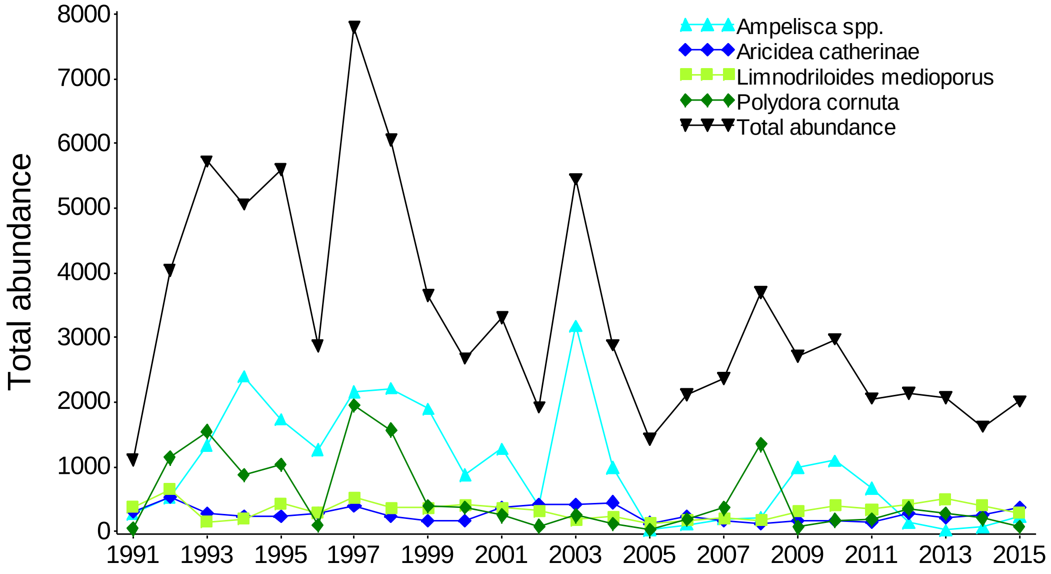


Figure 9. Total abundance of four dominant taxa at eight Boston Harbor stations, 1991-2015.

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 (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. The five-fold increase in *Ampelisca* at T03 in 2015 over 2014 and the increase in TOC at that station (Figure 4) could be related.

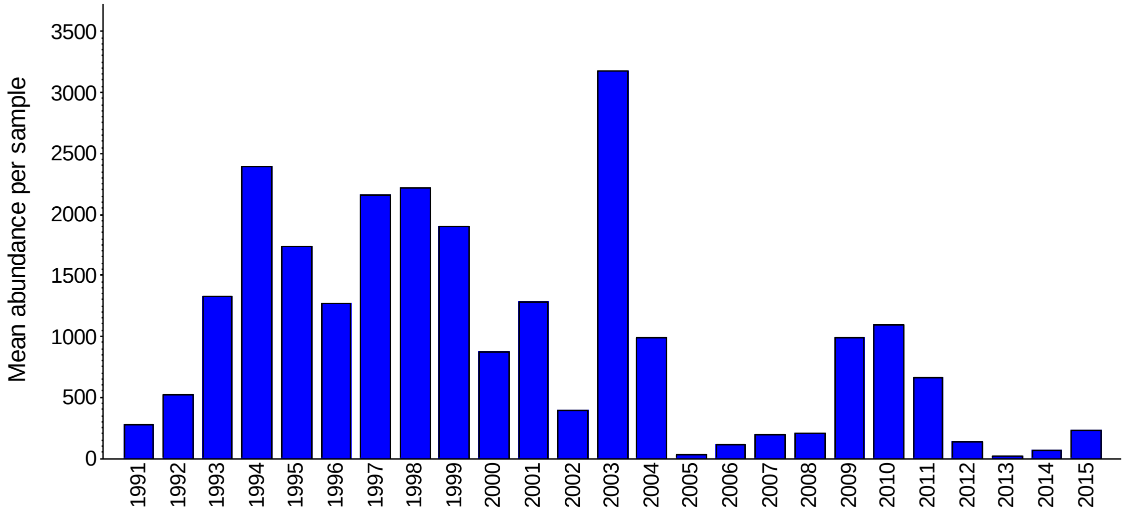


Figure 10. Mean annual abundance of *Ampelisca* spp. averaged over eight Boston Harbor stations, 1991-2015.

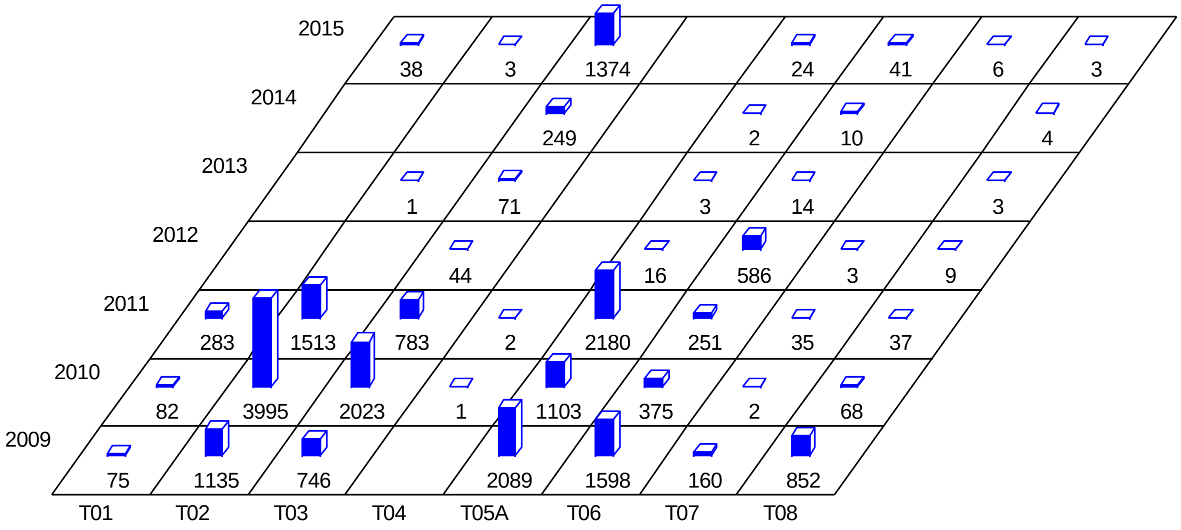


Figure 11. Spatial distribution of *Ampelisca* spp. at eight Boston Harbor stations, 2007-2015.

The numbers of species reported for 2015 ranged from 7 to 73 per station and averaged about 42 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 2015 than in 2014 but increased by more than 10 species at T01, T03, and T05A, all located in the northern part of the Outer Harbor. Stations T02, T03, and T08 were among the most species-rich stations from 2011 through 2014 (Pembroke et al. 2013, 2014, 2015); in 2015 species richness at T02 and T08 was at or below 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 an unusual peak in 2013, was closer to its historical pattern in 2014 and 2015 (Pembroke et al. 2013, 2014, 2015).

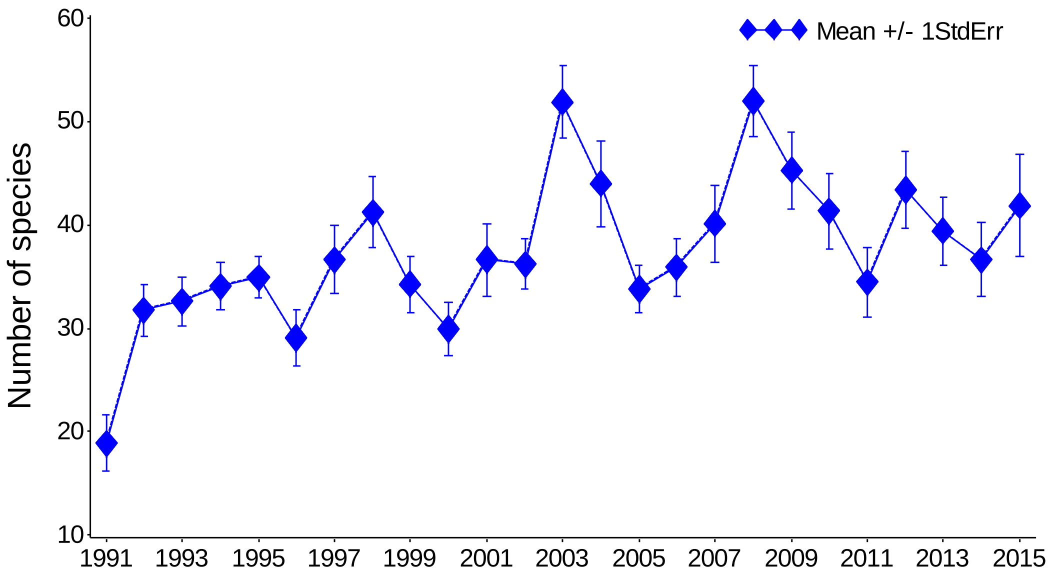


Figure 12. Mean species richness at eight Boston harbor stations, 1991-2015.

When averaged across the eight outer harbor stations, two measures of community structure, Pielou's evenness and Shannon-Weiner diversity, increased in 2015 as they did in 2014 (Figures 13 and 14), although the averages were driven by increases at fewer than half of the stations (Table 2 and Pembroke et al. 2015). 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 2014 and 2015 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, increased in 2015. Although the value in 2015 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

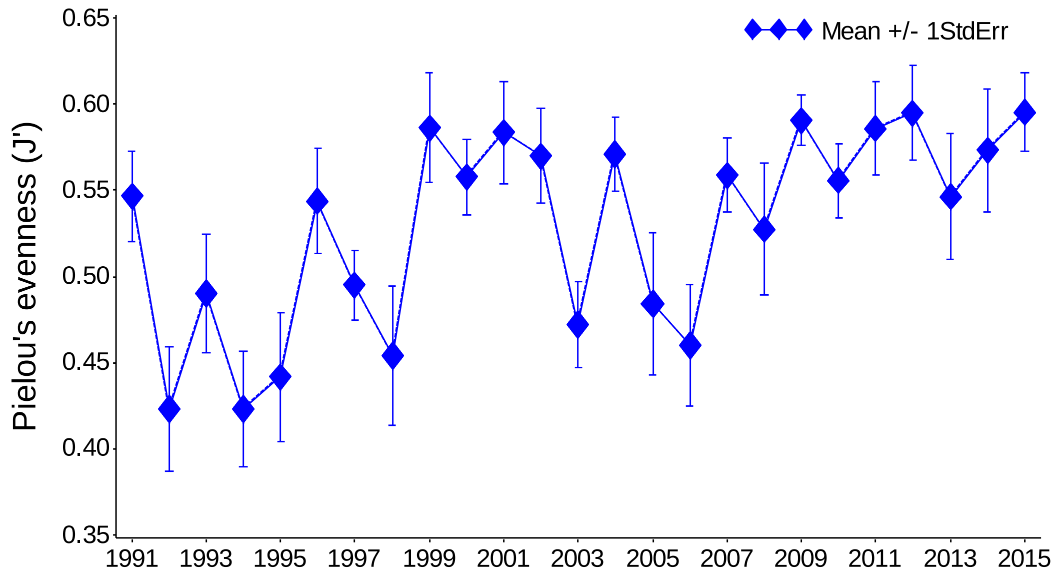


Figure 13. Mean community evenness at eight Boston Harbor stations, 1991-2015.

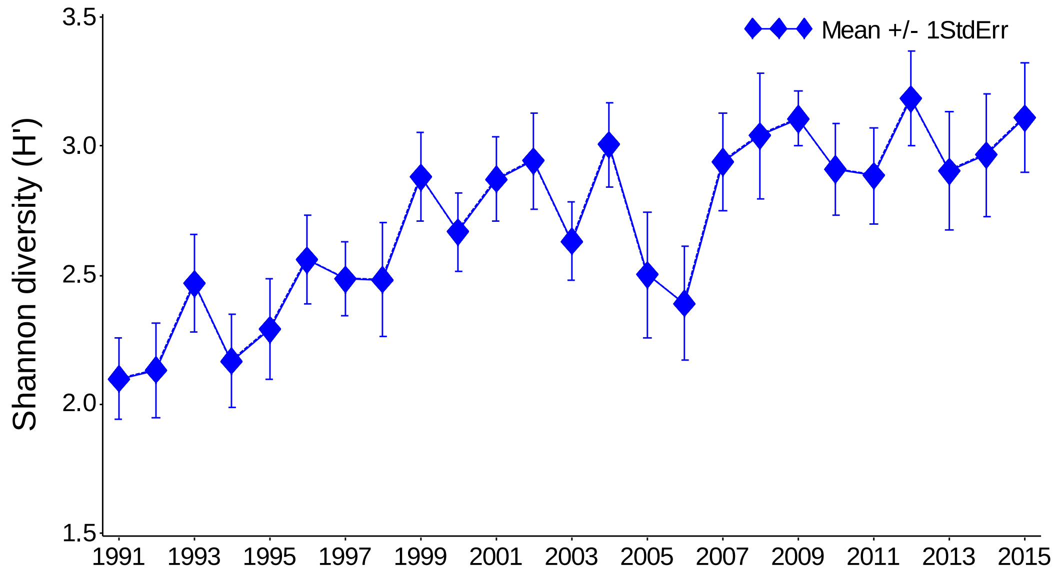


Figure 14. Mean Shannon-Weiner diversity at eight Boston harbor stations, 1991-2015.

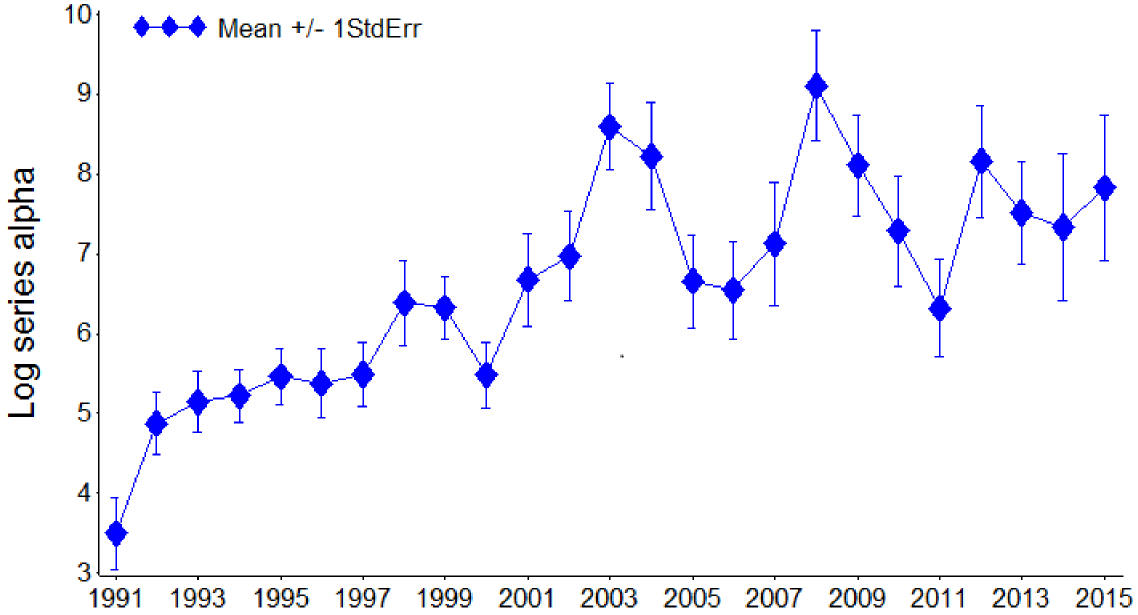


Figure 15. Mean log-series alpha diversity at eight Boston Harbor stations, 1991-2015.

lowest at T04 in 2015 (Table 2; Pembroke et al. 2014, 2015). The largest changes in log-series alpha compared to 2014 were a decrease at T08 and an increase at T01.

3.2.2 Infaunal Assemblages

Multivariate analyses were used to assess spatial and temporal patterns in the faunal assemblages at the Boston Harbor sampling stations. Replicates within each station exhibited high similarities in community structure. Two main assemblages were identified in a cluster analysis of the 18 samples from 2015 with the stations clustering into the same groups observed in 2014. Group I included both replicates of six stations (T01, T02, T03, T05A, T06, and T08), although species composition at T08 differed sufficiently from the other stations to be separated as a subgroup. Replicates from two other stations (T07 and C019) also formed their own discrete group (Group II, Figure 16), similar to 2014 (Pembroke et al. 2015). As in previous years, including 2014, the community observed at T04 in 2015 bore little resemblance to the other harbor stations resulting in its separation at a similarity value of less than 20% (Figure 16).

Main Group I was characterized by a relatively high species richness (averaging 51 species per collection). Five species (*Tubificoides intermedius*, *Aricidea catherinae*, *Limnodriloides medioporus*, *Ampelisca* spp., and *Scoletoma hebes*) had relatively high abundances (Table 5). Species composition, species richness, and total abundance differed between the two subgroups however. Species richness was moderate at Station T08 (Subgroup IA), but total abundances were low and the community was dominated by five species (*Polygordius jouniae*, *Tharyx acutus*, *Angulus agilis*, and *Limnodriloides medioporus*) most of which were not among the most abundant in the other Group I collections.

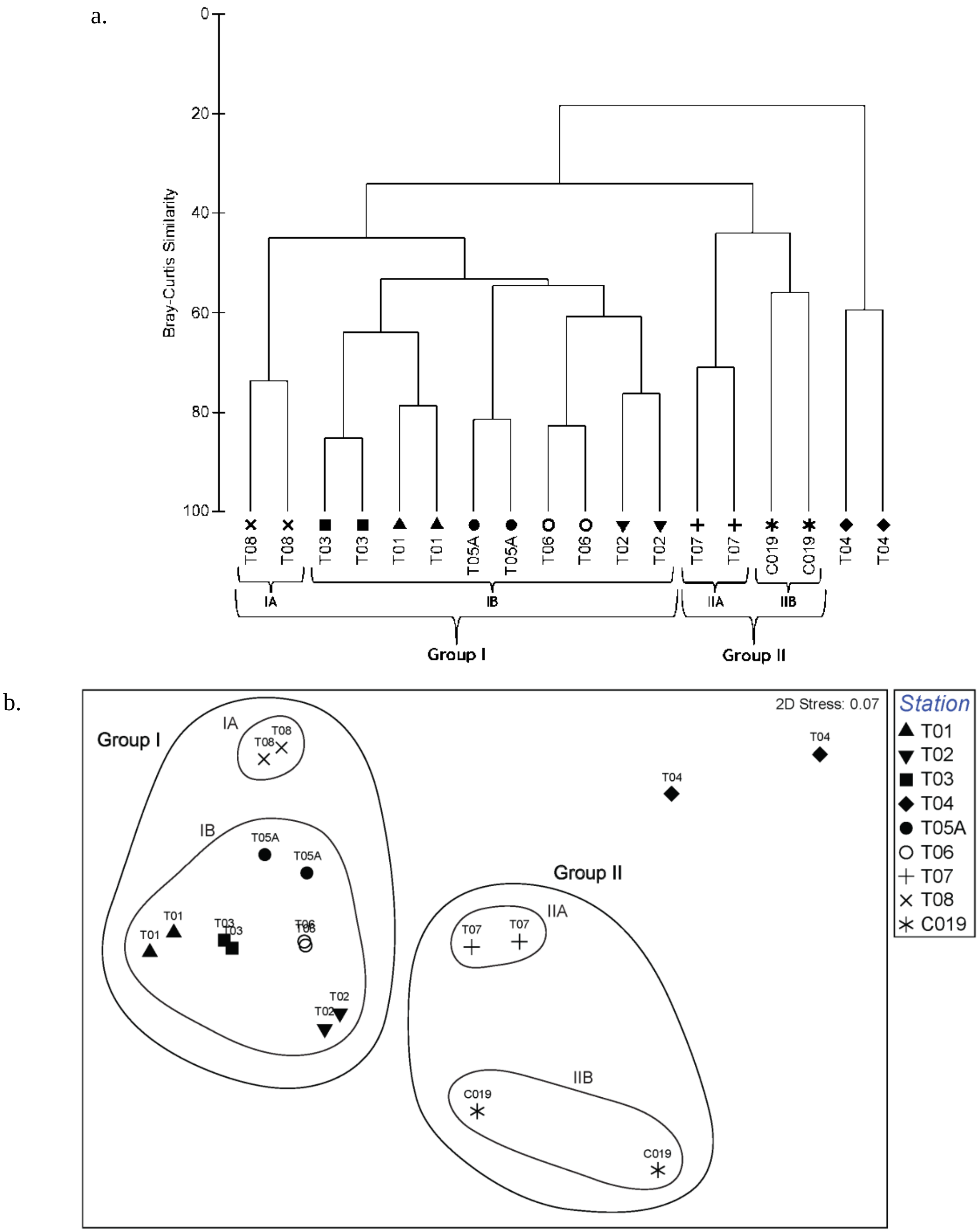


Figure 16. Results of (a) cluster analysis and (b) multidimensional scaling analysis of the 2015 infauna samples.

Table 5. Mean abundance of dominant taxa in 2015 Boston Harbor station groups defined by cluster analysis.

Phylum	Major Taxon	Family	Species	I	IA[a]	IB[a]	II	IIA[b]	IIB[b]	T04
Platyhelminthes	Turbellaria		*Turbellaria* spp.	**4.9**	19.0	2.1	-	-	-	-
Mollusca	Gastropoda	*Pyramidellidae*	*Boonea seminuda*	**44.4**	-	53.3	**0.3**	0.5	-	-
Mollusca	Bivalvia	Tellinidae	*Angulus agilis*	**21.3**	64.0	12.7	**3.8**	7.5	-	**3.5**
Annelida	Polychaeta	Capitellidae	*Capitella capitata* complex	**14.8**	3.5	17.0	**8.3**	0.5	16.0	-
			Mediomastus californiensis	**38.0**	-	45.6	**7.3**	-	14.5	-
		Cirratulidae	*Monticellina baptisteae*	**10.1**	30.5	6.0	-	-	-	-
			Tharyx acutus	**34.3**	77.5	25.7	**5.8**	3.0	8.5	**0.5**
		Cossuridae	*Cossura longocirrata*	**<0.1**	-	0.1	**2.5**	-	5.0	-
		Hesionidae	*Microphthalmus pettiboneae*	**16.9**	1.0	20.1	**3.3**	3.5	3.0	**0.5**
		Lumbrineridae	*Scoletoma hebes*	**152.0**	6.5	181.1	**9.5**	13.5	5.5	-
		Maldanidae	*Clymenella torquata*	**82.8**	32.0	92.9	-	-	-	-
		Nephtyidae	*Bipalponephtys neotena*	**7.9**	-	9.5	**81.5**	120.5	42.5	-
		Orbiniidae	*Leitoscoloplos robustus*	**8.4**	6.0	8.9	**3.2**	6.5	-	-
		Paraonidae	*Aricidea catherinae*	**424.5**	9.5	507.5	**2.0**	2.5	1.5	-
		Phyllodocidae	*Phyllodoce mucosa*	**41.8**	0.5	50.1	-	-	-	-
		Polygordiidae	*Polygordius jouinae*	**61.9**	218.0	30.7	-	-	-	-
		Spionidae	*Polydora cornuta*	**71.3**	1.0	85.4	**35.3**	57.5	13.0	**4.0**
			Spiophanes bombyx	**24.2**	26.0	23.8	-	-	-	-
			Streblospio benedicti	**17.8**	0.5	21.2	**61.3**	113.5	9.0	**248.0**
		Syllidae	*Exogene hebes*	**22.1**	30.5	20.4	-	-	-	-
Annelida	Oligochaeta	Tubificidae	*Limnodriloides medioporus*	**370.1**	45.5	435.0	**8.0**	16.0	-	**8.5**
			Naidinae sp. 1	**104.3**	30.0	119.1	**5.0**	10.0	-	**3.0**
			Tubificoides intermedius	**449.8**	17.0	536.4	**177.0**	94.0	260.0	**15.0**
			Tubificoides sp. 2	-	-	-	**0.3**	0.5	-	**85.0**
Arthropoda	Amphipoda	Ampeliscidae	*Ampelisca* spp.	**246.7**	3.0	295.4	**3.0**	6.0	-	-
		Corophiidae	*Leptocheirus pinguis*	**9.7**	-	11.6	**21.0**	-	42.0	-
			Monocorophium acherusicum	-	-	-	**0.3**	0.5	-	**0.5**

[a] distinct subgroup of Group I

[b] distinct subgroup of Group II

Oligochaete abundances were notably low at Station T08. Subgroup IB included five stations (T01, T02, T03, T05A, and T06). Total abundance was high in this subgroup, species richness was relatively high (52 species), and the dominant species were the same as in the main group. Five of the seven stations where *Ampelisca* spp. occurred in 2015 were included in Group IB.

Group II collections were characterized by low total abundance and relatively low species richness. Three taxa (*Tubificoides intermedius*, *Bipalponephtys neotena*, and *Streblospio benedicti*) were numerical dominants. The two subgroups each included only one station that differed primarily in terms of the most abundant species. *S. benedicti* and *B. neotena* co-dominated in Subgroup IIA (T07) and *T. intermedius* dominated in subgroup IIB (C019). Domination of T04 collections by *Streblospio benedicti* (Table 5) influenced its average community parameters, including Shannon-Weiner and log-series alpha diversity, and Pielou's evenness which were all notably lowest at T04 (Table 2).

Sediment conditions, particularly percent fines and TOC were likely factors in distinguishing the benthic communities among the Boston Harbor stations. Group I stations tended to have relatively low (<50%) silt-clay components and TOC (<2% except Station T03) and Station T08 had extremely low fines (2.9%) and TOC (0.1%; Table 1). In Group II, Station T07 had relatively low percent fines (49%) but high TOC (3.8%) whereas Station C019 had relatively high percent fines (89%) and high TOC (2.7%; Table 1).

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 2015, species richness and diversity measures were the highest of the harbor stations and evenness was relatively high at T01. All of these community parameters were higher than the values in 2014 (Pembroke et al. 2015). Mean abundance in 2015 was the highest observed since the diversion to the offshore outfall (Figure 17). Species richness, Shannon-Weiner diversity, log-series alpha were all on the high end of the range observed since the diversion (Figures 18, 19, and 20) while Pielou's evenness was about average for that period (Figure 21). Mean log-series alpha has fluctuated substantially since the diversion to the offshore outfall and in 2015 reached one of the highest values observed since the diversion, surpassing the high value observed in 2014 (Figure 20). In 2015, all of these community parameters continued to increase from the relatively low values observed in 2013 (Figures 17 through 21).

Station C019. Station C019 was initially included in the Harbor sampling program as part of the Sediment-Water Exchange (SWEX) study (Gallagher and Keay 1998). When first sampled in 1989, the benthic infauna consisted of only a few taxa and was overwhelmingly dominated by two polychaete species, *Streblospio benedicti* and *Chaetozone anasimus* (previously called *C. setosa*). Although mean abundance peaked in 2013, total numbers in 2014 and 2015 were again very low (Figure 17). Species richness also peaked in 2013 and has decreased in both 2014 and 2015 (Figure 18). Shannon-Weiner diversity, Pielou's evenness, and log-series alpha all reached their peak values in 2014; although they declined in 2015, they all remained higher than values prior to 2012 (Figures 19, 20, and 21). The polychaete *Bipalponephtys neotena* (formerly called *Nepthys cornuta*) had represented the majority of the infauna found at Station C019 from 2004-2011 (Figure 22) but the relative abundance of this species has

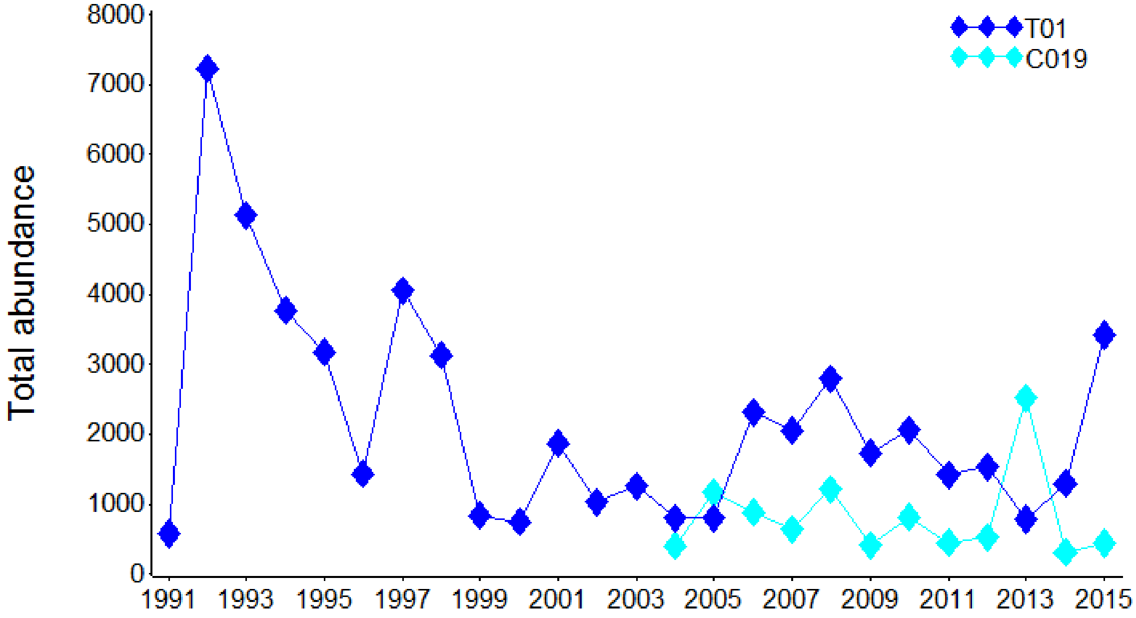


Figure 17. Mean total abundance at Boston Harbor Stations T01 and C019, 1991-2015.

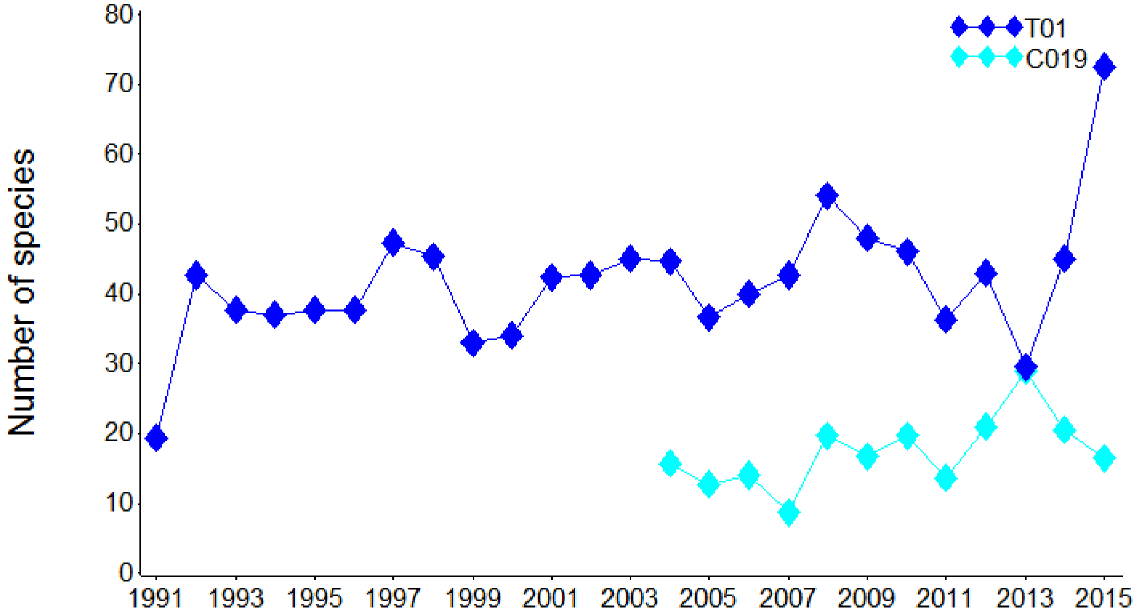


Figure 18. Mean species richness at Boston Harbor Stations T01 and C019, 1991-2015.

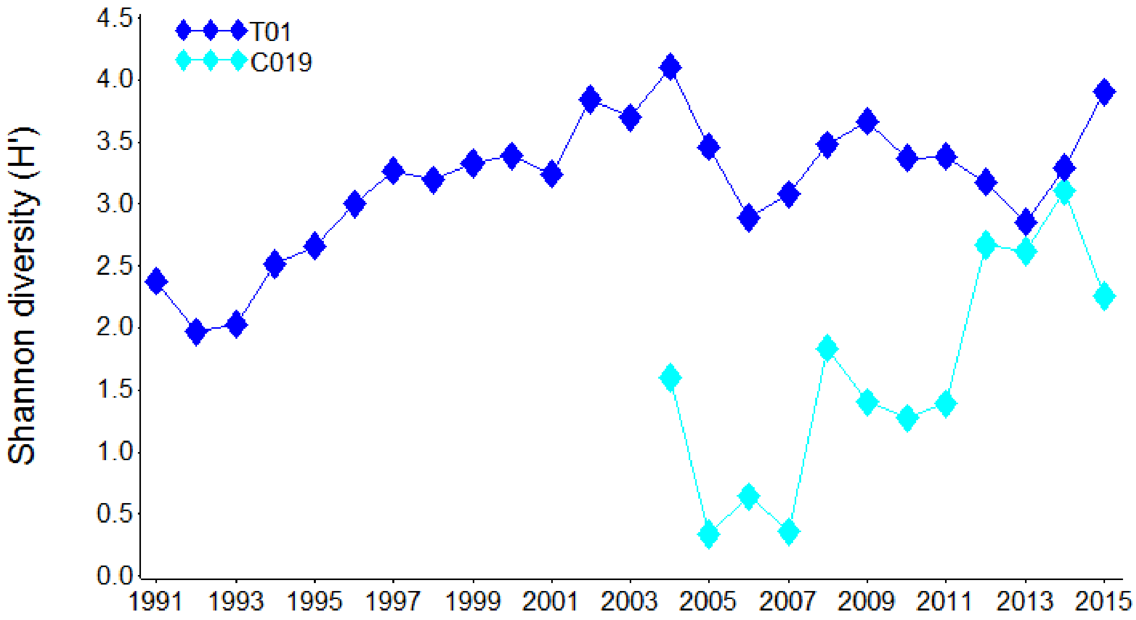


Figure 19. Mean Shannon-Weiner diversity at Boston Harbor Stations T01 and C019, 1991-2015.

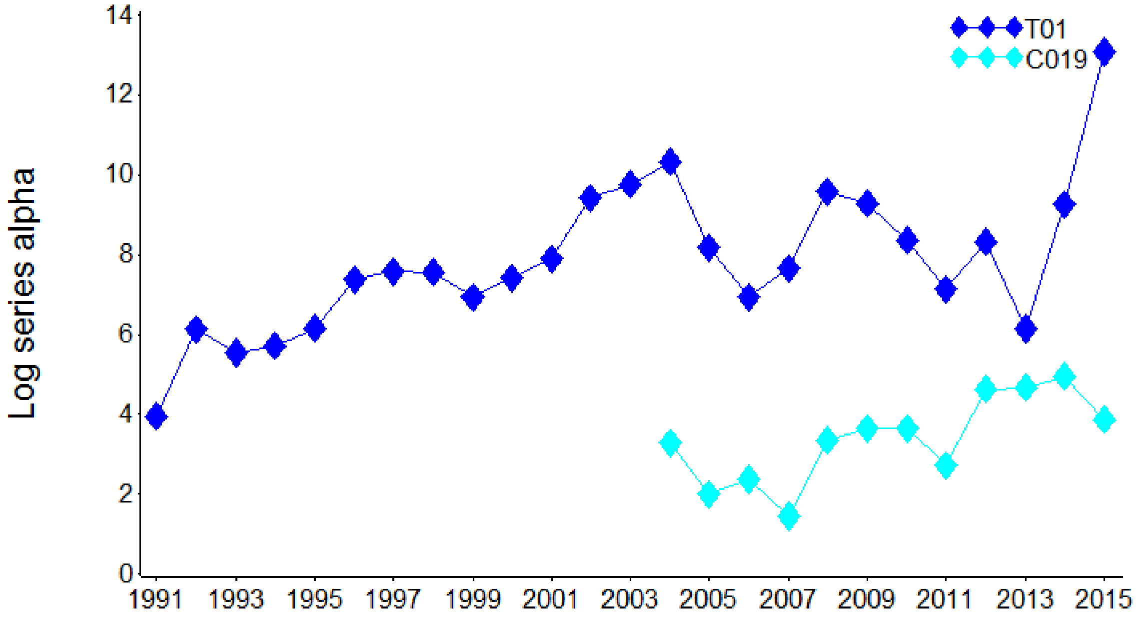


Figure 20. Mean log-series alpha diversity at Boston Harbor Stations T01 and C019, 1991-2015.

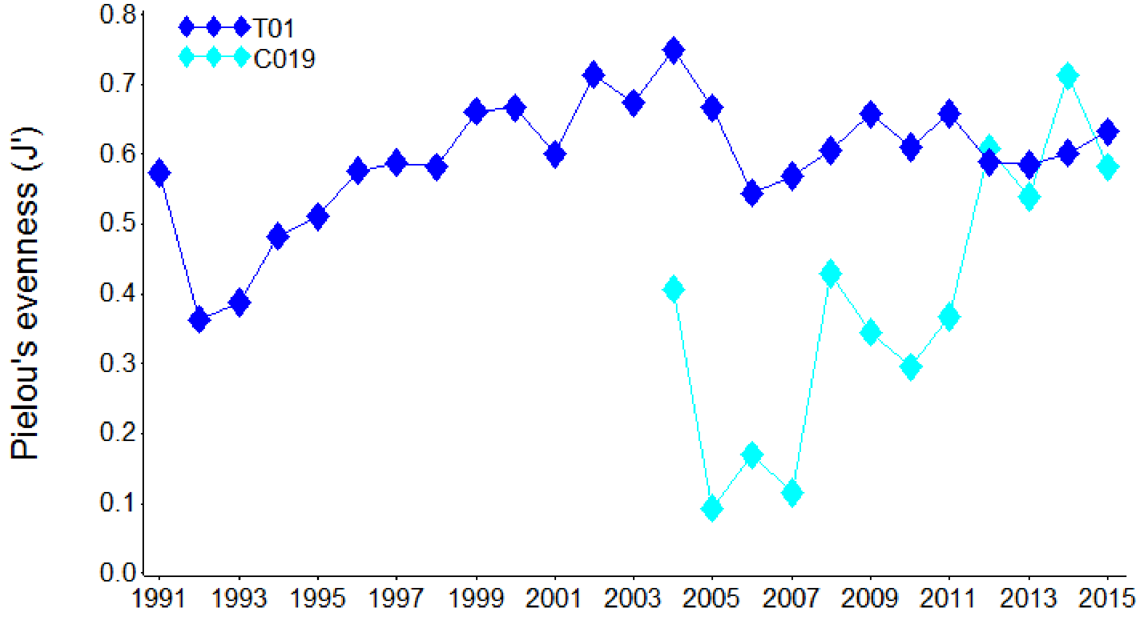


Figure 21. Mean evenness at Boston Harbor stations T01 and C019, 1991-2015.

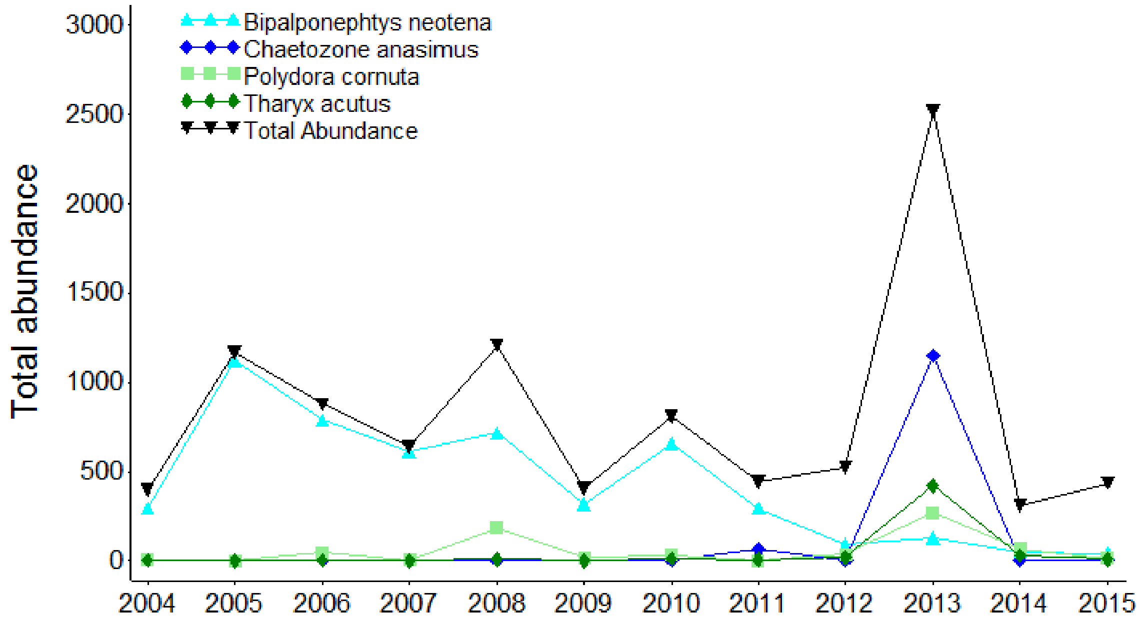


Figure 22. Mean abundance of *Bipalponephtys neotena* and other dominants and total community abundance at Station C019, 2004-2015.

been substantially lower since 2012 (Pembroke et al. 2013). In 2013 *C. anasimus* again dominated the infauna community (Pembroke et al. 2014), coincident with a sharp decrease in TOC (Figure 4). In 2015, the oligochaete *Tubificoides intermedius* dominated the infaunal community likely contributing to the decline in evenness and diversity values.

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 2001-2015 were virtually the same as for 2001-2014 (Pembroke et al. 2014) so it is apparent that this trend has continued.

3.3 Sediment Profile Imaging

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 lead to 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 mid-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 late 2000s to mid-2010s there were large year-to-year variations in patterns of benthic habitat quality and benthic communities. Overlaid on the annual variation was a general long-term trend of improvement (Pembroke et al. 2015).

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

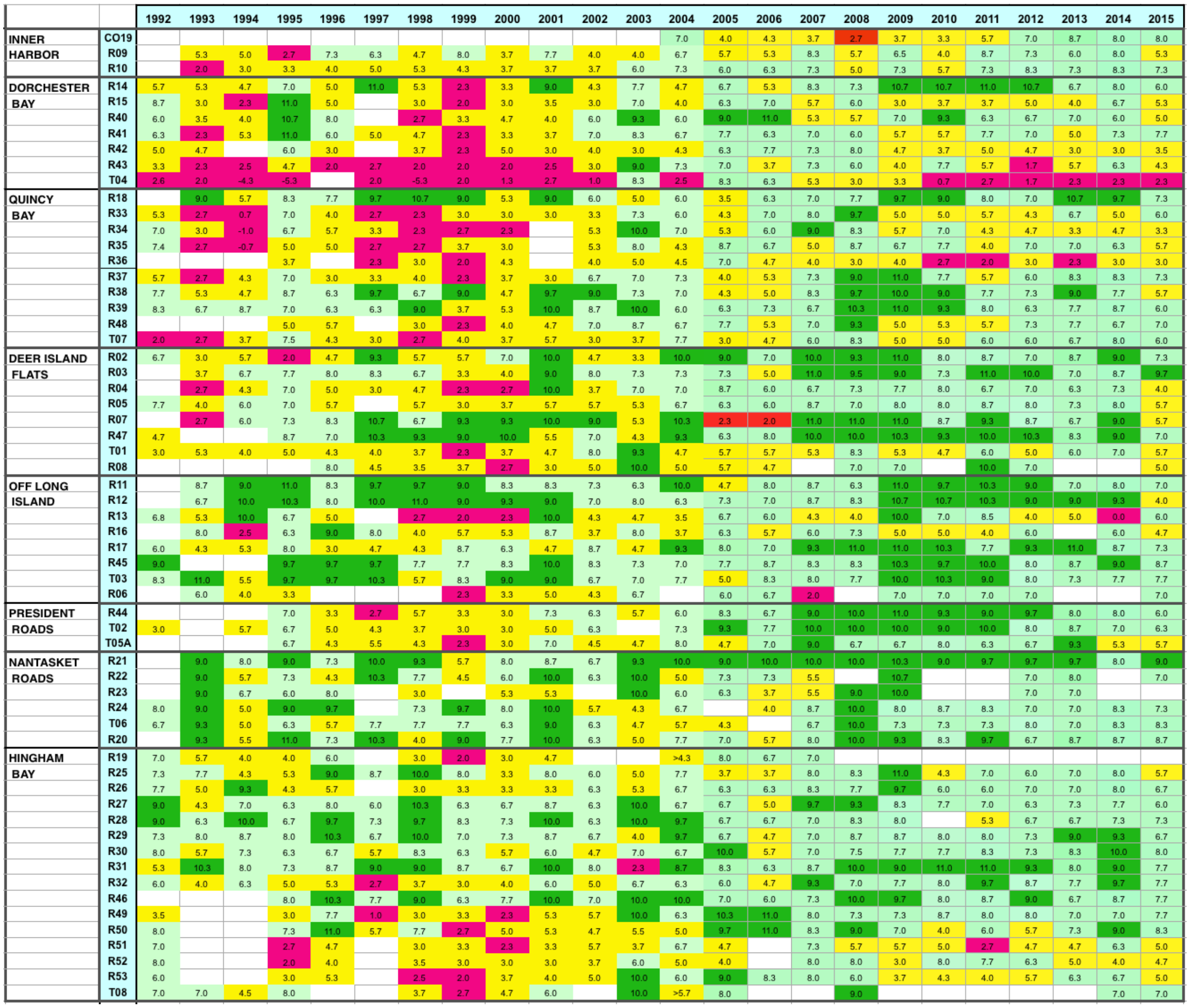
Parameter	Period I (prior to Dec. 1991)[a]		Period II (Dec. 1991-mid 1998)		Period III (mid-1998-Sept. 2000)		Period IV (after Sept. 2000)	
	Mean	Std Err	Mean	Std Err	Mean	Std Err	Mean	Std Err
Total Abundance	2,606	344	5,513	469	3,213	493	2,588	135
Log-series alpha	4.2	0.3	5.5	0.2	6.2	0.3	7.5	0.2
Shannon-Wiener Diversity (H')	2.12	0.1	2.4	0.1	2.8	0.1	2.9	<0.1
Pielou's Evenness (J')	0.48	0.02	0.47	0.01	0.58	0.02	0.55	0.01
Number of Species	25.5	2.1	34.7	1.1	33.6	1.7	41.2	1.0
Years included (with one year offset)	1991-1992		1993-1998		1999-2001		2002-2015	

In 2015, relative to 2014, soft bottom benthic habitat conditions within Boston Harbor appeared to regress as measured by the Organism Sediment Index (OSI) of Rhoads and Germano (1986). OSI provided a means of scaling sediment profile image (SPI) parameters to arrive at a score that can be used to assess benthic habitat quality. The OSI is based on estimated benthic successional stage, thickness of the apparent color redox potential discontinuity layer (aRPD), and apparent presence of low dissolved oxygen (Rhoads and Germano 1986). The OSI ranges from -10, poorest quality habitats, to 11, highest quality habitats. In northeastern estuarine and coastal ecosystems, such as Boston Harbor, values >6 were associated with higher quality habitats with well-developed macrofaunal communities. An OSI of <6 would indicate stressful benthic habitat conditions, although the OSI does not identify the source of stress.

While the OSI at most of the Harbor stations was above 6 in 2015, 15 stations that had an OSI above 6 in 2014 dropped below an OSI of 6 in 2015. Another six stations were below 6 both years (Figure 23). The OSI averaged by Harbor region was lower in 2015 for all regions (Table 7). Much of the change in OSI reflected a slight decline in the depth of the aRPD layer in 2015 relative to 2014 (Figure 24), and to a lesser extent a lowering of estimated successional stage designation based on the presence/absence of biogenic structures. Nantasket Roads was the only Harbor region that had a deeper average aRPD layer depth for 2015 (Table 7).

The 2015 decline in OSI was a departure from the trend of increasing OSI values, which started between 2001 and 2003. Overall, 2015 still represented improved benthic habitat quality over the early and late 1990s (Figure 25). The range of OSI from 1992 to 2015 was greatest for the inner Harbor regions of Dorchester Bay followed by Quincy Bay (Figure 26). These two regions were the only ones to have negative OSIs, but by mid to late 2000s OSI values were near highs of 11 at some stations within these regions (Figures 23 and 26). Habitat quality also improved in the Inner Harbor through time and by 2012 all stations had OIS values >6. Nantasket Roads was the only Harbor region to have consistently high OSI values from the late 2000s on to the present. President Roads had a similar pattern except for Station T05A which had low OSIs in 2014 and 2015. While mid Harbor regions of Deer Island Flats and Hingham Bay, and Off Long Island all had high OSIs from the late 2000s, the trend was for lower OSIs in 2015 (Figures 23 and 26).

Outer Harbor stations are more strongly influenced by hydrodynamic factors, being better flushed and with sandier sediments, and have always had high habitat quality. But outer Harbor regions also improved in habitat quality after the operation of the ocean outfall (Figures 23 and 26). From 1992 to the present there is strong evidence that benthic habitats throughout Boston Harbor shifted from a more anaerobic state to a more aerobic state and that these changes were directly related to changes in carbon loading associated with outfall placement and improvements in wastewater treatment (Taylor 2010, Tucker et al. 2014). Much of the change in habitat quality was driven by infaunal bioturbation that



		1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
INNER HARBOR	CO19													7.0	4.0	4.3	3.7	2.7	3.7	3.3	5.7	7.0	8.7	8.0	8.0
	R09		5.3	5.0	2.7	7.3	6.3	4.7	8.0	3.7	7.7	4.0	4.0	6.7	5.7	5.3	8.3	5.7	6.5	4.0	8.7	7.3	6.0	8.0	5.3
	R10		2.0	3.0	3.3	4.0	5.0	5.3	4.3	3.7	3.7	3.7	6.0	7.3	6.0	6.3	7.3	5.0	7.3	5.7	7.3	8.3	7.3	8.3	7.3
DORCHESTER BAY	R14	5.7	5.3	4.7	7.0	5.0	11.0	5.3	2.3	3.3	9.0	4.3	7.7	4.7	6.7	5.3	8.3	7.3	10.7	10.7	11.0	10.7	6.7	8.0	6.0
	R15	8.7	3.0	2.3	11.0	5.0		3.0	2.0	3.0	3.5	3.0	7.0	4.0	6.3	7.0	5.7	6.0	3.0	3.7	3.7	5.0	4.0	6.7	5.3
	R40	6.0	3.5	4.0	10.7	8.0		2.7	3.3	4.7	4.0	6.0	9.3	6.0	9.0	11.0	5.3	5.7	7.0	9.3	6.3	6.7	7.0	6.0	5.0
	R41	6.3	2.3	5.3	11.0	6.0	5.0	4.7	2.3	3.3	3.7	7.0	8.3	6.7	7.7	6.3	7.0	6.0	5.7	5.7	7.7	7.0	5.0	7.3	7.7
	R42	5.0	4.7		6.0	3.0		3.7	2.3	5.0	3.0	4.0	3.0	4.3	6.3	7.7	7.3	8.0	4.7	3.7	5.0	4.7	3.0	3.0	3.5
	R43	3.3	2.3	2.5	4.7	2.0	2.7	2.0	2.0	2.0	2.5	3.0	9.0	7.3	7.0	3.7	7.3	6.0	4.0	7.7	5.7	1.7	5.7	6.3	4.3
	T04	2.6	2.0	-4.3	-5.3		2.0	-5.3	2.0	1.3	2.7	1.0	8.3	2.5	8.3	6.3	5.3	3.0	3.3	0.7	2.7	1.7	2.3	2.3	2.3
QUINCY BAY	R18		9.0	5.7	8.3	7.7	9.7	10.7	9.0	5.3	9.0	6.0	5.0	6.0	3.5	6.3	7.0	7.7	9.7	9.0	8.0	7.0	10.7	9.7	7.3
	R33	5.3	2.7	0.7	7.0	4.0	2.7	2.3	3.0	3.0	3.0	3.3	7.3	6.0	4.3	7.0	8.0	9.7	5.0	5.0	5.7	4.3	6.7	5.0	6.0
	R34	7.0	3.0	-1.0	6.7	5.7	3.3	2.3	2.7	2.3		5.3	10.0	7.0	5.3	6.0	9.0	8.3	5.7	7.0	4.3	4.7	3.3	4.7	3.3
	R35	7.4	2.7	-0.7	5.0	5.0	2.7	2.7	3.7	3.0		5.3	8.0	4.3	8.7	6.7	5.0	8.7	6.7	7.7	4.0	7.0	7.0	6.3	5.7
	R36				3.7		2.3	3.0	2.0	4.3		4.0	5.0	4.5	7.0	4.7	4.0	3.0	4.0	2.7	2.0	3.0	2.3	3.0	3.0
	R37	5.7	2.7	4.3	7.0	3.0	3.3	4.0	2.3	3.7	3.0	6.7	7.0	7.3	4.0	5.3	7.3	9.0	11.0	7.7	5.7	6.0	8.3	8.3	7.3
	R38	7.7	5.3	4.7	8.7	6.3	9.7	6.7	9.0	4.7	9.7	9.0	7.3	7.0	4.3	5.0	8.3	9.7	10.0	9.0	7.7	7.3	9.0	7.7	5.7
	R39	8.3	6.7	8.7	7.0	6.3	6.3	9.0	3.7	5.3	10.0	8.7	10.0	6.0	6.3	7.3	6.7	10.3	11.0	9.3	8.0	6.3	7.7	8.7	6.0
	R48				5.0	5.7		3.0	2.3	4.0	4.7	7.0	8.7	6.7	7.7	5.3	7.0	9.3	5.0	5.3	5.7	7.3	7.7	6.7	7.0
	T07	2.0	2.7	3.7	7.5	4.3	3.0	2.7	4.0	3.7	5.7	3.0	3.7	7.7	3.0	4.7	6.0	8.3	5.0	5.0	6.0	6.0	6.7	8.0	6.0
DEER ISLAND FLATS	R02	6.7	3.0	5.7	2.0	4.7	9.3	5.7	5.7	7.0	10.0	4.7	3.3	10.0	9.0	7.0	10.0	9.3	11.0	8.0	8.7	7.0	8.7	9.0	7.3
	R03		3.7	6.7	7.7	8.0	8.3	6.7	3.3	4.0	9.0	8.0	7.3	7.3	7.3	5.0	11.0	9.5	9.0	7.3	11.0	10.0	7.0	8.7	9.7
	R04		2.7	4.3	7.0	5.0	3.0	4.7	2.3	2.7	10.0	3.7	7.0	7.0	8.7	6.0	6.7	7.3	7.7	8.0	6.7	7.0	6.3	7.3	4.0
	R05	7.7	4.0	6.0	7.0	5.7		5.7	3.0	3.7	5.7	5.7	5.3	6.7	6.3	6.0	8.7	7.0	8.0	8.0	8.7	8.0	7.3	8.0	5.7
	R07		2.7	6.0	7.3	8.3	10.7	6.7	9.3	9.3	10.0	9.0	5.3	10.3	2.3	2.0	11.0	11.0	11.0	8.7	9.3	8.7	6.7	9.0	5.7
	R47	4.7			8.7	7.0	10.3	9.3	9.0	10.0	5.5	7.0	4.3	9.3	6.3	8.0	10.0	10.0	10.3	9.3	10.0	10.3	8.3	9.0	7.0
	T01	3.0	5.3	4.0	5.0	4.3	4.0	3.7	2.3	3.7	4.7	8.0	9.3	4.7	5.7	5.7	5.3	8.3	5.3	4.7	6.0	5.0	6.0	7.0	5.7
	R08					8.0	4.5	3.5	3.7	2.7	3.0	5.0	10.0	5.0	5.7	4.7		7.0	7.0		10.0	7.0			5.0
OFF LONG ISLAND	R11		8.7	9.0	11.0	8.3	9.7	9.7	9.0	8.3	8.3	7.3	6.3	10.0	4.7	8.0	8.7	6.3	11.0	9.7	10.3	9.0	7.0	8.0	7.0
	R12		6.7	10.0	10.3	8.0	10.0	11.0	9.0	9.3	9.0	7.0	8.0	6.3	7.3	7.0	8.7	8.3	10.7	10.7	10.3	9.0	9.0	9.3	4.0
	R13	6.8	5.3	10.0	6.7	5.0		2.7	2.0	2.3	10.0	4.3	4.7	3.5	6.7	6.0	4.3	4.0	10.0	7.0	8.5	4.0	5.0	0.0	6.0
	R16		8.0	2.5	6.3	9.0	8.0	4.0	5.7	5.3	8.7	3.7	8.0	3.7	6.3	5.7	6.0	7.3	5.0	5.0	4.0	6.0		6.0	4.7
	R17	6.0	4.3	5.3	8.0	3.0	4.7	4.3	8.7	6.3	4.7	8.7	4.7	9.3	8.0	7.0	9.3	11.0	11.0	10.3	7.7	9.3	11.0	8.7	7.3
	R45	9.0			9.7	9.7	9.7	7.7	7.7	8.3	10.0	8.3	7.3	7.0	7.7	8.7	8.3	8.3	10.3	9.7	10.0	8.0	8.7	9.0	8.7
	T03	8.3	11.0	5.5	9.7	9.7	10.3	5.7	8.3	9.0	9.0	6.7	7.0	7.7	5.0	8.3	8.0	7.7	10.0	10.3	9.0	8.0	7.3	7.7	7.7
	R06		6.0	4.0	3.3				2.3	3.3	5.0	4.3	6.7		6.0	6.7	2.0		7.0	7.0	7.0	7.0			7.0
PRESIDENT ROADS	R44				7.0	3.3	2.7	5.7	3.3	3.0	7.3	6.3	5.7	6.0	8.3	6.7	9.0	10.0	11.0	9.3	9.0	9.7	8.0	8.0	6.0
	T02	3.0		5.7	6.7	5.0	4.3	3.7	3.0	3.0	5.0	6.3		7.3	9.3	7.7	10.0	10.0	10.0	9.0	10.0	8.0	8.7	7.0	6.3
	T05A				6.7	4.3	5.5	4.3	2.3	3.0	7.0	4.5	4.7	8.0	4.7	7.0	9.0	6.7	6.7	8.0	6.3	6.7	9.3	5.3	5.7
NANTASKET ROADS	R21		9.0	8.0	9.0	7.3	10.0	9.3	5.7	8.0	8.7	6.7	9.3	10.0	9.0	10.0	10.0	10.0	10.3	9.0	9.7	9.7	9.7	8.0	9.0
	R22		9.0	5.7	7.3	4.3	10.3	7.7	4.5	6.0	10.0	6.3	10.0	5.0	7.3	7.3	5.5		10.7			7.0	8.0		7.0
	R23		9.0	6.7	6.0	8.0		3.0		5.3	5.3		10.0	6.0	6.3	3.7	5.5	9.0	10.0			7.0	7.0		
	R24	8.0	9.0	5.0	9.0	9.7		7.3	9.7	8.0	10.0	5.7	4.3	6.7		4.0	8.7	10.0	8.0	8.7	8.3	7.0	7.0	8.3	7.3
	T06	6.7	9.3	5.0	6.3	5.7	7.7	7.7	7.7	6.3	9.0	6.3	4.7	5.7	4.3		6.7	10.0	7.3	7.3	7.3	8.0	7.0	8.3	8.3
	R20		9.3	5.5	11.0	7.3	10.3	4.0	9.0	7.7	10.0	6.3	5.0	7.7	7.0	5.7	8.0	10.0	9.3	8.3	9.7	6.7	8.7	8.7	8.7
HINGHAM BAY	R19	7.0	5.7	4.0	4.0	6.0		3.0	2.0	3.0	4.7			>4.3	8.0	6.7	7.0								
	R25	7.3	7.7	4.3	5.3	9.0	8.7	10.0	8.0	3.3	8.0	6.0	5.0	7.7	3.7	3.7	8.0	8.3	11.0	4.3	7.0	6.0	7.0	8.0	5.7
	R26	7.7	5.0	9.3	4.3	5.7		3.0	3.3	3.3	3.3	6.3	5.3	6.7	6.3	6.3	8.3	7.7	9.7	6.0	6.0	7.0	7.0	8.0	6.7
	R27	9.0	4.3	7.0	6.3	8.0	6.0	10.3	6.3	6.7	8.7	6.3	10.0	6.7	6.7	5.0	9.7	9.3	8.3	7.7	7.0	6.3	7.3	7.7	6.0
	R28	9.0	6.3	10.0	6.7	9.7	7.3	9.7	8.3	7.3	10.0	6.3	10.0	9.7	6.7	6.7	7.0	8.3	8.0		5.3	6.7	6.7	7.3	7.3
	R29	7.3	8.0	8.7	8.0	10.3	6.7	10.0	7.0	7.3	8.7	6.7	4.0	9.7	6.7	4.7	7.0	8.7	8.7	8.0	8.0	7.3	9.0	9.3	6.7
	R30	8.0	5.7	7.3	6.3	6.7	5.7	8.3	6.3	5.7	6.0	4.7	7.0	6.7	10.0	5.7	7.0	7.5	7.7	7.7	8.3	7.3	8.3	10.0	8.0
	R31	5.3	10.3	8.0	7.3	8.7	9.0	9.0	8.7	6.7	10.0	8.0	2.3	8.7	8.3	6.3	8.7	10.0	9.0	11.0	11.0	9.3	8.0	9.0	7.7
	R32	6.0	4.0	6.3	5.0	5.3	2.7	3.7	3.0	4.0	6.0	5.0	6.7	6.3	6.0	4.7	9.3	7.0	7.7	8.0	9.7	8.7	7.7	9.7	7.7
	R46				8.0	10.3	7.7	9.0	6.3	7.7	10.0	7.0	10.0	10.0	7.0	6.0	7.3	10.0	9.7	8.0	8.7	9.0	6.7	8.7	7.7
	R49	3.5			3.0	7.7	1.0	3.0	3.3	2.3	5.3	5.7	10.0	6.3	10.3	11.0	8.0	7.3	7.3	8.7	8.0	8.0	7.0	7.0	7.7
	R50	8.0			7.3	11.0	5.7	7.7	2.7	5.0	5.3	4.7	5.5	5.0	9.7	11.0	8.3	9.0	7.0	4.0	6.0	5.7	7.3	9.0	8.3
	R51	7.0			2.7	4.7		3.0	3.3	2.3	3.3	5.7	3.7	6.7	4.7		7.3	5.7	5.7	5.0	2.7	4.7	4.7	6.3	5.0
	R52	8.0			2.0	4.0		3.5	3.0	3.0	3.0	3.7	6.0	5.0	4.0		8.0	8.0	3.0	8.0	7.7	6.3	5.0	4.0	4.7
	R53	6.0			3.0	5.3		2.5	2.0	3.7	4.0	5.0	10.0	6.0	9.0	8.3	8.0	6.0	3.7	4.3	4.0	5.7	6.3	6.7	5.0
	T08	7.0	7.0	4.5	8.0			3.7	2.7	4.7	6.0		10.0	>5.7	8.0			9.0						7.0	7.0

Figure 23. Matrix of Organism Sediment Index (OSI) through time for Harbor regions. Red is OSI <3, Yellow is 3.0 to 5.9, Light green is 6.0 to 8.9, and Dark green is 9 and greater. An OSI of <6 would indicate stressful benthic habitat conditions.

Table 7. Average of SPI parameters for 2014 and 2015 used in calculation of OSI.

Location	Year	aRPD	Infauna	Burrows	Oxic Void	Anaer. Void	Gas Void		Succ.
		(cm)	#/image	#/image	#/image	#/image	#/image	OSI	Stage
INNER HARBOR	**2015**	1.9	1.0	1.0	0.9	0.9	0.2	6.9	I-III
	2014	2.0	4.3	0.8	2.0	0.8	0.0	8.1	I-III
DORCHESTER BAY	**2015**	1.3	0.9	0.3	0.8	0.2	0.6	4.9	II
	2014	1.4	3.4	0.2	1.2	0.0	1.9	5.7	I-III
QUINCY BAY	**2015**	1.2	1.2	0.5	1.1	0.6	0.0	5.7	I-III
	2014	1.8	4.5	0.7	1.4	0.1	0.0	6.8	I-III
DEER ISLAND FLATS	**2015**	2.1	1.9	0.5	1.1	0.6	0.5	6.3	I-III
	2014	2.7	6.3	1.2	2.0	0.5	0.0	8.3	II-III
OFF LONG ISLAND	**2015**	1.7	1.4	0.7	1.3	0.3	0.0	6.5	I-III
	2014	2.1	4.2	0.4	1.4	0.3	3.1	7.0	II-III
PRESIDENT ROADS	**2015**	1.4	2.2	0.6	1.4	0.3	0.0	6.0	II-III
	2014	2.4	7.7	0.4	2.2	0.1	0.6	6.8	I-III
NANTASKET ROADS	**2015**	3.5	2.1	0.4	0.6	0.1	0.0	8.1	II-III
	2014	2.6	3.8	0.2	0.9	0.3	0.0	8.3	II
HINGHAM BAY	**2015**	2.3	1.6	0.4	0.8	0.1	0.0	6.7	II
	2014	2.7	6.9	0.4	1.7	0.1	0.0	7.8	I-III

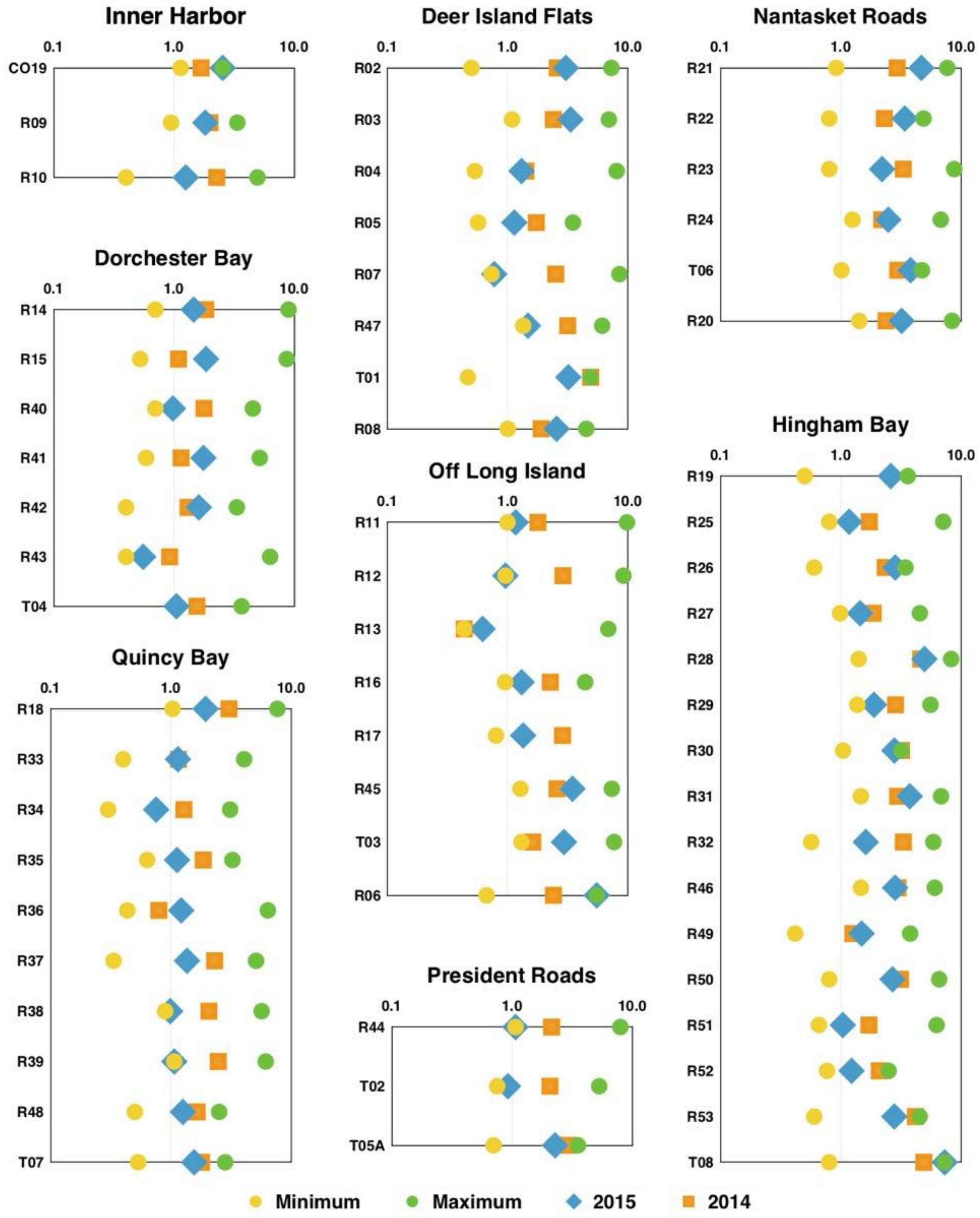


Figure 24. Range of aRPD layer depth grouped by Harbor region for the entire monitoring period from 1992 to 2015. Yellow circle is minimum aRPD measured, green circle is maximum measured, blue diamond is 2015 value, and orange square is 2014 value. Scale is logarithmic to expand the small differences between years. Minimum aRPD at T04 in 1995 and 1998 was zero.

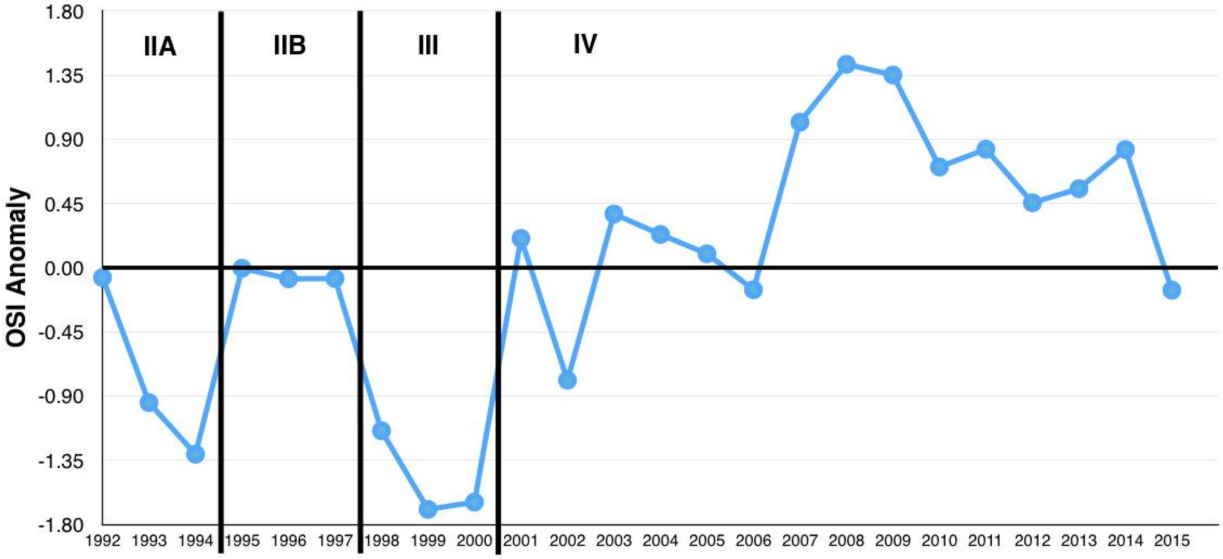


Figure 25. Plot of OSI anomaly (yearly - grand mean OSI) over the 24 years of SPI monitoring. Grand mean OSI is 6.5. Higher OSI years are positive and lower are negative values. Vertical lines separate periods of change in wastewater treatment based on Taylor (2010). IIA is post sludge disposal, IIB is full primary treatment, III is full secondary treatment, and IV is offshore diversion.

enhanced biogeochemical cycling. Station T02 provides a good example. From 2005 to 2007 Eh measurements showed that the RPD layer deepened from about 2 cm to 10 cm (Tucker et al. 2014). Over the same interval, SPI aRPD measurements went from 1.5 cm to 3.8 cm. By 2008, the sediments were oxic to about 6 cm and suboxic to at least 18 cm (Tucker et al. 2014). These changes corresponded with increased bioturbation from high densities of two filter-feeding amphipods, the tube building *Ampelisca* spp. (Mills 1967) and the burrowing *Leptocheirus pinguis* (Thiel 1997). High levels of bioturbation from large numbers of either or both *L. pinguis* and *Ampelisca* spp. created a sponge-like texture to surficial sediments facilitating biogeochemical cycling (Figure 27).

Along with the reduction in organic and nutrient loading to the Harbor, there were also corresponding decreases in primary production (Oviatt et al. 2007). Pelagic primary production, measured at the harbor mouth, decreased from 504 g C/m^{2}y in 1992-1994 (Oviatt et al. 2007) to 292 g C/m^{2}y in 2006-2008 (Libby et al. 2016). Relatively low chlorophyll and phytoplankton abundances characterized 2015 (Libby et al. 2016). Lower primary producer standing stocks may have contributed to reduced amphipod abundance and lower benthic habitat quality. In addition, severe winter 2014-2015 storms may have also reduced benthic habitat quality by disturbing *Ampelisca* spp. tube mats and other biogenic structures. Severe storm driven disruptions of bottom sediment in the Harbor were also likely to have occurred in 1991, 1992, 2003 and 2004 (Butman et al. 2008). Sediment profile image results from MWRA's benthic monitoring in Massachusetts Bay documented that the effects of winter storms resulted in a coarsening of sediments at 5 of the 23 nearfield stations in 2015 relative to 2014 (Nestler et al. 2016). Strong northeasters in October and February 2014, a northwester in March 2015, and a late northeaster in

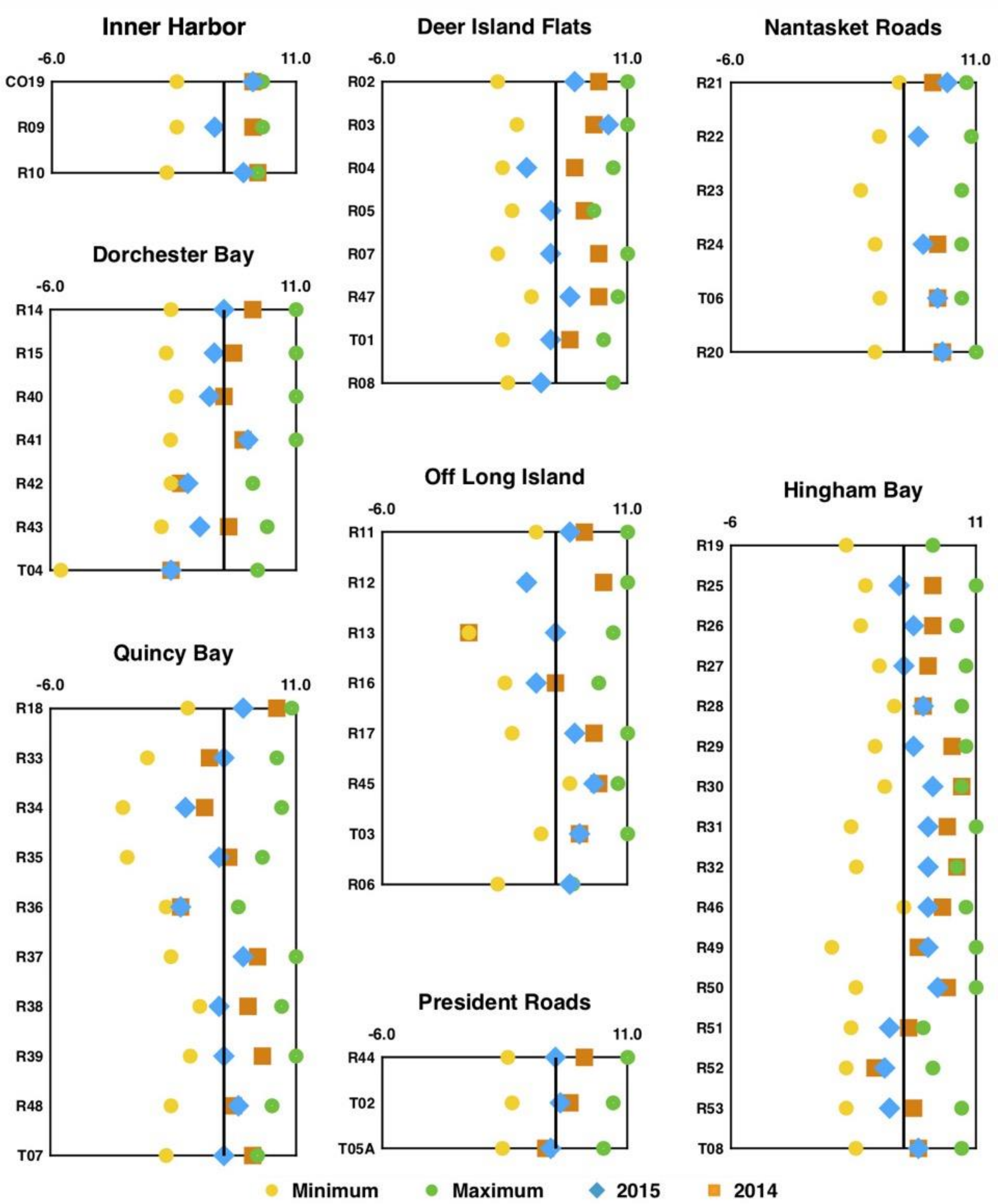


Figure 26. Range of OSI grouped by Harbor region for the entire monitoring period from 1992 to 2015. Yellow circle is minimum OSI, green circle is maximum, blue diamond is 2015 value, and orange square is 2014 value. Vertical line is OSI of 6, the breakpoint for stressed/unstressed benthic habitat.

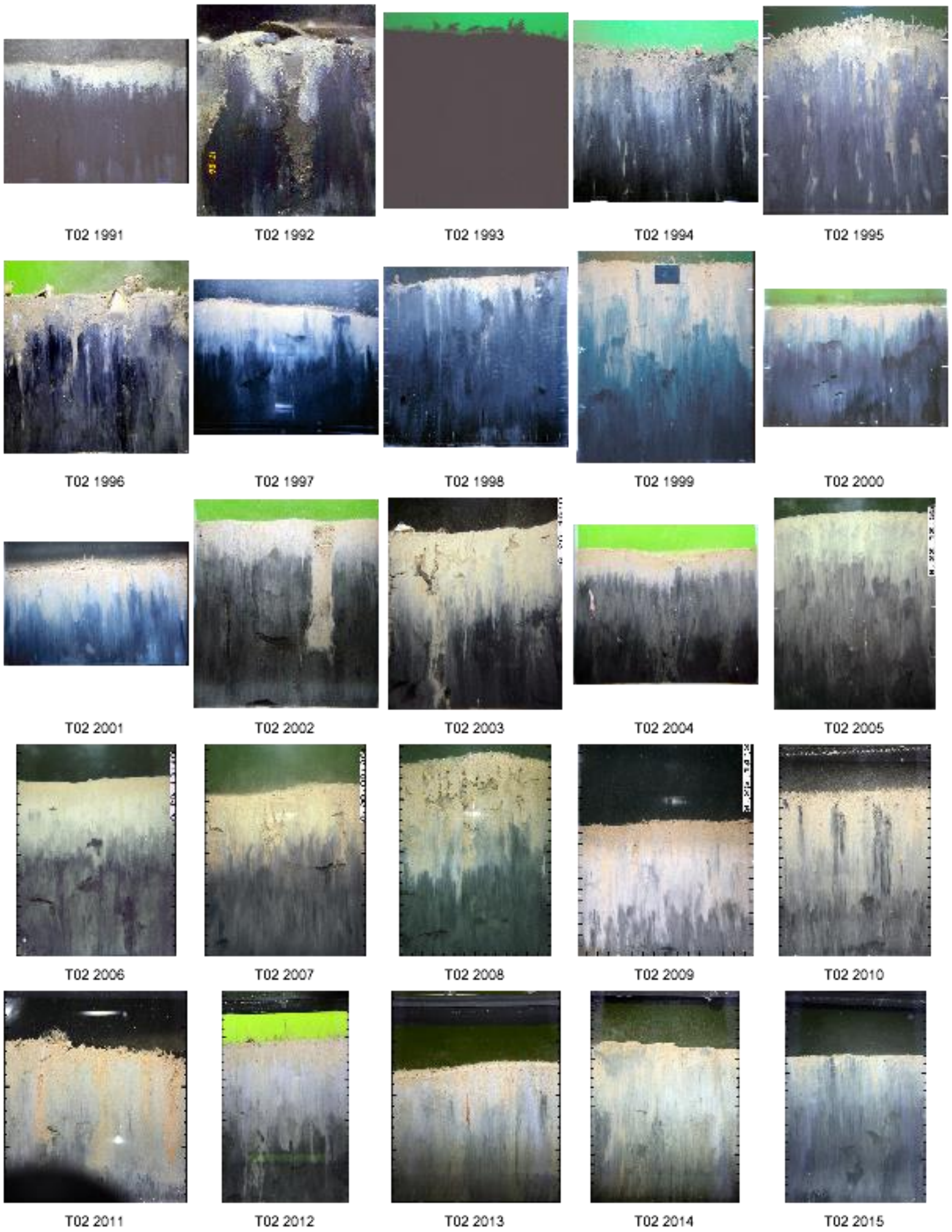


Figure 27. Thumbnail SPI from Station T02 located in President Roads. Sludge discharge ceased in late 1991, from 1992 to 1994 upgrades to primary treatment at Deer Island plant, from 1995 to 1997 full primary treatment, 1998 to 2000 phase-in of secondary treatment, and 2001 offshore diversion. By the mid-2000s sediments appear to becoming lighter in color with deeper bioturbation and the presence of deep-welling infauna and biogenic structures. *Ampelisca* spp. tube mats are present 1994, 1995, 1997, 2000, 2010, 2011, and 2012. Bioturbation by *Leptocheirus pinguis* is prominent in 1995, 2003, 2007, and 2008. In 1993 the strobe did not fire leaving only ambient light to illuminate sediment surface. Scale along the side of each image is in cm.

June 2015 all were capable of mixing the water column to depths greater than any of the harbor stations and could have affected surficial sediments by redistributing fine-grained sediments. In 2015, sediment at Stations R21 in Nantasket Roads, R26 in Hingham Bay, and R45 off Long Island appeared to be coarser relative to 2014. Stations R09 in the Charles River, and R13 and R16 off Long Island appeared to become finer between 2014 and 2015. The biggest change in modal grain-size was at Station R16 that went from fine-medium-sand in 2014 to fine-sandy-silt in 2015.

Despite the susceptibility of tube building *Ampelisca* spp. to storms or timing of August SPI sampling, much of the recovery in benthic habitat quality was linked to population dynamics of these tube building amphipods, along with burrowing *Leptocheirus pinguis*. Over the 24 years of SPI monitoring, biogenic activity associated with the presence of *Leptocheirus pinguis* and *Ampelisca* spp. had the most influence on benthic habitat quality (Diaz et al. 2008, Tucker et al. 2014). At some time between 1990 and 1992, when the SPI monitoring started, there was an increase in the occurrence of *Ampelisca* spp. tube mats (Figure 28). 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 relocation of the Nut Island outfalls to Deer Island and implementation of full primary treatment. 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

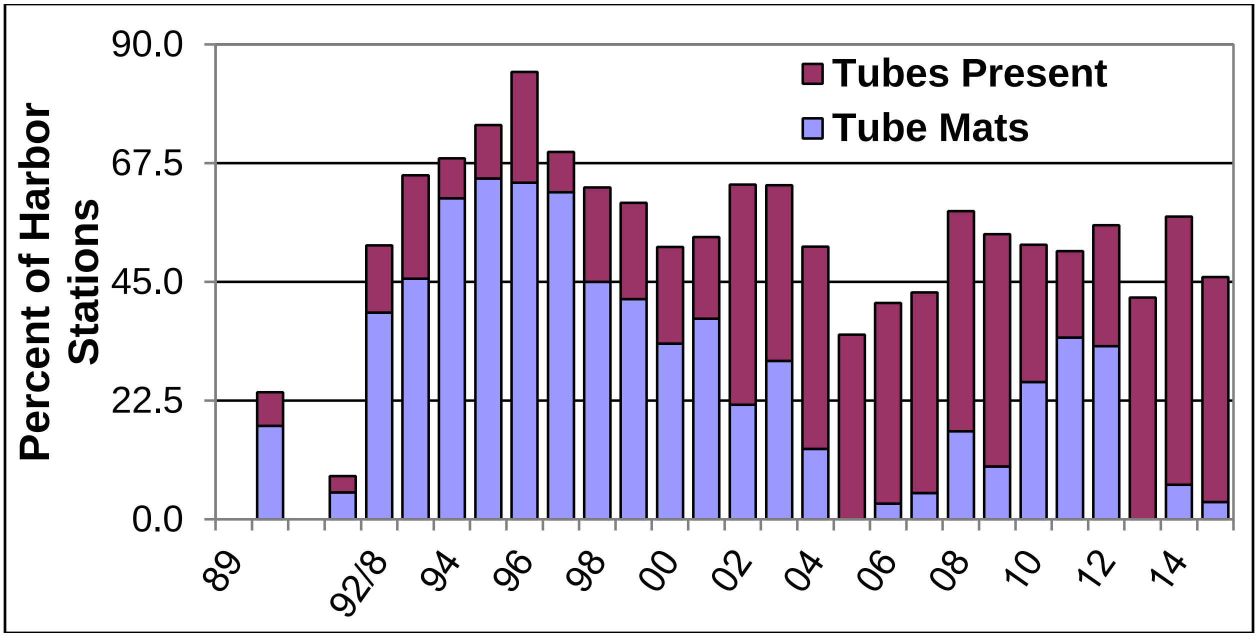


Figure 28. Histogram of *Ampelisca* spp. tubes present at Harbor stations. Total bar represents percent of stations with tubes present. Mats densities of tubes are the bottom part of the bar in blue. There are no data from 1989 or 1991, but in 1989 there were mat densities of polychaete tubes present at some of the benthic grab stations. There were two sample periods in 1992, spring and summer (92/8). Baseline years are up to 2000. Post-baseline years are from 2001.

sensitivity to pollutants (Wolfe et al. 1996). As the organic and pollutant loading declined greatly with implementation of full secondary treatment and diversion of sewage offshore, primary production within the Harbor also continued to decline as did mat densities of *Ampelisca* spp. This started in 1998 and by 2005 no tube mats were observed. A strong storm in late 2004 may have disrupted tube mats resulting in their complete absence at SPI stations in 2005. *Ampelisca* spp. tube mats reappeared 2006 and increased to levels seen in the late 1990s in 2011 and 2012. In 2013 no tube mats were observed for the second time in the 24-year monitoring record. In 2014 tube mats reappeared at four stations and were present at Stations R45 and T03 (Figure 29) off Long Island in 2015. Station T03 had tube mats 19 of the 24 monitoring years. In 2015, *Ampelisca* spp. tubes at less than mat densities occurred at 26 of 61 stations. In total, 46% of the stations had *Ampelisca* spp. tubes in 2015 which is down from 57% in 2014 (Figure 28).

Further evidence of improvement in benthic habitat quality is the eelgrass (*Zostera marina*) bed that has persisted at Station R08 since 2008 in SPI images (Figure 30). There also appeared to be large amounts of macro algae within the grass bed in 2015. The largest and most persistent beds of eelgrass occurred in the Winthrop-Logan Airport area (MassDEP Eelgrass Mapping Project, http://maps.massgis.state.ma.us/images/ dep/eelgrass/eelgrass_map.htm). In 2012, there were 31.4 ha (77.6 acres) of eelgrass in the Winthrop Harbor survey area (Figure 31). Of the ten SPI stations within the Winthrop Harbor area, only R08 had eelgrass. The areal extent of eelgrass at R08 is not known but is likely small relative to major areas nearer shore. Other areas of Boston Harbor with eelgrass beds were Hull Bay off Nahant and Lynn Harbor, Whitehead Flats in Hingham Bay, western and southwestern sides of Calf Island, and off Long Island. In a statewide analysis of eelgrass trends between 1996 and 2007, Costello and Kenworthy (2011) found eelgrass area declined within Boston Harbor from about 81 ha to 27 ha between 1996 to 2001and then increased to 47 ha by 2007. The increase in Harbor eelgrass coincided with the startup of the offshore outfall. Costello and Kenworthy (2011) reported a similar decadal scale recovery of eelgrass in a small embayment on Long Island Sound following the removal of a municipal wastewater discharge source. They concluded that with improved management of water quality, environmental conditions exist in Massachusetts where seagrasses can either thrive or expand.

Overall, the improvements in wastewater treatment and moving the outfall offshore have led to improvements in benthic habitats within Boston Harbor by favoring processes that enhance bioturbation or the mixing of sediment by organisms, which led to more aerobic sediment conditions. These improvements through time were captured by the OSI that integrated much of the biogeochemical and benthic community change documented by Tucker et al. (2014) and Pembroke et al. (2015). The eight Traditional stations sampled for both SPI and benthos since the early 1990s (infaunal sampling at station CO19 began in 2004) spanned a broad range of benthic habitats within Boston Harbor with a gradient in habitat quality from lowest at Station T04 to highest at T05A and T08 with T01, T02, T03, T06, and T07 in between. This pattern was first described from SPI and benthic parameters for 1993 to 2006 monitoring datasets (Diaz et al. 2008) and has remained the same with inclusion of data from 2007 to 2015 (Figure 32a, b). Parameters characterizing higher benthic habitat quality were higher total species, Fisher alpha diversity, deeper aRPD layers and lower total organic carbon (TOC). Lower habitat quality

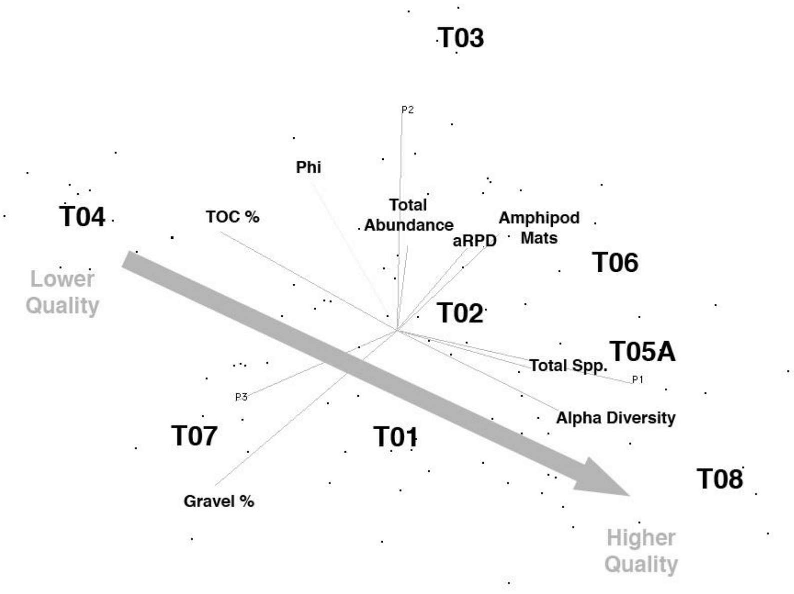
Figure 29. ***Ampelisca*** **spp. tube mat at T03, off the northwest tip of Long Island. Scale on side of image is in cm.**

was characterized by finer sediment grain-size and higher TOC. Station T04 had the finest sediments with high TOC and the lowest values for diversity and aRPD. Stations T05A and T08 were opposite of T04 with lower TOC, higher diversity, and deeper aRPD. The center of the habitat quality gradient was characterized by *Ampelisca* spp. tube mats and higher total abundance (Stations T02, T03, and T06). Stations T01 and T07 were separated from the other stations primarily because of lower total abundance, *Ampelisca* spp. tube mats, and coarse gravel sediments.

Figure 30. Eelgrass bed at station R08 on Deer Island Flats. The bed first appeared in SPI in 2008 and has persisted. Prior to 2008, R08 was always fine-sand with macroalgae. Scale on sediment profile image is in cm.

Figure 31. Locations of SPI stations and eelgrass beds in the Winthrop-Logan Airport area in 2012 (MassDEP Eelgrass Mapping Project; http://maps.massgis.state.ma.us/images/dep/eelgrass/eelgrass_map.htm).

A.



B.

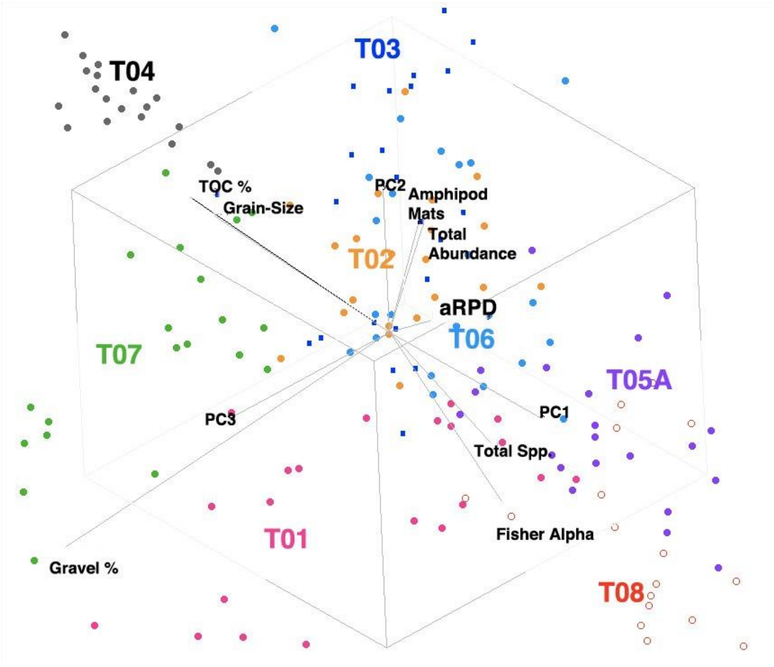


Figure 32. Biplot of eight sediment, infauna, and SPI variables from PCA of station-averaged data. Plot is arranged looking down on the first three principle component axes (P1, P2, and P3) at about a 45° angle. A. PCA of monitoring data from 1993 to 2003 based on Diaz et al. (2008). Arrow indicates general cline of habitat quality from a lower at T04 to higher at T08. B. PCA of monitoring data from 1993 to 2015. The arrangement of stations in the ordination space was similar for both time periods analyzed.

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 enhanced bioturbation rates by infaunal and epibenthic species and has led to more aerobic and 'healthy' 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 2015 exhibited minor changes from recent years but were consistent with longer-term trends (Pembroke et al. 2015). Concentrations of both TOC and *Clostridium perfringens*, indicators of organic enrichment and deposition from municipal wastewater discharge, have remained low compared to the levels occurring prior to the offshore diversion.

Community structure measures also continue to point to improving benthic conditions. Since municipal wastewater and sludge discharges have been eliminated from the harbor, total abundance has trended downward, particularly for opportunistic species such as *Capitella capitata*. Species richness, while variable, has trended upward as did evenness (J'), Shannon diversity (H'), and log series alpha diversity. Although abundances of individual taxa, such as the dominants *Ampelisca* spp., *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 2015 survey are consistent with the recovery of benthic habitats from decades of inadequately treated sewage discharges.

5. REFERENCES

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

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

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

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

Costello, CT and WJ Kenworthy. 2011. Twelve-year mapping and change analysis of eelgrass (*Zostera marina*) areal abundance in Massachusetts (USA) identifies statewide declines. Estuaries and Coasts 34:232-242.

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

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

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

Libby PS, Borkman DG, Geyer WR, Turner JT, Costa AS. 2016**.** 2015 Water column monitoring results. Boston: Massachusetts Water Resources Authority. Report 2016-12. 42 p.

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

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

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

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

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, Pembroke AE, Keay KE. 2016. Outfall Benthic Monitoring Report: 2015 Results. Boston: Massachusetts Water Resources Authority. Report 2016-09. 33 pp. plus Appendices.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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