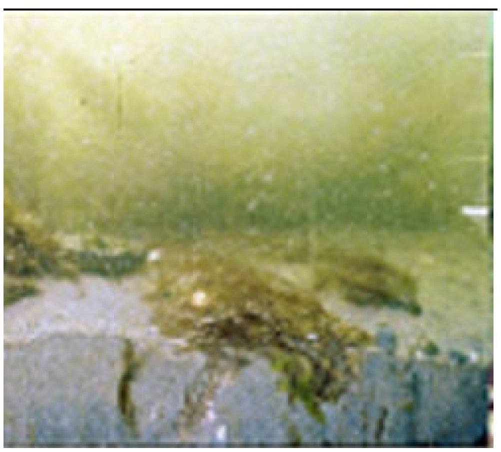
2023 Boston Harbor Benthic Monitoring Report



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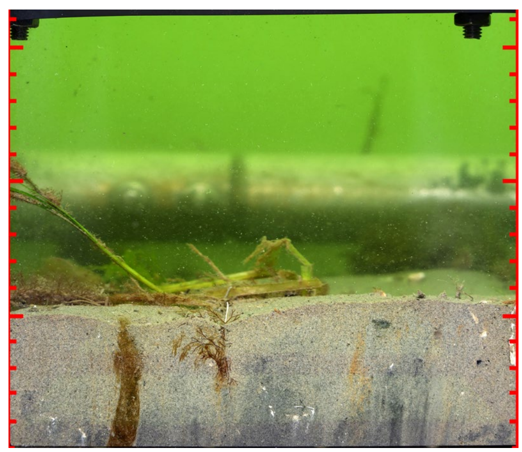

2023

Massachusetts Water Resources Authority
Environmental Quality Department
Report 2024-12

Citation:

Rutecki DA, Diaz RJ, Madray M, Goode KL. 2024. **2023 Boston Harbor Benthic Monitoring Report**. Boston: Massachusetts Water Resources Authority. Report 2024-12. 65 p.

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2023 Boston Harbor Benthic Monitoring Report

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January 2025

Environmental Quality Report No. 2024-12

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EXECUTIVE SUMMARY

The Massachusetts Water Resources Authority's (MWRA) Deer Island Treatment Plant (DITP) treats sewage from more than 40 communities in Greater Boston. Discharge of sludge into Boston Harbor from the treatment process stopped in 1991. However, effluent was discharged into Boston Harbor until September 2000. Direct discharge of sludge and wastewater with limited treatment into the harbor had affected both water quality and ecological conditions. Since September 2000, the effluent has been discharged offshore to Massachusetts Bay via a 9.5-mile outfall tunnel with additional secondary treatment. MWRA has conducted ongoing benthic monitoring in Boston Harbor since 1991 to evaluate changes to the ecosystem and the benthic (seafloor) community resulting from reductions in contaminated discharges over time. The conditions in the sediments and the associated benthic infaunal community reflect cumulative water quality exposures. This report summarizes the results of the 2023 benthic surveys, which include sediment conditions, benthic infauna, and sediment profile imagery.

Sediment conditions were characterized based on analyses of sediment grain size composition, total organic carbon (TOC), and colony counts of the anaerobic bacterium *Clostridium perfringens,* an indicator of the presence of sewage. Grain size composition ranged from predominantly sand at Outer Harbor stations to almost entirely silt and clay in Savin Hill Cove (Station T04) and the Inner Harbor. The highest TOC concentrations in 2023 were observed in Savin Hill Cove and Station C019 in the upper Inner Harbor. *C. perfringens* counts during 2023 were highest at Stations T04 and C019, consistent with recent post-diversion years and. Sediment conditions observed in 2023 were generally consistent with longer-term trends (Rutecki et al. 2023). Concentrations of both TOC and *C. perfringens* have remained low compared to the levels in the early 1990s.

The monitoring program evaluates benthic infauna by measuring species abundance and other benthic community measures. These measures continue to indicate improving benthic conditions in 2023. Since the cessation of MWRA discharges to the harbor, total species abundance has decreased, particularly for opportunistic species such as *Capitella capitate*. Total species abundance has been fairly stable for the last decade. Species richness and other biodiversity measures have trended upward.

Although abundances of individual taxa 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.

Sediment profile imaging showed that benthic habitats continue to maintain good ecological conditions as measured by the Organism Sediment Index. The long term trends observed in previous years, including a reduction of indicators of organic enrichment and increases in species diversity, continued in the 2023 survey. These results are consistent with the recovery of benthic habitats from decades of inadequately treated sewage discharges.

Overall, benthic monitoring results in 2023 were consistent with results in the years since the discharge was moved offshore and indicate recovery of the harbor benthic community continues.

1. INTRODUCTION

Boston Harbor was once considered among the most degraded urban estuaries in the country. Direct discharge of sludge and wastewater with limited treatment into the harbor had affected both water quality, seafloor, and ecology. Through litigation, the EPA prevailed upon the Commonwealth of Massachusetts to take actions to improve these conditions, and the Massachusetts Water Resources Authority (MWRA) was created in response. In 1985, MWRA initiated a multi-faceted plan to meet these mandates, including elimination of sludge disposal into the harbor, an upgrade to secondary treatment at the Deer Island Treatment Plant, and relocation of wastewater discharge through an offshore diffuser located 9.5 mi off Deer Island in Massachusetts Bay. By 2001, MWRA had met all of these goals. 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).

The upgrades 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 the mixing of sediment by organisms. At one time, the sediment organic matter in Boston Harbor was derived primarily from sewage but since changes in wastewater treatment and disposal were initiated, marine-derived organic material has become more 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.

Conditions in the sediments and the associated benthic infaunal community reflect cumulative water quality exposures, which make them good indicators of overall ecosystem health. MWRA has conducted ongoing benthic monitoring in Boston Harbor since 1991 to evaluate changes to the ecosystem and the benthic community resulting from reductions in contaminated discharges over time. This report summarizes the results of the 2023 benthic surveys, which 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 included soft-bottom sampling for sediments and infauna at 9 stations and sediment profile imaging (SPI) at 61 stations. This program 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 Rutecki et al. (2023) for previous monitoring years. Detailed descriptions of the methods are contained in the Quality Assurance Project Plan (QAPP) for Benthic Monitoring (Rutecki et al. 2020a). A brief overview of methods, focused on information that is not included in the QAPP, is provided in Sections 2.1 to 2.3.

2.1 FIELD METHODS

Sediment and infauna sampling was conducted at 9 stations on August 7, 2023, stations T01-T08 and C019. (Figure 2-1). These soft-bottom stations were sampled for grain size composition; total organic carbon (TOC); the sewage tracer *Clostridium perfringens*, an anaerobic bacterium found in the intestinal tract of mammals; and benthic infauna. At each station, one sediment sample and triplicate infauna samples were collected. Sediment profile imaging (SPI) was collected in triplicate at 61 stations from August 1-2, 2023 (Figure 2-1).

2.2 LABORATORY METHODS

Laboratory methods for benthic infauna and sediment profile imaging (SPI) image analyses were consistent with the QAPP (Rutecki et al. 2020a). Two of the infauna samples from each site were randomly selected for processing, while the third was archived. Analytical methods for grain size (Folk 1974), TOC, and *Clostridium perfringens* (Emerson and Cabelli 1982) are described in Constantino et al. (2014).

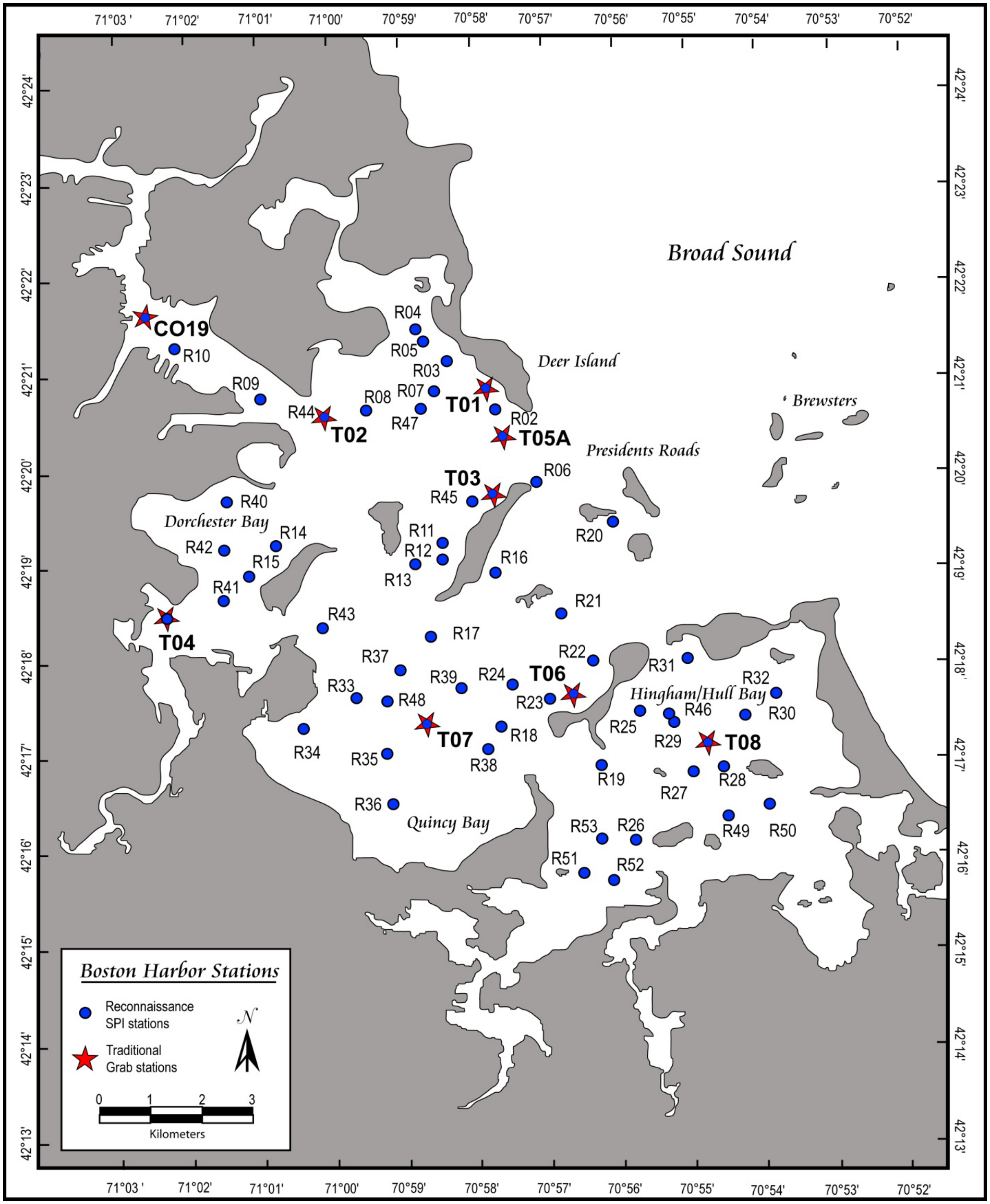

Figure 2-1. Locations of soft-bottom sampling and sediment profile imaging stations for 2023.

2.3 DATA HANDLING, REDUCTION, AND ANALYSIS

All benthic data were extracted directly from the MWRA 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. 2020a) or in Maciolek et al. (2008). Data are presented graphically as means (averages per station) unless otherwise noted. The Shannon-Weiner diversity index (H') was calculated using log base 2. Multivariate analyses were performed using PRIMER v7 (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 (nMDS). 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 in order to delineate among sites with distinct community structure. nMDS 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 nMDS 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 nMDS 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). The periods denote significant events that had a likelihood of affecting the harbor benthic community, including, cessation of 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). Since sediment communities can take time to respond to changes, for example reductions in the deposition of organic matter, these periods were offset by one year. 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).

Details on parameters and analysis of SPI images can be found in Diaz et al. (2008). Median grain size was estimated graphically using cumulative percentage weights of Phi intervals from sediment analysis. Modal Phi was the interval with the highest percentage weight. For this report, quantitative SPI parameters (e.g., apparent redox potential discontinuity [aRPD] layer depth) were averaged from the three replicate images. For categorical parameters (e.g., presence of biogenic structures), the median value of the three replicate images was assigned to a station. As the selection of station locations in the Harbor was non-random, fixed-effect nominal logistic models, which treat each station measurement as a separate observation, were used to analyze patterns in categorical data (Agresti 1990). For continuous variables, general linear models (GLM) were used to test for differences within and between quantitative parameters. Trends in quantitative variables were tested using various GLMs (simple linear regression, segmented linear regression, analysis of variance). Significance of odds was tested using logistic regression. All statistical tests were conducted with the statistical package R version 3.6.2 (2019-12-12, R Foundation for Statistical Computing).

For creating image mosaics of selected stations, all images were standardized so that they could be compared despite interannual changes in equipment or ambient light. First, the images were histogram equalized with the red, green, and blue pixel distributions clipped from 1 to 5%. Some scanned film images were also adjusted for poor exposure and color balance. Images were then sharpened with unsharp mask and scaled to a width of 400 pixels before mosaics were made. Variation in image color between years was due to a combination of factors. The primary factors were the film development processes and which camera was used. The greatest variation between images occurred from 1991 to 2001 when film cameras were used (Olympus OM1 in 1992, Hulcher Model M or W in 1991 and 1993 to 2001). Variation in development of the film and subsequent digitization of images led to the largest imbalances in color rendition. Starting in 2002 digital cameras were used. From 2002 to 2009 the cameras used were Minolta Dimage7 or Dimage7i with 5-megapixel sensors. From 2010 to 2019 the cameras were Canon EOS 7D with 18-megapixel sensors. From 2020 to 2023 the cameras were Canon EOS R with 30-megapixel sensors. An additional factor was ambient light at shallow-water stations that tended to wash out sediment color.

3. RESULTS AND DISCUSSION

3.1 SEDIMENT CONDITIONS

Sediment conditions in Boston Harbor were characterized in 2023 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 3-1).

Table 3-1. Monitoring results for sediment condition parameters in 2023.

Parameter		C019	T01	T02	T03	T04	T05A	T06	T07	T08
Grain Size	**Gravel (%)**	0	2.59	0.39	2.27	0.33	0.23	1.25	0.79	0.86
	Sand (%)	0.75	76.12	30.55	45.67	3.88	77.79	61.64	28.41	91.17
	Silt (%)	42.18	9.77	37.8	27.34	43	7.6	18.7	38.55	1.8
	Clay (%)	57.07	11.52	31.26	24.72	52.79	14.37	18.41	32.25	6.16
	Percent Fines (Silt + Clay)	99.25	21.29	69.06	52.06	95.79	21.97	37.11	70.8	7.96
Total Organic Carbon	**TOC (%)**	2.14	0.3	1.15	1.21	3	0.26	0.73	1.77	0.25
	TOC normalized to fines (%TOC/%fines)	0.02	0.01	0.02	0.02	0.03	0.01	0.02	0.03	0.03
Clostridium perfringens	**Not Normalized**	6050	350	2020	1400	1350	165	319	1140	79.1
	Normalized (cfu/g dry/%fines)	60.96	16.44	29.25	26.89	14.09	7.51	8.6	16.1	9.94

Grain Size. Surface sediments at the nine stations sampled during 2023 included a wide range of sediment types (Table 3-1, Figure 3-1). Grain size profiles ranged from predominantly sand (T08) to almost entirely silt and clay (C019 and T04). Most stations had mixed sediments. The Outer Harbor stations generally had more than 45% sand with varying fractions of silt-clay. Grain size at Station T03, in the lee of Long Island, has had higher percentages of fines (silt plus clay) than sand since 2017. Although this trend started before the 2018 dredging of the President Roads Anchorage, the dredging could have enhanced this trend post-2018. The grain size composition at each station in 2023 generally remained within the ranges reported in prior years, though percent fines increased at most stations from 2022 values (Figure 3-2). 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 large drops in percent fines (Figure 3-2).

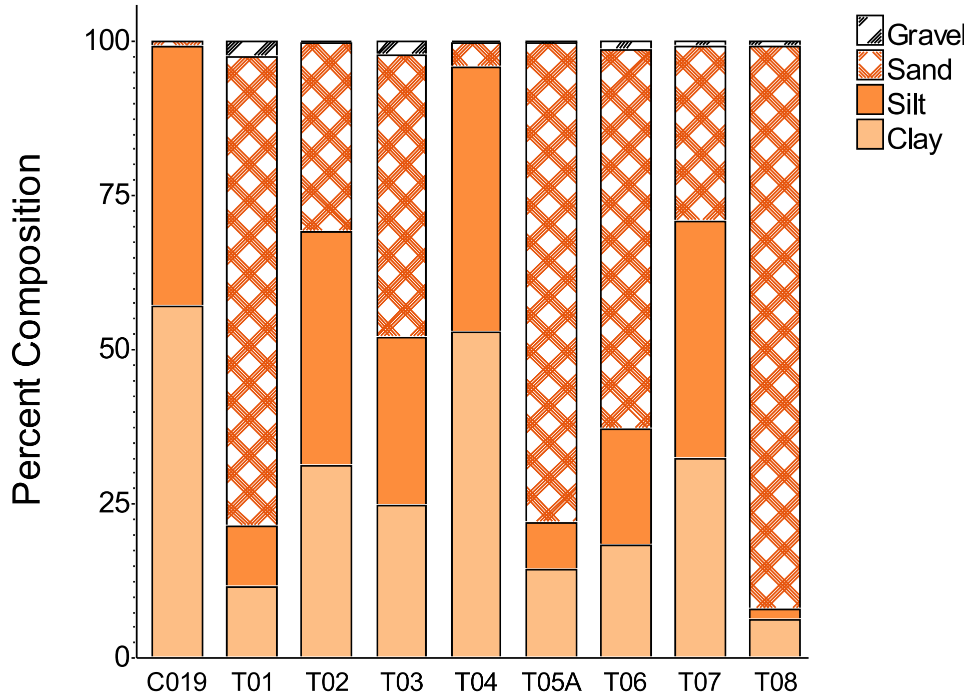

Figure 3-1. Monitoring results for 2023 sediment grain size in Boston Harbor.

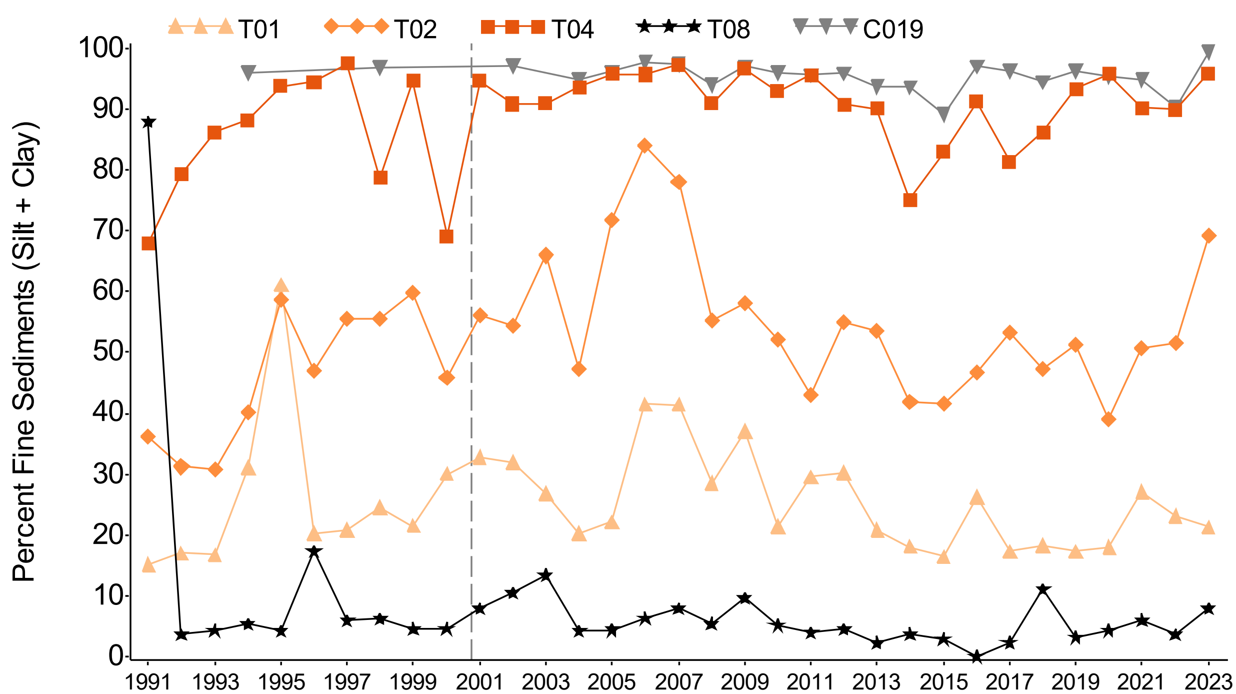

Figure 3-2. Mean percent fine sediments at five stations in Boston Harbor, 1991 to 2023. Five stations selected to illustrate the trends in percent fine sediments at stations in the Outer Harbor (T08), Mid Harbor (T01 and T02), and Inner Harbor (T04 and C019). The vertical dashed gray line represents the date DITP discharge was moved to Massachusetts Bay.

Total Organic Carbon. Concentrations of total organic carbon (TOC) in 2023 were generally similar to the values reported in 2022 and recent years at most stations. TOC concentrations remained within the ranges reported in previous years (Figure 3-3). Higher TOC values were generally associated with higher percent fine sediments (Figures 3-2 and 3-3). During 2023, Stations T02, T04, T07, and C019 had among the highest concentrations of TOC and had the highest proportions of fines (Table 3-1). 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 2023 are consistent with this trend. The lowest TOC concentrations for 2023 were reported at Stations T01, T05A, and T08 which have predominantly sand sediments.

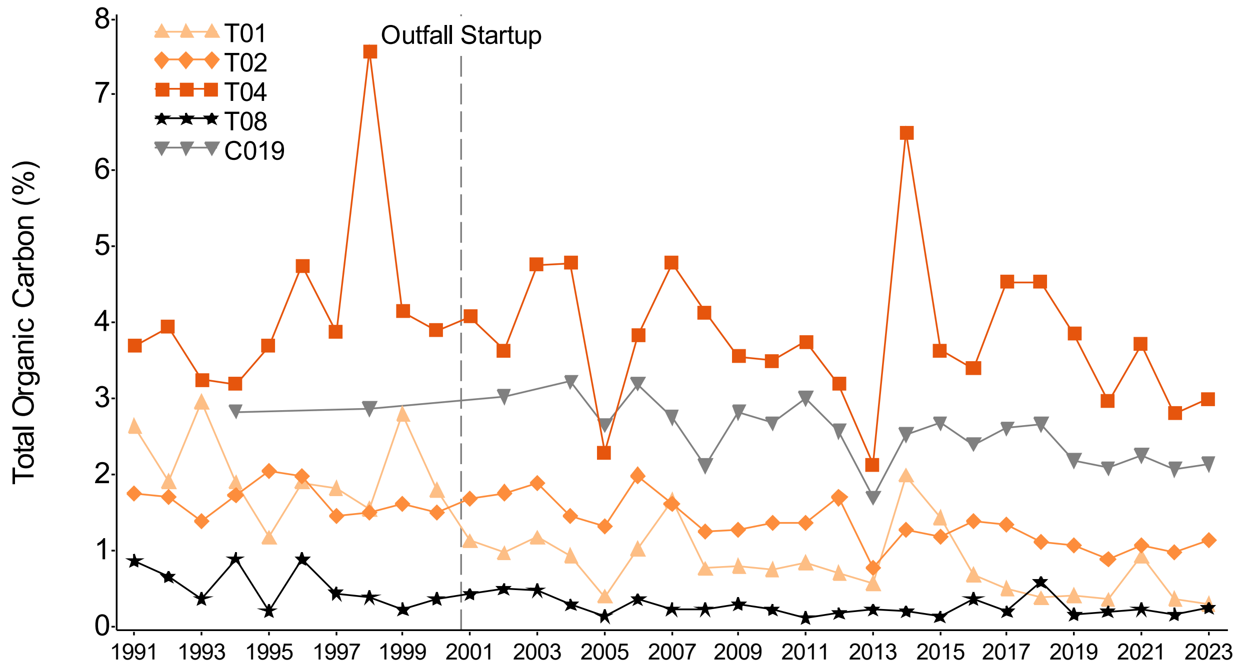

Figure 3-3. Mean concentrations of TOC at five stations in Boston Harbor, 1991 to 2023. Five stations selected to illustrate the trends in TOC at stations in the Outer Harbor (T08), Mid Harbor (T01 and T02), and Inner Harbor (T04 and C019).

Clostridium perfringens. *Clostridium perfringens* provide a sensitive tracer of sewage effluent. *C. perfringens* abundances were reported as colony forming units per gram dry weight, normalized to percent fines (cfu/g dry/% fines). Abundances were normalized to percent fines because the distribution of *C. perfringens* has been found to vary with the proportion of fine-grained material in the sediments (Parmenter and Bothner 1993), and normalization provides a more conservative means of evaluating the data for trends. Abundances of *C. perfringens* (normalized to percent fines) during 2023 (Table 3-1) declined at all stations from 2022 values, and were generally low and comparable across all monitoring stations, especially when compared to historic data (Figure 3-4). Abundances at T04, a depositional site in Savin Hill Cove, historically exhibited relatively high variability among years. Since 2014, *C. perfringens* counts at T04 have remained relatively low and steady through 2023 (Figure 3-4). Normalized *C. perfringens* counts at Station T08 had consistently been low since 2010 with the exceptions in 2016, 2020, and 2022. The 2016 occurrence was largely an artifact of the atypically low percent fines at T08 that year, which may also be the case for 2022. *C. perfringens* concentrations in Quincy Bay (T07) and Hingham Bay (T08) may also have been impacted by untreated sanitary sewage discharges from stormwater outfalls in the City of Quincy, MA (*United States of America v. City of Quincy, MA* 2021, US EPA 2021). Except at Inner Harbor station C019, *C. perfringens* counts at Harbor stations have generally remained below historical averages since the late 1990's (Figure 3-4). Station C019 is a depositional area located in the upper Inner Harbor near several CSOs. *C. perfringens* counts at C019 declined in 2017, remained low compared to historic data through 2020, and then increased in 2021. The 2023 concentration was lower than the 2022 concentration and was consistent with the low concentrations recorded in 2017-2019 and 2021 (Figure 3-4). The decline may have reflected the completion of the Reserved Channel Sewer Separation project in 2015 that minimized CSO discharges to meet Class SB (cso) water quality standards.

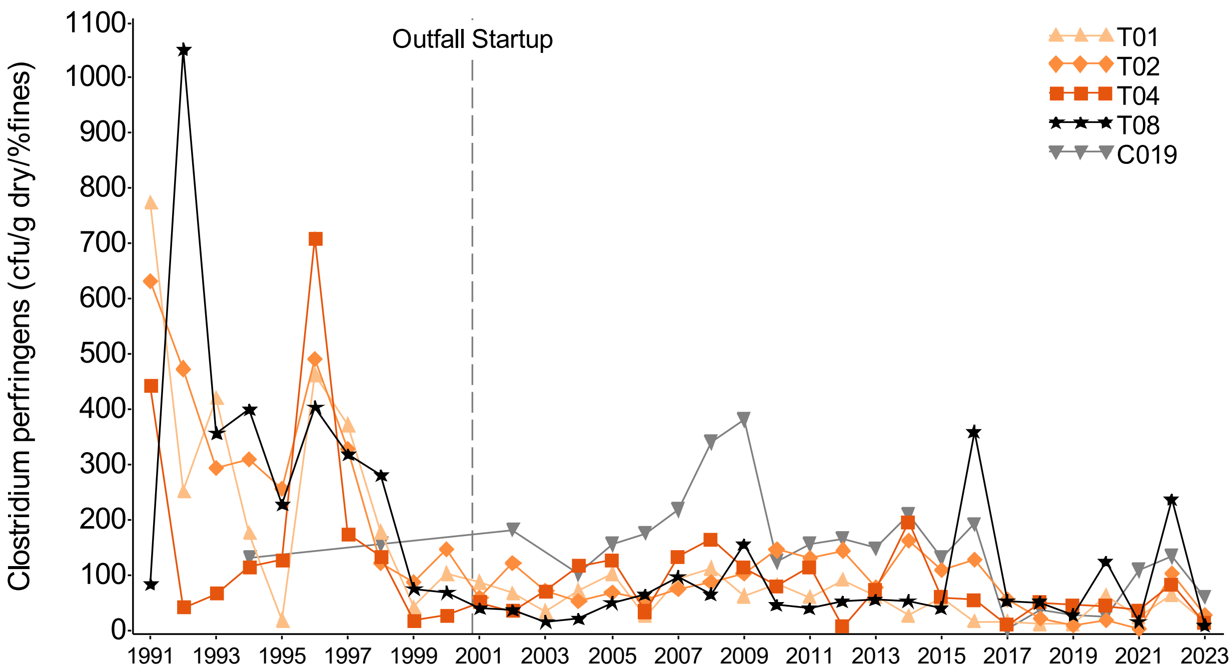

Figure 3-4. Mean normalized concentrations of *Clostridium perfringens* at five stations in Boston Harbor, 1991 to 2023. Five stations selected to illustrate the trends in *Clostridium perfringens* at stations in the Outer Harbor (T08), Mid Harbor (T01 and T02), and Inner Harbor (T04 and C019).

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. We are currently in Period IV which started with the implementation of the offshore outfall. The data is offset from the Taylor (2006) periods by one year to allow time for the benthic communities to respond to the reduced loadings of eutrophication-related materials to Boston Harbor. Results during 2023 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; Rutecki et al. 2023). 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 3-5 and 3-6). In Figures 3-5 and 3-6, Period IV has been divided into multi-year segments in comparison to the most recent year, 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, Taylor et al. 2020, Maciolek et al. 2008).

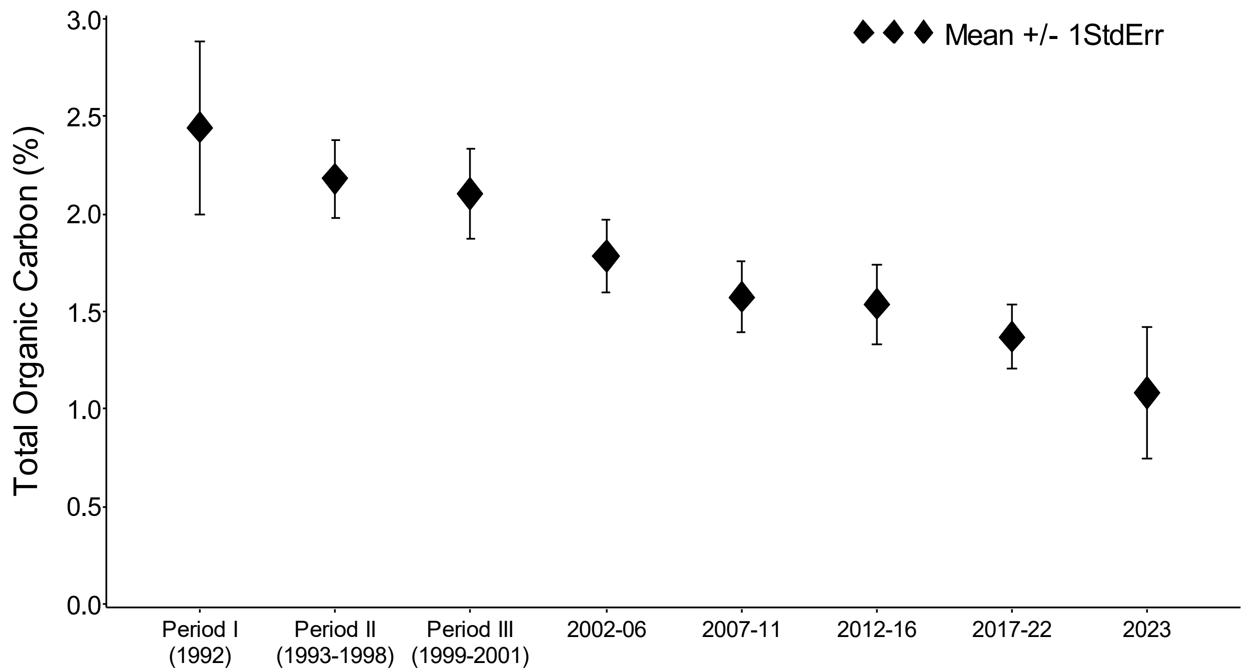

Figure 3-5. Comparison of TOC across time periods (offset by one year) at Boston Harbor stations (T01-T08) from 1992 to 2023 (1991 excluded).

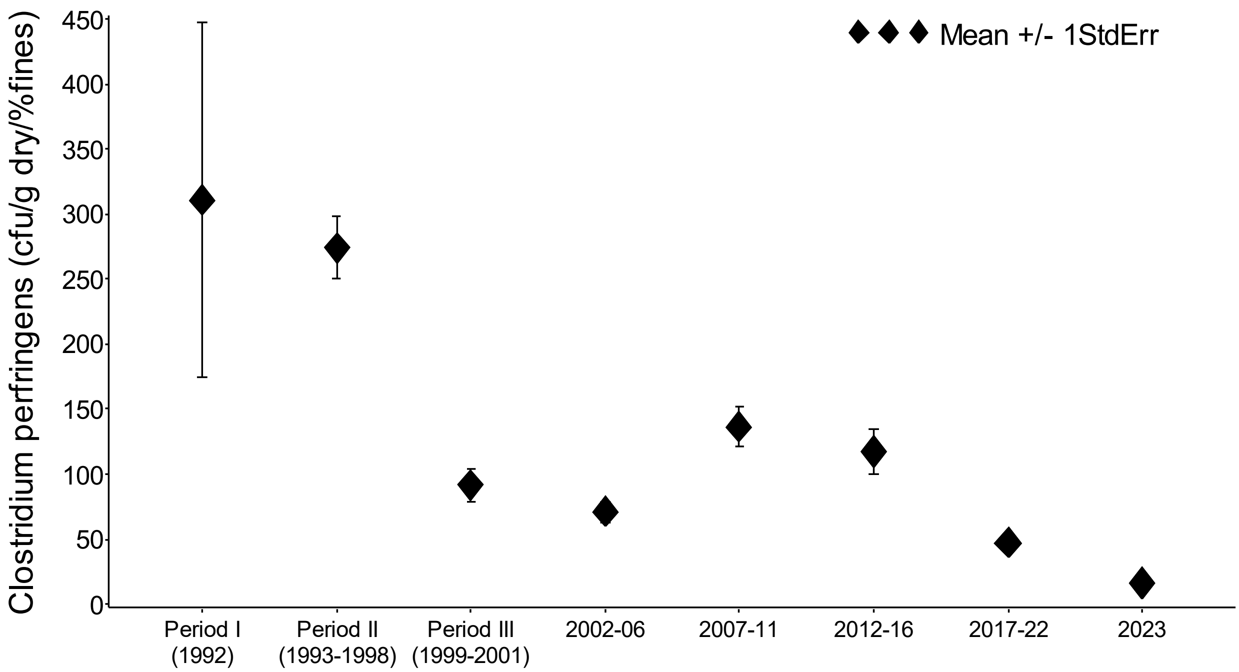

Figure 3-6. Comparison of *Clostridium perfringens* across time periods (offset by one year) at Boston Harbor stations (T01-T08) from 1992 to 2023 (1991 excluded).

3.2 BENTHIC INFAUNA

3.2.1 Community Parameters

A total of 19,686 infaunal organisms were counted from the 18 samples processed in 2023 (2 samples per station, 9 stations). Organisms were classified into 139 discrete taxa, 122 of which were species-level identifications. Ninety-seven percent of the individuals were identified to species; all remaining individuals were identified to genus or family. These species differentiation 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 3-2). Data are presented in figures as means (averages per station) unless otherwise noted.

Table 3-2. Mean 2023 infaunal community parameters by station.

Station	Total Abundance	Number of Species	Pielou's Evenness (J')	Shannon-Wiener Diversity (H')	Log-series alpha
C019	654.5	22.0	0.58	2.57	4.40
T01	835.0	37.0	0.61	3.17	7.97
T02	1268.5	40.0	0.68	3.62	7.90
T03	1005.0	33.0	0.66	3.30	6.56
T04	214.0	8.0	0.51	1.55	1.77
T05A	1986.0	57.0	0.62	3.64	10.99
T06	1841.0	39.0	0.44	2.34	7.00
T07	1045.0	31.5	0.65	3.13	6.38
T08	994.0	34.0	0.49	2.51	6.83

Mean total abundance at the eight traditional Harbor stations reported for 2023 (1,149 organisms) was lower than in 2022 (2,014 organisms) and the lowest value in the post-diversion period (Figure 3-7). Prior to 2023, abundance during the post-diversion period ranged from 1,418 organisms in 2005 to 5,451 organisms in 2003, with a mean annual average of 2,407 organisms. In 2023, increases in mean abundance occurred only at Stations T07 and T08, with increases of 189% and 22% respectively. The large increase in abundance recorded at Station T07 in 2023 was the result of increases in both *Cossura sp.* 1 and *Tubificoides intermedius* numbers. The five most abundant species in 2023 each contributed 4.0% or more of the animals counted, and together they provided 56% 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 2023 (Table 3-3) although the rank order changed. One polychaete species and two oligochaete taxa comprised the top three most abundant taxa in 2023. The five most abundant taxa in 2023 have frequently been among the most abundant in the harbor during previous years (Table 3-4). Certain spatial patterns of abundance also appeared to be consistent with previous years; T04 continued to support low infaunal abundance and richness (Table 3-2). Station T05A had the highest abundance in 2023, and Station T02, T03, and T06 continued to support some of the highest abundances among the harbor stations.

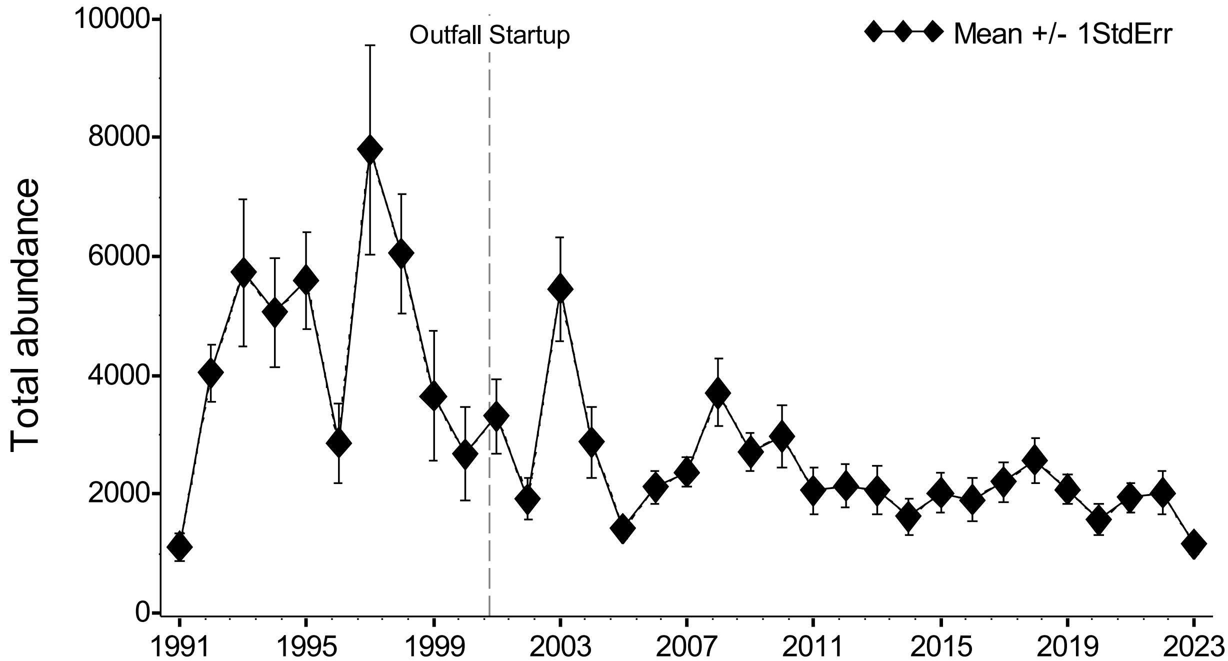

Figure 3-7. Mean abundance of benthic infauna at eight Boston Harbor stations (T01-T08), 1991-2023.

Table 3-3. Dominant taxa at eight grab stations (T01-T08) in Boston Harbor in August 2023.

Taxon	Total 2023 Abundance (compared with 2022)[a]
Aricidea catherinae	3,928 (decrease)
Tubificoides intermedius	2,355 (similar)
Naidinae sp.1	1,883 (similar)
Tharyx acutus	1,050 (similar)
Limnodriloides medioporus	1,004 (decrease)
Polydora cornuta	442 (decrease)
Ampelisca spp.	442 (decrease)

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

Temporally, benthic infaunal abundance in the harbor has been controlled by a limited number of species (Table 3-4). 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 3-8. *A. catherinae* and *L. medioporus* have exhibited little interannual variation in abundance whereas both *P. cornuta* and *Ampelisca* spp. have exhibited fluctuations of one to two orders of magnitude. Mean abundances of both species in 2023 were low (27.6 organisms per sample; Table 3-4 and Figure 3-8). *P. cornuta* and *Ampelisca* spp. 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). Changes in water temperature resulting from climate change could also be affecting the abundance of these species (Mills et al. 2013, Hale et al. 2017, Jacox et al. 2020, Amaya et al 2023).

Table 3-4. Mean abundance per sample of dominant taxa during four discharge periods at eight Boston Harbor stations (T01-T08), 1992-2023.

Phylum	Higher taxon	Family	Species[a]	Period I	Period II	Period III	Period IV	2023
Annelida	Polychaeta	Capitellidae	*Capitella capitata complex*	65.2	88.8	3.4	6.0	2.0
		Cirratulidae	*Tharyx acutus*	50.6	111.8	52.4	59.0	65.6
		Cossuridae	*Cossura sp. 1*	-	-	-	3.1	32.4
		Lumbrineridae	*Scoletoma hebes*	3.4	10.5	4.2	75.1	26.6
		Nephtyidae	*Micronephthys neotena*[b]	-	11.4	10.3	150.3	37.1
		Paraonidae	*Aricidea (acmira) catherinae*	325.0	237.4	204.3	259.6	245.5
		Phyllodocidae	*Phyllodoce mucosa*	7.7	39.4	42.6	26.1	28.7
		Polygordiidae	*Polygordius jouinae*	19.2	22.4	44.0	21.1	44.2
		Spionidae	*Polydora cornuta*	525.8	1053.0	269.6	264.6	27.6
			Spiophanes bombyx	16.2	41.4	65.9	39.2	44.6
			Streblospio benedicti	236.0	298.6	27.7	86.3	25.9
	Oligochaeta	Tubificidae	*Limnodriloides medioporus*	484.7	297.9	315.2	217.1	62.8
			Naidinae sp. 1	-	0.01	0.03	28.5	117.7
			Tubificoides intermedius	42.6	101.4	231.2	230.3	147.2
Arthropoda	Amphipoda	Ampeliscidae	*Ampelisca* spp.	354.3	1698.3	1205.9	444	27.6
		Corophiidae	*Corophiidae* spp.	16.1	336.2	23.0	2.0	16.6
			Crassicorophium bonellii	7.9	217.3	37.3	5.9	-
			Leptocheirus pinguis	29.0	117.4	66.0	62.3	2.4
		Photidae	*Photis pollex*	11.4	77.0	86.8	24.1	0.4
		Phoxocephalidae	*Phoxocephalus holbolli*	28.0	116.9	125.9	5.4	0.1

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

[b] Previously identified as *Nepthys cornuta* and *Bipalponephtys neotena.*

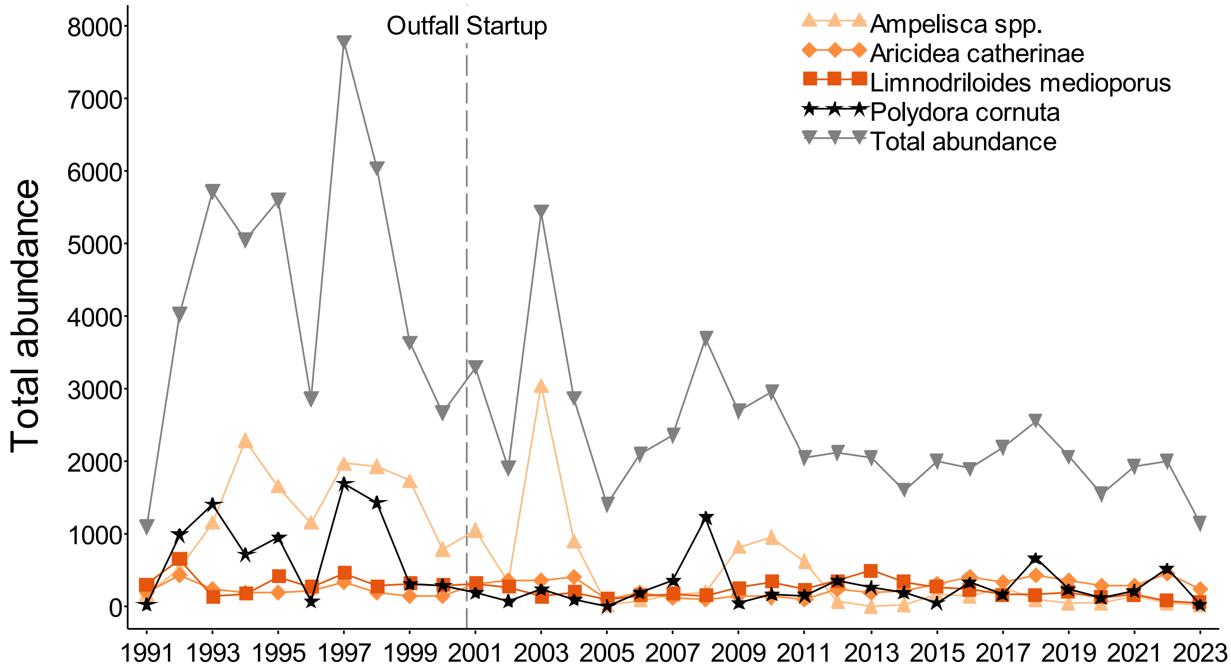

Figure 3-8. Total abundance of four dominant taxa at eight Boston Harbor stations (T01-T08), 1991-2023.

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 and the tolerance of *Ampelisca abdita* to highly enriched sediments. 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 to storm events and subsequent recruitment (around 2005 through 2009; Maciolek et al. 2006, 2011). *Ampelisca* abundance in 2023 was lower than 2022, and the lowest since 2013 (Figure 3-9). *Ampelisca* spp. have been most abundant at Stations T03 (ranging from 139 in 2023 to 1,656 organisms in 2017) and T06 (ranging from 25 in 2018 to 382 organisms in 2017; Figure 3-10). No *Ampelisca* mats were observed in 2023, and mean abundances at all stations decreased from 2022 counts. 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 and in 2018 could also have resulted in disturbances (sedimentation or substrate contact from anchored vessels) to stations T03 and T05A. *Ampelisca* abundances at Station T06 increased from 2019 through 2021, then declined by nearly half in 2022, and again in 2023 (Figure 3-10).

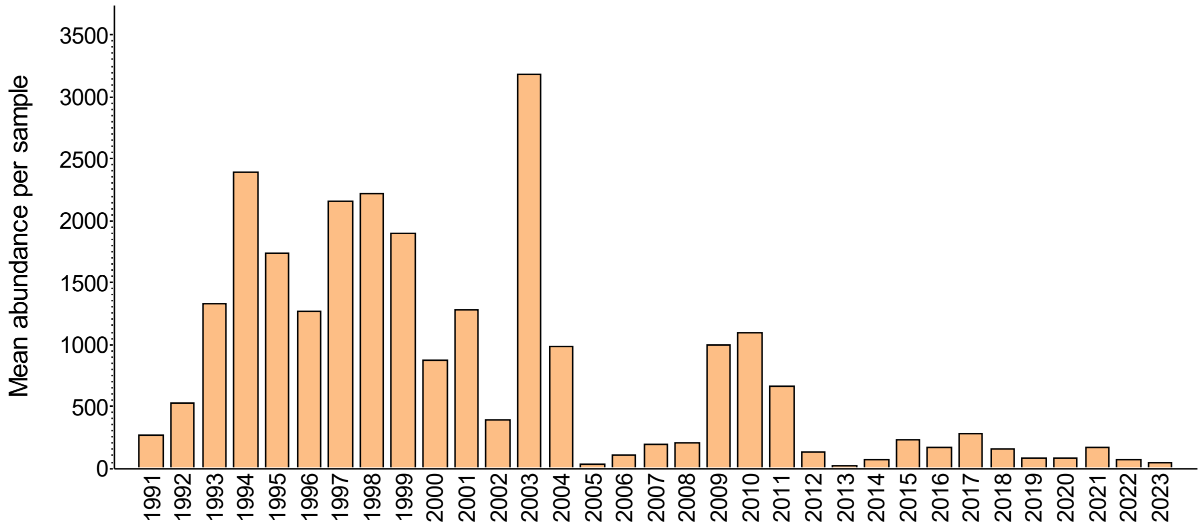

Figure 3-9. Mean annual abundance of *Ampelisca* spp. averaged over eight Boston Harbor stations (T01-T08), 1991-2023.

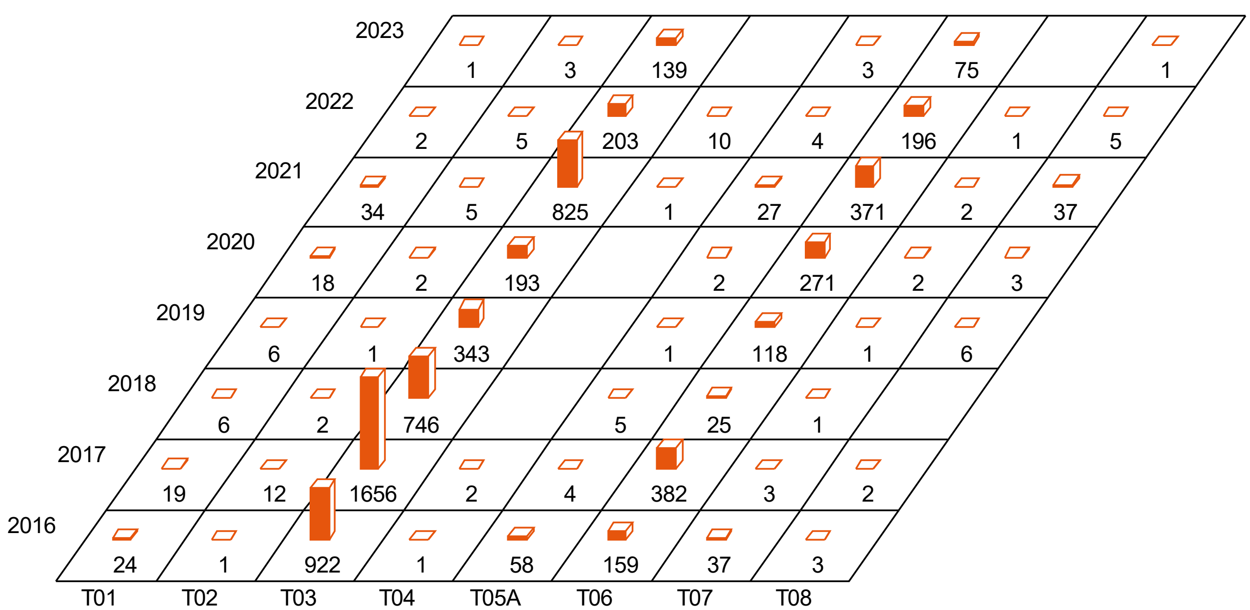

Figure 3-10. Spatial distribution of *Ampelisca* spp. at eight Boston Harbor stations (T01-T08), 2016-2023.

Species-level identifications of *Ampelisca* spp. (i.e. *A. abdita* and *A. vadorum*), which began in 1995, indicate that the changes in abundance discussed above are also related to changes in the species of *Ampelisca* spp. present in the Harbor. From 1995 through 2012, *Ampelisca abdita* was the predominant species of *Ampelisca* accounting for 80 to 100% of the individuals collected. Beginning in 2013, the percentage of *A. abdita* declined to nearly zero and remained low through 2019 ranging from 0 to 20%. In 2023, *A. abdita* accounted for approximately 35% of the *Ampelisca* spp. collected. *Ampelisca vadorum* generally now accounts for the majority of the *Ampelisca* collected, although abundances of *A. vadorum* do not appear to have changed from 1995 through 2023 (Figure 3-11). These two species of *Ampelisca* have different habitat preferences, *A. abdita* inhabits fine sediments (i.e., find sand and mud) and *A. vadorum* occurs on coarse sand. *A. abdita* occurs at lower salinities than *A. vadorum* (Mills 1967). Changes over time in the populations of *Ampelisca* relative to changes in salinity were further discussed in Rutecki et al. (2020b).

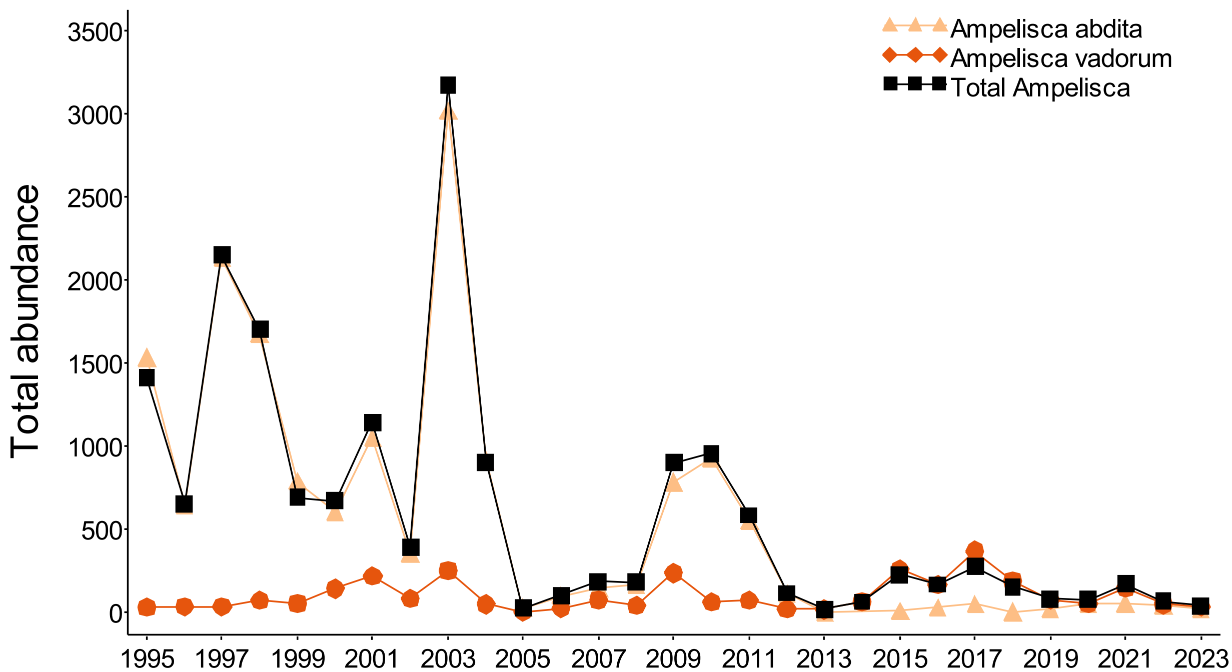

Figure 3-11. Mean total abundance of the two dominant *Ampelisca* taxa at eight Boston Harbor stations (T01-T08), 1995-2023.

The mean number of species per station reported for 2023 ranged from 8.0 at Station T04 to 57.0 at Station T05A, with an overall annual average of 34.9 species per station (Table 3-2). The 2023 average was below the post-diversion period average of 41 species but was within the range of historical variation (Figure 3-12). Stations T02, T03, and T08 were among the most species-rich stations from 2011 through 2022 (Rutecki et al. 2023); in 2023 species richness at each these three stations were at or above average for the Harbor. Station T04 has consistently supported the lowest species richness in this time frame, and in 2023 was significantly lower than the next lowest richness value at Station C019 (22.0). Station T05A exhibited an unusually high species richness compared to prior years and was the highest of the Harbor stations (57.0; Table 3-2).

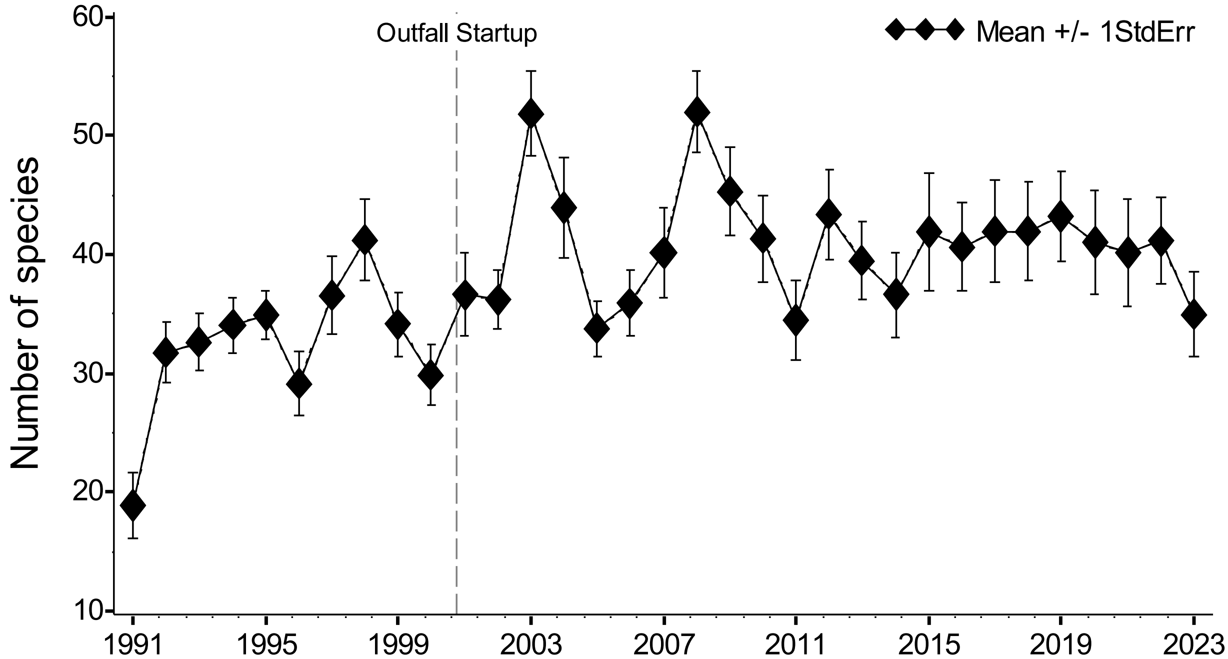

Figure 3-12. Mean species richness at eight Boston harbor stations (T01-T08), 1991-2023.

Two community index parameters, Pielou's evenness (J') and Shannon-Weiner diversity (H'), were averaged across the eight Harbor stations. Among stations in 2023, Pielou's evenness indices ranged from 0.44 at Station T06 to 0.68 at Station T02 (Table 3-2). The 2023 annual average (0.58) was above the average post-diversion value (2001 to 2022 [0.55]; Figure 3-13). Shannon-Weiner diversity indices among stations in 2023 ranged from 1.55 at T04 to 3.64 at Station T05A. The annual average (2.91) was slightly above the post-diversion mean (2.89; Figure 3-14). Average diversity for the harbor stations, as measured by log-series alpha, decreased in 2023 (6.9) compared to 2022 (7.9, Rutecki et al. 2023), but remained well above pre-diversion values (1991-2000; Figure 3-15). The highest log-series alpha diversity in 2023 occurred at Station T05A (11.0), which is atypical as Stations T08 or T01 have historically had the highest log-series alpha diversity in the Harbor. Consistent with recent patterns, log-series alpha diversity was lowest at T04 in 2023 (1.8; Table 3-2; Pembroke et al. 2017, Rutecki et al. 2023). The largest change in log-series alpha from 2022 to 2023 was the increase at T05A (7.91 to 10.99) which occurred after the large decline observed from 2020 to 2022 (from 10.82 to 7.91, Rutecki et al. 2023).

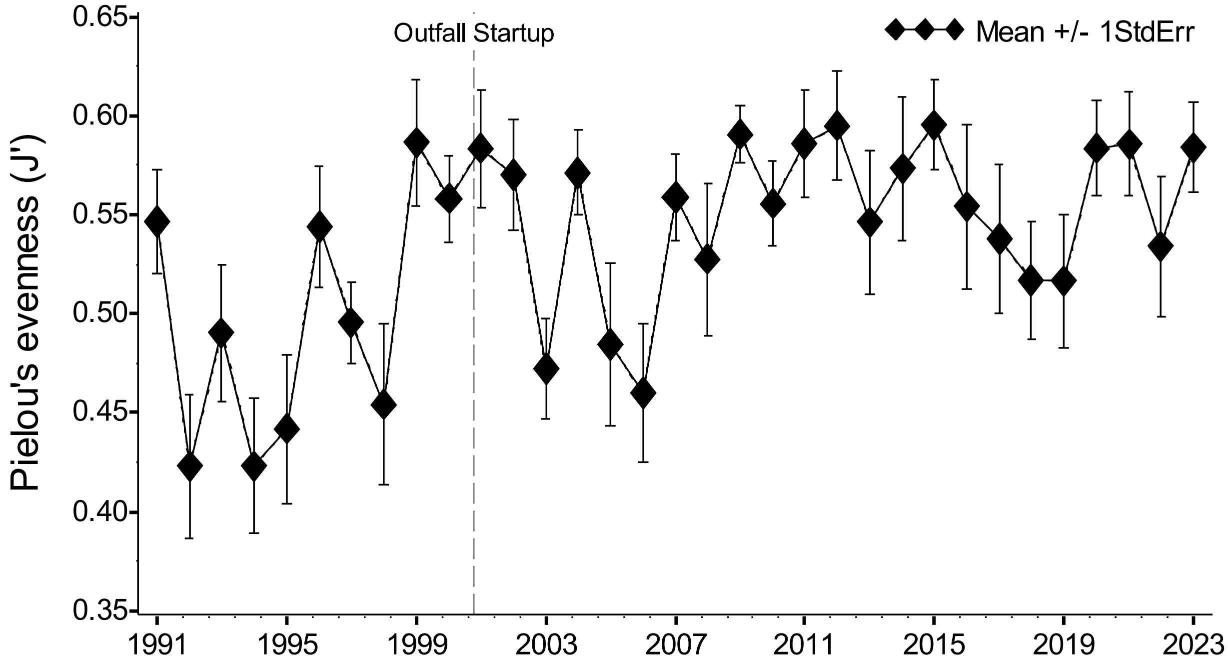

Figure 3-13. Mean community evenness at eight Boston Harbor stations (T01-T08), 1991-2023.

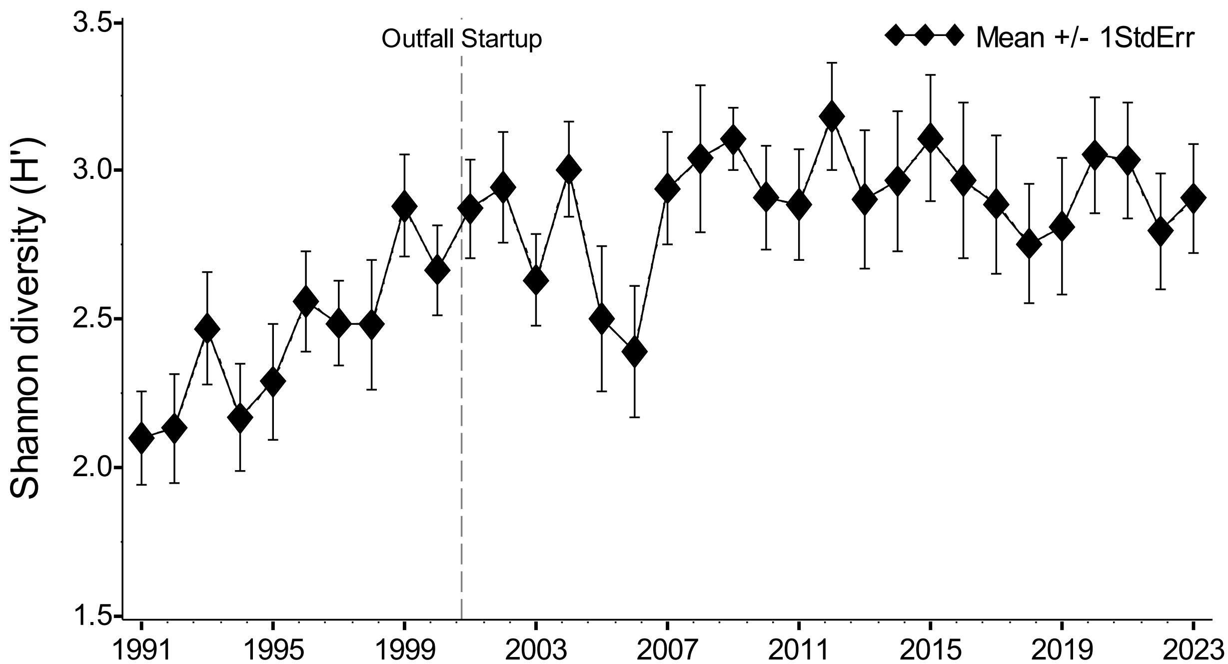

Figure 3-14. Mean Shannon-Weiner diversity at eight Boston harbor stations (T01-T08), 1991-2023.

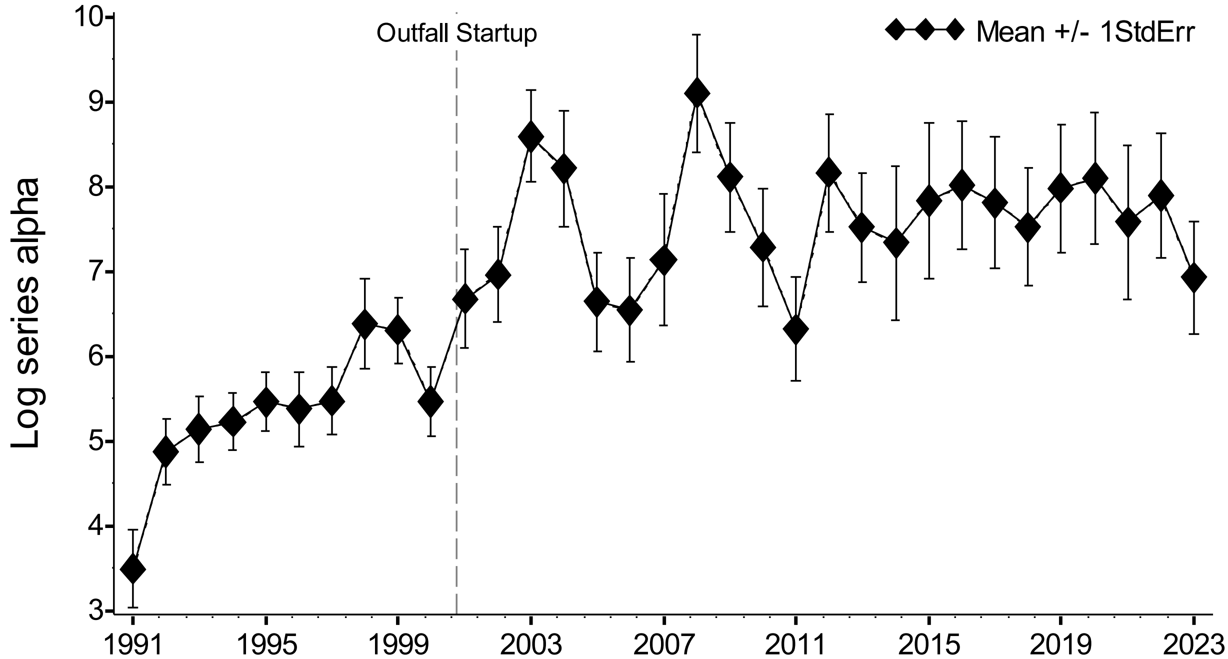

Figure 3-15. Mean log-series alpha diversity at eight Boston Harbor stations (T01-T08), 1991-2023.

3.2.2 Infaunal Assemblages

Multivariate analyses were used to assess spatial patterns in the faunal assemblages at the Boston Harbor sampling stations. Replicates within each station exhibited high similarities in community structure and grouped together. Six main assemblages were identified in a cluster analysis of the 18 samples from 2023 (Figure 3-16a). Patterns identified through cluster analysis were confirmed in the nMDS ordination plot for the 2023 Harbor samples (Figure 3-16b). All assemblages were dominated by polychaetes or oligochaetes (Table 3-5). Spatial patterns in the faunal assemblages of Boston Harbor reflect a gradient from species-poor stations C019, T04, and T07, to more diverse stations which tend to be in the Outer Harbor.

The Group IA assemblage was found at Outer Harbor Station T08 (Hingham/Hull Bay); the Group IB assemblage was at Station T05A (Deer Island); and the Group IC assemblage was found at Outer Harbor to mid-Harbor stations (T01, T02, T03 off Deer Island and the Main Ship Channel, and T06 in outer Quincy Bay); the Group IIA assemblage comprised Station C019 in the Inner Harbor and one sample from Station T07 (Quincy Bay); the Group IIB assemblage was the other sample from Station T07; and the Group III 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 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 most of the Outer Harbor stations (T01, T02, T03, T05A, T06, and T08) characterized by relatively high abundance (averaging 1,322 individuals) and species richness (averaging 40 species per collection). Abundances for five species of polychaetes and oligochaetes (*Aricidea (Acmira) catherinae*, *Tubificoides intermedius*, *Naidinae* sp. 1, *Tharyx acutus*, and *Limnodriloides medioporus*) were relatively high (Table 3-5). Within Group I, Station T08 was distinct enough to form Group IA while Station T05A formed Group IB. Both subgroups were characterized by high species richness (averaging 34 and 57 species per collection, respectively). Group IA was dominated by *T. acutus* and *Polygordius jouinae*; while Group IB was dominated by *T. intermedius*, *Spiophanes bombyx* and *Naidinae* sp. 1. Group IC, composed of Stations T01, T02, T03, and T06, was characterized by high abundance and species richness (averaging 37 species per collection). Dominants included *A. catherinae, Naidinae sp. 1,* and *L. medioporus* (Table 3-5).

The main Group II consisted of Stations C019 and T07 and was dominated by *T. intermedius*, *Cossura* sp. 1, and *Micronephthys neotena* (Table 3-5). Station C019 and one replicate of Station T07 formed Group IIA which was dominated by *Cossura* sp. 1, *M. neotena,* and *T. intermedius*. The other replicate of Station T07 formed Group IIB which was dominated by *T. intermedius, Monocorophium acherusicum, Cossura sp.* 1. These two subgroups were characterized by relatively low abundance and species richness (averaging 27 species per collection).

The main Group III consisted solely of Station T04. This station had a relatively low abundance and species richness (averaging 8 species and 214 organisms per collection) and was dominated primarily by *Tubificoides* sp. 2, *Streblospio benedicti* and *M. neotena* (Table 3-5).

Sediment conditions, particularly percent fines and TOC were likely factors in distinguishing the benthic communities among the Boston Harbor stations. Comparisons of faunal distribution to habitat conditions indicated that patterns in the assemblage distribution follow differences in habitat types at the sampling stations and are associated with sediment type and depth (not shown) at the stations (Figure 3-17). Group IA (T08) and Group IB (T05A) both contain predominantly sand and very low TOC, however the difference in percent sand (91% versus 78%, respectively) between the two stations was enough to affect the species present at each station resulting in two distinct subgroups. Sediments at stations in Group IC ranged from approximately 30 to 76% sand with moderate to low TOC (0.3 to 1.2%). Sediments at Group IIA and IIB (Stations C019 and T07) were approximately 99.2% and 70.8% fine sediments, respectively, with moderate TOC (2.1% and 1.8% respectively). Sediments at T04 (Group III) were predominantly fines (95.8%) with a TOC value higher than all other locations (3.0%; Table 3-1).

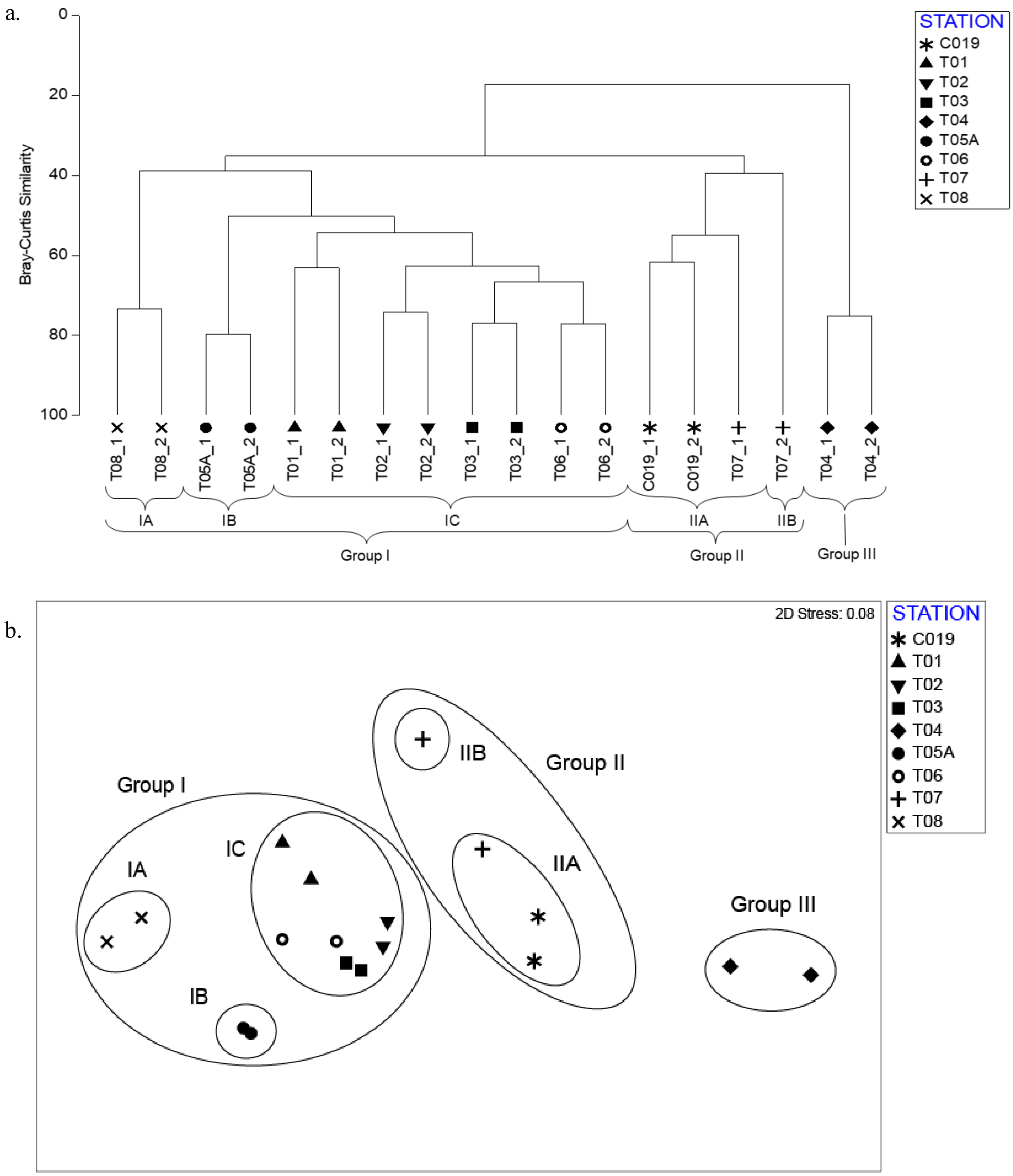

Figure 3-16. Results of (a) cluster analysis and (b) nMDS analysis of the 2023 infauna samples.

Table 3-5. Mean abundance of dominant taxa in 2023 Boston Harbor station groups defined by cluster analysis. Bold numbers denote the three main assemblages.

Major Taxon	Family	Species	I	IA[a]	IB[a]	IC[a]	II	IIA[b]	IIB[b]	III
Turbellaria		*Platyhelminthes* sp. 16	**0.4**	-	0.5	0.5	**-**	-	-	**0.5**
Gastropoda	Nassariidae	*Ilyanassa trivittata*	**-**	7.5	38.5	3.9	**-**	4.0	2.0	**-**
Bivalvia	Mactridae	*Spisula solidissima*	**2.2**	3.5	1.0	2.1	**0.3**	0.3	-	**1.0**
	Pharidae	*Ensis leei*	**-**	11.0	1.5	0.9	**-**	0.3	-	**-**
	Tellinidae	*Ameritella agilis*	**-**	63.0	104.5	10.5	**-**	4.3	7.0	**-**
	Yoldiidae	*Yoldia sapotilla*	**-**	-	1.5	1.1	**-**	2.7	-	**-**
Polychaeta	Capitellidae	*Mediomastus californiensis*	**9.3**	-	38.5	4.3	**1.3**	1.7	-	**0.5**
	Cirratulidae	*Tharyx acutus*	**86.8**	458.5-	15.5	11.8	**3.0**	2.0	6.0	**-**
	Cossuridae	*Cossura* sp. 1	**22.3**	-	-	33.4	**158.3**	159.7	154.0	**1.5**
	Lumbrineridae	*Scoletoma hebes*	**34.9**	2.0	6.0	50.4	**1.8**	1.7	2.0	**-**
	Microphthalmidae	*Microphthalmus pettiboneae*	**6.8**	-	23.5	4.3	**1.5**	1.7	1.0	**6.5**
	Nephtyidae	*Micronephthys neotena*	**33.1**	-	-	49.6	**110.8**	138.0	29.0	**10.5**
		Nephtys incisa	**5.2**	-	3.5	6.9	**8.8**	11.0	2.0	**7.0**
	Paraonidae	*Aricidea (Acmira) catherinae*	**320.3**	63.5	72.5	446.5	**21.3**	17.3	33.0	**-**
	Phyllodocidae	*Phyllodoce mucosa*	**37.8**	0.5	88.5	34.4	**1.8**	0.3	6.0	**-**
	Polygordiidae	*Polygordius jouinae*	**58.8**	265.5	87.0	0.1	**0.3**	-	1.0	**-**
	Spionidae	*Polydora cornuta*	**30.0**	-	12.5	41.9	**76.8**	83.3	57.0	**0.5**
		Spiophanes bombyx	**59.5**	19.0	326.0	3.0	**-**	-	-	**-**
		Streblospio benedicti	**14.6**	-	-	21.9	**54.8**	26.3	140.0	**38.0**
	Syllidae	*Parexogone hebes*	**-**	15.5	77.0	5.3	**-**	-	-	**-**
	Terebellidae	*Polycirrus eximius*	**-**	8.5	1.0	-	**-**	-	8.0	**-**
Oligochaeta	Tubificidae	*Limnodriloides medioporus*	**83.7**	6.5	37.5	114.5	**0.3**	0.3	-	**-**
		Naidinae sp. 1	**150.4**	13.5	245.5	160.9	**19.5**	-	78.0	**-**
		Tubificoides intermedius	**159.3**	-	584.0	93.0	**180.8**	101.7	418.0	**-**
		Tubificoides sp. 2	**0.7**	4.0	-	-	**-**	-	-	**147.0**
Amphipoda	Ampeliscidae	*Ampelisca* spp.	**36.8**	0.5	3.0	54.4	**-**	-	-	**-**
	Aoridae	*Microdeutopus anomalus*	**0.3**	-	-	0.4	**25.3**	-	101.0	**-**
	Corophiidae	*Apocorophium acutum*	**-**	-	-	-	**-**	-	20.0	**-**
		Monocorophium acherusicum	**0.6**	0.5	-	0.8	**56.8**	-	227.0	**-**

[a] distinct subgroup of Group I
[b] distinct subgroup of Group II

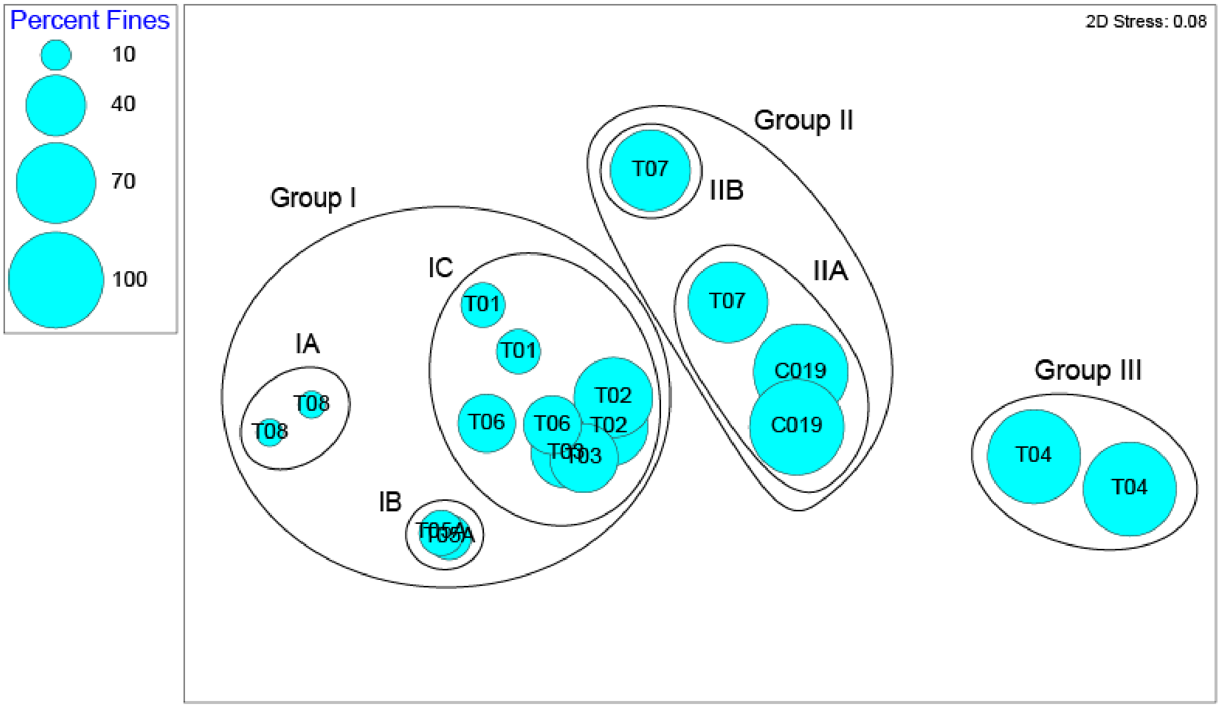

Figure 3-17. Percent fine sediments superimposed on 2023 nMDS ordination plot of the 2023 Harbor infauna samples.

3.2.3 Selected Stations

Station T01. Infaunal community structure at Station T01, located near Deer Island Flats north of President Roads, has typically exemplified conditions at most stations in the Harbor throughout the survey period. In 2023, species richness, Shannon-Weiner diversity, evenness, and log-series alpha were relatively high at T01. All four parameters declined slightly compared to 2022 but remained within the ranges of values recorded in recent years (Rutecki et al. 2023). Mean abundance declined noticeably in 2022 (999.5) and again in 2023 (835.0) to just above the 2013 value (783.5) which was the lowest observed in the post-diversion period (Figure 3-18). Species richness, log-series alpha, and Shannon-Weiner diversity have declined since 2020 but were above the low values observed in 2013 (Figures 3-19 through 3-21). Pielou's evenness has remained steady since 2018 (ranging from 0.61 to 0.62; Figure 3-22).

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, *S. benedicti* and *Chaetozone anasimus* (previously called *C. setosa*). Mean abundance ranged from 223.5 in 2021 to 2,521 in 2013. The 2023 abundance (654.5) was below the 2004 to 2022 average (814.0) but was within the historical range (Figure 3-18). Species richness ranged from 8.7 in 2007 to 29 in 2013. The 2023 value (22) was above the study period mean (17.4; Figure 3-19). Log-series alpha has varied over the study period, ranging from 1.5 in 2007 to 5.0 in 2014. The 2023 value (4.4) was relatively high compared to the time-series mean (3.3; Figure 3-20). The 2023 Shannon-Weiner diversity (2.6) was well above the study period mean (1.8) which ranged from 0.3 in 2005 to 3.1 in 2014 (Figure 3-21). Pielou's evenness ranged from 0.09 in 2005 to 0.71 in 2014 and was well above the mean (0.45) in 2023 (0.58; Figure 3-22). Overall, Shannon diversity and evenness have increased over the study period indicating the benthic community has improved at this station since the mid-2000's. The polychaete *Micronephthys neotena* (formerly called *Nepthys cornuta* and *Bipalponephtys neotena*) had represented the majority of the infauna found at Station C019 from 2004-2011 (Figure 3-23) 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 other dominants including *C. anasimus* in 2013 (Pembroke et al. 2014), the oligochaete *T. intermedius* in 2015 and 2022, and *P. cornuta* in 2016. *Cossura* sp 1 has historically dominated the community structure from 2017 through 2021. In 2023, the dominant species was *Cossura* sp 1 with *T. intermedius* as the second most abundant species (Figure 3-23).

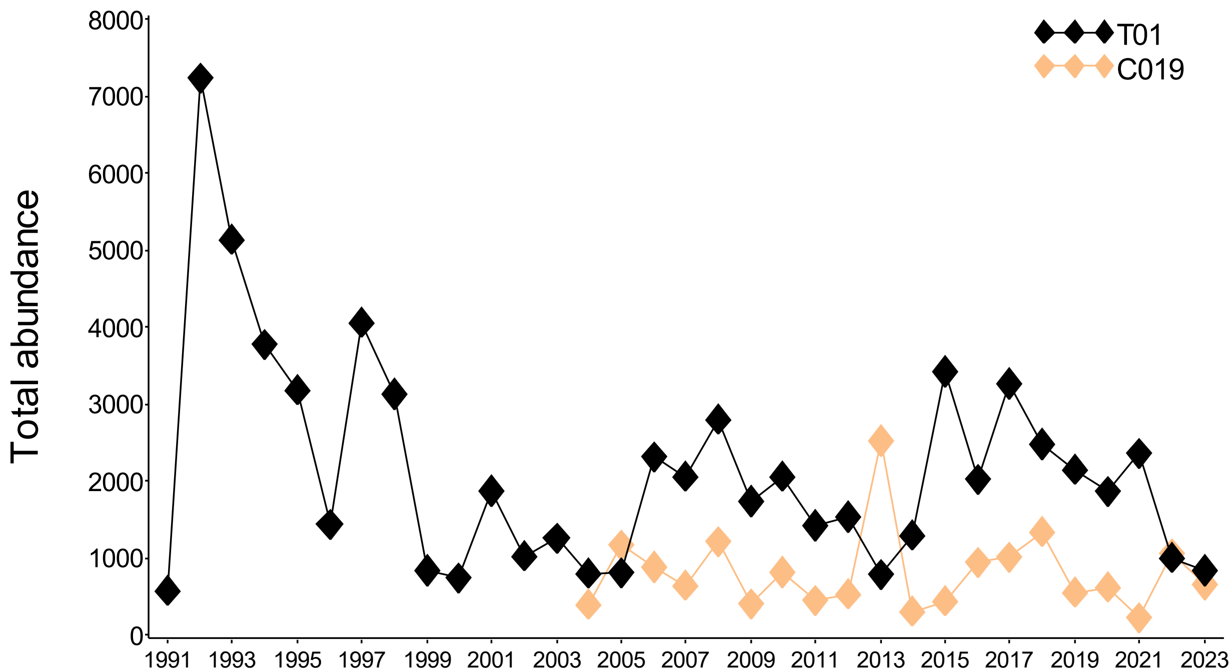

Figure 3-18. Mean total abundance at Boston Harbor Stations T01 and C019, 1991-2023.

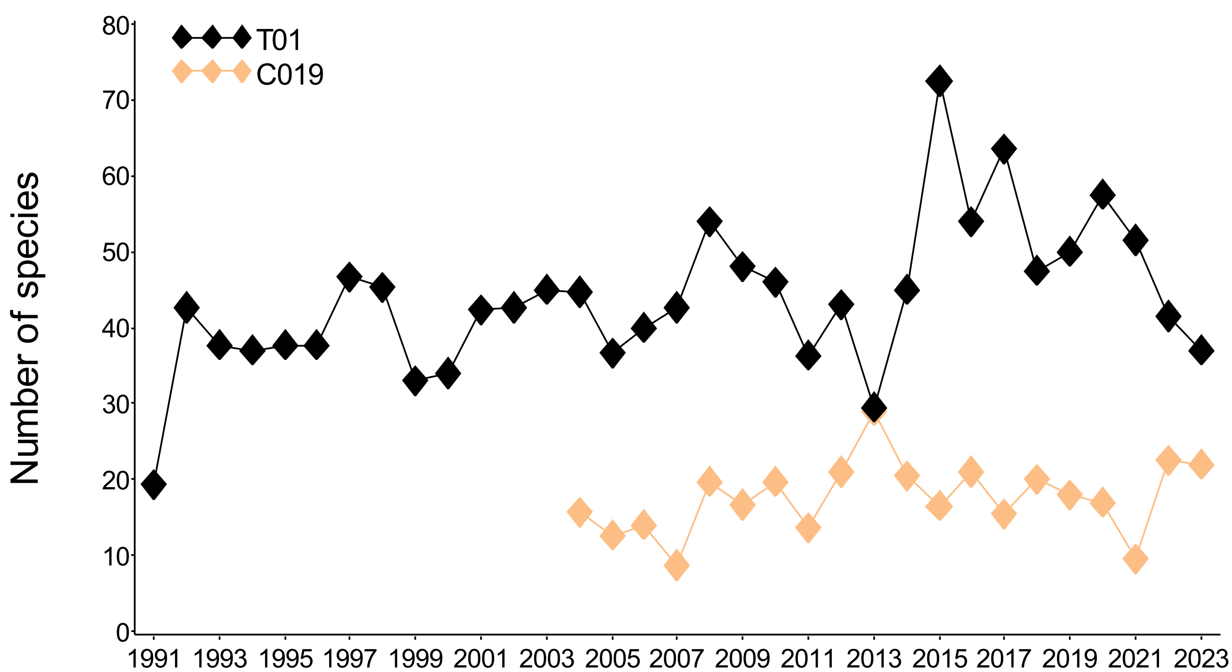

Figure 3-19. Mean species richness at Boston Harbor Stations T01 and C019, 1991-2023.

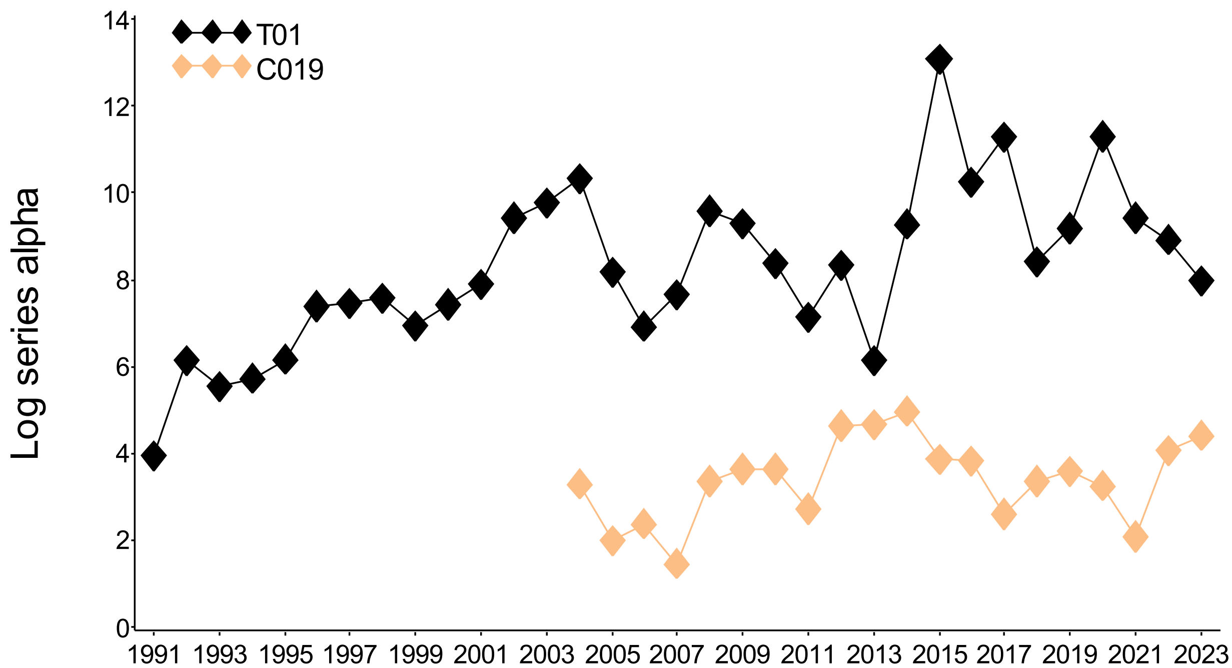

Figure 3-20. Mean log-series alpha diversity at Boston Harbor Stations T01 and C019, 1991-2023.

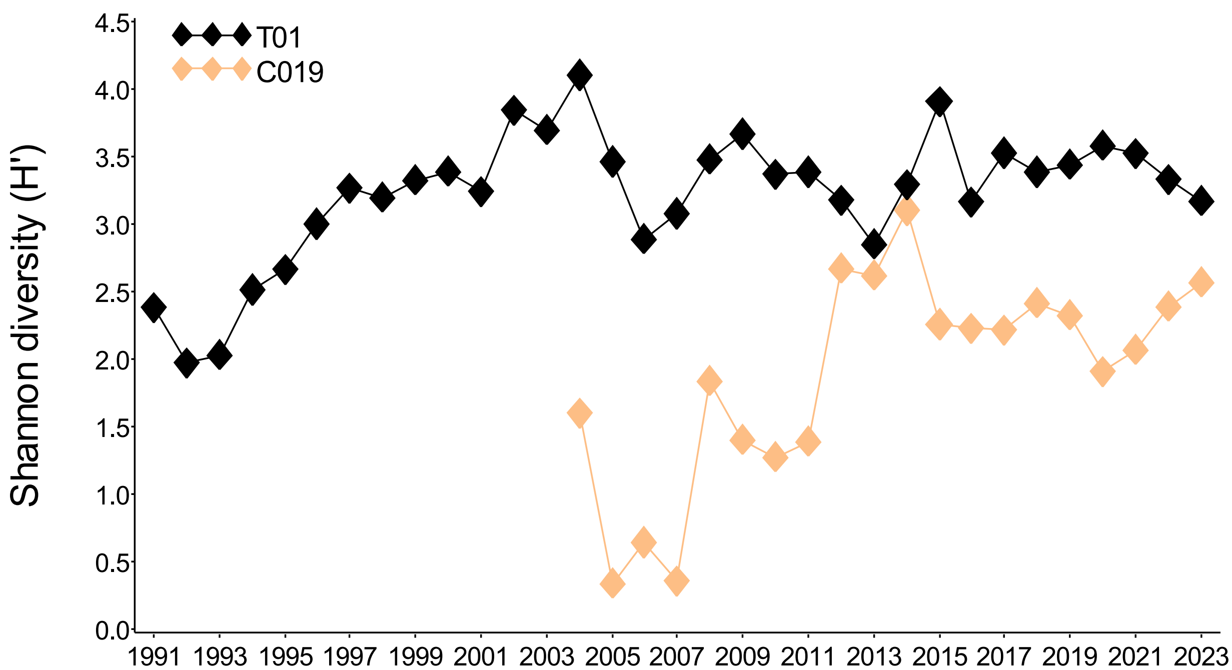

Figure 3-21. Mean Shannon-Weiner diversity at Boston Harbor Stations T01 and C019, 1991-2023.

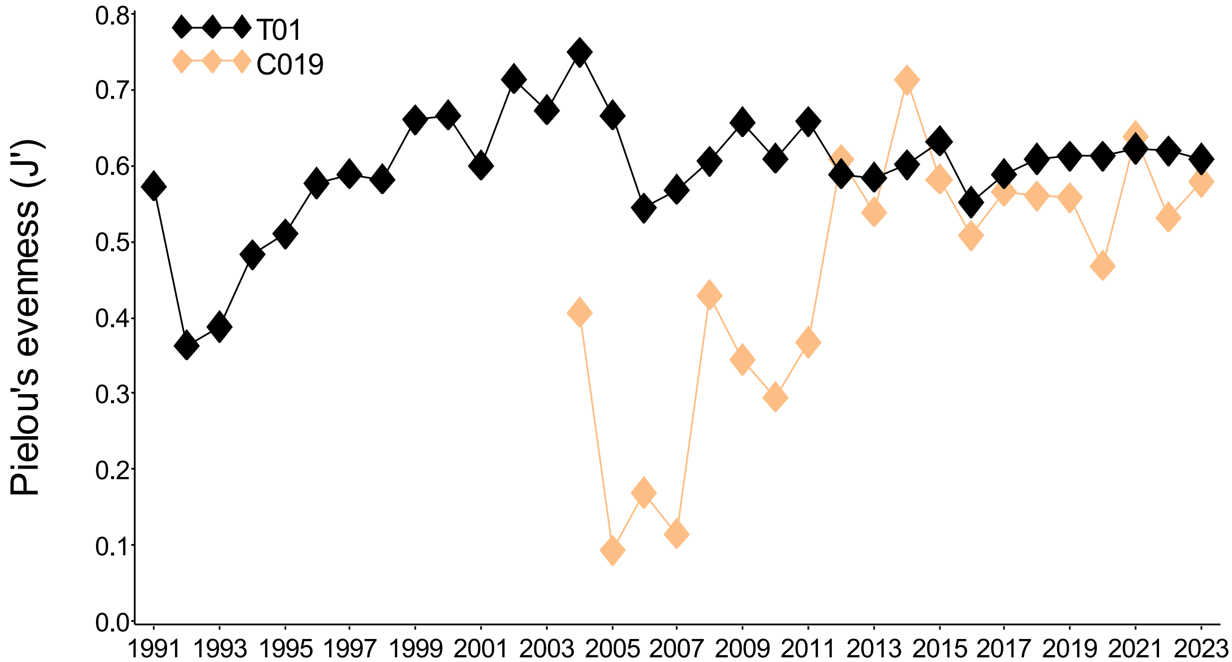

Figure 3-22. Mean evenness at Boston Harbor stations T01 and C019, 1991-2023.

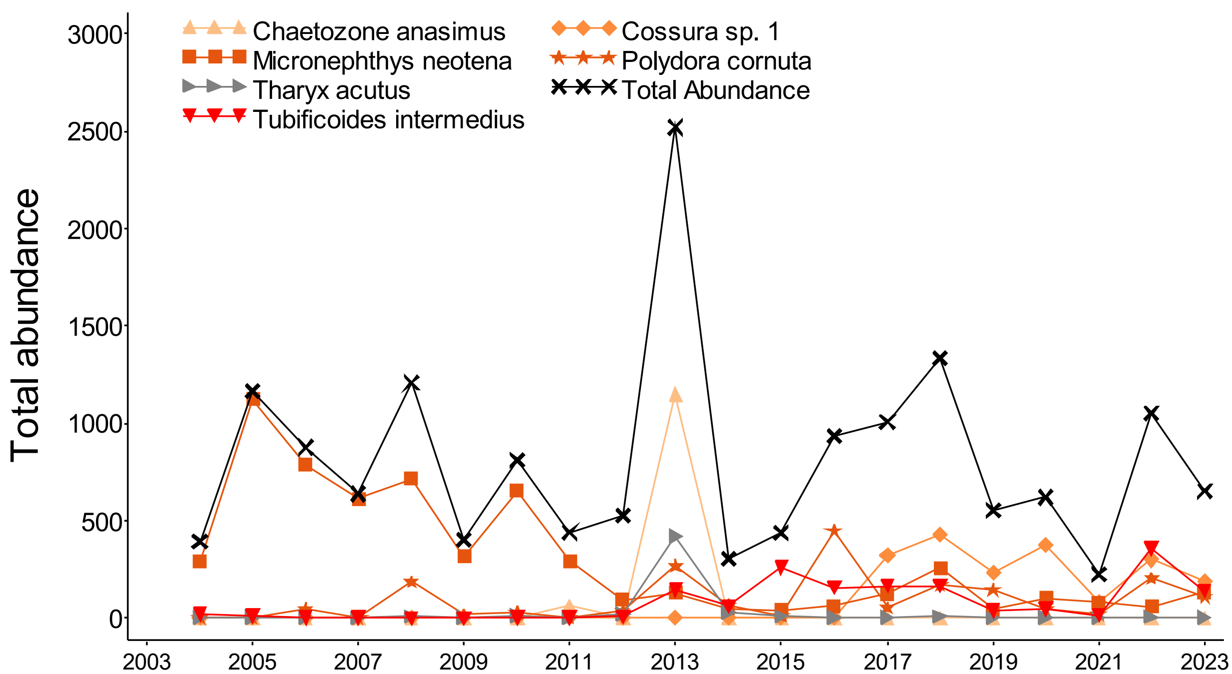

Figure 3-23. Mean abundance of *Micronephthys neotena* and other dominant species along with total community abundance at Station C019, 2004-2023.

3.2.4 Temporal Trends

Benthic community parameters for Boston 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 3-6). While mean total abundance has not changed dramatically between Period I and Period IV, increases in species richness, evenness, and diversity through the four periods have been notable and the trend in all of these parameters suggests a response to the reduction in pollutant loading into the Harbor. Mean Period IV values for number of species, evenness, Shannon-Weiner diversity, and log-series alpha diversity for 2002-2023 continue to indicate a positive trend. It should be noted that the mean total abundance doubled in Period II largely as a result from sharp increases in *Ampelisca* spp. abundance in those years at some stations, especially T03, T06, and T08. For example, abundances of *Ampelisca* spp. at Station T03 were observed at > 6,000 individuals/sample during those years (Maciolek et al. 2008).

Table 3-6. Benthic community parameters for stations T01-T08, summarized by time periods defined by Taylor (2006).

Parameter	Period I (1991-1992)		Period II (1993-1998)		Period III (1999-2001)		Period IV (2002-2023)	
	Mean	Std Err	Mean	Std Err	Mean	Std Err	Mean	Std Err
Total Abundance	2,606.4	343.6	5,513.4	469.0	3,213.3	492.6	2391.7	101.8
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	0.04
Pielou's Evenness (J')	0.48	0.02	0.47	0.01	0.58	0.02	0.55	0.01
Number of Species	25.4	2.1	34.7	1.1	33.6	1.7	41.1	0.8

3.3 SEDIMENT PROFILE IMAGING

3.3.1 General Benthic Habitat Conditions

Benthic habitats and communities within Boston Harbor have substantially recovered from past excessive organic and nutrient loading due to improvements in wastewater treatment and diversion to the offshore outfall September 2000 (Diaz et al. 2008, Tucker et al. 2014, Taylor et al. 2019). Much of the change occurred early in the wastewater-improvement project, prior to 2000 and were associated with the biggest reductions in loadings (Blake et al. 1998, Taylor et al. 2019). Averaged benthic habitat conditions in the Harbor for 2023 were similar to 2022 (all 61 SPI stations, see Figures 2-1 and 3-24 for locations), as measured by the Organism Sediment Index (OSI, Rhoads and Germano 1986; Figure 3-25). This represented a leveling off and dip in the trend of increasing benthic habitat quality within the Harbor which started in 2018 (Taylor et al. 2019, Rutecki et al. 2023). The cause of the harbor-wide downward trend in 2023 was likely lingering effects of the 2018 dredging and continuing ship traffic disturbance in President Roads (Figure 3-26). The minimum OSI dip in 2018 was related to dredging disturbance at R02 and R09 in President Roads. The low in 2015 was related to a slight decline in averaged apparent redox potential discontinuity (aRPD) layer depth and total biogenic structures. For both of these years the modal and mean OSI for the Harbor remained above 6 (the breakpoint between stressed and non-stressed benthos). Minimum OSIs in 1990s were related to low dissolved oxygen (hypoxia) in the Dorchester Bay region between 1994 and 1998. The last year the averaged Harbor's benthic habitat quality dipped below 6 was 2002 (Figure 3-25) and was related to a decline in the number of stations with the highest quality habitat category (OSI = 11).

Regional patterns in OSI were related to organic budgets and location within the Harbor. The lowest OSI values were consistently observed on the western side of the Harbor and Deer Island Flats until the early-mid 2000s. The greatest improvements in OSI also occurred on the western side. The outer, eastern regions consistently had higher OSI though time (Figure 3-27).

An increase in biogenic structures (the number of feeding voids, burrows, and infauna per image) and total abundance of subsurface deposit feeding species (for example maldanid polychaetes) was associated with improved habitat quality. These two parameters were correlated at Stations T02 ($r = 0.57$, $n = 30$, $p = 0.001$, Figure 3-28) and T03 ($r = 0.58$, $n = 30$, $p = 0.001$), but not at the other T-Stations. Sediment at Stations T05A, T06, and T08 were too sandy to support large numbers of biogenic structures, and at Station T04 the sediment was too muddy. Sediments at T01 and T07 were fine-sand-silts and capable of supporting biogenic structures but there was no relationship with total subsurface deposit feeders.

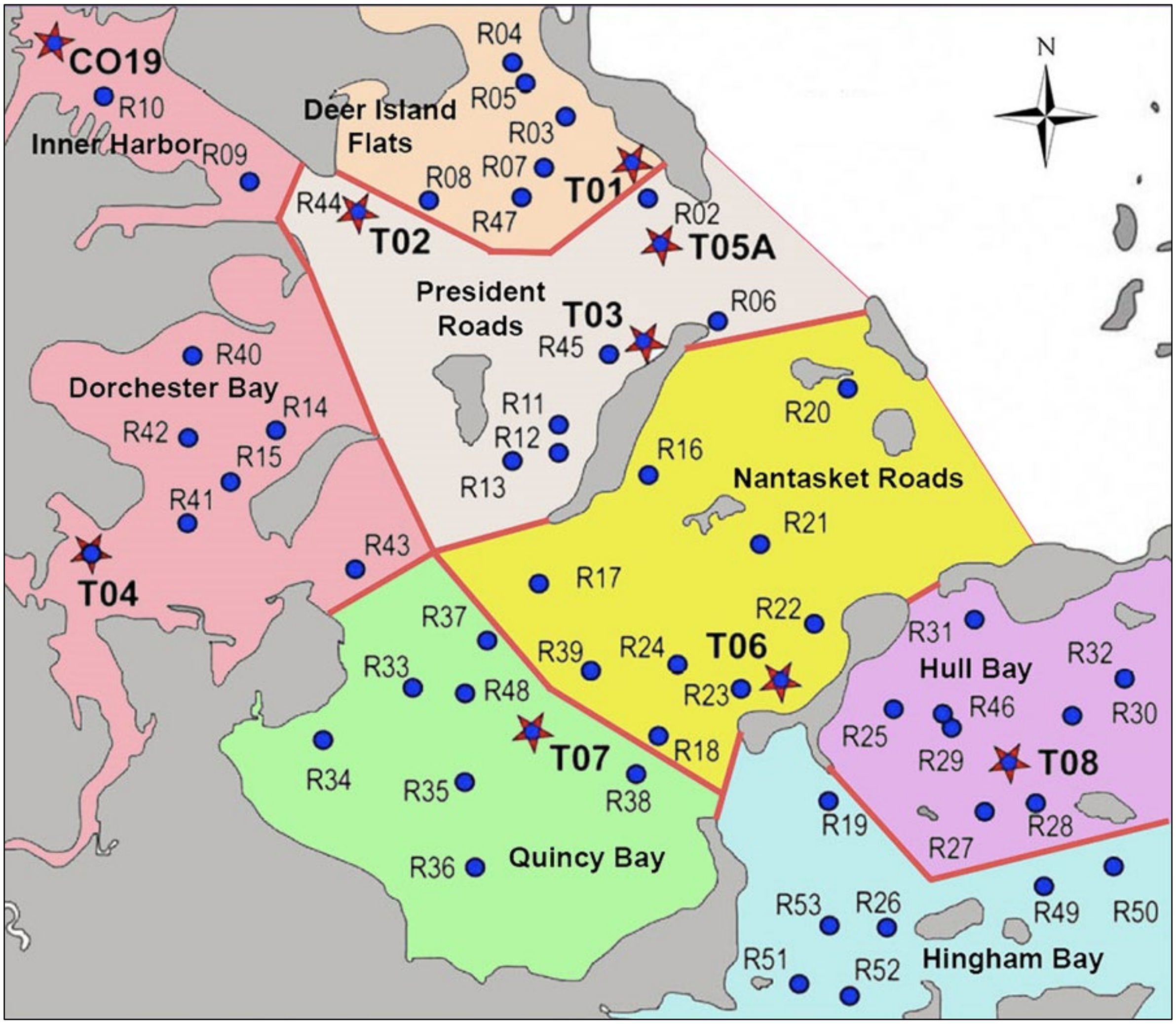

Figure 3-24. Sediment profile imaging stations (blue points) and soft-bottom sampling locations (stars) delineated by Boston Harbor regions.

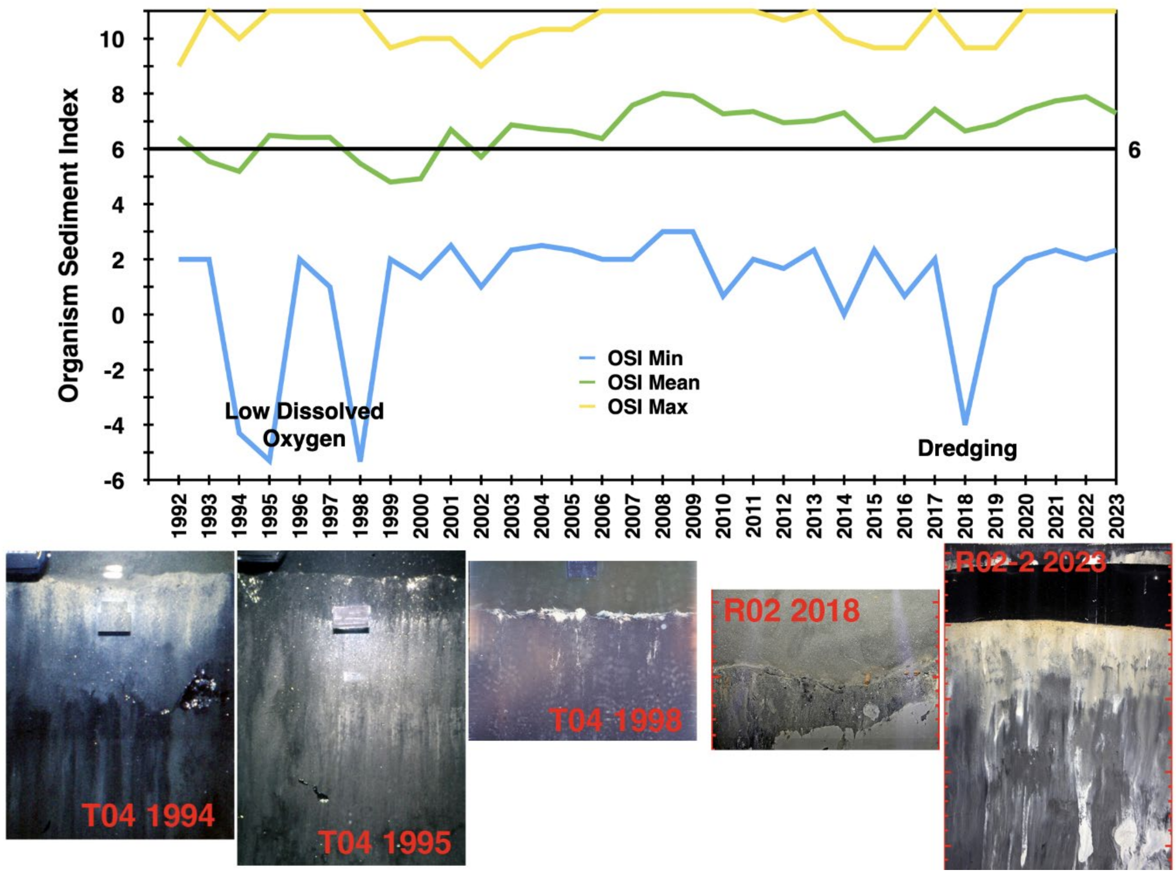

Figure 3-25. Maximum, mean, and minimum OSI for all 61 Harbor stations by year. Horizontal line at 6 is the breakpoint between stress and non-stress benthos (>6 represents good benthic habitat). Example images are 15 cm wide.

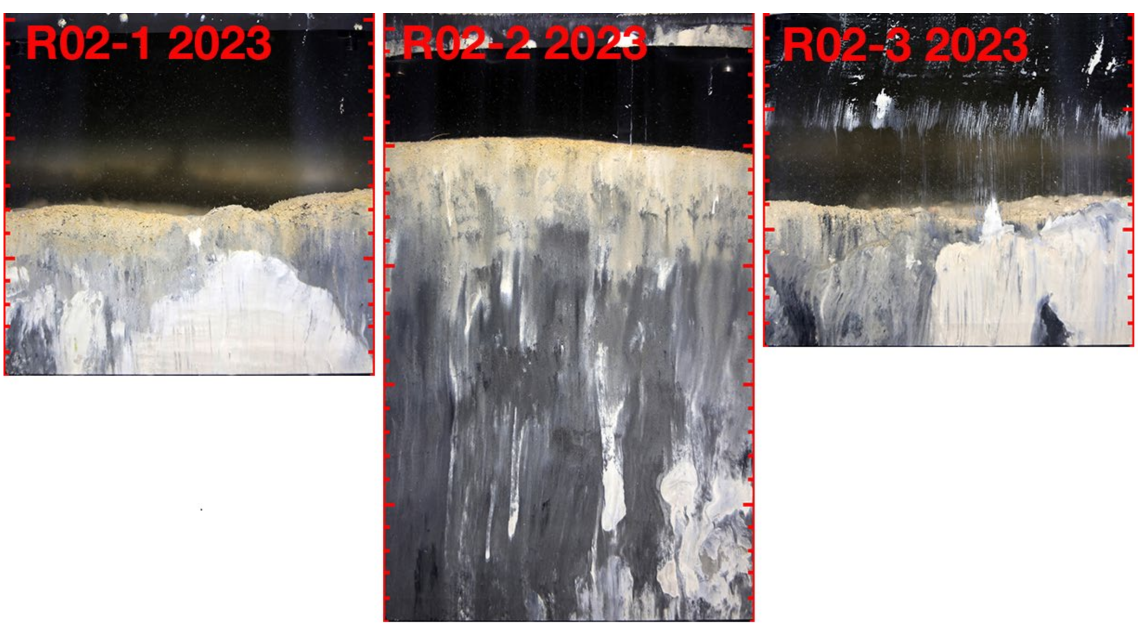

Figure 3-26. Station R02 within the boundaries of President Roads 2018 dredging. Relic clay is white to lite gray. Scale on side of images is in cm.

		92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
INNER HARBOR/ DORCHESTER BAY	CO19	IND												7.0	4.0	4.3	3.7	2.7	3.7	3.3	5.7	7.0	8.7	8.0	8.0	7.0	6.7	8.0	7.0	6.3	8.3	6.0	6.7
	R09	7.0	5.3	5.0	2.7	7.3	6.3	4.7	8.0	3.7	7.7	4.0	6.0	6.7	6.7	5.3	8.3	5.7	6.5	4.0	8.7	7.3	6.0	8.0	5.3	5.0	3.7	4.3	3.3	5.0	8.0	5.3	2.3
	R10	IND	2.0	3.0	3.3	4.0	5.0	5.3	4.3	3.7	3.7	3.7	3.7	7.3	4.3	5.0	7.3	5.0	7.3	5.7	7.3	8.3	7.3	8.3	7.3	6.7	8.3	4.3	6.0	8.7	8.0	8.0	8.0
	R14	5.7	5.3	4.7	7.0	5.0	11.0	5.3	2.3	3.3	9.0	4.3	6.7	4.7	7.7	5.3	8.3	7.3	10.7	10.7	11.0	10.7	6.7	8.0	6.0	5.0	7.0	7.7	8.0	8.0	8.3	8.7	8.0
	R15		3.0	2.3	11.0	5.0	IND	3.0	2.0	3.0	3.5	3.0	3.0	4.0	7.7	6.3	5.7	6.0	3.0	3.7	3.7	5.0	4.0	6.7	5.3	5.7	5.7	5.3	6.0	6.7	6.7	5.0	4.7
	R40	6.0	3.5	4.0	10.7	8.0	IND	2.7	3.3	4.7	4.0	6.0	7.0	6.0	9.0	7.0	5.3	5.7	7.0	9.3	6.3	6.7	7.0	6.0	5.0	6.3	8.0	6.7	8.0	6.7	9.3	8.3	7.7
	R41	6.3	2.3	5.3	11.0	6.0	5.0	4.7	2.3	3.3	3.7	7.0	7.3	6.7	7.3	7.0	7.0	6.0	5.7	5.7	7.7	7.0	5.0	7.3	7.7	5.0	7.3	5.7	8.7	6.7	8.0	8.0	7.0
	R42	5.0	4.7		6.0	3.0	IND	IND	2.3	5.0	3.0	4.0	5.0	4.3	9.3	7.7	7.3	8.0	4.7	3.7	5.0	4.7	3.0	3.0	3.5	3.3	6.7	5.0	4.7	5.0	8.0	5.0	5.0
	R43	3.3	2.3	2.5	4.7	2.0	2.7	2.0	2.0	2.0	2.5	3.0	4.7	7.3	7.3	7.3	7.3	6.0	4.0	7.7	5.7	1.7	5.7	6.3	4.3	2.7	6.7	5.0	6.3	6.3	7.0	6.0	6.3
	T04	2.6	2.0	-4.3	-5.3	IND	2.0	-5.3	2.0	1.3	2.7	1.0	2.3	2.5	2.3	2.0	5.3	3.0	3.3	0.7	2.7	1.7	2.3	2.3	2.3	1.3	4.3	2.0	1.0	5.0	2.3	4.3	3.3
QUINCY BAY	R33	5.3	2.7	0.7	7.0	4.0	2.7	2.3	3.0	3.0	3.0	3.3	4.7	6.0	8.7	6.0	8.0	9.7	5.0	5.0	5.7	4.3	6.7	5.0	6.0	7.3	6.0	7.0	5.7	7.7	7.7	7.3	8.0
	R34	7.0	3.0	-1.0	6.7	5.7	3.3	2.3	2.7	2.3		5.3	7.7	7.0	9.0	8.3	9.0	8.3	5.7	7.0	4.3	4.7	3.3	4.7	3.3	6.3	5.3	5.3	4.7	6.3	7.0	5.7	6.3
	R35	6.0	2.7	-0.7	5.0	5.0	2.7	2.7	3.7	3.0		5.3	4.7	4.3	6.3	7.7	5.0	8.7	6.7	7.7	4.0	7.0	7.0	6.3	5.7	5.3	7.0	7.0	6.3	2.0	8.0	7.7	8.7
	R36	IND			3.7	IND	2.3	3.0	2.0	4.3	IND	4.0	3.3	4.5	4.0	IND	4.0	3.0	4.0	2.7	2.0	3.0	2.3	3.0	3.0	3.0	2.0	2.0	2.7	8.3	2.7	2.0	2.5
	R37	5.7	2.7	4.3	7.0	3.0	3.3	4.0	2.3	3.7	3.0	6.7	8.0	7.3	4.7	8.0	7.3	9.0	11.0	7.7	5.7	6.0	8.3	8.3	7.3	4.7	7.7	7.7	8.0	8.0	7.7	8.7	8.7
	R38	7.7	5.3	4.7	8.7	6.3	9.7	6.7	9.0	4.7	9.7	9.0	10.0	7.0	4.0	5.3	8.3	9.7	10.0	9.0	7.7	7.3	9.0	7.7	5.7	6.3	8.0	7.0	8.0	8.3	7.7	7.7	7.7
	R48				5.0	5.7	IND	3.0	2.3	4.0	4.7	7.0	5.3	6.7	4.7	7.0	7.0	9.3	5.0	5.3	5.7	7.3	7.7	6.7	7.0	5.0	7.7	7.3	8.3	8.0	9.0	8.0	8.0
	T07	7.0	2.7	3.7	7.5	4.3	3.0	2.7	4.0	3.7	5.7	3.0	6.3	7.7	6.0	6.7	6.0	8.3	5.0	5.0	6.0	6.0	6.7	8.0	6.0	5.0	7.3	7.0	6.7	9.0	8.3	8.7	7.0
HINGHAM BAY	R19		5.7	4.0	4.0	6.0	IND	IND	2.0	IND	4.7	IND	IND	IND	IND	4.0	7.0	IND	IND	IND	IND	IND	IND	IND	IND	IND	IND	7.0	IND	7.3	7.0	7.5	7.3
	R26	7.7	5.0	9.3	4.3	5.7	IND	3.0	3.3	3.3	3.3	6.3	5.7	6.7	4.3	7.0	8.3	7.7	9.7	6.0	6.0	7.0	7.0	8.0	6.7	8.0	8.0	7.3	8.7	10.3	9.0	9.7	8.7
	R49	3.5			3.0	7.7	1.0	3.0	3.3	2.3	5.3	5.7	4.3	6.3	5.3	6.0	8.0	7.3	7.3	8.7	8.0	8.0	7.0	7.0	7.7	7.3	7.0	7.0	7.0	7.0	7.3	7.7	8.0
	R50	8.0			7.3	11.0	5.7	7.7	2.7	5.0	5.3	4.7	5.0	5.0	6.3	5.7	8.3	9.0	7.0	4.0	6.0	5.7	7.3	9.0	8.3	8.0	9.3	9.0	8.0	7.0	6.0	7.7	6.3
	R51	7.0			2.7	4.7	IND	3.0	3.3	2.3	3.3	5.7	5.0	6.7	6.0	4.7	7.3	5.7	5.7	5.0	2.7	4.7	4.7	6.3	5.0	5.0	5.7	6.3	4.7	7.7	4.3	7.7	4.7
	R52	IND			2.0	4.0	IND	3.5	3.0	3.0	3.0	3.7	4.0	5.0	6.7	6.7	8.0	8.0	3.0	8.0	7.7	6.3	5.0	4.0	4.7	3.5	7.3	6.3	5.0	7.7	5.0	7.3	4.0
	R53	8.0			3.0	5.3	IND	2.5	2.0	3.7	4.0	5.0	4.3	6.0	6.3	3.7	8.0	6.0	3.7	4.3	4.0	5.7	6.3	6.7	5.0	7.0	5.3	5.7	6.0	7.0	6.5	9.0	7.0
DEER ISLAND FLATS	R03		3.7	6.7	7.7	8.0	8.3	6.7	3.3	4.0	9.0	8.0	9.0	7.3	10.3	11.0	11.0	9.5	9.0	7.3	11.0	10.0	7.0	8.7	9.7	7.3	8.7	8.3	8.0	7.3	9.5	9.3	8.3
	R04		2.7	4.3	7.0	5.0	3.0	4.7	2.3	2.7	10.0	3.7	5.0	7.0	3.7	3.7	6.7	7.3	7.7	8.0	6.7	7.0	6.3	7.3	4.0	5.7	6.3	5.7	6.7	7.0	7.7	7.0	8.0
	R05	IND	4.0	6.0	7.0	5.7	IND	5.7	3.0	3.7	5.7	5.7	7.3	6.7	6.7	5.0	8.7	7.0	8.0	8.0	8.7	8.0	7.3	8.0	5.7	7.0	7.3	6.7	8.0	7.0	6.7	8.0	6.7
	R07		2.7	6.0	7.3	8.3	10.7	6.7	9.3	9.3	10.0	9.0	10.0	10.3	9.0	11.0	11.0	11.0	11.0	8.7	9.3	8.7	6.7	9.0	5.7	6.7	6.7	7.7	7.3	5.7	8.3	8.7	7.7
	R08		IND	IND	IND	8.0	4.5	3.5	3.7	IND	3.0	5.0	6.0	5.0	4.7	IND	IND	7.0	7.0	IND	10.0	7.0	IND	IND	5.0	7.0	7.0	IND	7.0	8.0	IND	7.0	6.7
	R47		IND	IND	8.7	7.0	10.3	9.3	9.0	10.0	5.5	7.0	7.3	9.3	9.0	10.0	10.0	10.0	10.3	9.3	10.0	10.3	8.3	9.0	7.0	6.7	9.3	9.7	8.0	7.0	10.7	10.7	8.0
	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	7.3	5.0	5.3	8.3	5.3	4.7	6.0	5.0	6.0	7.0	5.7	6.7	5.5	7.7	6.3	7.0	5.5	10.0	7.0
PRESIDENT ROADS	R02	6.7	3.0	5.7	2.0	4.7	9.3	5.7	5.7	7.0	10.0	4.7	8.3	10.0	6.3	7.0	10.0	9.3	11.0	8.0	8.7	7.0	8.7	9.0	7.3	8.0	7.3	-4.0	3.0	7.3	7.0	5.0	3.3
	R06	6.0	6.0	4.0	3.3	IND	IND	IND	2.3	3.3	5.0	4.3	8.0	IND	4.3	IND	2.0	IND	7.0	7.0	7.0	7.0	IND	IND	7.0	IND	IND	IND	7.0	7.0	7.0	IND	6.5
	R11		8.7	9.0	11.0	8.3	9.7	9.7	9.0	8.3	8.3	7.3	10.0	10.0	3.0	4.7	8.7	6.3	11.0	9.7	10.3	9.0	7.0	8.0	7.0	7.7	5.7	7.3	8.3	IND	7.7	8.0	7.3
	R12		6.7	10.0	10.3	8.0	10.0	11.0	9.0	9.3	9.0	7.0	10.0	6.3	6.3	6.3	8.7	8.3	10.7	10.7	10.3	9.0	9.0	9.3	4.0	6.7	7.7	7.3	7.3	7.7	8.3	9.0	8.0
	R13	6.8	5.3	10.0	6.7	5.0	IND	2.7	2.0	2.3	10.0	4.3	3.7	3.5	3.5	6.3	4.3	4.0	10.0	7.0	8.5	4.0	5.0	0.0	6.0	0.7	5.0	6.0	4.0	8.3	6.0	6.0	5.3
	R44				7.0	3.3	2.7	5.7	3.3	3.0	7.3	6.3	10.0	6.0	5.0	8.3	9.0	10.0	11.0	9.3	9.0	9.7	8.0	8.0	6.0	8.0	9.0	8.3	7.0	6.7	9.0	7.3	8.0
	R45	9.0			9.7	9.7	9.7	7.7	7.7	8.3	10.0	8.3	10.0	7.0	8.0	6.7	8.3	8.3	10.3	9.7	10.0	8.0	8.7	9.0	8.7	9.0	10.3	8.3	7.7	7.0	9.7	11.0	11.0
	T02	3.0		5.7	6.7	5.0	4.3	3.7	3.0	3.0	5.0	6.3	10.0	7.3	6.3	8.0	10.0	10.0	10.0	9.0	10.0	8.0	8.7	7.0	6.3	8.0	8.7	8.3	8.7	7.0	8.7	10.7	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	10.0	7.7	8.0	7.0	8.0	7.7	10.0	10.3	9.0	8.0	7.3	7.7	7.7	9.0	8.7	9.0	9.3	7.3	9.3	10.3	10.0
	T05A				6.7	4.3	5.5	4.3	2.3	3.0	7.0	4.5	7.0	8.0	7.0	4.7	9.0	6.7	6.7	8.0	6.3	6.7	9.3	5.3	5.7	6.0	5.7	5.3	6.7	8.7	7.3	7.0	8.0
NANTASKET ROADS	R16	8.7	8.0	2.5	6.3	9.0	8.0	4.0	5.7	5.3	8.7	3.7	7.0	3.7	6.7	4.7	6.0	7.3	5.0	5.0	4.0	6.0		6.0	4.7	7.0	8.0	3.0	4.3	8.7	7.0	4.0	5.7
	R17	6.0	4.3	5.3	8.0	3.0	4.7	4.3	8.7	6.3	4.7	8.7	10.0	9.3	9.7	11.0	9.3	11.0	11.0	10.3	7.7	9.3	11.0	8.7	7.3	7.0	7.3	7.0	8.0	5.0	8.0	8.7	8.0
	R18		9.0	5.7	8.3	7.7	9.7	10.7	9.0	5.3	9.0	6.0	9.3	6.0	6.3	6.0	7.0	7.7	9.7	9.0	8.0	7.0	10.7	9.7	7.3	7.7	7.7	7.0	7.0	7.0	8.7	9.7	9.0
	R20		9.3	5.5	11.0	7.3	10.3	IND	9.0	7.7	10.0	6.3	7.0	7.7	8.3	6.3	8.0	10.0	9.3	8.3	9.7	6.7	8.7	8.7	8.7	8.3	8.3	8.0	7.7	9.0	9.0	10.0	7.0
	R21	8.0	9.0	8.0	9.0	7.3	10.0	9.3	5.7	8.0	8.7	6.7	8.7	10.0	10.0	5.7	10.0	10.0	10.3	9.0	9.7	9.7	9.7	8.0	9.0	9.7	9.0	9.0	9.7	7.7	9.0	9.0	10.3
	R22		9.0	5.7	7.3	4.3	10.3	7.7	4.5	6.0	10.0	6.3	7.0	5.0	6.7	6.0	5.5	IND	10.7	IND	IND	7.0	8.0	IND	7.0	IND	IND	7.0	8.0	9.0	IND	7.0	7.0
	R23	7.5	9.0	6.7	6.0	8.0	IND	3.0	IND	5.3	5.3	IND	IND	6.0	7.0	6.0	5.5	9.0	10.0	IND	IND	7.0	7.0	IND	IND	IND	8.0	7.0	7.3	6.0	IND	7.3	7.0
	R24	8.0	9.0	5.0	9.0	9.7	IND	7.3	9.7	8.0	10.0	5.7	6.7	6.7	8.3	6.3	8.7	10.0	8.0	8.7	8.3	7.0	7.0	8.3	7.3	8.3	9.3	7.7	8.0	6.0	8.0	9.3	9.3
	R39	8.3	6.7	8.7	7.0	6.3	6.3	9.0	3.7	5.3	10.0	8.7	5.5	6.0	5.7	5.3	6.7	10.3	11.0	9.3	8.0	6.3	7.7	8.7	6.0	5.5	7.0	4.7	7.3	7.7	7.7	8.0	8.0
	T06	7.0	9.3	5.0	6.3	5.7	7.7	7.7	7.7	6.3	9.0	6.3	7.3	5.7	5.7	4.7	6.7	10.0	7.3	7.3	7.3	8.0	7.0	8.3	8.3	6.0	9.3	9.7	8.0	8.0	9.0	8.7	9.0
HULL BAY	R25	7.3	7.7	4.3	5.3	9.0	8.7	10.0	8.0	3.3	8.0	6.0	4.7	7.7	7.0	3.7	8.0	8.3	11.0	4.3	7.0	6.0	7.0	8.0	5.7	4.3	7.0	7.3	7.7	7.0	7.3	7.3	7.7
	R27	9.0	4.3	7.0	6.3	8.0	6.0	10.3	6.3	6.7	8.7	6.3	5.3	6.7	7.0	5.7	9.7	9.3	8.3	7.7	7.0	6.3	7.3	7.7	6.0	5.7	8.0	7.7	7.7	7.7	8.3	7.7	7.3
	R28	9.0	6.3	10.0	6.7	9.7	7.3	9.7	8.3	7.3	10.0	6.3	8.3	9.7	6.3	7.3	7.0	8.3	8.0		5.3	6.7	6.7	7.3	7.3	7.0	7.5	7.0	7.3	11.0	7.0	8.0	7.0
	R29	7.3	8.0	8.7	8.0	10.3	6.7	10.0	7.0	7.3	8.7	6.7	9.3	9.7	6.0	6.3	7.0	8.7	8.7	8.0	8.0	7.3	9.0	9.3	6.7	9.7	11.0	8.0	9.3	10.0	11.0	11.0	11.0
	R30	8.0	5.7	7.3	6.3	6.7	5.7	8.3	6.3	5.7	6.0	4.7	5.3	6.7	5.7	5.7	7.0	7.5	7.7	7.7	8.3	7.3	8.3	10.0	8.0	8.0	9.3	9.7	7.7	9.0	11.0	9.3	8.7
	R31	5.3	10.3	8.0	7.3	8.7	9.0	9.0	8.7	6.7	10.0	8.0	10.0	8.7	8.7	6.7	8.7	10.0	9.0	11.0	11.0	9.3	8.0	9.0	7.7	9.7	8.0	4.3	7.7	8.3	8.3	8.3	8.3
	R32	6.0	4.0	6.3	5.0	5.3	2.7	3.7	3.0	4.0	6.0	5.0	4.0	6.3	7.7	8.7	9.3	7.0	7.7	8.0	9.7	8.7	7.7	9.7	7.7	8.0	9.0	8.3	7.7	8.0	8.7	8.7	6.7
	R46				8.0	10.3	7.7	9.0	6.3	7.7	10.0	7.0	10.0	10.0	8.3	6.7	7.3	10.0	9.7	8.0	8.7	9.0	6.7	8.7	7.7	9.3	10.3	7.0	7.3	8.7	8.3	10.0	9.7
	T08	6.0	7.0	4.5	8.0	IND	IND	IND	2.7	4.7	6.0	IND	8.0	IND	8.0	IND	IND	9.0	IND	IND	IND	IND	IND	7.0	7.0	IND	9.7	9.7	7.0	8.3	IND	IND	IND

<3
3 to 5.9
6 to 8.9
9 to 11

Figure 3-27. Matrix of OSI for Boston Harbor regions through time. OSI of 6 is the breakpoint between stress and non-stress benthos (>6 represents good benthic habitat).

By the time the diversion occurred, the organic load within the harbor had declined by orders of magnitude with major consequences for biogeochemical cycling and community structure. The path from anaerobic to aerobic sediments was well documented at Station T02 (Tucker et al. 2014). Through time the transition point from aerobic to anaerobic sedimentary metabolism (Eh = 0 volts, known as the Redox Potential Discontinuity) became deeper in the sediments (Figure 3-29); As did the apparent color RPD in SPI images. The subsurface burrowing amphipod *Leptocheirus pinguis* appeared to be responsible for accelerating the transition to aerobic sediments at Station T02. Its abundance peaked seven years after diversion (2008) and was coincident with the largest increases in the depth of aerobic sediments (Figure 3-29). Prior to the mid-2000s, sediments were more reduced and had higher TOC. By 2010, TOC had significantly declined (Tucker et al. 2014). Bioturbation by subsurface deposit feeders was responsible for much of the improvement in sediment quality following sewage treatment upgrades and diversion to the offshore outfall.

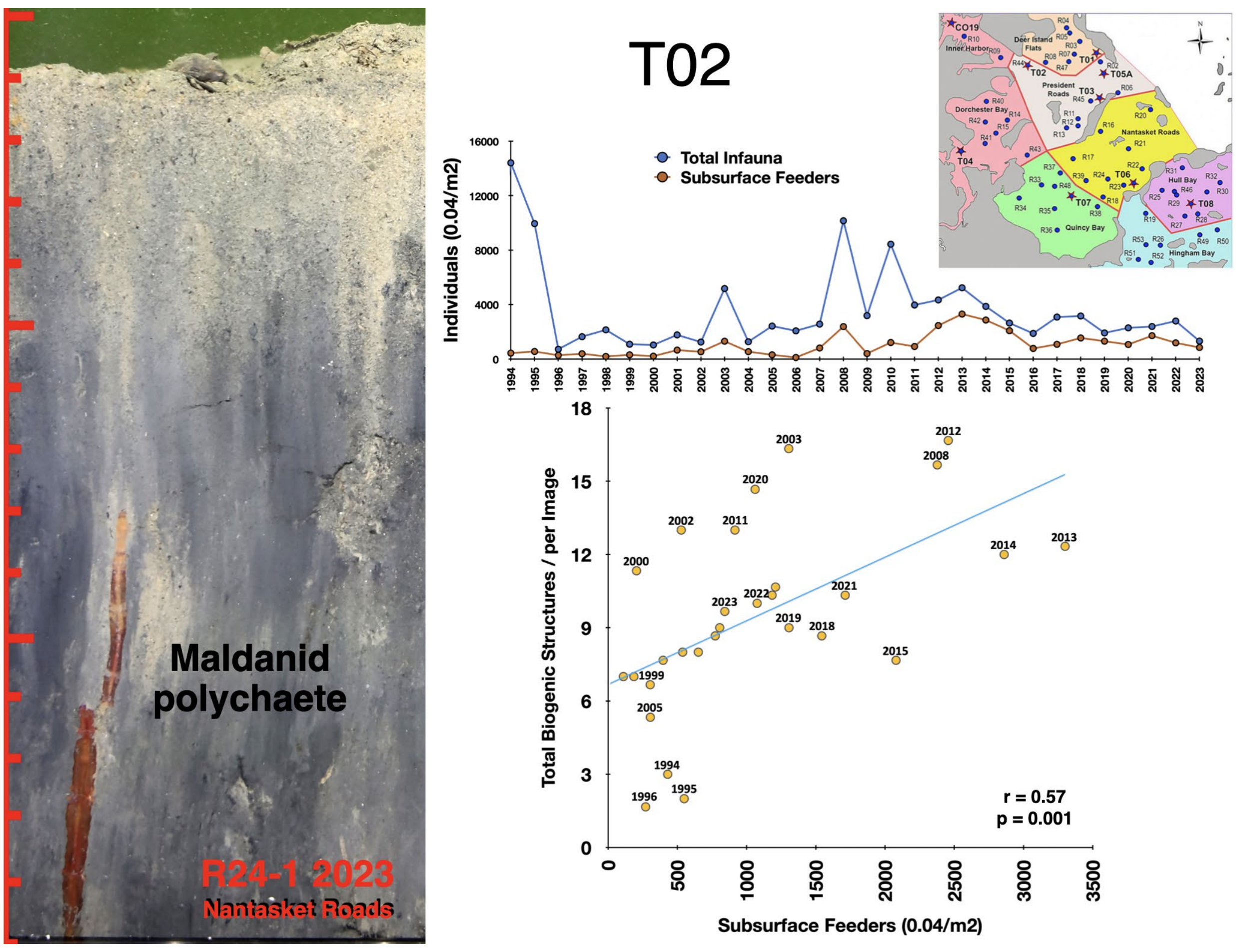

Figure 3-28. Relationship between biogenic structures in SPI and subsurface deposit feeders at Station T02. Example of a large subsurface feeder (maldanid polychaete) from Station R24. Spike in subsurface feeders in 2008 was due to the burrowing amphipod *Leptocheirus pinguis*. Spike from 2012 to 2015 was due to an increase in oligochaetes.

In general, the inner harbor regions improved more through time than the outer harbor regions. The most pronounced improvements in habitat quality occurred between 1992 and 2002 in the inner harbor regions (Inner Harbor/Dorchester Bay, Quincy Bay, and Hingham Bay) and Deer Island Flats (Figure 3-27). The greatest improvements in habitat quality were directly related to improved water quality (Diaz et al. 2008, Taylor et al. 2019). Deer Island Flats was the outer harbor region most affected by wastewater and sludge disposal due to the nearby Deer Island outfalls (Taylor 2010). By 2006, inner to outer harbor gradients were less obvious and primarily maintained by the Harbor’s complex geomorphology and hydrodynamics that control the distribution of sediments (Signell and Butman 1992).

Habitat quality was consistently highest in the other outer harbor regions from 1992 to 2002 with no obvious trends related to improved water quality. In Nantasket Roads, despite wastewater outfalls operating up until April 1998, habitat quality remained high (OSI >6), except in 1994 when seven of the ten stations within Nantasket Roads had OSI vales <6 due to declines in aRPD layer depth. Similarly, in President Roads with outfalls operating up until September 2000 (Taylor 2010), habitat quality was high except in 1999 (6 of 10 stations <6 OSI), 2000 (5 of 10), and 2005 (4 of 10). In 2023, only Station R16 had an OSI <6. Causes for the low OSIs varied but most were related to physical disturbance and shallower aRPD layer depths.

Over the years habitat quality at Station R36 in Quincy Bay was consistently low (OSI range of 2.0 to 4.5). In the early 1990s, kelp fronds were observed and from the mid-1990s to early 2010s shell, pebbles, and encrusting epifauna dominated sediment surfaces with little macroalgae present. By the mid-2010s, various species of filamentous algae became abundant (Figure 3-30). Station R36 had shallow water depth (about 4 m), and sediment surfaces dominated by physical processes throughout the monitoring. Over time, sediments changed from coarse/medium sands to fine sands between early 1990s and late 2000s; and from early 2010s on, sediments consistently appeared to be sandy silts.

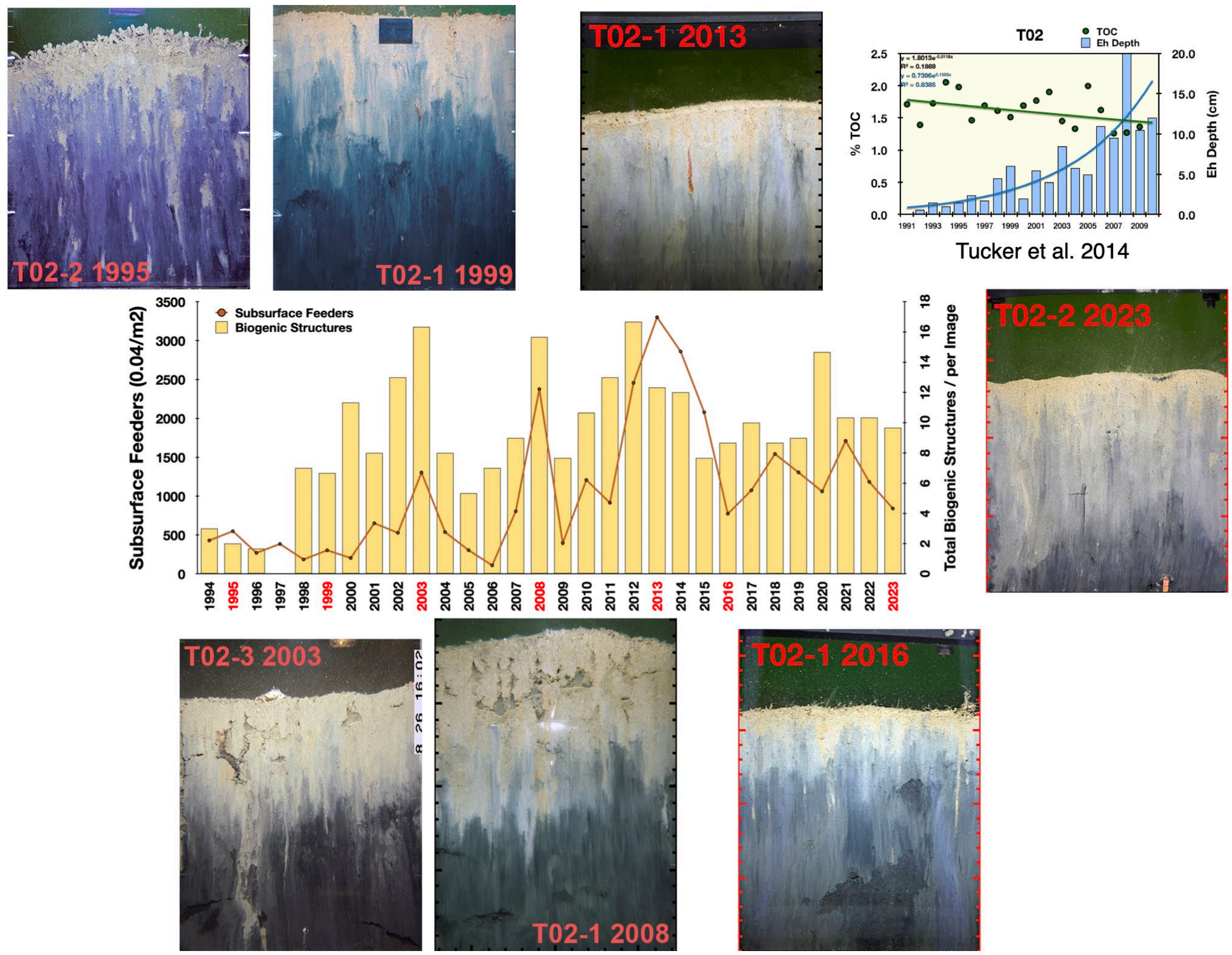

Figure 3-29. Changes in sediment quality at Station T02 over time. Image from 1995 shows *Ampelisca* sp. tube mat. Images from 2003 and 2008 show high levels of bioturbation from the burrowing amphipod *Leptocheirus pinguis*.

Of the ten stations in Nantasket Roads, Station R16 consistently had the lowest habitat quality throughout monitoring. Its average OSI was 5.8 from 1992 to 2023 with a range of 2.5 to 9.0 and was 5.7 in 2023. Both the highest and lowest habitat quality was observed in the 1990s and early 2000s (Figure 3-31). With declining organic and nutrient loading to the harbor, R16 was one of the stations that transitioned from biological to physical processes dominance of the surface sediments. *Ampelisca* spp. tube mats were present until 1997. By the mid-2000s, physical processes dominated and by the early 2010s sediments coarsened from sandy silts to fine-medium-sand. After 2014 sediments became finer and returned to being sandy silts.

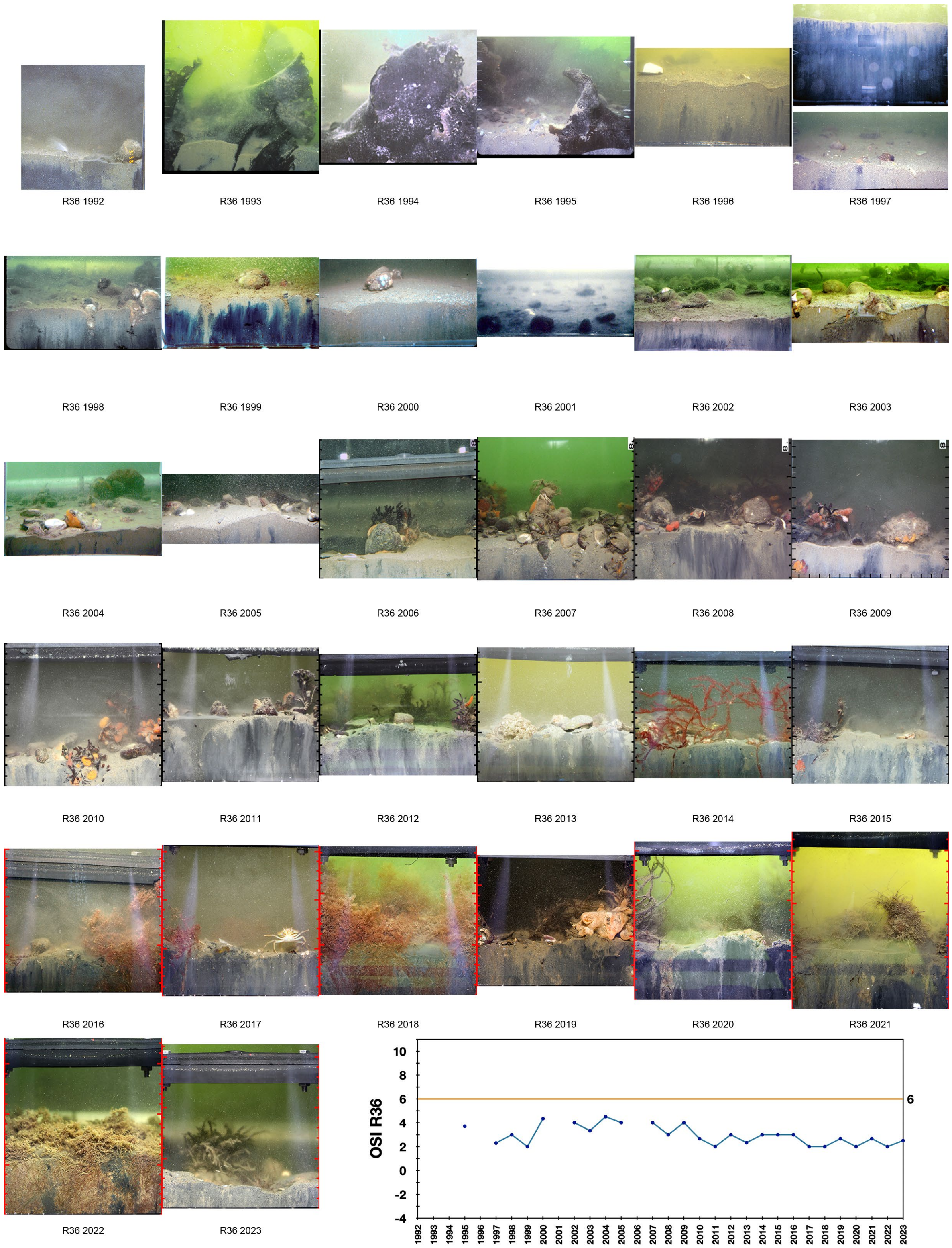

Figure 3-30. Mosaic of selected SPI from Station R36 in Quincy Bay, about 4 m depth. Images are all 15 cm wide. OSI plot is average of SPI replicates. Horizontal line at 6 is the breakpoint between stressed and non-stressed benthos (>6 represents good benthic habitat). Blank year indicates OSI could not be calculated.

Between 1992 and 2023, trends in benthic habitat quality closely followed major transitions in Boston Harbor related to: improvements in wastewater treatment between 1990 and 2000, offshore outfall diversion in 2001, Harbor's geomorphology, and broader regional climatic factors (Rutecki et al. 2024). From 2001 to approximately 2010, habitat quality transitioned from responding to improvements in wastewater treatment and the offshore outfall diversion, to other broader regional driving factors. Since the early 2010s, benthic habitat quality appeared to be driven by either harbor-wide factors such as storms and climate variability, or local-scale factors such as dredging or eelgrass restoration. Climate change has already altered sea level, storminess, wind and wave energy, temperature, and salinity in the Boston region, and is expected to play a larger role in the future (USGCRP 2017, Talke et al. 2018, Voorhies et al. 2018, Reguero et al. 2019, Codiga et al. 2019, Codiga et al. 2023, Werme et al. 2021).

Dredging operations in President Roads, part of the deep draft navigation improvement project (Massport and Corps 2013), temporarily reduced the habitat quality in President Roads. Station R02, off the southwest end of Deer Island was dredged in August 2018 just prior to SPI sampling. A year later, (August 2019), the effects of dredging were still seen in SPI, but there were indications that recolonization occurred, and surface sediments were starting to be reworked by a combination of physical and biological factors. In 2020, Station R02 still showed signs of disturbance, but habitat quality had improved, and by 2021 the OSI had recovered to pre-dredging conditions. However, the OSI then declined in 2022 and again in 2023 (Figure 3-27). The OSI at R02 was 7.3 prior to dredging, dropped to -4.0 in 2018, and has been variable from 2019 to 2023 (3.0 in 2019, 5.0 in 2020, 7.0 in 2021, 5 in 2022, and 3.3 in 2023). The area around Station T05A, also off the southwest end of Deer Island, was dredged sometime after August 2018, but never showed signs of having been dredged (Figure 3-32). It is likely that T05A being in a deep, high tidal current area (Signell and Butman 1992), either did not need to be dredged or the sandy sediment recovered quickly, and benthic habitat quality was not affected in the long-term by dredging. Long-term average OSI at Station T05A was 6.2 and 8.0 in 2023. Station R09, located in the center of the inner harbor channel, was within the dredging boundaries and continued to show signs of recent physical disturbance in 2023. Its location makes it prone to disturbance, likely from dredging and deep-draft ship traffic. Prior to dredging, R09 was about 12 m deep, from 2018 on it was about 18 m deep. Station R09 typically had low OSI and appeared disturbed most years (Figure 3-33). Similar light-gray colored clay sediments have been observed at R09 and at R02 (Figures 3-26 and 3-33).

The eelgrass (*Zostra marina*) bed planted around Station R08 on Deer Island Flats as part of a restoration efforts by MA Division of Marine Fisheries on Deer Island Flats (Evans et al. 2018) was still present in 2023 but did not appear to be healthy. The density of grass was low compared to previous years and was covered with epifaunal growth (Figure 3-34). Prior to 2008, Station R08 was a shallow (about 3 m) fine-sand habitat with macroalgae. Eelgrass beds, in general, serve as biologically complex habitats that were historically more widespread within Boston Harbor (Leschen et al. 2010, Costello and Kenworthy 2011).

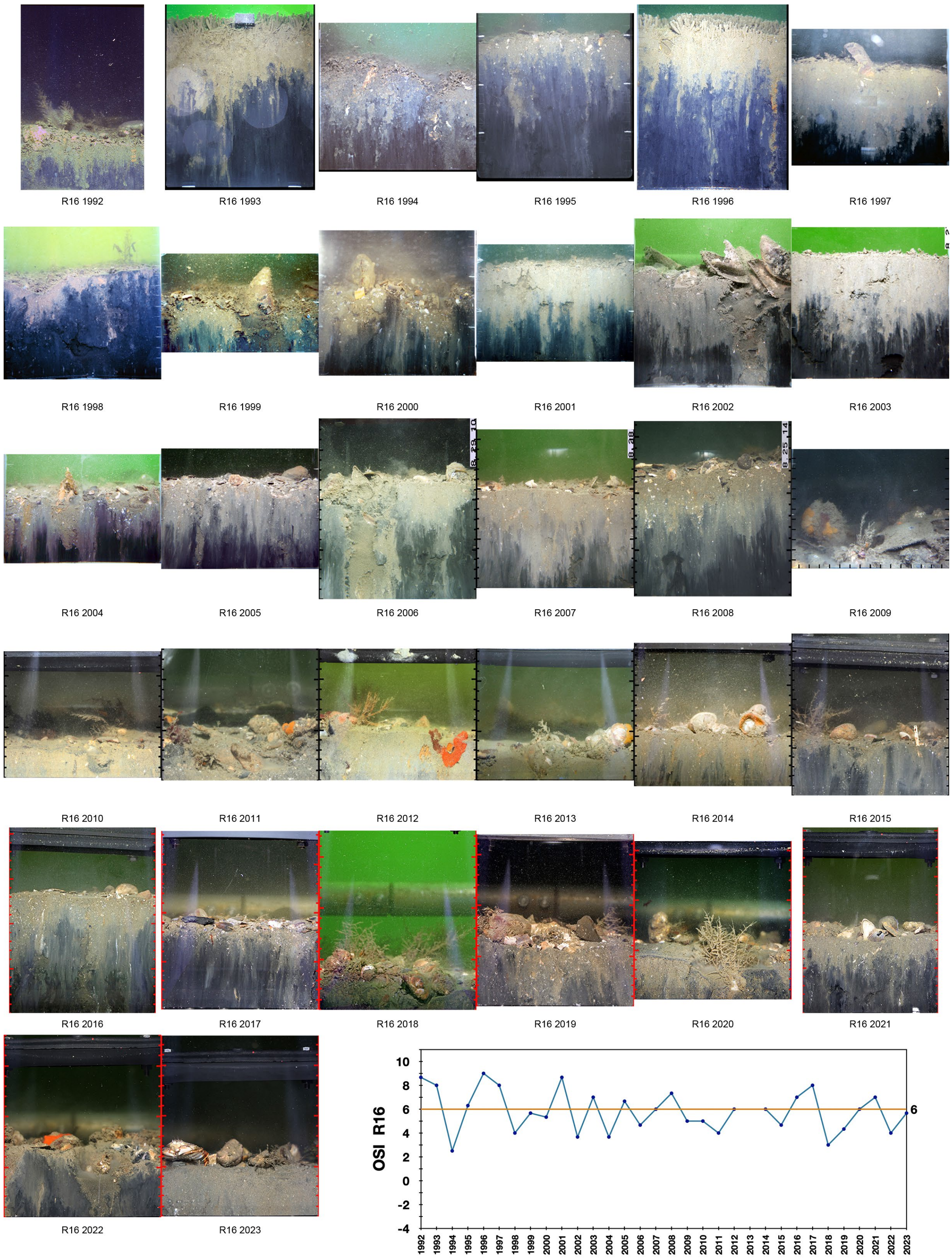

Figure 3-31. Mosaic of selected SPI from Station R16 in Nantasket Roads, about 8 m depth. Images are all 15 cm wide. OSI plot is average of SPI replicates. Horizontal line at 6 is the breakpoint between stressed and non-stressed benthos (>6 represents good benthic habitat). OSI could not be calculated in 2013.

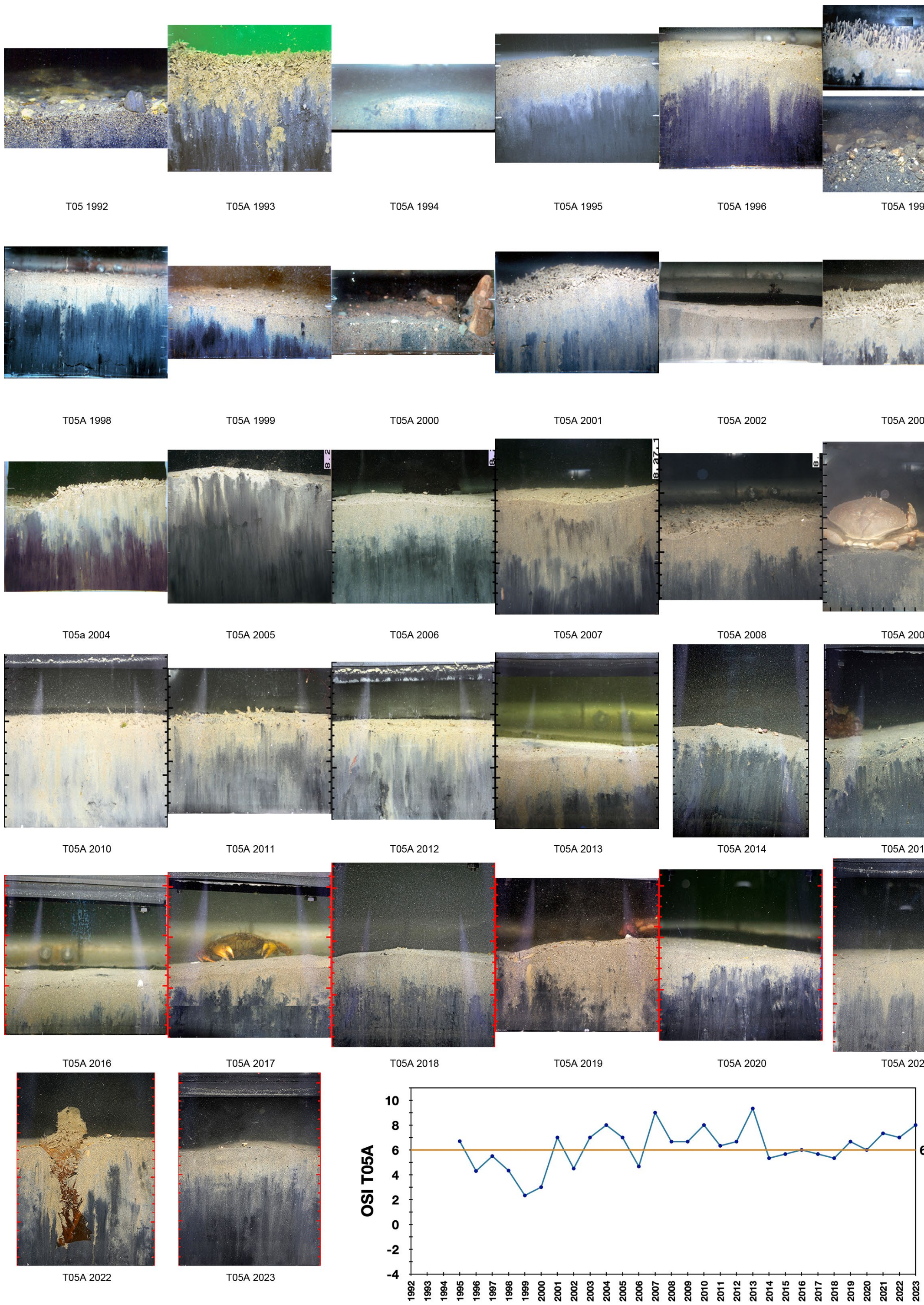

Figure 3-32. Mosaic of selected SPI from Station T05A in President Roads, about 18 m depth. The station may have been dredged in 2018. Images are all 15 cm wide. OSI plot is an average of SPI replicates. Horizontal line at 6 is the breakpoint between stressed and non-stressed benthos (>6 represents good benthic habitat).

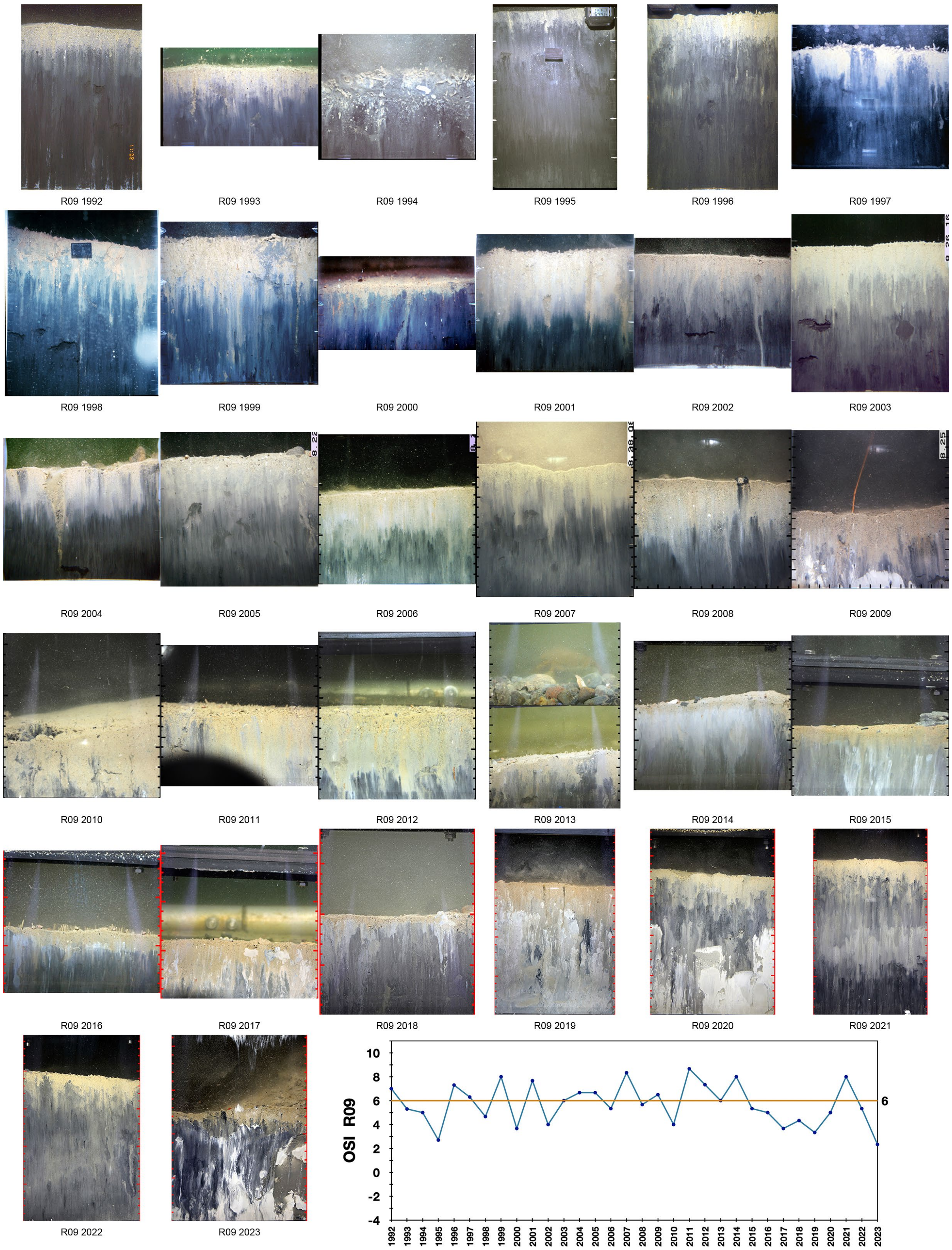

Figure 3-33. Mosaic of selected SPI from Station R09 in Inner Harbor, about 18 m depth. The station was dredged in 2018. Images are all 15 cm wide. OSI plot is average of SPI replicates. Horizontal line at 6 is the breakpoint between stressed and non-stressed benthos (>6 represents good benthic habitat).

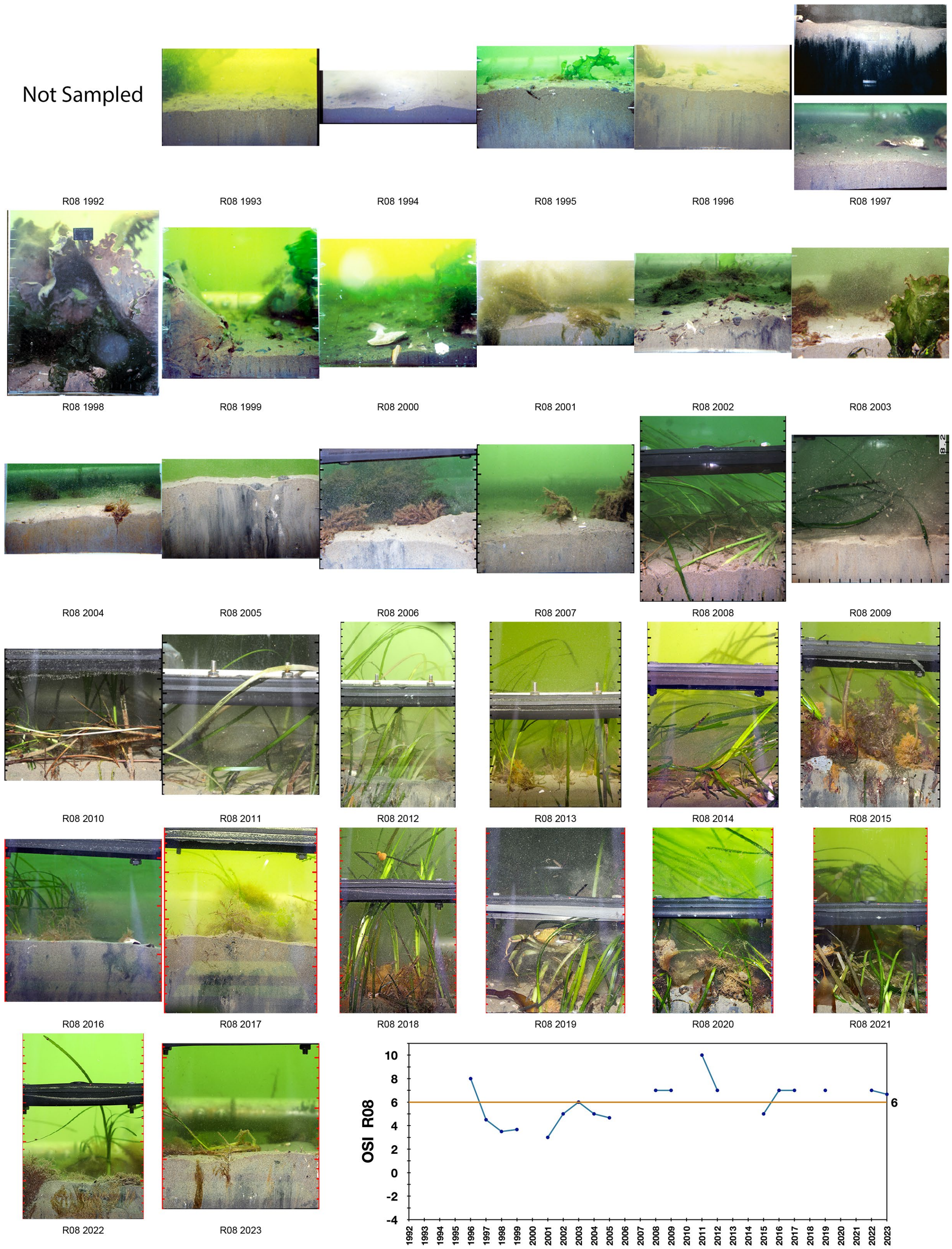

Figure 3-34. Mosaic of selected SPI from Station R08 on Deer Island Flats, about 4 m depth. Eelgrass bed was planted in 2007/2008. Images are all 15 cm wide. OSI plot is average of SPI replicates. Horizontal line at 6 is the breakpoint between stressed and non-stressed benthos (>6 represents good benthic habitat). Blank year indicates OSI could not be calculated. Scale on side of images is in cm.

3.3.2 Sediments

Bed Roughness. Bed roughness refers to the variabilities in the surface texture of a given substrate. Over the study period there has been a shift in the relationship between biological and physical processes structuring bed roughness (See Figure 3-35 for examples). The trend away from biological processes that dominated in the 1990s to physical processes that have dominated since the early 2000s correlates with major changes in organic and nutrient inputs to the Harbor, and to changing climatic conditions (higher temperatures, higher salinity, and increased storminess). In 2023, physical processes continued to structure surface sediments (Figure 3-36).

During post sludge disposal and implementation of full primary treatment (1992 to 1997) physical processes dominated as levels of organic and other toxic substances were likely too high (Hyland et al. 2003, 2005) for establishment of species that create biogenic structures. The influence of biological processes was strongest from 1998 to 2000 coinciding with implementation of full secondary treatment and declining organic production in the Harbor. The dominance of physical processes returned after the Deer Island outfall was diverted offshore (starting in 2001) and has continued through to 2023. In 2023, no station had a primarily biologically dominated bed roughness, 5 stations had a combination of biological and physical processes dominating bed roughness, and 56 were primarily dominated by physical processes.

The transition from biological to physical processes was mainly driven by declining organic and nutrient inputs, which lead to declining primary production. Both factors resulted in less food to support high population densities of infauna. This was most obvious in the declining number of stations with *Ampelisca* spp. tube mats, which require 120 to 240 g C m^2 per year to support populations at mat densities (Diaz et al. 2008). The magnitude and timing of the switch to dominance of physical processes was related to Harbor region. President Roads and Nantasket Roads were the last regions to switch in the late 2000s (Figure 3-36).

For the whole Harbor, the probability of bed roughness being dominated by physical processes through time was associated with both declining organic loading (Taylor et al. 2019) and an increased sum of winter-period IWindS storms (Rutecki et al. 2019). Declining organic production, through its influence on biology, and increased winter-period storm strength through its influence on physical bottom stress, had the strongest influences on bed roughness. Regionally, the western inner harbor (Inner Harbor, Dorchester Bay, Quincy Bay, and Hingham Bay) along with Deer Island Flats were less likely to have biologically dominated sediment surfaces. Outer harbor regions (President Roads, Nantasket Roads, and Hull Bay) were most likely to be biologically dominated and maintained biological dominance longer (Figure 3-36). Wind and tidal currents are the main physical factors that influence both sediment grain-size and bed roughness with bioturbation and biogenic structures being the main biological factors that influence bed roughness (Rhoads and Young 1970, Nowell et al. 1981, Trembanis et al. 2004).

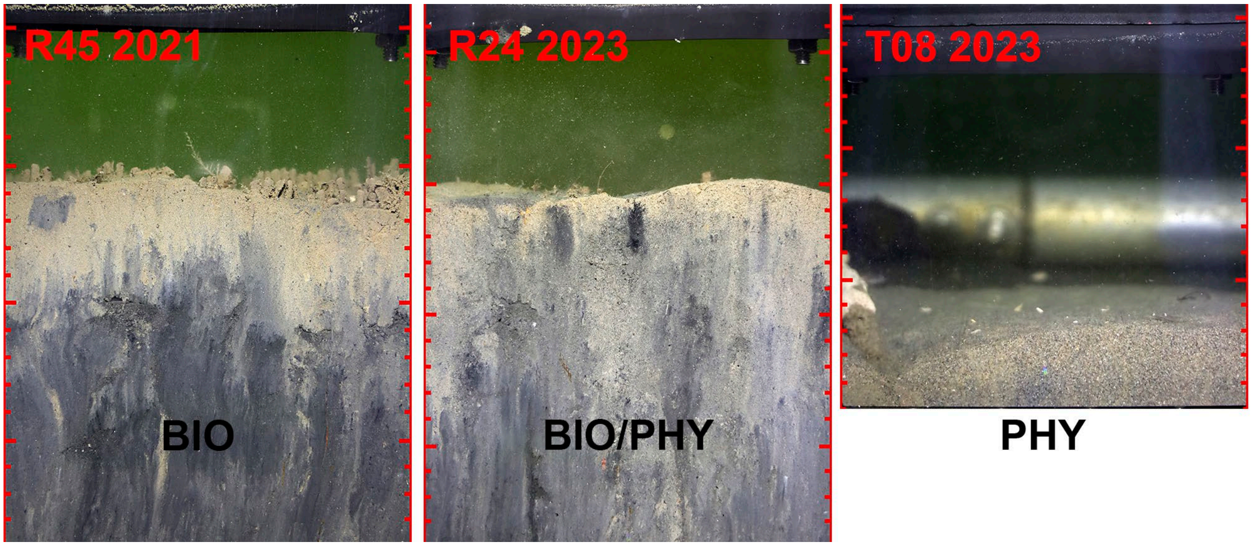

Figure 3-35. Examples of bed roughness being dominated by biological (BIO) and physical (PHY) processes. None of the station were biologically dominated in 2022. Station R45, from 2021, is in President Roads, R24 is in Nantasket Roads, and T08 is in Hull Bay. Scale on side of image is in cm.

Grain-Size. Overall, sediments in 2023 were similar to 2022. At most Harbor stations estimated modal grain-size from SPI was consistent from year to year with a fraction of stations either coarsening or fining in modal grain-size from one year to the next (Rutecki et al. 2024). In 2023, only Station R39 in Nantasket Roads coarsened slightly in modal grain-size going from silt-clay sediments to fine-sand-silt-clay. Layered sediments were observed at four stations. Station R29 in Hull Bay and T01 in Deer Island Flats appeared to have a fine-sand layer on top of fine-sand-silt sediments. Station R02 in President Roads and R09 in Inner Harbor appeared to have a silt-clay layer on top of clay sediments, likely related to dredging in 2018.

In 2023, median grain-size from grab samples at the T-Stations became finer compared to 2022 while SPI estimated modal grain-size remained unchanged. The fining of sediments in 2023 did not change the long-term coarsening of median grain-size at five of the eight stations (T01, T05A, T06, T07, and T08) by about 0.2 to 0.8 Phi per decade (Figure 3-37; linear regression, $n = 29$, $p = <0.001$ for all 5 stations). Stations T02, T03 and T04 were variable in median grain-size but no significant long-term trend was detected. Stations T01, T05A, and T08 coarsened one Phi unit, Station T06 coarsened by two Phi units, and Stations T07 by 0.5 Phi unit.

Over time Station T06 in Nantasket Roads, near the old Nut Island outfall, changed from fine-sand-silt (about 4.5 Phi) to fine-sand (about 2.5 Phi). Beginning in 2008, sediments at T06 were consistently fine-sand (Figure 3-38). Station T05A in President Roads, near the old Deer Island outfall, transitioned from very-fine-sand (3 to 4 Phi) to fine-medium-sand (about 2 Phi). Starting in 2014, sediments at T05A were consistently fine-medium-sand (Figure 3-39).

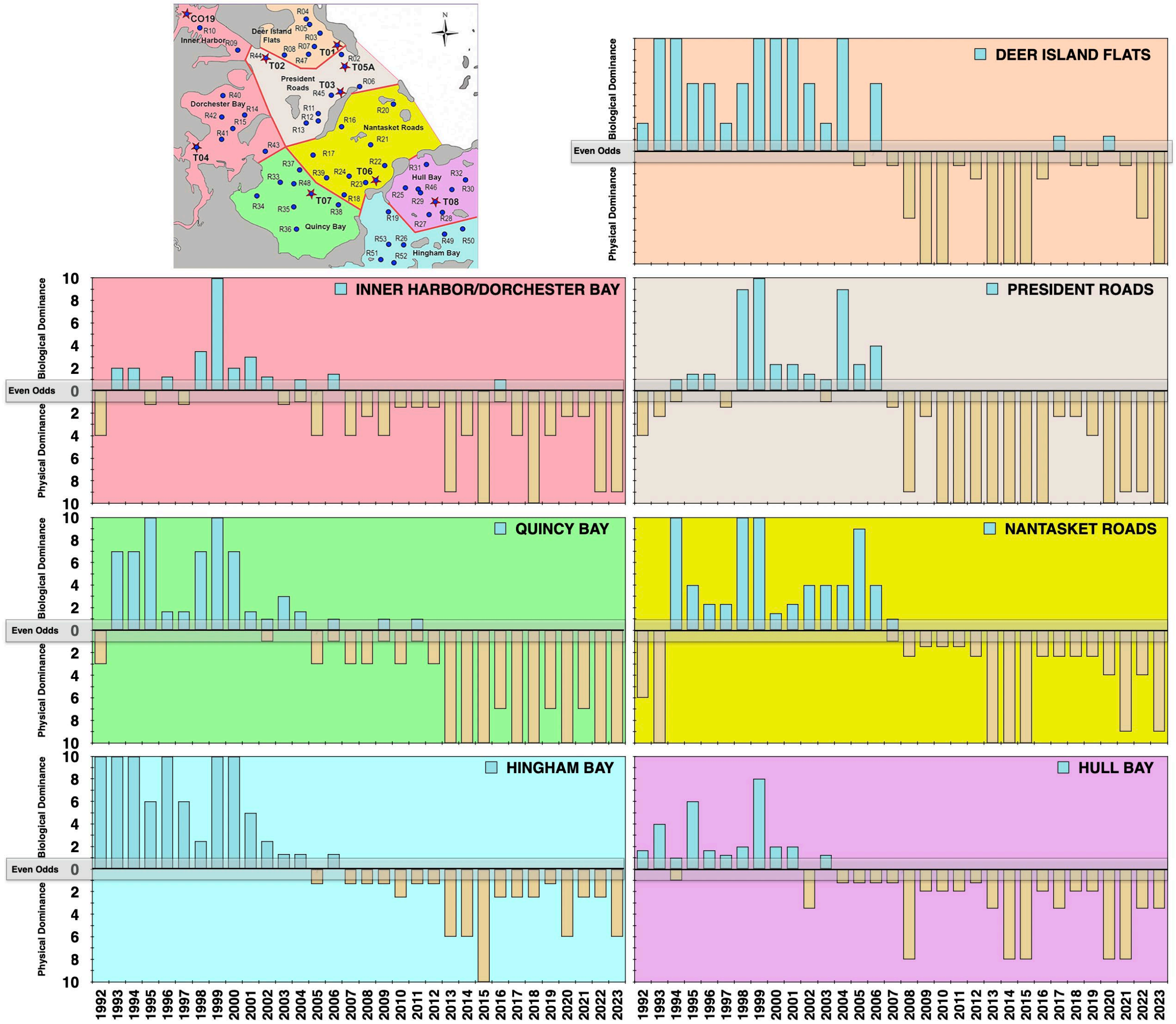

Figure 3-36. Odds of sediment surface being dominated by physical or biological processes by Harbor region. Gray area represents even odds. See Figure 3-12 for examples.

Along with the coarsening of sediment grain-size there was a decline in the percent total organic carbon (TOC) in the sediments at most T-Stations, even when the percent fines (Silt+Clay) were controlled for (Figure 3-40). Linear trends in TOC were detected at all stations except T04 and T07. Stations T01 and T08 had the largest declines in normalized TOC (% TOC / % fines; linear regression, n = 33, p = <0.005 for both stations). Even Station CO19 exhibited a decline in TOC over the study period (linear regression, n = 23, p = 0.002).

The decline in TOC at T01 was related to reduced inputs of TOC and not changes in percent fines. Even as median grain-size coarsened, there was no downward trend in percent fines at T01. The reduced organic loading over time at T01 can be visualized in SPI through the changing color of sediments. Early 1990s' sediments were darker with shallow aRPDs. By the early 2000s sediments were lighter in color and aRPD was deepening, an indication of increased faunal activity and reduced carbon loading to sediments. By the 2020s the change in grain-size at T01 was obvious in SPI (Figure 3-41).

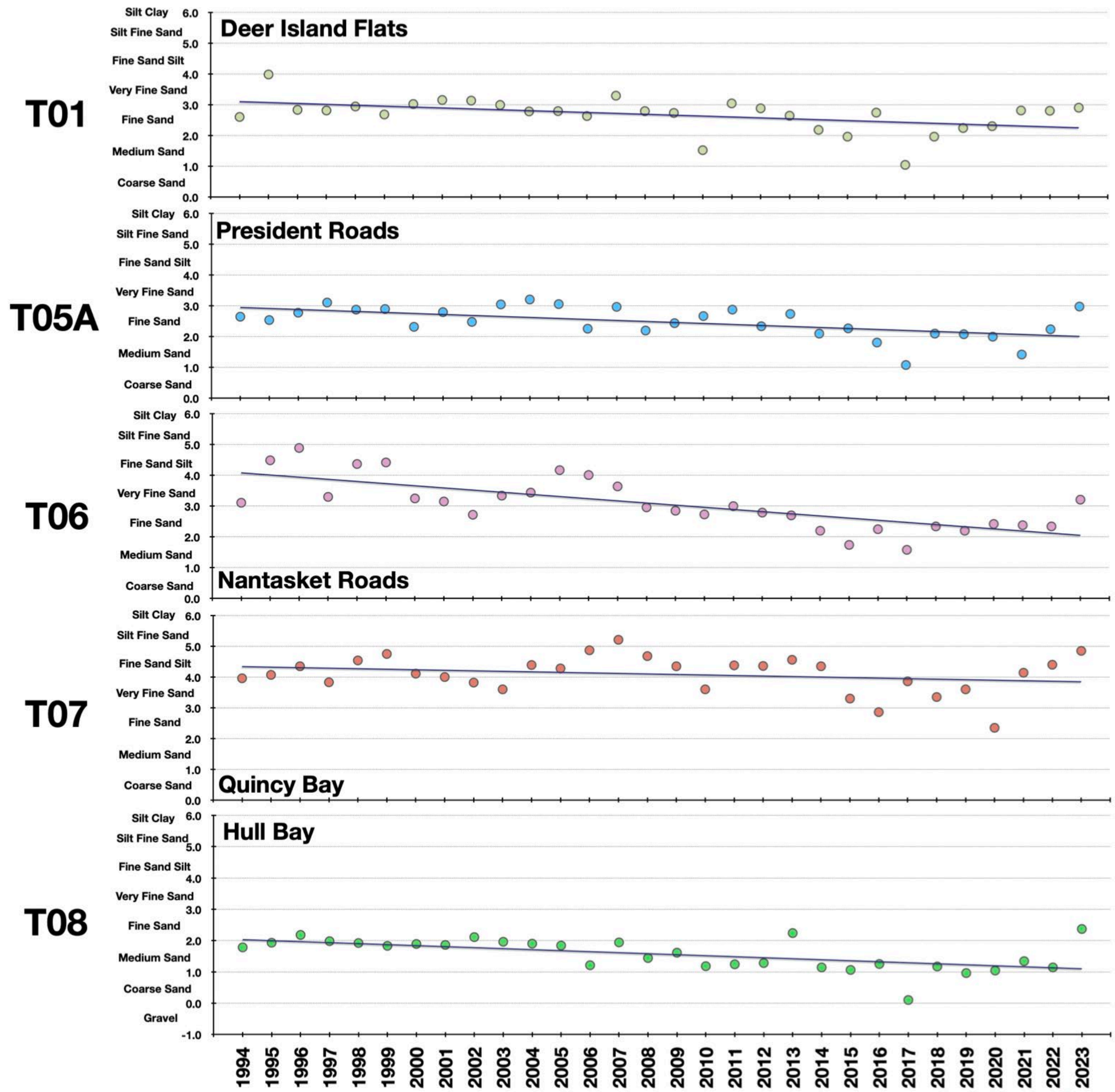

Figure 3-37. Long-term trend in median grain-size (from grab sediment analysis). Regression line indicates significant coarsening of sediment through time. Phi range for sediment classes: 4-8 for silt, 3-4 for very-fine-sand, 2-3 for fine-sand, 1-2 for medium-sand, 0-1 for coarse-sand.

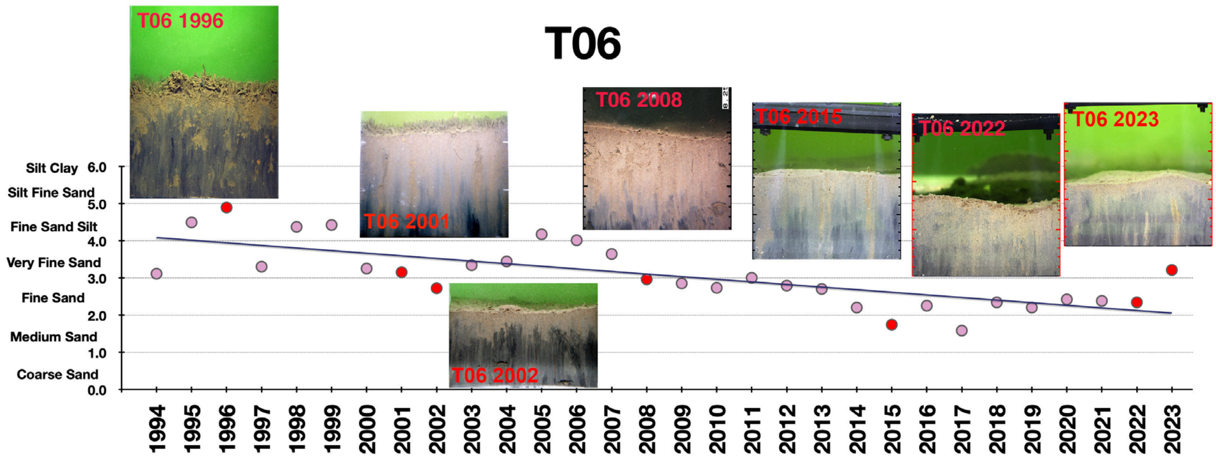

Figure 3-38. Median sediment grain-size trend at Stations T06 in Nantasket Roads. Red symbols have example SPI for the year indicated. Scale on side of images is in cm.

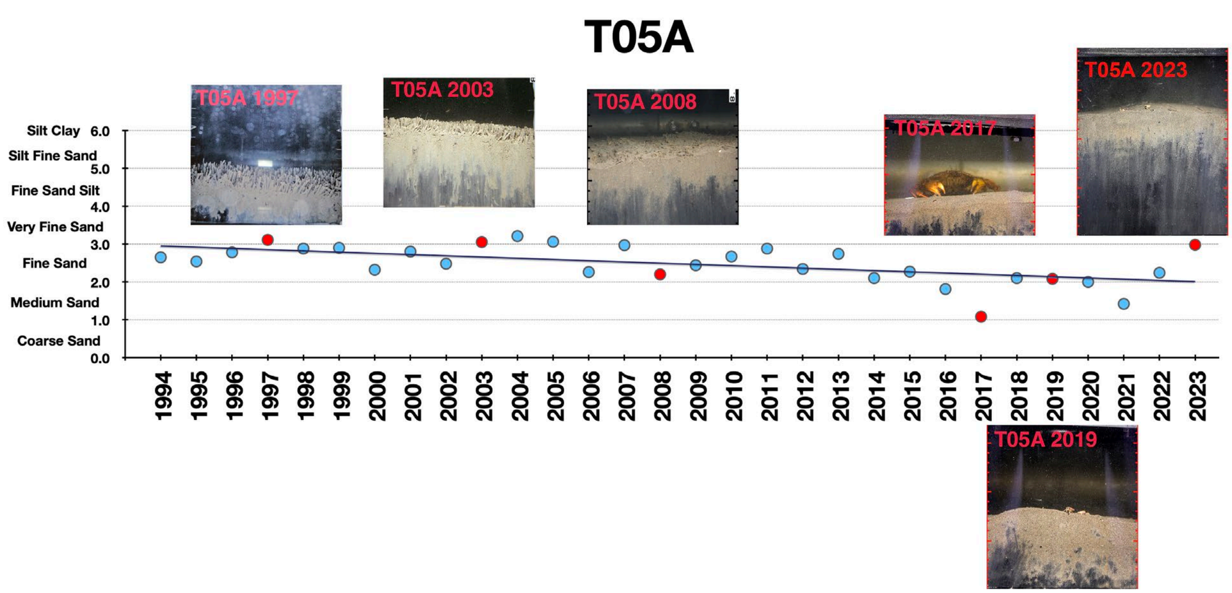

Figure 3-39. Median sediment grain-size trend at Stations T05A in President Roads. Red symbols have example SPI for the year indicated. Scale on side of images is in cm.

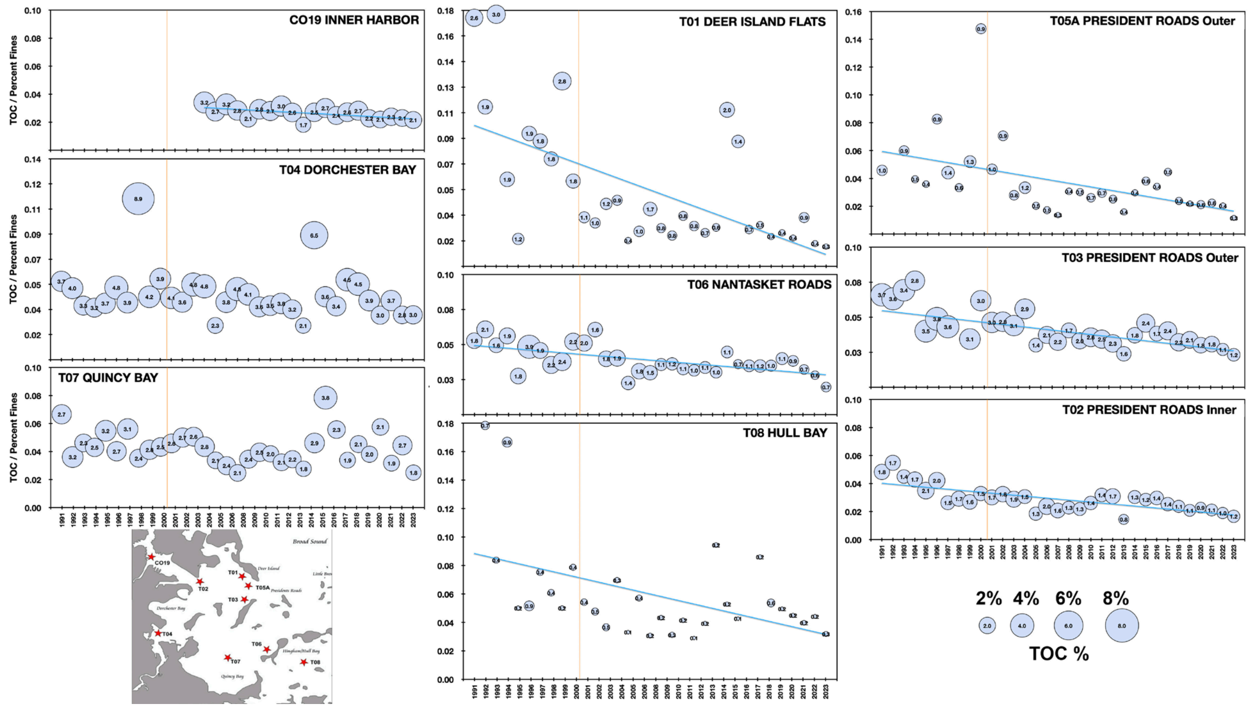

Figure 3-40. Trends in percent total organic carbon (TOC) controlling for percent fines (Silt+Clay) based on linear regression. Only significant trend lines are shown. Size of circles is proportional to percent TOC. Vertical orange line in September 2000 represents diversion of wastewater discharge from Boston Harbor to Massachusetts Bay.

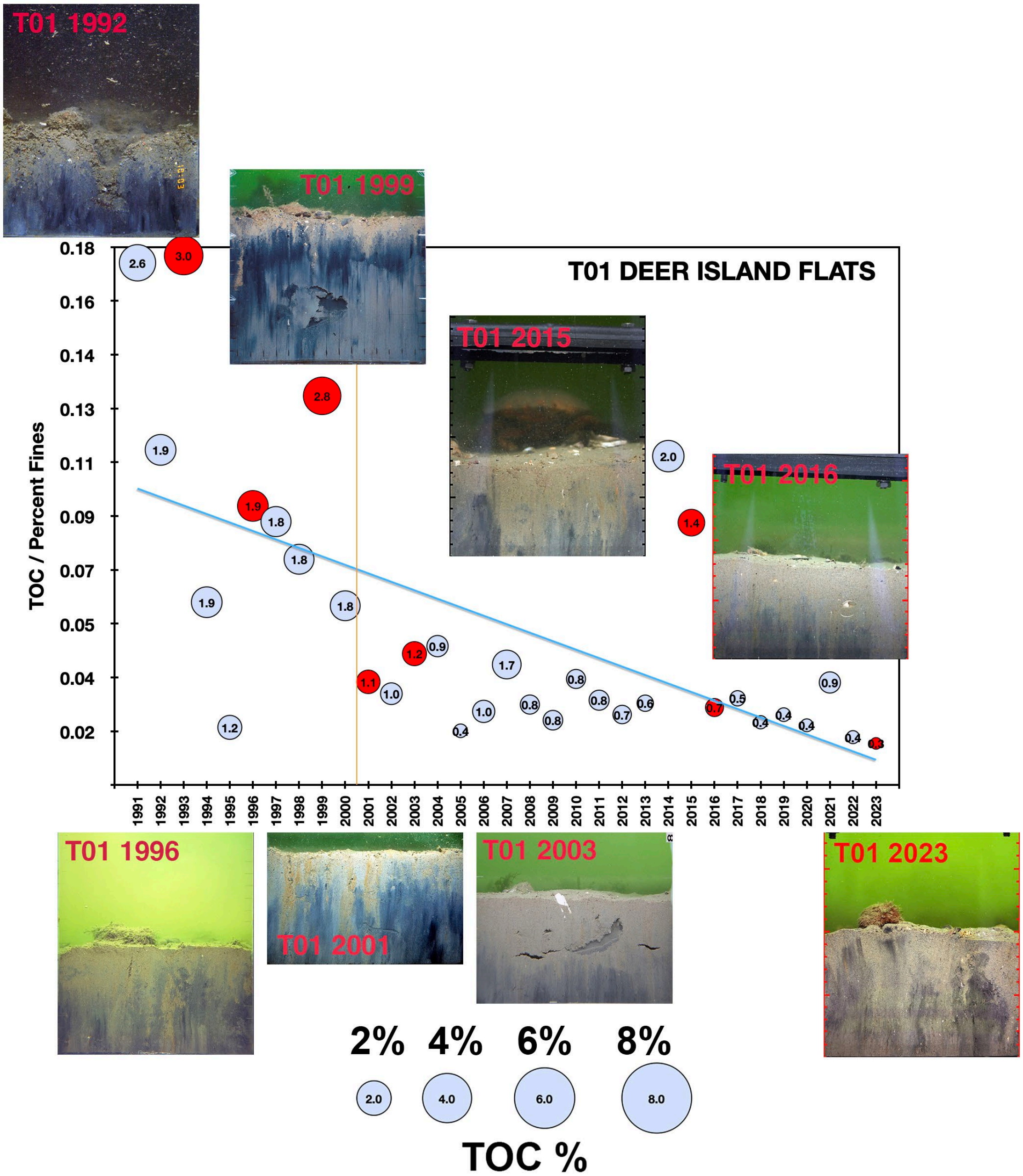

Figure 3-41. Trend in percent total organic carbon (TOC) controlling for percent fines (Silt+Clay) at Station T01 in Deer Island Flats, based on linear regression. Size of circles is proportional to percent TOC. Red circles have example SPI for the year indicated. SPI are 15 cm wide. Vertical orange line in September 2000 represents diversion of wastewater discharge from Boston Harbor to Massachusetts Bay.

3.3.3 *Ampelisca* spp. Trends

Ampelisca spp. tube mats were not observed at any of the 61 stations for the second year in a row (Figure 3-42). Since 1989 there have only been three other years with no tube mats, 2005, 2013, and 2022 (SAIC 1990, Rutecki et al. 2023). The highest abundance of *Ampelisca* spp. tubes in 2023 was at Stations R45 and T03 both in President Roads, where one replicate image almost reached the density level of a mat of tubes (Figure 3-43). Abundance of *Ampelisca* spp. in grab samples was also low in 2023, about half of the 2022 abundance. Of the 183 replicate SPI images for the 61 stations, 67 had *Ampelisca* spp. tubes in 2023. This is a reduction from 2022 when 97 replicate images had at least a few *Ampelisca* spp. tubes.

Harbor-wide abundance of *Ampelisca* spp. tubes was low; most stations had 1 to 17 *Ampelisca* spp. tubes per image. From the grab samples, only Stations T03 and T06 had more than 10 individuals per grab (0.04 m^2). Station T03, in President Roads, has consistently had the highest density of *Ampelisca* tubes over time. Station T03 has also had the highest occurrence of *Ampelisca* spp. tube mats (81% of years from 1992 to 2023). Stations R45 and R20 have also had high occurrence of *Ampelisca* spp. tube mats (62% of years).

Long-term occurrence of *Ampelisca* spp. tubes is related to both particulate organic carbon (POC) loading (Diaz et al. 2008) and possibly the intensity of winter period storms (Rutecki et al. 2019). As POC loading declined from 1991 to 2001, tube mats also declined from about 60% of stations to 0% in 2005, with a lag of about four years (Figure 3-44). The periods of high, but declining, POC loading (Periods I, II, and III in Taylor 2010) were also coincident with six of the ten lowest storm years (based on sum of winter period IWindS, Codiga et al. 2019) that would have favored tube-building species like *Ampelisca* spp. Between 2006 and 2017 when lower annual organic loading and production occurred, mat observations peaked twice, occurring at about 30% of stations. This was also coincident with nine of the top ten storm years occurring between 2006 to 2020. Although 2021 and 2022 were among the lowest storm years, tube mats did not expand. No mats were observed in 2022 or 2023 (2023 was likely not a stormy year, Geyer personal communication).

Beginning in 2005, the combination of lower food availability (internal and external organic sources) and increasing storminess were the likely factors leading to lower mat numbers and higher variability of mats from year to year. Diaz et al. (2008) estimated that the optimal annual organic load for maintaining large areas of amphipod tube mats was around 500 g C m^{-2} yr^{-1}. Above and below this level the area of tube mats in Boston Harbor declined. From 1990 to 2000, total organic load in the Harbor declined from over 1,000 g C m^{-2} yr^{-1} to about 500 g C m^{-2} yr^{-1}, and between 2003 to 2009 it averaged about 300 g C m^{-2} yr^{-1} (Taylor et al. 2019). While not a measure of primary production, the annual average phytoplankton abundance measured at the mouth of the Harbor (Station F23 south of Deer Island, Libby et al. 2023, Borkman 2023) was well below the long-term average for 2022 and 2023. For the monitoring region, phytoplankton abundance has been trending downward since 2008 (Libby et al. 2023, Borkman 2023). It is likely that increasing storminess across the region, which would tend to disrupt tube mats, is also a factor in fewer stations with *Ampelisca* spp. tube mats. However, the absence of mats in 2022 and 2023 indicates that availability of food may be more important to establishing dense populations of *Ampelisca* spp. than storminess.

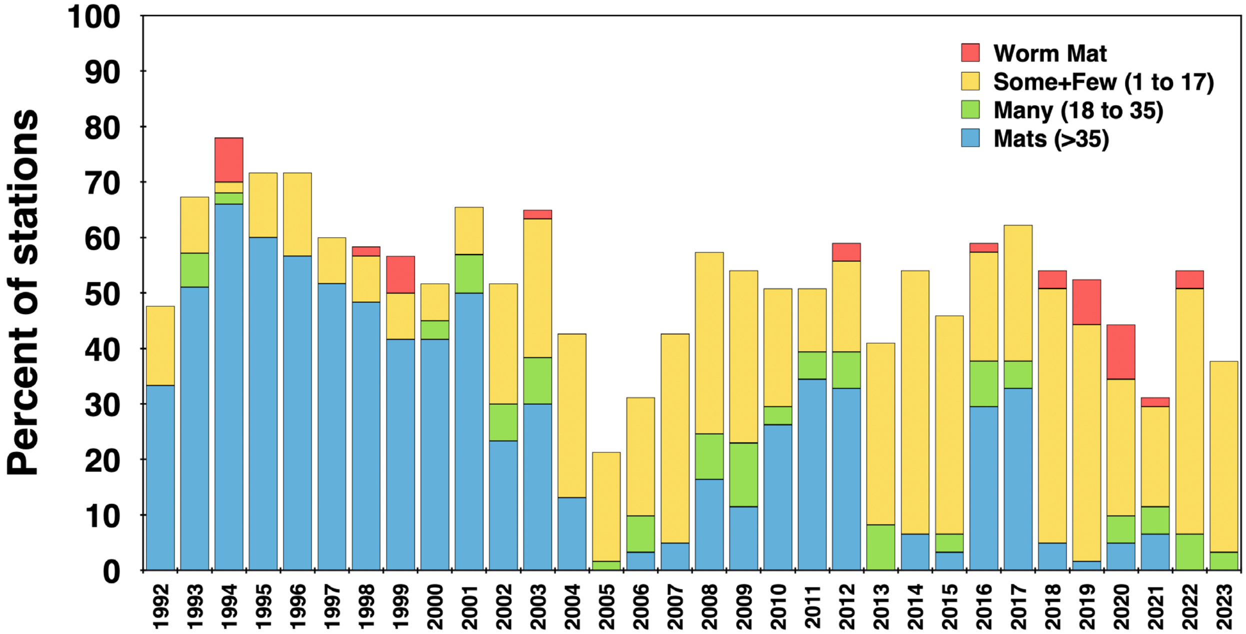

Figure 3-42. Histogram of *Ampelisca* spp. tubes and tube mats, and worm tube mats for all 61 Harbor stations.

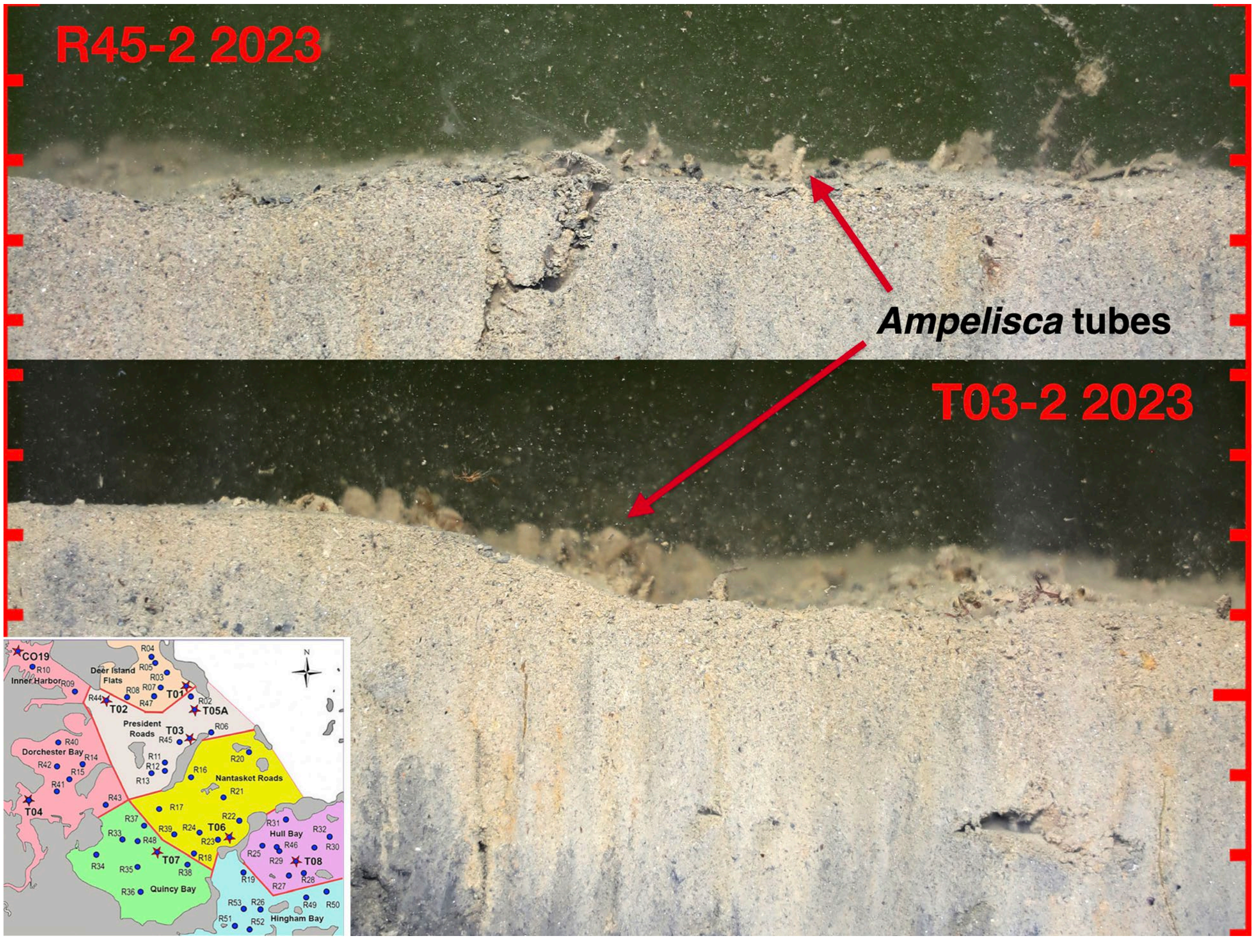

Figure 3-43. Highest density of *Ampelisca* spp. tubes for 2023. Station T03 and R45 are near each other in President Roads. Scales on both images are in cm.

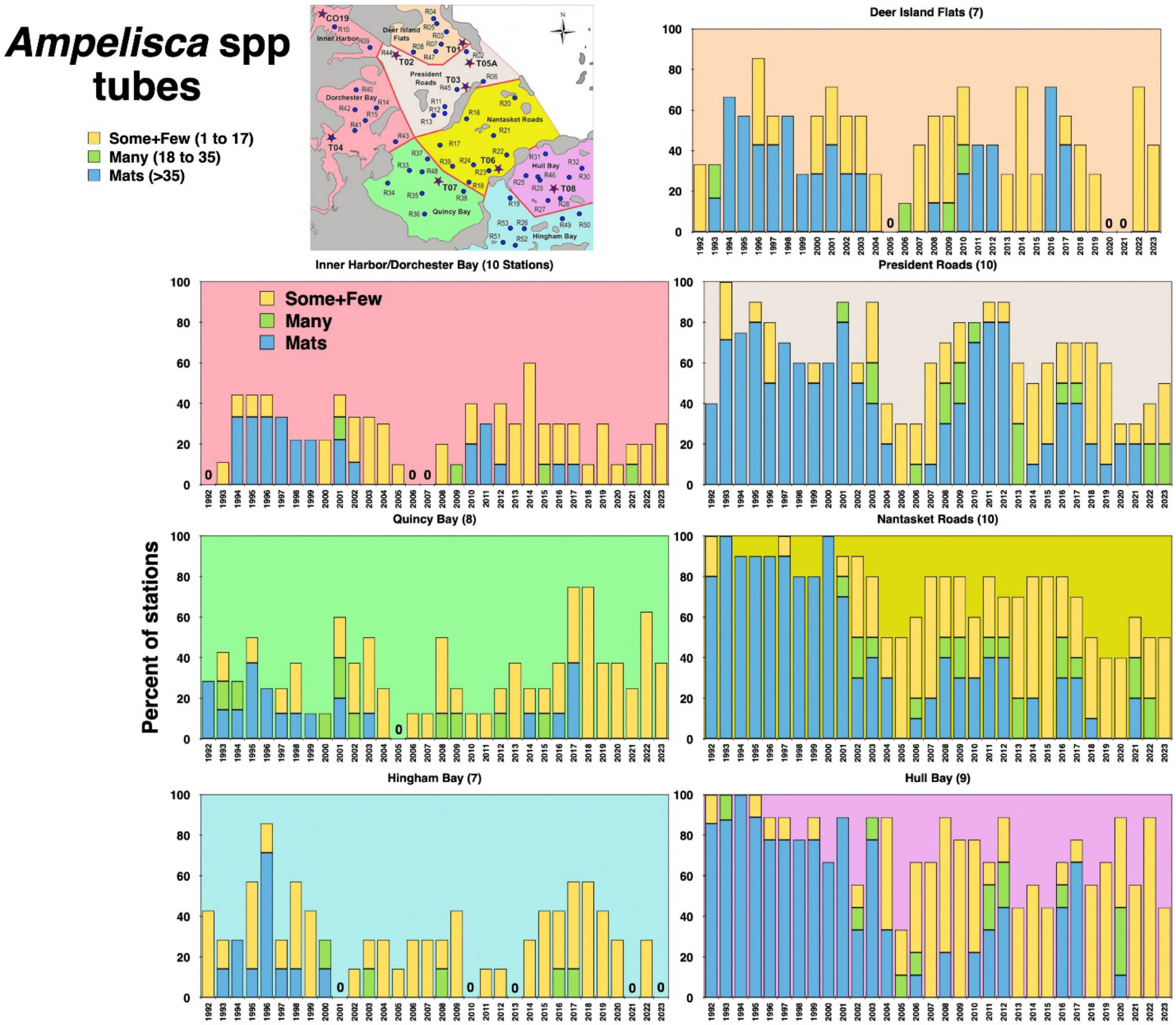

Figure 3-44. Histogram of percent stations with *Ampelisca* spp. tubes and tube mats by Harbor regions.

3.3.4 SPI Summary

- Overall, assessments using the Organism Sediment Index (OSI) indicate that benthic habitats (including assessments of infauna and sediments) are in good ecological condition.
- Consistent with previous findings, impacts from the 2018 dredging were obvious at Stations R02 and R09, but not at Station T05A.
- Physical processes continue to dominate sediment surfaces throughout the Harbor. The Harbor sediment surface flipped from a biological dominance to physical dominance in the mid-2000s. Factors that lead to this change were a combination of loading reductions and possibly changing climate conditions. While gradual, this change in state was the major event for the Harbor benthic habitats over the 32-years of monitoring.
- By the 2000s, sediment geochemistry also shifted from more anaerobic to more aerobic. In 2023, sediments continued to appear oxic[1], with no indication of organic buildup at any of the 61 stations.
- Abundance of *Ampelisca* spp. tubes was low. Tubes were observed at 38% of stations (23 of 61). There were no *Ampelisca* spp. tube mats for the fourth time (2005, 2013, 2022, 2023) since 1991. The decline in tube mats is directly related to lower organic and nutrient loading, and a key factor in the transition to a dominance of physical processes.
- The eelgrass bed planted in the area of Station R08 in 2008 does not appear to be healthy.
- The inner to outer harbor gradient remains prominent primarily due to:
    - Hydrodynamics
    - Sediment grain-size, and
    - Sediment organic content.

[1] Dissolved oxygen condition >0.5 mg/L

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 (see Tucker et al. 2014 and Taylor et al. 2020 for details on sediment recovery). Physical and biological properties of the soft substrate in Boston Harbor in 2023 exhibited minor changes from recent years but were consistent with longer-term trends (Rutecki et al. 2023). 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 have 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 2023 survey are consistent with the recovery of benthic habitats from decades of inadequately treated sewage discharges.

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