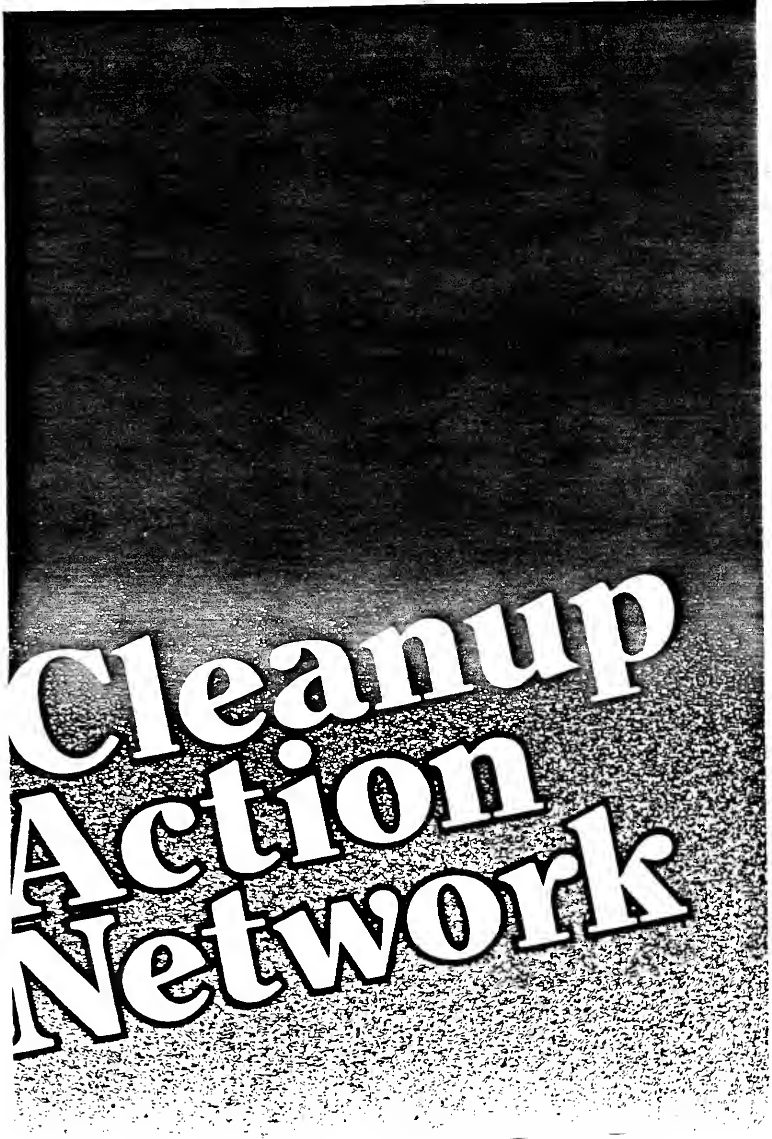

REPORT III.

Boston's Bad Bottom -
Sediments: A Resource in Distress

November, 1988

the boston harbor associates

for a clean, alive and accessible Boston Harbor

FOREWARD

The Boston Harbor Associates is pleased to present "Boston Harbor's Bad Bottom: Sediments - A Resource in Distress", the third product of the Cleanup Action Network.

TBHA has developed the Cleanup Action Network, "CAN", to research and analyze the technical and economic elements and issues of Boston Harbor cleanup and to provide this information in accessible language for a broad audience. The audience for "CAN" reports is TBHA's Board of Directors, its business and non--profit organization alliances, an array of elected and appointed officials with whom TBHA works, the media and the general public. It is our goal to provide timely and accurate information to serve as a basis for effective advocacy for harbor cleanup.

I would like to thank the Bank of Boston, Monsanto Chemical Co., Monsanto Fund and Loomis Sayles for their support of the Cleanup Action Network.

George Macomber
Chairman
The Boston Harbor Associates

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Any errors are the sole responsibility of the authors.

BOSTON HARBOR'S BAD BOTTOM

SEDIMENTS: A RESOURCE IN DISTRESS

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EXECUTIVE SUMMARY

Although in a degraded condition, Boston Harbor is a dynamic ecosystem; potentially rich in resources, landscape, and beauty. Its sediments support the living resources while absorbing the brunt of human pollution. This report reviews the nature of Boston Harbor sediments, what they are, why they are a dynamic component of Boston Harbor, what life they support, and how pollutants affect this precious ecosystem and ultimately the humans who enjoy its resources. Scientific understanding of Boston Harbor is inadequate and far less than for some other major harbors in the United States.

Marine sediment processes are complex, but they must be understood in order to formulate and implement sound policy for pollution abatement. A comprehensive and coordinated research effort is needed to provide a thorough understanding of Boston Harbor as an integrated ecosystem. This effort should go hand-in-hand with a monitoring program to ensure that implemented managerial programs are effective. This work would be cost-effective: money spent on research and monitoring would be a small percent of the overall pollution-abatement program. The management decisions necessary for designating sewage outfall sites and selecting treatment alternatives require a fundamental understanding of how Boston Harbor works. The $1.6 million earmarked for research through the federal penalty and the Massachusetts Bay/Cape Cod Bay Program is a good start, but only a beginning.

INTRODUCTION

The Boston Herald headline of April 28, 1987 proclaimed Boston Harbor the "Harbor of Shame". The National Oceanographic and Atmospheric Administration (NOAA) has deemed Boston Harbor the "most polluted harbor in the United States". The 1988 presidential race has placed national focus on Boston Harbor as a symbol of our imminent environmental problems. Does the Harbor deserve the notoriety? A casual observer may see only the natural beauty of the Harbor's waters and islands, but the problem lurks below the surface.

NOAA, after conducting a preliminary survey of the condition of U.S. harbors, based its conclusion on only a single sample and subsequent chemical analysis of Boston Harbor sediments, the subject of this paper. The levels of key pollutants such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), the banned pesticide DDT, and a variety of toxic metals, were the highest or near highest of any harbor sediment examined in the NOAA study. NOAA's findings reinforce the observations of citizens, scientists, and government agencies: the chronic accumulation of waste and sewage in the Harbor has led to a severely polluted environment.

Should we be concerned that the sediments are polluted to such appalling levels? After all, the contaminants are concentrated at the bottom of the Harbor, out of sight and out of mind. The answer is yes. The sediments of relatively shallow waters such as harbors and coastlines are the lifeblood of the system. They play a predominant role in the well being of the overlying waters and all the living organisms which live in and around the Harbor, including humans.

This report addresses Boston Harbor sediments. Sediments are integral to the Harbor as an ecosystem, and must be considered in every aspect of future plans for the Harbor. Our purpose here is three-fold; first, to provide a primer on the nature and role of sediments; second, to examine the effects of chronic pollution on Boston Harbor sediments and the implications to the ecosystem as a whole; and third, to evaluate options and recommend steps for understanding the Harbor system, for managing the Harbor, and for reversing the degradation of this valuable resource.

SEDIMENT: A PRIMER

PHYSICAL AND CHEMICAL PROPERTIES

What are Sediments? Webster's dictionary defines sediment as "any matter that settles to the bottom of a liquid". Thus, the sediments of Boston Harbor are a complex mixture of living and nonliving components: particles of minerals such as clays, quartz, flint, chert, and feldspar, and organic matter (material derived from plants and animals which include fats, sugars, and proteins or even particles of coal and coke[6]). The particles range in size from the microscopic (clays to the larger silt particles) to large visible particles (sand, cobble, pebbles, and boulders). The smaller particles, clays and silts, have a great affinity for organic matter that is dissolved in the water, and become coated with an organic film of fats, sugars, and proteins. This organic film has a great affinity for many pollutants; which explains why some pollutants may be found in concentrations thousands of times higher in sediments than in the overlying water.

Sources, Movement, and Distribution of Sediments. Boston Harbor is an estuary, a partially enclosed body of water where freshwater meets seawater. In common with other estuaries, Boston Harbor is a trap for sediment particles. Sediments accumulate over time, constantly building up the bottom. Navigators and marina owners know all too well the constant need to dredge the bottom as shipping channels and mooring areas fill up.

This influx of sediment particles has many sources. Particles are carried in by rivers, streams, outfalls, and land runoff; by fallout from the atmosphere, by the erosion of the adjacent coastline, by the resuspension of existing sediments, and by the creation of new particles from the growth of living organisms within the harbor.

Estuaries also accumulate particles from the sea itself, although we tend to think of the overall movement of water from land outward. This anomaly arises from the complex patterns of water circulation distinctive to estuaries, as well as the small relative difference in the force of ebb and flood tides. The landward flood tide carrying particles from the sea reaches its peak at high slack tide as it pauses before returning to the ocean. The stillness of the slack water allows more particles to settle. The return ebb tide tends to be slightly less forceful, resulting in a heavy accumulation of sediments within the estuary.

Another important aspect of sediment formation is internal redistribution and movement. Existing sediment particles can become resuspended into the overlying water by a variety of processes. The force of the water moving over the surface of the sediment, if great enough, can resuspend particles. These forces can vary daily with the tidal cycle, with weather changes, with seasons, and with longer term cycles. A major storm or flood can have a drastic long-term effect on the resuspension and formation of sediments. Also, the microbes and animals living in the sediments affect the ease with which sediments can become resuspended. The pervasive activity of tiny bacteria in the sediment leads to the formation of slime material which binds the sediment particles, making them resistant to resuspension. Similarly, animals living in the sediments ingest sediment particles and excrete them, glued together as fecal pellets. Other animal activity such as burrowing may have the opposite effect by enhancing the release of particles to the overlying water.

As its name suggests, sediment is derived from a constant rain of particles from the overlying water. Larger particles, such as sand grains, fall out faster than the smaller clays and silts. The rate at which the particles fall out from their water-suspended state depends not only on their size but also on the velocity of the moving water. The faster the water flow, whether by stream flow, tidal flow, or wind-driven movement, the longer the particles remain suspended in the water. The ultimate outcome of this process is the sorting of sediments by particle size. For example, in fast moving shallow channels the sediments tend to be sandy or even bedrock. In quiescent deep holes, on the other hand, the overlying water becomes still enough to allow the deposition of fine muds, often laden with pollutants.

This process of particle sedimentation is also affected by the chemical nature of the particles and surrounding water. One example of considerable importance to Boston Harbor is the effect of organic matter. The large amounts of sewage-derived organic matter dumped into Boston Harbor accelerates the deposition of suspended sediments[3]. As the organic matter sticks to individual suspended particles, it acts in a manner analogous to a glazing of glue, resulting in the agglomeration of several particles which will drop to the bottom faster than the individual particles. Therefore, the organic matter added to the ecosystem from sewage causes particles laden with pollutants to sink rather than escape the system in the tidal flow. The relative importance of different processes affecting sedimentation in Boston Harbor is still being investigated. However, the consensus view of several studies is that the major source of organic matter in Boston Harbor sediments is sewage[3,6].

A detailed knowledge of particle interaction and water circulation patterns, freshwater input from streams, runoff, and outfalls, is necessary to predictions of where particles are likely to end up. Such an analysis is vital to rational planning for decisions such as dredging for deepening shipping channels or constructing a new Harbor tunnel, and deciding where to place new sewage outfall pipes.

SEDIMENT BIOLOGY

The benthos (from the Greek for deep). If you stroll along a beach below the high tide mark, or explore a mudflat at low tide, you will quickly realize that the sand or mud underfoot is alive! Innumerable small holes reveal the subsurface dwellings of clams and worms. On a mudflat, piles of tiny round or cylindrical castings are the remains of the worms' feeding activities. The mud is crisscrossed with the long, winding trails of munching snails; while crabs and their smaller cousins, the bug-like amphipods, scurry and hop across the flat in search of food. At times, the mud is gilded with the golden-brown sheen of diatoms - microscopic plants which migrate to the surface, where they absorb the sunlight necessary for photosynthesis. This complex community of bottom-dwelling plants and animals is called the **benthos**, or **benthic community**.

The benthic community includes not only those creatures that are revealed to us at low tide, but also those that are permanently submerged below the low tide line. The floor of the entire World Ocean, from the edge of the sea to the deepest bottom trench; from the tropics to the coldest parts of the Arctic, is teeming with life! Some important causes of species' distribution and abundance in the benthos are: type of sediment (clay, silt, sand, gravel, or rock), climate and local temperature, salinity, available nutrients, currents and tides, as well as biological interactions. A burrowing worm cannot live on a rock, while a barnacle has to cement itself to a solid surface.

One benthic environment that typically supports a very diverse group of organisms is soft-bottom sediment. The most noticeable soft-bottom dwellers are large animals like lobsters, crabs, sea urchins and snails that inhabit the surface of sediments: the **epifauna**. The epifauna can move around to find food, or escape enemies and adverse environmental conditions. But benthic communities include much more than these surface-dwellers. An upturned shovelful of mud or sand will expose a multitude of creatures, the **infauna**, who make their homes within the sediment. Many of these animals are beautiful and exotic, like the **polychaete** (many-bristled) worm Pectinaria, the "ice-cream cone worm", builder of an exquisite conical tube of perfectly-fitted sand grains, and the tiny jewel-like clam Gemma; while others like the quahog and the soft-shelled clam are prized by people for food. Infauna and epifauna that are visible to the naked eye (bigger than 0.3 millimeter - the size of a sandgrain) are called the **macrofauna**. The macrofauna are far outnumbered by a poorly-described group, animals so small that they live between sand grains: the interstitial fauna or **meiofauna**. The meiofauna are comprised mostly of tiny worms, **nematodes**, and minute shrimp-like creatures, **harpacticoid copepods**, and larvae of other species. Smaller in size than the meiofauna are the **microfauna**, mostly **protozoans**: single-

celled organisms. Tiniest of all are the **microorganisms**, including **bacteria** and **fungi** (yeast and mold-like organisms). Microorganisms make up for their small size by their enormous numbers: a thimbleful of bottom mud contains over a billion bacteria. In the benthos, all these forms of life live together in an interdependent way: they modify their environment and their interactions can promote or inhibit the survival of various species in the community. The benthos is a complex web of life, and the make-up of the community depends both upon the physical environment and biological interactions[4].

What are these relationships, and what do these plants, animals, and microbes of the soft-bottom benthos actually do in their muddy environment? Like those of us who live on dry land, bottom-dwellers need a suitable place to live, and energy and nutrients to live and grow.

Sediment as home: physical factors. The kinds of organisms found in a given benthic environment depend in part on the nature of the sediment: whether muddy, sandy or gravely, or rich or poor in organic nutrients. For example, fine-grained sediments like muds often have poor water circulation and lower amounts of oxygen. Having less room between sediment grains, they support fewer interstitial fauna. Muddy, silty sediments are easily stirred up and resuspended in the water column, and therefore are unfavorable environments for **suspension-feeding** animals. Such animals, like bivalve mollusks (including quahogs and soft-shelled clams) and some **amphipods**, tiny crustaceans like the beach flea, feed by straining water through filtering devices, catching particles on mucal nets or in gills. The feeding apparatus of suspension feeders gets clogged up in muddy waters. Other organisms are adapted to a muddy environments: the **deposit feeders**. Many burrowing polychaete worms and snails belong to this group. The worms ingest the mud, digesting any usable nutrients in the mud, and defecate the indigestible sediment grains. Some deposit feeders, like snails, graze on the mud, selectively eating microalgae or stripping bacteria off sediment particles. Generally, as the sediment becomes more sandy, the percentage of suspension-feeders increases; and as the silt-clay proportion increases, more deposit-feeders are found[4].

Sunlight: the source of energy. For the benthos, as for terrestrial life, the ultimate source of energy is the sun, harnessed by plants through photosynthesis. In the marine environment, tiny one-celled plants (**microalgae**) floating in the water, the **phytoplankton**, carry out most photosynthesis. **Benthic diatoms**, types of microalgae that grow on the sediment surface, are a major source of food to the other inhabitants of shallow waters. The seaweeds like kelp (**macroalgae**) can also be an important food source where they grow. Like all plants, their growth depends on the amount of sunlight and fertilizer (nitrogen and phosphorus); the latter an important ingredient of sewage.

Phytoplankton are grazed by tiny animals floating in the water, the **zooplankton**. These zooplankton are **primary consumers**. They in turn are eaten by animals like fish fry and jellyfish. In relatively shallow water, dead phytoplankton and zooplankton can settle out to the bottom; but the primary contribution of phytoplankton as a food resource for the benthos is in the form of fecal pellets produced by the zooplankton. The fecal pellets sink rapidly to the bottom, where they can be consumed directly by benthic animals or decomposed by bacteria. The bacteria themselves are eaten by benthic animals.

Bacteria: the chemists of sediments. Microorganisms, particularly the bacteria, are a food source; but they have other critical roles in the benthos. Bacteria decompose the organic material that arrives on the bottom, converting the organic matter to carbon dioxide. Bacterial metabolism is important in the chemistry of sediments, and has great effect on the amount of oxygen in the sediments. The "sulfur cycle" is particularly important in marine sediments. Sulfates are abundant in seawater, and are also derived from the proteins of dead plants and animals. Some **anaerobic** (organisms that do not use oxygen) bacteria convert this sulfate to hydrogen sulfide. This poisonous gas produces the characteristic "rotten egg" smell of marine sediments at low tide and black color of the lower layers of marine sediments. Many **aerobic** (oxygen-respiring) faunal species cannot

live in this black, sulfide-rich zone unless they have some means of obtaining oxygenated water, such as a tube reaching above.

Bacteria also control the recycling of other important nutrients, like nitrogen and phosphorous from seawater and dead organic matter.

The amount of oxygen available in sediments is related to bacterial activity and the amount of organic material in the sediments. Normal sediments have easily discernable layers: a lighter brownish-gray oxygenated surface layer overlying a black, anaerobic layer. The depth of the oxidized layer depends on the type of sediment (porous sediment having a thicker oxygenated layer), and the amount of organic material available. Aerobic bacteria use up oxygen when they decompose organic matter. If the amount of organic matter is overabundant, all the oxygen can be rapidly depleted by bacteria, making the sediment totally anaerobic and black, even at the normally oxidized surface layer. This kind of anaerobic environment is inhospitable to most benthic animals.

Biological interactions in the benthos. So far, we have touched on some of the physical factors, like sediment type, and some biological processes like primary production, nutrient cycling and decomposition that can influence the composition of the benthic community. But biological interactions among the inhabitants of the benthos are equally important. As on dry land, the animals of the benthos modify their environment as they make their homes, feed, excrete, and reproduce. Benthic animals compete for resources, both with their own species and with other species. Predator-prey interactions are also important in determining the **community structure**, or what kinds of animals, coexist in a given environment.

One important ecological interaction is **competition**. Species compete for food and for space to live. For example, if two species require the same limited food resource, and one of those species can exploit the resource more efficiently, that species can exclude the other.

Diversity, the number of species in a community, can be influenced by **predation**. Predators, like crabs, fish, and some worms catch and eat other animals. Predation can decrease the density of prey animals, and alleviate competition among the prey for food resources. This alleviation of competition can permit more species to coexist in a given environment.

An important example of biological activity in the benthos is **bioturbation**. Animals that live in tubes extending deep into the bottom or that burrow around in the sediment alter their environment by 1) bringing oxygenated water deep into the sediment and 2) constantly "reworking" the sediments, bringing sediment from below to the surface, and vice-versa. a deeper oxygenated layer permits other animals to live below the surface, and increases the area of sediment subject to aerobic microbial activity and decomposition. More nutrients are thereby mobilized and made available to the ecosystem. Similarly, when deeper sediments are brought to the sediment surface, previously buried nutrients can be used by the surface creatures.

Bottom-dwellers live in a complex spatial and temporal mosaic. For example, it is common to find a dense patch of tube-dwelling worms. This patch of worms may interact with other species in different ways: 1) by taking up space, prevent the settlement of larvae of other species; 2) be eaten by predators, or die, creating new space for colonizers 3) actually facilitate the colonization of other species by stabilizing the mud.

BOSTON HARBOR SEDIMENTS

Boston Harbor sediments. Boston Harbor as with all New England coastal zones, is a relatively young geographical formation, born 12,000 to 14,000 years ago with the end of the last ice age. Since that time, sediments have been gradually accumulating. Through analysis of buried layers, it may be possible to reconstruct the climate and vegetation history of the area, the rates of normal deposition, historical rates of pollutant input, and

the effect of increasing pollution load. Because the sediments of Boston Harbor accumulate with time, they retain a physical diary of past events; each lower layer a record of an earlier time. This history is not always complete since storms can wash away records or sediment-burrowing animals can mix the records up. Still, in relatively undisturbed sediments, it is possible to analyze chemicals or the remains previous life (such as pollen) to reconstruct the history of deposition in the harbor. A relevant example is the work of Michael Fitzgerald[5]. He showed that the sediment records in Deer Island Flats, near Logan Airport, display an elevation in toxic metals corresponding to the point in time, 1936, when Shirley Gut was closed. Shirley Gut was a connection of Boston Harbor to Massachusetts Bay between Winthrop and Deer Island. Clearly, the closing of Shirley Gut altered the pattern of water circulation and resulted in the accumulation of metal-laden suspended particles in an area, Deer Island Flats, which was not impacted prior to the human intervention in the flow of water.

The bottom of Boston Harbor is a mosaic of differing patches of sediment types, ranging from muds composed of fine clays and silt to sandy bottoms to rock outcroppings. Some sediments are relatively uniform in size, for example, the Boston blue clay layer which was laid down soon after the last glaciers receded to the North thousands of years ago. However, variable mixtures of sizes are more typical. Sampling of Boston Harbor has revealed this great variability in sediments, but until now a detailed map, vital for understanding the processes working in the Harbor, has not been available. However, scientists from the U.S. Geological Survey are currently preparing such a map. As will be discussed below, a detailed map of the bottom type provides important evidence of how the bottom is formed, what forces are at play, what are the sources of particles and pollutants to the Harbor, and ultimately aiding in deciding what may be the best strategies to manage the Harbor.

Pollution in Boston Harbor sediments. Just as Boston Harbor is a trap for sediments, the sediments in turn act to trap many pollutants. The fine-grained clays and silts with their coats of organic matter, in particular, actively collect pollutants from surrounding water and concentrate them in the sediments. For example, at Deer Island Flats next to Logan Airport, where the water circulation patterns are complex, there are enclaves where gyres, or circular patterns, and slow water movement allow buildup of fine sediments - "pockets of pollution"[5]. In contrast, the bottom directly adjacent to the Deer Island outfalls has much lower amounts of fine particles and pollution because of the scouring action of the swift-moving currents in the relatively narrow channel. The pollutants of concern which display this proclivity to bind to fine sediments and suspended particles have become household names in the past 20 years: pesticides such as DDT, herbicides such as 2,4-D, products of combustion such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), oil, grease, gasoline, and toxic metals such as cadmium, lead, zinc, chromium, tin, copper, and mercury. These toxins originate from human activity, both domestic and industrial. They enter Boston Harbor in many ways; from sewage outfalls, sludge pipes, combined storm outlets, land runoff, streams feeding the Harbor, leaching of dump sites, and atmospheric fallout.

In the case of Boston Harbor, the relative contribution of each source to the total load of pollutants entering the Harbor is not well known. Establishing the relative importance of these sources is vital for abating pollution in the Harbor. The sewage treatment plant outfalls certainly contribute a significant amount of pollution, but how important are other sources? For example, scientists suspect that most lead in the Harbor arises from automobile exhaust and falls out from the atmosphere.

The pollutant load in Boston Harbor is egregiously high. Sediment pollutant analyses have been performed. Unfortunately, most sediment analyses have been conducted in an ad hoc manner by independent groups in order to address the environmental impact of specific local construction projects. This has resulted in a very fragmentary understanding of the extent and distribution of various pollutants. The story is incomplete for other reasons. Much of the existing data is old and was gathered by outdated and inaccurate techniques. The monitoring efforts have not been coordinated

among various groups to yield data useful beyond the narrow scope of the impact assessment. In spite of these limitations, the knowledge that we have supports the preliminary "most polluted harbor in the United States" report of NOAA.[9] A more comprehensive survey of PAHs in Boston Harbor sediments, for example[9], indicates gross contamination of Inner Harbor and Moon Island sediments, with levels as high as any reported in the scientific literature, even Tokyo Bay, Japan. The implications of high PAH contamination are ominous. Many PAHs are carcinogenic, and their high concentrations may help explain the high incidence of tumors in the flounders caught in the Harbor[7].

Ecology of sediments in Boston Harbor. A variety of habitats and biological communities are found in Boston Harbor. Saltmarshes (Belle Isle Marsh, the Neponset River marsh, on Thompson Island and in Hingham Harbor), are net exporters of nutrients, play an important role in fish reproduction, and are sanctuaries for many animal species. Hard or rocky bottom environments (the Graves, the Brewsters, even pilings) are home to starfish, barnacles, and mussels. But the most extensive and important habitat in the Harbor is soft-bottom sediment. Acres of mudflats, from Bird Island flats near the airport, to mudflats along the Neponset River, besides receiving the brunt of pollution also support shellfish, worms, benthic diatoms, and often shore birds. Beneath the low tide line, the species found include predominantly worms, bivalve mollusks, and some small crustaceans. Kelp beds grow in the deeper waters of the Harbor, grazed upon by sea urchins. Bottom-feeding fish eat these various benthic species.

In Boston Harbor, where the waters are quite shallow, there is a very close coupling between processes in the benthos and the water above, or water column. Dead plankton, as well as fecal pellets, reach the bottom quickly; while sediments stirred up by bioturbation, and invertebrates fed upon by fish make their contribution to the overlying water.

Effect of pollution on life in the Harbor: community structure. The pollution entering the harbor ecosystem is of a dual nature: the first is outright toxicity, from chemical poisons, (including the chlorine used in sewage treatment);and the second is "nutrient loading", mostly from domestic sewage. This includes a large input of carbon, nitrogen, phosphorous and sulfur; important nutrients for natural communities.

In the same manner as organic-coated sediment particles absorb toxic pollutants, phytoplankton and zooplankton also concentrate pollutants from the water. The pollutants make their way to the bottom packaged in fecal pellets after being digested by the small animals.

Toxic contaminants affect some species more than others. Often one of the most immediate effects of toxics on the benthic community is on predators: many predators are very sensitive to toxic effects, and are either killed off or leave. If a **keystone predator** is removed, the remaining animals increase in density, and compete more directly for food or space resources. This leads to reduced diversity of the prey species and disintegration of the community. Many parts of the Boston Harbor benthos, particularly large areas of the Inner Harbor, are now almost exclusively composed of a classical "pollution indicator" organism, the worm Capitella. A study done correlating levels of metals in Harbor sediments with benthic species diversity showed that decreased benthic diversity corresponded to increased concentrations of metals[5]. The decline of benthic diversity affects non-benthic organisms as well. For example, fish with specialized diets, feeding on only certain components of the benthos, may be left without food resources.

Acute toxicity and death of animals are not the only effects of pollution. More subtle, long-term effects have been observed in a variety of aquatic environments. Genetic deformities, impaired reproduction and development, reduced growth, and cancer-like diseases (neoplasias) have been documented in worms and shellfish in Oregon, Chesapeake Bay, and Maine[11]. In Boston Harbor, the bottom-dwelling winter flounder shows a high prevalence of fin rot and liver cancer[7]. This may be related to the high levels of aromatic hydrocarbons, or to a combination of the many pollutant insults; however, the exact components of pollution responsible for chronic ailments in Boston Harbor are complex scientific questions and as yet unknown.

Nutrient loading of sediments from domestic sewage can also have a devastating effect on the benthos. In Boston Harbor, an enormous proportion of the organic matter comes from sewage, not just algal photosynthesis. This excess production can have the effect of **eutrophication**, a process which leads to depletion of available oxygen by bacteria metabolizing the copious organic matter. This results in anaerobic sediment, essentially devoid of higher life. Another effect that the input of excess nutrients has is to favor only a limited number of benthic species, pollution-tolerant animals, who outcompete the normal diverse residents.

Interactions between sediment contaminants and benthic organisms. The sediment is often thought of as a "sink" for nutrients and pollutants, where they are buried and taken out of circulation. However, benthic animals interact with contaminants in sediments in a number of ways which result in the transfer of contaminants to other components of the ecosystem. Benthic organisms can **bioaccumulate** pollutants by ingesting the sediment. These contaminants are transferred up the food chain when contaminated benthic organisms are eaten. This can result in **biomagnification** effects, where animals higher up in the food chain develop higher concentrations of the pollutant in their tissues. (The increased mortality of eagles and hawks caused by DDT is an example of biomagnification. The DDT was not excreted by the birds that consumed it in their prey, but accumulated in fatty tissue, where the chemical interfered with egg shell formation.) Benthic organisms move in and out of contaminated sediments, redistributing the pollutants. Benthic invertebrates can metabolize, or **biodegrade** contaminants. This process is beneficial for the environment if it leads to the removal of the pollutant, but and unfortunately for the victim, metabolism of many organic pollutants by higher animals often converts relatively inert chemicals into potent cancer-causing agents. The stirring up and reworking of the sediments by burrowing worms and bivalve mollusks is another important way contaminants can be reintroduced into the overlying water column.

Bacteria play an important role in mobilizing pollutants. Metals, like mercury and tin are **methylated** by bacteria, a process which changes the chemical structure of the metal by adding an organic ingredient to the metal. In their methylated form, metals are more toxic and more easily absorbed by organisms, increasing their transfer up the food chain and biomagnification.

One paradoxical effect can be anticipated in Boston Harbor. As pollution abatement gets underway, the nutrient loading of the sediments will decrease, oxygenation will increase, augmenting bioturbation. This may actually result in temporarily increased levels of contaminants in the water, as animals exacerbate the release of contaminants now bound up in the sediments.

Public health effects. Humans are consumers at the top of the food chain, most susceptible to the effects of biomagnification of toxics. Studies in other environments, for example the Great Lakes, have shown that people who eat large amounts of fish have elevated PCB levels in their tissues. No studies have been done on consumers of Boston Harbor fish or shellfish.

We have known for centuries that sewage carries infectious diseases. Public health agencies have long made efforts to monitor sewage-impacted waters. Swimming beaches and shellfish beds are classified as safe or unusable on the basis of **coliform** (bacteria normally found in mammalian intestines) counts in the waters. (These subjects were treated in Cleanup Action Network Reports I and II.) Scientific studies show much greater numbers of disease-causing organisms and their indicators in sediments than the overlying waters. This is because bacteria accumulate in, and are protected by, sediments. One study in a Boston Harbor sediment showed 10,000-fold higher numbers of coliforms in the sediment than the water[10]. Polluted sediments are known to be a reservoir of disease-causing microbes.

Sediments accumulate toxic materials. Boston Harbor beachgoers, especially small children, who play in the sand and mud, stir up the bottom, and swallow more seawater than do adults, put themselves in direct contact with all the accumulated toxic materials

discharged by the sewer system of a major metropolitan area. It is known that some organic contaminants can be absorbed through the skin, but the health risk of bathing at Boston Harbor beaches has not been studied.

Finally, aesthetic concerns in the pollution of Harbor sediments are of great importance, as attempts are made to reclaim this resource. It would be difficult to overestimate how valuable it would be, both to the mental health of the citizens, and the attractiveness of the city to business, to have an accessible, well used, aesthetically pleasing waterfront.

Dredging. Dredging, the process of digging up sediments and moving them elsewhere, has a major impact on sediment processes and distribution. Dredging is necessary for maintaining shipping channels, marinas, ports, and recreation areas. Major waterfront construction projects also require massive dredging operations. The need for dredging in Boston Harbor is clear: Boston Harbor is the largest seaport in New England, handling over $2 billion in foreign trade annually (Task Force, CZM). Already, several major dredging projects have been planned for the next 15 years. An estimated 7.7 million cubic yards of material will be removed for disposal in the open ocean; however, up to 10% of the dredged sediments, called dredge spoil, may not pass the EPA's pollution standards for open ocean disposal[1].

Dredging may have severe impacts on the adjacent area. The major impact is due to the extensive resuspension of sediment particles clouding the water (turbidity). While turbidity may be fairly local, the finer grain clays and silts which do not settle very quickly can travel far, often miles, from the source. In the turbid area, the resulting blockage of light may inhibit algae and plants which are a major food source of estuarine animals. The resuspended and settling particles may also alter the habitat of many benthic animals by a variety of mechanisms. Outright dislocation and burial of animals is the most obvious mechanism. Less obvious but important impacts of dredging on benthic animals include impaired breathing and feeding, disruption and clogging of gills, and retarded egg development. Of course, if the particles are heavily contaminated, the pollutants will be transported downstream by currents and partially released to the overlying water.

CAN WE CLEAN BOSTON'S SEDIMENTS?

Clean-up. The public interest (and the requirement of the federal Clean Water Act) is to restore Boston Harbor to a healthy state conducive to fishing, shellfishing, boating, and swimming. The impending effort is to expand and improve the sewage treatment process and thereby reduce the amount of sewage entering Boston Harbor. This will clearly slow down or halt further deterioration of the Harbor, but will cessation of sewage dumping be adequate to restore the Harbor to a "clean" condition? Unfortunately, even if all the sources of pollution to Boston Harbor were abated, the Harbor would take decades to recover. The sediments themselves would become the major source of pollution to the overlying waters, although the rate at which individual contaminants might be released again to the water is conjectural.

There are natural or "self-cleaning" processes that work to lower the contamination levels in surface sediments; including 1) tidal action which continually fills and replaces the overlying waters, and 2) bioturbation, but many pollutants resist microbial attack and bind tightly to sediment particles. Therefore sediment-bound pollutants will be removed by tides or bioturbation slowly. The toxic metals, for example, cannot be removed from the Harbor by microbial activities. So without human intervention other than halting sewage dumping, the decades-long burial and dilution of contaminated sediment by fresh clean sediment particles will greatly outweigh removal by tides and microbial decomposition.

Perhaps we could take advantage of clean-up or remediation technologies to hasten the recovery of Boston Harbor. For example, the most contaminated sediments could be relocated to deep ocean sites or landfills. Effective but exorbitant technologies can

detoxify the sediments by passing them through special furnaces. Other options are to sequester the contaminated sediments by covering them with clean sediment or impervious liners or to plow the sediments to stimulate microbial degradation of the pollutants.

In extensive areas, such as Boston Harbor, remedial action may not be a reasonable alternative. It may be better to leave sediments in place and let natural mechanisms take their course. However, if "hot spots" which contain levels of pollutants that are a continuing threat to the harbor resources are identified, some remedial action may be required. The choices are many and they are costly but a detailed knowledge of the pollution[11] must be established first. Therefore, the problems unique to Boston Harbor must be identified and assessed. Only then can one decide if remedial action is warranted, which options are reasonable, and which options are cost-effective for Boston Harbor. As we have discussed previously, not enough information exists on Boston Harbor pollution to adequately identify the problem areas.

Recommendations. This review of Boston Harbor stresses the need for understanding the source of sediments, how they move about, how they transfer nutrients and pollutants to the overlying water, their effects on the plants and animals, and what steps to take to eventually cleanse them of pollutants. We recommend a comprehensive research program to develop a more complete understanding of the Boston Harbor ecosystem.

The National Research Council (NRC) in 1983 addressed the problem of coastal and estuarine pollution[8]. Their primary message was the need for an interdisciplinary approach, involving biologists, chemists, physicists, and mathematical modelers among other experts, to fill in the gaps in our knowledge. The NRC stressed the need for basic knowledge in three key areas: 1) the effect of pollutants on plants, animals, and microorganisms, 2) an understanding of water circulation and mixing in estuaries, and 3) the dynamics of suspended particles and dissolved matter in the overlying water.

Successful integrated studies of physical and biological environments of other urban estuaries, for example San Francisco Bay and the Chesapeake Bay, have been carried out. When the perennial questions and ensuing decisions regarding Boston Harbor arise, decision-makers often lack scientific knowledge. Instead of regulatory decisions based on scientific understanding providing rational options, decisions are often made for politically expedient reasons.

We recommend that a systematic, interdisciplinary scientific study of Boston Harbor be initiated. As a first approach, all the scientific knowledge which has accumulated piecemeal over the years should be collected, centralized, and examined critically to glean out the useful information. Simultaneously, a collection of basic information which is fundamental to describing the Harbor should be garnered by coordinated research and a rigorous monitoring effort. The monitoring is most important to ensure that the abatement efforts are effective. This information should be useful to developing a model of Boston Harbor processes. Predictive models are useful to regulatory agencies in estimating the potential effects of alternative actions on the Harbor. Models can be used to test the outcomes of different management strategies with the best available knowledge.

This research effort should be long-term, gradually encompassing other needs and questions. For example, how long do different pollutants stay in Boston Harbor sediments, how do they affect animal life, and what environmental factors affect the fate and removal of pollutants? A summary of the pressing scientific needs is given below. The result of such a plan would be an increasingly refined understanding of how Boston Harbor works. In the long run a comprehensive study would be cost-effective, saving the taxpayers of the Commonwealth the large cost of taking actions after the damage has become even more unwieldy. For example, a pressing issue now is where should the sewage effluent pipe be located? If a basic understanding of the Boston Harbor ecosystem existed as outlined below, it would provide clear answers to most of the scientific questions that cannot be answered with any good degree of certainty now. For example, how much of the material would return to the Harbor? What effect would the effluent have on the natural resources at the pipe or a given distance away from the pipe? Other issues that would

benefit from a solid understanding of the Harbor include the effectiveness of sewage treatment options, the disposal of dredge spoils, the Fan Pier project, the third harbor tunnel project, and other future development projects on the Boston Harbor shoreline.

The most important result of a comprehensive understanding of Boston Harbor would be the accelerated reversal of pollution and degradation of this important aesthetic, recreational, and economic resource.

Among the most important scientific issues that should be addressed immediately for Boston Harbor, Massachusetts. are the need to:

1. Determine the complex circulation patterns in Boston Harbor and Massachusetts Bay.
2. Determine the exchange of water, nutrients, and pollutants between Boston Harbor and Massachusetts Bay.
3. Develop a model to explain and predict circulation in Boston Harbor and Massachusetts Bay.
4. Describe in detail the pollutants (chemicals and disease-causing agents) in the water and sediments, their distribution, and their primary sources to the Harbor.
5. Determine the fate of these pollutants and disease-causing agents in Boston Harbor, and what factors are most important in their removal from the Harbor.
6. Determine how sediments are redistributed as a result of tidal currents and episodic storms, and identify the processes which control this movement.
7. Analyze in detail the plants and animals in Boston Harbor to determine types, numbers, seasonality, and distribution within the Harbor.
8. Develop an understanding of how the different plant and animal species interact with each other and with the variations in circulation and chemistry.
9. Establish long-term research goals to consider how natural stresses and pollution affect those interactions and the general structure and function of the Boston Harbor ecosystem.
10. Initiate a well-planned monitoring effort to follow the progress and effects of implemented managerial programs.

Again, we emphasize that the strength of this proposed study would be in its coordinated and interdisciplinary form. This is in direct contrast to the hodgepodge and ad hoc nature of the studies conducted to date.

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