

Contaminated Sediments in Boston Harbor

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Contaminated Sediments in Boston Harbor

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Contaminated Sediments in Boston Harbor

Executive Summary

Boston Harbor's sediments, like those of other urban harbors, are contaminated with priority pollutant organic compounds and metals. This is the result of decades of waste introduction from a variety of sources. The sediments have been at least a partial sink during this long history of contamination because of the common tendency for dissolved pollutants to be adsorbed by and transported with suspended and bottom sediments.

At sufficiently high concentrations, toxic contamination of sediments could kill animals and plants living in or on the harbor floor, interfere with their growth and reproduction, and reduce and degrade available habitat. Some toxic contaminants can also be transferred up the food chain, affecting the health of fish and shellfish that eat contaminated prey, and in turn presenting a human health risk to consumers of seafood. In addition, sediments can release some toxic compounds to the overlying water, slowing the improvement of harbor water quality.

To address concerns about the contamination of sediment in Boston Harbor, and the implications of sediment contamination for combined sewer overflow (CSO) planning, the Massachusetts Water Resources Authority (MWRA) received a grant from EPA Region I to conduct a study of the sources of contaminated sediment, the movement of contaminated sediment away from its sources, and the long-term exchange of contaminants between the sediment and the overlying water. The research addressed the following questions:

Where is the contaminated sediment in Boston Harbor coming from?

The largest source of most toxic metals and organic contaminants to the harbor is MWRA sewage effluent, followed by rivers, stormwater, and combined sewer overflows (CSOs). Before December 1991, sewage sludge was also a major source. When the effluent discharge is removed from the harbor in 1995, the rivers, stormwater, and CSOs will be the major remaining sources of pollutants.

Boston Harbor sediments have become polluted over the last century due to the contamination entering the watersheds of the Charles, Mystic, and Neponset Rivers, as well as contaminants entering the sewerage system. The load of many toxic contaminants from effluent, sludge, and CSOs has declined substantially over the past two decades, because of industrial pretreatment requirements.

Where in the harbor does contaminated sediment end up?

Of the solids discharged to the harbor from the above sources, about 43% are retained in the harbor. Only about 30% of the sewage effluent particles are retained in the harbor because these settle relatively slowly and are discharged close to the harbor mouth.

Contaminated particles that remain in the harbor eventually settle in depositional areas, with faster-settling particles settling close to their sources. Harbor sediments are heterogeneous in grain size and organic carbon content, and therefore the distribution of contaminants is heterogeneous as well. In depositional areas, contaminated particles are mixed with cleaner particles from natural sources. Natural sources -- shoreline erosion and suspended particles from offshore -- appear to contribute the majority of the sediment.

Contaminated particles in sewage effluent settle very slowly; they are well-distributed throughout the harbor, and most leave the harbor without ever settling. The harbor has several small, sheltered, high-depositional areas around its perimeter, which accumulate contaminants and sediment rapidly, not only from nearby sources (e.g. CSOs and stormwater) but from remote ones (e.g. rivers and effluent) as well.

Do contaminated sediments currently represent a source of metals and priority pollutant organic contaminants to the overlying water?

Sediments can trap or release contaminants, depending largely on the chemical properties of the sediment. For instance, priority pollutant organic contaminants are now being released to the overlying water. The load contributed from the sediments to the water could be about the same as that from the effluent discharge for some organic contaminants.

Metals, on the other hand, are firmly sequestered in the sediment because the decomposition of the large amounts of organic material in the sediments decreases oxygen in the sediments. This in turn causes the sediments to chemically bind metals so they do not move into the overlying water. The reduction in dissolved oxygen also degrades the health of the bottom-dwelling biological community, decreasing the animals' ability to mix and stir the sediment, which would enhance the rate of release of contaminants. In fact, at present the sediments are generally removing metals from the overlying water.

How will the exchange of contaminants between sediments and water change as point source discharges are eliminated?

When the large point source discharges from the treatment plants are removed from the harbor mouth, and as CSOs are controlled, harbor water will become cleaner. Expected reductions in the organic carbon load to the harbor will result in more biological activity in polluted sediments (in particular, in the Inner Harbor). This could increase the rate of release of priority pollutant organic contaminants, but probably not enough to approach violations of water quality criteria.

Increased biological activity will not only increase mixing and sediment irrigation by animals, but will deepen the oxygenated zone in the sediments. Since high concentrations of some metals are bound in the anoxic portion of the sediment, animal activity and the resulting change in sediment geochemistry could make the sediments release their store of metals, unless the natural sedimentation rate is so fast that new (cleaner) sediment buries the contaminated layers. The changeover to deep-mixing animals will be a gradual process, taking several years.

Eventually, the rates of release of contaminants to the water will decrease as the surface sediments become cleaner.

How long will it take for the harbor to clean itself as pollution control measures are put into place?

It will take several decades for the surface sediments to become clean with respect to priority pollutant organic contaminants; some of these contaminants will remain longer than others. The rate at which surface sediments become clean will depend strongly on the amount of organic material reaching the sediments, the rate of burial with new sediment, as well as the succession of deep-mixing animal communities. Metals will continue to be elevated in surface sediments as long as the harbor is rich in organic material, because the presence of large amounts of organic material tends to enhance the processes that sequester metals in sediments. However, these tightly bound metals may not be available to cause harm to sediment-dwelling animals.

How the amount of organic material reaching the sediments will change is not very well known. Organic matter derives from the discharge of treated sewage from primary and secondary treatment plants and CSOs and from natural sources, primarily the growth of algae in the water. If the amount of organic carbon reaching the sediments is reduced, the time for sediment recovery could be reduced several-fold as the flux of contaminants quickens due to the increased significance of biological cleansing.

Small high-depositional areas around the harbor, such as Savin Hill Cove and Fort Point Channel, will continue to collect particles from near and distant sources, and so will likely continue to be polluted as long as there are sources of contamination. Thus, removing the effluent discharge is as necessary to the recovery of these areas as abating local shoreline sources, but it may not be sufficient, since CSOs and stormwater do have an effect on the sediments in the immediate area.

To return harbor sediments to a pristine state, that is, to remove contamination throughout the depth of the sediment, may take centuries or indeed may never occur, because the most contaminated layers may be deeply buried. However, provided the organic carbon load to the sediments is reduced, a reduction in contaminant levels through the whole depth of the sediments would not be necessary for establishment of a healthy bottom-dwelling community. To confirm this, monitoring of the sediment contamination levels and the biological community should continue.

Other conclusions relating to management decisions

- Because the effects of CSOs on toxic contamination of sediments appear to be moderate -- important locally but not the major contributor to harbor sediments generally -- CSO control should be primarily directed at reducing the public health risk from disease-causing microorganisms. Given that, the optimum placement of any remaining CSOs depends on the desired use of various areas of the harbor. If management has the goal that all parts of the harbor should be of equal quality, remaining CSOs should be placed far from high-deposition areas where sediment and toxic contaminants tend to accumulate.
- Goals for sediment quality have not been established, so it is not clear how control of toxic contaminants should be weighted compared to other environmental quality factors important to CSO planning. Of the possible CSO strategies, elimination of CSO would have the largest effect on reducing loads to the harbor; however, given the relatively small contribution from CSOs, storage may not be necessary for adequate toxics control. Screening and disinfection are not intended to have significant effect on toxic loads, though chlorination could slightly enhance the production of chlorinated organic contaminants. Based on our best current estimate of the stormwater contribution to the toxic contaminant load, sewer separation would reduce the load of toxic contaminants to the harbor.

- The sediments of Boston Harbor do not appear to be such a large source of toxic contaminants to the water that pervasive or continuous violations of water quality criteria result. Moreover, the flux of sediments to the overlying water is generally not expected to increase enough to cause exceedances of water quality standards as the surface sediments clean themselves over the course of several decades. Therefore, remedial dredging with the object of removing the contaminants is not warranted from an environmental standpoint.
- Contamination of riverine sediment in the tributaries to Boston Harbor, by CSOs and other sources, is poorly understood and should be studied.
- Because the level of contamination varies around the harbor and rivers, and because the factors influencing contaminant distribution and ecological health are complex and variable, additional site-specific studies should be done to provide information for specific policy decisions.

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Contaminated sediments in Boston Harbor

1.0 Introduction/Background

1.1 Why is sediment contamination important?

In 1987, Boston Harbor was widely reported to be the "dirtiest harbor in America," based on sediment contamination levels measured by the National Status and Trends Program compared to those in other estuaries around the country. Although some of the media reports oversimplified the scientific information, Boston Harbor sediment quality places it among the most contaminated urban harbors, a group that includes New York, Mobile AL, San Diego, San Francisco, and Los Angeles. These contaminated sediments pose three potential problems to the environmental health of the harbor:

- **Toxicity/Habitat Loss** - Sediment contamination may be toxic to the animals and plants that live in and on the sediments, such as worms, flounder, and lobster. Contaminants can reduce their numbers, by affecting them directly, or indirectly, by reducing the amount of their prey.
- **Food Chain Transfer of Contaminants** - Some contaminants in the sediments may be transferred to fish and shellfish in the harbor either by direct exposure or through the consumption of contaminated prey.
- **Water Quality** - Violations of water quality standards may occur as sediments release toxic compounds to the overlying water.

1.2 Types of contaminants and their sources

Toxic contaminants are chemicals that are poisonous, can accumulate in living tissue to cause long-term effects, or move up through the food chain to cause toxicity to consumers. Most toxic chemicals enter the sewage system through industrial and residential wastewater; storm runoff can also be a source. This study evaluated two kinds of toxic contaminants: heavy metals, including cadmium, copper, lead, nickel, and silver; and priority pollutant organic compounds, including several different kinds of polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs).

Whether in water or wastewater, many toxic contaminants tend to be associated with particles. Small particles -- clay, silt, biological particles -- are usually coated with an organic film which has a strong affinity for many pollutants such as heavy

metals and priority pollutant organic compounds. Contaminants exchange between particles (in water or sediment) and water (wastewater, receiving water, porewater) depending on their chemistry and the chemical and biological processes acting on them. These particles can come from natural sources or man-made sources.

1.3 Sewage treatment and combined sewer overflows

The Massachusetts Water Resources Authority (MWRA) is presently constructing a modern wastewater treatment plant on Deer Island to bring the metropolitan Boston sewer system into compliance with the Clean Water Act. The discharge of sewage sludge to the harbor was already stopped, in December 1991. However, untreated sewage mixed with stormwater can still be discharged from over 80 combined sewer overflows (CSOs) during wet weather, when the capacity of the system is overwhelmed. A portion of the combined sewage discharge receives some treatment -- screening and chlorination -- but CSOs are a significant pollution source (MWRA, 1990). MWRA is evaluating ways to minimize the effects of CSOs; the solution may include storing combined sewage in tunnels and large conduits, and then pumping it to the treatment plant in dry weather (MWRA, 1990).

Although it addressed all sources of contaminated sediment, this project focused on combined sewer overflows, for several reasons:

- **Planning Window** - MWRA is now re-evaluating its approach to CSO control as part of the development of an overall master plan for the entire sewerage system. Available information on contaminated sediments is being used in CSO control decisions and master planning.
- **Complicated Problem** - CSOs are scattered about a large area and are highly variable sources. The effects of large point sources are better understood; this project provides information for the more difficult evaluation of CSO effects.
- **Significance to Harbor Health** - CSOs are located on or very near the shoreline, close to many sensitive resources. Although CSOs are a smaller source of most contaminants than the treatment plant discharges, their effects may be more important locally.

1.4 Study of contaminated sediment in Boston Harbor

MWRA received a grant from EPA to address the following questions:

- Where is the contaminated sediment in Boston Harbor coming from?
- Where in the harbor does contaminated sediment end up?
- Do contaminated sediments represent a potential source of metals and priority pollutant organic contaminants to the overlying water?

- How will the exchange of contaminants between sediments and water change as point source discharges are eliminated?
- Finally, how long will it take for the harbor to clean itself as pollution control measures are put into place?

To tackle the questions listed above, this contaminated sediment study was undertaken in three segments. In the first part of the study, the sources of priority pollutant organic contaminants and metals to the harbor were estimated to determine the relative importance of CSOs. The second part of the study evaluated how particles are moved away from their sources, how sediments may be moved around the harbor, and where contaminated sediments are likely to finally settle. Finally, the processes controlling exchange of contaminants between water and sediment were studied, to understand the present and future role of harbor sediments themselves as a source of contaminants, and to estimate the rate at which sediments will be naturally cleansed or buried by clean sediments. The following three chapters summarize the findings of the extensive research we conducted in these areas. The complete research findings from scientists at Massachusetts Institute of Technology, University of Massachusetts at Boston, Menzie-Cura Associates, and MWRA are described in separate reports. The final chapter discusses some of the policy implications of the study findings.

2.0 Sources

The contaminants that end up in Boston Harbor sediments come from sewage effluent (and, until December 1991, sewage sludge), combined sewer overflows, stormwater runoff, industrial discharges, groundwater, the atmosphere, and rivers (see Figure 1).

2.1 Revised source estimates

The loads from the above sources of contamination to Boston Harbor were estimated by Menzie-Cura and Associates (Menzie *et al.*, 1991). Their estimates were based on the best available knowledge of concentrations and flows as of 1990. We have revised the estimates given by Menzie *et al.* (1991) based on new information (Alber and Chan, 1994).

Estimates were updated with studies performed by various agencies, including MWRA, Boston Water and Sewer Commission, Massport, Boston Edison, and the US Geological Survey. Information on both PAH concentrations and the deposition of contaminants from the atmosphere is based on preliminary information from ongoing studies sponsored by the Massachusetts Bays Program (Menzie-Cura and Associates, 1992; D. Golomb, pers. comm.). The methods used for estimating loads from each source are described in Alber and Chan (1994).

Revised estimates of the discharge of the various sources to the harbor for flows, solids, metals, and PAHs are presented in Figure 2. Rather than total PAHs, as in Menzie *et al.* (1991), we present estimates of the loads of three common compounds: 2-methylnaphthalene, pyrene and benzo(a)pyrene. These were chosen because they represent low, mid, and high molecular weight (MW) compounds, respectively. Low MW compounds come primarily from fuel oil, high MW compounds are formed as combustion products, and intermediate weight compounds probably come from a combination of the two. These three compounds have been shown to have different distributions in Boston Harbor and Massachusetts Bay (Wade, 1993).

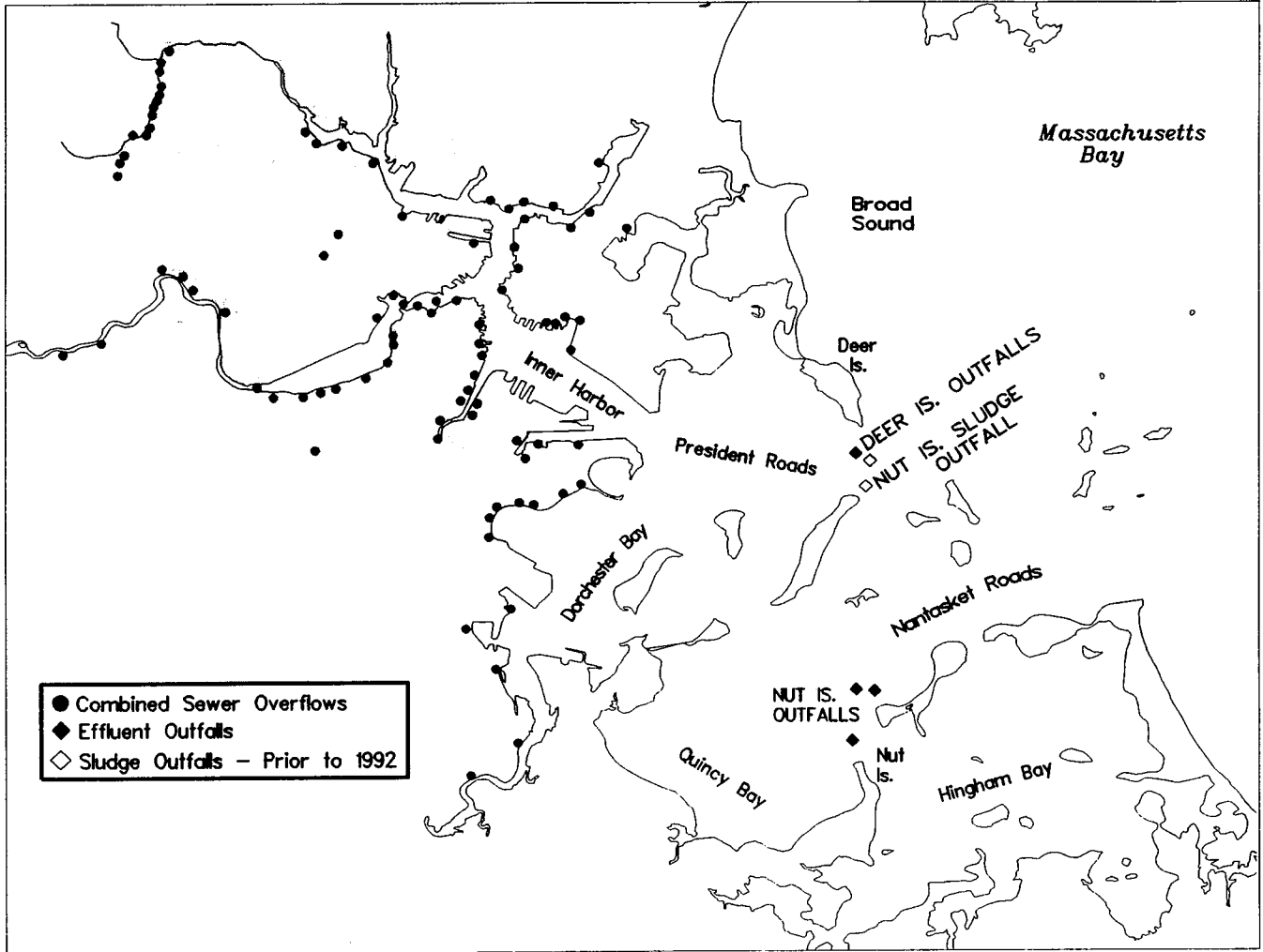


Figure 1: Map of Boston Harbor showing pollution source locations.

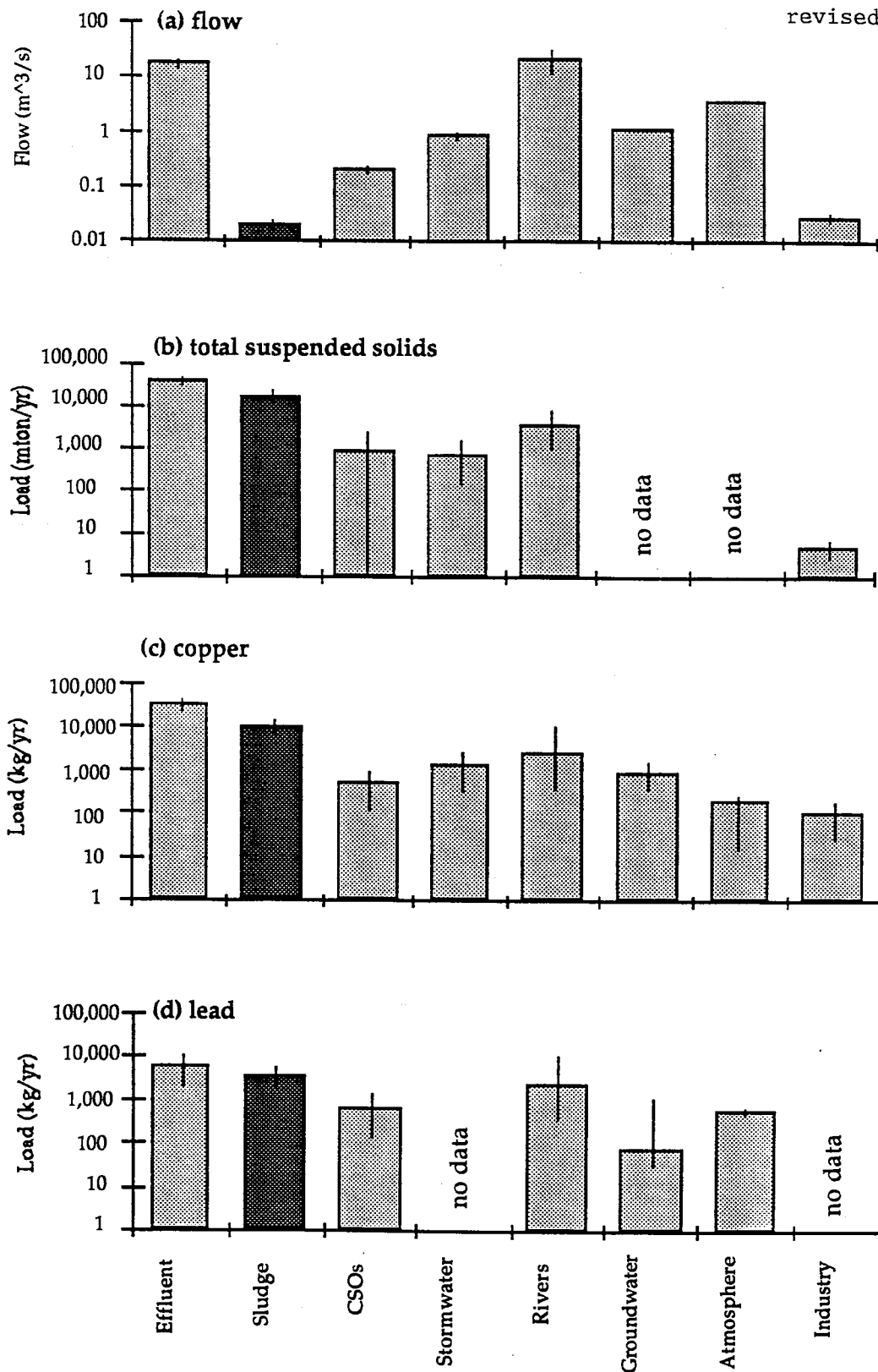


Figure 2: Sources of selected contaminants to Boston Harbor. Estimates of present-day annual average flows and loads are shown, except for sludge; discharge of sludge ceased in December 1991. Note that the y-axis in each graph is a log scale, which means that very large differences in load translate to small differences in the height of the bar. Vertical bar shows range of estimates. (a) flow, (b) TSS, (c) copper, (d) lead, (e) zinc, (f) 2-methylnaphthalene, (g) pyrene, and (h) benzo(a)pyrene

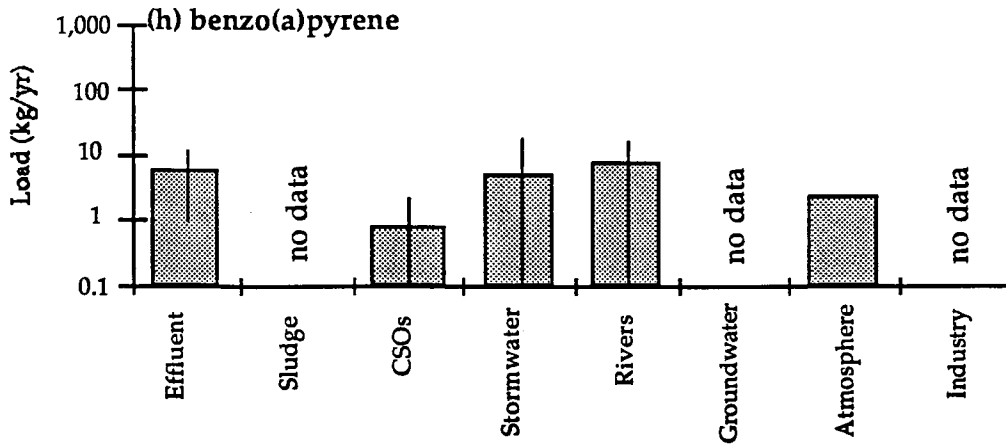
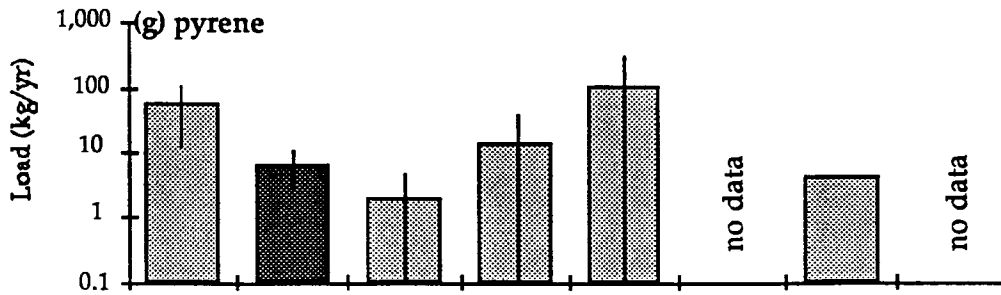
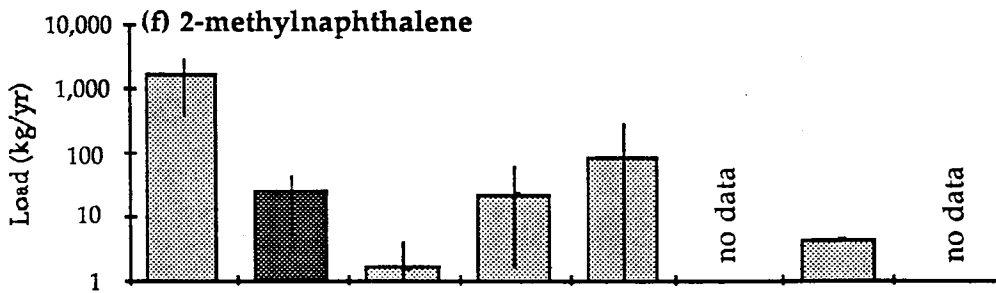
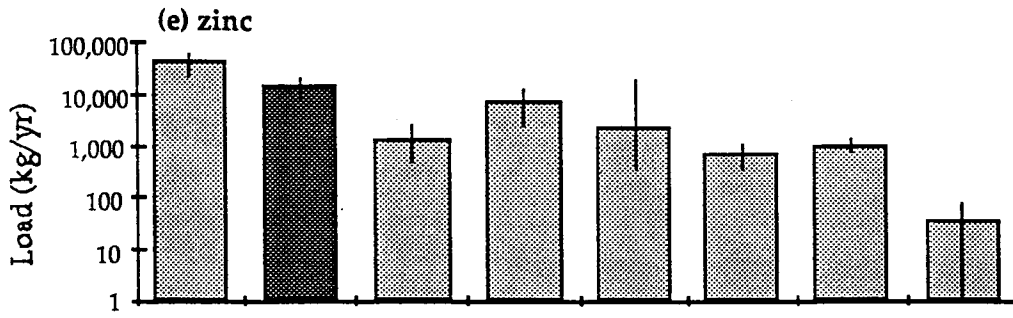


Figure 2, continued

These revised estimates of sources of contaminants to the harbor represent decreases in loads from sludge, effluent, CSOs, and stormwater as compared to those estimated by Menzie *et al.* (1991). These changes are partially due to an improvement in sewage quality (see section 2.2), and partially due to improved chemical analyses and sampling techniques.

The CSO and stormwater loads presented here are considerably lower than those given by Menzie *et al.* (1991), as recent measurements and better models of CSO flow show much less flow (MWRA, 1993; Adams and Zhang, 1991) and lower contaminant concentrations (MWRA, 1993; Boston Water and Sewer Commission quarterly CSO monitoring reports) than the estimates in the CSO Facilities Plan (MWRA, 1990). The estimates provided here are still likely to be upper bounds on CSO loads. Better estimates may be available in 1994 from the CSO planning project.

The riverine loads presented here are higher than those given by Menzie *et al.* (1991) because improved estimates of river flow (Menzie-Cura & Associates, 1991) are substantially higher than the earlier estimate. It should be noted that river loads are affected by contributions of CSO and stormwater into the rivers; these riverine CSOs and stormwater discharges are not included in the loads from CSOs and stormwater given in Figure 2.

Nonpoint sources such as stormwater and CSO are difficult to estimate, but ongoing studies by the Massachusetts Bays Program, MWRA, and BWSC will refine these nonpoint source estimates over the coming year.

2.2 Source trends

The most significant change to date in contaminant loading to the harbor is due to reductions in the concentrations of contaminants in the influent to the treatment plants. This is due to industrial pretreatment regulations imposed in the 1970s, the efforts of the MWRA's Toxics Reduction and Control Department, and increased public awareness. For example, the trend in influent copper and zinc concentrations is shown in Figure 3. The concentrations of PCBs in the influent have declined 700-fold since they were banned in the 1970s. The lower concentrations in influent resulted in lower concentrations in the effluent and sludge.

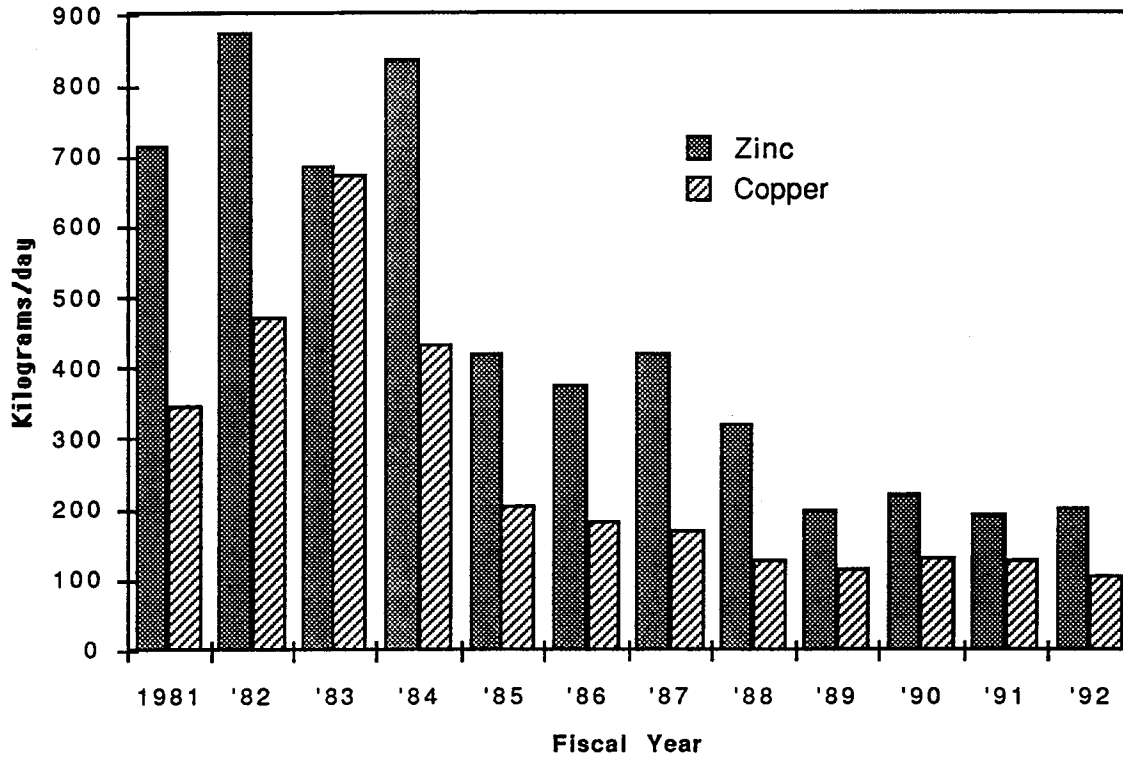


Figure 3: Metals trends in influent: Copper and zinc loadings from both treatment plants combined, by fiscal year. (Figure from Alber *et al.*, 1993)

The elimination of sludge from the harbor represents the most recent significant change in contaminant loading. This reduced total solids load to the harbor by 25% and reduced contaminant loads by a substantial fraction (see Figure 2). The next big change in contaminant loading to the harbor will come once the outfall is moved. This will greatly alter the importance of the remaining sources.

2.3 Inventory of contaminants in Boston Harbor surficial sediments

We can compare the loads of contaminants (the amount added per time) to the sediments of Boston Harbor to an estimate of the inventory of contaminants (the total amount accumulated) now present in harbor sediments. These data can then be used to get a rough estimate of the retention of solids in the harbor. The results for selected metals are shown in Table 1.

Table 1: Mean concentration of selected contaminants by region of harbor; estimated harbor contaminant inventory

	Depositional Area (km ²)	Reworked Area (km ²)	Cu (ppm)	Pb (ppm)	Zn (ppm)
Inner Harbor	8.0	0.00	233	245	374
Northwest Harbor	12.7	15.0	124	156	207
Central Harbor	15.8	7.0	107	123	206
Southeast Harbor	12.7	4.9	71	90	150
Total	49.3	26.9			
Harbor average weighted by area			118	140	211
- Background sediment concentration			- 57	-20	-80
Enrichment over background			61	120	131

Regions of the harbor are shown in Figure 5
Metals concentrations in each area from Hathaway *et al.* (1992)

<u>Eqn.</u>	<u>Cu</u>	<u>Pb</u>	<u>Zn</u>
(1) Inventory in top 2 cm (kg) ¹	4.7 x 10 ⁴	9.0 x 10 ⁴	1.0 x 10 ⁵
(2) Annual load (kg/yr) (incl. sludge)	4.84 x 10 ⁴	1.33 x 10 ⁴	7.06 x 10 ⁴
(3)= (1)/(2) Time needed to accumulate inventory from existing sources (years)	1	7	1.4
Percentage retention in harbor ²	10%	68%	14%

Both depositional and reworked areas were considered in this estimate, based on a map of harbor sedimentary environments produced by Knebel *et al.* (1991). This map (shown in Figure 4, and discussed in Chapter 3) does not cover the Inner Harbor. In the present estimate we have assumed that the Inner Harbor (8 km²) is all depositional (Table 1), and added that to the 42 km² depositional area estimated by Knebel *et al.* (1991).

¹ Assuming sediment density of 0.5 g dry wt/cm³ (Knebel *et al.*, 1991).

² Assuming non-erosional areas of the harbor accumulate sediments at a rate of about 0.2 cm/yr, the top 2 cm represents 10 years of accumulation (Fitzgerald, 1980).

The mean concentration of metals in surficial sediments was calculated from a large body of data by U.S. Geological Survey (USGS) researchers (Hathaway *et al.*, 1992). We can get a very rough estimate of the total amount of contamination in the top 2 cm by multiplying the average concentration by the non-erosional (depositional plus reworked) area of each region. These need to be corrected to account for the enhancement in sediment metal concentration over background. Average metal concentrations measured in shale (Krauskopf, 1967) were used to approximate the background concentrations one might expect in fine-grained sediments, and these were subtracted from the concentrations measured in Boston Harbor sediments.

The result of these calculations is that the top 2 cm of sediment represents only at most a few years of accumulation of copper and zinc at present loading rates (circa 1991, with sludge included). The comparatively large number of years required to accumulate the lead measured in the sediments is probably due to a general decrease in lead loadings in recent years as a result of the shift to unleaded gasoline. To the extent that sources have declined over the last decade (described in Section 2.2), these are overestimates and it may have actually taken fewer years to accumulate the existing sediment inventory.

Also, not all solids discharged to the harbor remain in the harbor. The data in Table 1 can also be used to estimate the percentage of solids that are retained in the harbor. Retention for copper and zinc ranges from 10 to 14%. Retention of lead is probably overestimated, for the reasons described above. Shea and Kelly (1992) used a similar approach to estimate percent retention. However, the current estimate is based on a revised loading estimate, and the calculations in Table 1 are adjusted for background concentration and sedimentary environment. The retention of solids is discussed further in Chapter 3.

To improve our estimate of the contaminant inventory, it would be necessary to consider the variation of concentration with depth. Although we have not attempted to do so for this report, this question is being considered by U.S. Geological Survey researchers. While at some sites there is a slight decrease in metal concentration in the narrow surface boundary layer (usually less than 1 cm), the concentration of most metals varies very little with depth down to at least 30 cm (M. Buchholtz ten Brink, personal communication). The depth of "available" contamination which could be released into the overlying water depends on the depth to which animals mix the sediment; we consider this issue further in Chapter 4.

3.0 Transport

The relative amount of pollutants contributed by different sources does not tell the whole story of their impact on the harbor. The fate of the contaminants depends on the physical characteristics of the source region, transport characteristics of the particles to which the contaminants are attached, and the circulation of the harbor as a whole. The location of the source of contamination is also important; the final sections of this chapter discuss sediment transport by regions of the harbor.

3.1 Physical environment of Boston Harbor

Boston Harbor consists of about 110 square kilometers of bays and tidal estuaries, with numerous small islands (Figure 1; Knebel *et al.*, 1991). The harbor is generally shallow (average depth is approximately 3 meters), with the exception of President Roads and Nantasket Roads. In these two shipping channels, water depths approach 15 m (mean low water). Boston Harbor has two unusual features: (1) one-third of its freshwater inflow comes from sewage effluent, which enters at the mouth rather than at the head of the estuary, and (2) water circulation in the harbor is dominated by strong tides (range of 2.7 m), so a large fraction (about 17%) of the water in the harbor is flushed out during a single ebb tide (Signell and Butman, 1992).

Boston Harbor is customarily separated into two main areas, the Inner and the Outer Harbor. However, the harbor is a complex system of many small bays and open-water areas. These areas are variously influenced by different sources of contamination and have different physical properties which, in turn, influence the fate of contaminants.

3.2 Sediment transport processes

Most toxic contaminants are attached to particles, as explained above. Besides the water circulation of the harbor, the fate of particles also depends on their size and shape. Contaminants tend to be associated with small, organic-rich particles. These very small particles remain suspended in the water for a long time (weeks or months) and move with the water. Unless that water stays in an area for at least the time required for a particle to settle, the particle will eventually leave the area.

Heavier particles that are not flushed out of the harbor eventually settle to the bottom in areas of the harbor that favor deposition. The deposition of sediment in the harbor is affected by the shape of the seafloor (Knebel *et al.*, 1991). For example, in flat areas, sediment tends to accumulate in seabed depressions where the currents are slightly slower. On the other hand, deep shipping channels channel the water

and increase the speed of tidal currents; these currents scour away fine sediments, leaving heavier sand and gravel behind (Knebel *et al.*, 1991; Lee, 1990). Around the shoreline and in very shallow areas, breaking waves erode sediment. Water movement and transport of particle-bound contaminants in Boston Harbor can vary considerably over very short distances (Signell and Butman, 1992, McDowell *et al.*, 1991).

Under the influence of a storm or an unusual tide, particle-bound contaminants in the surface layer of the bottom sediments can be resuspended into the water, carried to a different location, and sink again. This process of resuspension and transport moves contaminants away from their sources and even out of the harbor.

Contaminants attached to fine sediments are re-deposited on shallow mud flats or in deep, less-energetic parts of the harbor, and eventually become incorporated into the bottom sediment. In addition to these physical processes, organic carbon-rich sediments can chemically "scavenge" some organic and metal contaminants directly from the overlying water by chemically binding them to the surface sediments.

The sediment on the harbor floor consists primarily of natural particles that enter the harbor from offshore, or are created by erosion of the harbor shoreline (Knebel *et al.*, 1991). Particles from sewage effluent, sludge, and CSOs are deposited along with these "clean" particles throughout the harbor. The most contaminated bottom sediment is found close to sources, such as the Nut Island sludge outfall at the tip of Long Island, and in depositional areas.

The net result of these interacting processes, shown in Figure 4, is a patchy distribution of sediment types throughout the harbor; much of the Central and Northwest Harbor, and most of the Southeast Harbor, are depositional. Because trace metals and organic compounds are persistent, the accumulation of contaminant-laden particles in depositional areas results in localized high concentrations of contaminants. The resulting distributions for some contaminants are shown in Figure 5.

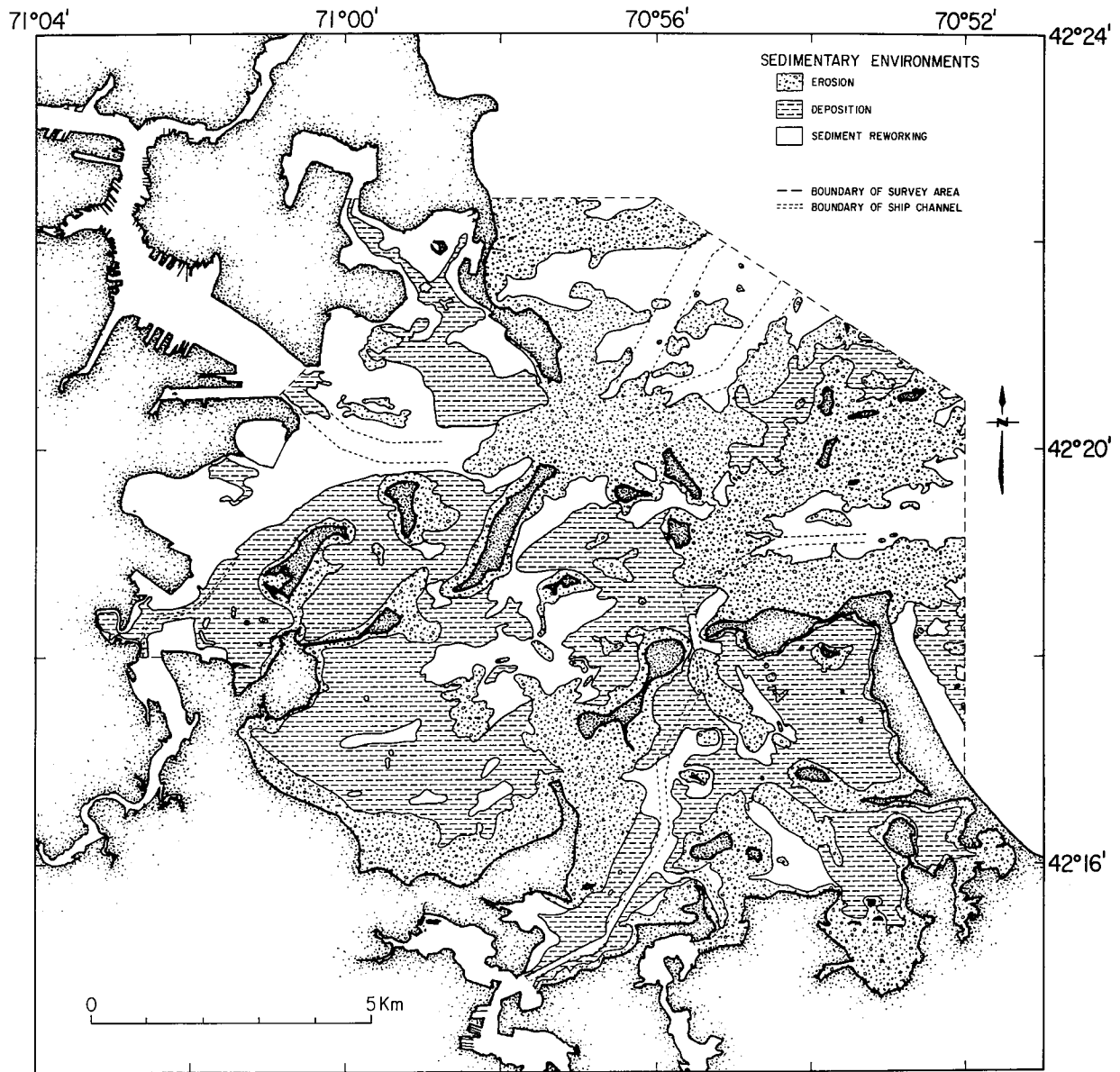
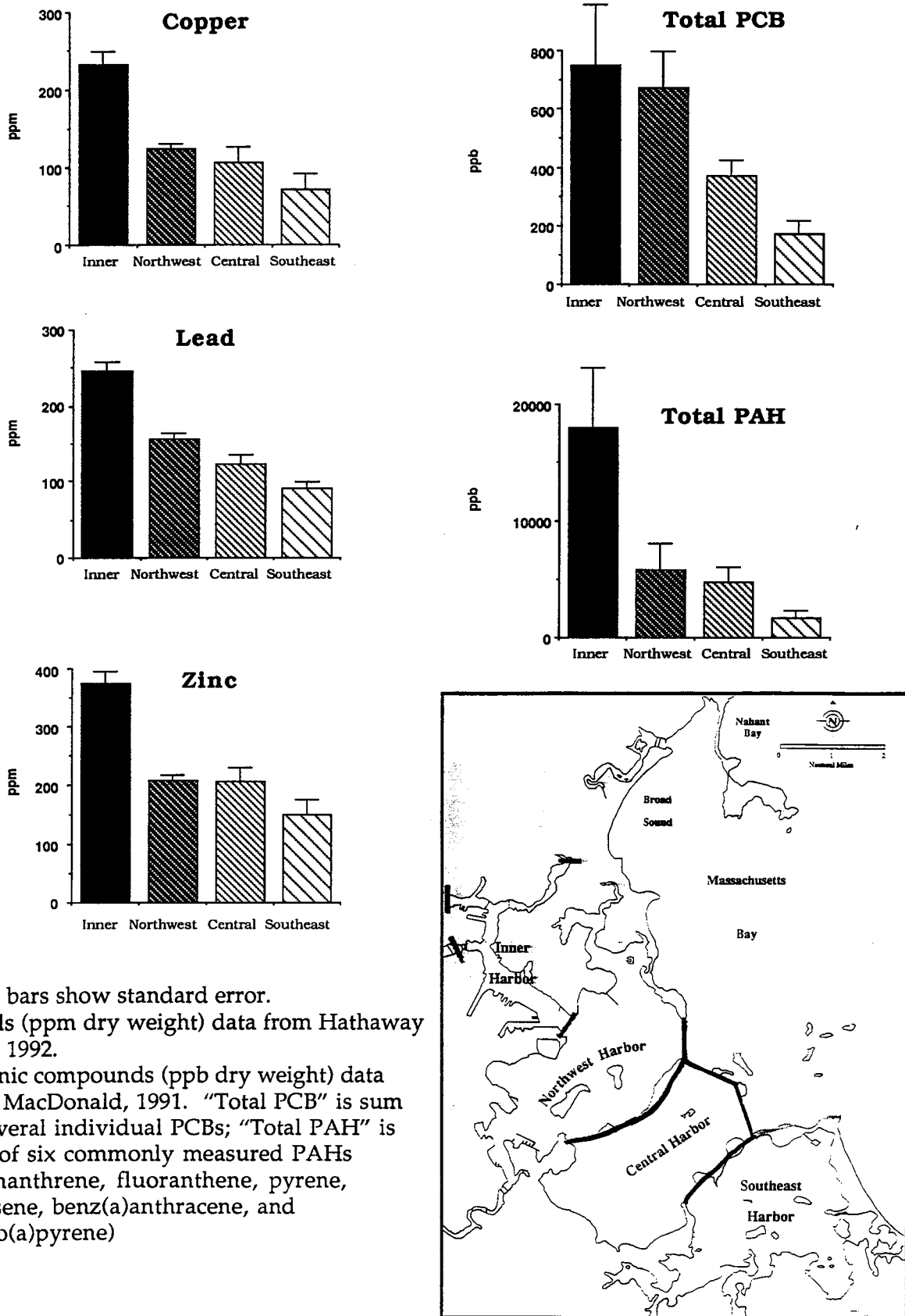


Figure 4: Map of erosional and depositional areas in Boston Harbor. This map, from the U.S. Geological Survey, shows the areas of the harbor in which bottom sediments are swept away (erosion) or accumulate (deposition). In many areas, both processes occur at different times (sediment reworking). The Inner Harbor and rivers were not mapped. (Figure from Knebel *et al.*, 1991.)



Error bars show standard error. Metals (ppm dry weight) data from Hathaway *et al.*, 1992. Organic compounds (ppb dry weight) data from MacDonald, 1991. "Total PCB" is sum of several individual PCBs; "Total PAH" is sum of six commonly measured PAHs (phenanthrene, fluoranthene, pyrene, chrysene, benz(a)anthracene, and benzo(a)pyrene)

Figure 5: Variation of mean sediment contaminant concentrations of selected contaminants around the harbor.

3.3 Overview of contaminated sediment transport studies

The transport and fate of sediment contaminants was studied by investigators at MIT and UMass/Boston in several sub-projects. A summary and synthesis can be found in Stolzenbach *et al.* (1992), with details in reports on the individual sub-projects. The study included fluorescent tracer experiments (Adams *et al.*, 1992), sediment sampling, measurements of sediment erodibility (Zreik, 1991), and computer modeling of particle transport (Lee, 1990).

The transport and ultimate fate of contaminated particles in Boston Harbor depends on the size of the particles, the local dispersion (spreading) of water (and of suspended particles), and the exchange of water between parts of the harbor and between the harbor and Massachusetts Bay. Figure 6 shows the relationship of spatial and temporal scales that pertain to particle transport in various regions.

Stolzenbach *et al.* (1992) draw the following conclusions about contaminated particle transport in Boston Harbor:

- The heaviest waste particles, discharged from sources other than those in President Roads, initially settle and are retained in regions within 100 to 1,000 meters from the point of discharge.
- Slower-settling particles or those initially depositing in areas where resuspension is probable become fairly well dispersed throughout the Harbor as suspended solids. The majority of these particles are ultimately transported out of the Harbor by tidal flushing; the remainder settle in regions where resuspension is rare or where deposition is enhanced by processes such as bottom scavenging.
- The accumulation of "natural" particles, *i.e.*, those imported from outside the Harbor, exceeds the average of deposition of waste particles by a factor of 5 to 10, even in areas where the deposition of waste particles is heavy -- such as Fort Point Channel.

It also appears that certain small embayments around the harbor margins accumulate sediments and contaminants at rates disproportionate to their small size.

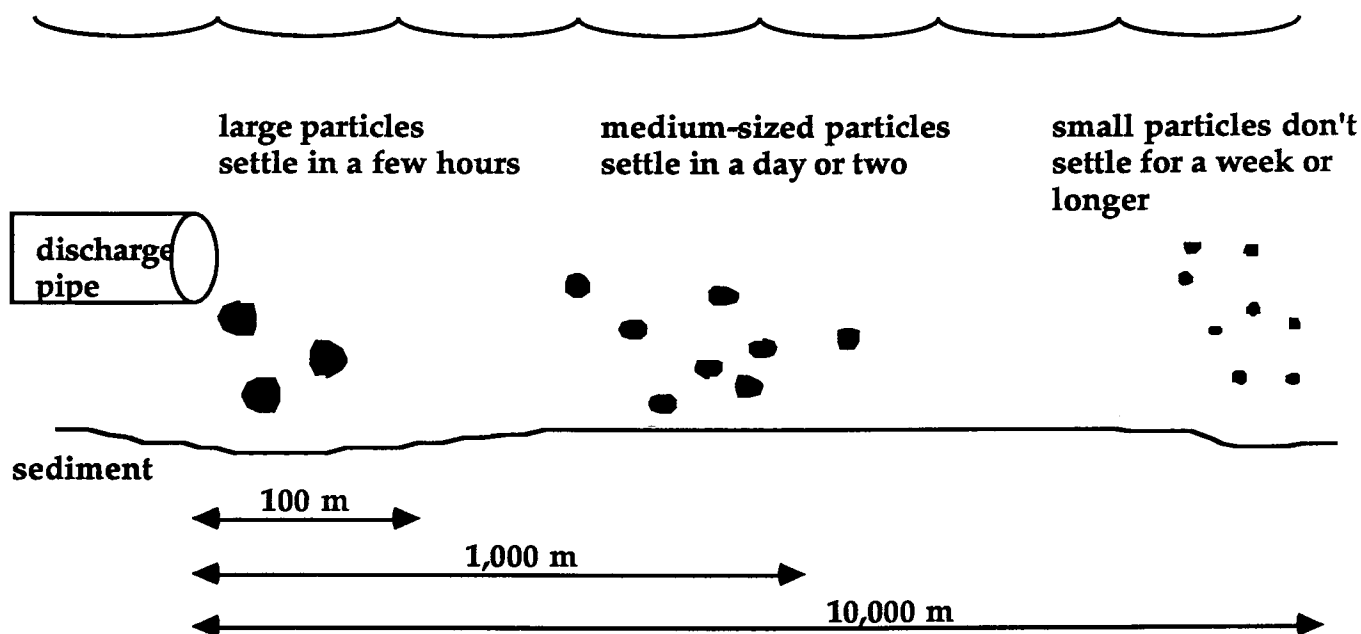


Figure 6: Temporal and spatial scales governing contaminated sediment transport and deposition. "Large" particles have a settling velocity of 10^{-3} m/s, "small" or "light" particles settle at about 10^{-5} m/s. 1,000 meters is about the scale of Fort Point Channel; 10,000 meters is about the scale of the entire harbor. (adapted from Figure 3.1 of Stolzenbach *et al.*, 1992)

In the following sections we look at the implications of these results for particular areas.

3.4 Harbor-wide sediment transport

In order to determine what areas in the harbor might accumulate contaminated particles from CSOs, effluent and sludge, and rivers, a computer model of harbor tidal currents was used (Lee, 1990). The strength of the current needed to keep particles from settling was estimated by comparing model predictions with observed patterns of sediment deposition and erosion (from Knebel *et al.*, 1991). About half of the Outer Harbor area (Knebel *et al.*, 1991) and most of the Inner Harbor (Rendigs and Oldale, 1990) are depositional. The model predicts rapid sediment accumulation in the Inner Harbor, moderately rapid accumulation over Deer Island Flats, and none in President Roads.

Model-predicted suspended sediment concentrations and sediment accumulation rates from the above sources were much less than actual measured rates (for example, Fitzgerald, 1980), indicating that most of the particles in the harbor come from another source. Some particles are probably imported into the harbor from offshore and deposited in the relatively quiescent harbor, but most probably derive from erosion of the harbor margins (Knebel *et al.*, 1991; Knebel, 1992).

If it is assumed that all sources contain about the same sized particles, with an average particle settling velocity of 10^{-5} cm/s (about 1 cm/day), the model predicts that one-third of the particles input from CSOs, treatment plants, and rivers settle in the harbor. The remaining particles are washed out of the harbor. However, because the treatment plant discharges are near the mouth of the harbor, and are thus transported out of the harbor by tidal currents, only about one quarter of the solid particles from effluent (and formerly sludge) discharges are predicted to settle in the harbor. CSOs, on the other hand, are located near shore, so about half of the particles discharged from them are predicted to settle within the harbor.

This model was refined to take into account the fact that particles from different sources are different sizes and weights. Deposition of particles depends not only on the effective scale of dispersion, as predicted by the model, but also on the settling rate of the particles. Dense particles settle more quickly. Stolzenbach *et al.* (1992) review literature values of settling velocities and calculate the retention of particles from sources to the harbor. Shoreline sources -- of which CSOs comprise 17% -- contain mostly fast-settling particles, so they will contribute most of their load to nearby depositional areas. In this model it is assumed that particles in shoreline sources settle at the same rate as particles in untreated sewage. Particles carried in effluent tend to be fine, so they are spread throughout the harbor, and in fact most will not settle in the harbor. Taking the different sizes of particles into account, Table 2 shows that shoreline sources will deposit nearly all their particles in the harbor, and that 43% of the total particles are likely to have been retained. (Without sludge, this is reduced slightly, to 37%.) About 30% of the solids from sewage effluent discharges to the harbor are deposited in the harbor.

These model-predicted retention rates assume that the settling velocity of small particles is 10^{-5} m/s. This figure has not been empirically determined for Boston Harbor, and is faster than some reported values (Table 3.2, Stolzenbach *et al.*, 1992). These retention rates may therefore represent an upper bound (E. Adams, pers. comm.). Note that they are slightly higher than the retention of copper and zinc estimated from the sediment inventory of contaminants in section 2.3 above.

Table 2: Percent of solids retained in Boston Harbor from different sources (prior to 1992)
 (Table 3.4 of Stolzenbach *et al.*, 1992, recalculated using new TSS load estimates)

Source	(a) % of total solids discharged to harbor	(b) % of solids with settling velocity faster than 0.003 cm/s (settle locally)	(c) = 1 - (b) % of solids settling more slowly	(d) % of slow-settling particles that settle in the harbor (Lee, 1990)	(e) = (b) + (c)*(d) estimated percent of solids discharged retained in hbr.	(f) = (a)*(e) contribution to weighted average
shoreline (rivers, CSOs, and stormwater)	9%	70%	30%	50%	85%	8%
sludge (prior to 12/91)	29%	40%	60%	25%	55%	16%
effluent	62%	7%	93%	25%	30%	19%
Percentage of solids retained in Harbor						43%

3.5 The mouth of Boston Harbor

The deep, narrow channels at the entrance to the harbor are subject to swift tidal currents that essentially keep sediment from settling. The existing sewage discharges (see map, Figure 1) are located in these channels to take advantage of the effective dispersion provided by these currents. As a result, sewage particles from these discharges are spread over a wide area. This conclusion is supported by measurements of the sewage tracer, spores of the bacterium *Clostridium perfringens*, in Massachusetts Bay sediments (Parmenter and Bothner, 1993; Keay *et al.*, 1992). Although the concentrations in Massachusetts Bay sediments are lower than concentrations in Boston Harbor, the tracer is spread out over a large area of the Bay. In fact, concentrations in western Massachusetts Bay are as high as the levels measured in the southeast harbor; this indicates that a considerable amount of sludge and sewage solids have exited the harbor and affected Massachusetts Bay. Significant exchange between harbor and bay is also demonstrated by measurements of sewage-derived nitrogen (Giblin *et al.*, 1992, Tucker *et al.*, 1993).

3.6 Open water depositional areas

Particles settle in open water areas where the currents are weak. Much of the central Outer Harbor is quiescent enough for deposition to occur (see Figure 4). The present rate of deposition was measured by Fitzgerald (1980) as approximately 0.2 cm/yr. This estimate is probably an upper limit since it ignores the influence of bioturbation. The average rate of deposition over the past several thousand years, however, was much less: 0.01–0.03 cm/yr (Knebel *et al.*, 1991). It is possible that the presence of sewage particles increases sedimentation by enhancing coagulation (Stolzenbach *et al.*, 1992). Deposition may also occur very close to large sources, in less quiescent areas, provided the currents do not strongly sweep the area -- in the harbor, this was observed at the former Nut Island sludge discharge at the tip of Long Island.

3.7 Beaches

Wave action in very shallow water can keep fine, contaminant-laden particles from accumulating. Knebel *et al.* (1991) argue that most of the harbor shoreline is erosional, and in fact that erosion provides much of the total particulate load to the harbor. Very few data exist on sediment contamination near eroding shorelines. Most harbor beaches, except Wollaston Beach, are actually low-energy areas where sand has been trucked in to form a swimming area. Beaches that are more sheltered, for example Tenean Beach in southern Dorchester Bay, are characterized by finer sediments and are discussed under "high-deposition areas" below.

Investigators from Battelle Ocean Sciences and MWRA examined the effects of several CSOs on sediments in Dorchester Bay (Durell *et al.*, 1991), including the Old Harbor/Carson Beach area. The study concluded that one of the larger CSOs, BOS-087, is probably a source of polycyclic aromatic hydrocarbons, and of certain metals, to the immediate area around the CSO. This CSO receives mostly stormwater and very little sanitary sewage (Paul Keohane, BWSC, personal communication 1990). For the most part, other contaminants and sewage tracers were evenly distributed around the study area, indicating that they are largely contributed from remote sources, *i.e.* the sewage effluent and sludge discharges at the harbor mouth. It is difficult to separate out the effects of remote discharges, stormwater, and CSO in this area.

3.8 Boston's Inner Harbor

The Inner Harbor receives a large fraction of the total CSO flow, particularly through the Roxbury Conduit and other Fort Point Channel CSOs, the Somerville Marginal CSO at the Amelia Earhart Dam on the Mystic River, and the Prison Point CSO just downstream of the Charles River Dam.

A tracer study of the effect of the Charles River on the Inner and Outer Harbor was conducted for the MWRA CSO Facilities Planning project (Adams *et al.*, 1993). The study indicated that bacteria leaving the river mouth tend to die or settle before leaving the Inner Harbor, and that the flushing time is about 3.5 to 4 days. In spite of this fairly rapid flushing, contaminated particles introduced by riverine, CSO, or stormwater sources most likely settle and remain in the Inner Harbor; the sediments of this area are highly contaminated (Shiaris and Jambard-Sweet, 1986; Hubbard, 1987; MacDonald, 1991; Manheim *et al.*, 1992)

3.9 High-deposition areas

Narrow, enclosed channels and small depositional areas fringing the harbor appear to trap contaminants (Wallace *et al.*, 1991; Gallagher *et al.*, 1992). This conclusion is supported by the results of the fluorescent tracer studies and sediment sampling conducted for this project in Fort Point Channel in the Inner Harbor. In Fort Point Channel, one very large CSO, BOS-070, and several small ones, discharge into a small area with restricted flushing. BOS-070 discharges a large fraction of the total system CSO flow. Since flow through BOS-070 is untreated, Fort Point Channel provides a "worst case" estimate of the effects of CSO on harbor water and sediment quality.

Dye was used to track the freshwater from the CSO; fluorescent paint (which is a suspension of tiny chips) was used as well in two of three experiments performed to track the motion and settling of suspended particles such as those discharged from CSOs (Adams *et al.*, 1992). Sampling for tracer concentration, salinity, and fecal coliform bacteria took place for about a week after each tracer injection.

The study indicated that more than half of the contaminated particles in combined sewer overflows to Fort Point Channel settle and are trapped in the channel and do not reach the Outer Harbor. It is possible that the channel bed sediments aggregate with suspended particles, removing them from the water column (Adams *et al.*, 1992). Fecal coliform bacteria, a common bacterial indicator of sewage-related disease-causing microorganisms, had a disappearance rate approximately equal to the water flushing rate. Consequently, it appears that 50 to 90% of the bacteria

discharged to Fort Point Channel are removed from the water (die or sink to the bottom) in the channel rather than escaping to contaminate beaches or shellfish areas in the Outer Harbor. The tracer studies are fully described by Adams *et al.* (1992).

In conjunction with the tracer studies in Fort Point Channel, sediment cores were collected along the channel and were analyzed for sediment and metal accumulation rates. Most of the channel is a depositional environment, that is, it accumulates sediment over time. The rate of sediment accumulation varied among sites, from 0.7 to 6.3 cm/yr. These are extremely high rates; they are ten times higher than rates that have been measured in the open-water areas of the harbor by other investigators (for example, Fitzgerald, 1980). If all the solids from all the CSOs in Fort Point Channel were deposited in the channel, it would account for only one-sixth of the total measured accumulation. In addition, the rate of copper accumulation is twelve times higher than the input to the channel from CSOs. Although we have not ruled out another unknown source to the channel, it appears that Fort Point Channel is acting as a "sediment focusing area," accumulating particles and contaminants not only from local CSOs, but also from more distant sources in the harbor.

Two studies of Dorchester Bay have identified two areas that also appear to act as sediment focusing areas. Savin Hill Cove has been found to accumulate sediments (and contaminants) extremely rapidly (Wallace *et al.*, 1991). Pine Neck Creek in southern Dorchester Bay was found to have higher concentrations of contaminants than some sites closer to CSOs (Durell *et al.*, 1991). This could be due to a stormwater source of contaminants, or this small creek could be an effective sediment trap with restricted circulation, acting to concentrate contaminants from throughout Dorchester Bay. Contamination is presumably also present in the sediments of Tenean Beach, which is located at the mouth of Pine Neck Creek.

Considering these studies of Fort Point Channel and Dorchester Bay, it is likely that there are other such small embayments around the harbor that act as sediment focusing sites. Headlands with small coves behind them occur in many parts of the harbor's shores and islands, which can also create small depositional areas. These are not all depicted in Figure 4, because the measurements on which the map is based (Knebel *et al.*, 1991) could not be made very close to shore and in these tiny areas. For example, small areas of rapid sediment accumulation such as Savin Hill Cove are not depicted as depositional. However, note that this conclusion cannot be applied universally; for example, in the Reserved Channel, shipping activity may keep sediment from accumulating.

Stolzenbach *et al.* (1992) note that in sediment focusing areas, control of a nearby CSO may not have much effect on the rate of contaminant accumulation.

3.10 Rivers

The tributary rivers to Boston Harbor, particularly the Charles and Mystic Rivers, receive high CSO inputs. Microbiological monitoring of the Charles, Mystic, and Neponset Rivers (MWRA, 1991; Rex, 1993) demonstrates that these rivers are highly contaminated by bacteria from CSOs and from other sources, such as contaminated stormwater. The Fore River in the southern part of the Outer Harbor does not contain CSOs, but is also contaminated with bacteria during wet weather (Fogarty and Menzie, 1993).

Very few data exist on sediment contamination of rivers, but those we have (Battelle, 1990; CH²M Hill, 1989; Menzie-Cura, unpublished data; O'Shea and Kennedy, 1989; Shiaris and Jambard-Sweet, 1986) indicate that river sediments are contaminated with priority pollutant organic contaminants and metals and exhibit some sediment toxicity. Nonetheless, riverine sediments are not quite as contaminated as the most contaminated portions of the harbor. For example, sediment metal concentrations in the Mystic River, Chelsea Creek, and Reserved Channel measured by the Army Corps of Engineers (USACE, 1990) are five to ten times less than in Fort Point Channel (Stolzenbach *et al.*, 1992). The Charles and Mystic Rivers are dammed at their mouths, which slows the flow of water and prevents tidal flushing. Contaminated particles would therefore tend to settle out in the river basins, which reduces the effect of these rivers on harbor sediments.

4.0 Exchange of contaminants between sediment and overlying water

Boston Harbor sediments contain a large inventory of contaminants resulting from many decades of human activity. In addition to possible effects on organisms living in or on the sediments, the harbor floor is potentially a source of contaminants to the overlying water. The exchange of contaminants between the water and sediment is governed in part by the relative concentrations of contaminants in each. Therefore, concerns have been raised that, as discharges of sewage are abated and the water becomes cleaner, the sediment may become a more important source of contaminants and could even result in violations of water quality criteria.

The exchange of contaminants between the sediment and the overlying water depends on several factors:

- the type of contaminant (metals, organic contaminants of various types) and its concentration,
- the partitioning of the contaminant between solid, dissolved, and colloidal phases, and its solubility,
- the sediment characteristics (*i.e.* organic carbon content, grain size, chemical state -- reducing *vs.* oxidizing), and
- the biological, physical and chemical processes acting on the sediment.

The contaminants present at levels above background in Boston Harbor sediments include metals (Fitzgerald, 1980), polycyclic aromatic hydrocarbons (PAHs), and polychlorinated biphenyls (PCBs) (Boehm *et al.*, 1984; Shiaris and Jambard-Sweet, 1986). The contamination levels vary widely around the harbor (see for example Figure 5 showing concentrations of contaminants in surficial sediments) and also vary with depth in the sediment.

Small particles (clay and silt), which tend to have high levels of organic carbon, have a high affinity for many pollutants. *Colloids* are tiny particles (actually, very large molecules), about 1 nm to 1 μ m in diameter, that pass through conventional filters and are generally included in the "dissolved" fraction when analyses are performed. Colloid motion can be a very effective mechanism for moving contaminants.

The processes that could release contaminants into the overlying water include the following:

- diffusion upward of contaminant-laden colloids and porewater constituents (when porewater is in direct contact with sediment particles, contaminants can dissolve into the porewater);
- flushing of porewater and its associated colloids from the sediment bed to the overlying water, especially where sediment-dwelling organisms irrigate the sediment (*bioirrigation*);
- desorption when there is direct contact between contaminated particles and (cleaner) overlying water [this can be caused by physical overturning of the sediment by the animals living therein (*bioturbation*) or by resuspension of erodible sediments up into the water column (Chin *et al.*, 1991, Wong, 1992)].

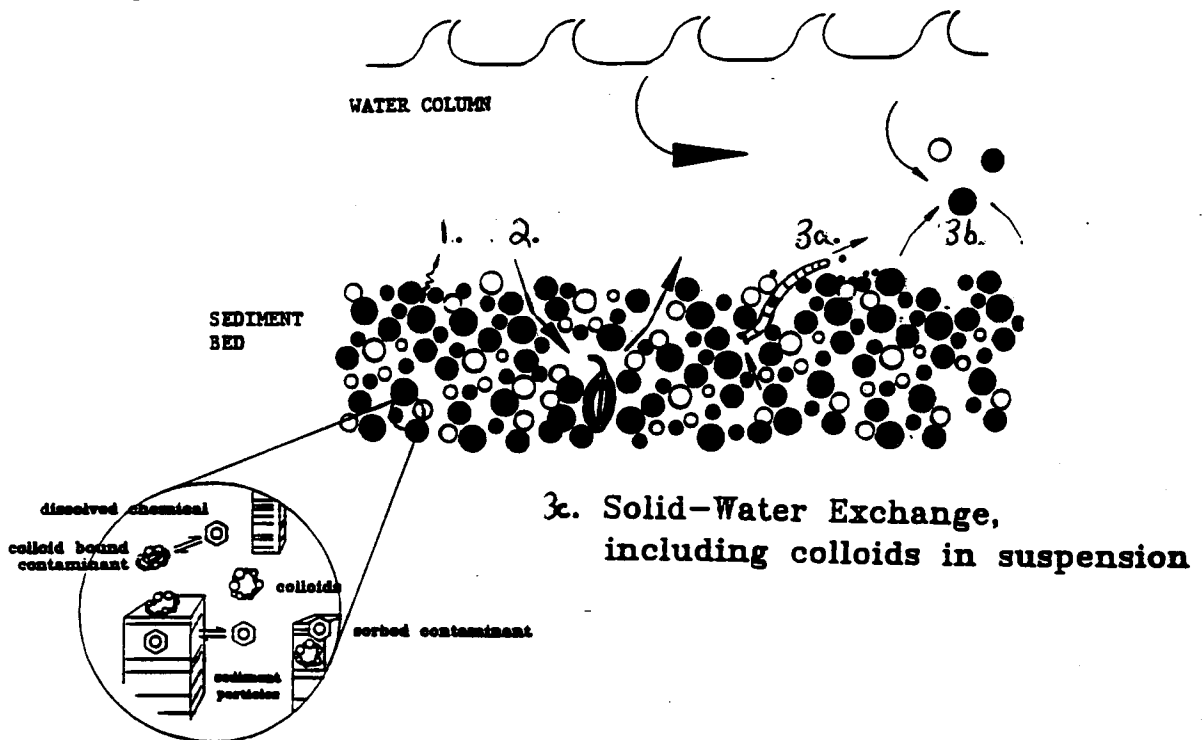


Figure 7: Schematic of processes driving sediment-water exchange of contaminants. (1) diffusion; (2) bioirrigation; (3) desorption, including: (3a) bioturbation, (3b) resuspension, (3c) exchange between particles, colloids, and water (figure from Chin *et al.*, 1991)

These processes are shown pictorially in Figure 7. Other mechanisms can also modify the rates of diffusion, flushing, or desorption. These include the rate of replacement of (clean) overlying water, tidal pumping, the binding of particles (and contaminants) into refractory fecal pellets, and the chemical state (reducing or oxidizing) of the sediment. In particular, sulfidic (reducing) sediments bind metals very strongly (DiToro *et al.*, 1990). Burial by cleaner sediment can reduce the rate of contaminant exchange. Areas of rapid sediment deposition tend to be more highly contaminated, but as sources of pollution are reduced these areas will also be buried more quickly with clean sediment.

4.1 Overview of sediment water exchange study

The sediment-water exchange of contaminants in Boston Harbor was studied by investigators at UMass/Boston and MIT. This part of the contaminated sediment project is described in Wallace *et al.* (in prep.), McGroddy (1993), and Wong (1992). The methods are described in the work/quality assurance project plan (part II) (Adams *et al.*, 1990).

In order to quantify the processes governing exchange of contaminants, detailed geochemical measurements were made on three sediment box cores. The sites were chosen to represent a range of conditions in the harbor, based on the results of a sediment survey. Cores were taken at the following sites:

- (1) Fort Point Channel: A core was taken from the mouth of Fort Point Channel, an area of restricted flushing close to several sources of contamination, including the largest untreated CSO in the system.
- (2) Peddocks Island: A core was taken south of Peddocks Island, in an area of slightly coarser sediments relatively far from pollution sources.
- (3) Spectacle Island: A core was taken north of Spectacle Island; this area is well-flushed, but is relatively close to a large former CSO discharge on Moon Island (BOS-125) and other Dorchester Bay CSOs.

The box cores were sectioned at 2 cm depth intervals for measurement of natural radionuclides, trace metals, and organic contaminants, as well as grain size, porosity, and organic carbon. Measurements were generally made in each of three fractions: porewater (dissolved constituents), porewater colloids, and solid sediment. Information about fluxes within and out of the sediment as well as historical contamination information can be determined by examining the shape of these vertical profiles.

Additional cores were taken adjacent to the geochemistry cores for enumeration of benthic macrofauna (animals living in and on the sediment), to obtain information about biological processes that might influence the contaminant profiles.

4.2 Summary of data from the cores

The cores document the history of sediments at each location over the past 30 to 40 years. The high concentrations of organic carbon and a bacterial sewage tracer, *Clostridium perfringens*, illustrate the long-term disposal of sewage in the harbor.

The three areas cored were relatively similar in terms of grain size. All three were primarily fine-grained muds, but there were differences in the amounts of alteration of the sediments by animals. Both the Peddocks Island and the Spectacle Island sites contained dense amphipod tube mats at the sediment water interface. There was no such structure at the Fort Point Channel site. Both the Fort Point Channel and the Peddocks Island cores showed substantial pelletization of the subsurface sediments, with *Capitella* fecal pellets reaching 50% by weight at 12 cm down the Peddocks Island core. Low pelletization was seen in the Spectacle Island core. Significant variation was seen in the pellet profiles from 2 cores taken adjacent to each other at the Peddocks Island site.

The organic carbon content of the cores was variable with depth, but averaged around 5.1% for the Fort Point Channel core and 4.2% for the Peddocks Island and Spectacle Island cores (Wong, 1992). These are typical values for harbor sediments (Mencher *et al.*, 1968; Fitzgerald, 1980; Kelly and Kropp, 1992).

The *Clostridium perfringens* spore counts in surficial sediments from the Peddocks Island core (3.2×10^4 /gram) and Spectacle Island core (5.0×10^4 /gram) were well within the range of Outer Harbor sediment samples from those areas (SAIC, 1990; Kelly and Kropp, 1992; Keay *et al.*, 1992). Although no surficial sediment data are available for the Fort Point Channel site, the spore counts at 6 cm depth (1.6×10^5) were also similar to surficial sediments from the Inner Harbor (SAIC, 1990; Kelly and Kropp, 1992; Keay *et al.*, 1992). All three cores showed high spore counts to the bottom of the cores (depths of at least 30 cm). This is similar to cores near the future outfall site taken by USGS, which show penetration of high counts of spores sometimes at depths exceeding 70 cm (Parmenter and Bothner, 1993).

The site at the mouth of Fort Point Channel, sampled in November 1989, contained extremely low abundances of benthic organisms, approximately 2,000/m². What few organisms were present were mostly in the upper parts of the core, near the

sediment-water interface. In contrast, the Peddocks Island cores, taken in June 1990, contained high abundances of ampeliscid amphipods, which formed a dense tube mat at the sediment-water interface. Total infaunal abundances in this core were approximately 300,000/m². Relatively few organisms were found deeper than 5 cm in the Peddocks Island cores. The Spectacle Island core, sampled in October 1990, showed a relatively dense tube mat (presumably ampeliscid) on the surface, but had few living amphipods and relatively low organism abundances.

The sedimentation rates, organic carbon contents, and *Clostridium perfringens* spore counts of the cores were typical of harbor sediments measured in other studies, as were the communities described at the three sites. Therefore, we believe the results of the detailed studies of sediment chemistry are representative of large portions of the harbor, and can be applied to the harbor as a whole.

Heavy metal concentrations were elevated and approximately constant with depth below reduced concentrations in the narrow surface boundary layer. Concentrations of organic contaminants were elevated in the three cores, and were variable with depth, possibly indicating an history of deposition from multiple, variable sources.

Significantly, most of the PAHs were bound to soot particles and were unavailable for exchange into the overlying water (McGroddy, 1993). For example, 40 to 90% of the pyrene in the Fort Point Channel core was unavailable, as is 90 to 95% of the pyrene in the Spectacle Island core.

From the vertical profiles of contaminant concentrations, we can infer that at present some priority pollutant organic contaminants are being released from Boston Harbor sediments, while trace metals are being absorbed. The processes by which organic contaminants are released are described in the following sections; trace metals are considered in section 4.7.

4.3 Diffusion

Diffusion acts across short distances, but can be significant, particularly when the concentration gradient is large. In undisturbed sediments with no biological activity, this is the most important process (Chin *et al.*, 1991).

Because colloids can diffuse through porewater along with dissolved substances (albeit at a different rate), diffusion is enhanced when colloids are plentiful, as they are in the harbor's organic-rich sediment. This effect is most important for chemicals with low solubility in water but a high affinity for colloids, for example benzo(a)pyrene (Chin *et al.*, 1991; Wong, 1992.) The presence of colloids enhances

the flux of benzo(a)pyrene by about 45 to 63% (Wong, 1992), but increases the flux of the more soluble pyrene by only 2 to 3%.

The Fort Point Channel site, with its low animal abundance, is an example of a site where diffusion is important. Wong (1992) used a numerical model and various assumptions about the sedimentation rate to calculate the rates of release of pyrene and benzo(a)pyrene by diffusion from Fort Point Channel sediments. The rates slow over time as the sediment becomes cleaner. The rates as a function of time are shown in Figure 8 (a) and (b).

Burial by clean sediment can decrease the diffusive flux or negate it. The effects of three different sedimentation rates are shown in Figure 8 and in Figures 9 and 10. For the Inner Harbor, 0.25 cm/yr is probably closest to the actual rate. Of course, if the overlying water or the new sediments are not clean, this would modify the flux. Assuming 0.25 cm/yr, it would take twenty to thirty years for the top 5 cm of Inner Harbor sediments to become clean (i.e. reach background levels for organic contaminants) with diffusion alone.

If there are animals living on or in the sediment, these diffusion-only rates need to be modified. As the sediment becomes cleaner, the fluxes may increase as bioturbation and bioirrigation come into play (Wong, 1992).

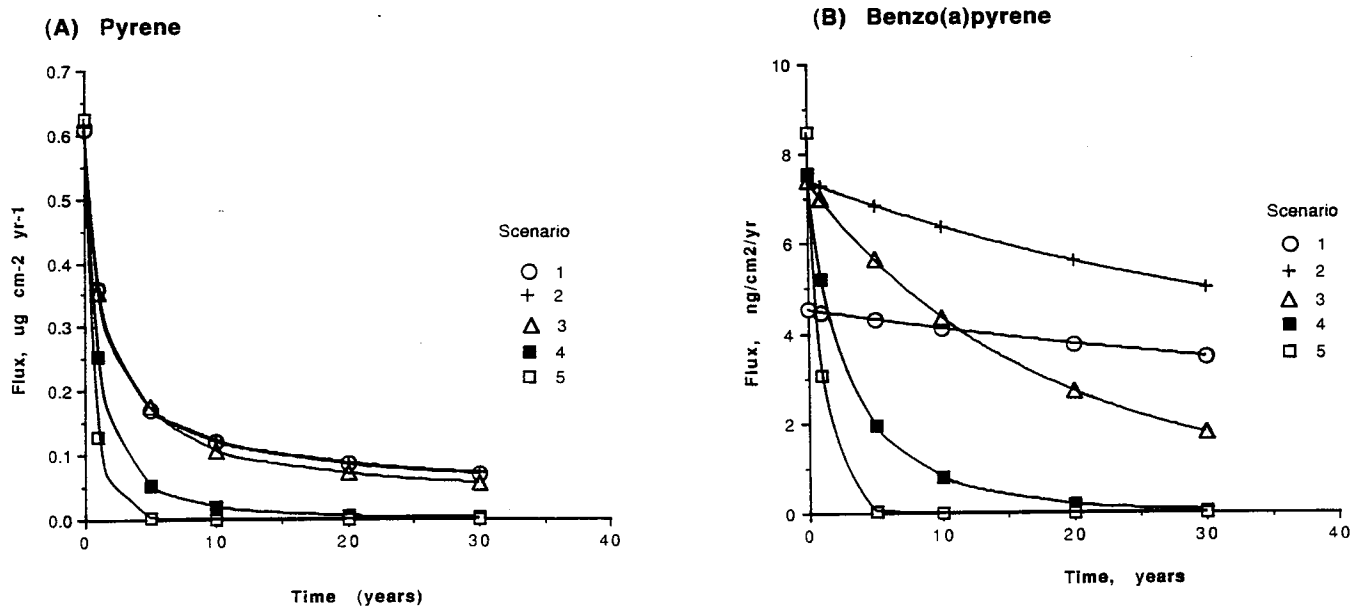


Figure 8: Variation over time of model-predicted fluxes from Fort Point Channel sediments. (a) pyrene; (b) benzo(a)pyrene. Scenarios shown are as follows:

- 1 - diffusion only
 - 2 - diffusion + colloids
 - 3 - diffusion + colloids + 0.01 cm/y clean sediment
 - 4 - diffusion + colloids + 0.1 cm/y clean sediment
 - 5 - diffusion + colloids + 0.25 cm/y clean sediment
- (from Tables 3-1 and 3-2 of Wong, 1992)

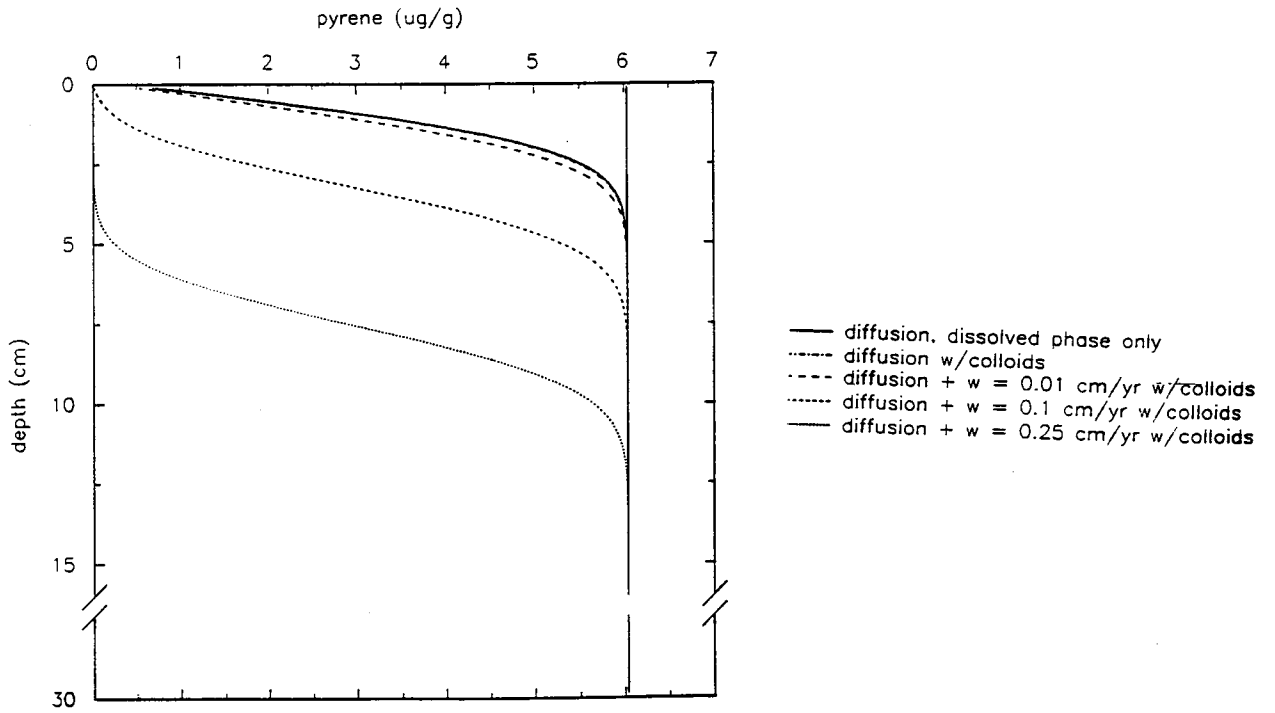


Figure 9: Predicted pyrene profiles in Fort Point Channel sediments after 30 years (from Figure 3-6 of Wong, 1992).

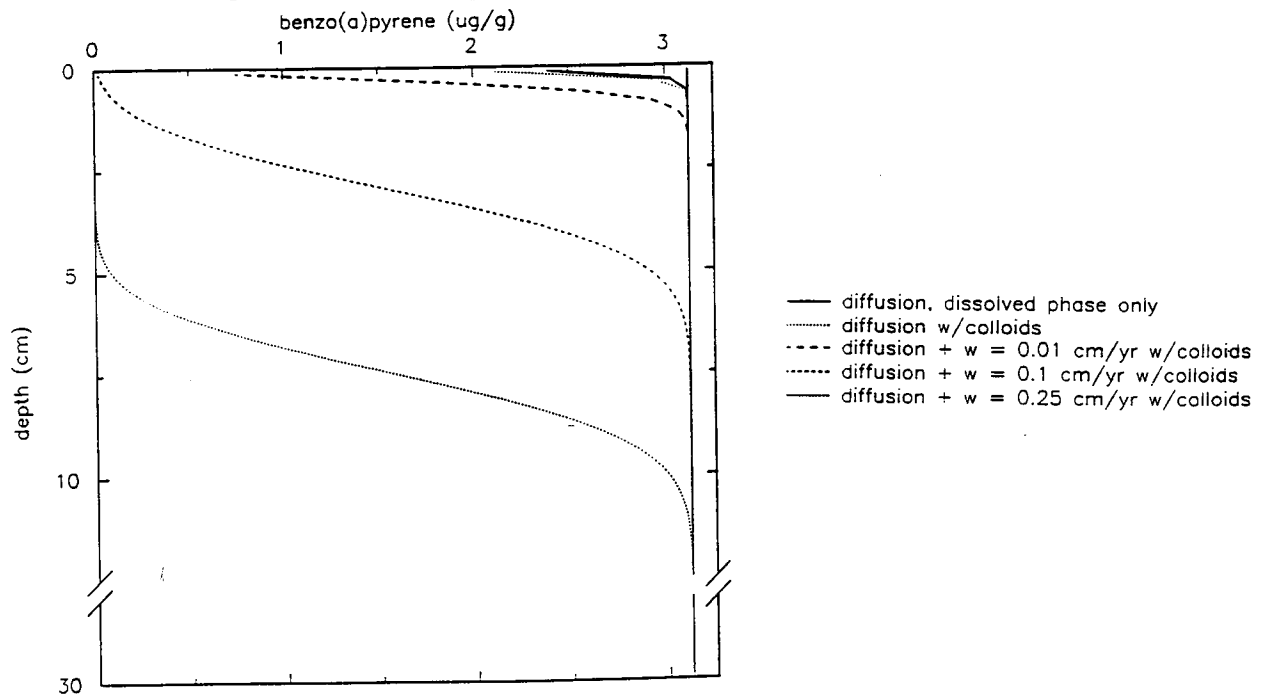


Figure 10: Predicted benzo(a)pyrene profiles in Fort Point Channel sediments after 30 years (from Figure 3-7 of Wong, 1992).

4.4 Flushing/bioirrigation

Flushing and diffusion of porewater and colloids out of the sediment are often estimated using measurements of the naturally occurring radioisotope radon-222, by comparing the vertical profile of radioactivity of the parent element, radium (radium-226), to the profile of ^{222}Rn activity. Lower Rn activity at the surface indicates removal of porewater from the sediment by diffusion or flushing.

During the course of the project, the investigators discovered that radon sorbs to sediment organic matter. This means that the widely-used method of estimating irrigation by porewater Rn profiles, which assumes that Rn does not sorb to particles, must be corrected (Chin and Gschwend, 1991; Chin *et al.*, 1991; Wong *et al.*, 1992; Wong, 1992). Up to 60% of the radon can be sorbed, and the usual method can underestimate the irrigation rate by up to 30% (Wong *et al.*, 1992; Wong, 1992).

As is the case for diffusion, the presence of colloids enhances the flux of contaminants due to irrigation. In a related study, Chin *et al.* (1991) showed that the flux of benzo(a)pyrene from a core taken on Deer Island Flats is expected to be more than four times higher with colloids than without, while the flux of the less particle-reactive pyrene remains essentially unchanged.

Unlike the Fort Point Channel core, the Peddocks Island and Spectacle Island cores showed evidence of vigorous mixing and irrigation. The radon data indicate flushing to a depth of about 10 cm; the porewater in the surface sediments is replaced about every 5 to 10 days.

The Spectacle Island core was collected in October. Although the radiochemistry shows evidence of very deep irrigation (8 to 10 cm), only a few large macrofaunal organisms of the type capable of such deep irrigation were found there. The radon data indicate a porewater replacement time of about 10 to 20 days in the irrigated area.

The rates of irrigation in all three cores probably vary seasonally; benthic organisms are much more active in the summer.

4.5 Desorption

When contaminated sediment particles (or colloids) are brought into contact with the overlying water, which is relatively clean, contaminants can dissolve into the water. This process depends on the rate at which contaminated sediments reach the sediment-water interface, the solubility of the contaminant, and whether the particle is in contact with the water long enough for desorption to take place.

Two main processes bring contaminated sediment particles into contact with the overlying water: physical mixing of the sediment by animals (bioturbation) or other disturbances (*e.g.* storms), and erosion of the sediment surface, which causes particle resuspension.

The radioisotope thorium-234 was used to estimate bioturbation. The importance of bioturbation can be expressed as an effective diffusivity, D_B . The Fort Point Channel core showed little or no evidence of bioturbation ($D_B = 0$). The Peddocks Island and Spectacle Island cores showed evidence of deep biological reworking -- to about 10 cm. In addition, the estimated flux due to bioturbation was significant at both Peddocks Island ($D_B = 1.2 \times 10^{-5} \text{ cm}^2\text{s}^{-1}$) and Spectacle Island ($D_B = 6.3 \times 10^{-6} \text{ cm}^2\text{s}^{-1}$) (Wong, 1992).

Biological samples from the two Outer Harbor sites contradicted the radioisotope data. The Peddocks Island core had a large benthic community, but it did not contain animals capable of deep mixing. The Spectacle Island core did not show the high biological activity expected from the apparent bioturbation implied by the radioisotope data. The mixing could have been due to other mechanisms, such as wave mixing, physical disturbance by large organisms such as crabs, or gas production within the sediment. It is also possible that benthic macrofauna capable of such deep mixing were present earlier in the year, but gone by October.

Quantitative estimates of fluxes of organic contaminants due to desorption are not available. However, we can say in general that bioturbation in the Inner Harbor is likely to be negligible, while fluxes in the Outer Harbor are not likely to be large because of the lower concentrations of organic contaminants in the sediments. Once contaminated particles or colloids reach the sediment-water interface, desorption is governed by the solubility of the contaminants, and, for PAHs, by the availability of the compound. Those PAHs that have a higher fraction bound in soot particles will have a smaller flux out of the sediments. For the available fraction of PAHs, bioturbation will be a bigger factor for the more soluble compounds (*e.g.* pyrene).

4.6 Sediment-to-water flux estimates - extrapolation to whole harbor

Using the model results for the release of PAHs described above and in Wong (1992), a rough extrapolation to the entire harbor can be made. Suppose we assume that:

- PAH concentrations are elevated (about 1 ppm) in the approximately 42 km² (Knebel *et al.*, 1991) of the Outer Harbor that is depositional,
- approximately an additional 5 km² has the higher concentrations and fluxes represented by the Fort Point Channel site (about 10 ppm),
- the water overlying the sediments is free of PAH,
- burial by clean sediment is negligible, and
- we can neglect resuspension, bioaccumulation, redeposition of contaminants from water to sediment, and binding of PAH in unavailable forms (*i.e.* soot).

With those assumptions, we estimate that an average of few hundred kg/yr of pyrene and about 20 kg/yr of benzo(a)pyrene would be released. These loads are greater than estimated annual loads from the effluent, and about the same as the total load from all sources (see Figure 2). The Inner Harbor would contribute the bulk of the sediment PAH flux, in spite of its small size. This release would continue for on the order of decades, assuming the top 10 cm of sediments is contaminated.

Again, it is important to note that burial has been neglected in this model; moderate deposition could effectively “cap” the contaminated sediments. Conversely, if new animals colonize (*e.g.* Fort Point Channel), they could mix and irrigate the sediment and increase the flux out of the sediments.

Because so much of the PAH is bound to soot particles and is unavailable for exchange, (McGroddy, 1993), one must keep in mind that model-predicted fluxes of PAHs are overestimated because the model does not yet take into account this PAH binding. This also means that sediment PAHs are presumably less available for uptake by organisms than would be expected based on their concentrations in the sediment phase.

An analytical model of sediment-water exchange of organic contaminants has been constructed by MIT researchers under separate EPA funding (Chen, 1993). This model allows comparison of the sensitivity of estimated fluxes on various factors. Chen's model indicates the following:

- The effect of bioirrigation on total flux is small.
- The effect of bioturbation depth is small, but the effect of mixing intensity is large.
- Porewater organic colloid concentration may greatly influence the total concentration of organic contaminants in sediment, but the amount of colloids does not have a large effect on the flux of these contaminants out of the sediment.
- Flux is sensitive to the water-solubility of the organic compound.
- Flux is moderately sensitive to the organic carbon content of the sediment, especially at low organic carbon levels.
- Flux does not depend strongly on porosity or on the size of sediment particles at the sediment-water boundary.
- The most important factor affecting the flux -- especially for low-solubility PAHs like benzo(a)pyrene -- is the thickness of the boundary layer of stagnant water overlying the sediment. In general, flux decreases as boundary layer thickness increases. Over smooth sediment, this thickness depends on the bottom stress due to water currents; most of the harbor has vigorous tidal currents, so the layer is thin -- about 0.1 mm thick. In stagnant areas, the boundary layer may be ten times thicker, and the flux of organic contaminants into the overlying water is consequently much smaller.

In both Wong's and Chen's models, the overlying water has been assumed to have no PAH; even water column PAH concentrations too low to measure easily could significantly reduce the PAH flux.

Even though organic contaminants are presently being released from the sediment to the overlying water, the concentrations of total PAHs in harbor water are about a thousand times lower than water quality criteria. Therefore, even if fluxes were increased due to increased biological activity, it seems unlikely that violations of water quality standards would result.

4.7 Trace metals

Comparison of trace metal concentrations in the overlying water and in the porewater from the top of all three cores shows that concentrations of most metals are higher in the overlying water; assuming equilibrium, this indicates a flux into the sediment for most metals. Although trace metal concentrations in the harbor have decreased over time (Sung, 1991; Pitts, 1991; Wallace *et al.*, 1993), the sediment metal concentrations are nearly constant with depth below a narrow surface boundary layer.

These results are not surprising given the high organic carbon content of the sediments in all three locations. Organic-rich sediments tend to be nearly completely anoxic, as bacteria in the sediment have used up all the oxygen in metabolizing the carbon. This results in the predominance of anaerobic bacteria, which use sulfur in the place of oxygen. Consequently, the sediments are high in sulfides. Such sediments effectively strip metals from the water and bind it in the sediments (DiToro *et al.*, 1990).

As sewage discharges to the harbor are abated, the organic carbon content of the sediments may decrease, and their macrofaunal communities may shift more towards deep-burrowing or -mixing organisms. These processes will act to deepen the oxic layer in the sediment, and trace metals will no longer be bound so strongly by sulfides. The flux of metals into the sediment could become a flux out, governed by the same processes described above now acting on organic contaminants.

Metals will continue to be elevated in surface sediments as long as the harbor is rich in organic material and the sediments remain anoxic. Because metals are tightly bound in anoxic sediments, they may not be bioavailable. If the sediments do begin releasing metals, it could take as long as several decades for the surface sediments to become clean. However, if the amount of organic carbon reaching the sediments is reduced, the time for surficial sediment recovery could be reduced to several years.

5.0 Policy Implications

In this section we discuss the policy implications of the results of this study to harbor sediment management. First, we describe the importance of a management policy for the sediments as a whole and of setting goals for the uses of different areas of the harbor. Then, we relate the results of the present study to sediment management issues.

5.1 Massachusetts sediment policy: A basis for pollution control strategies

Trying to interpret the policy implications of this research is difficult since there is no overall sediment quality strategy for the harbor. At present, the Massachusetts Water Quality Standards treat sediment quality very generically, as follows:

Bottom Pollutants or Alterations - All surface waters shall be free from pollutants in concentrations or combinations or from alterations that adversely affect the physical or chemical nature of the bottom, interfere with the propagation of fish or shellfish, or adversely affect populations of non-mobile or sessile benthic organisms. (314 CMR 4.05 (5)(b))

Since more information has now become available on sediments, it would be possible to develop more specific sediment quality standards.

As is the case for water quality standards, the development of sediment quality standards is a two-part process: determining sediment quality goals for different areas, and developing quantitative criteria associated with each of those goals. Although developing quantitative criteria is technically complex, several Federal agencies have made progress in this area. However, these criteria are of no use unless the Commonwealth determines what its goals for sediment quality are. The particular goals chosen will, in turn, help direct the development of strategies for the control of point and non-point source discharges to Boston Harbor and other state waters.

5.2 Potential sediment goals for Boston Harbor

The amount of data now available on harbor sediment chemistry and biology makes it possible to begin to craft goals for the harbor.

5.2.1 Sediment management goals consistent with water quality goals

The simplest model for developing harbor sediment goals would be to adapt the existing goals developed for Water Quality Standards. Currently the state has three levels of water quality classification/protection:

- Class SA waters have the highest goals, and are designated to serve as "*an excellent habitat for fish, other aquatic life, and wildlife ...* ." Goals for Class SA waters include sustaining swimming and unrestricted shellfishing.
- Class SB waters have slightly lower goals than do class SA waters, but are still designated to be "*a habitat for fish, other aquatic life, and wildlife ...* ." Goals for class SB waters include swimming and, in areas, restricted shellfishing with depuration.
- Class SC waters have the state's lowest level of protection. These waters need not meet the swimming standards and may be closed to shellfishing altogether, but are still designated to serve as "*a habitat for fish, other aquatic life, and wildlife ...* ." There are currently no designated Class SC waters in Massachusetts.

In attempting to use the water quality standards to propose possible sediment quality goals for a harbor sediment management policy, we have derived the following conceptual model.

- Areas designated to have Class SA-S ("S" denotes sediments) sediment goals would have the highest level of protection. As an example, one goal might be to have no anthropogenic contaminants above the strictest sediment quality criteria established by EPA or sensitive effects ranges (ER-L) suggested by Long and Morgan (1990). Such sediments might be expected to show no toxicity to sensitive life stages of indicator species in sediment toxicity assays, would maintain oxygen penetration into the sediments to some minimum depth, and sustain relatively "pristine" benthic communities similar to those from undeveloped estuaries in that region.
- Areas designated to have Class SB-S sediment goals would have a slightly lower, but still high level of protection. Anthropogenic contaminant concentrations in these sediments would rarely exceed a more permissive sediment quality criteria, such as the moderate effects range (ER-M) developed by Long and Morgan (1990). Such sediments might be expected to show little or no toxicity to sensitive test organisms, to maintain oxygen

penetration into the sediments to a lesser, but still substantial depth, and to sustain vigorous benthic communities that may show some evidence of anthropogenic alteration.

- Areas designated to have Class SC-S sediment goals would have the lowest level of protection. Several contaminants might exceed sediment quality criteria. Although these areas might be expected to show some sediment toxicity to sensitive test organisms, they would still maintain at least a minimal level of oxygen penetration into the sediments, and to sustain at least surficial tube-dwelling communities (similar to that sampled at the Peddocks Island site in this study).

In addition, to meet any of the three goals, the contamination levels could not be so high as to cause a flux from the sediments that would violate the relevant water quality standard.

5.2.2 Current status of harbor sediments

To test the implications of this model for sediment standards, our preliminary conclusions of how harbor sediments would be classified are described below, and we tentatively predict what improvements should result from pollution abatement efforts. This classification of harbor sediments is very preliminary because sediment toxicity data are not available for most of the harbor. We have used MWRA's benthic monitoring data (reported in SAIC, 1992; Kelly and Kropp, 1992; SAIC, 1990; Blake *et al.*, 1993) to indicate the current status of harbor sediments in different areas.

Inner Harbor. This area is the only harbor area where sediment toxicity data are available. Sediments in much of the Inner Harbor show significant toxicity to test organisms, are frequently anoxic, and have an extremely degraded biological community (MWRA benthic surveys; Hubbard and Bellmer, 1989). Proposed sediment criteria are also violated (Cahill and Imbalzano, 1991). The Inner Harbor would not now meet the speculative "SC-S" standard described above, and some parts of the Inner Harbor, like Fort Point Channel, may sometimes have no benthic animals.

Northwest Outer Harbor. As shown in Figure 4, this part of the harbor includes depositional sediments, areas of sediment reworking, and erosional areas. The biological communities found here vary both spatially and through time. Recent sampling in some areas like Savin Hill Cove and the Deer Island Anchorage Area showed only very few organisms and shallow sediment oxygenation (Kelly and

Kropp, 1992; Blake *et al.*, 1993). Other areas, like Deer Island Flats, showed less impacted, dense communities of ampeliscid amphipods. Some areas in the northern Outer Harbor appear to have alternated between very degraded and less impacted biological communities (Blake *et al.*, 1989; Blake *et al.*, 1993). There are exceedances of proposed EPA sediment quality criteria (Cahill and Imbalzano, 1991). Depositional areas in much of the northern Outer Harbor would not now meet the speculative "SC-S" standard, but nondepositional areas might meet this standard.

Central and Southeast Outer Harbor. Quincy, Hingham, and Hull Bays are probably the least contaminated parts of Boston Harbor. Some depositional areas here have probably been affected by discharges from the Nut Island treatment plant, but generally there are now abundant populations of organisms at the sediment surface, sometimes mixed with more deeply burrowing animals. Cores taken at the Peddocks Island site showed that pollution indicator species were more abundant in the past. Oxygen consistently penetrates more deeply into the sediments in the Southeast Harbor than in other parts of the harbor (Blake *et al.*, 1993). Thus, all the sediments in the Central and Southeast Harbor at least meet the speculative "SC-S" standard. Much of the region, especially the Southeast Harbor, might meet or be better than the speculative "SB-S" standard.

5.2.3 Attainable sediment quality goals

Given the present condition of Boston Harbor sediments, what levels of recovery do we expect are attainable, and how does this anticipated recovery relate to our speculative sediment classifications? Although the sediments of the harbor are starting to become less contaminated (Wallace *et al.*, 1991, Manheim *et al.*, 1993), attaining sediment quality goals may take many years to many decades, depending on the region.

After the sewage effluent outfall is moved, improvements in the harbor's benthic communities are likely to occur swiftly. The time scale for predicted biological recovery (1 to 5 years) is much faster than the time scale for release or burial of chemical contaminants (decades). This is based on the results of new studies, which have shown that the primary cause of degradation of benthic communities in Boston Harbor is excess organic carbon caused by sewage discharges -- rather than a direct effect of toxic contamination (Gallagher *et al.*, 1992). Thus, alleviation of organic carbon pollution by reducing BOD, suspended solids, and nutrient input to harbor sediments may eventually lead to relatively healthy bottom-dwelling communities, despite large concentrations of toxic contaminants remaining in the sediments.

Future reduction of harbor sediment contaminant levels will depend on the rate of burial of existing sediments and the metal and priority pollutant organic contaminant fluxes out of the sediment. In addition, the rapid biological improvements described above will increase bioirrigation/bioturbation and oxygen penetration into the sediments.

Predicted changes for different regions of Boston Harbor are described below.

Inner Harbor. The studies described in this report indicate that the Inner Harbor is a depositional area which accumulates contaminants not only from nearby sources, but also from treatment plant discharges. Therefore, when the sewage effluent discharges are moved out of the harbor in 1995, Inner Harbor sediments should begin to improve significantly. However, CSOs, rivers and stormwater will continue to have an impact on the sediments, and the heavy use of the Inner Harbor as a commercial port will also contribute some contaminants. Because the present reservoir of toxic contaminants in the Inner Harbor sediments is large, and because there will still be significant sources to this area, improvements will probably be slow (on the order of decades). The cleanest "attainable goal" is likely to be our speculative "SC-S" standard, but some areas, like Fort Point Channel, are so degraded that even this level of sediment quality may not be possible.

Northwest Harbor. The major source of contamination to sediments in the Northwest Harbor is sewage effluent from the Deer Island treatment plant; sludge was a significant source until December 1991. CSOs, stormwater, and rivers appear to have a relatively minor effect, except on sediments immediately adjacent to discharge points. Since the relocation of the effluent discharge outside the harbor will alleviate the effects of excess organic carbon (by reducing TSS, BOD, and nutrient loads), this should result in dramatic improvements in benthic communities. In high-depositional areas, and at the mouth of the Inner Harbor, the levels of toxic contamination in sediments should slowly (years to decades) improve to the speculative "Class SC-S" level, and much of the Northwest Harbor should eventually reach the "Class SB-S" level.

If CSOs are eliminated in Dorchester Bay, then even high-depositional areas close to the present overflow sites may slowly show both biological improvement and sediment contamination improvement to our speculative "Class SC-S" level.

Central and Southeast Harbor. The most vigorous benthic communities and the lowest levels of anthropogenic contamination in Boston Harbor are found in this region, although there are some significantly degraded areas. Effluent from the Nut Island treatment plant is the major source of contamination to the sediments in the

Central and Southeast Harbor. When the discharges from Nut Island cease, these degraded areas should substantially improve both biologically and in levels of sediment contamination. This region will continue to receive contaminants from the atmosphere, stormwater, and rivers, and so will not reach a pristine, pre-industrial condition. The Central and Southeast Harbor should improve to the Class "SB-S" standard.

5.3 Harbor sediment management

The findings of these studies relate to five issues in harbor sediment management:

- effluent and sludge disposal,
- CSO control strategies,
- shellfish management strategies, and
- remedial dredging.

5.3.1 Effluent and sludge disposal

Harbor sediment studies have shown the dramatic effect of solids discharged from the sludge and effluent outfalls. Removing the big discharges from the harbor either through land application (sludge) or offshore discharge (effluent) will benefit not only the area near the discharges but the harbor as a whole. Abating these discharges appears to be necessary, but not sufficient, to improve sediment quality in susceptible high-deposition areas.

Sludge Abatement

MWRA stopped discharging sludge in December 1991, reducing the discharge of total solids to the harbor by approximately 18,000 metric tons/year. There are already some indications that removing this discharge has had a salutary impact upon the sediments immediately surrounding the outfall from which Nut Island sludge was discharged (near the tip of Long Island), although another two to three years of monitoring will be required to confirm this.

Effluent improvements and outfall location

The new primary treatment plant will begin treatment of present Deer Island flow late in 1994. Diversion of Nut Island flow to the new plant and commissioning of the Massachusetts Bay effluent outfall are scheduled for mid-1995. These successive improvements in level of treatment and relocation of the effluent outfall will lead to major improvements in harbor water and sediment quality.

When the new effluent outfall tunnel goes on-line, effluent will no longer be discharged to the harbor. It should be noted that Massachusetts Bay sediments will not accumulate contaminants from the discharge the way Boston Harbor sediments have, for a number of reasons including smaller loads and greater dilution. With the completion of the new secondary treatment plant, the loads of both solids and BOD discharged in the effluent will decrease substantially, since secondary treatment removes additional material. These additional solids will end up in the sludge³, and will no longer be discharged to the marine environment.

Once the effluent is diverted from the harbor, the key to the sediments' recovery will be the rate at which the sediments are re-oxygenated, which in turn depends on how quickly animals can colonize the sediments and metabolize the high concentrations of organic matter. That recolonization process could occur in months or it could take many years, depending on how much organic matter remains in the sediments, additional organic deposition during the year, and the supply of oxygen in the overlying water for colonizing animals.

To the extent that decreased loading of BOD and TSS to the harbor results in decreased organic matter loading to the sediments, this should lead to improvements in sediment quality. Less well understood is the effect of the reduction in nutrient loads on the recovery of the harbor sediments. Nutrients stimulate phytoplankton production (and settling), but it not clear how much of the organic matter that reaches the sediments is due to nutrients, nor how the reduction in nutrients will affect phytoplankton. Ongoing MWRA monitoring of sediment recovery may provide the most conclusive information.

5.3.2 CSO control strategies

There are three basic CSO control strategies:

- **Separation** of sanitary sewers from storm sewers
- **Satellite treatment** (e.g. screening and chlorination)
- **Storage** of combined sewage so it is not discharged but rather treated during dry weather

³ Because of aggressive measures to reduce sources of toxic contaminants to the sewer system, MWRA's sludge fertilizer will continue to meet Massachusetts state standards.

The benefits of sewer separation on sediment quality would be intermediate to those of the other two strategies. With this strategy, sanitary flow would decrease since it would be captured and transported to the treatment plant. However, stormwater from small storms is currently transported to the treatment plant, so some of the solids (and toxic contaminants) are now removed. With sewer separation, the discharge of stormwater solids would therefore increase. As noted earlier, stormwater contribution of toxic contaminants is not believed to be very high (BWSC, 1993), but additional measurements of the stormwater contribution of solids and toxic contaminants would be necessary to quantify the net impact of sewer separation.

Satellite treatment would most likely continue to keep harbor-wide sediment impacts to a minimum -- CSOs would continue to represent only a small fraction of total sources, but could still have significant local impact (within 100 m) in the region of each outfall. Chlorination is moderately effective at reducing microbial pollution, but could increase the amount of chlorinated organic contaminants contributing to total sediment toxic contamination.

Storage alternatives would eliminate the regional impacts of CSOs on the sediments harbor-wide, particularly once the outfall is moved offshore. It is possible that local impacts (closer than 100 m) will exist at any CSOs that remain for overflows during the rainier storms that exceed system capacity. Decisions about where to locate CSO outfalls that must remain as part of any strategy to handle flows that exceed the design capacity of the treatment plant should consider the tradeoffs between confining CSO solids within the Inner Harbor and/or the rivers, and maximizing the dilution and transport of the solids discharged.

5.3.3 Beach management strategies

One concern that has been raised is the potential risk to bathers of dermal exposure to contaminated sediments (or to young children who might ingest contaminated sediments). Although there are no epidemiological data relating toxic contamination of Boston Harbor sediments to human disease rates, we can compare levels of contamination in Boston Harbor sediments to levels used in risk assessments in other areas. For example, a risk assessment was done for the New Bedford Harbor Superfund site (EPA, 1989). Average shoreline metal concentrations (copper, cadmium and lead) at the New Bedford site were 3 to 10 times higher than in Boston Harbor. The EPA study concluded that "direct contact exposure to these contaminants {dermal and/or ingestion} is not considered to present a human health risk." At sites in New Bedford Harbor where PCBs were 10 to 100-fold higher than in Boston Harbor, exposure to sediments was "not

considered a public health risk." (At locations in New Bedford where PCB concentrations were 1,000-fold higher than in Boston, the report did conclude that there was a potential risk to public health).

Although contamination of water by disease-causing microorganisms in raw sewage from CSOs is the primary public health concern in beach areas, viruses or other pathogens that are sequestered in the sediments may be resuspended from the bottom and cause a hazard to bathers. Wound infection could also occur if someone with an open wound contacted contaminated sediments.

Planning for CSO and stormwater controls should incorporate the goal of diverting discharges away from beach areas to avoid contamination from either microorganisms or toxic contaminants.

5.3.4 Remedial dredging

Dredging of Boston Harbor is a complex, controversial issue, and most of the discussion concerns what to do with the material once it is dredged, whether that is open ocean or upland disposal. In this report we address only whether dredging is likely to be necessary to improve the sediment quality of the harbor, which we refer to as *remedial dredging*.

Remedial dredging of the harbor would primarily focus on the Inner Harbor, and possibly the rivers and small high-deposition areas that trap sediment and contaminants. The concerns addressed by remedial dredging would be contaminated sediment effects on water quality, sediment toxicity and habitat loss, and risks to human health from contaminated seafood. However, even without remedial dredging, the surface sediments -- those in which contaminants could have an ecological effect -- are expected to clean themselves over the course of several decades.

While there can be a rapid flux of material out of the existing sediments, it seems that this flux will not represent a very high risk to water column contamination (Chen, 1993). Even Inner Harbor sediments are probably not a large source of toxic contaminants to the water, compared to other existing sources. As harbor sediments become cleaner, the flux will eventually decline.

The ecological effects of contaminated sediments are briefly described in Section 5.2 above. In the absence of sediment quality criteria or alternative means of sediment classification and a harbor sediment management strategy, it is not possible to give a definite answer about the need for remedial dredging. However, we believe the

contaminated sediment study results indicate that remedial dredging is probably not necessary.

An analysis of the impacts of navigational dredging is beyond the scope of this document. Navigational dredging in the Inner Harbor could remove some of the contaminated sediment as a side benefit, but would involve only part of the channel. If any dredging does take place in Boston Harbor, it will most likely be driven by navigational needs.

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