

Section 7: Using Sediments to Monitor Environmental Change in Massachusetts Bay and Boston Harbor

By Michael H. Bothner, Michael A. Casso, Richard R. Rendigs, Paul J. Lamothe, and Sandra M. Baldwin

On September 6, 2000, the discharge of 350 million gallons of secondary treated sewage per day was switched from outfalls at the mouth of Boston Harbor to a new outfall 15.2 km to the east in Massachusetts Bay (fig. 7.1). This significant step in the Boston Harbor cleanup program was accomplished after considerable public debate (Gelbspan, 1991; McLaughlin, 1992) and legal challenges based on concerns that the use of Massachusetts Bay outfall would transfer Boston's pollution problems to the waters beyond Boston Harbor and threaten the whales on Stellwagen Bank and in Cape Cod Bay. The USGS played a key role by providing unbiased scientific information based on numerical models of the dilution and path of the effluent plume. Model simulations predicted that the new outfall would result in a cleaner harbor without adversely affecting the environments of Massachusetts and Cape Cod Bays. Testing this hypothesis became an important scientific and legal objective; monitoring the concentrations of contaminants in the bay and harbor sediments became one of the primary testing criteria.

The USGS has been measuring the chemical composition of bottom and suspended sediments near the site of the Massachusetts Bay outfall since 1989 as part of the comprehensive outfall monitoring plan for Massachusetts Bay (Station 3, fig. 7.1). The first objective was to establish a pre-outfall set of baseline concentrations in order to determine the magnitude, cause, and possible consequences of any chemical changes in sediments after the new outfall began operation. The variables measured included concentrations of heavy metals such as silver (Ag), copper (Cu), and lead (Pb); sediment texture; and concentrations of *Clostridium perfringens*, a chemically resistant bacterial spore that is found in sewage (Buchholz ten Brink and others, 2000). This section evaluates the changes in chemical composition and properties of sediment with respect to the timing of improvements in the waste-processing system in Boston.

Bottom Sediment Time Series

Silver (Ag) is emphasized in this study because it is a sensitive, inorganic chemical tracer for sewage particles in marine sediments and suspended matter (Bothner and others, 1994). Its concentration is elevated in sewage because of its use and discharge by the photographic, health care, electronics, and electroplating industries. In 1980, Boston's sewage sludge contained 55 ppm of Ag (dry weight) on average, about 1,000 times higher than the concentration found in uncontaminated fine-grained

marine sediments. The discharge of Ag from Boston's sewage-treatment facility decreased from 8.1 kilograms per day (kg/d), or about 18 pounds per day (lb/d), in 1990 to 0.54 kg/d, or about 1.2 lb/d, in 2004 (M. Hall, Massachusetts Water Resources Authority, written commun., 2005). This decrease was accomplished by stopping sludge discharge to the harbor in 1991, by strictly enforcing industrial discharge limits for Ag, and by upgrading to secondary sewage treatment. Since 1990, a significant decrease in the discharge of other metals has also been documented (fig. 7.2).

Station 3 (fig. 7.1) was selected as a monitoring station because a pre-outfall sidescan sonar mapping and sampling survey of the seabed (Bothner and others, 1992) identified it as the closest region to the proposed outfall site where muddy sediment was observed in a topographic depression about 1 km² in area. Later surveys further confirmed this identification (fig. 2.5B; Butman and others, 2003a, b, c). In this section, we summarize the results of analyses for Ag, *C. perfringens*, and clay content determined on the surfaces (0–0.5 cm) of sediment cores collected at the monitoring station from 1989 to early 2005 (fig. 7.3). Key events in the time series are a major storm in December 1992 and the start of flow from the Massachusetts Bay outfall in September 2000.

From 1989 to mid-October 1992, the concentrations of Ag in surface sediments at Station 3 ranged from 0.4 ppm to 0.8 ppm, considerably above the background concentrations of 0.03–0.05 ppm. Concentration of Ag increased more than twofold prior to the next sampling cruise in February 1993 (fig. 7.3A). Similar changes were measured for spore counts of *C. perfringens* (fig. 7.3B) and clay content (fig. 7.3C). The concentrations of these constituents remained relatively high for about a year, until about February 1994.

The best explanation for increases in concentrations of Ag and *C. perfringens* from September 1992 to February 1993 is that fine-grained sediment, containing high concentrations of these sewage indicators, was resuspended and transported from inshore areas and deposited in deeper depositional areas offshore, such as the area at Station 3 (Bothner and others, 2002). The driving force for this redistribution was an unusually strong, slow-moving northeast storm, from December 11–16, 1992, that generated waves at this site with maximum significant wave height of 7.1 m. Large storms from the northeast typically cause resuspension and offshore bottom currents at this site (Section 6; Butman and Bothner, 1997; Signell and List, 1997).

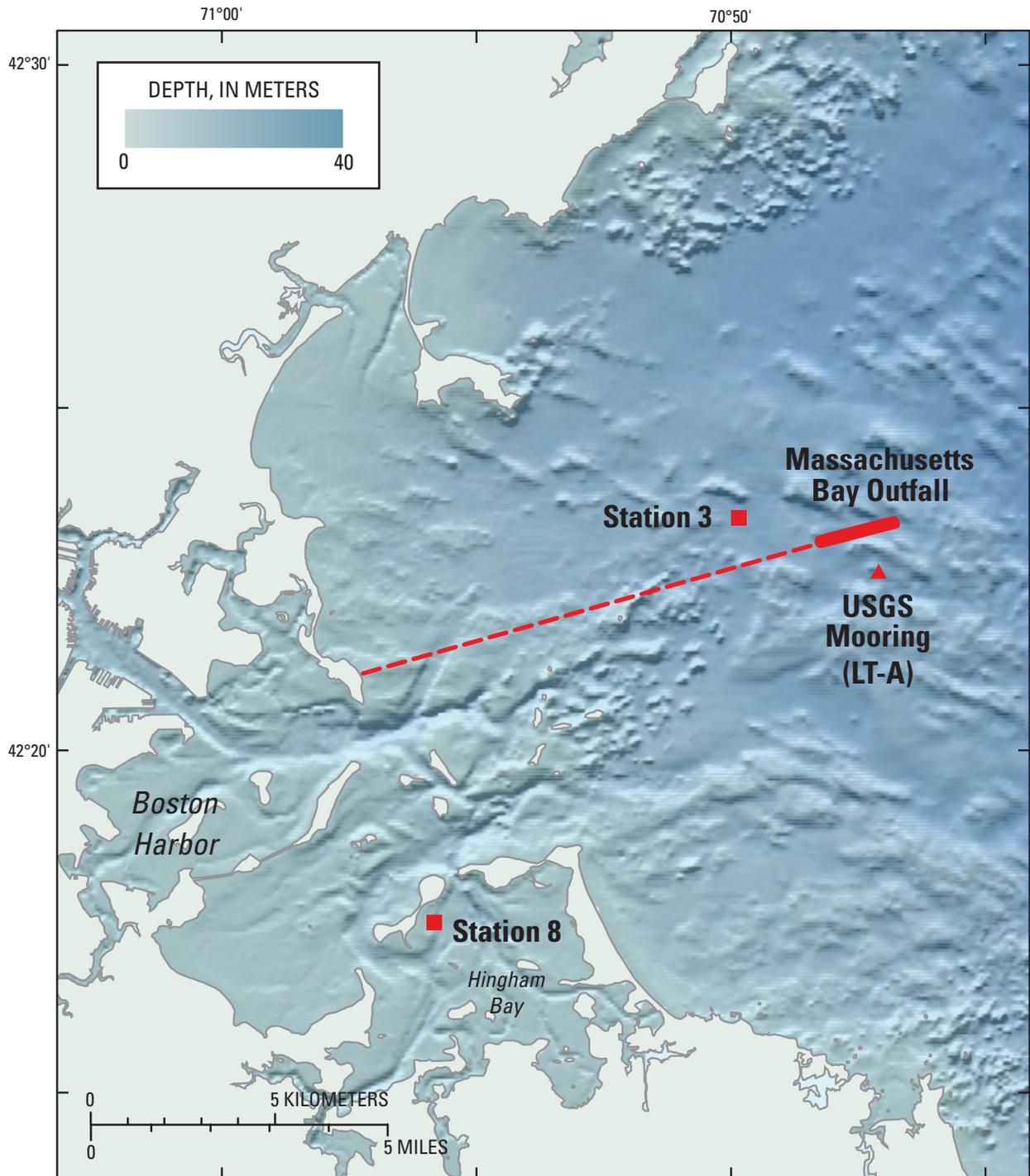


Figure 7.1. Locations of the Massachusetts Bay outfall (red rectangle), the outfall tunnel (dashed line), the USGS mooring and sediment-trap site (red triangle), and the bottom sediment sampling site (Station 3, red square). Time-series data from oceanographic instruments and chemical measurements have been made at these sites since 1989. Cores have been taken periodically since 1978 from a site in Boston Harbor (Station 8). See figure 2.5B for a high-resolution backscatter intensity map of the sea floor near the outfall.

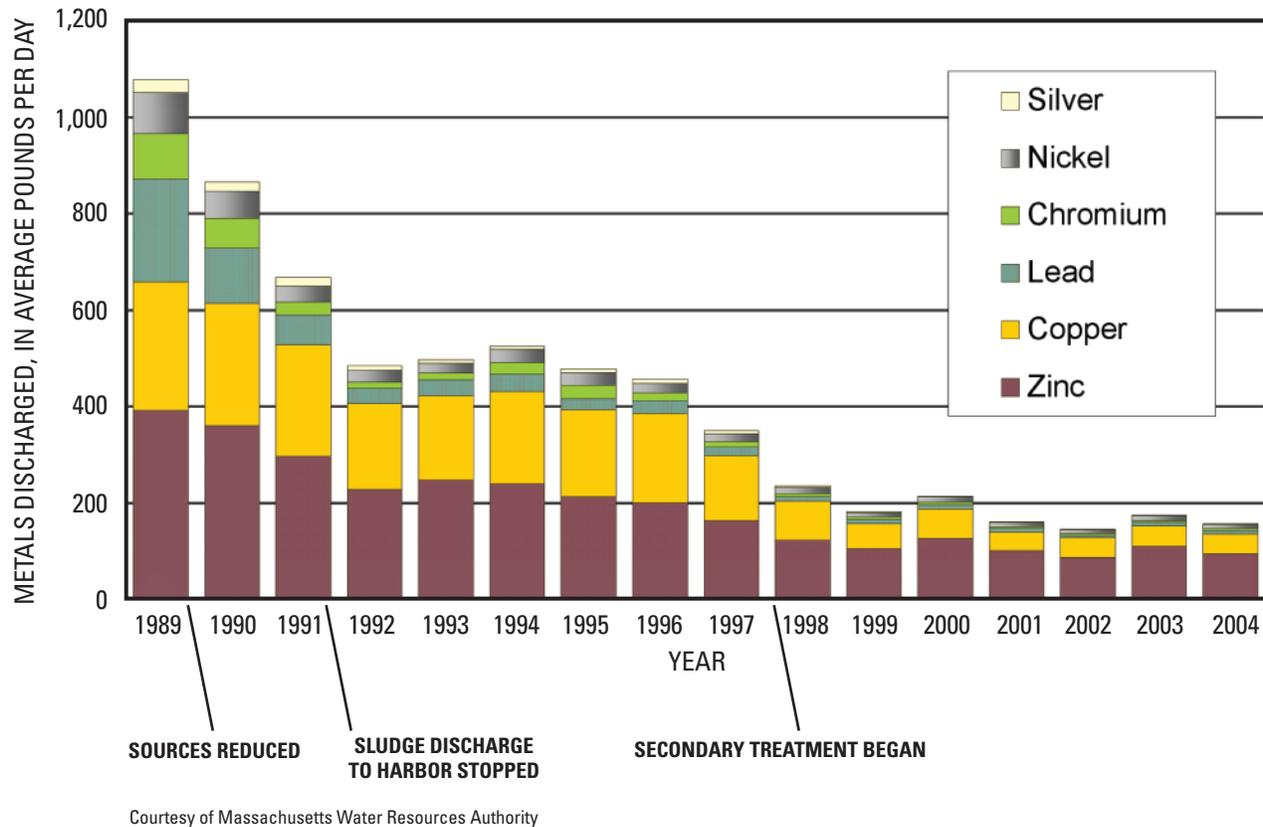


Figure 7.2. The decrease in discharge of metals by the Massachusetts Water Resources Authority sewage-treatment plants from 1989 to 2004 (Werme and Hunt, 2004).

This long time series of pre-outfall data for surface sediments is important because it defines the range of changes in concentration that can result from natural processes. Had the outfall begun operation in January 1993, one might have incorrectly assumed that the new outfall was responsible for the observed increase in Ag and *C. perfringens* concentrations.

No significant increases from the post-outfall concentrations of silver, as well as other trace metals and *C. perfringens* were observed compared to the average pre-outfall values at the 95-percent level of confidence. The increases following the major storm in December 1992, when contaminated fine-grained sediments were transported to the monitoring station, represent the largest changes in the concentrations of these sewage indicators during the 16-year study period.

It is of interest to point out that during the 3-year period immediately before outfall startup (1997–2000),

relatively lower concentrations of Ag and *C. perfringens* and lower values for clay content were measured than after the outfall startup. Clay normalization (the ratio of Ag to clay content and *C. perfringens* to clay content) was used to correct for the commonly found influence of the fine-sediment percentage on the metal content of bulk sediments. Plots of clay-normalized values reveal no differences throughout the period from 1997 to 2004 and reinforce the conclusion that there were no outfall-related increases in concentrations of Ag and *C. perfringens* in bottom sediments.

A comprehensive geochemical study by Dahlen and others (2006) also concluded that there were no outfall-related increases in concentrations of metals (or organic contaminants) in surface sediments of Massachusetts Bay. They did observe, however, post-outfall increases in *C. perfringens* in sediments within 2 km of the outfall.

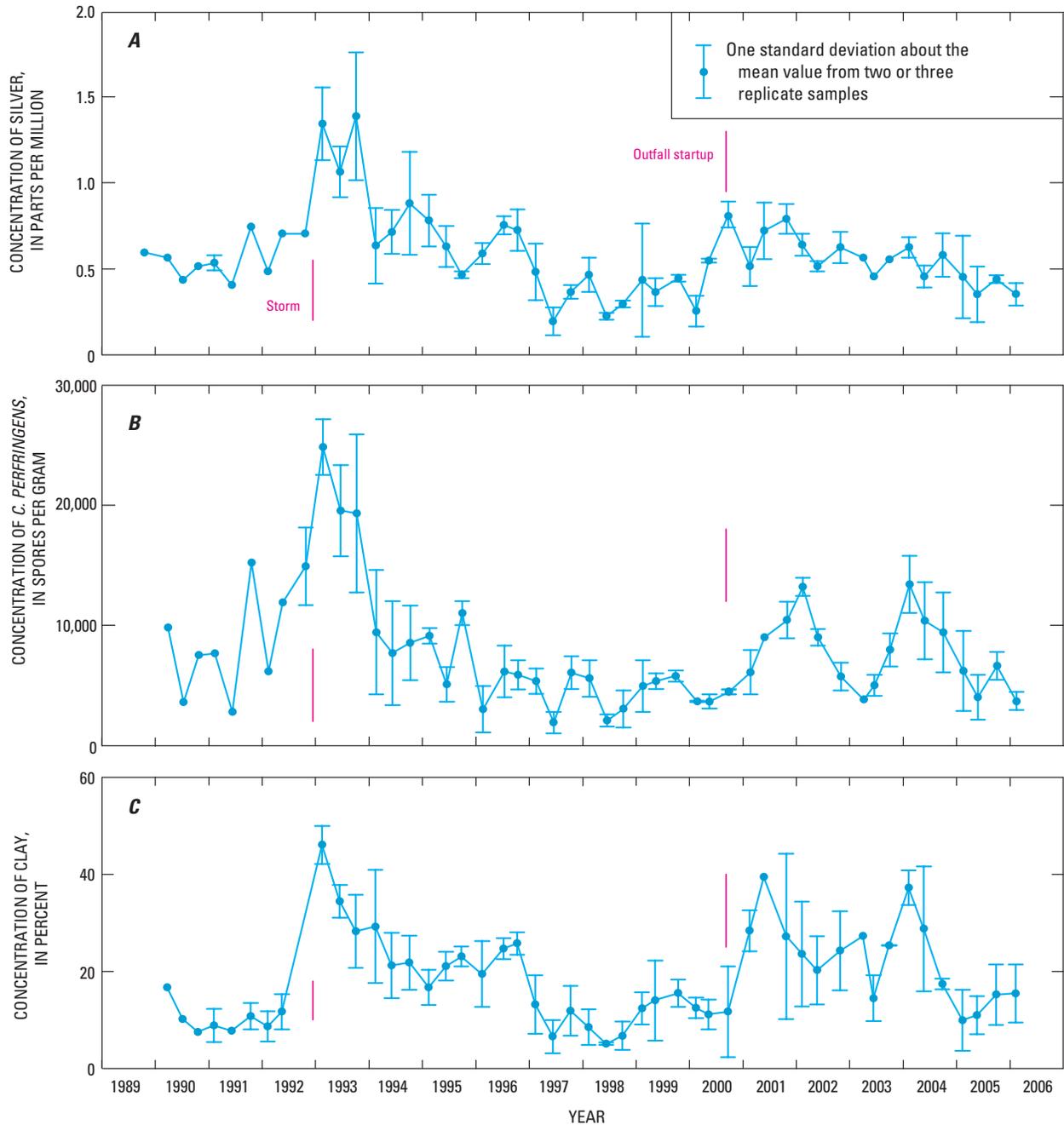


Figure 7.3 (A) Silver (Ag) concentrations in surface sediments at depths of 0–0.5 cm at Station 3. The highest Ag concentrations were observed in 1993 and are attributed to the transport of fine-grained sediment bearing Ag (possibly from the harbor or winnowed from nearshore sediments) to this location during the intense storm of December 11–16, 1992. Average post-outfall concentrations of Ag at Station 3 are not statistically different from average pre-outfall concentrations (even with storm-related values in 1992 and 1993 removed from pre-outfall average). The post-outfall concentrations of Ag are not increasing with time. Error bars are defined by analysis of two or three replicate samples. (B) The variations in concentrations of the bacterium spore, *Clostridium perfringens*, in surface sediments at depths of 0–0.5 cm with time at Station 3. Highest concentrations, like those for Ag, follow the storm of December 11–16, 1992. Average post-outfall concentrations of *C. perfringens* at Station 3 are not statistically different from average pre-outfall concentrations (even with storm-related values removed from pre-outfall average). The post-outfall concentrations of *C. perfringens* are not systematically increasing with time. (C) The clay fraction of the surface sediment at depths of 0–0.5 cm at Station 3. The clay fraction reached its highest value following the storm of December 11–16, 1992. Post-outfall clay content in the 5 years following outfall startup (September 2000) were, on average, higher and more variable than during the 3-year period prior to outfall startup. The variations in clay content of the surface sediment possibly account for the similar patterns observed in Ag and *C. perfringens* concentrations during the period.

Trapped Sediment Time Series

Sediment traps (figs. 3.4 and 3.5) were used to collect suspended sediment at the USGS long-term mooring station about 1 km south of the outfall (fig. 7.1). Analysis of material collected with sediment traps may be a more sensitive method for identifying outfall-related chemical changes than analysis of surficial bottom sediment. Unlike bottom sediments that are continuously mixed and diluted with older sediment of different composition by benthic organisms (Wheatcroft and others, 1994), particles collected in sediment traps are isolated from such mixing and potential dilution. One limitation of sediment traps is that they do not measure the net vertical flux of material to the sea floor. The rate of collection depends upon a complicated set of variables that includes: trap design, current speed, and sediment fall velocity (Baker and others, 1988; Butman, 1986), as well as the frequency and magnitude of sediment resuspension (Gardner and others, 1983). The re-deployment of traps of the same design in the same place, however, preserves the ability to compare concentrations of sewage tracers in trapped sediment collected under similar oceanographic conditions before and after the start of the new outfall.

The trap that is placed at the highest elevation (16 mab—meters above bottom) optimizes sensitivity for detection of sewage particles for two reasons. First, because of its height above the bottom, this device traps less material resuspended from the sediment surface than traps close to the bottom where resuspended material can dilute particles originating from the outfall plume. Second, in summer, the trap is a few meters below the seasonal pycnocline, which impedes the upward mixing and maintains the top of the sewage plume close to the trap elevation.

Of the suite of metals analyzed from these trap samples, only Ag has been shown to have a statistically higher concentration (at $p=0.01$) in post-outfall samples ($1.04 \text{ ppm} \pm 0.36 \text{ ppm}$) compared to pre-outfall values ($0.42 \text{ ppm} \pm 0.25 \text{ ppm}$; fig. 7.4). The concentrations of Ag were from 0.5 to 1.0 ppm in the early 1990s with the exception of one high value (not plotted) that appeared to result from spurious sample contamination. Concentrations were lowest during the late 1990s when, coincidentally, the discharge of Ag and other metals through the outfall at the harbor mouth was decreasing as secondary sewage treatment was beginning in 1997. The highest concentrations of Ag in post-outfall samples were observed during summer deployments. This is consistent with the plume being concentrated beneath the thermocline near the depth of this trap. The highest concentration was 1.8 ppm, well below the 3.7-ppm warning level established for bottom sediments by MWRA's outfall monitoring program.

Concentrations of *C. perfringens* also increased during the post-outfall period (fig. 7.4). Whereas the concentrations of *C. perfringens* spores in the 16-mab trap during the pre-outfall period were from 1,000 to 16,000 spores per gram, concentrations increased beginning at the time of outfall startup and rose to a maximum of 73,000 spores per gram in the post-outfall data that are available. Toxicity guidelines for *C. perfringens* spores have not been found in a literature search.

There were no statistically significant ($p=0.01$) changes in the average concentrations of Cu or Pb between the pre- and post-outfall periods. The average post-outfall concentrations of Cu and Pb in the 16-mab trap are $32 \pm 8 \text{ ppm}$ and $65 \pm 8 \text{ ppm}$, well below the warning levels (270 ppm and 218 ppm, respectively) for sediments.

It is worth noting that these warning levels (equivalent to the effects range—median (ERM) values of Long and others, 1995) are based on studies with bottom sediments. Trapped sediments typically have higher proportions of fine-grained particles and organic carbon and higher concentrations of metals than surficial bottom sediments from the same region. Comparing the concentrations of metals in trapped sediment to the warning criteria is thus a conservative application of the criteria, which none of the metals exceeded.

The clear post-outfall increase in *C. perfringens* and Ag permits a rough estimate of how the new outfall has contributed more particulates to the area monitored by the sediment trap. There are only two measurements of *C. perfringens* in final effluent from the new Deer Island Sewage Treatment Plant. The average value is 5,100 spores per milliliter, which is equivalent to 4.6×10^6 spores per gram dry weight, if the spores are assumed to be part of the total suspended solids load (Maurice Hall, MWRA, unpublished data, 2004). Taking these estimates as representative, the observed increase could be explained if 1 percent of the trapped particles originated from the outfall. An additional and important assumption is that the particles in the effluent plume (about 16 milligrams per liter (mg/L)) behave in the ocean in the same manner as the natural particulate matter (at 1–2 mg/L). A similar preliminary estimate of sewage-particle contribution can be made with the silver data. Estimated concentrations of Ag in particulates of the final effluent are $25 \text{ ppm} \pm 16 \text{ ppm}$ (Maurice Hall, MWRA, unpublished data, 2004). The average observed increase in silver concentrations (on the basis of a 3-year pre-outfall average) could be explained if 3 percent of the material trapped originated from the outfall. These estimates have large uncertainties but they seem reasonable given that the effluent dilution model (Signell and others, 2000) indicates the 3-year average plume concentration is about 1 percent at the trap location.

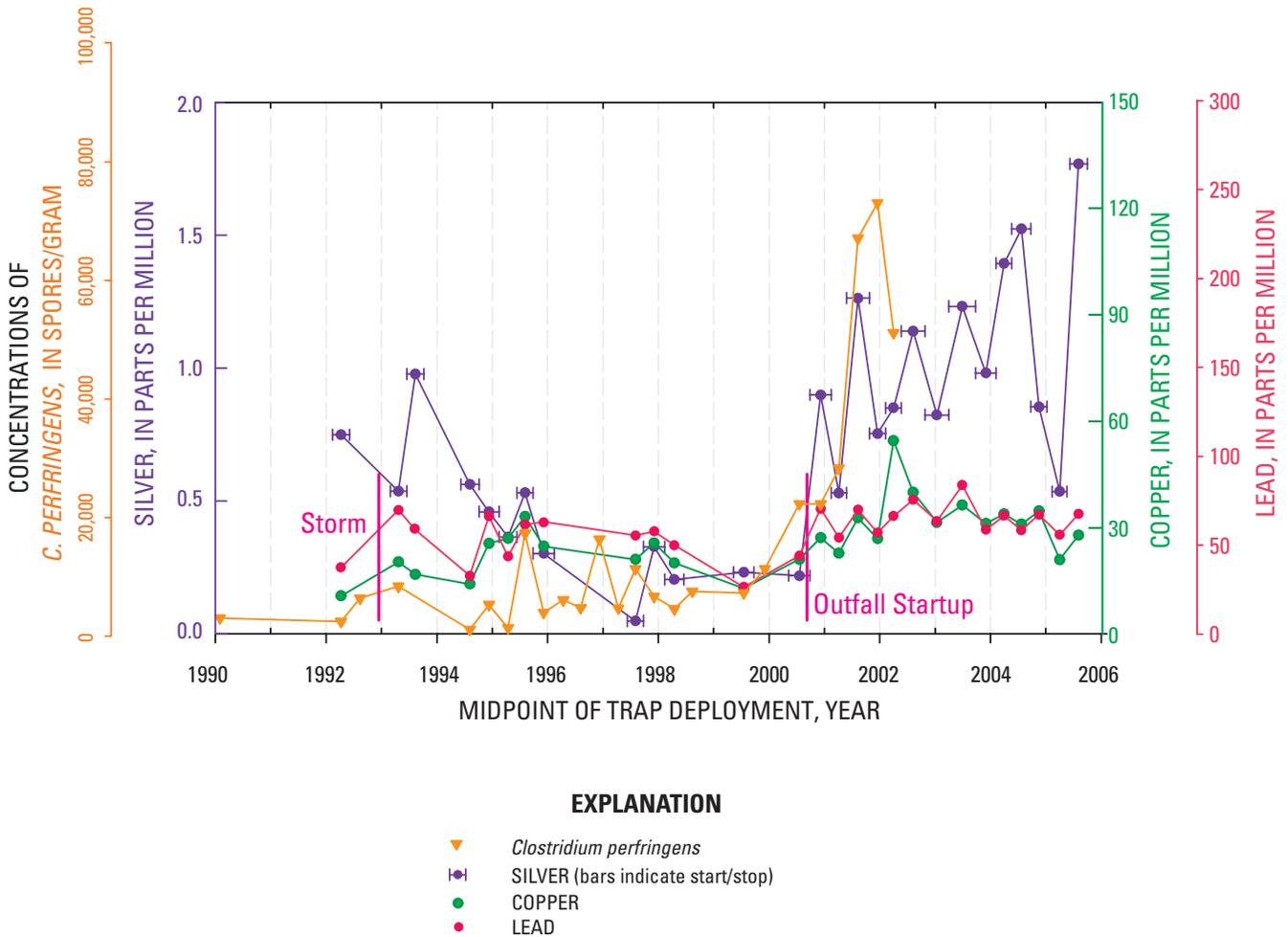


Figure 7.4. Concentrations of silver (Ag), copper (Cu), lead (Pb), and *Clostridium perfringens* in sediment traps at 16 mab near the Massachusetts Bay outfall. There is a significant increase (at the >95-percent level of confidence) in the concentrations of Ag and *Clostridium perfringens* in post-outfall trap samples compared to the average values from pre-outfall traps. Most of the post-outfall peaks in Ag concentration are during the summer trap deployments (typically June through September), consistent with the increased effluent concentration at the depth of the trap when the outfall plume is confined below the seasonal thermocline. No significant changes were measured in Cu or Pb following the outfall startup. The maximum concentrations of Ag and other metals in trap samples are well below the warning levels adopted for the outfall-monitoring program. The horizontal bars shown for the Ag data represent the start and stop dates for the trap deployment. Due to a change in analytical procedures, *Clostridium perfringens* data after mid-2002 were not directly comparable to previous data and therefore are not shown.

Decreasing Concentrations of Metals in Harbor Sediments

Since 1977, the USGS has periodically measured metal concentrations in surficial bottom sediments of Boston Harbor. The recent data from the most frequently sampled station in the south harbor (Station 8, fig. 7.1) confirms trends from previous studies (Bothner and others, 1998) that show that metal concentrations are decreasing with time. Compared to the concentrations at the start of the harbor study, the concentrations have decreased, on average, about 50 percent during the past 25 years (fig. 7.5). In that time, there have been significant decreases in the inputs of metals to the harbor. Removal of Pb from gasoline has reduced the atmospheric deposition of Pb globally. In Boston, strictly enforcing discharge regulations for industries, stopping sludge discharge to the harbor, implementing secondary sewage treatment, and moving the outfall have been significant steps in reducing metal inputs.

Although the surficial sediments are becoming less contaminated, deeper sediments recovered by coring contain high metal concentrations that remain a potential source of contamination after primary sources are reduced or eliminated (fig. 7.6). Maximum concentrations of Ag (12 ppm), Pb (310 ppm) and zinc (Zn) (500 ppm) in the core from Station 8 are higher than the ERM guidelines for toxicity to benthic animals (Long and others, 1995). Based on assigning a date of 1963 to the depth corresponding to a subsurface maximum in the activity of ^{137}Cs , the highest concentrations of metals at this location were deposited about 1945, a time when war-related ship building activities in Boston Harbor were ending (Bothner and others, 1998; Bergeson, 1993). New studies with colleagues at WHOI are being conducted to determine the rates and processes by which these metals can be recycled between particulate and dissolved phases within the upper sediment column. The continuing work has documented that these metals can be released into the overlying water by diffusion, advection of pore water, and/or by particulate resuspension and desorption (see Section 10). This information has contributed to our understanding of the long-term fate and effects of contaminants in coastal sediments.

Conclusions

The Massachusetts Bay outfall has had minimal impact on the concentrations of toxic metals in nearby sediments. The average concentrations of *C. perfringens*, Ag, and other metals in bottom sediments collected at Station 3 (2.5 km west of the outfall) after the outfall startup (September 6, 2000) are statistically no different than values measured in pre-outfall samples at the 95-percent level of certainty.

Post-outfall sediment trap samples collected 16 meters above the bottom at the USGS's long-term monitoring station have higher concentrations of *C. perfringens* and Ag than pre-outfall samples; however, the highest concentrations of Ag are well below warning levels. Toxicity guidelines for *C. perfringens* spores in sediment have not been found in a literature search. Based on preliminary estimates, the enrichments of Ag and *C. perfringens* can be explained if 1–3 percent of the total sediments collected by the traps are derived from the sewage effluent. The effluent dilution model indicates that the average plume concentration is about 1 percent at the location of this trap. An assumption in this comparison is that natural and sewage-derived particles are collected by traps with equal efficiency.

The major storm in December 1992 caused a twofold increase in the concentrations of *C. perfringens* and silver at Station 3, presumably by transporting fine-grained sediment from inshore locations to this long-term monitoring site near the location of the Massachusetts Bay outfall. This result demonstrates that knowledge of how natural physical processes can affect contaminant concentrations is important in order to distinguish between natural and outfall-related changes.

The concentrations of metals in surficial bottom sediments of Boston Harbor have been decreasing with time since the late 1970s in response to decreases in metal inputs. The average decrease in concentrations of Ag, Cu, and Pb during the past 25 years at Station 8 was about 50 percent. Subsurface sediments in some areas of Boston Harbor have metal concentrations that exceed toxicity guidelines. These represent a potential source of contamination that can continue after the primary sources have been reduced or eliminated. Processes and rates of reintroduction of metals from deeper sediments are under continuing investigation.

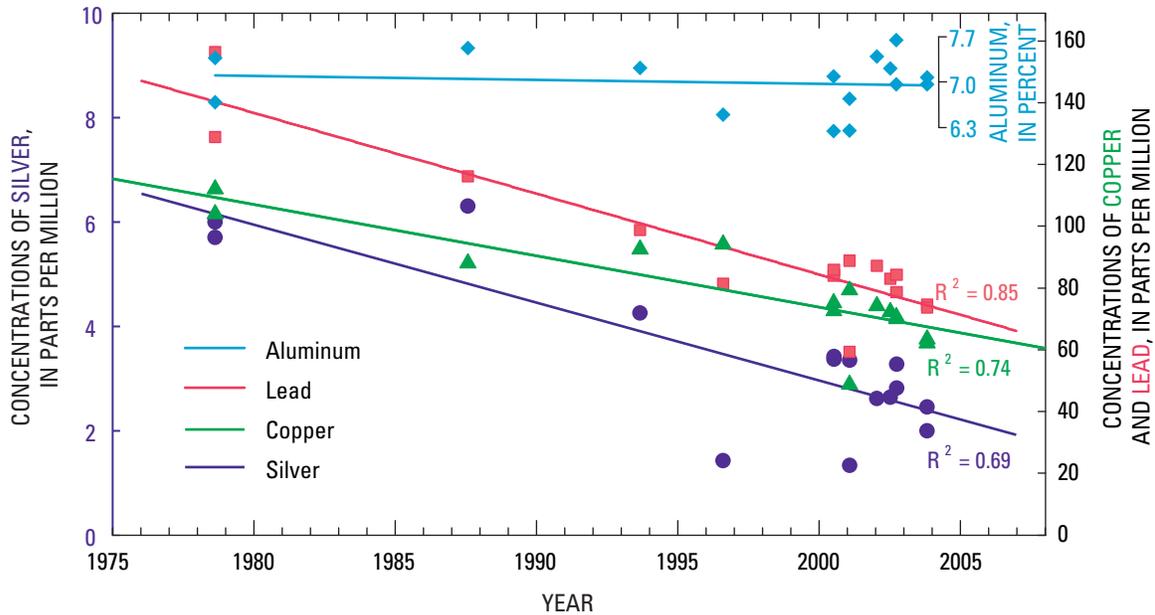


Figure 7.5. Decrease in concentrations of silver, copper, and lead with time in surface sediments at depths of 0–2 cm at Station 8 in Boston Harbor (location plotted in fig. 7.1). The average concentration decrease from 1978 to 2004 is about 50 percent. Concentrations of aluminum (in percent), a nonanthropogenic metal in this setting, did not change with time. The decreasing concentrations of anthropogenic metals, also found at other depositional areas in the harbor, indicate that environmental conditions in the harbor are improving as contaminant loadings have decreased. R^2 is the coefficient of determination.

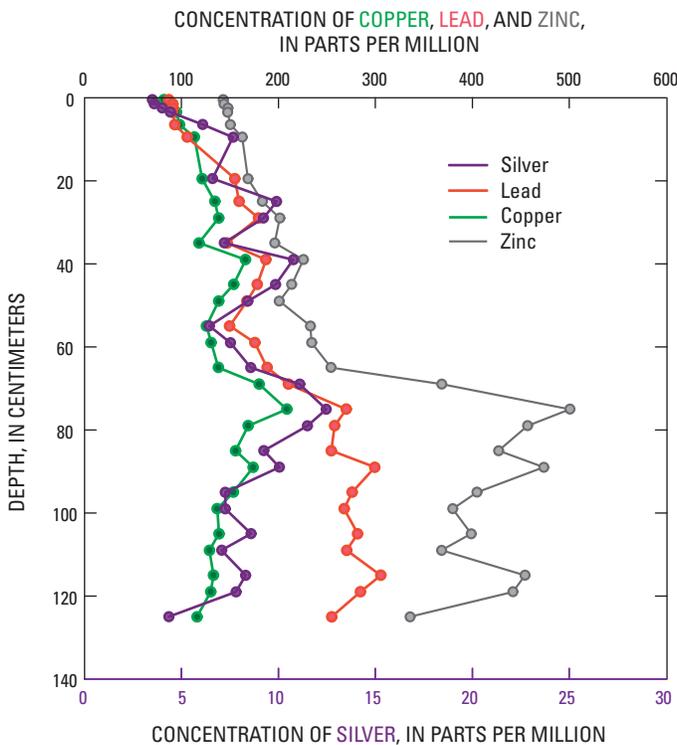


Figure 7.6. Concentrations of silver, copper, lead, and zinc as a function of depth in a piston core collected in 2000 at Station 8 in Boston Harbor (fig. 7.1). Concentrations of these metals, except for copper, exceed the Effects Range Median (ERM, Long and others, 1995) guidelines for toxicity in some horizons of the core. This core is not long enough to establish the time period when contaminants first began to exceed background concentrations. Previous work (Bothner, 1998) suggests that this increase began in the 1880s.