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A major effort, costing in the neighborhood of $2 billion, is under way to restore the environmental quality of Boston Harbor. While Boston Harbor is unquestionably one of the most polluted urban estuaries in the world, it is also one of the least understood with respect to the basic physics, chemistry, and biology involved. This information is essential for the purpose of identifying processes that control the transport, effect, and fate of contaminants entering the estuary. Failure to obtain this information may lead to continued inappropriate and unnecessarily expensive solutions to a complex environmental problem. An effective solution will require commitment to a substantial multidisciplinary research effort to supply the necessary comprehensive data base on the harbor and adjacent environments of Massachusetts and Cape Cod bays. Only then can intelligent, informed decisions be made to assure restoration and maintenance of the environmental quality of our coastal waters. Development of a well-informed and vocal citizens' action group may be a critical step in the achievement of this goal.

Boston Harbor is one of the most beautiful urban estuaries in the continental United States. Carved out by glaciers some ten thousand years ago, it still retains the basic characteristics that we find most desirable in our coastal waters: safe refuge for both large and small vessels; sheltered coves; beautiful and surprisingly remote islands; a variety of shorelines, ranging from sandy beaches to rugged, rocky foreshore; and abundant fish and shellfish that support both commercial and recreational fisheries.

A History of Abuse

Boston Harbor is also among the most battered and abused water bodies in the world. Levels of contaminants in its sediments and in its water equal or exceed

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those of the most polluted estuaries of the world. The history of abuse leading to this condition extends back well into the past century and beyond. The presence of Boston—New England's premier "city by the sea"—has exacted a severe toll on this great resource. A portion of this destruction it will never recover from—such as the loss of over 50 percent of the wetlands in the inner part of the harbor to accommodate large sections of Boston's expansion and growth.

More recent insults are the growing input of contaminants in the harbor, which has paralleled the growth of Boston and her neighboring communities, and an incredible lack of environmental awareness and concern on the part of the local citizenry. The combination of these factors has produced what is generally recognized as an international disgrace, especially for one of the most advanced nations in the world. Only now, as the result of pressure from active conservation groups, such as the Conservation Law Foundation, and from the courts, former judge Paul Garrity, and a dynamic EPA Region I administrator, Michael Deland, are steps being taken to begin the reclamation of Boston Harbor. It will be a long, painful, and very expensive process, and it is taking place in an almost total absence of scientific understanding of the harbor and its adjacent waters, Massachusetts and Cape Cod bays.

The Price of Ignorance

In the text that follows I hope to establish an awareness that the absence of scientific knowledge regarding the issue at hand raises significant questions concerning the reclamation and future of the harbor and the future of Massachusetts and Cape Cod bays. I write this article from the perspective of a scientist working in the area of marine science and, more specifically, as one who is actively conducting research concerning the transport, fate, and biological effects of metals in marine waters. This area of research represents but a small fraction of current efforts to determine the sensitivity of oceanic and coastal environments to anthropogenic (man-made) influence. The need for information from such studies is becoming even greater as man's ability to affect environmental conditions grows.

Most researchers working in the environmental sciences quickly learn that they must be aware of and consider many different processes when attempting to solve environmental problems. The solution to most such problems must address important variables in the fields of biology, physics, and chemistry which influence the phenomenon under scrutiny. Failure to do so may lead to improper interpretation of results and therefore to erroneous conclusions. In short, most environmental questions are inherently complex, requiring a multidisciplinary approach for their solution.

The Scientist and the Manager

And therein lies another problem. In general, scientists are conservative in their judgment as to when a given problem has been "solved." Invariably, in the conduct of scientific research, the solution to one question raises additional questions. Given his inquisitive nature, the practicing scientist finds this aspect of his work extremely rewarding, but to those who wish to apply the solution to existing problems, it is immensely frustrating. The manager who needs to translate

research results into action in order to solve a given environmental problem is often working under a time constraint. He or she is frequently viewed as more than willing to sacrifice thoroughness of knowledge for the sake of meeting deadlines. The scientist, on the other hand, is often perceived as wishing to prolong support of his or her own research interests beyond what is required to "satisfactorily" answer the question posed and, as a result, is thought not to be genuinely concerned about the needs of the manager.

There is some truth in both these views. The trouble is that this mutual distrust results in a reluctance on the part of both the manager and the academic scientist to work with the other, and it is only through their cooperation that state-of-the-art techniques can be brought to bear upon important environmental problems. The lack of a working partnership leads to less than satisfactory resolution of environmental problems and, ultimately, to the application of remedial action which, in many cases, is extremely expensive to implement. Recent and current activities aimed at improving the environmental quality of Boston Harbor serve to demonstrate these unhappy consequences.

Boston Harbor/Massachusetts Bay, A Worst Case Scenario

I know of no other major estuary adjacent to a large U.S. population center of which so little is understood in terms of the system's basic physics, chemistry, and biology. Perhaps there are two principal reasons for this lack of understanding. The first is a general tendency for marine scientists to focus on globally important phenomena rather than on coastal marine problems. Certainly this is reflected in the objectives of the major funding agencies that supply most of the monies for research in the marine environment. Second, those estuaries and adjacent coastal waters that do enjoy a more comprehensive data base are in proximity to academic institutions with active marine research programs. For example, Narragansett Bay benefits from the presence of the University of Rhode Island's Graduate School of Oceanography; Buzzards Bay, from the Woods Hole Oceanographic Institution; Long Island Sound, from the marine programs at the University of Connecticut and Yale University; Delaware Bay, from the University of Delaware's College of Marine Studies; Chesapeake Bay, from the University of Maryland's Chesapeake Biological and Horn Point laboratories; and so on. The list of such associations continues around the coastal regions of the country.

I do not mean to imply that there have been no studies made of Boston Harbor. On the contrary, there have been many, dealing with various aspects of the harbor and costing millions of dollars. But most of them have been site specific and have dealt with such activities as dredging and construction; they are not of the nature required to develop an overall, comprehensive working knowledge of the harbor—one that is capable of supporting intelligent management decisions now and in the future. The recent development of Boston's 301(h) application for a waiver from the Clean Water Act's requirement that all communities adopt secondary sewage treatment is a good example of the inadequacy of such studies.[1]

Boston's 301(h) Waiver Application

A waiver from the Clean Water Act's mandated requirement for secondary treat-

ment of sewage can be granted to coastal communities provided they can demonstrate a lack of significant environmental impact on the ecosystem receiving the primary treated wastes.[2] Specific criteria are to be met in this regard, and the applicant is required to furnish evidence that existing or future discharges will meet such criteria. The Boston 301(h) waiver application was an expensive, narrowly focused information-gathering exercise that realistically could not have been expected to provide the comprehensive understanding needed to support long-term management strategy for the harbor and adjacent bays. Such knowledge cannot be amassed on short notice to expedite a particular project, no matter how important or urgent the project may be.

Given that extensive knowledge of the harbor/bay ecosystem had not already been secured, it was impossible to judge whether the criteria stated in the application had been met—for example, the requirement that the population of organisms living on the seafloor would not be significantly affected by the discharge of wastes.[3] Careful evaluation of naturally occurring changes in the native community structure of the bottom-dwelling organisms is required before changes due to pollutant stress can be determined. The work needed to perform this evaluation is time-consuming and expensive. Most municipalities have neither the expertise nor the willingness to support the effort needed to adequately define the balanced indigenous population. The effort made in this regard for the Boston waiver application fell short of providing a rigorous characterization of these communities for either Boston Harbor or Massachusetts Bay.

Environmental studies conducted in the harbor have been designed largely to meet specific regulatory or legal objectives. As a result, they generally fail to recognize the broader environmental consequences of the decisions they produce. Boston's 301(h) waiver application is an example of one of these studies. It did not consider the overall environmental consequences of the choice between primary and secondary treatment of its sewage. For instance, secondary treatment may well lower the input of contaminants to coastal waters but at the same time increase the risk that limited groundwater supplies will be contaminated (from land-filled secondary treatment sludge) and that there will be a deterioration of air quality (from incineration of sludge). In my opinion, we can no longer afford to maintain this myopic approach to problems that affect more than one segment of the environment. A recent decision by the EPA to tentatively deny a similar 301(h) waiver for the South Essex Sewerage District discharge was based largely on potential interference with recreational use of waters in the vicinity of the waste discharge.[4] Surely preservation of recreational water uses should not receive higher priority than increased human health risks posed by landfills or incineration of the toxin-laden sludge generated by most secondary plants.

It may be further argued from a scientific perspective that studies like the one conducted in preparation of the 301(h) waiver application inherently require comprehensive knowledge of the fundamental biological, physical, and chemical processes that may be affected by or that may affect contaminants released to coastal environments. For example, biological consequences of the contaminants include the inhibition of growth and reproduction and sometimes the death of organisms living in the vicinity of the waste discharge. Physical processes involve the circulation patterns that control the dispersion and transport of toxic substances away from the point of discharge of the waste. And chemical reactions

may occur that either enhance or decrease the toxicity of contaminants in the discharged waste. All these processes interact, making the accurate prediction of the effects of these contaminants difficult. The research necessary to produce such knowledge has been conducted for few if any such coastal areas in this country or, for that matter, in the world, largely because of the emphasis on expenditures for specific applied pieces of research that do not provide the perspective needed to adequately support critical management decisions. The study conducted for the Boston 301(h) waiver application is just one example of many such unsatisfactory expenditures. Indeed, the scientific community is probably better able to predict the consequences of waste disposal in open-ocean waters than in coastal waters, despite the more immediate relevance of the latter to human health and welfare.

Therefore, Boston's 301(h) waiver application, while attempting and often failing to meet specific requirements mandated by the law, also completely failed to generate the comprehensive picture required for future management decisions. The cost of this failure in dollar terms alone was and will continue to be immense: in excess of $2 million just for development of the waiver application and $2 billion plus worth of construction to clean up Boston Harbor.[5] Delays in the state's commitment to secondary treatment of its sewage while the waiver application was being prepared have resulted in the loss of hundreds of millions in federal cost-sharing dollars.[6] Costly errors in environmental decision making are likely to be repeated as long as there is a continued emphasis on narrowly defined, site-specific projects at the expense of an in-depth understanding of the basic issues involved.

Scientific Uncertainty

A brief description of the extent of current ignorance concerning the harbor and its adjacent bays is in order. The three primary areas of concern are biological, physical, and chemical processes.

Biological Processes

Boston Harbor supports an important recreational fishery (winter flounder) and commercial fishery (lobster and clams). Both are intimately coupled with and dependent on the production and growth of other members of the biological community, such as the primary and secondary producers. (Primary producers are plants that are capable of utilizing sunlight to produce organic matter. The organic matter of the plants may then be consumed by animals—the secondary producers—who in turn may be eaten by other animals, such as the fish and shellfish found in the harbor.) Disruption to any members that form a link in the harbor's "food chain" may substantially affect its other members. The dynamic linkage between various elements in this food chain has not been defined. Evidence gathered in the course of preparing the 301(h) waiver indicates that the bottom-dwelling communities in the harbor have been severely impacted. Winter flounder in Boston Harbor have one of the highest rates of cancer observed in any coastal fishery so far examined.[7]

Another increasingly common problem in estuarine and coastal waters is a phenomenon called eutrophication, which results from the addition of large

amounts of nutrients to natural waters. Nutrients essential to the growth of plants, such as inorganic nitrogen and phosphorous, are frequently present in high concentrations in primary and especially secondary treated sewage effluents. When excessive amounts of these nutrients are introduced into coastal waters, for example from the discharge of treated sewage effluents, higher than normal production of plant organic matter may result. Under some environmental conditions, the subsequent death and decay of the excess plant matter may lead to such a depletion of the water's oxygen that most forms of marine life cannot survive. The degree of eutrophication is dependent on a complex array of biological, physical, and chemical factors.

The extent to which eutrophication of the harbor and adjacent bays has already occurred or is now occurring has not been characterized. Low oxygen values have been observed both in the harbor and in Massachusetts Bay, but the information at hand is insufficient to establish the immediate causes of this condition.

Physical Processes

The extent to which we understand the physics of the harbor/bay system is crucial. Physical processes control the circulation patterns in the system and thus the rate at which the waters of the harbor are exchanged with those outside of it. These processes are therefore of major importance in the transport and ultimate distribution of contaminants released to the harbor's waters and in their eventual impact on the harbor and adjacent bay ecosystems. Assessment of the impact of waste disposal to such waters is obviously partly dependent on the extent of our knowledge in this regard.

Available information on the physics of the harbor is restricted to results of sporadic measurements of the temperature and freshwater content of harbor waters; evaluation of the mean tidal currents for navigational purposes; and several site-specific studies in the vicinity of existing and proposed major outfalls (the word *outfall* refers to the point at which a drain or pipe discharges wastes into a body of water). None of the results of these studies have appeared in the peer-reviewed scientific literature.[8] Measurements of the distribution of temperature, freshwater content, and velocity of harbor waters have been conducted neither frequently enough nor in enough locations to define how long water resides in the harbor (residence time) or to determine the physical circulation patterns of its water. Knowledge of both is required before the distribution and transport of contaminants in the harbor can be understood. For example, the concentration of a given pollutant in harbor waters depends in part on how long the water remains in the vicinity of a waste discharge. Clearly, a longer residence time will result in a higher concentration of contaminants in the water before it moves from the vicinity of the discharge. The residence time of water in different sections of the harbor can vary in order of magnitude, depending on a number of factors that have yet to be completely defined.

Several attempts have been made to develop mathematical models that describe the physical circulation of the waters in Boston Harbor and thus predict the dispersion of contaminants from the outfalls and combined sewer outfalls.[9] These include efforts by Hydroscience, Inc., in 1971 and 1973; EG&G in 1984; and M.I.T. in 1984 and 1985.[10] None of these models has been satisfactorily validated,

although work this year by R. F. Kossik, who compared the distribution of volatile organic compounds emanating from the Deer Island outfall with that predicted by the M.I.T. models, is a first step in the right direction.[11] Again, none of this work has been published in peer-reviewed journals.

Chemical Processes

Contaminant distributions within the harbor and adjacent bays have been only partially described. Sediment concentrations of metals are among the highest reported in the world's estuaries.[12] The limited data on organic contaminants, such as PAHs (polycyclic aromatic hydrocarbons) and PCBs (polychlorinated biphenyls), also establish Boston Harbor as one of the most grossly contaminated estuaries in the world.[13] The toxic properties of these inorganic and organic contaminants have been well established. These contaminants are also present in the sediments of Massachusetts Bay.[14] What we do not know is the exact nature of the sources of these contaminants, the mode of their transport, and their final fate and biological impact. For example, the degree to which contaminants released from the Deer Island and Nut Island outfalls are trapped in Boston Harbor sediments has not been adequately determined. M. G. Fitzgerald tentatively estimated that only about 3 percent of the input of selected metals to the harbor from the Deer Island and Nut Island plants is retained in harbor sediments.[15] If Fitzgerald's estimate is correct, the remaining 97 percent of the input has been transported to Massachusetts Bay and has therefore contributed to the contamination of its sediments. No such estimates are available for the retention of organic contaminants.

Concentrations of metals in the waters of Boston Harbor are ten to one hundred times higher than those expected in clean coastal seawater.[16] Concentrations of copper in the harbor frequently exceed current EPA water quality criteria. The distribution of this and other metals in harbor waters also indicates that sources other than the sewer outfalls may be of importance, especially in the Mystic and Chelsea rivers, where discharges from combined sewer outfalls may be most significant.

Sources of contaminants to Massachusetts Bay are even less well understood. Preliminary data obtained by Wallace and Gardner (in preparation) indicate that inputs from the Merrimack River and the atmosphere, not inputs from coastal waste discharges, are by far the most important sources of copper contamination in Massachusetts Bay. These sources may also be significant in the supply of organic contaminants to Massachusetts Bay waters and sediments.[17] Wallace and Gardner's data also suggest that metal concentrations in the water column of Massachusetts Bay may be two to three times higher than those of adjacent Gulf of Maine waters.

It is evident that the sources of contaminants to the harbor and Massachusetts and Cape Cod bays have not been well characterized. Even less is known of the transport and effects of these contaminants in this ecosystem. We do know that both physical and biological processes influence the movement and destiny of contaminants in coastal ecosystems. Contaminants released in areas having high-dilution rates may satisfy end-of-the-pipe requirements while still producing a selective concentration of the same contaminants in areas of active sediment deposition. This process, sometimes referred to as sediment focusing, may lead to

anomalously high concentration of contaminants in sediments and must be considered whenever wastes are disposed in the near-shore coastal zone. Information is nonexistent on the significance of this process in both the harbor and adjacent bay environments.

It has also been established that the toxicity of contaminants in aquatic environments is a function of their chemical and physical form. The particular form (speciation) of a contaminant—that is, whether it exists free, attached to a particle, or in association with another dissolved constituent to form a complex —greatly affects its toxicity, because these different forms are more or less likely to interact with a given organism. For example, a toxic metal attached to a particle cannot pass into the interior of a plant cell, whereas the same metal, if dissolved in water, may readily enter the cell and thus interfere with its internal biochemical machinery. Knowledge of the speciation of these contaminants is therefore of paramount importance if one is to assess the potential impact on the biological community. Failure to consider this factor may lead to major errors in the assessment of potential toxicity of contaminants. This in turn may lead to correspondingly large errors in determining the degree of control required to limit the input of contaminants to the ecosystem. The consideration of speciation is therefore of fundamental importance in the development of environmentally sound pretreatment requirements.[18] Ignorance of the speciation of contaminants, however, is not unique to Boston Harbor; it is a major concern among scientists and regulators worldwide.

Perhaps one of the best overall indicators of the current state of knowledge of the physics, biology, and chemistry of the harbor is the fact that fewer than ten papers describing the results of research conducted in Boston Harbor have been published in the peer-reviewed scientific literature.

The Need for a Vocal Constituency

I have already suggested the reasons for this current state of affairs—the lack of adequate funding for research in our coastal waters and a specific lack of interest in conducting research in Boston Harbor and Massachusetts and Cape Cod bays. The latter certainly to some extent reflects the former; that is, most who wished to pursue research in the harbor quickly recognized the inadequacy of support for such an effort at both the state and federal level. In contrast, other coastal estuaries enjoy an active and vocal support of efforts to understand and protect what people in adjacent communities consider to be an essential resource. This support has not gone unnoticed by the state and federal legislators who represent these vocal constituents, and the result has been the allocation of funds to support at least some of the research needed to protect and wisely manage these estuaries.

The lack of support for such efforts with regard to Boston Harbor and its adjacent bays was made painfully evident to myself and some of my colleagues when we were asked to define the problems facing Boston Harbor at a meeting held in Washington, D.C., more than a year ago. Sponsored by the National Oceans and Atmospheric Administration's Estuarine Programs Office and the United States Environmental Protection Agency, the meeting was designed to focus attention on the plight of many of our most severely impacted estuaries

and garner the necessary legislative support to begin to address these problems. Of the approximately fifty people attending the presentation, none could be readily identified as representing one of our legislative delegates to Washington.

On the other hand, those presenting the case for Chesapeake Bay attracted an audience of over twelve hundred. The Chesapeake is one of the estuaries chosen for inclusion in the EPA Bays Program. Also included in the program are Puget Sound, San Francisco Bay, Albemare Sound, Long Island Sound, Narragansett Bay, and Buzzards Bay. All enjoy a vocal citizens' constituency and/or the attention of influential legislators.

It is clear that until such attention is attracted to the needs of Boston Harbor and its adjacent bays, there is little hope of acquiring federal funds for support of the needed research. The scientific justification for funds is clearly there, indeed, perhaps more so than for most of the bays currently being considered for inclusion in the EPA Bays Program. The popular and political support is not yet in place. Recent progress has been made in this regard, however, with the formation of Save the Harbor–Save the Bay, Inc., a concerned citizens action group that has already made significant progress in the effort to build the necessary popular support.

Even if the required support were in place and the Boston Harbor/bay system were included in the EPA Bays Program, there is a reasonable doubt as to whether the heavily management-oriented and grossly underfunded Bays Program would permit the development of the necessary fundamental information. The common sense argument that one cannot hope to effectively manage what one does not understand has apparently failed to convince those responsible for the management of coastal resources that there is a need for comprehensive research programs. The agelong debate between the relative merits of so-called applied and basic research continues at the expense of progress in unraveling the mysteries of these complex environments. Unfortunately, it is the public who must pay the price in the end.

The $2 million plus cost of the recent Boston 301(h) waiver application is perhaps the best example of the cost of ignorance in this regard. Had the fundamental knowledge of the biology, physics, and chemistry of the harbor/bay system been available, the answers to the questions posed in the application process would have been at hand. Instead, a very limited and extremely expensive study was conducted which did little to alleviate our ignorance of the workings of this ecosystem. The cost became even greater when the federal share of support for the result of this study—a $2 billion planned cleanup of the harbor—dropped from 90 to 55 percent while the application was still being prepared. The price tag for persisting ignorance may become still greater, as waste disposal practices in Massachusetts coastal waters continue to be developed in the absence of information recognized as fundamentally important by scientists working in the field.[19]

The Need for Research

Why do we need to initiate a major research program to study Boston Harbor and Massachusetts and Cape Cod bays? One reason is that our lack of knowledge about the basic characteristics of this ecosystem has become coupled with

an immediate requirement for critical management decisions. The most urgent issue in this regard involves determination of the location for the outfall from the new secondary treatment facility to be built on Deer Island. The decision must be made by September 1987, in accord with a federally mandated court order.[20] This will be the largest such outfall in terms of flow in the country. It is also important to note that the secondary outfall effluent will still contain substantial concentrations of toxic contaminants and as such may significantly affect the quality of the receiving water. It is entirely possible that if the outfall remains in the harbor, EPA water quality criteria for copper may be violated. Continued degradation of the harbor environment will occur, although the impact will presumably not be as great.

Extension of the outfall to a location somewhere out in Massachusetts Bay may well be required. This decision should, however, be carefully weighed. The flux of contaminants to the bay may increase, depending on the efficiency with which the sediments of Boston Harbor serve as an effective trap of the contaminants now being released into it. Also, because the secondary treatment process does little to remove nutrients from the effluent and in fact may actually increase their concentration, the input of these nutrients to Massachusetts Bay may also become greater.[21] The enhanced flux of nutrients to Massachusetts Bay may serve to further aggravate the low oxygen levels that have been previously observed. Indeed, the observation of depressed oxygen concentrations in the bay contributed to the decision of the EPA to deny Boston's application for the 301(h) waiver. Unfortunately, information on the nutrient and oxygen dynamics of Massachusetts Bay does not exist, nor does knowledge of the necessary facts concerning the biological, physical, and chemical processes that can be expected to influence the fate and impact of the secondary effluent contaminants. In effect, because of our ignorance in these matters, we are about to initiate an environmental experiment of very large dimensions, the consequences of which may be substantially different from those anticipated.

Another reason to initiate a major study of the harbor/bay system is the fact that other sources of contaminants to Massachusetts and Cape Cod bays may be as important or more important than currently recognized ones. Future management strategies must take into account this possibility. Such huge expenditures of money as the $2 billion investment to clean up Boston Harbor must be justified by a demonstration of their real contribution to improved environmental quality.

Clearly, the transition from the current rudimentary primary treatment to secondary treatment will ameliorate the quality of the harbor environment. However, contaminants will continue to enter the harbor/bay system. We must do our homework and gain a much more sophisticated knowledge of what now must be considered one of the least understood harbor/bay systems in the country. The ultimate cost of the needed research, while substantial, is minute in comparison to the billion-dollar price tags for correcting past mistakes. Only when the results of such research are in hand will we be in a position to make the judicious decisions that will be necessary to guide the current reclamation and future preservation of our invaluable harbor resource. ❧

Notes

1. The formal title of this document is *Application for a Waiver of Secondary Treatment for the Nut Island and Deer Island Treatment Plants (Commonwealth of Massachusetts, Metropolitan District Commission, 1979).* Section 301(h) of the Clean Water Act of 1977 (Public Law 95-217) amended the Federal Water Pollution Control Act Amendments of 1972 (Public Law 92-500) to allow waiver of the requirement for a minimum of secondary treatment by publicly owned treatment works discharging to marine waters. The applicant must demonstrate compliance with a number of requirements defined in the law. Approval of the application must be obtained from both the state and the administrator of the Environmental Protection Agency. A general overview of the evolution of laws governing discharges into marine waters may be found in James E. Krier, "Ocean Discharge of Municipal Wastes: Legal and Institutional Aspects," in *Ocean Disposal of Municipal Wastewater: Impacts on the Coastal Environment*, ed. Edward P. Myers and Elizabeth T. Harding (Cambridge, Mass.: Sea Grant College Program, M.I.T., 1983).

2. Primary treatment of sewage involves partial removal of solid matter and contaminants followed by addition of chlorine to the remaining waste effluent for disinfection purposes. Secondary treatment incorporates a second treatment stage to remove a much greater fraction of the suspended solids and contaminants from the raw sewage. The solids removed from the original sewage by either of these two processes are referred to as sewage sludge. The sewage sludge from the secondary process contains much higher concentrations of toxic contaminants than does the sewage sludge formed from the primary treatment because of the more efficient removal of toxins by the secondary treatment process. It should be noted that the secondary process, while more effective than the primary process, still leaves high concentrations of contaminants in the effluent.

   The water and residual solid material remaining after treatment by either process are then discharged through pipes, called outfalls at the point of discharge, which extend from the treatment plant into nearby coastal waters.

3. A wide variety of organisms live on the seafloor; this community is called the benthos (*benthus* is a Greek word meaning seafloor), or the bottom-dwelling community. The organisms present often are sensitive to alterations in their habitat incurred both by natural phenomena (storms, seasonal changes in temperature and food supply, and so on) and man's activities (for instance, waste disposal and dredging). The introduction of pollutants to the seafloor may substantially alter the abundance and composition of the communities of organisms originally present (referred to in the federal regulatory jargon as the "balanced indigenous population"), as the more sensitive species are replaced with more pollution-tolerant ones.

4. The EPA's decision to deny the waiver was conveyed in a letter to Mr. Craig Stepno, chairman of the South Essex Sewerage District in Salem, Massachusetts, from Michael R. Deland, EPA Region I administrator, on 9 April 1985.

5. The cost of preparation of the 301(h) waiver application was communicated to the author by Leslie O'Shea, chief of monitoring, Massachusetts Water Resources Authority. The estimate of the $2 billion plus cost to clean up the harbor was obtained from a report to the Commonwealth of Massachusetts Metropolitan District Commission entitled *Combined Sewer Overflow Project Inner Harbor Area Facilities Plan*, December 1982, prepared by O'Brien & Gere Engineers, Inc., of Boston, and from the *Supplemental Draft Environmental Impact Statement/Report On Siting of Wastewater Treatment Facilities for Boston Harbor*, December 1984, prepared by C. E. Maguire, Inc., of Providence, Rhode Island.

6. See Krier, "Ocean Discharge of Municipal Wastes." The present level of federal support for construction of wastewater treatment plants is expected to decrease under the current administration (information communicated to the author by Paul DiNatale, press secretary, Massachusetts Water Resources Authority, in a conversation on October 10, 1986).

7. R. A. Murchelano and R. E. Wolke, "Epizootic Carcinoma in the Winter Flounder, Pseudopleuronectes americanus," *Science* 228 (1985): 587.

8. Publication in the peer-reviewed scientific literature generally implies three things: one, that the work provides a significant advancement in our knowledge of the subject being investigated; two, that the methodology used was appropriate to the task; and three, that the interpretation of results and the conclusions drawn were justified by the data gathered.

9. Drains used to collect both stormwater and sewage are commonly referred to as combined sewers. Under normal flow conditions, the two types of wastes are kept separate by a barrier inside the pipe, and the stormwater part of the flow is collected and discharged through a pipe leading to the harbor, while the sewage part of the flow is collected and sent to the treatment plant. However, under conditions of heavy rainfall, the sewage becomes mixed in with the stormwater, resulting in discharge of untreated sewage through the combined sewer outfall. Even during dry weather, untreated sewage present in the combined sewer outfalls is flushed into the harbor. This is caused by nine- to eleven-foot tides that force water from the harbor to enter the combined sewer outfall; when the tide recedes, sewage is flushed out the end of the pipe. One-way gates are supposed to prevent intrusion of this tidal water into the pipes. However, many of these gates are malfunctioning. If this were not the case, most of the pollution from the combined sewer outfalls would be caused by occasional very heavy rainfall. As it is, the dry-weather discharges are more significant.

10. Hydroscience, Inc., *Development of Water Quality Models of Boston Harbor* and *Development of Hydrodynamic and Time Variable Water Quality Models of Boston Harbor*, prepared for the Massachusetts Water Resources Commission, Boston, 1971 and 1973, respectively; EG&G, *Oceanographic Study of Various Outfall Siting Options for the Deer Island Treatment Plant*, prepared for Havens & Emerson/Parsons Brinckerhoff, Boston, 1984; J. J. Westerink, K. D. Stolzenbach, and J. J. Connor, "A Frequency Domain Finite Element Model for Tidal Circulation," *Report No. 85-006, Massachusetts Institute of Technology Energy Laboratory* (Cambridge, Mass., 1985); and A. M. Baptista, E. E. Adams, and K. D. Stolzenbach, "The Solution of the 2-D Unsteady, Convective Diffusion Equation by the Combined Use of the FE Method and the Method of Characteristics," *Report No. 296, R. M. Parsons Laboratory for Water Resources and Hydrodynamics, Massachusetts Institute of Technology* (Cambridge, Mass., 1984).

11. R. F. Kossik, "Tracing and Modeling Pollutant Transport in Boston Harbor," Master's thesis, Department of Civil Engineering, Massachusetts Institute of Technology (Cambridge, Mass., 1986).

12. Gordon T. Wallace, "Boston Harbor and Massachusetts Bay, Status of the Habitat: Chemical Considerations," *NOAA Technical Report* (Washington, D.C., in press).

13. Michael P. Shiaris and Douglas Jambard-Sweet, "Polycyclic Aromatic Hydrocarbons in Surficial Sediments of Boston Harbor, Massachusetts, USA," *Marine Pollution Bulletin* (in press).

14. T. R. Gilbert, A. M. Clay, and C. A. Karp, "Distribution of Polluted Materials in Massachusetts Bay," *Technical Report of the New England Aquarium* (Boston, Mass., 1976).

15. M. G. Fitzgerald, "Anthropogenic Influence on the Sedimentary Regime of an Urban Estuary-Boston Harbor," Ph.D. diss., MIT/Woods Hole Oceanographic Institution, WHOI-80-38 (Cambridge, Mass., 1980).

16. G. T. Wallace, Jr., J. H. Waugh, and K. A. Garner, "Metal Distribution in a Major Urban Estuary (Boston Harbor) Impacted by Ocean Disposal," in *Urban Wastes in Coastal Marine Environments,* ed. D. A. Wolfe and T. P. O'Conner (in press).

17. John G. Windsor, Jr., and Ronald A. Hites, "Polycyclic Aromatic Hydrocarbons in Gulf of Maine Sediments and Nova Scotia Soils," *Geochimica et Cosmochimica Acta* 43 (1979): 27.

18. Pretreatment consists of removal of toxic substances from industrial waste water before the water is discharged into the sewer system.

19. A document entitled *Study Plan for Basinwide Management of the Boston Harbor/Massachusetts Bay Ecosystem* has been prepared for the Marine Resources Coordinating Committee of the Massachusetts Executive Office of Environmental Affairs, by the Technical Advisory Group for Boston Harbor and Massachusetts Bay. The document identifies those research and monitoring efforts deserving highest priority in light of currently recognized management needs. The Technical Advisory Group is composed of marine and social scientists as well as representatives of local, state, and federal regulatory agencies and public interest groups. Copies of the document may be obtained by writing Dr. Judith Pederson, Coastal Zone Management Office, Executive Office of Environmental Affairs, 100 Cambridge St., Boston, MA 02202.

20. *Schedule I Compliance Order*, U.S. District Court Case, *United States of America* v. *Metropolitan District Commission et al.*, Civil Action 85-0489-MA; and *Conservation Law Foundation of New England, Inc.*, v. *Metropolitan District Commission et al.*, Civil Action 83-1614-MA.

21. C. B. Officer and J. H. Ryther, "Secondary Sewage Treatment Versus Ocean Outfalls: An Assessment," *Science* 197 (1977): 1056.