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By Michael H. Bothner and Bradford Butman

Introduction

Most of the major urban centers of the United States including Boston, New York, Washington, Chicago, New Orleans, Miami, Los Angeles, San Francisco, and Seattle—are on a coast (fig. 1.1). All of these cities discharge treated sewage effluent into adjacent waters. In 2000, 74 percent of the U.S. population lived within 200 kilometers (km) of the coast. Between 1980 and 2002, the population density in coastal communities increased approximately 4.5 times faster than in noncoastal areas of the U.S. (Perkins, 2004). More people generate larger volumes of wastes, increase the demands on wastewater treatment, expand the area of impervious land surfaces, and use more vehicles that contribute contaminants to street runoff. According to the National Coastal Condition Report II (U.S. Environmental Protection Agency, 2005a), on the basis of coastal habitat, water and sediment quality, benthic index, and fish tissue, the overall national coastal condition is only poor to fair and the overall coastal condition in the highly populated Northeast is poor.

Scientific information helps managers to prioritize and regulate coastal-ocean uses that include recreation, commercial fishing, transportation, waste disposal, and critical habitat for marine organisms. These uses are often in conflict with each other and with environmental concerns. Developing a strategy for managing competing uses while maintaining sustainability of coastal resources requires scientific understanding of how the coastal ocean system behaves and how it responds to anthropogenic influences. This report provides a summary of a multidisciplinary research program designed to improve our understanding of the transport and fate of contaminants in Massachusetts coastal waters.

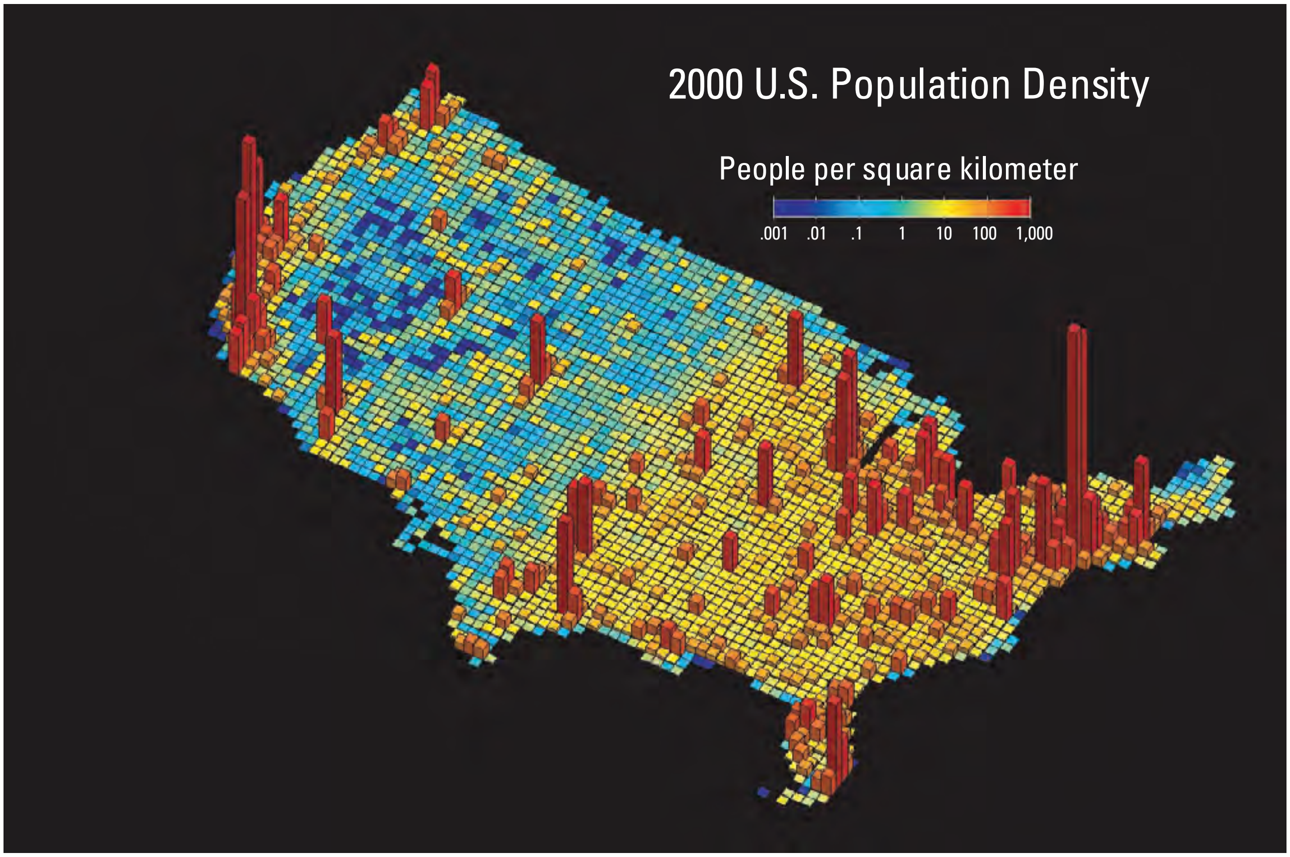

Figure 1.1. Where people live in the United States, based on the 2000 Census. The highest population densities are adjacent to the coast and concentrated in the major metropolitan centers. In 2000, 74 percent of the U.S. population lived within 200 km of the coast.

Massachusetts Bay and Boston Harbor have been a focus of U.S. Geological Survey (USGS) research because they provide a diverse geographic setting for developing a scientific understanding of the geology, geochemistry, and oceanography of coastal systems in general. Scientific data from this region can also be used to inform decisions about important economic, environmental, and political issues. From the economic viewpoint, the annual value of tourism and shipping in Massachusetts and Cape Cod Bays is about $1.5 billion and $1.9 billion, respectively. Commercial and recreational fishing generates about $240 million per year in the same region (U.S. Environmental Protection Agency, 2005b).

The environmental issue is the 300-year history of waste discharge from the Boston metropolitan area into the harbor. This history is punctuated by cycles of environmental degradation, public outcry, and improvements in the sewage treatment system. With each improvement, however, the continuous growth of population in greater Boston (fig. 1.2) and the resulting increase in the volume of waste exceeded the capacity of the treatment system, thereby setting the stage for a new contamination crisis. By the 1980s, the levels of contaminants in sediments of Boston Harbor were among the highest in the nation (National Oceanic and Atmospheric Administration, 1987). Fish were diseased, shellfish beds were closed, and swimming beaches were unsafe after heavy rains; in general, water quality and aesthetics were below acceptable standards.

Legal and political issues have always been part of Boston Harbor's history. The environmental conditions in the 1980s were highlighted in a 1983 legal suit brought by the city of Quincy against the Metropolitan District Commission (MDC, the state agency responsible for sewage treatment) and heads of three state agencies for discharging untreated or poorly treated sewage into the harbor (Dolin, 2004). The suit never went to trial, but through the actions of a Massachusetts Superior Court, the issue of Boston Harbor contamination remained on the political and public agenda. The judge called the harbor "unsafe, unsanitary, indecent, in violation of the law (Clean Water Act), and a danger to the health and welfare of the people" (Forman, 1984). To force the state legislature to implement a plan to improve harbor conditions, the judge threatened to place the MDC in receivership and curtail new sewage hookups for industry. Under intense lobbying by business, the legislature created the Massachusetts Water Resources Authority (MWRA) in December 1984. The independent MWRA was established to manage Boston's waste treatment system and was given the authority to float bonds to pay for major improvements in the treatment system.

In 1985, a Federal court began hearings on a suit brought by the Conservation Law Foundation, the Environmental Protection Agency (USEPA), and towns of Quincy and Winthrop against the MDC and MWRA (as heir to responsibilities of the MDC) for years of violation of the Clean Water Act. The judge ruled against the defendants and required all the parties to submit a construction plan and schedule for a new sewage treatment system. From these submissions, he developed a schedule for treatment system upgrades that would give the "citizens of this commonwealth a public assurance that Boston Harbor will be cleaned up within a defined period of time" (Dolin, 2004).

The MWRA's Boston Harbor cleanup program (Levy and Connor, 1992) has transformed the Boston sewage system. Key improvements were to (1) reduce contaminants at the industrial source; (2) remediate leaks in the sewage-collection system; (3) eliminate sewage sludge discharge to the harbor; (4) upgrade sewage treatment from primary to secondary; (5) construct a new ocean outfall 15.2 km offshore in Massachusetts Bay for discharge of treated effluent (fig. 1.3); and (6) implement improvements in the combined-sewer-overflow system.

As part of the harbor cleanup program, the MWRA developed a comprehensive monitoring program (summarized in MWRA, 2004) to assess changes in the harbor and bays that specifically related to the new sewage system. Additional information about conditions and processes in the coastal system on a regional scale and over a long time period was and continues to be important in predicting and interpreting local change. Implementation of the MWRA's program and the mission of the USGS to understand the geology of the nation's offshore waters provided an opportunity to conduct a cooperative multidisciplinary research program. This USGS program addresses basic scientific questions as well as concerns raised by management regarding the design, implementation, and assessment of the new sewage treatment system. Already active in Boston Harbor during the late 1970s, the USGS expanded research into Massachusetts Bay with a multidisciplinary program in 1989.

View of Boston, July 4, 1870 by F. Fuchs delineator and lithographer. Chromolithograph by New England Lithographic Company, 605 Sansome Street, Boston, John Weik publisher.
Digital TIFF acquired from I.N. Phelps Stokes Collection, Miriam and Ira D. Wallach Division of Art, Prints and Photographs, The New York Public Library, Astor, Lenox and Tilden Foundations.

Figure 1.2. View of Boston and Boston Harbor in 1870, depicting the concentration of dwellings 6 years prior to development of the first centralized sewer system. This system simply collected wastes and diverted them to holding ponds on an island until they were released to the harbor on the ebb tide.

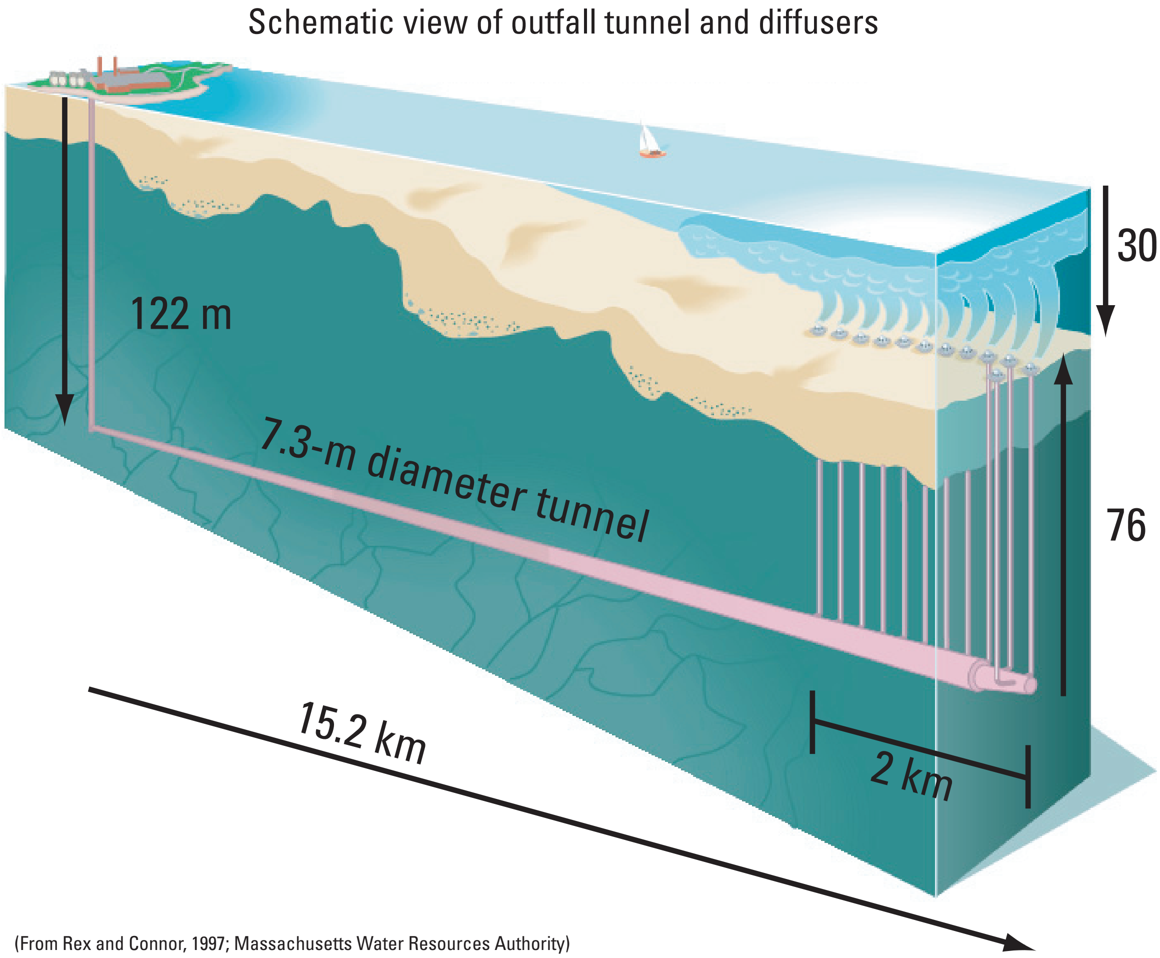

Figure 1.3. The Massachusetts Bay outfall consists of 53 diffuser ports connecting to a tunnel that transports 350 Mgal/d of secondary treated sewage effluent from the Deer Island Treatment Plant.

Regional Geologic Setting

Massachusetts Bay and Cape Cod Bay form a semi-enclosed basin about 100 km long and 50 km wide in the western Gulf of Maine offshore of Boston, Massachusetts (figs. 1.4, 1.5). Massachusetts Bay is open to the Gulf of Maine along the eastern boundary between Cape Ann and Cape Cod. Stellwagen Bank, a shallow bank along the eastern side of Massachusetts Bay, rises to within about 30 meters (m) of the sea surface, and partially separates the bay from the Gulf of Maine. Two channels, one to the south of Cape Ann and one to the north of Cape Cod, provide connection to the Gulf of Maine at about 60-m water depth. Stellwagen Basin, a topographic low to the west of Stellwagen Bank, is the deepest part of Massachusetts Bay with maximum water depth of 95 m. Cape Cod Bay, between Cape Cod and the Massachusetts coast, is open to Massachusetts Bay to the north; the greatest water depth is 40 m.

The major topographic features and the distribution of sediment types in this coastal region provide clear evidence of its past glacial history. Twenty-one thousand years ago, the continental ice sheet was about 1,500 m thick in this region (Denton and Hughes, 1981). The glacier scoured what is now Stellwagen Basin, deposited boulders in elongated low hills (drumlins) in western Massachusetts Bay, and contributed coarse sand and gravel to what is now Stellwagen Bank. Extensive erosion of glacial sediments took place as the shoreline crossed the inner continental shelf three times following ice retreat (Oldale and others, 1993). Modern current patterns, particularly those during storms, continue to winnow deposits of glacially derived sand and gravel from Stellwagen Bank and Jeffreys Ledge (20–40 m water depth). The inner shelf of western Massachusetts Bay, covered by rock, gravel, and sand with almost no mud to a depth of 40–50 m, is exposed frequently to wave-generated currents associated with storms from the

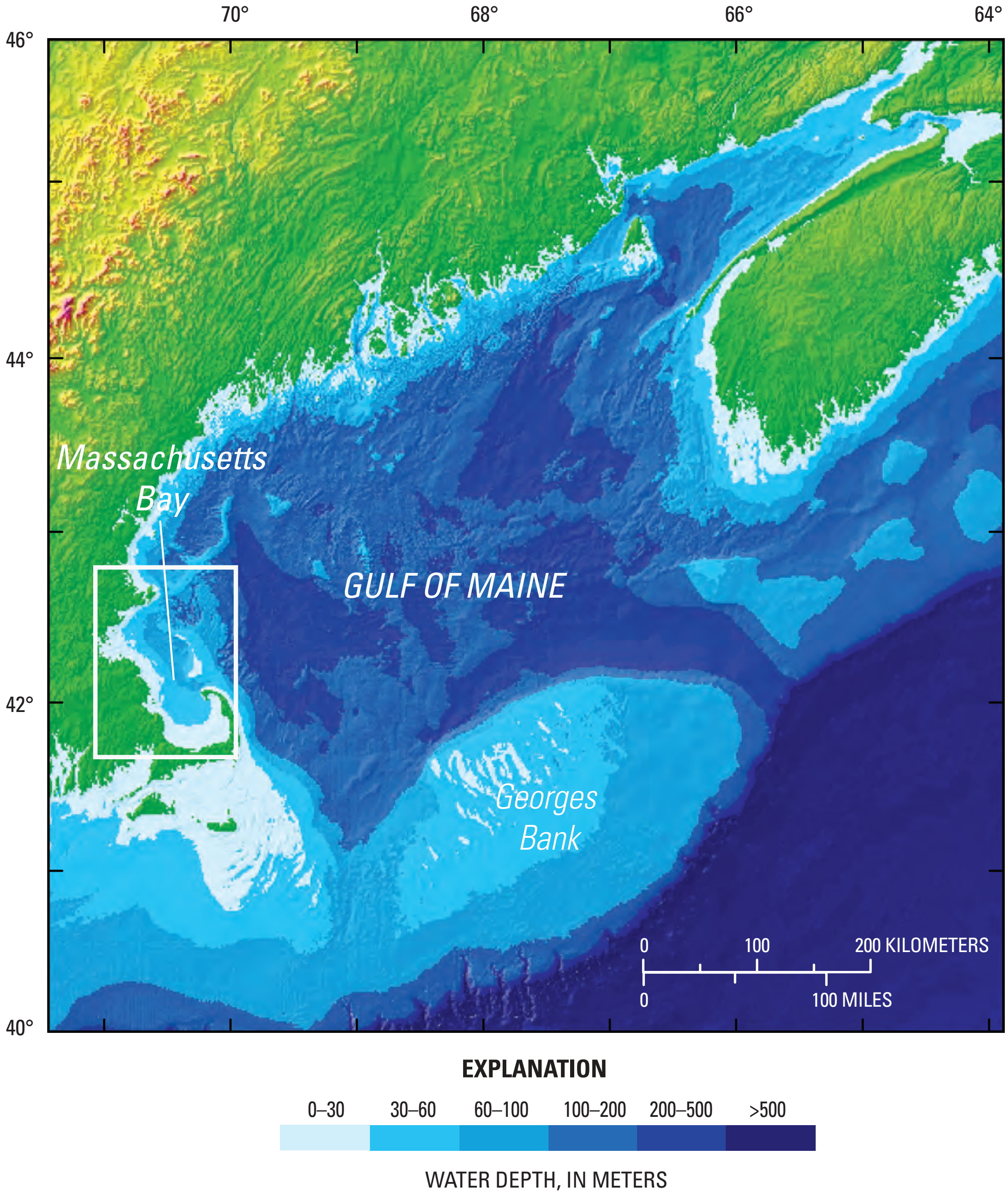

Figure 1.4. The location of Massachusetts Bay in the western Gulf of Maine (image from Roworth and Signell, 1998). The white box outlines the area of figure 1.5.

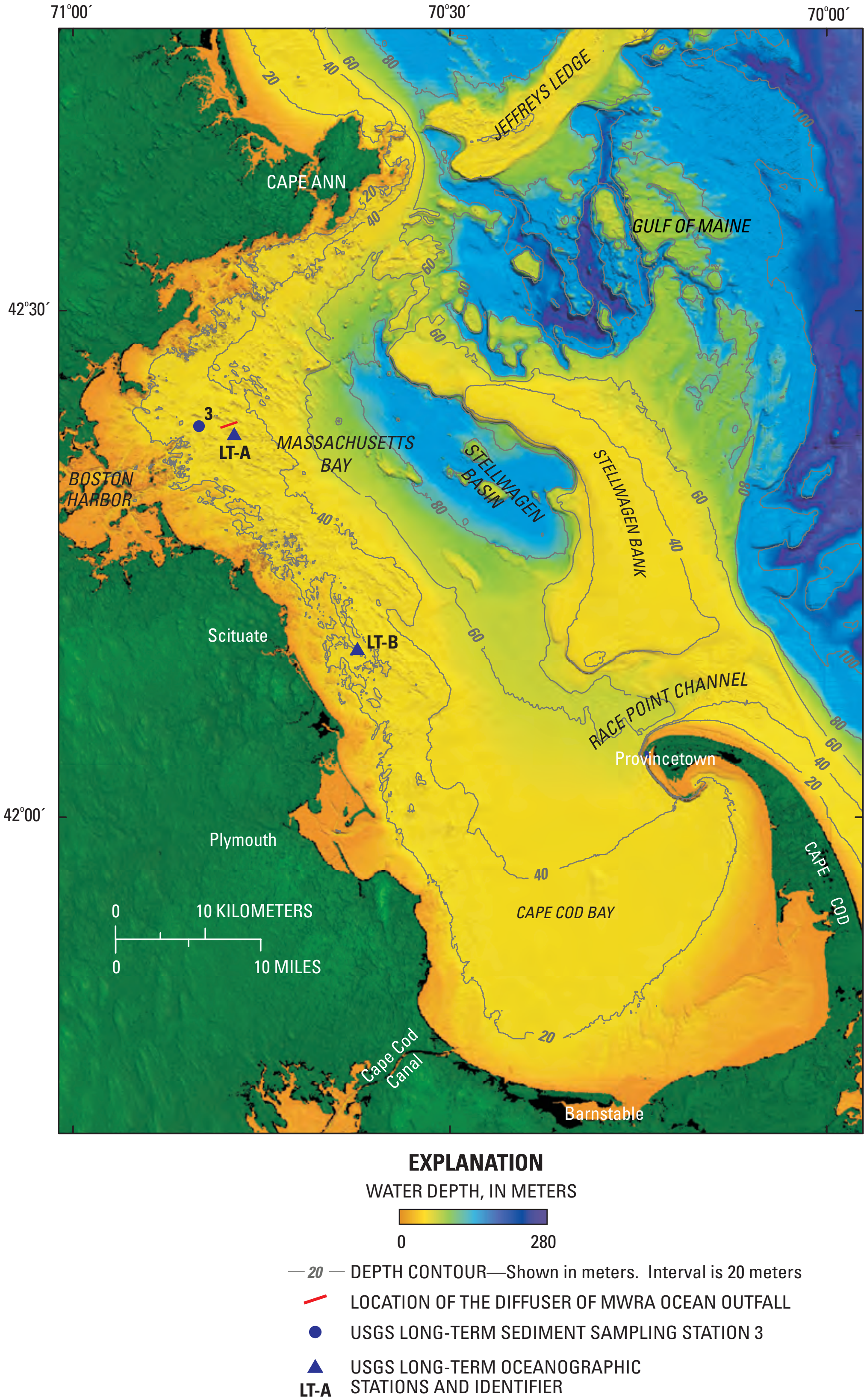

Figure 1.5. The shaded relief topography, colored by water depth, of the Massachusetts Bay region offshore of Boston, Massachusetts. The location of the diffuser of MWRA's ocean outfall is shown as a red line, the USGS long-term oceanographic stations LT-A and LT-B as blue triangles, and the USGS long-term sediment sampling station 3 as a blue circle.

northeast. Stellwagen Basin is floored with fine-grained mud. The basin is generally considered to be a tranquil long-term depositional site for sediments winnowed from the inshore areas and the shallow banks. Sediment accumulation rates here are less than 0.3 cm/yr (Crusius and others, 2004).

The complex topography, different sediment types, and energetic oceanographic conditions off coastal Massachusetts provide a wide variety of habitats for marine organisms; these factors have contributed to the importance of this region as the focus of multidisciplinary environmental studies.

The USGS Program

The USGS has led a multidisciplinary research program designed to provide answers to science and management questions associated with contaminant transport and fate in coastal waters. This program has been carried out in collaboration with colleagues from the Woods Hole Oceanographic Institution (WHOI) and in cooperation with the MWRA and the U.S. Coast Guard in Massachusetts Bay and Cape Cod Bay. The program's overarching objective is to develop and test the capability to predict the transport and long-term fate of wastes discharged to the coastal oceans.

Sediments are the focus of this study because they adsorb many contaminants dissolved in seawater and serve as a vehicle for contaminant transport. Fine-grained sediments (silt and clay-sized particles) are strong adsorbers because of their large surface area per unit mass. Understanding the mechanisms and rates by which sediments are resuspended, transported, buried, and bioturbated yields insight into the fate of particle-bound contaminants. Once introduced to the bottom sediments, some contaminants undergo redox-driven reactions and cycle between dissolved and particulate phases, migrate within the sediment column, and under some conditions, diffuse back into the overlying water. Repeating the cycle, the contaminants may be again adsorbed and transported by suspended sediment. The complexity of these processes adds to the challenge of understanding contaminant buildup and variability.

This report describes examples of progress in understanding marine processes that influence the behavior, transport, and fate of contaminants in coastal waters of Massachusetts. The USGS research program consisted of the four major components described below. A summary of results on these four components is presented in the following nine sections of this report. The Appendix contains a list of publications (1989–2006) resulting from this and related programs.

Sea-Floor Mapping

The USGS mapping approach combines sidescan sonar, high-resolution multibeam echosounding, seismic reflection profiling (fig. 1.6), sediment sampling, and bottom photographs and video observations to characterize the sea floor. In contrast to earlier maps that were based on widely spaced data, the new surveys provide maps of the sea floor with resolutions of a few meters; these maps are similar in detail to aerial photographs (Butman and others, 2004b; Butman and others, 2003a, b, c). The maps can be interpreted to show on a broad regional scale the locations of sediment types, areas of sediment deposition and erosion, and the effects of human activities, such as waste disposal and bottom trawling with fishing gear. Because the sea floor in Massachusetts Bay is extremely variable over small spatial scales, early versions of these new USGS maps (Bothner and others, 1992) were critical for determining appropriate sampling sites for the MWRA monitoring program and for selecting the location of the new offshore outfall. Results of the sea-floor mapping studies are presented in Section 2.

Current and Sediment Transport Measurements

Arrays of moored instruments (fig. 1.7) that have made almost continuous measurements of oceanographic parameters such as temperature, salinity, currents, pressure, light transmission, and bottom characteristics have been maintained at two sites in Massachusetts Bay (fig. 1.5, Butman and others, 2004a). The instruments document oceanographic conditions during infrequent events, such as red tide outbreaks, and during more frequent events, such as storms, which are responsible for resuspending and transporting sediment and sediment-bound contaminants. The instruments also define seasonal and interannual variability of oceanographic conditions. Descriptions of the long-term current and sediment transport measurements are presented in Sections 3, 4, and 6.

Geochemical Measurements and Database

From 1989 to 2006, samples of the surficial and subsurface sediments have been collected three times per year in Massachusetts Bay near the new ocean outfall to monitor temporal trends in metal concentrations and bacterial spores for indications of sewage (fig. 1.8). Samples have also been collected in the Boston Harbor and throughout Massachusetts Bay, although less frequently. During the last few years, special studies have been conducted with colleagues at WHOI on geochemical processes within the surface sediments. These studies have examined the rates and depths of oxygen penetration into

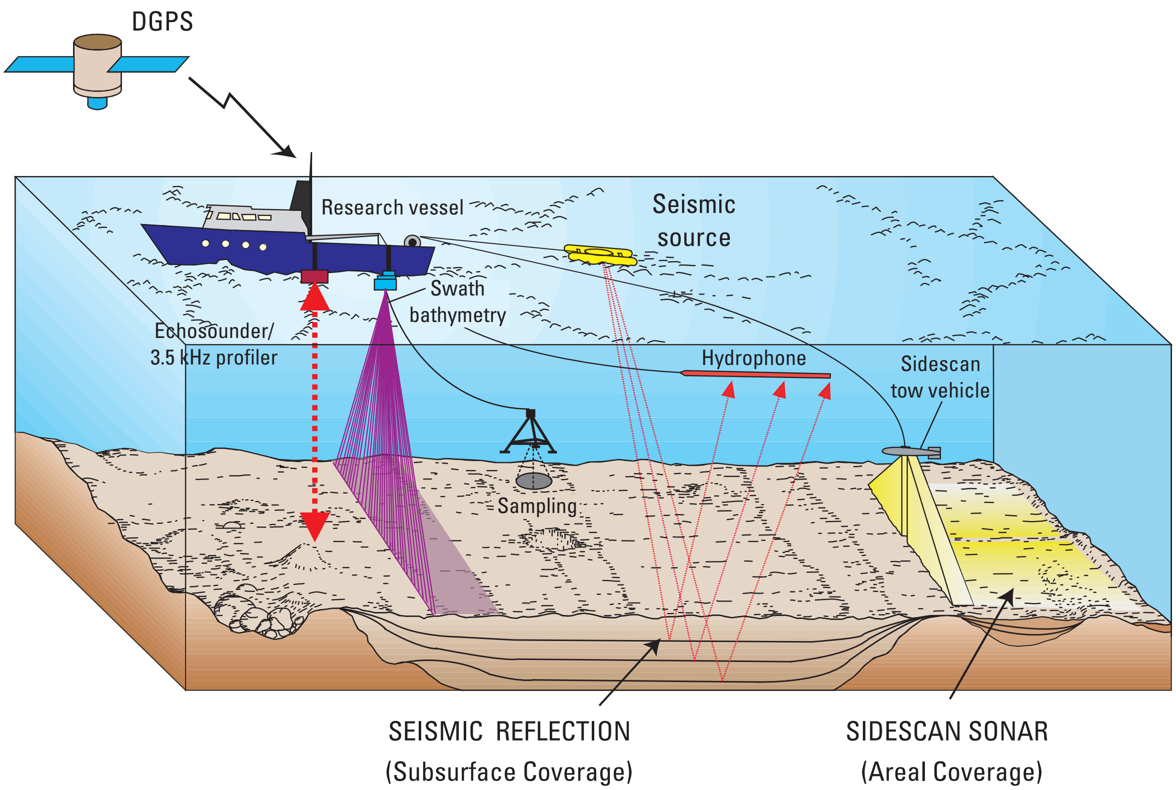

Figure 1.6. The sea floor is mapped with instruments that measure the intensity of reflected sound waves to image the surface or subsurface layers of the seabed. Swath bathymetry and sidescan sonar provide information concerning topography and reflectivity of surface sediment from which interpretations about sediment types can be made. Sound of lower frequency penetrates the sediment surface and thus enables interpretation of subsurface stratigraphy. The ship and towed instruments are navigated within a few meters by using the Differential Global Positioning System (DGPS). Photographs of the sea floor and sediment samples are obtained when the vessel is stopped.

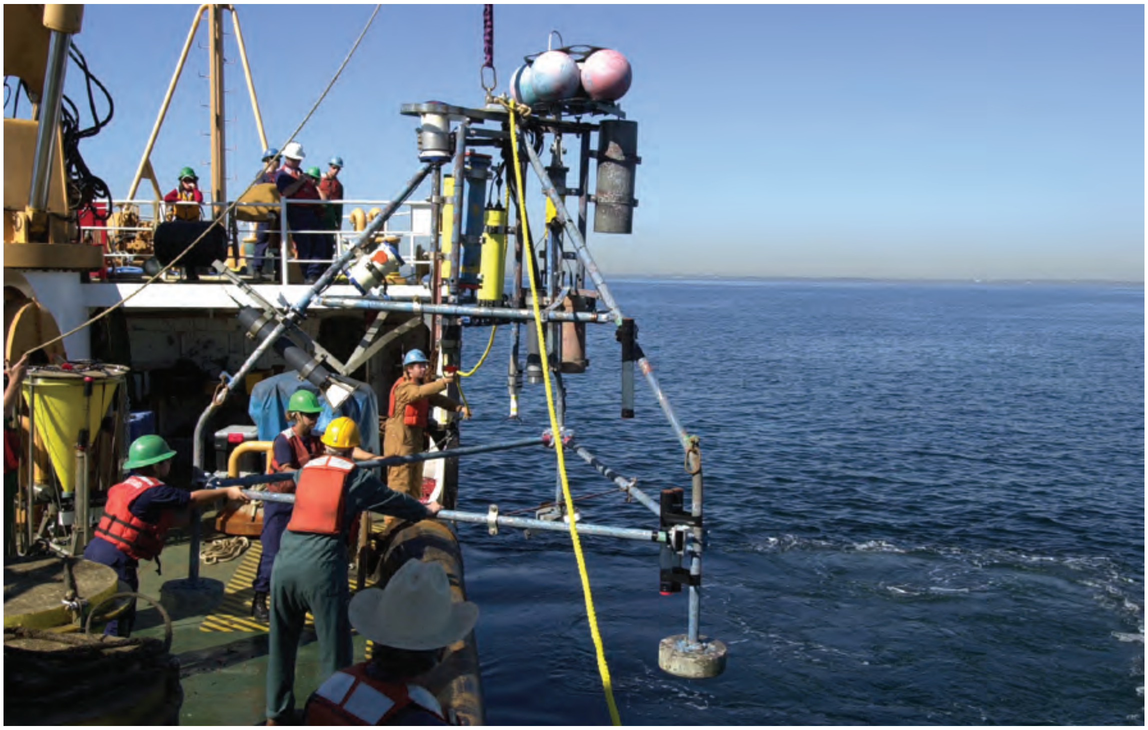

Figure 1.7. A USGS instrumented tripod being deployed in Massachusetts Bay from the U.S. Coast Guard Cutter *Marcus Hanna*. The frame and attached instruments are lowered to the sea floor where they collect and receive data (temperature, salinity, pressure, current, light transmission) for about 4 months.

sediments, the cycling of metals between pore waters and the sediment particles, and the release of dissolved metals from contaminated sediments to overlying water by diffusion, advection, and resuspension (Kalnejais, 2005).

An early phase of the geochemical work on this project included the compilation and synthesis of existing data from published and unpublished sources. The resulting Contaminated Sediments Database for the Gulf of Maine (Buchholtz ten Brink and others, 2003) has been instrumental for assessing temporal trends in coastal sediments and for identifying gaps in information that can be considered in the design of future studies. Results of the geochemical studies are presented in Sections 7–10.

Modeling Circulation and Sediment Transport

The USGS has used the Estuarine and Coastal Ocean Model (ECOM) originally developed by Blumberg and Mellor (1987) to study the flushing characteristics of Boston Harbor, to provide input for a baywide water-quality model, and to predict the dilution of effluent entering the bay at the new outfall. Over the past 15 years, the oceanographic community has further refined the model. The model (Signell and others, 2000) simulates currents and water properties in three dimensions over time, as a function of wind, river runoff, offshore discharges from the outfall, surface heating and cooling, tides, and sea-level fluctuations in the open ocean (fig. 1.9). Modeling of sediment transport recently has been carried out using the Regional Ocean Modeling System (ROMS). Results of the dilution and sediment-transport modeling are in Sections 5 and 6, respectively.

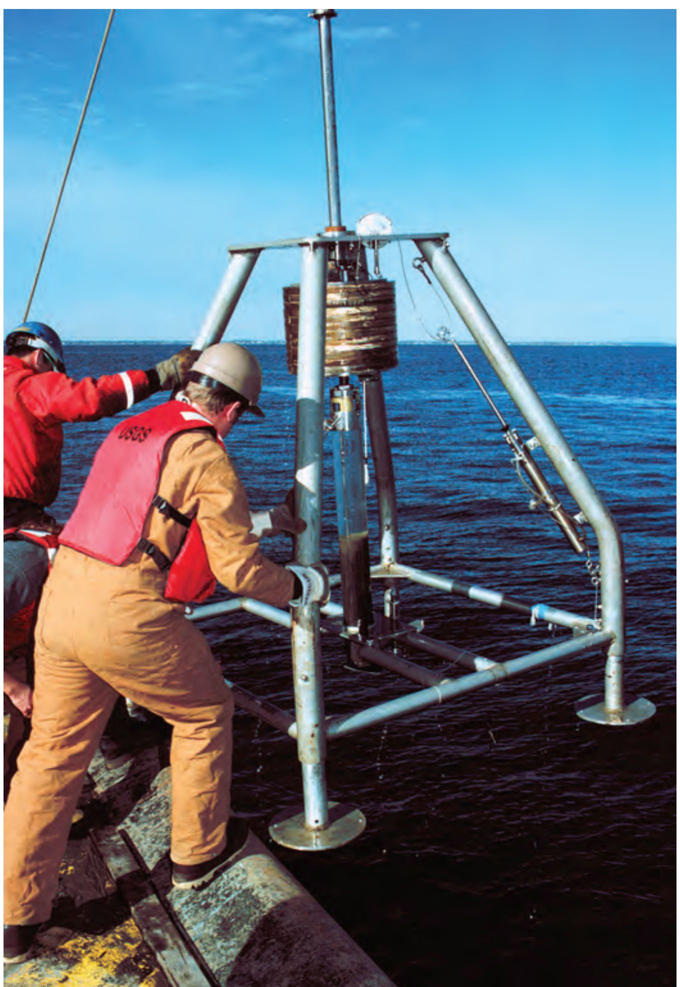

Figure 1.8. Sediment samples were obtained with a hydraulically damped gravity corer, which collects sediment cores (of 10.7 cm internal diameter and up to 50 cm long) with minimal disturbance of material at the water-sediment interface (Bothner and others, 1997).

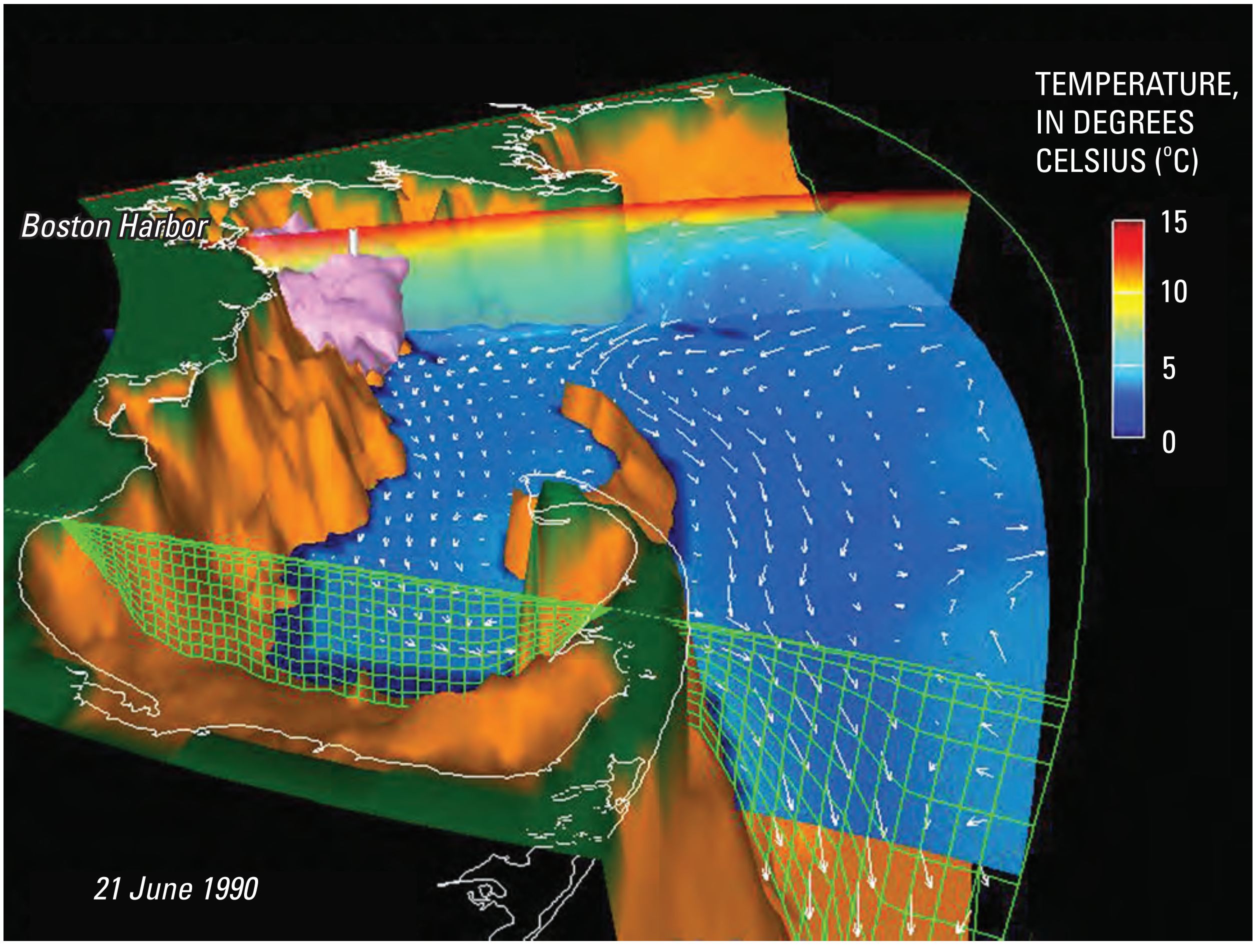

Figure 1.9. This perspective of Massachusetts Bay, looking from south to north, illustrates some of the features and predictive capabilities of the Estuarine and Coastal Ocean Model (ECOM) (Blumberg and Mellor, 1987), as modified by USGS for work in Massachusetts Bay. This example simulation for June 21, 1990 was during a year of extensive oceanographic observation in Massachusetts Bay that provided an opportunity to evaluate the model performance. The model calculates oceanographic parameters (temperature, salinity, current) on a grid (illustrated by the green latticework) that has greater vertical resolution in shallow water and greater horizontal resolution near the coast. A cross section, extending east from Boston Harbor, shows the vertical and horizontal variation in water temperature (red to blue scale). The white arrows show the simulated mean current direction and speed at 50-m water depth. The pink cloud southeast of Boston Harbor depicts the predicted limit of 200-fold diluted effluent from the Massachusetts Bay outfall (location indicated by a vertical white bar). Model predictions of the dilution of sewage effluent from the Boston Harbor outfalls and from the new outfall are discussed in Section 5. Predictions of the transport and fate of sediments by winter storms using the Regional Ocean Model System (ROMS) are discussed in Section 6.