Trends in sediment contaminant concentrations in northern Dorchester Bay and other Boston Harbor stations, 1990-2002

Massachusetts Water Resources Authority

Environmental Quality Department
Report ENQUAD 2005-01

Citation:

Lefkovitz L, Wisneski C and Hunt C. 2006. **Trends In Sediment Contaminant Concentrations In Northern Dorchester Bay And Other Boston Harbor Stations, 1990-2002**. Boston: Massachusetts Water Resources Authority. Report ENQUAD 2005-01. 123 pp.

TRENDS IN SEDIMENT CONTAMINANT CONCENTRATIONS IN NORTHERN DORCHESTER BAY AND OTHER BOSTON HARBOR STATIONS, 1990-2002

submitted to

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March 2006

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EXECUTIVE SUMMARY

Combined sewer systems were designed to collect sewage, as well as stormwater runoff, and to transport both to treatment facilities. During heavy rains, overflows from these combined systems—called combined sewer overflows (CSOs)—discharge a mixture of sewage and storm runoff directly into local waters, potentially affecting public health. In 1997, the Massachusetts Water Resources Authority (MWRA) agreed to plan and build projects to control CSOs hydraulically connected to the Deer Island Treatment Plant. As of March 2002, just before the sampling described in this report, MWRA has completed 13 of the 25 projects proposed under the original CSO Control Plan. These completed projects include, among others, the upgrading of five CSO treatment facilities (Fox Point, Commercial Point, Cottage Farm, Prison Point, and Somerville Marginal), two sewer separations, the closing of 21 CSO outfalls, the installation of floatable controls, and two hydraulic relief projects. These projects have decreased CSO discharges. Several other projects are currently in the construction or design phases. The overall effect of these ongoing improvements has been the decrease of CSO discharges from 3.3 billion gallons per year in 1988 to 1.0 billion gallons per year in the first quarter of 2002 (MWRA, 2003).

The main goals of this study were to assess the effects of specific CSOs on the concentrations of pollutants in the sediments around the CSOs, and to determine if sediment concentrations of these pollutants at specific stations in Dorchester Bay have declined among the sampling years 1990, 1994, 1998, and 2002. Two areas of Dorchester Bay were studied: (1) the Old Harbor area, which may receive direct discharge from seven untreated CSOs (BOS-81 through BOS-87), and (2) the area near Fox Point (BOS-89) and Commercial Point (BOS-90) CSOs, which may receive direct discharge from these two CSO treatment facilities and from BOS-88. The Fox Point/Commercial Point area at one time received indirect discharges from two CSO outfalls located in the Neponset River; however, these CSOs were closed as of June 2000. Several other Boston Harbor stations, outside the Dorchester Bay area, were included in the 2002 sampling cruises to compare sediment quality at locations not directly impacted by the CSOs.

Because there are many sources of contaminants to Boston Harbor, it is usually difficult to measure the relative impact from each source. To help differentiate the pollution due to treatment plants and CSO discharges from other confounding point and nonpoint contamination sources, the microbial indicator, *Clostridium perfringens*, and sewage tracers, such as linear alkyl benzenes (LABs) and coprostanol, were included in the monitoring. Organic and metal contaminants were measured to help associate contaminated sediments with specific CSOs.

The data generated by this study were compared to data generated by similar studies performed in 1990, 1994, and 1998, and to other historical data to assess if contaminant concentrations have changed in recent years. In all surveys, sediments were collected near to (“Near” stations) and far from (“Far” stations) known CSO outfalls to determine if the CSOs are likely to significantly impact the local sediment quality. Several stations in Boston’s Outer Harbor were included in the sampling and, for the purposes of the 2002 report, are termed “Harbor” stations. Statistical analyses were used to determine if there were significant differences in contaminant levels among “Near” and “Far” stations (“Harbor” stations were not statistically analyzed), and to determine if contaminant concentrations had changed since the previous CSO surveys (1994 and 1998) (1990 data were not statistically analyzed).

Percent Fines and Total Organic Carbon (TOC)

Percent fines in 2002 were highest at “Near” Station CO19 and “Far” Station DB10 while TOC concentrations were found to be highest at “Far” Station DB10 and “Near” Station DB14. Temporal trends are difficult to discern for both percent fines and percent TOC. Some stations have experienced significant increases or decreases over time; however, statistical comparison of both fines and TOC data among the three analyzed sampling years (1994, 1998, 2002) did not show consistent temporal trends. Rather, temporal changes in TOC and percent fines appeared to be station specific.

Organic Contaminants

Statistical analyses of PAHs, measured as total (sum of all target PAH compounds, excluding benzothiozole) and 24-PAHs (subset of 24 total PAH compounds), between 1994, 1998, and 2002 did not consistently exhibit distinct decreasing or increasing trends except at one station near Carson Beach (DB01), where concentrations decreased from 1994, to 1998, to 2002. In general, PAH concentrations at stations near CSOs were higher than those measured at stations far from CSOs and much higher than PAH concentrations measured in “Harbor” stations. The relatively high concentrations measured at “Near” stations (and some “Far” stations) are not surprising given that those stations are located in an urban setting, adjacent to highly industrial areas and in a known depositional area of Boston Harbor. Stations near CSOs at Fox Point and Commercial Point (DB13/T04 and DB14) showed a marked increase in PAHs in 1998, only to significantly decrease again in 2002. This spike in concentration in 1998 could be related to a heavy precipitation event that occurred in June 1998 two months prior to sampling. The relative amounts of petrogenic (sum of petroleum-related PAHs) and pyrogenic (sum of combustion-related PAHs) appeared to remain relatively similar at most stations from 1994 to 2002, with the exception of the Fox Point station in 1998 and the Commercial Point station in all years. In 2002, the Commercial Point station showed a significant decrease in the relative amount of pyrogenic PAHs compared to 1994 levels. At the other stations near CSOs, as well as at most of the “Far” and “Harbor” stations, where the ratio has remained relatively stable, the sources of PAHs Harbor-wide may not have changed much since 1994.

PCB and DDT concentrations were variable among the ‘”Near” and “Far” stations sampled, with the lowest concentrations found in the “Harbor” stations. Both PCBs and DDTs decreased significantly ($p<0.05$) in 2002 relative to 1998 at all “Near” and “Far” locations except the station located at the mouth of the Neponset River (DB10) and one station in the Old Harbor (DB03). Harbor stations also appeared to show a marked decrease in 2002 relative to 1998. Overall, both PCB and DDT levels appear to be decreasing in sediments not only in the nearshore areas but in the harbor as well. These decreases may be attributed to the national controls set for these compounds in the early 1970s as well as recent Harbor-wide decreases in discharges including the relocation of the Deer Island outfall.

Sewage Tracers

Linear alkyl benzenes (LABs) are the aromatic by-products produced during industrial synthesis of LAB sulfonates, which are widely used anionic surfactants in detergents. The highest LAB concentrations were consistently observed at “Near” stations. The highest concentrations in all years, except 1998, were found at “Near” station DB14. The Fox Point station showed a significant increase ($p<0.05$) in LAB concentrations between 1994 and 1998 and between 1998 and 2002 and Station DB14 showed a significant increase ($p<0.05$) in LAB levels between 1998 and 2002. Aside from these stations, the majority of stations, including “Far” and “Harbor” stations, showed decreases in LAB concentrations between the 1994 and 1998 sampling years and similar concentrations in 1998 and 2002. This trend was not isolated to Dorchester Bay, however, as illustrated by the consistent, steady decline in LABs in Boston Inner Harbor (C019).

Coprostanol is a sterol that is found in human feces and can be used as an indicator of sewage in sediments. Trends in coprostanol concentrations mirrored those of LABs with the highest coprostanol concentrations found at “Near” station DB14 (except for 1998) and the next highest concentrations observed at the station near the Fox Point CSO. At most stations (“Near”, “Far”, and “Harbor”) concentrations appeared to progressively decrease after 1994 with two exceptions: stations near the Fox Point and Commercial Point CSOs in 1998. As observed with LABs, coprostanol concentrations spiked in 1998 at the Fox Point station and then returned to similar “Near” station concentrations in 2002. Coprostanol concentrations at the Commercial Point station (DB14) also significantly increased in 1998 (a nearly 50% increase), but unlike at Station DB13, concentrations continued to increase (though not statistically significantly) in 2002. The overall 2002 decreasing coprostanol levels, especially those observed in the “Far” and “Harbor” stations, may be a result of the Nut Island closing and the Deer Island outfall diversion, with inputs no longer directly entering the Harbor from the treatment plant as of September 2000.

Evaluation of the LAB/Coprostanol ratios spatially and temporally can indicate if there are localized and year-to-year changes in the indicator sources. The LAB/Coprostanol ratios observed from 1990 through 1998 are generally similar at “Far” and “Harbor” stations (except at the Fox Point and Commercial Point stations in 1998) within a given year but show a marked change in 2002 from previous years. Assuming similar sources and transport processes, these ratios appear to indicate a harbor wide source that is consistent across stations with a few localized impacts and a regional shift in the source and type of sewage tracers in the system between 1998 and 2002. The localized change in the LAB/Coprostanol ratio was observed at the Fox Point and Commercial Point “Near” stations in 1998 and may be a result of an increase in sewage-related discharge from the nearby CSOs due to the major rain event that occurred in 1998 just prior to sampling that year. The regional shift observed in 2002 can be attributed to an apparent Harbor-wide decrease in coprostanol levels, most likely a result of the closure of the Nut Island plant in 1998, coupled with the diversion of the Deer Island outfall to nine miles offshore in 2000.

Clostridium levels have dropped considerably at “Near” stations and most “Far” stations since 1990 (*Clostridium* was not measured at “Harbor” stations in 1990). Since 1994, however, *Clostridium* levels have not significantly changed at any “Near” or “Far” stations with the exception of a significant decrease at “Far” station DB06 in both 1998 and 2002, and a significant increase in 2002 at “Near” station DB14.

Metal Contaminants

Sediment samples were analyzed for silver (Ag), aluminum (Al), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), mercury (Hg), nickel (Ni), lead (Pb), and zinc (Zn). In general, Cd, Cu, Pb, and Zn concentrations in 2002 were similar to or lower than those measured in 1994 at most “Near”, “Far”, and “Harbor” stations, with “Near” stations generally showing more statistically significant decreases than “Far” stations. Unlike Pb, Cd, Cu, and Zn temporal trends, Cr and Ni concentrations showed no significant decreases in 2002 compared to 1994. Hg concentrations were variable over time and showed a significant decrease from 1998 values at the Fox Point station. Ag, however, showed significant decreases from 1994 levels at “Near” stations; two in North Dorchester Bay (DB01 and DB04) and the Fox Point station (DB13/T04), and at two “Far” stations; one in the Neponset River (DB10) and one in the Old Harbor (DB12). This is consistent with an overall decrease in Ag concentrations Harbor-wide. Al and Fe are both crustal elements and in the absence of significant anthropogenic sources or major changes in sedimentology, would not be expected to show temporal changes. Both Al and Fe levels remained similar at most stations from 1990 through 2002, with lower levels found at two “Far” stations in North Dorchester Bay and Old Harbor (DB03 and DB06), consistent with the fact that these two stations have the lowest percent fines. The only statistically significant ($p<0.05$) change noted in aluminum measurements was at the station in the Neponset River, where concentrations increased significantly between 1998 and 2002, which corresponds to a significant increase in fines at this station in 2002. Fe also showed a statistically significant increase at this station in 2002.

CSO Influence on Sediment Quality

Many factors can control the quality of sediments, especially in an urban setting where both anthropogenic and naturally-occurring contaminant sources are present. CSOs are just one anthropogenic influence on sediment quality in Boston Harbor. Correlation of measured contaminants to TOC and fines in stations adjacent (“Near”) to CSOs and stations removed (“Far”) from CSOs showed that, as is typically observed in marine sediments, increases in total organic carbon concentration were positively correlated with increases in percent fines at the “Far” stations. The relationship of percent fines to TOC at the “Near” stations is not as well defined and appears to be negatively correlated. The proximity of some sampling stations to CSO outfalls may help to explain the variations in percent fines and TOC over the years. In addition, TOC appears to be an important factor affecting contaminant concentrations, especially at "Near" stations where strong and positive correlation was found between most contaminants and TOC compared to percent fines. Comparison of contaminants at "Near" and "Far" stations by study year, using the student T-test, show that the concentrations of most parameters were significantly different at "Near" and "Far" stations ($p < 0.05$), and therefore support the grouping of sampling stations into "Near" and "Far" classifications. These results also lend themselves to the conclusion that there is some level of impact from CSOs related to sediment quality in the vicinity of the CSOs. Three parameters were consistently found to have similar concentrations at "Near" and "Far" stations in all years: Total DDT, Total PCB, and *Clostridium*. While the "Near"/"Far" grouping supports some level of impact common to stations "Near" CSOs, the concentrations of these three parameters appear to be controlled on a broader basis and changes in concentrations of these parameters are reflected Harbor-wide.

One way ANOVAs were performed to evaluate parameter trends over time at "Near" and "Far" stations. Only six parameters (percent fines, Cd, Fe, Ag, Total DDT, and coprostanol) differed significantly between the three sampling years ($p<0.05$). A significant decrease from 1994 and 1998 to 2002 was observed for Cd, Ag, and Total DDT at "Near" stations and coprostanol significantly decreased from 1994 to 2002 at "Far" stations only. Percent fines and Fe significantly increased from 1994 to 2002 at "Near" stations. The fact that coprostanol only decreased significantly at the "Far" stations may be related to the recently observed statistically significant decrease in another sewage tracer, *Clostridium,* which was attributed to the implementation of secondary treatment of sewage in 1998 and cessation of effluent from Nut Island, and the relocation of the Deer Island Outfall in 2000. No significant decrease in *Clostridium* was observed at the "Near" or "Far" stations although an apparent decrease is observed at the "Harbor" Stations (Figure 3-11). This may indicate that there is still a source to these "Near" stations, possibly the nearby CSOs, or these stations are located in depositional areas resulting in sediment focusing.

CSO Outfall Discharge and Potential Impacts Due to Precipitation Events

Impacts to sediment quality are variable and cannot necessarily be attributed directly to CSOs. Few parameters showed statistically significant temporal trends, though slightly more parameters show a significant temporal decrease at "Near" stations compared to "Far" stations. Most parameters showed variable or possibly decreasing concentrations from 1994 to 2002. However, a number of notable spikes in contaminant concentrations were observed in 1998 relative to 1994, 2002, and where available, 1997 results. One possible explanation for these isolated increases could be a significant rain event that occurred in June of 1998. A number of parameters showed an increase in concentration at "Near" stations DB13/T04 and DB14 in 1998, possibly a result of the June storm event. While overall, concentrations of most contaminants appear to be decreasing since 1990, a spike in TOC, PAH (marked by an increase in the petrogenic PAH fraction), LABs, Coprostanol, Hg, Pb, and Zn concentrations was observed in 1998 at Station DB13/T04 and in some cases at Station DB14. This increase was not observed at the other "Near" stations (DB01 and DB04). In addition, significant increases of PAHs were observed at one "Far" station, Station DB10, in 1998; though without the same increase in petrogenic fraction noted above. Interestingly, concentrations of the sewage tracers, LABs and Coprostanol, did not increase in 1998 at Station DB10. While Station DB10 is not near a CSO, it is adjacent to a large storm drain which was also likely impacted by the significant precipitation of June 1998. These observations indicate that impacts from CSOs are most likely localized; however, other inputs such as storm drains can also have significant localized impacts to sediment quality.

Conclusions

The overall general decrease in contaminant concentrations observed since 1990 may be an indication of a Harbor-wide reduction, rather than a CSO-related decrease, and may be attributable to wastewater treatment upgrades (removal of sludge, implementation of secondary treatment, and the relocation of the Deer Harbor outfall to Massachusetts Bay in 2000). Decreases in total PCB and total DDT for example, are most likely attributed to institutional control of these compounds (i.e., banning of DDT in 1972 and regulation of PCBs in 1976). More subtle impacts to sediment quality relative to CSO inputs were illustrated by the increase in petrogenic PAHs after a storm event in June 1998. This change in the sediment PAH ratio at two "Near" stations (DB13/T04 and DB14) reflected a change in PAH source to those sediments. The ratio of PAHs at "Far" stations in 1998 were similar to previous years, indicating that the impacts observed in the sediments were isolated to nearshore stations, particularly those near to specific CSOs.

As CSO improvements continue, the results presented in this report will be most useful in combination with past and future results so that temporal trends can be identified and causal connections between sediment quality and CSO system improvements can be better understood. Improvements to the study sampling design may also aid in drawing direct links to CSO improvements. Additional sampling stations relative to individual CSOs laid out in a grid adjacent and away from individual CSOs would allow investigation of spatial relationships relative to CSOs. In this way, concentration gradients, if observed, relative to CSOs would give more information about the relative spatial impacts from a given CSO. Increased sampling (i.e., seasonal sampling events within a given year) would allow greater temporal resolution and possibly provide more evidence of the effects of meteorological events on short and long-term sediment quality. Finally, more detailed information on the CSO flow measurements on a tighter time scale as well as actual chemical analyses of CSO discharges would provide information to make more direct comparisons between CSO discharge and sediment quality.

1.0 INTRODUCTION

Combined sewer and stormwater systems collect sewage and storm water for transport to treatment facilities. During heavy rains, relief points, called combined sewer overflows (CSOs), are designed to discharge into local waters if the capacity of the system is exceeded, providing a "safety valve" preventing back-ups of wastewater into homes and businesses and flooding in city streets. CSOs can affect public health through the introduction into the local waters of pathogens and chemicals.

In 1987, MWRA agreed to plan and build small-scale projects to control CSOs in its combined sewer communities. These improvements have included blocking off rarely used CSOs, increasing the storage capacity of others, constructing treatment facilities, disconnecting illegal sewer hook-ups, and installing tide gates to keep seawater out, thereby increasing capacity. Projects completed as of 2002 have resulted in decreased CSO discharges, enabling more sewage to be pumped to the Deer Island treatment plant during rainy weather.

MWRA has been monitoring receiving water quality since 1989, focusing on sewage bacteria indicators. Results (Rex, 1991; Rex, 1993; BWSC, 1990a, b) have shown substantial decreases in bacteria in Boston Harbor and its tributary rivers. For example, fecal coliform concentrations between 1992 and 1996 were reduced by approximately 35 percent (Rex, 2000).

MWRA has conducted periodic surveys to assess the potential impact of CSOs on sediment quality in Dorchester Bay (Durell *et al.,* 1991; Durell, 1995; Lefkovitz *et al.,* 2000). These surveys targeted toxic contaminants. Previous surveys were conducted in November 1990, August 1994, and August 1998. The study described in this report was conducted in August 2002.

1.1 Combined Sewer Overflow Progress Since 1998 Report

As of March 2002, MWRA completed 13 of the 25 MWRA-managed improvement projects proposed under the original 1997 CSO Control Plan. These completed projects include, among others, the upgrading of five CSO treatment facilities (Fox Point, Commercial Point, Cottage Farm, Prison Point, and Somerville Marginal), two sewer separations (including one along the Neponset River, which empties into the study area (Figure 1-1)), the closing of 21 CSO outfalls, the installation of floatable controls, and two hydraulic relief projects. Several other projects are currently in the construction or design phases. The overall effect of these ongoing improvements has been the decrease of CSO discharges from 3.3 billion gallons per year in 1988 to 1.0 billion gallons per year as of the first quarter of 2002 (MWRA, 2003). Improvements and increased capacity at the Deer Island Sewage Treatment Plant may have also contributed to decreased flows to the CSOs since 2000.

Table 1-1 shows progress as of March 2002 on the 12 CSO outfalls and two CSO treatment facilities located in the vicinity of the MWRA CSO sediment study area. Figure 1-1 shows the locations of these outfalls and facilities. BOS-93 was closed February 1998, and BOS-95 was closed June 2000. The two treatment facilities (Fox Point (BOS-89) and Commercial Point (BOS-90)) were upgraded (MWRA, 2003). Another component of the MWRA CSO Control Plan involves separating combined systems into separate storm drainage and sanitary sewers, eliminating CSOs. As of the sediment surveys in 2002, sewer separation had been completed for small areas along the Neponset River and was ongoing for a large section of South Dorchester. Although sewer separation has not totally prevented overflows from occurring from the CSO outfalls, it has prevented sewage originating in the areas that have completed sewer separation from being discharged during overflow events. Other sections of Dorchester will be undergoing sewer separation construction within the next few years, eventually resulting in the cessation of overflows containing sewage to South Dorchester Bay.

Table 1-1. CSO Status as of 2002.

Project	Location	Activity
CSO OUTFALLS		
BOS-60	Fort Point Channel	Active
BOS-57	Fort Point Channel	Active
BOS-62	Fort Point Channel	Active
BOS-64	Fort Point Channel	Active
BOS-73	Fort Point Channel	Active
BOS-65	Fort Point Channel	Active
BOS-72	Fort Point Channel	Active
BOS-68	Fort Point Channel	Active
BOS-70	Fort Point Channel	Active
BOS-81	Old Harbor/North Dorchester Bay	Active but scheduled to be closed; Proposed storage facility to be constructed to hold run-off from a 25-yr, 24-hr storm event
BOS-82	Old Harbor/North Dorchester Bay	
BOS-83	Old Harbor/North Dorchester Bay	
BOS-84	Old Harbor/North Dorchester Bay	
BOS-85	Old Harbor/North Dorchester Bay	
BOS-86	Old Harbor/North Dorchester Bay	
BOS-87	Old Harbor/North Dorchester Bay	
BOS-88	South Dorchester Bay	Active; scheduled to be closed
BOS-89	South Dorchester Bay	Active; scheduled to be closed
BOS-90	South Dorchester Bay	Active; scheduled to be closed
BOS-93	Neponset River	Outfall closed February 1998
BOS-95	Neponset River	Outfall closed June 2000
CSO TREATMENT FACILITIES		
Fox Point	South Dorchester Bay; adjacent to BOS-88	Upgraded screening, chlorination, and dechlorination facilities completed mid-2002.
Commercial Point	South Dorchester Bay; adjacent to BOS-90	

1.2 Objectives

The primary objectives for the 2002 study were to

1. Generate sediment quality data for specific Dorchester Bay locations;
2. Discuss changes in contaminant concentrations between 2002 and historical studies (1998, 1994, and 1990); and,
3. Consider the apparent impact of the studied CSOs on the local sediment quality.

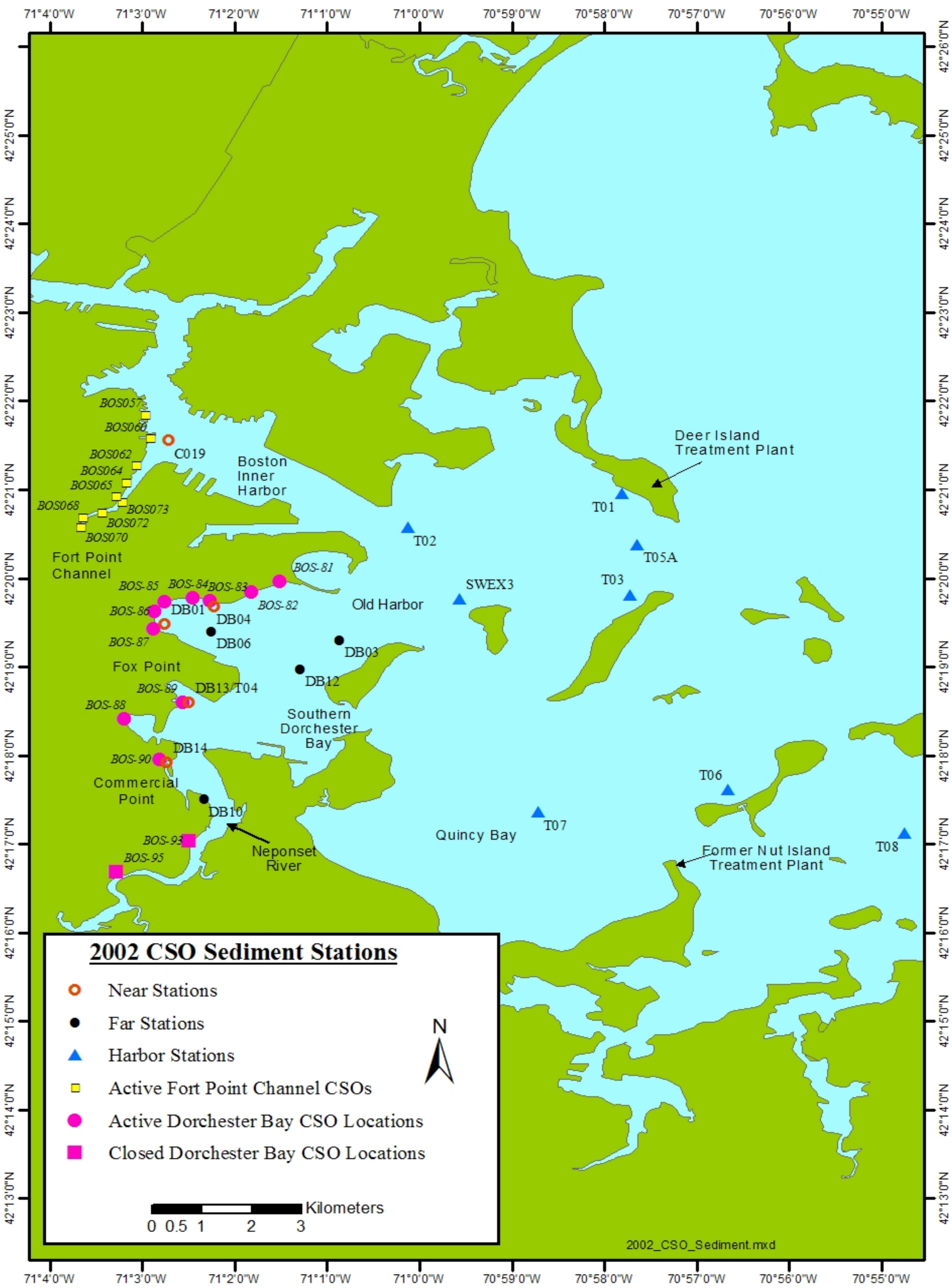

Figure 1-1 Station Locations for 2002 Survey and Locations of CSOs.

These objectives were met by measuring concentrations of selected contaminants (toxic metals, organic pollutants, and sewage tracer compounds) in sediments at sites that were expected to be affected by CSOs ("Near" stations) and at sites that are in the same general area but were expected to be relatively free of CSO-related impacts ("Far" and "Harbor" stations). Comparisons of 2002 survey results to results from the three previous studies were made to determine if sediment contaminant concentrations have changed in the past twelve years and whether any observed changes can be attributed to the presence of CSOs or to CSO improvements. This report is not intended to be an exhaustive contaminant impact assessment study; rather, it provides a summary of the sediment quality in Dorchester Bay at the sites near CSOs relative to the sites farther away.

2.0 TECHNICAL APPROACH

Pathogen contamination is generally considered to be the primary water quality impact associated with untreated CSOs; however, CSOs also contribute toxic chemicals, BOD, and nutrients to receiving waters. To help discriminate the impact from wastewater treatment plants and CSO discharges from other confounding point and nonpoint sources of contamination to Boston Harbor, the microbial indicators *Clostridium perfringens* spores, *Enterococcus*, and fecal coliform, and sewage tracers such as linear alkyl benzenes (LABs) and coprostanol, were included in the monitoring study. Toxic chemical pollutants (selected organic and metal contaminants) in sediments were measured in relation to specific CSOs.

In August 2002, sediment samples were collected from 17 stations (Figure 1-1) in Boston Harbor, most of which are located in Dorchester Bay. The field and laboratory procedures used in 2002 are the same as those used to conduct the 1990, 1994, and 1998 CSO surveys (Durell *et al.*,1991; Durell, 1995; Lefkovitz *et al.*, 2000). The technical procedures are only briefly summarized in this report; detailed technical descriptions regarding sample collection, transport, storage, and analysis can be found in the survey plan (Williams, 2002) and the combined work/quality assurance project plan (CW/QAPP) (Williams *et al.*, 2002).

Sediment samples were analyzed for grain size, total organic carbon (TOC), organic contaminants (including total PAHs, total 24-PAHs, petrogenic PAHs, pyrogenic PAHs, total PCBs, and total DDTs), sewage tracers (including total LABs, coprostanol, fecal coliform, and *Clostridium perfringens*), and selected metals (including silver (Ag), aluminum (Al), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), mercury (Hg), nickel (Ni), lead (Pb), and zinc (Zn)). The data were reviewed to determine the differences in sediment quality among sites expected to be significantly influenced by CSOs (“Near” stations) and sites remote from CSO sources (“Far” stations and “Harbor” stations). Additionally, the data were compared with data from the earlier surveys (Durell *et al.,* 1991; Durell, 1995; Lefkovitz *et al.*, 2000) to determine if contaminant concentrations have changed.

2.1 Station Selection — Rationale and Objectives

The locations of the 17 sampling stations selected for this study are presented in Figure 1-1 and Table 2-1. The descriptions and rationale for the selection of these stations (except Station T07, which was added in 1998) are provided in detail in the 1994 CSO report (Durell, 1995). Station DB13, which was surveyed in 1998, is located 0.01”W of Station T04, and therefore is considered equivalent to Station T04.

Sampling stations in Dorchester Bay are referred to as “Near” CSO discharges (n=5) or “Far” from CSO discharges (n=4), based on their physical distance from the nearest CSO outfall. Nine other stations are referred to as “Harbor” stations because they are located in outer Boston Harbor, relatively far from any CSO discharge points. The “Near” designations are consistent with station groupings in the 1994 and 1998 CSO reports (Durell, 1995; Lefkovitz *et al.*, 2000). These stations represent areas likely to be most influenced by CSO discharges.

For purposes of this report, statistical analyses were conducted only on “Near” and “Far” stations located within Dorchester Bay. This precluded Station CO19, which is located in Boston’s Inner Harbor, from statistical analyses. Inclusion of Station CO19 in the analyses of the Dorchester Bay stations confounded the evaluation of impacts from CSOs because, while this station is adjacent to several CSOs, these CSOs are not among those being considered in this study, and the station’s location makes it subject to other factors that are not directly impacting sediment quality at the Dorchester stations. The study focused on the Old Harbor area of Dorchester Bay (Stations DB01, DB03, DB04, DB06, and DB12), South

Dorchester Bay (Stations DB10, DB13/T04, and DB14), and Boston's Outer Harbor (T01, T02, T03, T05A, T06, T07, T08, and SWEX3).

Three new stations were sampled in 2002 (T03, T05A, and T06). To simplify data analysis and to ensure data comparability over time, only stations that were sampled for the complete list of parameters and in all study years were included in evaluating temporal trends. This precluded inclusion of 1990 data because the parameters measured in that year were limited.

Table 2-1. Sampling Locations for 2002 CSO Survey.

Stations	"Near" (N) "Far" (F) or "Harbor" (H)	CSO	Station Arrival	Latitude	Longitude	Depth (m)
Old Harbor						
DB01	N	BOS-86, BOS-87, BOS-82, BOS-84, BOS-81, BOS-85, BOS-83	8/7/02 11:34	42°19.48'N	71°02.75'W	3.0
DB03	F	No direct CSO input	8/7/02 10:42	42°19.30'N	71°00.86'W	5.0
DB04	N	BOS-86, BOS-87, BOS-82, BOS-84, BOS-81, BOS-85, BOS-83	8/7/02 9:25	42°19.68'N	71°02.22'W	4.0
DB06	F	No direct CSO input	8/7/02 8:43	42°19.39'N	71°02.25'W	2.0
South Dorchester Bay						
DB10	F	No direct CSO input	8/7/02 7:14	42°17.50'N	71°02.33'W	2.0
DB12	F	No direct CSO input	8/7/02 10:10	42°18.97'N	71°01.29'W	5.0
DB14	N	BOS-90	8/7/02 7:54	42°17.92'N	71°02.73'W	2.0
DB13/T04	N	BOS-89	8/8/02 7:56	42°18.60'N	71°02.49'W	3.2
Outside Dorchester Bay						
T01	H	No direct CSO input	8/8/02 9:33	42°20.95'N	70°57.81'W	4.0
T02	H	No direct CSO input	8/8/02 8:43	42°20.57'N	71°00.12'W	6.8
T03	H	No direct CSO input	8/8/02 11:41	42°19.81'N	70°57.72'W	8.7
T05A	H	No direct CSO input	8/8/02 10:07	42°20.38'N	70°57.64'W	17.5
T06	H	No direct CSO input	8/8/02 12:25	42°17.61'N	70°56.66'W	6.6
T07	H	No direct CSO input	8/8/02 6:48	42°17.36'N	70°58.71'W	5.9
T08	H	No direct CSO input	8/8/02 13:16	42°17.12'N	70°54.75'W	11.3
C019	N*	CSOs in Fort Point Channel	8/7/02 12:25	42°21.55'N	71°02.71'W	7.9
SWEX3	H	No direct CSO input	8/7/02 13:00	42°19.76'N	70°59.56'W	8.0

* C019 is located "Near" several CSOs; however, it is outside of Dorchester Bay and therefore not included in statistical evaluations presented in Sections 3 and 4.

2.2 Sample Collection and Field Procedures

2.2.1 Vessel/Navigation

The CSO sediment survey was conducted onboard the Battelle-owned *R/V Aquamonitor*. Navigation procedures followed those described in the Water Column CW/QAPP (Libby *et al.,* 2002). Station positioning within 30 m of the target location was considered acceptable for sediment sampling (Williams *et al.,* 2002).

2.2.2 Grab Sampling

At each station, three replicate samples were collected with a Kynar-coated 0.1-m^2 Ted Young-modified van Veen grab sampler. The top two centimeters of the grab were removed and processed for sedimentological, chemical, and microbiological parameters. Samples were analyzed for sediment grain size, total organic carbon (TOC), fecal coliform, *Enterococcus,* and *Clostridium perfringens*, as well as the organic and metal contaminants summarized in Table 2-2. Samples for grain size, fecal coliform, *Enterococcus,* and *C. perfringens* analysis were placed on ice in coolers, whereas the samples for TOC, organics, and metal analyses were frozen. A total of 51 samples were collected for analysis.

Table 2-2. Sediment Chemistry Analytes and Target Method Detection Limits (MDL).

Analyte	MDL[1]	Analyte	MDL[1]
Physical Sediment Parameters		**PAH (Continued)**[5,6]	
Total organic carbon	0.01%	dibenzofuran	0.251
Grain size[2]	0.01%	C$_1$-fluorenes	0.044
Sewage Tracers		C$_2$-fluorenes	0.044
Clostridium perfringens	NA	C$_3$-fluorenes	0.044
Coprostanol[3]	26-129	Anthracene*	0.057
Fecal coliform, *Enterococcus*	NA	Phenanthrene*	0.0664
Linear alkyl benzenes[4]		C$_1$-phenanthrenes/anthracene*	0.0664
phenol decane	5	C$_2$-phenanthrenes/anthracene	0.0664
phenyl undecane	5	C$_3$-phenanthrenes/anthracene	0.0664
phenyl dodecane	5	C$_4$-phenanthrenes/anthracene	0.0664
phenyl tridecane	5	dibenzothiophene	0.0145
phenyl tetradecane	5	C$_1$-dibenzothiophenes	0.0145
Metals		C$_2$-dibenzothiophenes	0.0145
Al Aluminum	2300	C$_3$-dibenzothiophenes	0.0145
Fe Iron	6	Fluoranthene*	0.0579
Ag Silver	0.063	Pyrene*	0.0621
Cd Cadmium	0.058	C$_1$-fluoranthenes/pyrenes	0.0621
Cr Chromium	9	benzo(a)anthracene*	0.0623
Cu Copper	2	Chrysene*	0.0338
Hg Mercury	0.028	C$_1$-chrysene	0.0338
Ni Nickel	2	C$_2$-chrysene	0.0338
Pb Lead	2	C$_3$-chrysene	0.0338
Zn Zinc	2	C$_4$-chrysene	0.0338
Polychlorinated biphenyls[5]		benzo(b)fluoranthene*	0.0898
2,4-Cl$_2$(8)	0.244	benzo(k)fluoranthene*	0.0704
2,2’5-Cl$_3$(18)	0.107	benzo(a)pyrene*	0.0865
2,4,4’-Cl$_3$(28)	0.168	dibenzo(a,h)anthracene*	0.0693
2,2’3,5’-Cl$_4$(44)	0.132	indeno(1,2,3-c,d)pyrene*	0.0404
2,2’,5,5’-Cl$_4$(52)	0.162	Perylene*	0.059
2,3’,4,4’-Cl$_4$(66)	0.192	benzo(e)pyrene*	0.0327
3,3’,4,4’-Cl$_4$(77)	0.242	benzo(g,h,i)perylene*	0.0569
2,2’4,5,5’-Cl$_5$(101)	0.139	Benzothiozole[3]	1.25
2,3,3’,4,4’-Cl$_5$(105)	0.0675	**Pesticides**[4, 5]	
2,3’,4,4’5-Cl$_5$(118)	0.105	Hexachlorobenzene	0.156
3,3’,4,4’,5-Cl$_5$(126)	0.159	Lindane	0.0759
2,2’,3,3,4,4’-Cl$_6$(128)	0.283	Heptachlor	0.135
2,2’,3,4,4’,5-Cl$_6$(138)	0.0836	Aldrin	0.11
2,2’4,4’,5,5’-Cl$_6$(153)	0.164	Heptachlorepoxide	0.108
2,2’3,3,4,4’,5-Cl$_7$(170)	0.090	alpha-chlordane	0.105

Table 2–2. Sediment Chemistry Analytes and Target Method Detection Limits (MDL) continued.

Analyte	MDL[1]	Analyte	MDL[1]
2,2’,3,4,4’,5,5’-Cl$_7$(180)	0.0922	trans-Nonachlor	0.118
2,2’,3,4,5,5’,6-Cl$_7$(187)	0.0832	Dieldrin	0.085
2,2’,3,3’,4,4’,5,6-Cl$_8$(195)	0.0753	Endrin	0.0736
2,2’,3,3’4,4’,5,5’,6-Cl$_9$(206)	0.0667	Mirex	0.0889
Decachlorobiphenyl-Cl$_{10}$(209)	0.0732	2,4’-DDD	0.112
Polynuclear Aromatic Hydrocarbons[5,6]		4,4’-DDD	0.0816
Naphtalene*	9.47	2,4’-DDE	0.257
C$_1$-naphthalenes*	9.47	4,4’-DDE	0.0869
C$_2$-naphthalenes*	9.47	2,4’-DDT	0.246
C$_3$-naphthalenes*	9.47	4,4’-DDT	0.0998
Biphenyl*	0.0912	DDMU	0.162
Acenaphthylene*	0.0614		
Acenaphthene*	0.0742		
Fluorene*	0.044		

[1] μg/g dry weight for metals; ng/g dry weight for organics
[2] Detection limit is based on analytical sensitivity of balance and is adjusted for sample size
[3] Detection limit is based on a reporting limit derived from the low calibration standard and adjusted for sample processing volumes/factors.
[4] Detection limits are reporting limits (RL) calculated from the low calibration standard and adjusted for sample processing factors. RL=(conc. in low std × final extract volume × dilution factor) ÷ (sample dry weight).
[5] MDL concentrations for PAHs, PCBs, and pesticides are based on surrogate corrected data. These MDLs are representative of year 2000 MDL study results. MDLs are updated annually and are available upon request. Batch-specific achieved MDLs will be reported with the data.
[6] MDL concentrations for alkyl homologues are based on the MDL of the unsubstituted, parent compound.
* Compounds are included in the calculation of Total 24-PAHs.

Grain size, TOC, fecal coliform, *Enterococcus,* and *Clostridium perfringens* samples were shipped, on ice, to Battelle subcontractors for subsequent analysis. GeoPlan Associates in Hingham, Massachusetts performed the grain size analysis. TOC analysis was performed by Applied Marine Sciences in League City, Texas. Fecal coliform, *Enterococcus,* and *C. perfringens* analyses were performed by MTH Environmental Associates in Marston Mills, Massachusetts. The samples for analysis of organic and metal contaminants were placed in a freezer at Battelle and stored at or below -20°C until laboratory processing was initiated.

2.3 Laboratory Sample Analysis Procedures

Sediment samples were analyzed for grain size, total organic carbon (TOC), organic contaminants (including tot PAHs, total 24-PAHs, petrogenic PAHs, pyrogenic PAHs, total PCBs, and total DDTs), sewage tracers (including total LABs, coprostanol, fecal coliform, and *Clostridium perfringens*), and selected metals (including silver (Ag), aluminum (Al), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), mercury (Hg), nickel (Ni), lead (Pb), and zinc (Zn). Table 2-2 presents the list of analytical parameters, as well as the approximate method detection limit for each. Laboratory procedures followed those outlined in the Benthic Monitoring CW/QAPP (Williams *et al*., 2002). Concise summaries of the procedures are provided below.

2.3.1 Grain Size, TOC, fecal coliform, Enterococcus, and *Clostridium perfringens* Analyses

Grain Size. Samples were analyzed for grain size by a sequence of wet sieving and dry sieving. Methodologies followed those of Folk (1974). The sand/gravel fraction was separated from the mud fraction and then transferred to a 200-mL beaker, decanted, and dried overnight at 95°C. The dried sand/gravel fraction was mixed by hand to disaggregate the material, and then dry-sieved on stacked sieves ranging in size from -1 to 4 phi. Each size class was weighed to the nearest 0.1 mg on a top-loading balance. Particles smaller than 4 phi were analyzed using the pipette method. The data were presented in weight percent by size class. Percent fines are defined as the sum of the percent clay and percent silt in a sediment sample. In addition, the gravel:sand:silt:clay ratio, and a numerical approximation of mean size and sorting (standard deviation), were calculated.

TOC. A portion of the sample analyzed for TOC content was dried for 24-36 hours and then ground into a fine powder. The sample was treated with 10% HCl to remove inorganic carbon and dried at 70° for 24 hours. Between 10 and 500 mg of dry, finely ground, and homogenized sample was weighed to the nearest 0.1 mg and placed in a crucible that had been precombusted for 4 hours at 500°C. The analyzer operated through the high-temperature conversion of all carbon in the treated sample to carbon dioxide in the presence of oxygen. The carbon dioxide was quantified by coulometric detection, and results were reported as % dry-weight.

Fecal coliform, *Enterococcus*, and *Clostridium perfringens*. Sediment extraction methods for microbiological parameters followed those developed by Emerson and Cabelli (1982), as modified by Saad (1992). Analysis of the supernatant was performed by membrane filtration. Enumeration of fecal coliform and *Enterococcus* are described in EPA method 821/R-97/004 (EPA, 2000) with modification to the *Enterococcus* method following Messer and Dufour (1998).

The filters for enumeration of *C. perfringens* spores were incubated anaerobically at 44.5°C for 24 hours. Following incubation, the filters were exposed to ammonium hydroxide for 15-30 seconds. Yellowish colonies that turned red to dark pink upon exposure were counted as *C. perfringens*. Data were reported as spores per gram dry weight of sediment. The filters for enumeration of fecal coliform were incubated at 35°C for 2 hours, followed by incubation at 44.5°C for 18-20 hours. Yellow colonies were counted and recorded as fecal coliform.

2.3.2 Organic Contaminant Analyses

Analyses of sediments for organic contaminants were performed according to methods listed in Table 2-3. Detailed information is provided in Williams *et al.* (2002). Analytical methods for organic contaminants used in the 2002 study are completely comparable to those used by the historical CSO studies (Lefkovitz *et al.,* 2000; Durell, 1995; Durell *et al.,* 1991).

Table 2-3. Sediment Organic Contaminant Analysis Methods.

Parameter	Analysis Lab	Unit of Measurement	Method	Reference
Linear Alkyl Benzenes (LABs)	Battelle	ng/g	GC/MS	Battelle SOP 5-157-07
Polycyclic Aromatic Hydrocarbons (PAHs)	Battelle	ng/g	GC/MS	Battelle SOP 5-157-07
Polychlorinated Biphenyls (PCBs)/Pesticides	Battelle	ng/g	GC/ECD	Battelle SOP 5-128-06
Coprostanol	Battelle	ng/g	GC/MS	Battelle SOP 5-157-07

GC/MS = gas chromatography/mass spectrometry
GC/ECD = gas chromatography/electron capture detection
SOP = standard operating procedure

Reporting Polynuclear Aromatic Hydrocarbons (PAHs). Consistent with the 1998 study, polynuclear aromatic hydrocarbon (PAH) data are presented as total PAHs, total 24-PAHs (consistent with the National Oceanographic and Atmospheric Administration's (NOAA) Status and Trends PAH list), petrogenic PAHs, pyrogenic PAHs, and %pyrogenic PAHs of the total PAHs. Total PAHs are defined as the sum of target PAH compounds (listed in Table 2-2), excluding benzothiozole. The total 24-PAH parameter is a subset of total PAHs (asterisked compounds in Table 2-2). The petrogenic PAH (petro-PAH) parameter is the sum of petroleum-related PAHs, whereas pyrogenic PAHs (pyro-PAH) represent the sum of pyrogenic (combustion and creosote, coal-tar related) PAHs. The petro-PAHs are mostly found in refined and unrefined petroleum products and are primarily the lighter-molecular-weight PAHs. For this report, the petro-PAHs are defined as those PAHs in Table 2-2 from naphthalene through C3-dibenzothiophene. The pyro-PAHs are primarily principal components of creosote and coal-tar mixtures or are derived from the combustion of fossil fuels and are generally the heavier-molecular-weight PAHs. The pyro-PAHs are defined as those compounds in Table 2-2 between fluoranthene and benzo(g,h,i)perylene. Although PAH compounds cannot be attributed exclusively to one of these two source types, this classification represents a general approximation of the relative proportion of petrogenic and pyrogenic PAH compounds.

2.3.3 Metal Analyses

Analyses of sediments for metal contaminants were performed according to methods listed in Table 2-4. Detailed information is provided in Williams *et al.,* (2002). Analytical methods for metal contaminants used in the 2002 study are completely comparable to those used by the historical studies (Lefkovitz *et al*., 2000; Durell, 1995; Durell *et al*., 1991; Blake *et al*., 1998; NOAA, 1998).

Table 2-4. Sediment Metal Contaminants Analysis Methods.

Parameter	Analysis Lab	Units	Method	Reference
Major Metals (Al, Fe)	KLM	µg/g	EDXRF	KLM Procedure XRF-01
Trace Metals (Cr, Ni, Pb, Zn, Cu)	KLM	µg/g	EDXRF	KLM Procedure XRF-01
Trace Metals (Ag, Cd, and Hg)	Battelle	µg/g	CVAA (Hg) ICP-MS (Ag, Cd)	CVAA: Battelle SOP MSL-I-016 ICP-MS: Battelle SOP MSL-I-022

EDXRF = Energy Dispersive X-ray Fluorescence
CVAA = Cold Vapor Atomic Absorption
ICP-MS = Inductively Coupled Plasma - Mass Spectrometry
SOP = standard operating procedure

2.4 Data Analysis Procedures

Data analyses were performed on station mean data (i.e., the mean of three replicates from each station). Sediment grain size, as percent fines (sum of silt/clay), TOC, *Clostridium perfringens*, and organic and metal contaminant concentrations (station mean) were compared using bar charts. Note that in 2002, one of the three replicate values for PAHs measured at Station DB14 was anomalously high; this apparent outlier (no formal outlier test was performed) was removed from all data analyses. Therefore, the mean PAH values reported for Station DB14 in 2002 were calculated using two replicates rather than three.

Statistical analyses were used to determine if there were significant differences in contaminant levels among CSO-impacted sites and sites expected to be relatively unimpacted by CSOs, and to determine if contaminant concentrations had changed since the previous CSO surveys in 1994 and 1998.

2.4.1 General Data Treatment Using the SAS System

All data used for statistical analyses were tested for normality and homogeneity of variance prior to performing statistical analysis. An alpha level of 0.05 was used to assign statistical significance. Levene's test was used to determine the homogeneity of variance. Using the Box and Cox method, it was determined that using the $\log_{10}$ transformation of abnormally distributed data would produce a better analysis. Data that were $\log_{10}$ transformed are noted in the tables of this report with an asterisk. An apparent outlier existed for one of the three samples collected at DB14 and analyzed for PAHs during the 2002 sampling event. This outlier was removed from all PAH analyses.

Normalization of data to TOC was investigated as a technique for decreasing the variance in the data and improving statistical evaluations in the 1998 report (Lefkovitz *et al.,* 2000). Since this evaluation showed that normalization to TOC did not change the results of the analyses, the raw data values (or $\log_{10}$ transformed values where appropriate) were used for all statistical analyses.

2.4.2 Statistical Analyses

One-Way ANOVA. One-way Analysis of Variance (ANOVA) analyses were used to examine temporal trends between 1994 and 2002 at stations sampled during this time period (i.e., DB01, DB03, DB04, DB06, DB10, DB12, DB13, and DB14). Results were evaluated to determine if there was a statistically significant difference among results of individual parameters at each station over the three years (i.e., 1994, 1998, and 2002). Similar to the t-test analyses discussed below, the parameters evaluated at each of the stations included TOC, sediment grain size (measured as percent fines), *Clostridium perfringens*, PAHs (measured as total PAHs, total 24-PAHs, petrogenic PAHs, and pyrogenic PAHs), total LABs, coprostanol, PCBs (measured as total PCBs), DDTs (measured as the sum of six DDTs), and various metals. The tables containing the ANOVA results are presented with each relevant parameter and can be read as follows: 'a', 'b', and 'c' represent the years 1994, 1998, and 2002, respectively. If two or more letters are listed together within a set of parentheses, then the measurements of the given parameter in those years are not significantly different. Letters that are not listed together within the same set of parentheses represent years that are significantly different. The letters are listed in each cell in order of descending value, with the year with the maximum value listed first. For example, the ANOVA result for percent fines for Station DB01 (as shown in Table C-1 (a) in Appendix C) is (cb)a. In this case, "a" is significantly lower than both "b" and "c". However, "b" and "c" are not significantly different from one another, although "c" is higher than "b", as indicated by the order in which the letters are shown. Results of the ANOVA tests are presented in Appendix C and discussed where relevant in Section 3.

ANOVA analyses were also run to evaluate differences in various parameters at "Near" sites across the three sampling years (1994, 1998 and 2002) and at "Far" sites across the three sampling years (1994, 1998, and 2002). "Near" stations included DB01, DB04, DB13/T04, and DB14; "Far" stations included: DB03, DB06, DB10, and DB12. "Near" and "Far" comparisons across the years (1994, 1998, and 2002) were run for all parameters: metals (Al, Cd, Cr, Cu, Fe, Pb, Hg, Ni, Ag, Zn), total DDTs, total LABs, total PCBs, total PAHs, total 24-PAHs, total petro-PAHs, total pyro-PAHs, *Clostridium perfringens*, and coprostanol. Results for these ANOVA analyses are presented in Section 4.3.3.

Correlations. Pearson product-moment correlation analyses were used to evaluate if a relationship existed between TOC and all other parameters and between percent fines and all other parameters. "Near" stations included DB01, DB04, DB13/T04, and DB14; "Far" stations included DB03, DB06, DB10, and DB12. Data from all years were used in the correlation analyses. The common parameters among years included Al, Cd, Cr, Cu, Fe, Pb, Hg, Ni, Ag and Zn, *Clostridium perfringens*, coprostanol, total PAHs, total 24-PAHs, total petro-PAHs, total pyro-PAHs, total LABs, total DDTs, and total PCBs. The results of the correlations are discussed in Section 4.3.1.

Student t-test. To address whether the "Near" and "Far" stations differed significantly from each other for any given parameter measured in 2002, stations were grouped to constitute "Near" (DB01, DB04, DB13, DB14) and "Far" (DB03, DB06, DB10, and DB12) stations as described previously. These groups were compared using student t-tests. "Near" versus "Far" comparisons were made for each year (1994, 1998, and 2002) for all parameters: metals (Al, Cd, Cr, Cu, Fe, Pb, Hg, Ni, Ag, Zn), total DDTs, total LABs, total PCBs, total PAHs, total 24-PAHs, total petro-PAHs, total pyro-PAHs, *Clostridium perfringens*, and coprostanol. Sample size (n) for any given analysis was 12 for the "Far" stations and 12 for the "Near" stations (3 samples per station per year). The results of the t-tests are discussed in Section 4.3.2.

Principal Component Analysis. Principal components analysis (PCA) was employed to evaluate potential differences in PCB congener patterns in "Near", "Far" and "Harbor" stations and relate those differences to potentially different sources. PCA is a chemometric technique for visualizing intersample and intervariable relationships. It achieves this by reducing the "n" dimensionality of the data (where n = number of variables or samples, whichever is smaller) by finding linear combinations of the variables in the data set which account for the maximum amounts of variance. These linear combinations are the principle components. The 1st principle component (PC) accounts for the maximum amount of variance and each successive PC accounts for less of the remaining variance. PCA yields a distribution of samples (*e.g.*, sediment samples) in n-dimensional space, where n is the number of variables (*e.g.*, PCB Group). A log transformation of all analytes was performed to minimize bias associated with the large range of parameter values. PCA was performed by using Pirouette (Version 3.02; Infometrix, Inc., Seattle, WA).

3.0 RESULTS

The primary goals of this study are to generate sediment quality data for specific Boston Harbor locations, consider the apparent impact of the studied CSOs on the local sediment quality, and discuss changes in contaminant concentrations between 2002 and historical studies (1990, 1994, and 1998).

Historical data collected in the Fox Point/Commercial Point area (Eaganhouse and Sherblom, 1990; Wallace *et al.,* 1991; Gallagher *et al.,* 1992) showed higher contaminant concentrations there than at the surrounding Harbor areas. However, Gallagher *et al.* (1992) concluded that the data were insufficient to attribute the increased concentrations of organic and metal contaminants in this area to the Fox Point CSO. Instead, they suggested that most sediment contaminants measured in Dorchester Bay originated from Deer Island and Nut Island sewage treatment plant discharges. Elimination of sludge discharges from the Deer Island and Nut Island facilities in December 1991 significantly reduced the amount of contaminants available for transportation into Dorchester Bay (Werme and Hunt, 2003). The loading of contaminants to Boston Harbor was further reduced beginning in 1997 when secondary treatment at the Deer Island Treatment Plant was phased in and the Nut Island discharge into Quincy Bay was closed in 1998. Additional reductions occurred in 2000 with the transfer of Deer Island effluent to the Massachusetts Bay outfall.

Section 3.1 through 3.4 present the results of physical and chemical measurements at all stations studied from 1990 through 2002 and discuss the results relative to the results of the one-way ANOVA analyses, where relevant. Data in this section are presented as bar charts, including error bars, for all parameters for all available years. Section 4 discusses the results of additional statistical evaluations of the data including the correlation of contaminants to grain size and TOC, the comparison of contaminant concentrations at "Near" and "Far" stations and temporal trends at "Near" and "Far" stations. The data collected in 2002, with results for each individual station, including means and standard deviations between replicates, are presented in Appendix A. Summaries of historical contaminant means from 1990, 1994, 1998 and 2002 are presented in Appendix B. Results of the one-way ANOVA analyses for individual stations are provided in Appendix C.

3.1 Grain Size and TOC Results

Overall, in 2002, the sampling stations located in the vicinity of the CSOs (the "Near" stations) exhibited the highest average percentage of fine sediments (clay and silt) and percent TOC (Appendix B, Table B-1; Figure 3-1). Percent fines were highest at Station CO19 (97%) and Station DB10 (97.1%) (Appendix B, Table B-1; Figure 3-1). In 2002, TOC concentrations were found to be highest at Station DB14 (8.6%) and at Station DB10 (4.26%) (Appendix B, Table B-1; Figure 3-2). The lowest percent fines and TOC concentrations were both found at Station DB06. These data are consistent with results from previous years; percent fines and TOC over all years were highest at stations adjacent to CSOs, which includes Station C019 located outside of Dorchester Bay in Boston's Inner Harbor.

Temporal trends are difficult to discern for both percent fines and percent TOC. While ANOVA analyses (Appendix C) show that some stations have experienced significant increases or decreases over time, statistical comparison of both fines and TOC data among the three analyzed sampling years (1994, 1998, 2002) did not show consistent temporal trends. Rather, temporal changes in TOC and percent fines appeared to be station specific. For example, TOC and fines were significantly lower ($p<0.05$) at Station DB10 in 1998 compared to 1994 and 2002 (Figures 3-1 and 3-2). The significant decrease in percent fines in 1998 could be a result of the large storm event that occurred in June of that year, possibly from scouring the area at the mouth of the River. The percent fines and TOC returned to previously measured levels in

2002; however, the two CSO outfalls in the Neponset River upstream from Station DB10 were both closed as of 2000, suggesting that the higher TOC and percent fines values observed in 2002 may have been caused by an alternate source, such as the storm drain or other sources upstream in the Neponset River. Conversely, a significantly higher percent TOC concentration in 1998 relative to 1994 and 2002 ($p<0.05$) was observed at Station DB13/T04 (Figure 3-2). Percent fines at Station DB13/T04 showed significantly lower levels ($p<0.05$) in 1998 relative to 2002 (Figure 3-1).

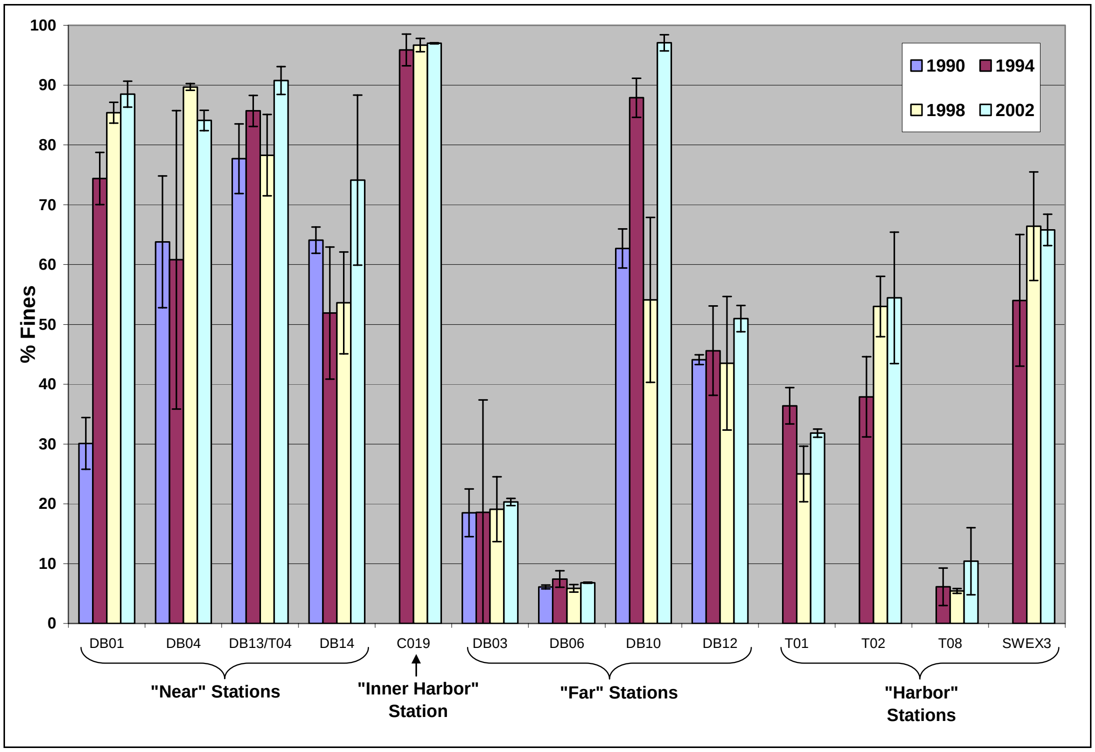

Figure 3-1. Sediment Percent Fines from 1990, 1994, 1998, and 2002 Samples.

Note: Error bars are one standard deviation.

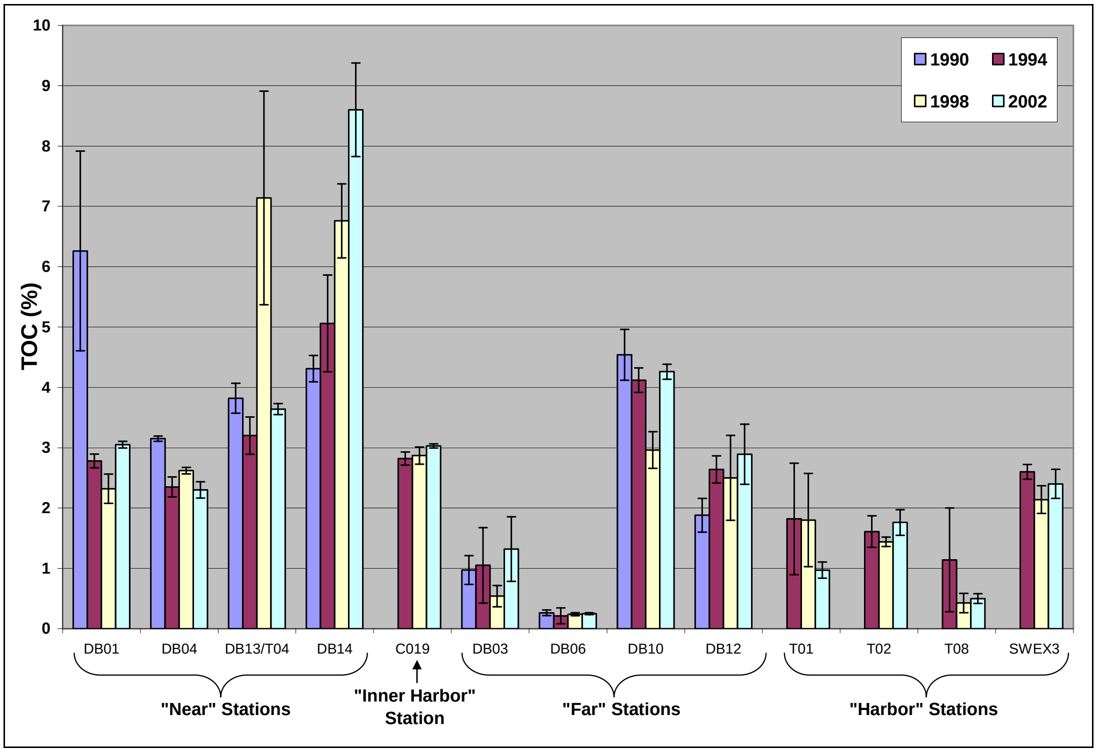

Figure 3-2. Total Organic Carbon from 1990, 1994, 1998, and 2002 Samples.

Note: Error bars are one standard deviation.

3.2 Organic Contaminant Results

Organic contaminant concentrations as well as microbiological data for stations sampled in 1990, 1994, 1998, and 2002 are provided in Table B-2 in Appendix B. The following sections discuss the data by parameter and reference the one way ANOVA analyses where relevant (See Appendix C for ANOVA results).

3.2.1 PAH Concentrations

PAH concentrations are presented in Table B-2 in Appendix B as total PAHs, total 24-PAHs (consistent with NOAA Status and Trends PAH list), petrogenic PAHs, pyrogenic PAHs, and % pyrogenic PAHs of the total PAHs (as described in Section 2.3.2). Because spatial and temporal trends in PAH concentrations are generally similar for all PAH groupings, and only the 24-PAH subset was measured in all study years, only total 24-PAH results are discussed here (Figure 3-3).

In general, PAH concentrations at stations "Near" CSOs were higher than those measured at stations "Far" from CSOs and much higher than PAH concentrations measured in Harbor stations. The relatively high PAH concentrations measured at "Near" stations (and some "Far" stations: DB10 and DB12) are not surprising given that those stations are located in an urban setting, adjacent to highly industrial areas and in a known depositional area of Boston Harbor. Total 24-PAH concentrations measured at these stations were generally similar to typical background levels in urban impacted sediments, which were found to contain less than 20,000 ng/g total PAH (based on the sum of 16 priority pollutant PAH compounds) (Stout *et al*., 2003). Highest PAH concentrations have consistently been found at Station DB14, with concentrations as high as 120,000 ng/g Total 24-PAH observed in 1998. PAH concentrations measured at

Harbor stations were similar to or slightly higher than those measured from relatively non-impacted sediments in Massachusetts Bay (Maciolek *et al.*, 2005).

While PAH concentrations at "Near" stations are generally higher than those found at "Far" stations, PAH concentrations and trends at individual stations are quite variable (Figure 3-3). With the exception of Station DB01, PAH concentrations at "Near" stations did not show any consistent nor significant temporal trends. Station DB01 is the only Dorchester Bay station to display significant decreases in PAH levels for each sampling year ($p<0.05$). A spike in PAH concentrations was observed at "Near" Stations DB13/T04 and DB14 and at "Far" station DB10 in 1998 followed by a significant decrease ($p<0.05$) in PAH concentrations in 2002 at these locations. This 1998 increase in PAHs may have been due to rainfall events experienced in 1998, just before sampling began (see Section 4.2.2 for further discussion).

The only other "Far" station to exhibit significant changes in PAH concentrations was DB06, which experienced significant increases in total PAHs between 1998 and 2002 ($p<0.05$). In contrast, at "Harbor" stations, while not statistically analyzed, concentrations appeared to remain relatively stable since 1994 (Harbor "T" stations were not sampled in 1990). Only "Harbor" Station T08 showed a slight concentration increase between 1998 and 2002, but 2002 levels were similar to 1994 levels.

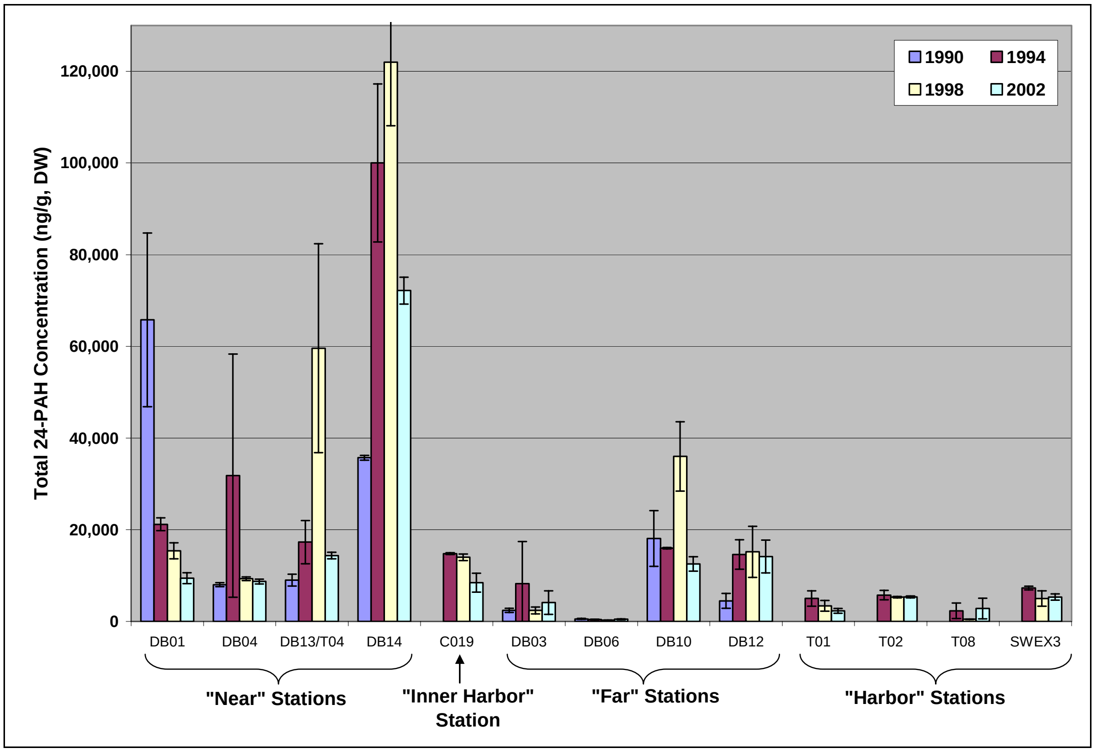

Figure 3-3. Total 24-PAHs in 1990, 1994, 1998, and 2002 Samples.

Note: Error bars are one standard deviation.

The types of PAH compounds present in the sediment can provide some information on sources and can help in the interpretation of temporal and spatial trends. Pyrogenic PAHs are derived from combustion of organic materials, including petroleum products, and are characterized by 3 to 5 ring, higher molecular weight PAH compounds, while petrogenic PAHs are derived from refined and unrefined petroleum products and are generally characterized by the one to three ring, lower molecular weight PAH compounds. While petrogenic PAHs are present in most marine sediments, they usually are less abundant than pyrogenic PAHs, except near point sources of petroleum hydrocarbons such as oil spills, refineries, or other sources of petroleum products (Neff, 2002).

Table B-2 in Appendix B presents the pyrogenic and petrogenic PAH data from 1994, 1998, and 2002 (Note: A limited number of PAHs were measured in 1990 making the calculation of pyrogenic and petrogenic PAH concentrations less accurate). Figure 3-4 shows the relative amount of pyrogenic PAHs as a percentage of total PAH and illustrates the changes in PAH distribution in the sediments. As expected, the percent pyrogenic PAH is in all cases is greater than 50% of the Total PAH and is generally at or above 70%. At "Near" stations, the percentage pyrogenic PAH has remained between 70 and 75% from 1994 to 2002, with the exception of Station DB13/T04 in 1998 and Station DB14 in all years. At DB14 the relative amount of pyrogenic PAHs decreased significantly ($p<0.05$) from 1994 levels. At the other "Near" stations as well as at most of the "Far" and "Harbor" stations, where the ratio has remained relatively stable, the sources of PAHs Harbor-wide may not have changed much since 1994.

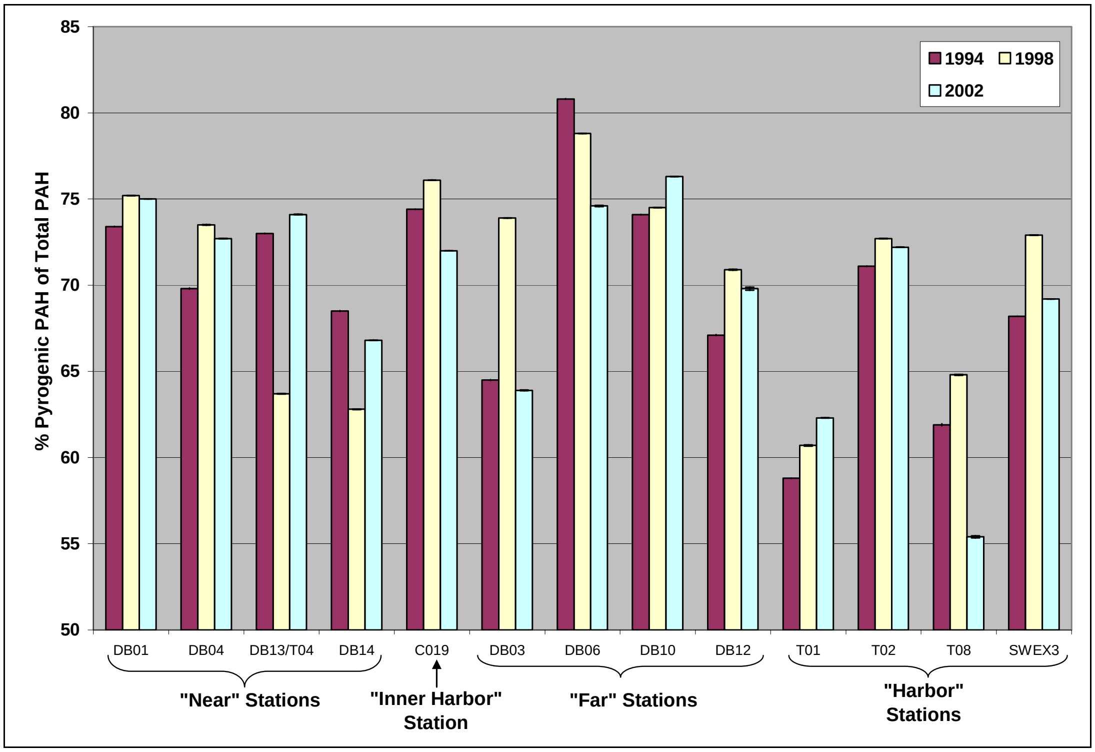

Figure 3-4. Pyrogenic PAHs as a Percentage of Total PAHs in 1994, 1998, and 2002 Samples.

Note: Error bars are one standard deviation.

3.2.2 PCB and Pesticide Concentrations

Total PCB and total DDT values for 1994, 1998 and 2002 are presented in Table B-2 in Appendix B and Figures 3-5 and 3-6 (PCBs and DDTs were not measured in 1990). Total PCBs is defined as the sum of the target PCB congeners (listed in Table 2-2), and Total DDTs is the sum of the six DDT compounds (2,4- and 4,4- isomers of DDT, DDD, and DDE). Statistical comparison of results from the three years measured are provided in Appendix C and discussed below where relevant.

Total PCB concentrations in 2002 ranged from a low of 4.53 ng/g dry weight ("Far" Station DB06) to 204 ng/g dry weight ("Far" Station DB10). DDT concentrations ranged from a low of 0.90 ng/g dry weight ("Far" Station DB06) to 57.3 ng/g dry weight ("Near" Station DB14). PCB and DDT concentrations were variable among "Near" and "Far" stations with the lowest concentrations found in "Harbor" stations. The high PCB levels at DB10 are not surprising given the major source of PCBs originating from the Neponset River, upstream from station DB10 (Zimmerman and Breault, 2003).

Both PCBs and DDTs decreased significantly ($p<0.05$) in 2002 relative to 1998 at all "Near" and "Far" locations except Stations DB03 and DB10. "Harbor" stations also appeared to show a marked decrease in 2002 relative to 1998. Overall, both PCB and DDT levels appear to be decreasing in sediments not only in the nearshore areas but in the Harbor as well.

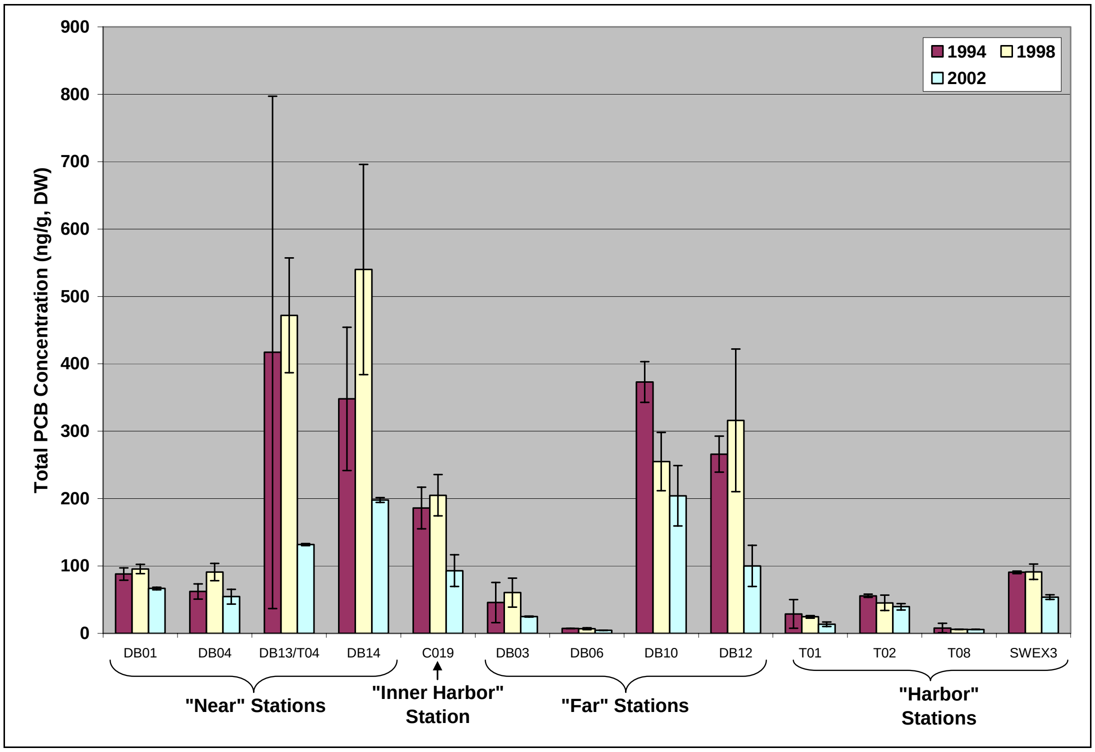

Figure 3-5. Total PCB Concentrations in 1994, 1998, and 2002 Samples.

Note: Error bars are one standard deviation.

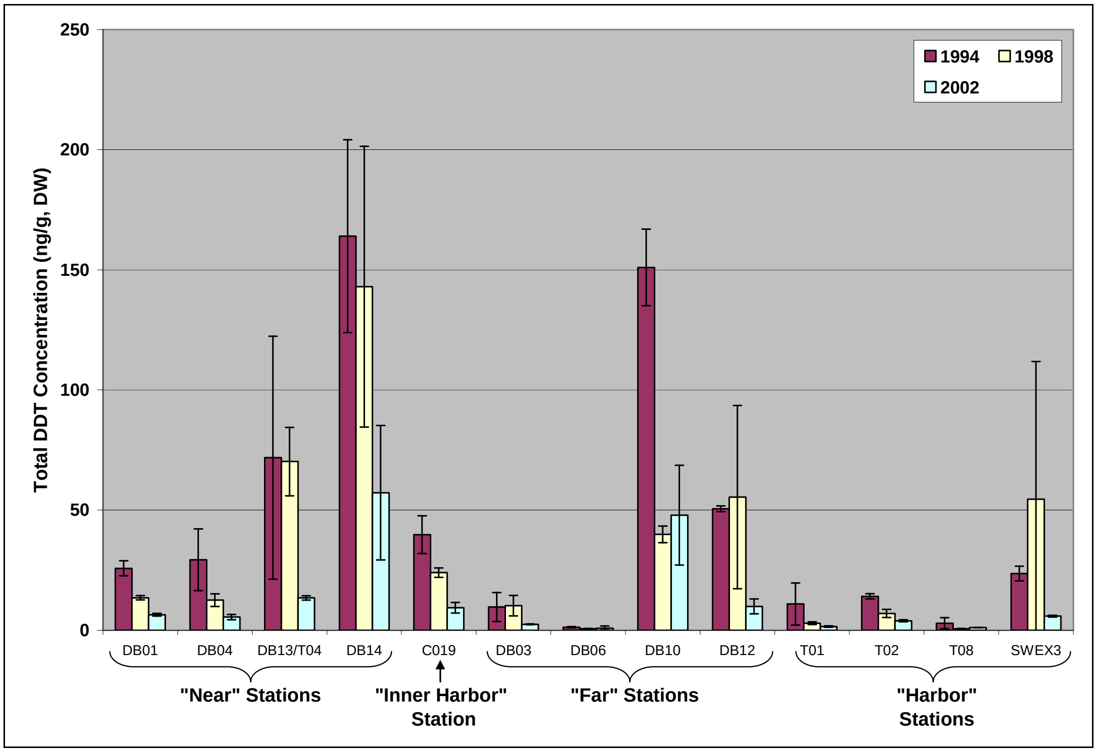

Figure 3-6. Total DDT Concentrations in 1994, 1998, and 2002 Samples.

Note: Error bars are one standard deviation.

While it is not surprising to find elevated levels of PCBs in sediments from stations within Boston Harbor, it is difficult to determine the sources. An evaluation of PCB congener patterns in “Near”, “Far” and “Harbor” stations using principal component analysis (PCA) revealed that PCBs in sediment from Station DB10 were different from other sediment samples (see Figure 3-7, Group A). PCBs from Station DB14 in 1994 and 1998 also showed a very different PCB pattern (Figure 3-7, Group B), indicating that the source of PCBs to that station in those years may have been localized, or at least different from the source to other stations and to the Harbor. The remaining stations grouped together (See Group C) indicating that the pattern of PCB congener distribution in these samples was similar and closer to the pattern of Aroclor 1254 (A-1254).

The PCB pattern in sediments from Station DB13/T04 in 1994 and 2002 and DB14 in 2002 fall between those of Station DB10 (Group A) and the remaining stations (Group C). This is consistent with the physical location of these stations: Station DB14 is located in the mouth of the Neponset and DB13/T04 is located just beyond Station DB14. This does not explain the very different pattern found at Station DB14 in 1994 and 1998 and at Station DB13/T04 in 1998 (Group B) which would indicate a secondary source of PCBs to those stations in those years (possibly the nearby CSOs) was more significant than that of sediments coming down the Neponset River. The storm event of 1998 may also have played a role.

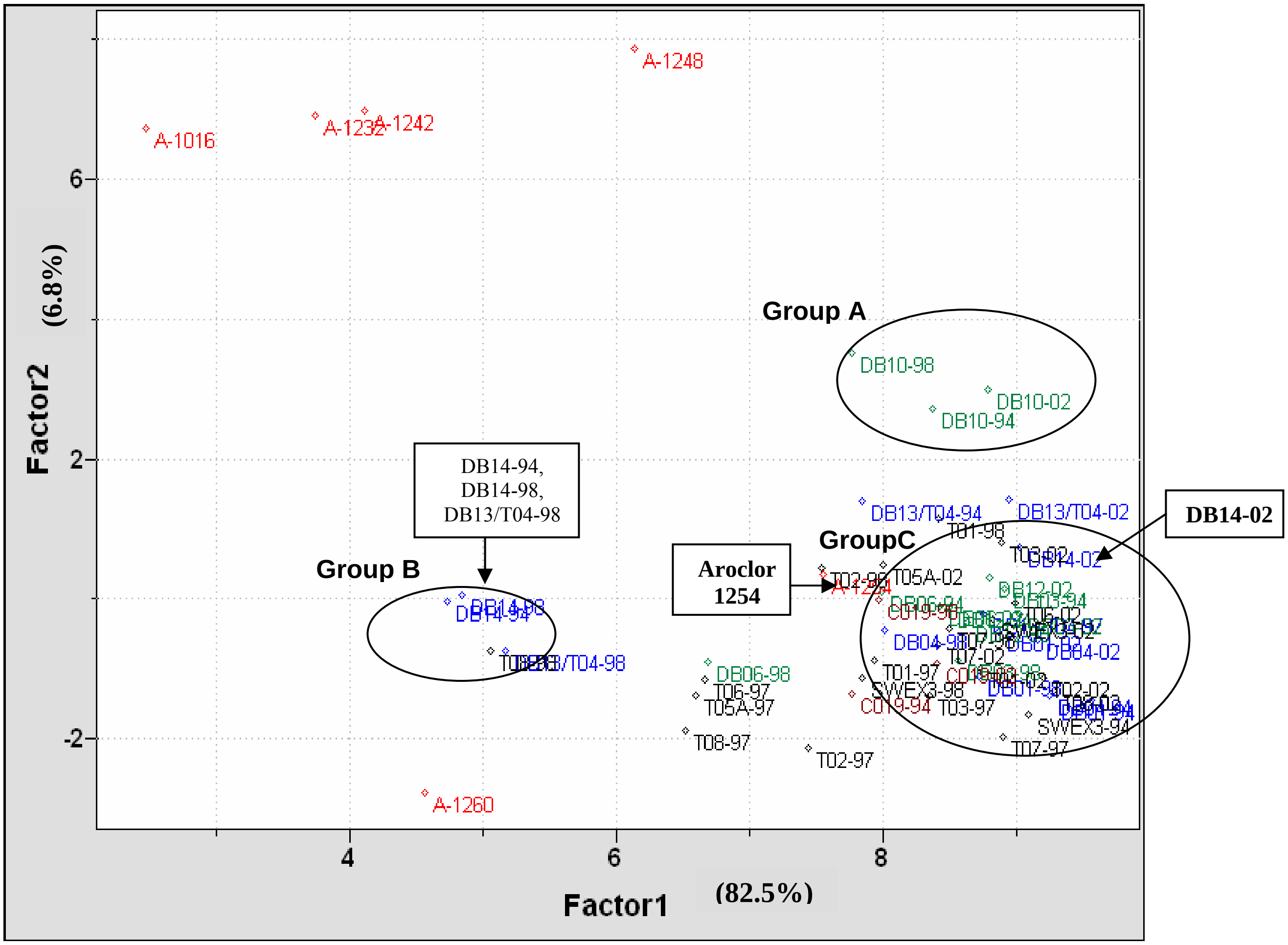

Figure 3-7. Principal Component Analysis of PCB Congener Distributions Relative to Aroclors 1016, 1232, 1242, 1248 1254, and 1260.

Note: **Group A** : DB10-94, 98, 2002; **Group B**: DB14-94, 98; DB13/T04-98 and T08-98; **Group C**, remaining “Near", "Far" and "Harbor" stations.   A = aroclor

3.3 Sewage Tracer Results (LABs, Coprostanol, *Clostridium perfringens*)

Linear alkyl benzenes, coprostanol and *Clostridium perfringens* are all parameters associated with sewage and wastewater and can be used to trace sewage inputs to Dorchester Bay and Boston Harbor through CSOs or wastewater treatment facilities. Concentrations of these parameters measured in 1990, 1994, 1998, and 2002 are summarized in Table B-2 in Appendix B. Statistical analyses (one-way ANOVAs) were performed to compare concentrations of total LABs, coprostanol, and *Clostridium perfringens* by station over time. Results of these analyses are presented in Appendix C and discussed below where relevant.

Linear alkyl benzenes (LABs) are the aromatic by-products produced during industrial synthesis of LAB sulfonates, which are widely used anionic surfactants in detergents. Sources of LABs in Boston Harbor include waste from industrial production, as well as household and commercial cleaning activities. The environmentally relevant LABs can be divided into five groups: phenyldecanes (C_{10}-LAB), phenylundecanes (C_{11}-LAB), phenyldodecanes (C_{12}-LAB), phenyltridecanes (C_{13}-LAB), and phenyltetradecanes (C_{14}-LAB). Total LABs are defined as the sum of C_{10}-, C_{11}-, C_{12}-, C_{13}-, and C_{14}-LABs.

As shown in Figure 3-8, the highest LAB concentrations were consistently observed at “Near” stations. The highest concentrations in all years, except 1998, were found at “Near” Station DB14. Station DB13/T04 showed a significant increase ($p<0.05$) in LAB concentrations between 1994 and 1998 and between 1998 and 2002 and Station DB14 showed a significant increase ($p<0.05$) in LAB levels between 1998 and 2002. Aside from these stations, the majority of stations, including “Far” and “Harbor” stations, showed decreases in LAB concentrations between the 1994 and 1998 sampling years and similar concentrations in 1998 and 2002. This trend was not isolated to Dorchester Bay, however, as illustrated by the consistent, steady decline in LABs at Station C019 located in Boston’s Inner Harbor.

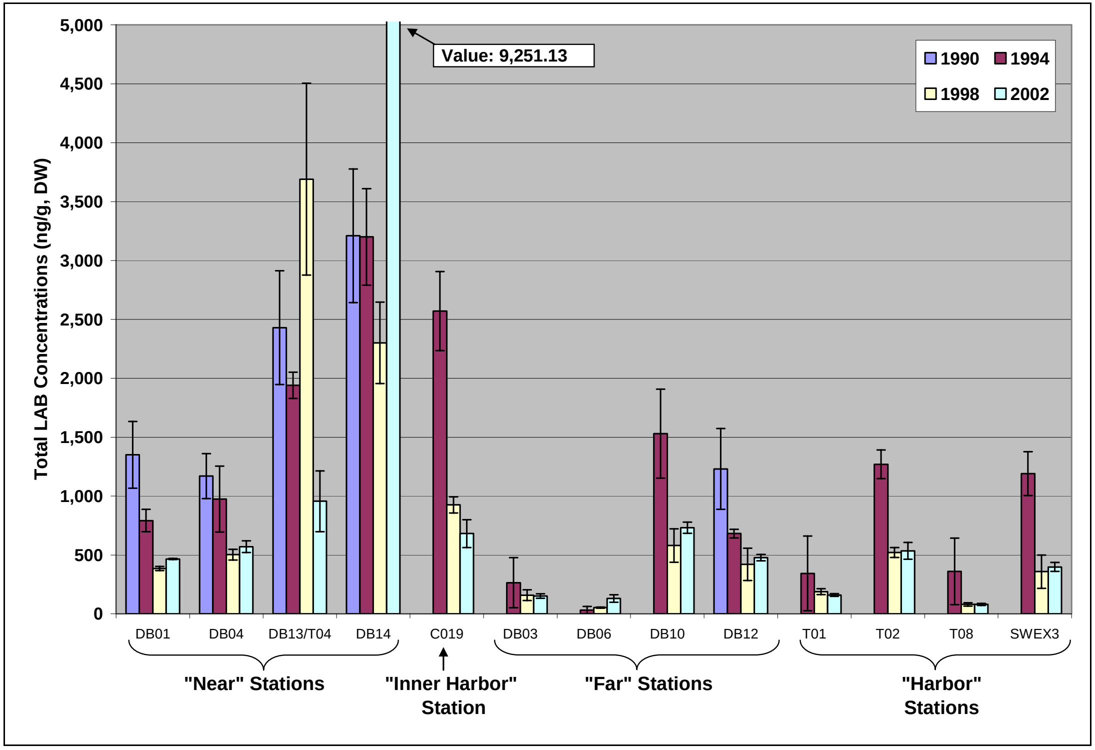

Figure 3-8. LAB Concentrations in 1990, 1994, 1998, and 2002 Samples.

Note: Error bars are one standard deviation.

Coprostanol is a sterol that is found in human feces and can be used as an indicator of sewage in sediments. It is particularly useful as a tracer because its concentration is generally unaffected by chlorination and aeration and because it persists in anoxic sediments. The coprostanol data represent the total concentration of two coprostanol isomers: coprostanol (5β-cholestan-3β-ol) and epicoprostanol (5β-cholestan-3α-ol). The coprostanol concentrations measured in 1990, 1994, 1998, and 2002 are summarized in Table B-2 in Appendix B and are shown in Figure 3-9. Trends in coprostanol concentrations mirrored those of LABs with the highest coprostanol concentrations found at “Near” Station DB14 (except for 1998) and the next highest concentrations observed at “Near” Station DB13/T04. At most stations (“Near”, “Far” and Harbor) concentrations appeared to progressively decrease after 1994 with two exceptions: Stations DB13/T04 and DB14 in 1998. As observed with LABs, coprostanol concentrations spiked in 1998 at station DB13/T04 and then returned to similar “Near” station concentrations in 2002. Coprostanol concentrations at “Near” Station DB14, also significantly increased in 1998 (a nearly 50% increase), but unlike at Station DB13, concentrations continued to increase (though not statistically significantly) in 2002. The overall 2002 decreasing coprostanol levels, especially those observed in the "Far" and "Harbor" stations, may be a result of the Nut Island closing and the Deer Island outfall diversion, with inputs no longer directly entering the Harbor from the treatment plant as of September 2000.

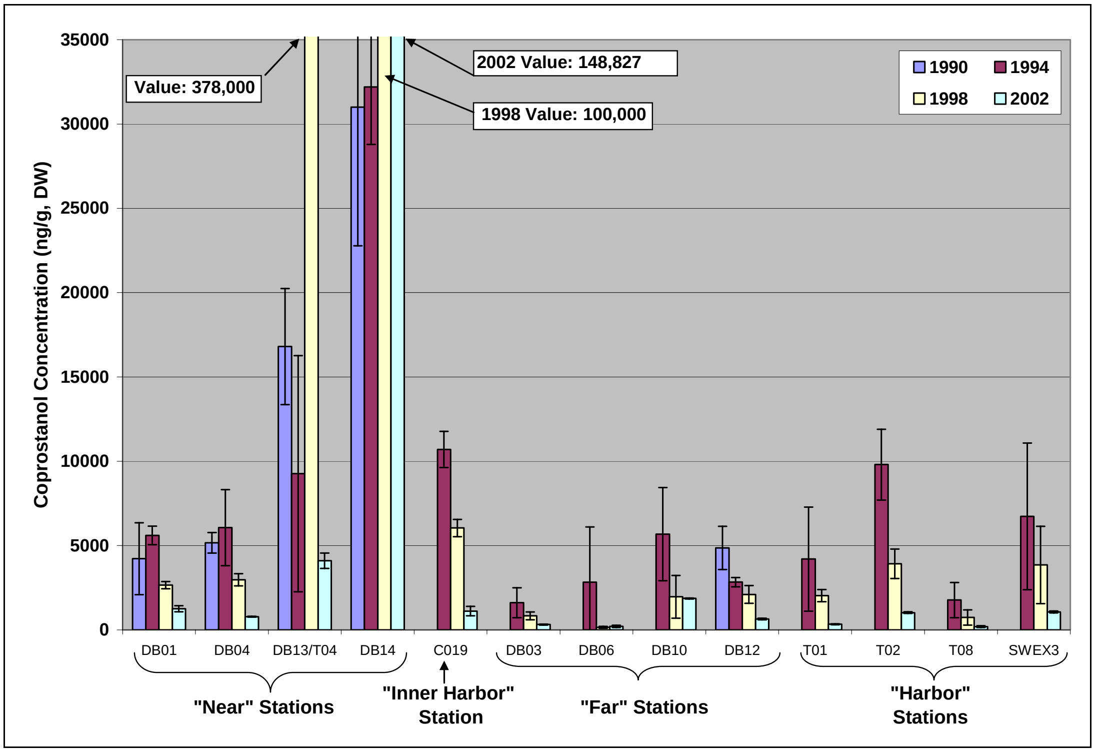

Figure 3-9. Coprostanol Concentrations in 1990, 1994, 1998, and 2002 Samples.

Note: Error bars are one standard deviation.

LAB/Coprostanol ratios can indicate if there are year-to-year changes in the indicator sources. In the late 1980s, Eaganhouse *et al.* (1988) and Eaganhouse and Sherbloom (1990) found that LAB/Coprostanol signatures in Dorchester Bay sediments matched the industrially enhanced signatures from the Nut Island sludge solids which were very different from the nearby Fox Point CSO discharge (BOS-089) or Deer Island sludge, indicating that localized impacts may be limited. With some exceptions, the LAB/Coprostanol ratios observed from 1990 through 1998 are generally similar at "Far" and "Harbor" stations within a given year but show a marked change in 2002 from previous years (Figure 3-10). Assuming similar sources and transport processes, these ratios appear to indicate a Harbor-wide source that is consistent across stations. However, localized impacts were possibly observed at two "Near" Stations (DB13/T04 and DB14) where a decrease in the LAB/Coprostanol ratio was observed in 1998. This change in ratio is a result of a significant increase in coprostanol concentrations relative to LABs in 1998. This localized change may be a result of an increase in sewage related discharge from the nearby CSOs as a result of the major rain event that occurred in 1998 just prior to sampling that year.

On a regional basis, a large increase in LAB/Coprostanol ratios was observed in 2002. Ratios increased to levels well above those observed in both 1994 and 1998 at all stations, except "Near" stations DB13/T04 and DB14. This Harbor-wide increase in LAB/Coprostanol ratios was a result of a significant decrease in coprostanol concentrations at most stations. This apparent Harbor-wide decrease in coprostanol levels between 1998 and 2002 was most likely a result of the closure of the Nut Island plant in 1998, coupled with the diversion of the Deer Island outfall to nine miles offshore in 2000.

While LAB/Coprostanol ratios also increased at stations DB13/T04 and DB14 in 2002 relative to 1998, 2002 levels at these stations were similar to or lower than levels observed in 1994. It is likely that at these stations, localized impacts from nearby CSOs have played a part in sediment quality as evidenced by the consistently different LAB/Coprostanol signatures relative to other "Near", "Far", and "Harbor" stations sampled during the study years.

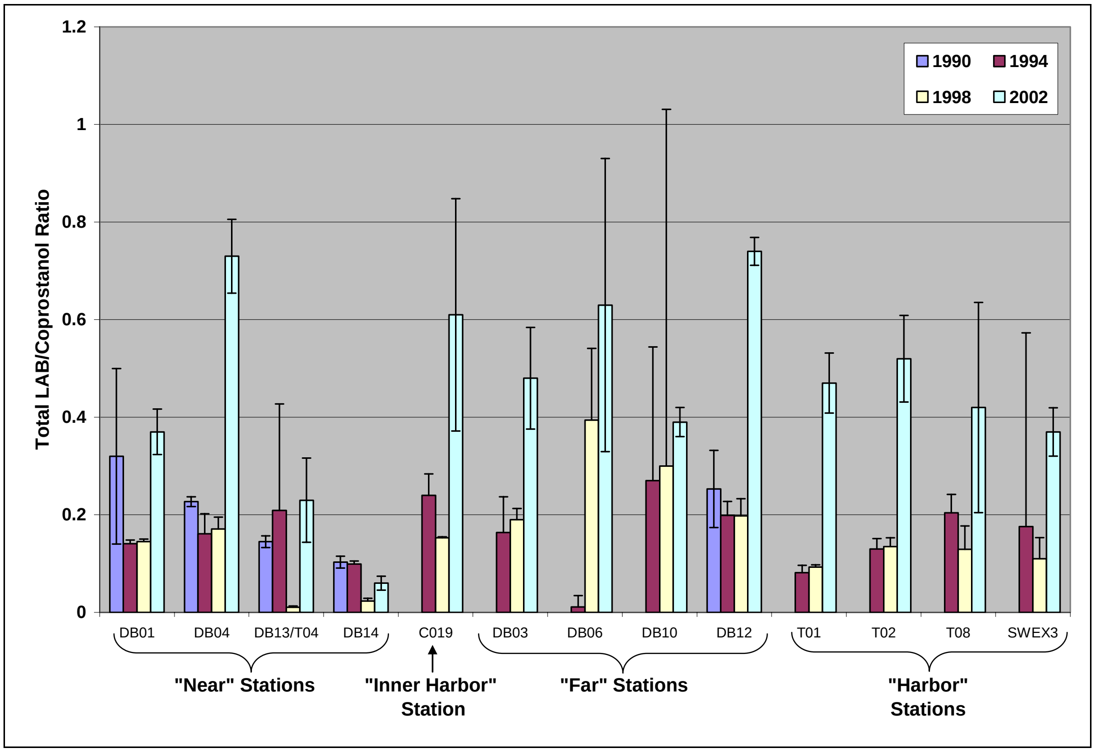

Figure 3-10. LAB/Coprostanol Ratios for 1990, 1994, 1998, and 2002 Samples.

Note: Error bars are one standard deviation.

Clostridium perfringens, a spore-forming bacteria, can be found in the intestines of humans and other mammals and, therefore, can be a useful sewage tracer in sediments. *Clostridium perfringens* data for all samples collected since 1990 are presented in Table B-2 in Appendix B and Figure 3-11.

Clostridium levels have dropped considerably at "Near" stations and most "Far" stations since 1990 (*Clostridium* was not measured at "Harbor" stations in 1990). Since 1994, however, *Clostridium* levels have not significantly changed at any "Near" or "Far" stations with the exception of a significant decrease at "Far" Station DB06 in both 1998 and 2002, and a significant increase in 2002 at "Near" Station DB14.

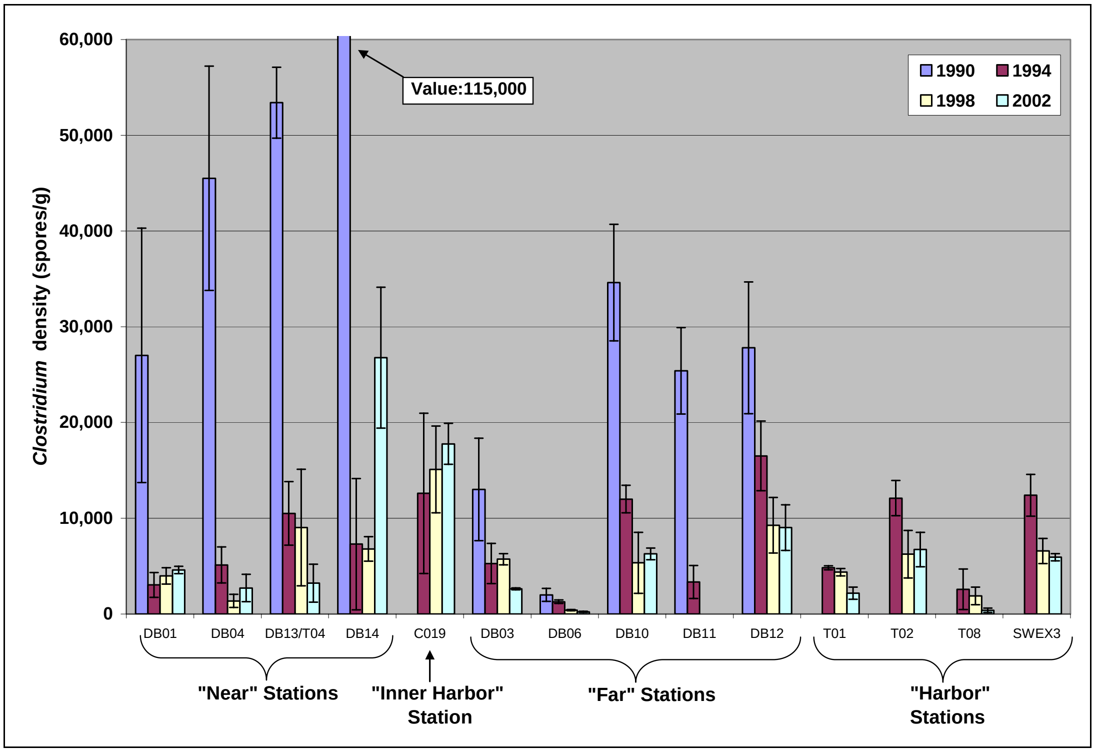

Figure 3-11. Densities of *Clostridium perfringens* in 1990, 1994, 1998, and 2002 Samples.

Note: Error bars are one standard deviation.

3.4 Metal Contaminant Results

Sediment samples were analyzed for silver (Ag), aluminum (Al), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), mercury (Hg), nickel (Ni), lead (Pb), and zinc (Zn). Concentrations of these parameters measured in 1990, 1994, 1998, and 2002 are summarized in Table B-3 in Appendix B. Statistical analyses (one-way ANOVAs) were performed to compare concentrations of metals over time by station as μg/g dry weight. Al and Fe results are presented on a percent dry weight basis. The non-normalized data for all stations are provided in Figure 3-12 through Figure 3-21. Results of the statistical analyses are presented in Appendix C and discussed below where relevant.

3.4.1 Cadmium, Copper, Lead, and Zinc

Cadmium (Cd), copper (Cu), lead (Pb), and zinc (Zn) levels are shown in Figures 3-12 through 3-15. In general, the “Near” sampling stations had higher average concentrations of each of the metals than “Far” or “Harbor” sampling stations in 2002, and overall, concentrations of these metals either remained similar to or showed an apparent decrease from 1994 to 2002. “Near” Station DB14 had the highest concentrations of Cd, Pb, and Zn of all the stations in 2002. Despite DB14 having the highest concentrations of these three metals, the 2002 Cd, Pb, and Zn concentrations are still less than the 1998 concentrations, with statistically significant lower concentrations ($p<0.05$) of Cd and Pb. Cu concentrations at Station DB14 showed a statistically significant increase in 2002 relative to 1994 levels, although 2002 concentrations were similar to those measured in 1990. Other statistically significant changes in metals concentrations over time include decreases in 2002 relative to 1998 for Cd at “Near” Stations DB13/T04 and DB04 and at “Far” Station DB10 and Pb and Zn decreases at Station DB13/T04. In general, Cd, Cu, Pb, and Zn concentrations in 2002 were similar to or lower than those measured in 1994 at most “Near”, “Far”, and “Harbor” stations.

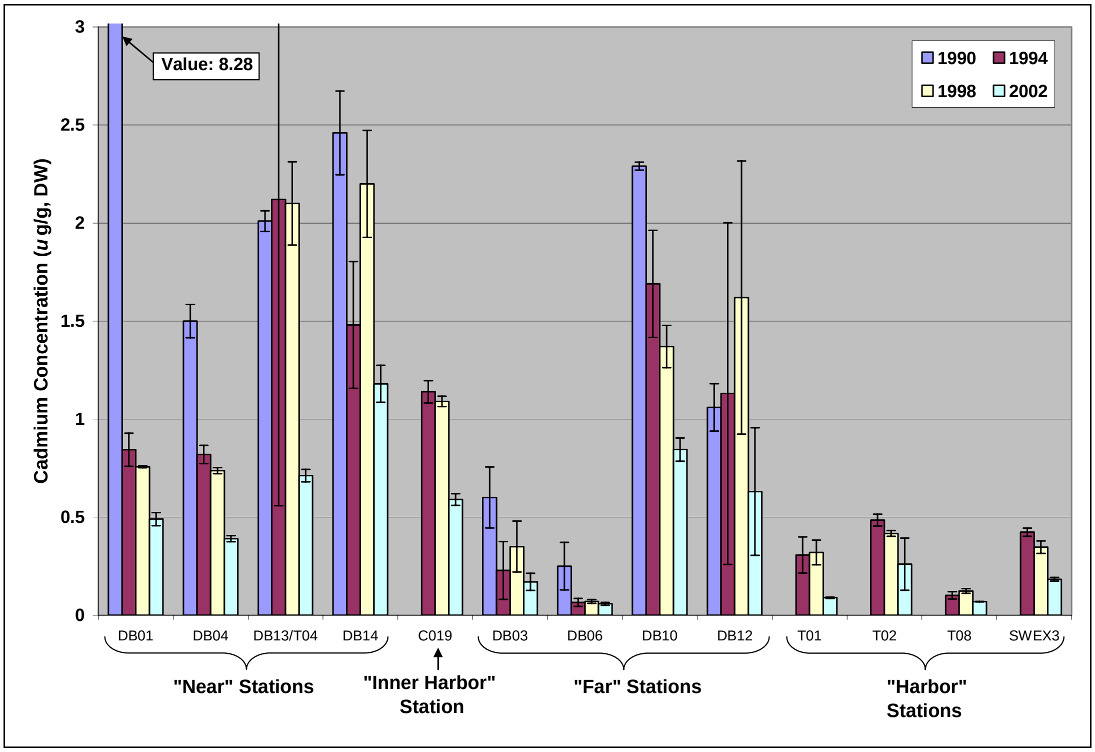

Figure 3-12. Cadmium Concentrations in 1990, 1994, 1998, 2002 Samples.

Note: Error bars are one standard deviation.

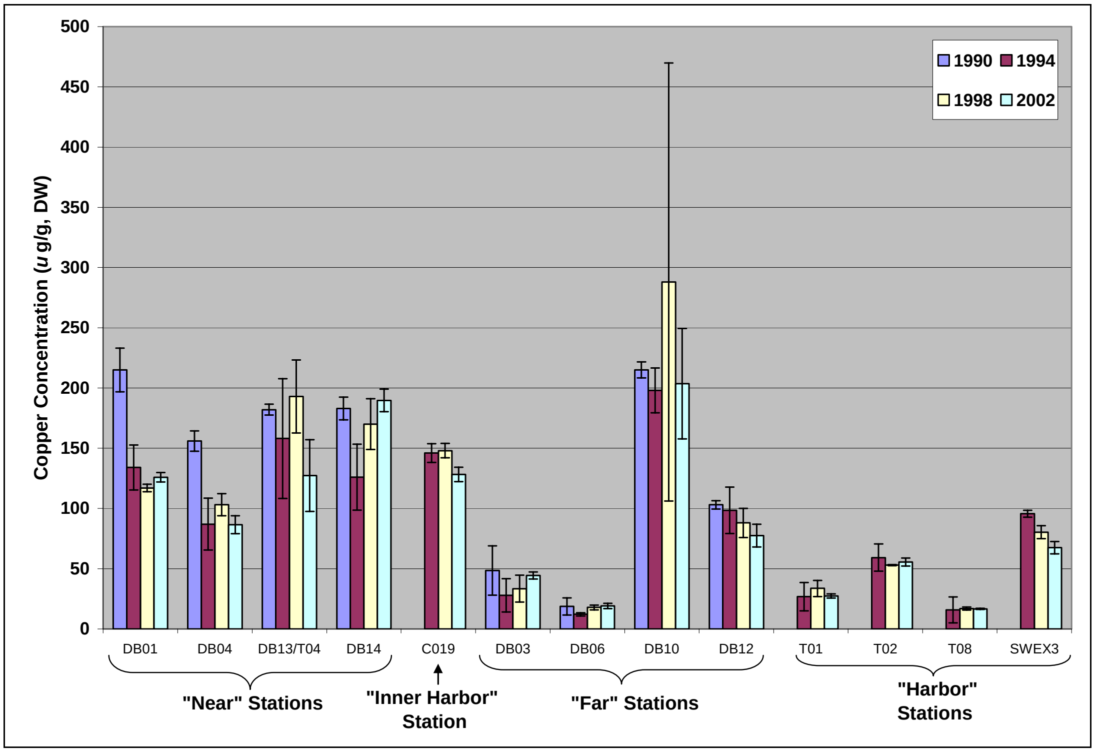

Figure 3-13. Copper Concentrations in 1990, 1994, 1998, and 2002 Samples.

Note: Error bars are one standard deviation.

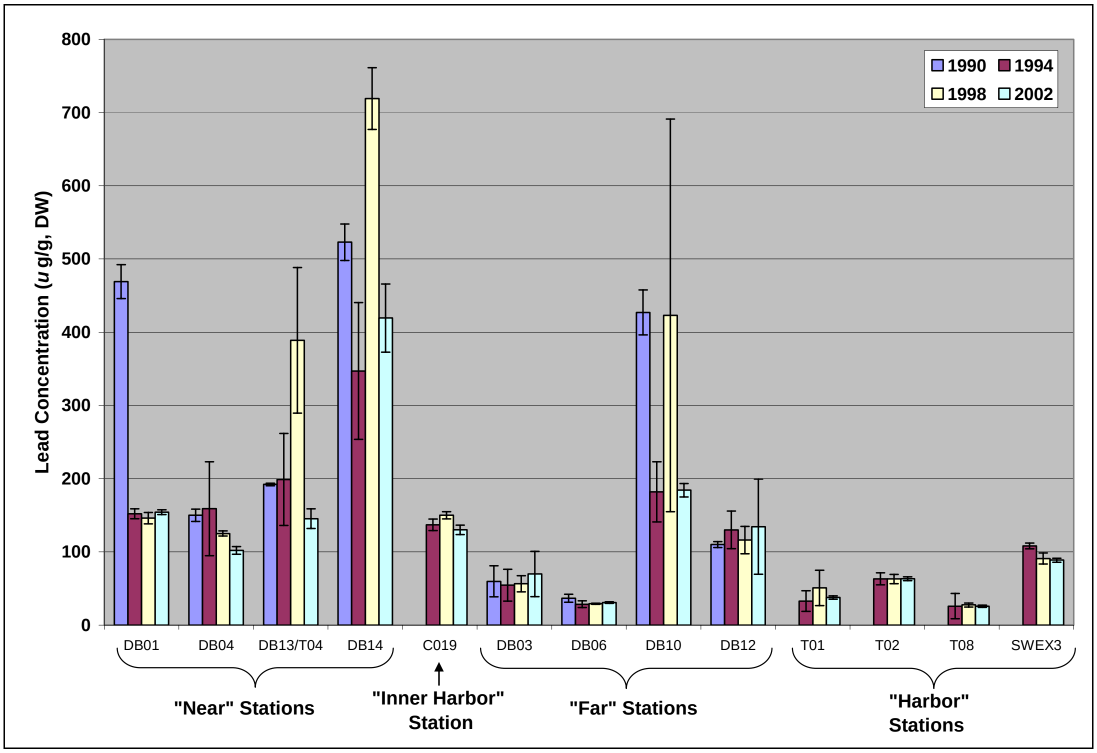

Figure 3-14 Lead Concentrations in 1990, 1994, 1998, and 2002 Samples.

Note: Error bars are one standard deviation.

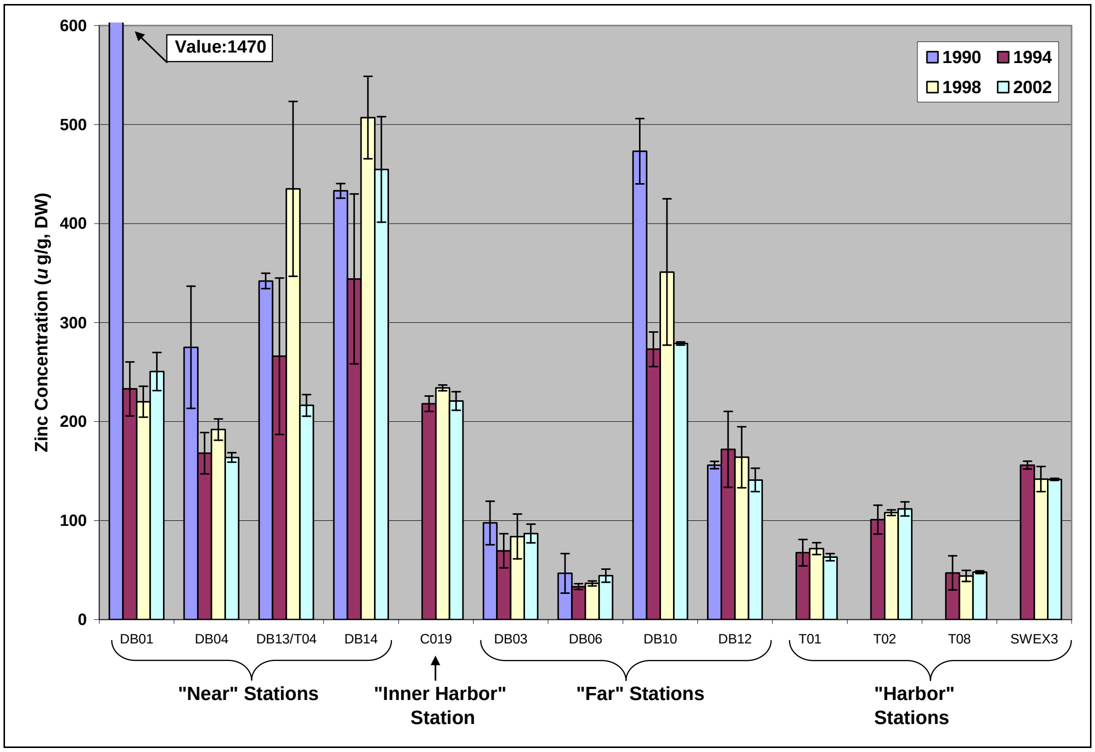

Figure 3-15. Zinc Concentrations in 1990, 1994, 1998, and 2002 Samples.

Note: Error bars are one standard deviation.

3.4.2 Chromium, Nickel, Mercury, and Silver

Chromium (Cr), nickel (Ni), mercury (Hg), and silver (Ag) levels are shown in Figures 3-16 through 3-19. Average concentrations of Cr, Ni, Hg, and Ag were found to be similar at most "Near" and "Far" stations with the exception of Stations DB03 and DB06 which have had consistently lower concentrations overall and across the years. Unlike Pb, Cd, Cu, and Zn temporal trends, Cr and Ni concentrations showed no significant decreases in 2002. Hg concentrations were variable over time and showed a significant decrease from 1998 values at Station DB13/T04. Ag, however, showed significant decreases from 1994 levels at three "Near" stations (DB01, DB04 and DB13/T04) and at two "Far" stations (DB10 and DB12). This is consistent with an overall decrease in Ag concentrations Harbor-wide (Bothner *et al*., 1998).

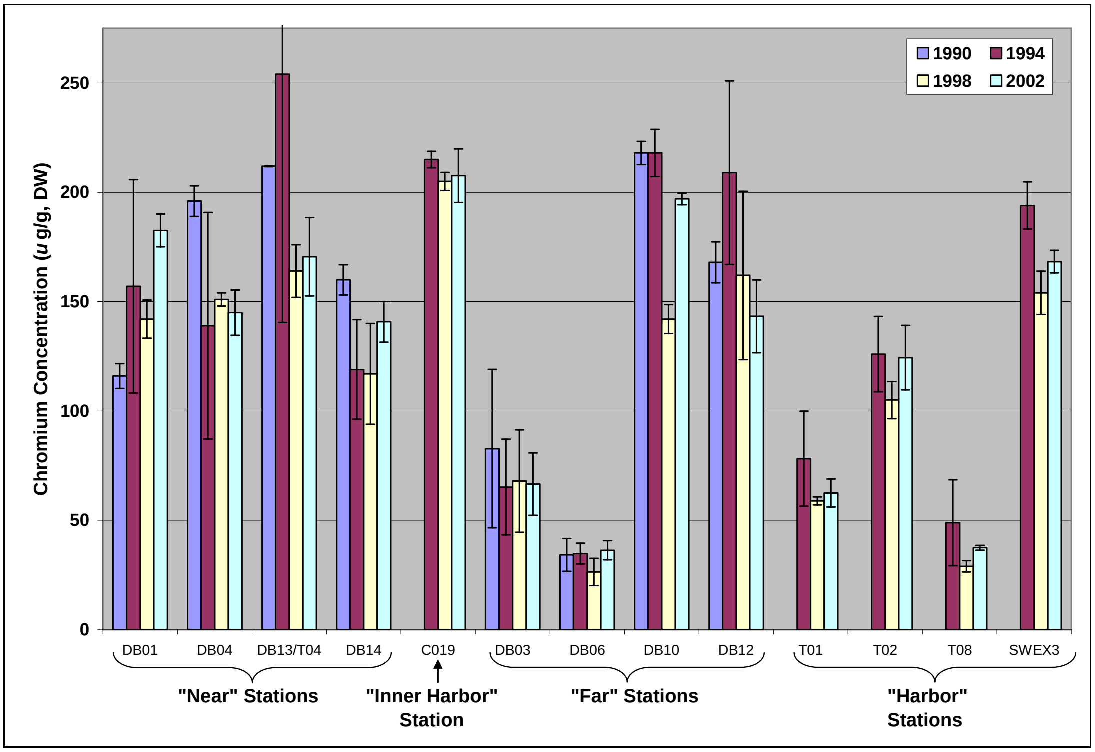

Figure 3-16. Chromium Concentrations in 1990, 1994, 1998, and 2002 Samples.

Note: Error bars are one standard deviation.

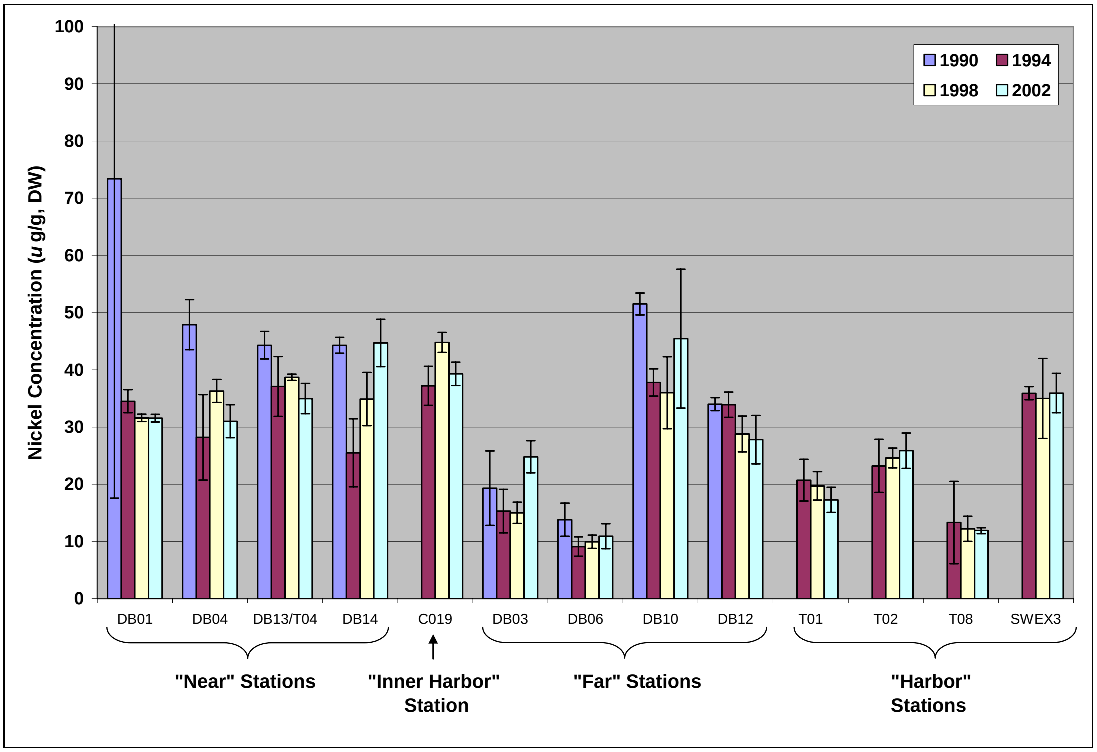

Figure 3-17. Nickel Concentrations in 1990, 1994, 1998, and 2002 Samples.

Note: Error bars are one standard deviation.

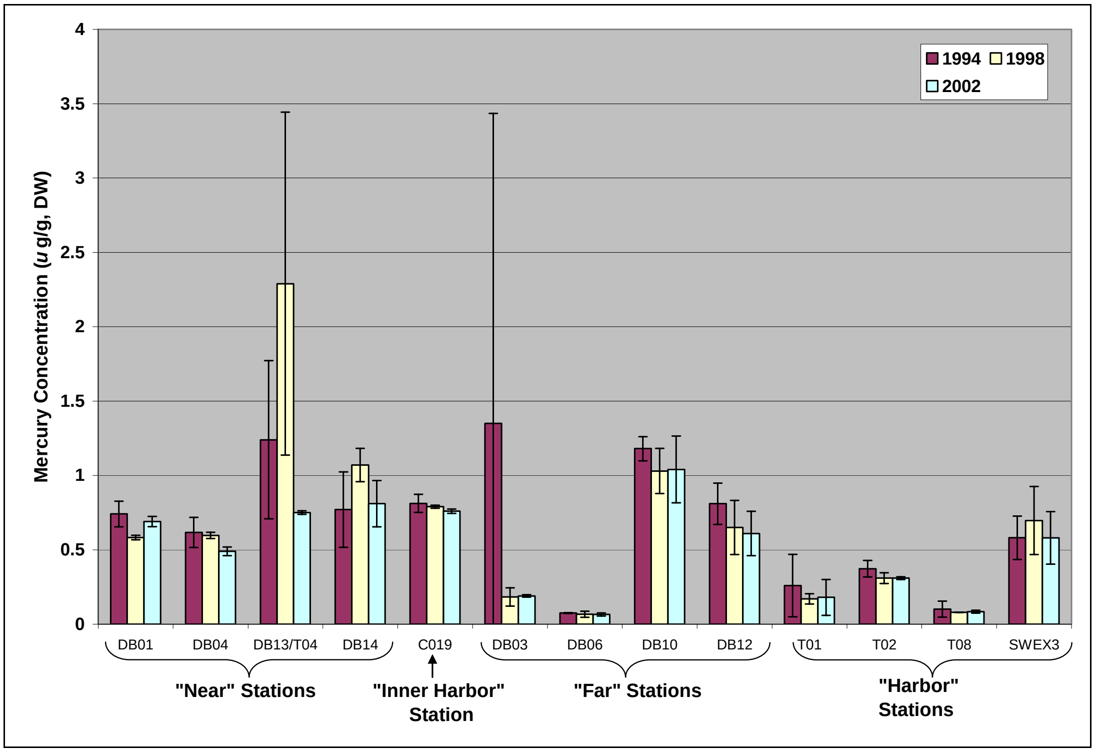

Figure 3-18. Mercury Concentrations in 1994, 1998, and 2002 Samples.

Note: Error bars are one standard deviation.

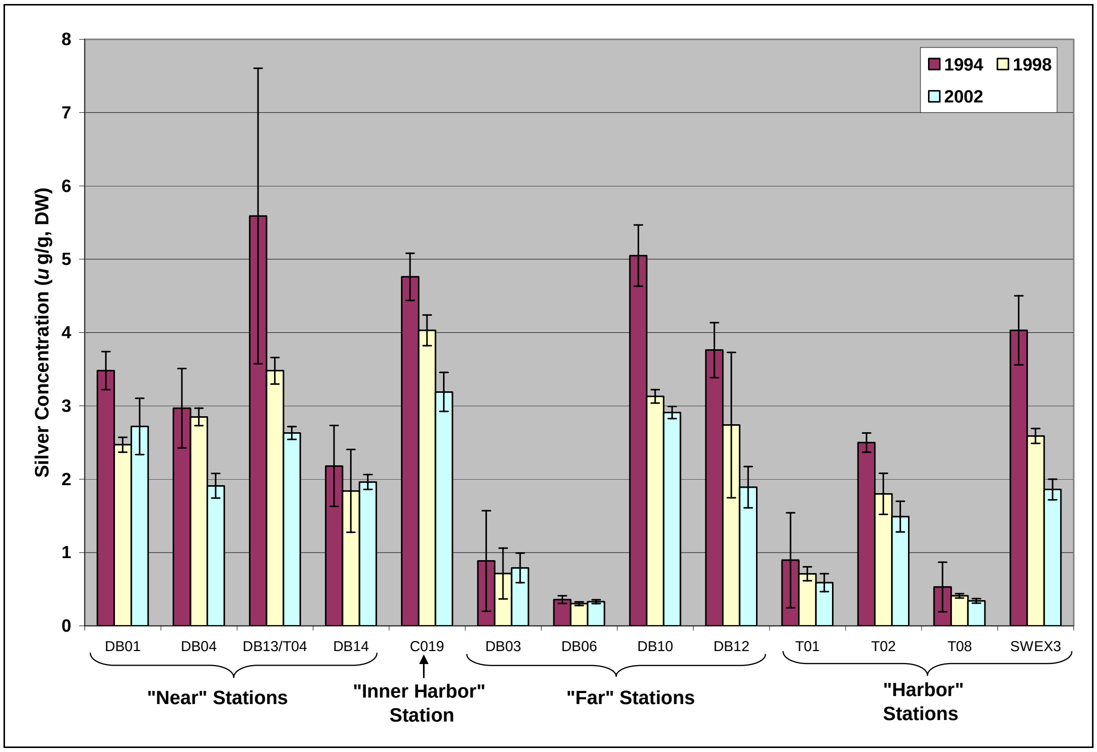

Figure 3-19. Silver Concentrations in 1994, 1998, and 2002 Samples.

Note: Error bars are one standard deviation.

3.4.3 Aluminum and Iron

Aluminum (Al) and iron (Fe) concentrations, reported as percent dry weight, are shown in Figures 3-20 and 3-21, respectively. Al and Fe are both crustal elements and in the absence of significant anthropogenic sources or major changes in sedimentology, would not be expected to show temporal changes. Both Al and Fe levels remained similar at most stations from 1990 through 2002, with lower levels found at two “Far” stations, DB03 and DB06, consistent with the fact that these two stations have the lowest percent fines (Figure 3-1). The only statistically significant ($p<0.05$) change noted in aluminum measurements was at “Far” Station DB10, where concentrations increased significantly between 1998 and 2002, which corresponds to a significant increase in fines at this station in 2002. Fe also showed a statistically significant increase at DB10 in 2002.

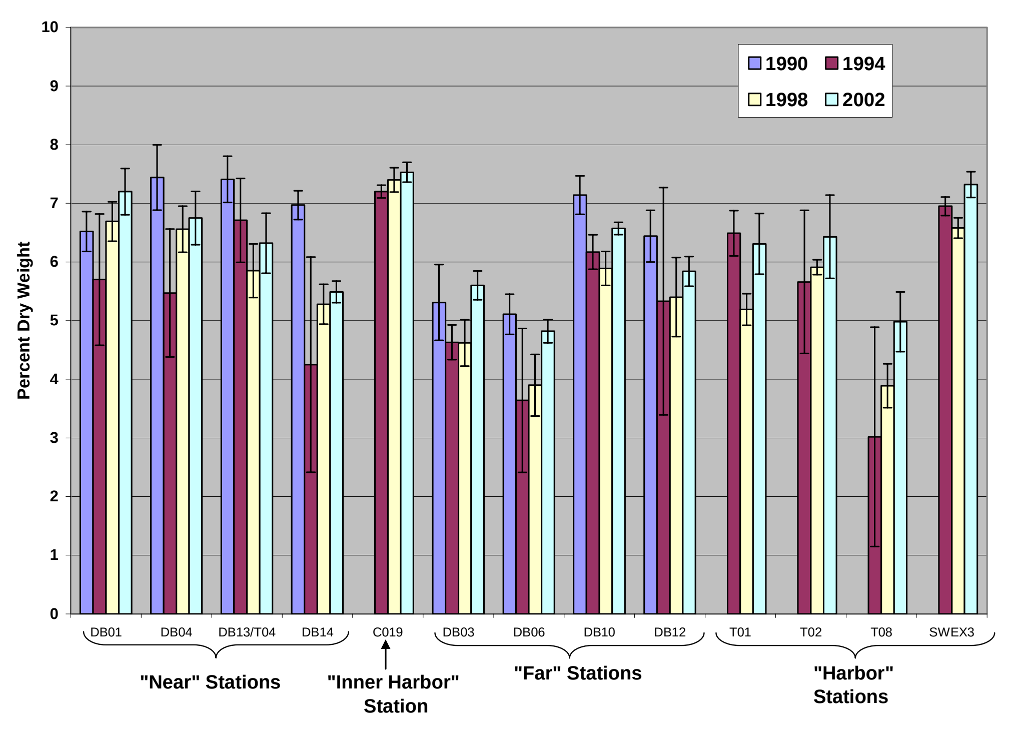

Figure 3-20. Aluminum Concentrations in 1990, 1994, 1998, and 2002 Samples.

Note: Error bars are one standard deviation.

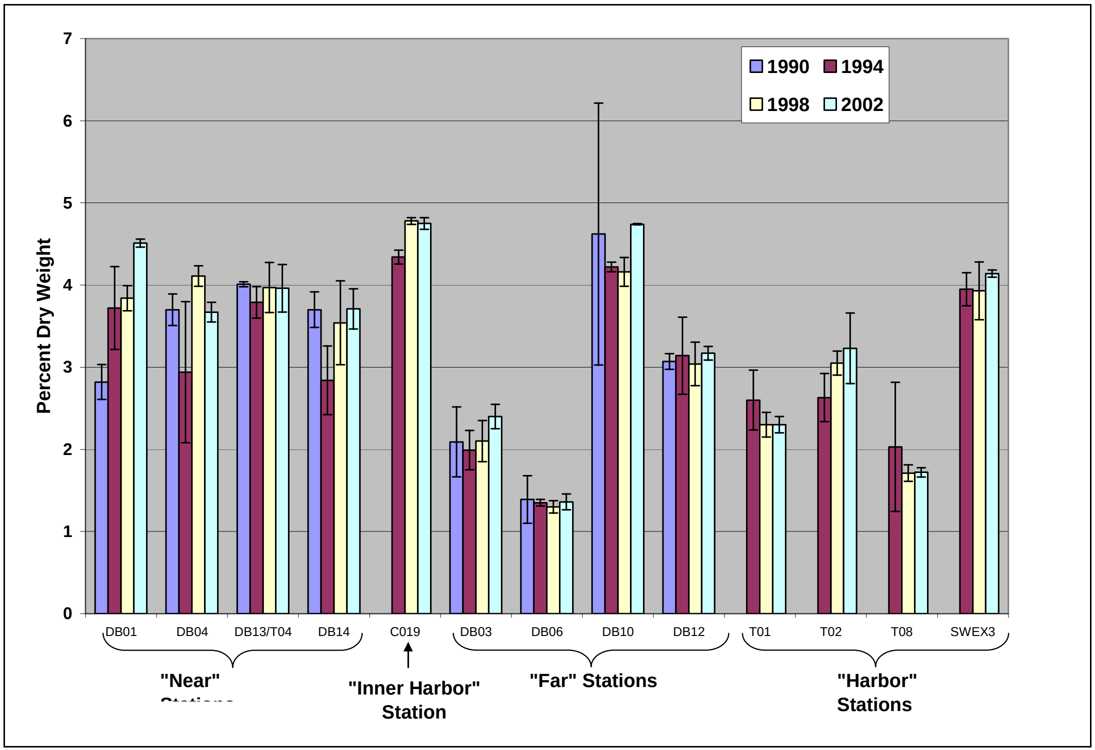

Figure 3-21. Iron Concentrations in 1990, 1994, 1998, and 2002 Samples.

Note: Error bars are one standard deviation.

4.0 DISCUSSION

4.1 Overview of Sediment Quality in Boston Harbor

Like other urbanized coastal embayments in the Northeast United States, Boston Harbor has a long history of use as a repository for domestic and industrial wastes. As early as the seventeenth century, sewers funneled household wastes and stormwater runoff to numerous discharge locations in the Harbor. In 1833, local ordinances allowed human waste to be discharged into the evolving combined sewer system (Dolin, 1990). During this same period, wide scale filling of the Harbor's tidal areas inhibited the transport of these wastes away from the near-shore waters of the Harbor. In response to a severe cholera epidemic in the 1860s, plans were developed to upgrade the sewer system by centralizing stormwater and untreated domestic/commercial waste discharge off Moon Island in Quincy Bay. The success of this project led to the expansion of sewer services to neighboring communities and to the building of additional outfalls off Deer Island in 1895 and Nut Island in 1904. Primary treatment plants were built at these locations in 1968 and 1952, respectively (Havens and Emerson/Parsons Brinkerhoff, 1983). However, these facilities soon lapsed into disrepair, and even when functioning properly, mixed digested sludge back into the effluent for discharge into the Harbor. This made the plants relatively ineffective at removing contaminants from the wastestream.

Despite the improvements in the sewer system, a burgeoning population and the impacts of industrialization throughout the first half of the twentieth century increasingly stressed Boston Harbor, as it did many urbanized coastal areas (Stolzenbach and Adams, 1998). In response, federal legislation was passed in the early 1970s mandating wastewater facilities to upgrade to secondary treatment, providing substantially greater removal of most chemical and domestic wastes. Further federal regulation of toxic chemicals and banning of contaminants like PCBs and DDTs in the 1970s and 80s led to the continued reduction in toxic discharges over the past 30 years.

The MWRA was created in 1985 with a mandate for short-term and long-term remediation activities to decrease anthropogenic contamination discharge into the Harbor. During the late 1980s these included more rigorous enforcement of toxic contaminants entering the wastewater system from industry, the cessation of sludge scum discharge into the Harbor, and more reliable chlorination of wastewater discharge. In December 1991 a major milestone was met as all sludge dischargers into the Harbor ended. Throughout the 1990s, pumping capacity in the system increased allowing for more Combined Sewer Overflow flows to be diverted to the newly improved Deer Island treatment plant. The first batteries of secondary treatment came on line in late 1997 and early 1998. The completion of the inter-island tunnel resulted in the transfer of all flow from the Nut Island treatment plant to be pumped, treated, and discharged from the Deer Island facility in July 1998. This allowed for most wastewater effluent to receive secondary treatment. All treated wastewater discharge to Boston Harbor ended in September 2000 as the new deepwater outfall was opened in Massachusetts Bay. Continued improvements in wastewater quality were the result of the third battery of secondary treatment coming on line in March 2001, implementation of corrosion control in the water supply system which reduced copper and lead leaching into the source water, and continued work with dental and medical facilities to reduce mercury discharge into the sewer system.

Evidence of the effectiveness of these source reduction actions have been reported for Boston Harbor from sediment core and other data. Other cores from the region indicate that contaminant input to the sediments (documented with lead profiles in sediments) gradually increased from the latter half of the nineteenth century, peaked in the post World War II era, and has decreased since (Bothner *et al*., 1998). Bothner *et al*. (1998) report the level of lead and other metal contaminants in Boston Harbor decreased substantially between 1977 and 1993. Support for this conclusion was documented by analysis of trace metals in surface sediments from four stations in the outer portions of Boston Harbor, contaminant profiles from cores collected in depositional areas of the harbor, and a compilation and analysis of historical data from the harbor. A decrease of 46% ± 12% in background corrected lead levels in the upper two cm of core samples was observed and similar decreases in chromium, copper, mercury, silver, and zinc reported. Bothner *et al.* (1998) suggest these decreases are due to cessation of sewage sludge discharge to the Harbor in 1991 by MWRA, source reduction efforts by industry, improved wastewater handling and treatment, and for lead, diminished use in gasoline beginning around 1973.

4.2 Contaminant Levels in Boston Harbor and Massachusetts Bay

Recent data (1994 to 2002) for contaminant chemicals in the surface sediments (upper two cm) of Boston Harbor and Massachusetts Bay show a wide range in concentration within a contaminant class (e.g., persistent organic chemicals such as PAH, PCB, DTT) and for individual metals (Hunt *et al.,* 2005). From a system wide perspective, contaminant levels are generally lowest in offshore Massachusetts and Cape Cod Bays and highest in the inner portion of Boston Harbor and Quincy Bay. The highest concentrations for most contaminants are consistently found in Dorchester Bay and the inner Boston Harbor. However, variability within a given station and in sampling time is high and often reflects differences in bulk sediment characteristics such as grain size distribution and total organic carbon content. This is especially evident in the stations located near the MWRA outfall in Massachusetts Bay, an area known to be highly heterogeneous and dynamic with respect to sediment properties, and in the Dorchester Bay where several storm water and combined sewer discharges (CSOs) are located.

Long-term MWRA sediment monitoring data show that on average contaminant levels in Dorchester Bay are 2.5 to 6 times higher than those in the outer Harbor. Total DDT and PCB show the largest difference ranging up to six fold higher in Dorchester Bay. In contrast, PAH, Cu, Pb, and Cd concentrations are ~2.5 times higher in Dorchester Bay than the outer Harbor. This pattern is apparent in data from 1994 and also from 2002. Time series data from these regions also show apparent decreases in the average level for several contaminants. For example, PAH, PCB, DDT, mercury, cadmium, and silver each decrease on average since 1994 in both the inner Harbor, outer Harbor, and Dorchester Bay. These trends are compared in Figures 4-1 and 4-2 which show Ag and DDT concentrations from 1994 to 2002. In contrast to these contaminants, Pb and Cu levels (Figure 4-3) do not appear to have decreased in the Harbor since 1994. Thus, some contaminants appear to continue to decrease in Harbor sediments since the early 1990s. However, the variability in the data and limited number of samples from each area makes the observed decrease statistically insignificant. Moreover, systematic trends in the data are difficult to prove due to the high variability and changes in response to events such as storms (Lefkovitz *et al*., 2000), especially for contaminants such as Pb, Cd, and PAH that are associated with urban runoff. The major storm of June 1998 likely contributed to the apparent slight average increase in the Dorchester Bay data from 1998 relative to the longer term trend. Regardless, observations from individual stations and for areas within the Harbor through 2004 suggest many contaminants in Boston Harbor sediments have continued to experience the downward trend through the mid 1990s, as observed by Bothner *et al.* (1998).

Within the context of the observed spatial distributions and apparent temporal trends, an understanding of the major sources of contaminants to Boston Harbor and sediment transport processes affecting the fate of these contaminants is important for understanding the role of the CSO discharges on Harbor sediment quality. One of the most difficult problems in environmental monitoring is to measure the relative contributions and impacts of different sources of pollution. CSOs are never the sole source of pollutants. Besides the treatment plants and CSOs, known sources of contaminants to the Harbor include atmospheric deposition, stormwater runoff (including street runoff), upstream river sources, boats, and deposition and transport of pollutants originating elsewhere in the Harbor. For example, precipitation can have a large impact on CSO discharges as well as on contaminant concentrations in sediments near CSO outfalls during years with heavy amounts of precipitation resulting in larger CSO discharges. It is impossible to accurately determine the exact proportion of a contaminant originating from a specific CSO, although relative magnitudes of a pollutant originating at a source may be determined if sufficient information is available.

Historically, sewage effluent dominated the contaminant sources to Boston Harbor, contributing at least 75 percent of the metals and PAH loads in the early 1990s (Alber and Chan, 1994). CSOs and stormdrains contributed a very small percentage (<10%) of the estimated metals and PAH load. Throughout the 1990s the load from the MWRA treatment plants decreased as advanced primary and then secondary treatment was brought on line. By 2000, the contributions from this source were essentially eliminated, elevating the relative importance of the other known sources.

The aspect of transport and fate of contaminants introduced into in Boston Harbor was considered at length in Stolzenbach and Adams (1998). They concluded that Boston Harbor acted as a sink for most contaminants and particularly noted that areas near sources and with weaker transport functions (e.g., lower energy input, less bottom shear stress, faster particle settling rates) tend to retain particles and associated contaminants. Conversely areas that have stronger transport functions (i.e., erosional areas) located in the entrance channels of the outer Harbor were less likely to be the final repository of contaminants. The areas within the Harbor that are typically depositional in nature are close to the sources or are shallow regions with limited advective movement and dispersion of the sediments. These areas typically accumulate sediment and contaminants, are characterized by high organic carbon content, and are dominated by clays and silts (fine grained sediments). Of particular note relative to this CSO study are the findings of Wallace *et al.* (1991) who studied the areas near the Fox Point CSO discharge and concluded that that a CSO source alone could not account for the observed sedimentation rate and contaminant levels in nearby Savin Hill Cove. They thus concluded that this area of the Harbor tended to focus fine particles and contaminants from other areas of the Harbor and would retain these signals for longer periods.

Given the types and location of the present dominant sources of contaminants to the Harbor (atmospheric deposition, rivers, stormwater runoff, CSO discharge), it is not surprising that the distribution of contaminants is as it is (high closer to the terrestrial sources and in areas that focus sediment accumulation) and that certain chemicals, especially those that are slow to degrade in the environment (PAHs) or are highly particle-reactive (e.g., copper and lead) display only slow responses to the Harbor clean up. It is less clear why some contaminants such as DDT, silver, and cadmium are apparently decreasing more rapidly. This in part may be due to the nature of the sources and geochemical changes occurring as the sediments transition to lower levels of reactive carbon (Zago *et al.*, 2001) and hence less reducing and more oxidizing conditions. These considerations are important to the ability to detect and understand the contaminant response in sediments near CSO discharges to facility upgrades and termination of discharges, particularly in Dorchester Bay which may serve to accumulate contaminants from throughout the Harbor system and will respond more slowly that those areas only accumulating contaminants from nearby sources.

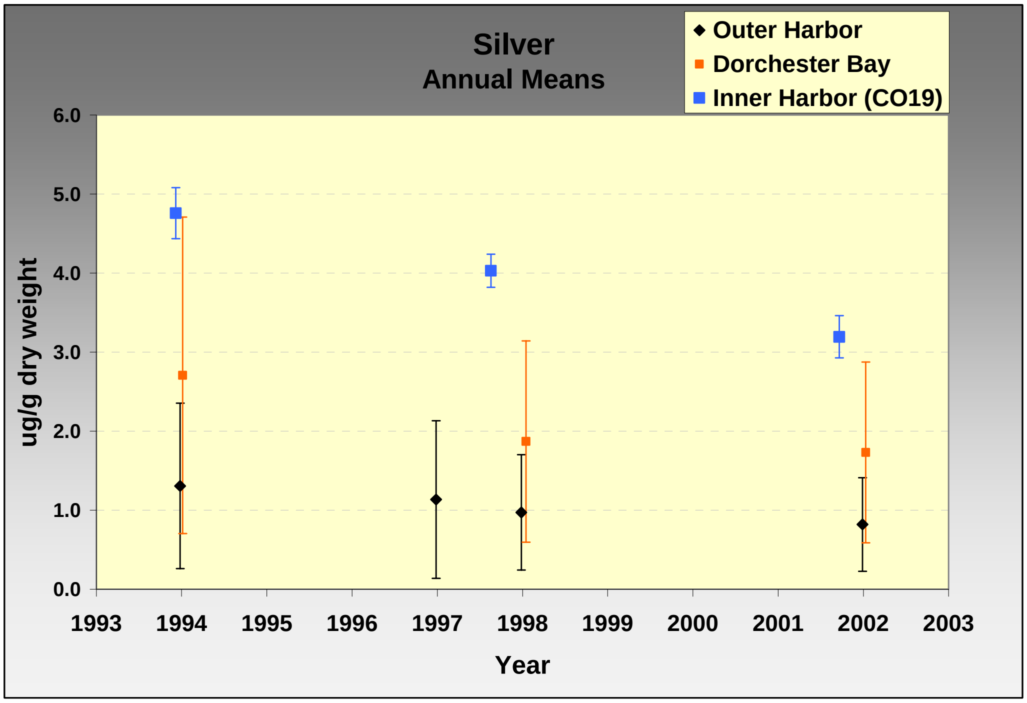

Figure 4-1. Silver concentrations from Boston Harbor surface sediments are low in the outer Harbor and generally appear to be declining since the early 1990s.

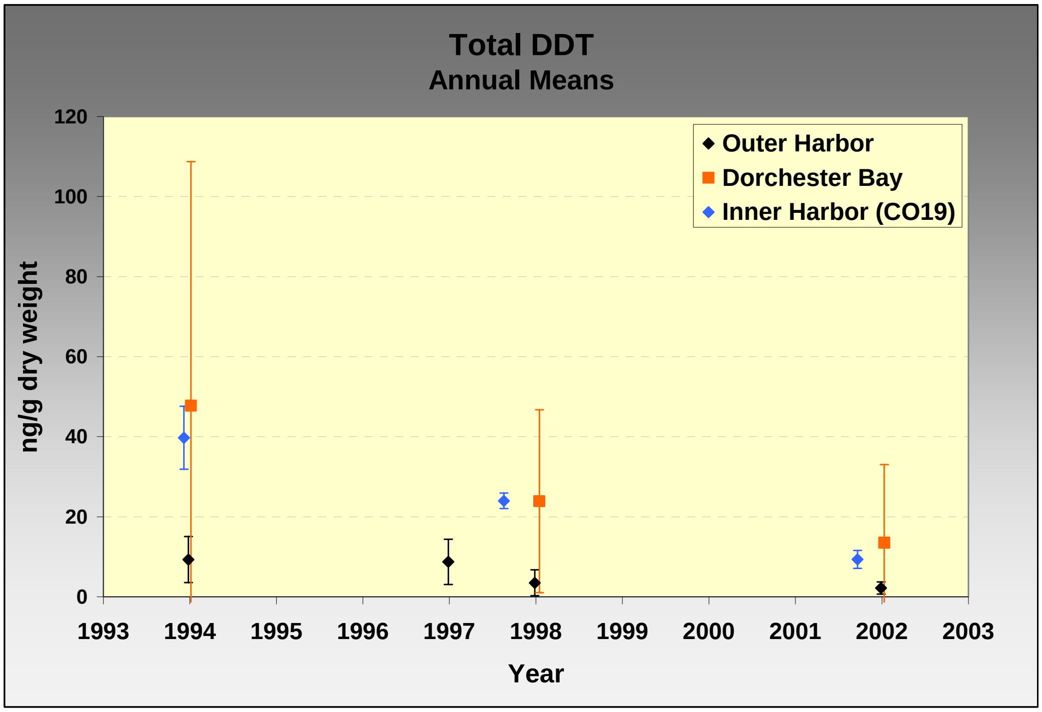

Figure 4-2. Total DDT concentrations in Boston Harbor surface sediments are low in the outer Harbor and generally appear to be declining since the early 1990s.

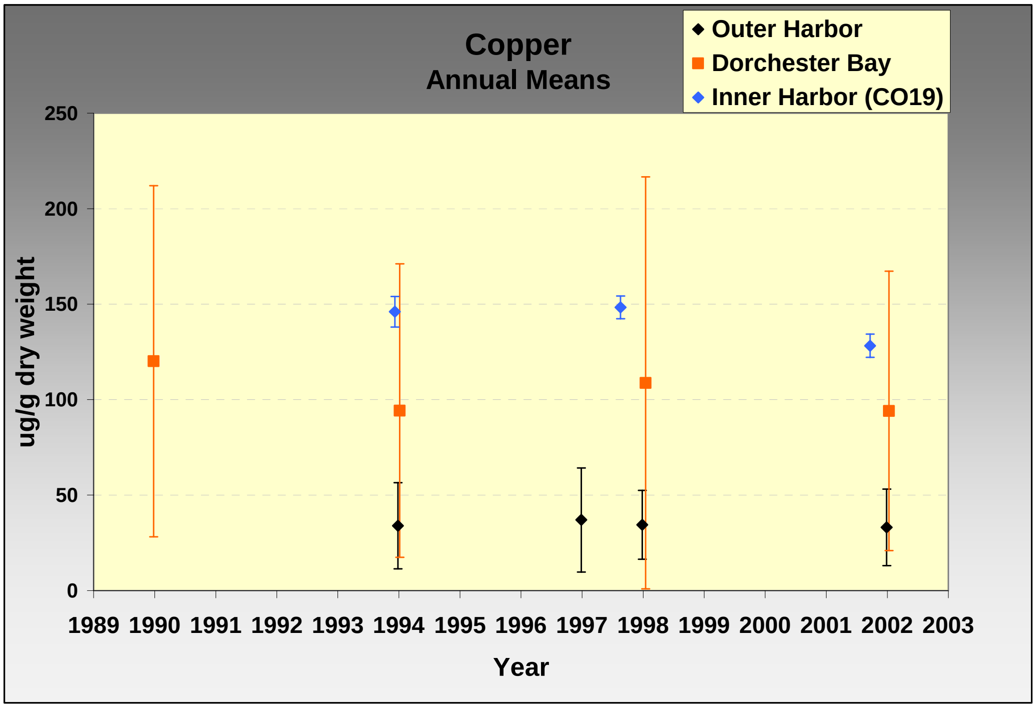

Figure 4-3. Copper concentrations in Boston Harbor surface sediments are high in Dorchester Bay and the Inner Harbor with little evidence of decline since the early 1990s.

4.3 CSO Influence on Sediment Quality

Many factors can control the quality of sediments, especially in an urban setting where both anthropogenic and naturally-occurring contaminant sources are present. Physical factors such as proximity to source and depositional nature of the sedimentary environment influence the fate of contaminants. Grain size and organic carbon levels also play a large role in controlling levels of contaminants in marine sediments. Moreover, bottom conditions relating to the oxidative state of the sediments also affect the fate of contaminants in sediments. Under anoxic conditions, some metals such as manganese are released, and others become tightly bound to sulfides and are sequestered (Hunt *et al.*, 2005). The abundance and types of organisms living in the sediment can also play a part in sediment quality through advective mixing and irrigation, which distribute contaminants from the surface sediments to deeper sediments and visa versa. Precipitation and resulting flows into the Harbor from CSOs, storm drains, rivers, and terrestrial run-off can also have an impact on sediment quality both locally and regionally.

CSOs are just one anthropogenic influence on sediment quality in Boston Harbor. Determining whether contaminant inputs from CSOs affect sediment quality and whether the impact is local or regional is difficult. Temporal variability in contaminant levels in sediments confounds the discussion of CSO influence. The following discussion of the data collected during CSO studies from 1994, 1998, and 2002 presents the correlation of measured contaminants to TOC and fines in stations adjacent (“Near”) to CSOs and stations removed (“Far”) from CSOs to help determine if there are measurable differences attributable to proximity to CSOs. Comparison of contaminants at these “Near” and “Far” stations by study year, using the student T-test, is also made to see if localized impacts are discernable. In addition, one-way ANOVAs were performed to evaluate parameter trends over time at “Near” and “Far” stations.

4.3.1 Correlation of Contaminant Concentrations to TOC and Fines

Total organic carbon (TOC) and grain size, presented here as percent fines (percent clay and silt), are often used to characterize sediment type. The relationship of TOC and percent fines in estuarine and marine sediment not impacted by anthropogenic sources of contaminants, generally show good correlation; the coarser the sediment (lower percent fines) the lower the organic carbon content. Figures 4-4 and 4-5 illustrate the relationship between TOC and fines at “Far” and “Near” stations measured as part of this study from 1990 to 2002. As is typically observed in marine sediments, increases in total organic carbon concentration were positively correlated with increases in percent fines at the “Far” stations. The relationship of percent fines to TOC at the “Near” stations is not as well defined and appears to be negatively correlated (Figure 4-5). The proximity of some sampling stations to CSO outfalls may help to explain the variations in percent fines and TOC over the years.

TOC and percent fines can also be predictive of contaminant concentrations in sediments. Correlation of contaminants measured in 1994, 1998, and 2002 were evaluated using Pearson Product Moment Correlations to determine parameter correlations with TOC and percent fines. Table 4-1 presents a summary of the Pearson Product Moment correlation coefficients for TOC and fines for 1994, 1998, and 2002 combined, relative to metals, Total DDT, Total PCB, Total LAB, Total PAH, petrogenic PAH, pyrogenic PAH, *Clostridium*, and coprostanol.

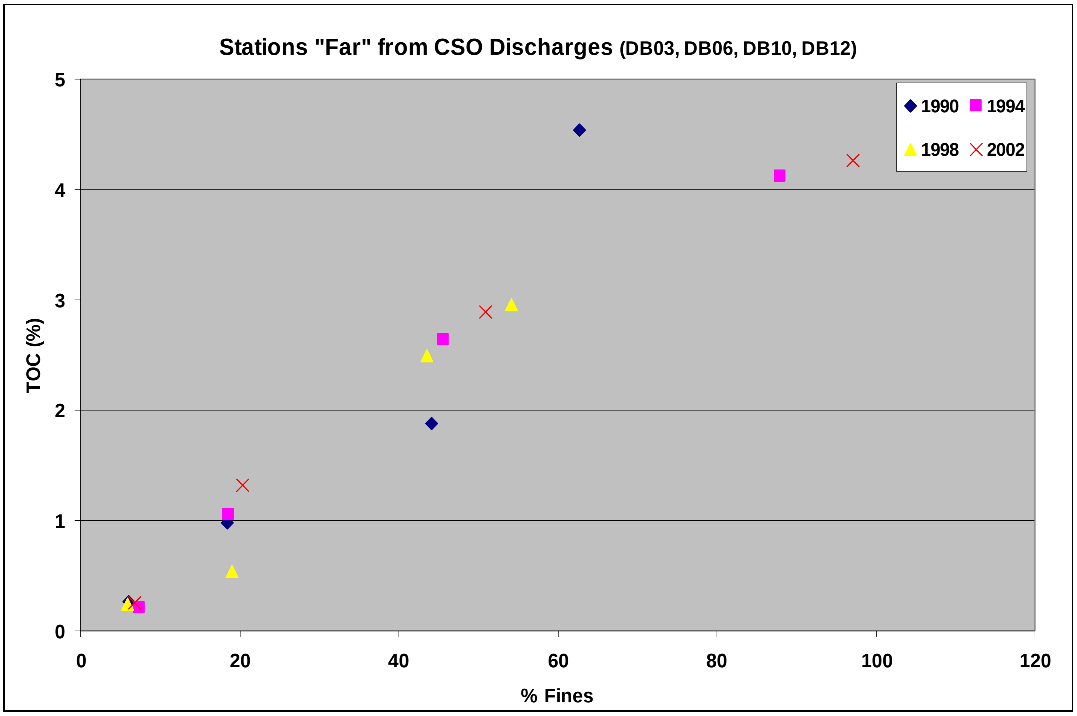

Figure 4-4. Mean TOC vs. Percent Fines for “Far” Stations.

Note: Data are from stations common to all four sampling years.

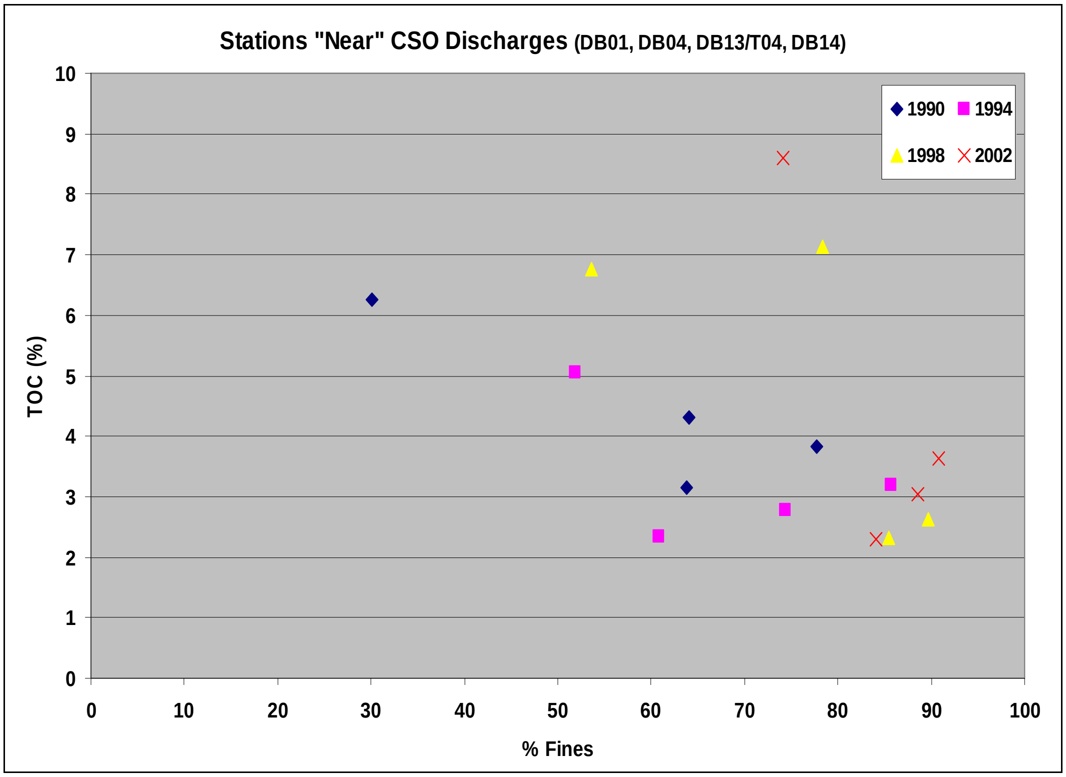

Figure 4-5. Mean TOC vs. Percent Fines for “Near” Stations.

Note: Data are from stations common to all four sampling years.

Table 4-1. Summary of Pearson Product Moment Correlation Coefficients for TOC and Fines at "Near” and "Far" Stations.

	“Far” Stations				“Near” Stations			
	TOC		Fines		TOC		Fines	
Parameter	Pearson Product Moment Correlation Coefficient (r)	p	Pearson Product Moment Correlation Coefficient (r)	p	Pearson Product Moment Correlation Coefficient (r)	p	Pearson Product Moment Correlation Coefficient (r)	p
TOC*	1.00		0.85	<0.0001	1.00		-0.39	0.02
Fines	0.85	<0.0001	1.00		-0.39	0.02	1.00	
Aluminum	0.67	<0.0001	0.72	<0.0001	-0.42	0.01	0.62	<0.0001
Cadmium*	0.82	<0.0001	0.73	<0.0001	0.64	<0.0001	-0.45	0.005
Chromium*	0.93	<0.0001	0.85	<0.0001	-0.14	0.41	0.47	0.004
Copper*	0.92	<0.0001	0.90	<0.0001	0.76	<0.0001	-0.17	0.33
Iron	0.90	<0.0001	0.94	<0.0001	-0.06	0.72	0.62	<0.0001
Lead*	0.85	<0.0001	0.77	<0.0001	0.85	<0.0001	-0.62	<0.0001
Mercury*	0.88	<0.0001	0.77	<0.0001	0.62	<0.0001	-0.13	0.43
Nickel	0.89	<0.0001	0.87	<0.0001	0.47	0.004	0.29	0.09
Silver*	0.85	<0.0001	0.82	<0.0001	-0.24	0.16	0.39	0.02
Zinc*	0.92	<0.0001	0.87	<0.0001	0.93	<0.0001	-0.40	0.02
Total DDT*	0.87	<0.0001	0.83	<0.0001	0.70	<0.0001	-0.65	<0.0001

Table 4-1. Summary of Pearson Product Moment Correlation Coefficients for TOC and Fines at "Near" and "Far" Stations, continued.

Parameter	"Far" Stations				"Near" Stations			
	TOC		Fines		TOC		Fines	
	Pearson Product Moment Correlation Coefficient (r)	p	Pearson Product Moment Correlation Coefficient (r)	p	Pearson Product Moment Correlation Coefficient (r)	p	Pearson Product Moment Correlation Coefficient (r)	p
Total LAB*	0.83	<0.0001	0.76	<0.0001	0.88	<0.0001	-0.44	0.007
Total PCB*	0.91	<0.0001	0.82	<0.0001	0.78	<0.0001	-0.38	0.02
Total PAH*	0.94	<0.0001	0.76	<0.0001	0.81	<0.0001	-0.71	<0.0001
Total 24 PAH*	0.93	<0.0001	0.76	<0.0001	0.80	<0.0001	-0.71	<0.0001
Total petroPAH*	0.93	<0.0001	0.72	<0.0001	0.82	<0.0001	-0.70	<0.0001
Total pyroPAH*	0.94	<0.0001	0.77	<0.0001	0.80	<0.0001	-0.71	<0.0001
Clostridium	0.79	<0.0001	0.65	<0.0001	0.65	<0.0001	-0.26	0.12
Coprostanol	0.55	0.0005	0.59	0.0002	0.90	<0.0001	-0.49	0.002

Note: shaded values indicate $p<0.05$ = statistically significant

* indicates data log transformed prior to statistical analysis

As observed in Figures 4-4 and 4-5, TOC and fines at "Far" stations show a highly positive significant correlation ($r = 0.85$). In contrast, the correlation coefficient for TOC and fines for "Near" stations is much lower and actually shows a negative correlation ($r = -0.39$). Aluminum is strongly correlated to fines in both the "Near" and "Far" stations which is to be expected because aluminum is a crustal element and in the absence of anthropogenic sources it is directly related to the sediment geochemistry.

TOC is significantly correlated to all parameters for "Far" stations. All correlations for TOC with metals, PAHs, total DDTs, total PCBs and total LABs were positive and exhibited fairly strong relationships (i.e., $r > 0.80$). A positive, fairly strong correlation also exists between TOC and *Clostridium* ($r = 0.79$). Coprostanol and TOC showed the weakest correlation ($r = 0.55$).

Similarly, correlations at "Far" stations for percent fines with metals, PAHs, total DDTs, total PCBs, and total LABs were positive and exhibited fairly strong relationships (i.e., $r > 0.70$). Although exhibiting significantly positive relationships with percent fines, both *Clostridium* and coprostanol had lower r values (0.65 and 0.59, respectively) suggesting a slightly weaker relationship with percent fines than the other parameters.

In contrast, not all parameters were significantly correlated with TOC at "Near" stations. For example, Cr, Fe, and Ag did not show a significant correlation to TOC (i.e., $p > 0.05$). The other parameters at the "Near" stations showed significant correlations with TOC, with a weak negative correlation observed between Al and TOC ($r = -0.42$) but moderately strong ($0.62 \leq r \leq 0.76$) and strong positive correlations ($r \geq 0.78$) were exhibited by TOC and the other parameters. At the "Near" stations, the coprostanol correlation with TOC was very strong ($r = 0.90$), as opposed to the "Far" station coprostanol correlation with TOC of 0.55.

Unlike the data from the "Far" stations, Cu, Hg, Ni, and *Clostridium* did not show a significant correlation with percent fines at "Near" stations. The remaining parameters were significantly correlated ($p < 0.05$)

with percent fines, but they showed mostly negative relationships rather than the positive correlations observed in the “Far” data. Only the PAHs showed relatively strong correlations ($r \geq 0.70$) with fines at the “Near” stations.

Overall, the weaker and negative correlations at the “Near” stations may be a result of increased impacts from anthropogenic sources, possibly including the nearby CSOs. The negative correlation between TOC and percent fines at the “Near” stations may be a result of high inorganic particulate loads coming from CSOs. The significantly positive correlations observed at most “Far” stations between TOC and fines and between these parameters and many of the organic parameters and metals appear to indicate that these sediments are less impacted by anthropogenic inputs.

TOC appears to be a controlling factor in sediments discussed here. CSOs can be a source of TOC to the sediments and depending on the size of the particles, deposition can be relatively localized, in some cases within 100 to 1000 meters from the source (Stolzenbach and Adams, 1998). This can act to focus contaminants in localized areas and depending on sedimentation rates and other geochemical processes, can lead to localized contaminant distributions.

4.3.2 Comparison of Organic and Metals Concentrations at “Near” and “Far” Stations

As discussed previously, determining the nature and extent of CSO impact on local and regional sediment quality is difficult. Grouping stations as “Near” and “Far” from CSOs within Dorchester Bay was another way to discern if local impacts relative to proximity of CSOs were discernable. Student t-tests were used to determine if the concentrations of various parameters measured at the “Near” stations within Dorchester Bay (DB01, DB04, DB13/T04, and DB14) were significantly different from the concentrations of those same parameters at the “Far” stations (DB03, DB06, DB10, DB12) (Table 4-2) in 1994, 1998, and 2002. The results of this analysis were also used to support the “Near”/ “Far” grouping discussed throughout this report.

Table 4-2 shows the t-statistic and p-value for student t-test results comparing concentrations at “Near” and “Far” stations from 1994, 1998, and 2002 for 19 parameters. In 1994, the “Near” stations were significantly different from the “Far” stations for 10 parameters. The exceptions were Al, Cr, Fe, Hg, Ni, Ag, Total DDT, Total PCB, and *Clostridium*. In 1998 the “Near” stations were significantly different from the “Far” stations for 16 parameters the exceptions being Total DDT, Total PCB, and C*lostridium.* The differences between the two groups in 2002 were similar to 1998 with the addition of Ni which was found not to be significantly different between “Near” and “Far” stations. When results were significant, concentrations for the parameter being compared were always greater at the “Near” stations.

The analyses show that the concentrations of most parameters were significantly different at “Near” and “Far” stations ($p < 0.05$), and therefore support the grouping of sampling stations into “Near” and “Far” classifications. These results also lend themselves to the conclusion that there is some level of impact from CSOs related to sediment quality in the vicinity of the CSOs. Three parameters were consistently found to have similar concentrations at “Near” and “Far” stations in all years: Total DDT, Total PCB, and *Clostridium*. While the “Near”/”Far” grouping supports some level of impact common to stations “Near” CSOs, the concentrations of these three parameters appear to be controlled on a broader basis and changes in concentrations of these parameters are reflected Harbor-wide.

4.3.3 Temporal Trends at “Near” and “Far” Stations

As discussed in Section 4.2, it appears that concentrations of many contaminants Harbor-wide have shown a decrease since 1990. The cause for this decrease is most likely not attributed to one event but the general trend toward environmental control of contaminant releases combined with the improvements in sewage control in the Harbor (Werme and Hunt, 2002). CSOs appear to have some local effect on sediment quality but whether these impacts affect a wider area or are long term is not clear. One-way ANOVAs were run to evaluate temporal changes to sediment quality at both “Near” and “Far” stations for various parameters across the three sampling years (1994, 1998, and 2002). Significant differences in concentrations over the three sampling years are noted in Table 4-3. When significant differences are

Table 4-2. Summary of Student t-Test results for "Near” and “Far” Stations in 1994, 1998 and 2002.

	1994					
	“Far”		“Near”		t-test result	
Parameter	Mean	Std. Dev.	Mean	Std. Dev.	t-statistic	p-value
Aluminum	4.83	± 1.47	5.5	± 1.61	-1.06	0.3
Cadmium*	0.78	± 0.79	1.31	± 0.88	-2.67	0.02
Chromium*	131.8	± 88.6	167.3	± 79.3	-1.61	0.13
Copper*	84.3	± 77.8	126.3	± 38.0	-2.57	0.02
Iron	2.68	± 1.17	3.32	± 0.65	-1.68	0.11
Lead*	98.8	± 67.5	214.1	± 99.1	-3.66	0.002
Mercury*	0.85	± 1.03	0.84	± 0.36	-1.61	0.13
Nickel	24.1	± 12.9	31.5	± 6.7	-1.77	0.09
Silver*	2.51	± 2.08	3.56	± 1.61	-2.13	0.053
Zinc*	137	± 100	253	± 84	-3.28	0.006
Total DDT*	53.3	± 62.8	72.7	± 64.5	-1.84	0.08
Total LAB*	628	± 626	1,726	± 1,022	-2.9	0.01
Total PCB*	173	± 160	229	± 234	-1.41	0.18
Total PAH*	12,706	± 9,827	53,730	± 47,754	-3.5	0.003
Total 24 PAH*	9,820	± 7,656	42,619	± 37,689	-3.58	0.003
Total petro PAH*	3,891	± 3,176	16,176	± 15,654	-3.2	0.006
Total pyro PAH*	8,815	± 6,813	37,554	± 32,219	-3.63	0.002
*Clostridium**	8,758	± 6,425	6,481	± 4,451	0.34	0.7
Coprostanol*	3,234	± 2,438	13,290	± 12,026	-4	0.0006

	1998					
	“Far”		“Near”		t-test result	
Parameter	Mean	Std. Dev.	Mean	Std. Dev.	t statistic	p value
Aluminum	4.95	± 0.89	6.09	± 0.68	-3.51	0.002
Cadmium*	0.85	± 0.75	1.45	± 0.75	-2.38	0.03
Chromium*	99.8	± 60.8	143.4	± 21.4	-2.53	0.03
Copper*	106.8	± 136.8	146	± 42.1	-2.62	0.02
Iron	2.65	± 1.13	3.87	± 0.35	-3.57	0.003
Lead*	156.3	± 200.4	344.7	± 254.8	-2.89	0.008
Mercury*	0.48	± 0.42	1.13	± 0.88	-3.11	0.007
Nickel	22.4	± 11.3	35.4	± 3.5	-3.78	0.002
Silver*	1.72	± 1.36	2.66	± 0.68	-2.61	0.02
Zinc*	159	± 130	339	± 148	-3.5	0.003
Total DDT*	26.5	± 28.3	59.8	± 61.4	-2.01	0.06
Total LAB*	303	± 234	1,720	± 1,478	-4.13	0.0004
Total PCB*	159	± 144	300	± 230	-2.01	0.06
Total PAH*	16,788	± 18,914	65,687	± 62,199	-3.07	0.006
Total 24 PAH*	13,475	± 15,361	51,517	± 48,272	-3.1	0.005
Total petroPAH*	4,475	± 4,904	23,533	± 24,222	-3.13	0.005
Total pyroPAH*	12,313	± 14,043	42,154	± 38,012	-3.04	0.006
*Clostridium**	5,182	± 3,785	5,291	± 4,047	-0.51	0.62
Coprostanol*	1,258	± 1,033	120,856	± 175,338	-4.6	0.0003

Table 4-2. Summary of Student t-Test results for "Near" and "Far" Stations in 1994, 1998 and 2002, continued.

	2002					
	"Far"		"Near"		t-test result	
Parameter	Mean	Std. Dev.	Mean	Std. Dev.	t statistic	p value
Aluminum	5.71	± 0.68	6.44	± 0.74	-2.51	0.02
Cadmium*	0.43	± 0.37	0.69	± 0.32	-2.5	0.03
Chromium*	110.8	± 66.7	159.8	± 20.9	-2.73	0.02
Copper*	86.1	± 76.8	132.4	± 41.0	-2.71	0.02
Iron	2.93	± 1.29	3.97	± 0.39	-2.67	0.02
Lead*	104.8	± 68.9	205.3	± 132.4	-2.79	0.01
Mercury*	0.48	± 0.42	0.69	± 0.14	-2.48	0.03
Nickel	27.3	± 14.0	35.6	± 6.2	-1.87	0.08
Silver*	1.48	± 1.06	2.31	± 0.43	-2.82	0.02
Zinc*	138	± 93	271	± 118	-3.51	0.002
Total DDT*	15.3	± 21.9	20.7	± 25.3	-1.58	0.13
Total LAB*	372	± 261	2,810	± 3,963	-3.42	0.003
Total PCB*	83	± 85	113	± 60	-2.01	0.06
Total PAH*	10,944	± 8,851	28,264	± 32,268	-2.4	0.03
Total 24 PAH*	7,824	± 6,286	21,991	± 24,948	-2.58	0.02
Total petroPAH*	3,114	± 2,665	8,559	± 11,070	-2.24	0.04
Total pyroPAH*	7,829	± 6,463	19,705	± 21,212	-2.48	0.02
*Clostridium**	4,535	± 3,676	9,325	± 11,049	-1.51	0.15
Coprostanol*	756	± 688	38,739	± 68,925	-3.34	0.005

Note: Shaded cells indicate significant differences ($p < 0.05$).
* indicates data log- transformed prior to analysis.

noted, the highest value is listed first and the line below the values groups the years that are significantly different from one another.

At "Near" stations, five parameters (Percent fines, Cd, Fe, Ag and Total DDT) differed significantly between the three sampling years ($p<0.05$). A significant decrease from 1994 and 1998 to 2002 was observed for Cd, Ag, and Total DDT. Percent fines and Fe significantly increased from 1994 to 2002. At "Far" stations, only coprostanol differed significantly among the three sampling years. Coprostanol concentrations were significantly greater in 1994 than in 1998 or 2002. Coprostanol concentrations did not differ significantly between 1998 and 2002.

With the exception of percent fines and Fe, the parameters showing temporal trends at "Near" Stations all showed significant decreases in 2002 relative to one or both of the previous sampling years. This is consistent with ANOVA results for individual parameters by station (see Appendix C) as discussed in Section 3. This relationship was observed only for Coprostanol at the "Far" stations which may be related to the recently observed statistically significant decrease in another sewage tracer, *Clostridium* (Macioleck *et al.,* 2005) attributed to the implementation of secondary treatment of sewage in 1998 and cessation of effluent from Nut Island, and the relocation of the Deer Island Outfall in 2000. No significant decrease in *Clostridium* was observed at the "Near" or "Far" stations although an apparent decrease is observed at the "Harbor" stations (Figure 3-11). This may indicate that there is still a source to these "Near" stations, possibly the nearby CSOs or these stations are located in depositional areas resulting in sediment focusing (Stolzenbach and Adams, 1998).

Table 4-2 Summary Of One Way ANOVA Results for "Near" and "Far" stations from 1994, 1998 and 2002.

	"Near"				"Far"		
Parameter	F statistic	P	Specific Differences**	Parameter	F statistic	P	Specific Differences**
TOC*	0.86	0.43		TOC*	0.27	0.76	
% Fines	4.36	0.02	Year 2002 1998 1994 Mean (84.37) (76.73) (68.21) --------------------- ---------------------	% Fines	0.57	0.57	
Aluminum	2.27	0.12		Aluminum	2.39	0.11	
Cadmium*	7.11	0.003	Year 1998 1994 2002 Mean (1.45) (1.31) (0.69) -------------------- ------	Cadmium*	0.55	0.58	
Chromium*	0.57	0.57		Chromium*	0.27	0.76	
Copper	0.79	0.46		Copper	0.13	0.88	
Iron	6.18	0.005	Year 2002 1998 1994 Mean (3.97) (3.87) (3.32) ------------------- ------	Iron	0.2	0.82	
Lead*	1.55	0.23		Lead*	0.13	0.88	
Mercury	1.96	0.16		Mercury	0.2	0.82	
Nickel	1.93	0.16		Nickel	0.44	0.65	
Silver*	4.56	0.02	Year 1994 1998 2002 Mean (3.56) (2.66) (2.31) --------------------- ----------------------	Silver*	0.2	0.82	
Zinc*	1.4	0.26		Zinc*	0.06	0.94	
Total DDT*	6.68	0.004	Year 1994 1998 2002 Mean (72.7) (59.8) (20.7) ------------------- -------	Total DDT*	1.22	0.31	
Total LAB*	0.22	0.8		Total LAB*	0.16	0.85	
Total PCB*	2.93	0.07		Total PCB*	0.6	0.55	
Total PAH*	2.28	0.12		Total PAH*	0.01	0.99	
Total 24 PAH*	2.42	0.11		Total 24 PAH*	0.02	0.98	
Total petro PAH*	2.21	0.13		Total petro PAH*	0.03	0.97	
Total pyro PAH*	2.32	0.12		Total pyro PAH*	0	1	
*Clostridium**	0.47	0.63		*Clostridium**	1.56	0.23	
Coprostanol*	2.08	0.14		Coprostanol*	8.16	0.001	Year 1994 1998 2002 Mean (3,234) (1,258) (756) --------- ------- ---------

* Indicates data log transformed.

** Line groups years that are significantly different; highest value listed first. Value in parenthesis is annual mean concentration.

4.4 CSO Outfall Discharge and Potential Impacts Due to Precipitation Events

As discussed above, impacts to sediment quality are variable and cannot necessarily be attributed directly to CSOs. Few parameters showed statistically significant temporal trends, though slightly more parameters show a significant temporal decrease at “Near” stations compared to “Far” stations. Most parameters showed variable, or, possibly decreasing concentrations from 1994 to 2002. However, a number of notable spikes in contaminant concentrations were observed in 1998 relative to 1994, 2002 and where available, 1997 results. One possible explanation for these isolated increases could be a significant rain event that occurred in June of 1998. The following sections discuss the estimated CSO flows relative to precipitation and the possible impact this rain event had on sediment quality related to proximity of CSOs.

4.4.1 Summary of CSO Estimated Discharges and Annual Precipitation from 1990 to 2002

CSO discharge is a combination of storm sewer runoff and sanitary sewer overflow. The amount of flow from individual CSOs is related to a number of factors including the amount and intensity of precipitation, temperature, the background flow through the sewerage system, the state of the tide and the ability of the Deer Island treatment facility to accept flow as well.

CSO flow data presented in Figure 4-6 are not measured directly but are modeled. While actual CSO flows are driven by weather (*i.e.,* precipitation, temperature etc.) and tides, the estimates are upgraded to also include infrastructure changes in the collection system and as sewer separation and other improvements come online. Table 4-4 shows the estimated flows by CSO from 1990 through 2002. As of the sampling event for this report, only two CSO outfalls in the vicinity of the study area had been closed; BOS-93 and BOS-95 were closed entirely as of February 1998 and June 2000, respectively (Table 1-1 and Table 4-4).

Infrastructure changes affecting the CSO discharge in the study area have coincided with improvements at Deer Island and highly variable patterns of precipitation. For example, in 1998, BOS-89 and BOS-90 (which are near stations DB13/T04 and DB14, respectively) experienced the largest discharges in several years (Table 4-4). Recorded precipitation data (Figure 4-6) show that over 53 inches of rain fell in 1998, more than in any of the other study years; over 20% of which fell during a significant storm in June of that year (Figure 4-7). The measured rainfall in June 1998 exceeded the annual mean by approximately 8.5 inches, most of which fell in a two-day period. This substantial input of precipitation overwhelmed Boston's wastewater system and led to enormous overflows of stormwater and sewage into Boston Harbor, as can be seen from estimated flow data (Figure 4-6). While increased precipitation was measured in 1994 and 1996, along with coinciding high CSO flows, the difference between these years and the record rainfall of 1998 was that in 1998 a large percentage of the measured annual precipitation occurred over a period of days. Since 2000, the annual amount of CSO overflow discharged to Boston Harbor appears to have leveled off (Figure 4-6). This decrease and flattening of the discharge amounts may be due to a combination of meteorological events and the diversion/consolidation of flow between and among outfalls and the expected effect of having a larger discharge capacity provided by the Massachusetts Bay outfall which enables greater throughput of treated water and less back pressure in the collection system.

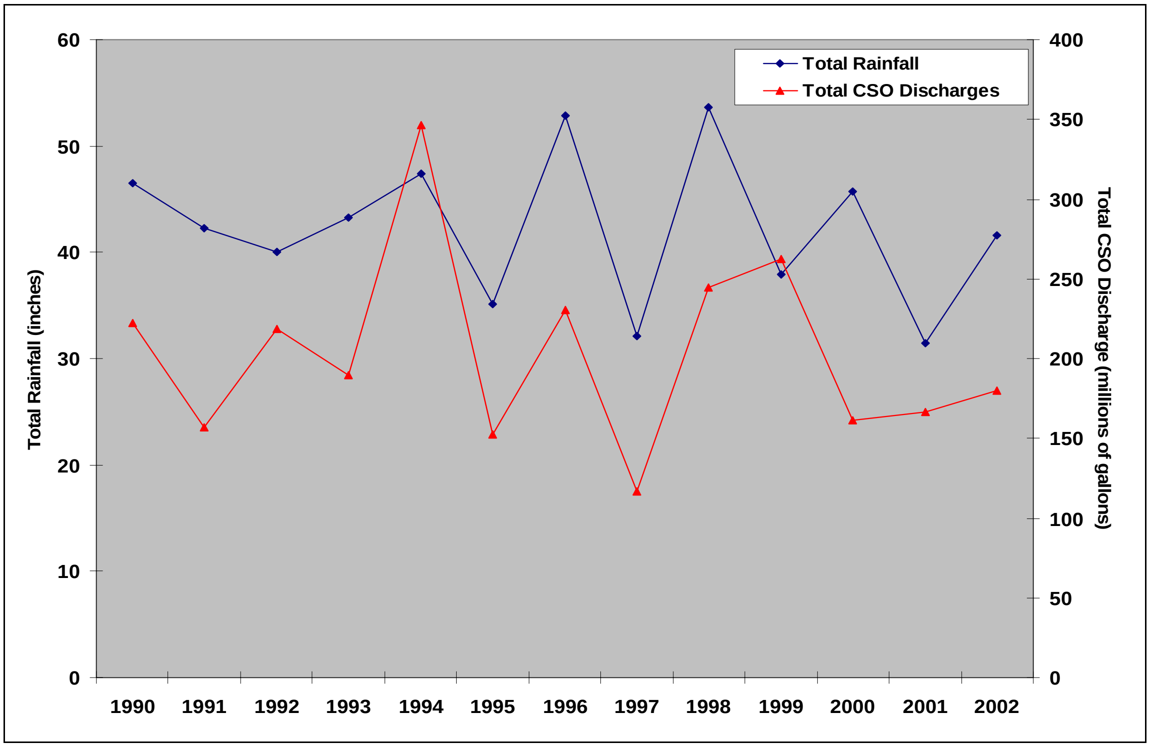

Figure 4-6. Total Annual Rainfall and Modeled Total Annual Discharges from CSOs*, 1990-2002.

*The CSO outfalls included in these totals are BOS-81 through BOS-90, BOS-93, and BOS-95 (see Figure 1-1); total CSO Discharge is an estimated value based on modeled discharge amounts.

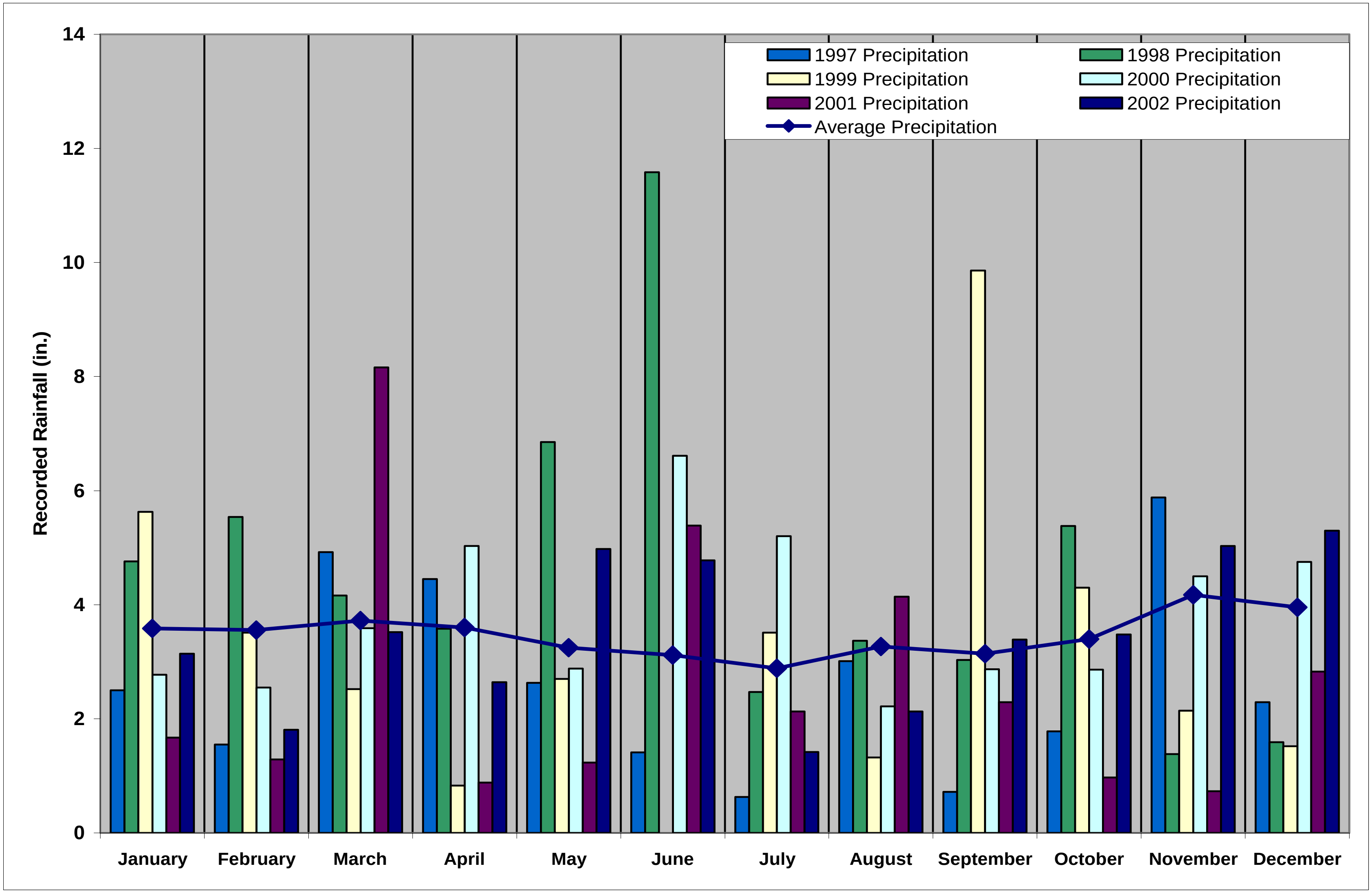

Figure 4-7. Monthly Recorded Rainfall Amounts and Average Expected Rainfall Amount, 1997-2002.

Table 4-3. Modeled Discharge Amounts for Old Harbor and Dorchester Bay CSOs (millions of gallons) and Annual Rainfall (inches), 1990-2002.

	BOS-81	BOS-82	BOS-83	BOS-84	BOS-85	BOS-86	BOS-87	BOS-88	BOS-89	BOS-90	BOS-93	BOS-95	Total CSO Flow (Mgal)	Total Annual Rainfall (inches)
1990	2.6	5.7	1.1	5	1.2	12.6	7.2	5.7	91.7	86.2	3.5	No Data	222.5	46.5
1991	2.4	5.5	0.7	4.8	0.1	5.6	0.3	2.7	52.8	78.2	3.5		156.6	42.25
1992	2.4	5.4	0.9	4.7	0.3	66.9	0.7	3.5	52.2	77.6	4.2		218.8	40.02
1993	0.6	3.5	0.4	2.6	0	91.5	1.5	4.5	36	46.8	2.3		189.7	43.31
1994	0.2	5.7	0.8	3	0.3	250	3.6	6.1	43.2	30.7	3.2		346.8	47.72
1995	0.1	3.5	0.6	1.8	0.1	93.6	2.3	3.2	26.7	18.5	2.3		152.7	35.1
1996	0.1	6.4	0.8	3.4	0	128.7	3.8	5.5	46.9	31.1	3.6		230.3	52.88
1997	0	1.5	0.2	0.8	0	88.2	0.9	1.4	13.5	9.6	0.8		116.9	31.77
1998	0.4	8	1.3	4.3	0.6	112.7	5.7	13.4	54.3	43.8	0		244.5	53.47
1999	0.5	5.5	1.1	3	0.4	176.9	3.8	4.6	38.7	27.6	0		262.1	37.84
2000	3.44	5.92	1.86	1.76	0.18	3.13	0.59	0	65.53	79.13	0	0.1	161.64	45.83
2001	3.24	6.34	2.09	3.34	1.31	5.38	1.78	0	30.67	111.69	0	0.72	166.56	31.71
2002	1.24	1.62	0.5	0.25	0	0.02	0.07	0	78.94	97	0	0	179.64	41.6

4.4.2 The Effect of Precipitation on Sediment Quality

As discussed above, record rainfall in June 1998 may have resulted in a temporary increase in CSO flow into Boston Harbor. CSOs BOS-89 (adjacent to Station DB13/T04) and BOS-90 (adjacent to Station DB14) both appeared to be impacted by this significant, short term precipitation event. Changes in discharge levels may be an explanation for variations in sediment contaminant levels at sampling stations near those outfalls. For example, a number of parameters showed an increase in concentration at “Near” Stations DB13/T04 and DB14 in 1998, possibly a result of the June storm event. While overall, concentrations of most contaminants appear to be decreasing since 1990, a spike in TOC (Figure 3-2), Total 24-PAH (Figure 3-3), Total PCB (Figure 3-5), LABs (Figure 3-8) Coprostanol (Figure 3-9), Hg (Figure 3-18), Pb (Figure 3-14) and Zn (Figure 3-15) was observed in 1998 at Station DB13/T04 and in some cases at Station DB14. This increase was not observed at the other “Near” stations (DB01 and DB04). In addition, significant increases of PAHs were observed at one “Far” station, Station DB10, in 1998 (Figure 3-3). Interestingly, concentrations of the sewage tracers, LABs and Coprostanol, did not increase in 1998 at Station DB10 (See Figures 3-8 and 3-9, respectively). While Station DB10 is not near a CSO, it is adjacent to a large storm drain which was also likely impacted by the significant precipitation of June 1998. These observations indicate that impacts from CSOs are most likely localized; however, other inputs such as storm drains, can also have significant localized impacts to sediment quality.

In terms of temporal effects of these localized impacts, comparison of the 1998 data at selected locations (Harbor Stations T01 through T08 and “Near” Station DB13/T04) was made to data collected in 1997 during the annual MWRA Harbor Benthic Surveys (Blake *et al*., 1998). Interestingly, concentrations of most parameters in 1997 were similar to or lower than levels measured during the 1990 and 1994 CSO studies (Figures 4-8, 4-9, and 4-10). In addition, the spike in concentrations in 1998 appears to have been temporary because concentrations measured at these same stations in 2002 were found to be similar to or lower than 1994 levels for almost all parameters.

Another interesting observation is the change in PAH pattern at the two "Near" Stations (DB13/T04 and DB14) in 1998. As discussed above, the amount of Total PAH at both of these "Near" stations as well as at "Far" Station DB10 increased significantly in 1998 (Figure 4-10), most likely attributed to the rain event in June of that year. In addition, the types of PAH compounds at "Near" Stations DB13/T04 and DB14 also changed in 1998. Figure 4-11 shows the decrease of percent pyrogenic PAHs in 1998 at stations DB13/T04 relative to previous years, including 1997. This decrease in percent pyrogenic PAHs was also observed at Station DB14. However, a similar change in PAH composition was not observed at Station DB10. The change in percent pyrogenic PAHs at the "Near" stations is most likely due to the composition of the effluent from the nearby CSOs, possibly as a result of increased run-off in nearby areas due to the storm event. The fact that total PAH increased significantly at Station DB10, which is not near a CSO but is near a large storm drain, with no similar change in PAH pattern indicates that while the total increase in PAHs is still likely due to the increased runoff as a result of the June 1998 storm, the source of the PAHs to the sediments at Station DB10 is different than the source of the increased PAHs to the "Near" stations.

The relative percent pyrogenic PAHs at the two "Near" stations returned to previously measured values in 2002 indicating the temporary extent of the impact (Figure 4-11). The PAH concentrations and the ratio of PAHs at the other "Near" and "Far" stations, in 1998 were similar to previous years, indicating that the impacts observed in the sediments were isolated to nearshore stations, particularly those near to specific CSOs or possibly large storm drains. It may be that the other "Near" stations (DB01, DB04, and CO19) did not experience a similar increase in PAH concentrations because the outfalls in the vicinity of these stations did not experience a dramatic increase in discharges following the 1998 event, unlike the CSO adjacent to DB13/T04.

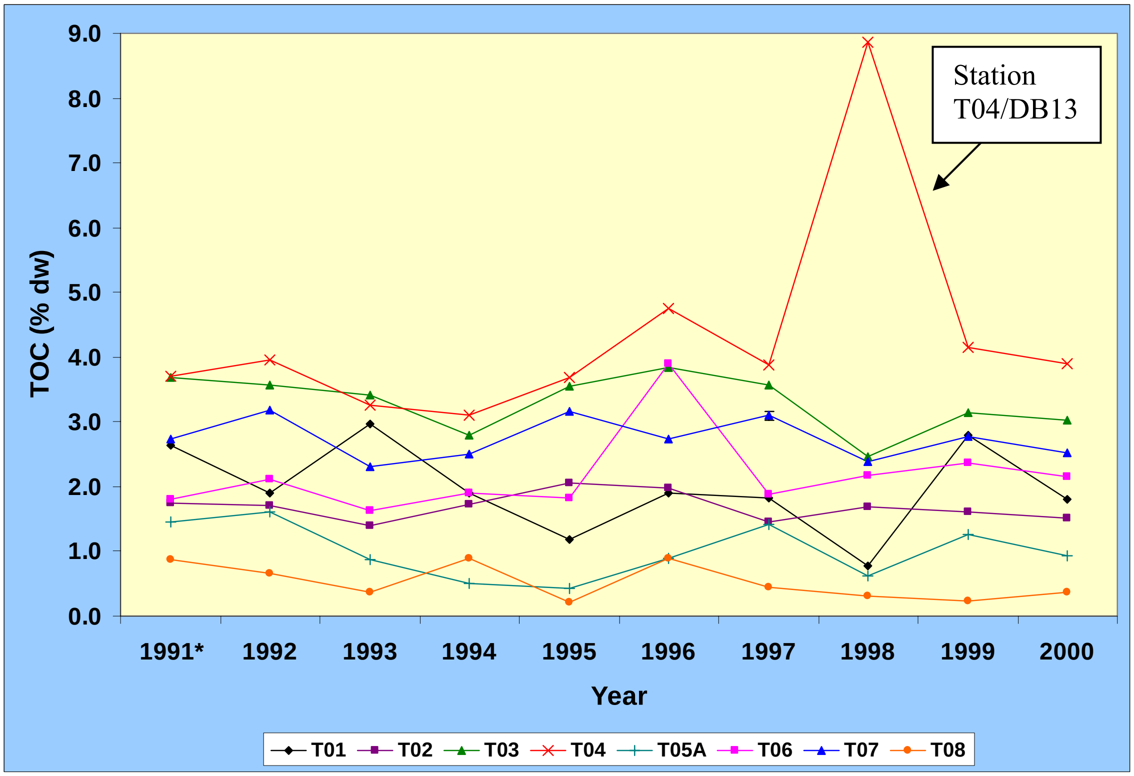

Figure 4-8. TOC Concentration from MWRA Harbor Benthic Surveys (1991-2000).

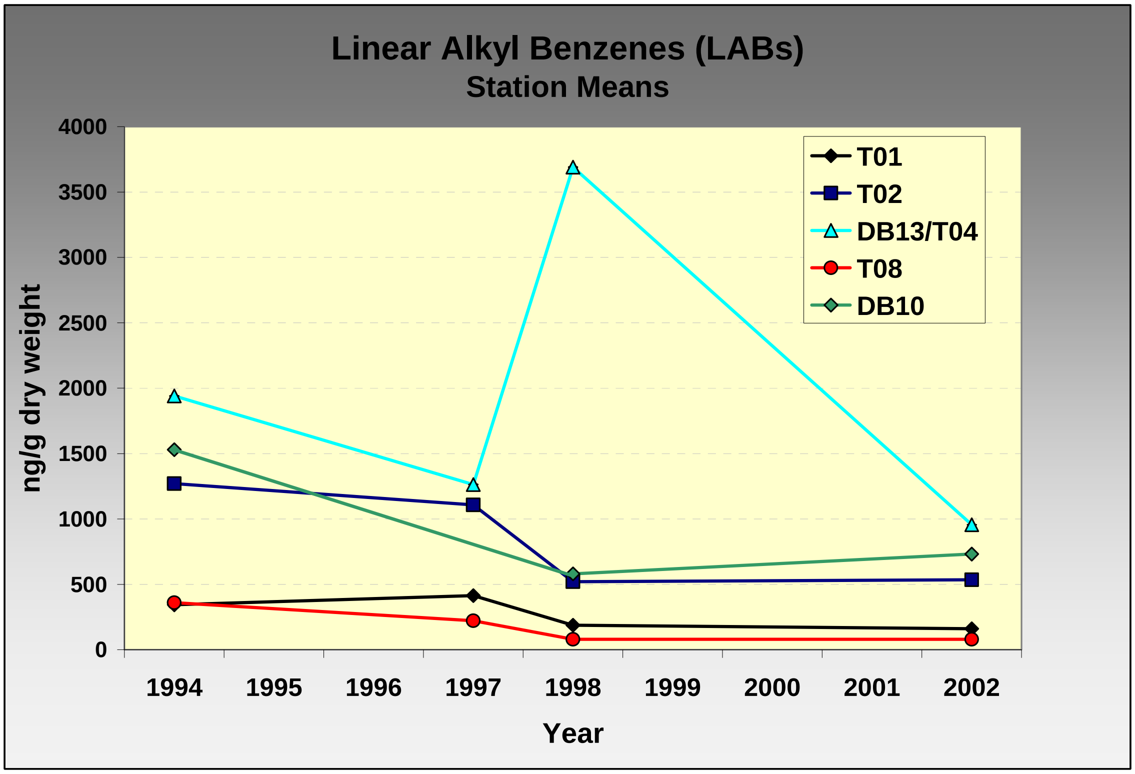

Figure 4-9. Total LAB Measurements for 1994, 1997, 1998, and 2002.

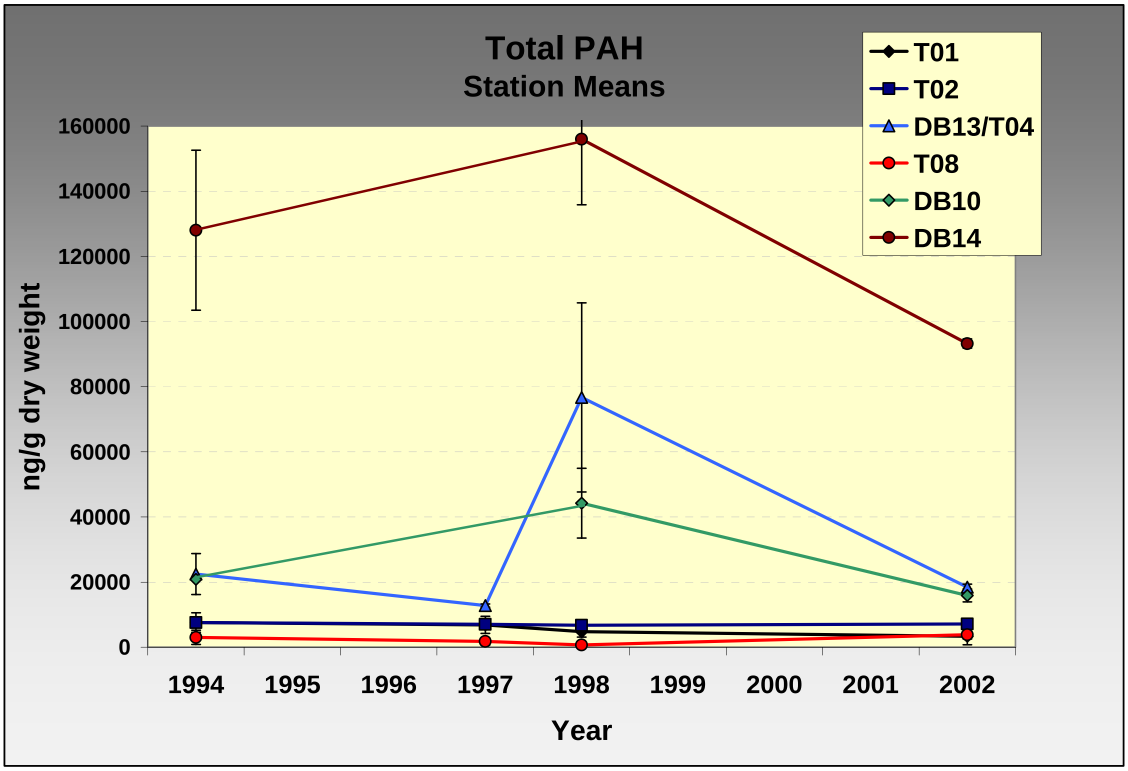

Figure 4-10. Total PAH concentrations for 1994, 1997, 1998, and 2002.

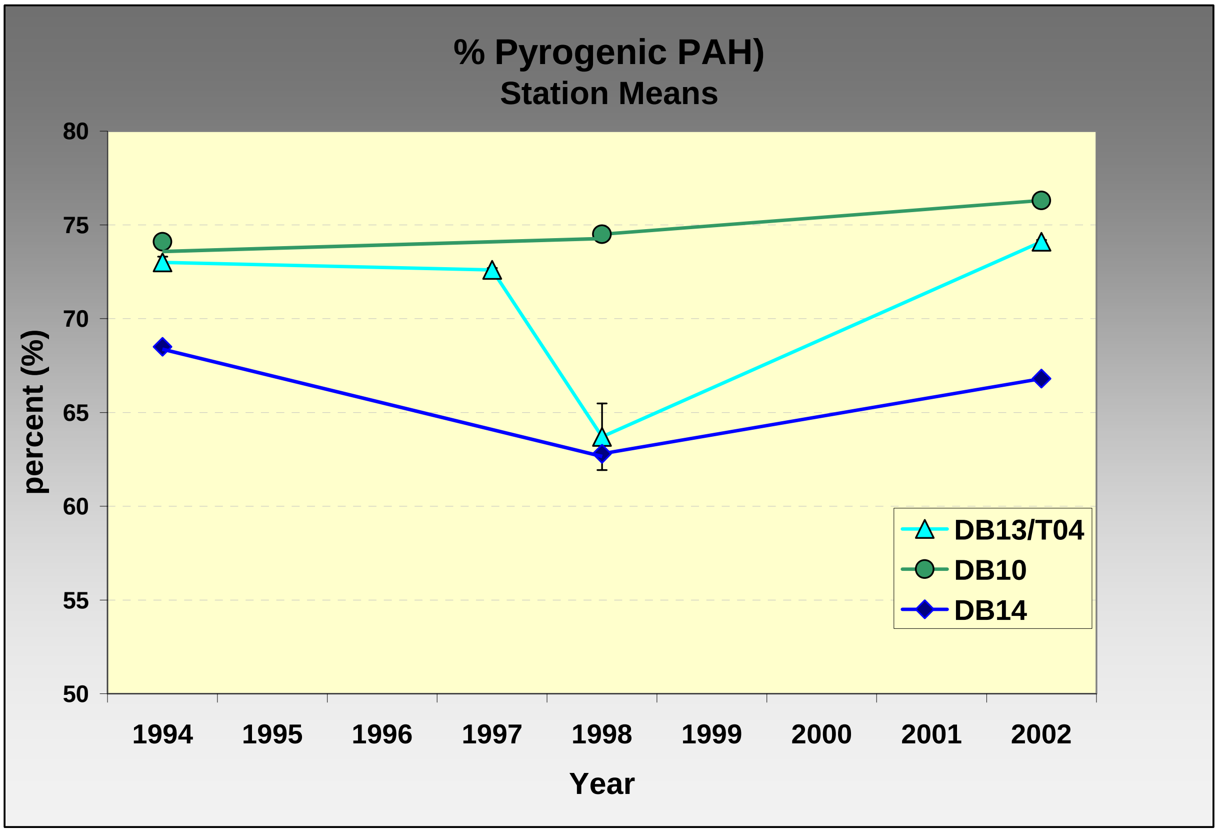

Figure 4-11. Percent Pyrogenic PAHs of Total PAHs at DB13/T04, DB14 and DB10 in 1994, 1997, 1998, and 2002.

5.0 CONCLUSIONS

The purpose of the 2002 CSO Sediment Study was to determine if there have been changes over time to the sediment quality in the Boston Harbor study area and whether the changes (if any) could be attributed to CSO outfalls in the area. Of particular interest were the changes in sediment contaminant concentrations related to the ongoing improvements to the CSO system in the study area. Overall, contaminant concentrations in sediments both near and far from CSOs have shown a general decline since 1994, but few statistically significant decreases in concentrations were observed in 2002 compared to levels measured in 1994 (statistical comparisons did not include 1990 due to the limited data set available for that year). DDTs, PCBs, Coprostanol, and Cd, Pb, Hg, and Pb all showed significant decreases at least at one station in 2002 compared to 1994, with most significant decreases observed at “Near” stations.

Sediment quality impacts resulting from CSO improvements are difficult to discern, particularly because many aspects of the CSO improvement program had not been fully implemented at the time of sampling and the general depositional nature of the Dorchester Bay area, which collects contaminants from other parts of the Harbor. In addition, sediment quality impacts from CSOs appear to be temporary and localized, as evidenced by the spike in some parameters (PAHs, PCBs, Coprostanol for example) in 1998 relative to measurements made just the previous year and the subsequent decrease to previously measured concentrations in 2002. At the time of the sampling event, only two CSO outfalls in the vicinity of the study area had been closed (BOS-93 and BOS-95). However, the overall annual amount of overflow discharged into Boston Harbor decreased considerably between 1999 and 2000 and then appeared to level off. This decrease and flattening of the discharge amounts may be due to a combination of meteorological events and the diversion/consolidation of flow between and among outfalls and from the increased discharge capacity added to the system by the Deer Island Treatment Facility and the diversion of the outfall to Massachusetts Bay.

The overall general decrease in contaminant concentrations observed since 1990 may be an indication of a Harbor-wide reduction, rather than a CSO-related decrease, and may be attributable to wastewater treatment upgrades (removal of sludge, implementation of secondary treatment, and the relocation of the Deer Harbor outfall to Massachusetts Bay in 2000). Decreases in total PCB and total DDT for example, are most likely attributed to institutional control of these compounds (i.e. banning of DDT in 1972 and regulation of PCBs in 1976). More subtle impacts to sediment quality relative to CSO inputs were illustrated by the increase in petrogenic PAHs after a storm event in June 1998. This change in the sediment PAH ratio at two “Near” stations (DB13/T04 and DB14) reflected a change in PAH source to those sediments. The ratio of PAHs at “Far” stations in 1998 were similar to previous years, indicating that the impacts observed in the sediments were isolated to nearshore stations, particularly those near to specific CSOs.

As CSO improvements continue, the results presented in this report will be most useful in combination with past and future results so that temporal trends can be identified and causal connections between sediment quality and CSO system improvements can be definitively drawn. Improvements to the study sampling design may also aid in drawing direct links to CSO improvements. Additional sampling stations relative to individual CSOs laid out in a grid adjacent to and away from individual CSOs would allow investigation of spatial relationships relative to CSOs. In this way, concentration gradients, if observed, relative to CSOs would give more information about the relative spatial impacts from a given CSO. Increased sampling (i.e. seasonal sampling events within a given year) would allow greater temporal resolution and possibly provide more evidence of the effects of meteorological events on short and long-term sediment quality. Finally, more detailed information on the CSO flow measurements on a tighter time scale as well as actual chemical analyses of CSO discharges would provide information to make more direct comparisons between CSO discharge and sediment quality.

6.0 REFERENCES

Alber M and Chan A. 1994. Sources of contaminants to Boston Harbor: revised loading estimates. Boston: Massachusetts Water Resources Authority. Report 1994-01. 93 pp.

Blake JA, Maciolek NJ, Rhoads DC, Gallagher E, and Williams IP. 1998. Boston Harbor Soft-Bottom Benthic Monitoring Program, 1996 and 1997 results. Final report submitted by ENSR to Boston: Massachusetts Water Resources Authority. October 30, 1998.

Bothner, MH, MR Buchholtz ten Brink, and ET Manheim. 1998. Metal concentrations in surface sediments of Boston Harbor-Changes with time. *Mar. Environ. Res.* 45(2):127-155.

BWSC. 1990a. CSO monitoring report, second quarter. Boston: Massachusetts Water and Sewer Commission, August 15, 1990.

BWSC. 1990b. Work/quality assurance project plan for the Boston Water and Sewer Commission, Boston, Massachusetts. Prepared by Rizzo Associates, Inc.

Dolin EJ. 1990. Dirty Water/Clean Water. A Chronology of Events Surrounding the Degradation of Boston Harbor. MIT Sea Grant Press. Cambridge, MA 144 pp.

Durell GS., Ginsburg LS, Shea D. 1991. CSO effects on contamination of Boston Harbor sediment. Boston: Massachusetts Water Resources Authority. Report ENQUAD 91-08. 146 pp.

Durell GS. 1995. Concentrations of contaminants in Dorchester Bay and Boston Harbor sediments collected in the vicinity of CSO discharges and comparison to 1990 concentrations. Boston: Massachusetts Water Resources Authority. Report ENQUAD 95-14. 128 pp.

Eaganhouse RP, Olaguer DP, Gould BR, and Phinney CS. 1988. Use of Molecular Markers for the Detection of Municipal Sewage Sludge at Sea. *Mar. Environ. Res.* 25:1-22.

Eaganhouse RP, and Sherblom P. 1990. Assessment of the Chemical Composition of the Fox Point CSO Effluent and Associated Subtidal and Intertidal Environments: Organic Chemistry of CSO Effluent, Surficial Sediments and Receiving Waters. Final Report. Massachusetts Department of Environmental Protection.

Emerson DJ and Cabelli VJ. 1982. Extraction of *Clostridium perfringens* spores from bottom sediment samples. *Appl. Environ. Microbiol.* 44:1144-1149.

EPA (U.S. Environmental Protection Agency). 2000. Improved Enumeration Methods for the Recreational Water Quality Indicators: *Enterococci* and *Escherichia coli.* EPA 827/R-97/004. U.S. Environmental Protection Agency, Office of Science and Technology, Washington, DC.

Folk, RL. 1974. *Petrology of Sedimentary Rocks*. Hemphill Publishing Company, Austin, TX. 184 pp.

Gallagher ED, Wallace GT, and Eaganhouse RP. 1992. A synthesis of Phase-1 Biological and Chemical Studies to Identify the Impact of the Fox Point CSO before modification. Final Report. Massachusetts Department of Environmental Protection.

Havens and Emerson/Parsons Brinkerhoff. 1983. Deer Island Facilities Report - Appendix A. Prepared for Metropolitan District Commission, Boston, MA.

Hunt CD, Hall M, Pala S, Dahlen D. 2005. A Review and Summary of Contaminants in Boston Harbor and Massachusetts Bay: 1990 to 2005. Boston: Massachusetts Water Resources Authority. Technical Report (In preparation).

Lefkovitz L, Dahlen DT, Hunt CD, and Ellis BD. 2000. 1998 CSO Sediment Study Synthesis Report. Boston: Massachusetts Water Resources Authority. Report ENQUAD 1999-12. 68 pp.

Libby PS, Gagnon C, Albro CS, Mickelson MJ, Keller AA, Borkman D, Turner JT and Oviatt CA. 2002. Combined work/quality assurance plan (CWQAPP) for water column monitoring 2002 - 2005. Boston: Massachusetts Water Resources Authority. Report ms-074. 79 pp.

Maciolek NJ, Diaz RJ, Dahlen DT, Hunt CD, and Williams IP. 2005. 2003 Boston Harbor Benthic Monitoring Report. Boston: Massachusetts Water Resources Authority. Report ENQUAD 2005-06. 83 pages plus appendices.

Massachusetts Water Resources Authority (MWRA). 2003. Combined Sewer Overflow Control Plan: Annual Progress Report 2002. MWRA: Boston, Massachusetts. 55 pp.

Messer JW and Dufour AP. 1998. A rapid specific membrane filtration method procedure for enumeration of enterococci in recreational water. *Applied Environmental Microbiology* 678-680.

National Oceanographic and Atmospheric Administration (NOAA). 1998. Sampling and analytical methods of the National Status and Trends Program Mussel Watch Project: 1993-1996 Update. NOAA Technical Memorandum NOS ORCA 130. March 1998. U.S. Department of Commerce, National Oceanographic and Atmospheric Administration, Washington, DC.

Neff JM. 2002. Bioaccumulation in Marine Organisms. Effects of Contaminants from Oil Well Produced Water. *Elsevier Science Publishers*, Amsterdam. 452 pp., Chapter 15.

Rex AC. 1991. Combined sewer overflow receiving water monitoring: June 1989-October 1990. Boston: Massachusetts Water Resources Authority. Report 1991-02. 337 pp.

Rex AC. 1993. Combined sewer overflow receiving water monitoring: Boston Harbor and its tributary rivers. Boston: Massachusetts Water Resources Authority. Report 1993-04. 210 pp.

Rex AC. 2000. The state of Boston Harbor 1997-1998: Beyond the Boston Harbor Project. Boston: Massachusetts Water Resources Authority. Report 2000-05. 24 pp.

Rex AC, Wu D, Coughlin K, Hall M, Keay KM, and Taylor DI. 2002. The State of Boston Harbor: Mapping the Harbor’s Recovery. Massachusetts Water Resources Authority. Report 2002-09. 41 pp.

Saad DL 1992. Simplified method for extraction of *Clostridium perfringens* spores and indicator bacteria from marine sediments. In: *Seasonal Disinfection with Respect to Marine Waters*. Ph.D. dissertation, University of Rhode Island, Kingston, RI.

Stolzenbach KD and Adams EE. Eds. 1998. *Contaminated Sediments in Boston Harbor*. MIT Sea Grant Publication 98-1, MIT Sea Grant College Program. Cambridge MA. 170 pp.

Stout S, Uhler AD, Emsbo-Mattingly SD. 2003. Characterization of Ambient Anthopogenic PAH in Urban Sediments. Battelle International Symposium, Orlando FL. June 2003.

Wallace GT, Krahforst C, Pitts L, Shrine J, Studer M, and Bollinger C. 1991. Assessment of the Chemical Composition of the Fox Point CSO Effluent and Associated Subtidal and Intertidal Environments: Analysis of CSO Effluents , Receiving Water and Surface Sediments for Trace Metals Prior to CSO Modification. Final Report. Prepared by the University of Massachusetts at Boston for the Department of Environmental Protection and the Coastal Zone Management Office of the Commonwealth of Massachusetts. November 1, 1991

Werme C and Hunt CD. 2003. 2002 Outfall monitoring overview. Boston: Massachusetts Water Resources Authority. Report ENQUAD 2003-12. 80p.

Williams IP. 2002. MWRA Harbor Traditional Benthic Survey and Combined Sewer Overflow (CSO) Survey – HT022/HC021– HT022/HC021.

Williams, IP, Maciolek, NP, Boyle JD, Dahlen DT, and Baptiste-Carpenter E. 2002. Combined work/quality assurance plan for benthic monitoring: 2002-2005. MWRA Environmental Quality Department Miscellaneous Report Number ms-076. Massachusetts Water Resources Authority, Boston MA. 109 pp.

Zago C, Giblin AE, Bergamesco A. 2001. Changes in the metal content of surficial sediments of Boston Harbor since the cessation of sludge discharge. *Mar. Environ. Res*. 51(5):389-415.

Zimmerman MJ and Breault RF. 2003. Sediment quantity and quality in three impoundments in Massachusetts: U.S. Geological Survey Water-Resources Investigations Report 03-4013, 36p

Appendix A

2002 Data, Individual Replicates, Means and Standard Deviations

Appendix B

Historical Means 1990, 1994, 1998 and 2002

Table B-1. Sediment Grain Size and TOC Results – 1990, 1994, 1998, and 2002.

	1990		1994		1998		2002	
Station	**%Fines[a]**	**TOC (%)**	**%Fines**	**TOC (%)**	**%Fines**	**TOC (%)**	**%Fines**	**TOC (%)**
DB01 (N)	30.1	6.26	74.4	2.78	85.4	2.32	88.5	3.05
DB04 (N)	63.8	3.15	60.8	2.35	89.7	2.62	84.1	2.3
DB13/T04 (N)	77.7	3.82	85.7	3.2	78.3	7.14	90.77	3.64
DB14 (N)	64.1	4.31	51.9	5.06	53.6	6.76	74.13	8.6
C019 (N)	-	-	95.9	2.82	96.7	2.87	97	3.03
DB03 (F)	18.5	0.973	18.6	1.05	19.1	0.54	20.3	1.32
DB06 (F)	6.1	0.263	7.43	0.213	5.87	0.24	6.81	0.25
DB10 (F)	62.7	4.54	87.9	4.12	54.1	2.96	97.1	4.26
DB11 (F)	-[b]	-	39.6	1.12	-	-	-	-
DB12 (F)	44.1	1.88	45.6	2.64	43.5	2.5	50.97	2.89
T01 (H)	-	-	36.4	1.82	25	1.8	31.83	0.97
T02 (H)	-	-	37.9	1.61	53	1.44	54.43	1.76
T03 (H)	-	-	-	-	-	-	59.73	2.8
T05A (H)	-	-	-	-	-	-	12.4	0.87
T06 (H)	-	-	-	-	-	-	26.4	1.6
T07 (H)	-	-	-	-	57.4	2.16	54.5	2.73
T08 (H)	-	-	6.13	1.14	5.43	0.427	10.4	0.5
SWEX3 (H)	-	-	54	2.6	66.4	2.14	65.8	2.4

[a] Percent fines is the sum of %silt and %clay

[b] No data available

(N) "Near", (F) "Far", (H) "Harbor"

Table B-2. Comparison of Sediment Organic Contaminants (ng/g dry wt.) and Microbiological Data for 1990, 1994, 1998, and 2002 Samples. Raw data are not normalized.

Station	**Total PAH (ng/g, DW)**	**Total 24 PAH (ng/g, DW)**	**Petro-PAH (ng/g, DW)**	**Pyro-PAH (ng/g, DW)**	**%Pyro of Total PAH**	**Total PCB (ng/g, DW)**	**Total DDT (ng/g, DW)**	**Total LAB (ng/g, DW)**	**Copro-stanol (ng/g, DW)**	**Total LAB/ Copro-stanol**	**Fecal Coliform (cfu/g DW)**	**Entero-coccus (cfu/g DW)**	***C. per-fringens* (spores/g DW)**	***C. per-fringens* Log 10**
1990														
DB01	-[a]	65800	-	-	-	-	-	1350	4220	0.32	3.2	15.4	27000	4.43
DB04	-	8030	-	-	-	-	-	1170	5160	0.227	9.3	4.7	45500	4.66
DB13	-	9010	-	-	-	-	-	2430	16800	0.145	22.4	46.2	53400	4.73
DB14	-	35700	-	-	-	-	-	3210	31000	0.103	35.1	190	115000	5.06
DB03	-	2400	-	-	-	-	-	-	-	-	8.0	4.9	13000	4.11
DB06	-	550	-	-	-	-	-	-	-	-	16.4	6.3	1990	3.3
DB10	-	18100	-	-	-	-	-	-	-	-	33.3	27.1	34600	4.54
DB11	-	-	-	-	-	-	-	-	-	-	56.9	31.8	25400	4.4
DB12	-	4490	-	-	-	-	-	1230	4860	0.253	8.5	5.4	27800	4.44
1994														
DB01	26300	21200	6980	19300	73.4%	88.1	25.8	792	5600	0.141	-	-	3040	3.48
DB04	39800	31800	12800	27000	69.8%	62.2	29.3	974	6060	0.161	-	-	5120	3.71
DB13	22600	17300	6140	16400	73.0%	417	71.8	1940	9260	0.209	-	-	10500	4.02
DB14	128000	100000	40800	87500	68.5%	348	164	3200	32200	0.0992	-	-	7290	3.86
C019	19600	14800	5010	14500	74.4%	186	39.8	2570	10700	0.24	-	-	12600	4.1
DB03	10400	8250	3860	6540	64.5%	45.7	9.68	264	1610	0.164	-	-	5280	3.72

Station	Total PAH (ng/g, DW)	Total 24 PAH (ng/g, DW)	Petro-PAH (ng/g, DW)	Pyro-PAH (ng/g, DW)	%Pyro of Total PAH	Total PCB (ng/g, DW)	Total DDT (ng/g, DW)	Total LAB (ng/g, DW)	Copro-stanol (ng/g, DW)	Total LAB/ Copro-stanol	Fecal Coliform (cfu/g DW)	Entero-coccus (cfu/g DW)	*C. perfringens* (spores/g DW)	*C. perfringens* Log 10
DB06	495	424	96.5	399	80.8%	7.21	1.28	32.2	2820	0.0115	-	-	1280	3.11
DB10	20800	16000	5380	15400	74.1%	373	151	1530	5680	0.27	-	-	12000	4.08
DB11	8400	6320	2190	6210	73.5%	127	23.1	425	21410	0.199	-	-	3340	3.52
DB12	19400	14600	6440	12900	67.1%	266	50.6	681	2830	0.241	-	-	16500	4.22
T01	7620	5010	3130	4490	58.8%	28.8	10.9	343	4200	0.0817	-	-	4830	3.68
T02	7580	5750	2180	5400	71.1%	55.8	14.1	1270	9800	0.13	-	-	12100	4.08
T08	3000	2340	1230	1770	61.9%	7.9	2.94	360	1770	0.204	-	-	2570	3.41
SWEX3	9960	7300	3170	6790	68.2%	90.6	23.6	1190	6730	0.176	-	-	12400	4.09
1998														
DB01	18700	15400	4650	14100	75.2%	95.5	13.5	384	2650	0.145	ND[b]	ND	3980	3.59
DB04	11600	9330	3080	8550	73.5%	90.9	12.5	502	2970	0.171	ND	ND	1360	3.09
DB13	76700	59600	28200	48500	63.7%	472	70.2	3690	378000	0.0106	373	9000	9030	3.84
DB14	156000	122000	58200	97500	62.8%	540	143	2300	100000	0.0234	866	4133	6790	3.83
C019	17300	14000	4130	13200	76.1%	205	24	925	6040	0.153	ND	ND	15100	4.16
DB03	3180	2420	820	2360	73.9%	60.5	10.2	158	832	0.19	ND	ND	5720	3.76
DB06	371	303	78.6	292	78.8%	6.77	0.599	53.5	148	0.394	ND	ND	397	2.59
DB10	44200	36000	11300	32900	74.5%	255	39.9	580	1960	0.611	ND	91.7	5340	3.64
DB12	19400	15200	5720	13700	70.9%	316	55.4	420	2100	0.198	ND	ND	9270	3.95
T01	4790	3410	1930	2860	60.7%	24.5	2.93	188	2030	0.0929	ND	ND	4370	3.64
T02	6730	5300	1840	4890	72.7%	45.3	6.98	520	3920	0.135	ND	113	6250	3.78
T07	5200	4120	1360	3840	73.8%	83.2	12	1270	3530	0.366	ND	ND	7760	3.89
T08	650	482	229	421	64.8%	5.92	0.59	80.1	733	0.129	ND	ND	1890	3.25
SWEX3	6540	5000	1800	4740	72.9%	91.3	54.5	358	3850	0.11	ND	ND	6590	3.81
2002														
DB01	11873	9444	2963	8909	75%	66.6	6.45	465	1257	0.37	ND[f]	ND	4600	3.66
DB04	11189	8708	3057	8131	72.7%	54.4	5.49	570	775	0.73	ND	ND	2713	3.43
DB13/T04	18439	14368	4774	13664	74.1%	131.9	13.45	956	4096	0.23	23.3	23.3	3220	3.51
DB14	93199	72168	30883	62316	68.7%	197.9	57.25	9251	148827	0.06	236	10126	26766	4.43
C019	11226	8465	3139	8086	72%	93.1	9.35	681	1112	0.61	ND	ND	17766	4.25
DB03	5457	4095	1966	3491	63.9%	25	2.48	151	313	0.48	ND	ND	2623	3.42
DB06	628	486	155	472	74.6%	4.53	0.896	130	205	0.63	ND	5	213	2.33
DB10	15898	12537	3762	12135	76.3%	204.1	47.87	731	1859	0.39	76.6	ND	6276	3.8
DB12	21790	14180	6573	15217	69.8%	100.1	9.89	477	645	0.74	ND	ND	9026	3.95
T01	3370	2307	1268	2102	62.3%	13.5	1.52	160	336	0.47	ND	ND	2160	3.33
T02	7152	5357	1982	5170	72.2%	39.5	3.92	535	1018	0.52	ND	ND	6733	3.82
T03	8837	6591	3363	5474	61.9%	104.4	9.03	1169	2383	0.49	ND	ND	9106	3.95
T05A	45221	33499	17658	27563	60.9%	110.4	9.15	338	580	0.58	ND	ND	453	2.65
T06	4064	3071	1251	2813	69.2%	30.1	2.56	389	719	0.54	ND	ND	1770	2.23
T07	5438	3948	1674	3764	69.2%	79.68	10.74	960	803	1.2	ND	ND	8116	3.91
T08	3816	2827	1701	2115	55.4%	5.75	1.11	80	187	0.42	ND	ND	386	2.58
SWEX3	7189	5322	2214	4975	69.2%	53.8	5.86	398	1064	0.37	ND	ND	5930	3.77

[a] “-“ indicates “not analyzed”

[b] ND indicates “not detected”

Table B-3. Comparison of Sediment Metal Contaminants (ug/g dry wt.) for 1990, 1994, 1998, and 2002 Samples. Raw data are not normalized.

(μg/g, dry weight)											
Station	**Ag**	**Al[a]**	**Cd**	**Cr**	**Cu**	**Fe[a]**	**Hg**	**Ni**	**Pb**	**Zn**	**%Fines[b]**
1990											
DB01	-[c]	6.52	8.28	116	215	2.82	-	73.4	469	1470	30.1
DB04	-	7.44	1.5	196	156	3.7	-	47.9	150	275	63.8
DB13	-	7.41	2.01	212	182	4.01	-	44.3	192	342	77.7
DB14	-	6.97	2.46	160	183	3.7	-	44.3	523	433	64.1
DB03	-	5.31	0.6	82.8	48.5	2.09	-	19.3	59.7	97.6	18.5
DB06	-	5.11	0.25	34.2	18.6	1.39	-	13.8	36.7	46.7	6.1
DB10	-	7.14	2.29	218	215	4.62	-	51.5	427	473	62.7
DB12	-	6.44	1.06	168	103	3.07	-	34	110	156	44.1
1994											
DB01	3.48	5.7	0.844	157	134	3.72	0.741	34.5	152	233	74.4
DB04	2.97	5.47	0.82	139	87	2.94	0.617	28.2	159	168	60.8
DB13	5.59	6.71	2.12	254	158	3.79	1.24	37.1	199	266	85.7
DB14	2.18	4.25	1.48	119	126	2.84	0.771	25.5	347	344	51.9
CO19	4.76	7.2	1.14	215	146	4.34	0.812	37.2	137	218	95.9
DB03	0.885	4.63	0.228	65.2	27.9	1.99	1.35	15.3	54.6	69.5	18.6
DB06	0.359	3.64	0.0651	34.8	12.1	1.35	0.075	9.1	28.4	33.3	7.43
DB10	5.05	6.17	1.69	218	198	4.22	1.18	37.8	182	273	87.9
DB11	1.2	4.19	0.585	77	41.2	1.95	0.402	13.5	63.5	95.5	39.6
DB12	3.76	5.33	1.13	209	98.5	3.14	0.81	33.9	130	172	45.6
T01	0.895	6.49	0.307	78.2	26.8	2.6	0.26	20.7	32.8	67.6	36.4
T02	2.5	5.66	0.485	126	59.2	2.63	0.373	23.2	63.1	101	37.9
T08	0.53	3.02	0.101	48.9	15.8	2.03	0.101	13.3	25.9	47.2	6.13
SWEX3	4.03	6.95	0.423	194	95.7	3.95	0.581	35.9	108	156	54
1998											
DB01	2.47	6.69	0.757	142	117	3.84	0.583	31.6	146	220	85.4
DB04	2.85	6.56	0.737	151	103	4.11	0.597	36.3	125	192	89.7
DB13	3.48	5.85	2.1	164	193	3.97	2.29	38.7	389	435	78.3
DB14	1.84	5.28	2.2	117	170	3.54	1.07	34.9	719	507	53.6
CO19	4.03	7.4	1.09	205	148	4.78	0.79	44.8	150	234	96.7
DB03	0.713	4.62	0.35	68	33.4	2.1	0.183	15	56.4	83.9	19.1
DB06	0.303	3.9	0.07	26.4	17.8	1.3	0.0667	9.93	29.2	36.5	5.87
DB10	3.13	5.89	1.37	142	288	4.16	1.03	36	423	351	54.1
DB12	2.74	5.4	1.62	162	88	3.04	0.65	28.8	116	164	43.5
T01	0.71	5.19	0.32	58.9	33.6	2.3	0.17	19.7	50.8	71.8	25
T02	1.8	5.91	0.417	105	52.9	3.05	0.31	24.6	62.9	108	53
T07	5.56	6.1	0.943	165	99	3.38	0.827	32.5	110	147	57.4
T08	0.41	3.89	0.123	29	16.9	1.71	0.08	12.2	27.5	44.1	5.43
SWEX3	2.59	6.58	0.347	154	80.3	3.93	0.697	35	90.8	142	66.4
2002											
DB01	2.72	7.2	0.49	182.6	125.9	4.51	0.69	31.56	154.2	250.6	88.5
DB04	1.91	6.75	0.39	145	86.5	3.67	0.49	31	102.1	163.7	84.1
DB13/T04	2.63	6.32	0.712	170.6	127.3	3.96	0.75	34.96	145.36	216.3	90.77
DB14	1.96	5.49	1.18	140.8	189.7	3.71	0.81	44.7	419.3	454.6	74.13
CO19	3.19	7.53	0.59	207.6	128.2	4.75	0.76	39.3	130.1	220.8	97
DB03	0.79	5.6	0.17	66.56	44.35	2.4	0.19	24.8	69.8	86.9	20.3
DB06	0.33	4.82	0.058	36.3	19.07	1.36	0.065	10.9	30.7	44.4	6.8

(µg/g, dry weight)										
Station	**Ag**	**Al[a]**	**Cd**	**Cr**	**Cu**	**Fe[a]**	**Hg**	**Ni**	**Pb**	**Zn**	**%Fines[b]**
DB10	2.91	6.57	0.845	197	203.6	4.74	1.04	45.45	184.2	278.8	97
DB12	1.89	5.84	0.63	143.3	77.5	3.17	0.61	27.8	134.4	141	50.93
T01	0.59	6.31	0.089	62.5	27.3	2.3	0.18	17.26	37.7	63.06	31.83
T02	1.49	6.43	0.26	124.4	55.47	3.23	0.31	25.86	63.23	111.7	54.5
T03	2.87	6.97	0.269	187	88	39	1.08	36	106	159.6	59.73
T05A	0.42	5.49	0.349	58.7	30.56	1.91	0.183	14.06	45.76	76.56	12.4
T06	1.47	6.48	0.149	103.46	44.63	3.01	0.394	24.03	61.36	103.1	26.4
T07	4	5.6	0.473	167	88.8	3.11	0.84	29.06	107.26	140.46	54.5
T08	0.34	4.98	0.069	37.48	16.6	1.72	0.084	11.88	25.76	47.9	10.4
SWEX3	1.86	7.32	0.183	168.3	67.46	4.14	0.58	35.93	88.7	141.6	65.8

[a] Al and Fe reported as percent dry weight

[b] Percent Fines is the sum of percent silt and percent clay

[c] “-“ indicates “not analyzed”

Appendix C

Results of One-Way ANOVA for individual stations

Table C-1 (a). One-Way ANOVA Results for Non-normalized Percent Fine Fraction and TOC of Sediments Collected in 1994, 1998, and 2002. a=1994, b=1998, c=2002.

Station	TOC	Fines
DB01	(ca)b	(cb)a
DB04	(ba)(ac)	(bc)a
DB13/T04	b(ca)	(ca)(ab)
DB14	(cb)(ba)	(cb)(ba)
DB03	(cab)	(cba)
DB06	(cba)	(acb)
DB10	(ca)b	(ca)b
DB12	(cab)	(cab)

Note: Letters are arranged in order from the year of highest concentration to the year of lowest concentration.

Table C-1 (b). The p-values Corresponding to One-Way ANOVA Results for Non-normalized Percent Fines Fraction and TOC of Sediments Collected in 1994, 1998, and 2002.

Station	TOC	Fines
DB01	0.0033	0.0028
DB04	0.0412	0.0182
DB13/T04	0.0068	0.0357
DB14	0.0032	0.0332
DB03	0.2099	0.9807
DB06	0.9837	0.1661
DB10	0.0007	0.0016
DB12	0.6745	0.5187

Note: Shaded cells indicate statistical significance

Table C–2 (a). One-Way ANOVA results for non-normalized PAH, 24 PAH, petro-PAHs and pyro-PAH concentrations in sediments collected from 1994, 1998, and 2002.

a=1994, b=1998, c=2002.

Station	Total PAHs*	Total 24 PAHs*	Total petro PAHs*	Total pyro PAHs*
DB01	(a)(b)(c)	(a)(b)(c)	(a)(b)(c)	(a)(b)(c)
DB04	(abc)	(abc)	(abc)	(abc)
DB13/T04	b(ac)	b(ac)	b(ac)	b(ac)
DB14	(ba)(ac)	(ba)(ac)	(ba)(ac)	(ba)(ac)
DB03	(acb)	(acb)	(acb)	(acb)
DB06	(ca)(ab)	(cab)	(ca)(ab)	(ca)(ab)
DB10	b(ac)	b(ac)	b(ac)	b(ac)
DB12	(cab)	(bac)	(cab)	(cba)

Note: Letters are arranged in order from the year of highest concentration to the year of lowest concentration.
*Parameters have been log transformed

Table C-2 (b). The p-values for One-Way ANOVA results for non-normalized PAH, 24 PAH, petro-PAH, and pyro-PAH concentrations in sediments collected from 1994, 1998, and 2002.

Station	Total PAHs*	Total 24 PAHs*	Total petro PAHs*	Total pyro PAHs*
DB01	0.0002	0.0003	0.0003	0.0003
DB04	0.0589	0.0606	0.0726	0.0559
DB13/T04	0.0029	0.0029	0.0016	0.004
DB14	0.030	0.021	0.040	0.022
DB03	0.4524	0.4951	0.2775	0.5699
DB06	0.031	0.0556	0.0189	0.0522
DB10	0.0007	0.0003	0.0005	0.0008
DB12	0.6626	0.979	0.8471	0.6152

Shaded cells indicate statistical significance.
*Parameters have been log transformed

Table C–3 (a). One-Way ANOVA results for non-normalized DDT and PCB concentrations in sediments collected from 1994, 1998, and 2002. a=1994, b=1998, c=2002.

Station	Total PCBs*	Total DDT*
DB01	(ba)c	(a)(b)(c)
DB04	(ba)(ac)	(a)(b)(c)
DB13/T04	(ba)(ac)	(ba)c
DB14	(ba)(ac)	(ab)(bc)
DB03	(bac)	(bac)
DB06	(ab)c	(acb)
DB10	(ab)(bc)	a(cb)
DB12	(ba)c	(ab)c

Note: Letters are arranged in order from the year of highest concentration to the year of lowest concentration
*Parameters have been log transformed

Table C-3 (b). The p-values for One-Way ANOVA results for non-normalized DDT and PCB concentrations in sediments collected from 1994, 1998, and 2002.

Station	Total PCBs*	Total DDT*
DB01	0.0026	<0.0001
DB04	0.027	0.0014
DB13/T04	0.053	0.0044
DB14	0.0057	0.0241
DB03	0.3248	0.0524
DB06	0.0079	0.2569
DB10	0.0097	0.0028
DB12	0.0053	0.0121

Shaded cells indicate statistical significance
*Parameters have been log transformed

Table C–4 (a). One-Way ANOVA results for non-normalized LABs, coprostanol, and *C. perfringens* concentrations in sediments collected from 1994, 1998, and 2002. a=1994, b=1998, c=2002.

Station	Total LABs*	Coprostanol*	C. perfringens spores*
DB01	(a)(c)(b)	(a)(b)(c)	(cba)
DB04	a(cb)	(a)(b)(c)	(acb)
DB13/T04	(b)(a)(c)	b(ac)	(abc)
DB14	c(ab)	(cb)a	(cb)a
DB03	(abc)	(ab)(bc)	(ba)(ac)
DB06	(cba)	a(cb)	(a)(b)(c)
DB10	a(cb)	(acb)	(acb)
DB12	(acb)	(ab)c	(abc)

Note: Letters are arranged in order from the year of highest concentration to the year of lowest concentration
*Parameters have been log transformed

Table C-4 (b). The p-values for One-Way ANOVA results for non-normalized LABs, coprostanol, and C. perfringens concentrations in sediments collected from 1994, 1998, and 2002.

Station	Total LABs*	Coprostanol*	C. perfringens spores*
DB01	<0.0001	<0.0001	0.1667
DB04	0.0122	<0.0001	0.0652
DB13/T04	0.0006	0.0001	0.1628
DB14	0.0001	0.0002	0.0340
DB03	0.9806	0.0157	0.0242
DB06	0.1784	0.0098	0.0001
DB10	0.0031	0.1194	0.1197
DB12	0.0649	<0.0001	0.0504

Shaded cells indicate statistical significance
*Parameters have been log transformed

Table C–5 (a). One-Way ANOVA Results for Non-normalized Metal Concentrations of Sediments Collected in 1994, 1998, and 2002. a=1994, b=1998, c=2002.

Station	Al	Cd*	Cr	Cu*	Fe	Pb*	Hg*	Ni	Ag*	Zn
DB01	(cba)	(ab)c	(cab)	(acb)	(cb)(ba)	(cab)	(ac)(cb	(abc)	a(cb)	(cab)
DB04	(cba)	(a)(b)(c)	(bca)	(bca)	(bca)	(abc)	(abc)	(bca)	(ab)c	(bac)
DB13/T04	(acb)	(ba)(ac)	(acb)	(bac)	(bca)	b(ac)	(ba)(ac	(bac)	(ab)(bc	(ba)(ac)
DB14	(cba)	b(ac)	(cab)	(cb)(ba)	(cba)	b(ca)	(bca)	(cb)(ba	(acb)	(bca)
DB03	(cab)	(bac)	(bca)	(cba)	(cba)	(cba)	(acb)	c(ab)	(acb)	(cba)
DB06	(cba)	(bac)	(cab)	(cb)a	(cab)	(cba)	(abc)	(cba)	(acb)	(cb)(ba)
DB10	c(ab)	(ab)c	(a)(c)(b)	(bca)	c(ab)	(bca)	(acb)	(cab)	a(bc)	(bca)
DB12	(cba)	(bac)	(abc)	(abc)	(cab)	(cab)	(abc)	(abc)	(ab)(bc	(cab)

Note: Letters are arranged in order from the year of highest concentration to the year of lowest concentration.
*Parameters have been log transformed

Table C-5 (b). The p-values Corresponding to One-Way ANOVA Results for Non-normalized Metal Concentrations of Sediments Collected in 1994, 1998, and 2004.

Station	Al	Cd*	Cr	Cu*	Fe	Pb*	Hg*	Ni	Ag*	Zn
DB01	0.1017	0.0002	0.2935	0.2253	0.0382	0.3110	0.0190	0.0443	0.0097	0.2765
DB04	0.2248	<0.0001	0.8835	0.3570	0.0771	0.2533	0.1082	0.1931	0.0152	0.0915
DB13/T04	0.3191	0.0315	0.2596	0.1590	0.6598	0.0110	0.0318	0.4394	0.0510	0.0164
DB14	0.3146	0.0088	0.3229	0.0359	0.0834	0.0009	0.2133	0.0096	0.6735	0.0704
DB03	0.0518	0.3978	0.9875	0.2548	0.1035	0.6861	0.8246	0.0082	0.9013	0.4158
DB06	0.1205	0.6302	0.1043	0.0083	0.5599	0.6110	0.5944	0.4902	0.2574	0.0516
DB10	0.0068	0.0007	<0.0001	0.6594	0.0010	0.1765	0.4910	0.3758	<0.0001	0.1073
DB12	0.8683	0.4608	0.1282	0.2760	0.8700	0.8580	0.3175	0.1202	0.0308	0.2765

Shaded cells indicate statistical significance
*Parameters have been log transformed

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