Predicting the Long-Term Fate of Sediments and Contaminants in Massachusetts Bay

Contaminants in the Coastal Ocean

Contaminants have accumulated in the sediments of Massachusetts Bay, typical of many coastal areas near major metropolitan centers that have been used for waste disposal since colonial times. Developing an understanding of where and why contaminants accumulate is essential for making informed management decisions about uses of these coastal areas and for developing sound strategies for monitoring environmental change.

The environmental health of Boston Harbor and Massachusetts Bay is of public concern. Massachusetts Bay, Cape Cod Bay, and the adjacent Gulf of Maine (fig.1) are used for transportation, fishing, recreation, and waste disposal and are an important habitat for endangered marine animals. Elimination of the discharge of sewage sludge to the harbor, improved sewage treatment, and pollution source control have significantly reduced contaminant loads to the harbor. However, there remains concern about the effects of moving the discharge of treated sewage effluent from Boston Harbor into Massachusetts Bay scheduled to begin in 1998. Understanding this coastal system and long-term monitoring are essential in order to assess environmental change.

Many contaminants introduced into the coastal ocean are associated with particles. After repeated cycles of transport, deposition, resuspension, and biological and chemical interactions, contaminants on particles eventually may be buried in bottom sediments. U.S. Geological Survey (USGS) studies in Boston Harbor and Massachusetts Bay are designed to provide an understanding of how sediments and associated contaminants are transported and where they accumulate in the Massachusetts Bay system.

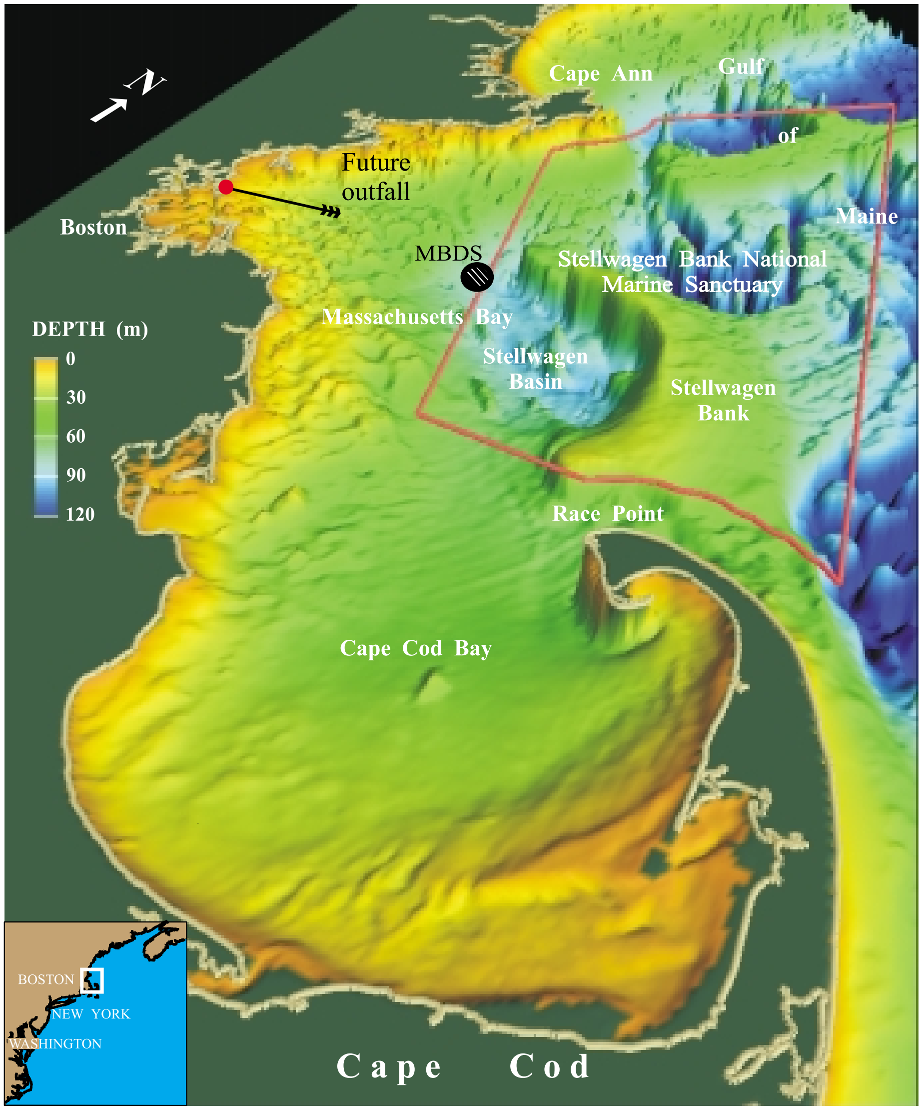

Figure 1. Perspective map of Massachusetts Bay and Cape Cod Bay illustrating the complex underwater topography. The region is approximately 100 km long and 40 km wide. Stellwagen Bank rises to within about 20 m of the sea surface and partially isolates Massachusetts Bay from the Gulf of Maine. Beginning in 1998, the discharge of treated sewage effluent from the Boston metropolitan area will be relocated from Boston Harbor to a new site 15 km offshore (approximately 35-m water depth) in Massachusetts Bay. The location of the Deer Island Treatment Plant (red dot), the future outfall, the Massachusetts Bay disposal site (MBDS), and the Stellwagen Bank National Marine Sanctuary (SBNMS) are also shown. Note that the MBDS is located outside the SBNMS. Vertical exaggeration is 100X.

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Mapping the Sea Floor

Maps of the sea-floor geology identify the locations where fine-grained sediment and associated contaminants accumulate. Remote-sensing techniques such as side-scan sonar and high-resolution seismic reflection profiling allow detailed mapping of the texture and distribution of sediment types on the sea floor on a regional basis. These maps illustrate that sediment texture and other bottom features are patchy and that major changes occur over a wide range of spatial scales. The variability is due to the irregular bottom topography, past and present sources of sediment, and the processes causing transport. Maps show the location and extent of erosional and depositional environments and provide a regional context for the interpretation of bottom samples and benthic observations. Fine-grained sediments typically indicate areas of sediment accumulation; coarse-grained sediments or boulders define areas where the sediments are scoured and winnowed by currents.

Maps of the sea-floor geology identify sampling sites for monitoring of long-term environmental change (fig. 2). Areas of fine-grained sediments are often the best areas to monitor changes in contaminant concentrations. Using high-resolution sea-floor maps ensures selection of sites having similar texture and sufficient size that they can accommodate long-term monitoring and provide samples that are directly comparable. The maps also ensure that samples can be efficiently obtained without damage to sampling equipment, as frequently occurs in areas of rough or hard bottom. The USGS, as part of the Massachusetts Water Resources Authority (MWRA) Outfall Monitoring Program, has established sediment monitoring stations at two sites in the vicinity of the new ocean outfall. Samples have been obtained at these sites three times each year since 1989.

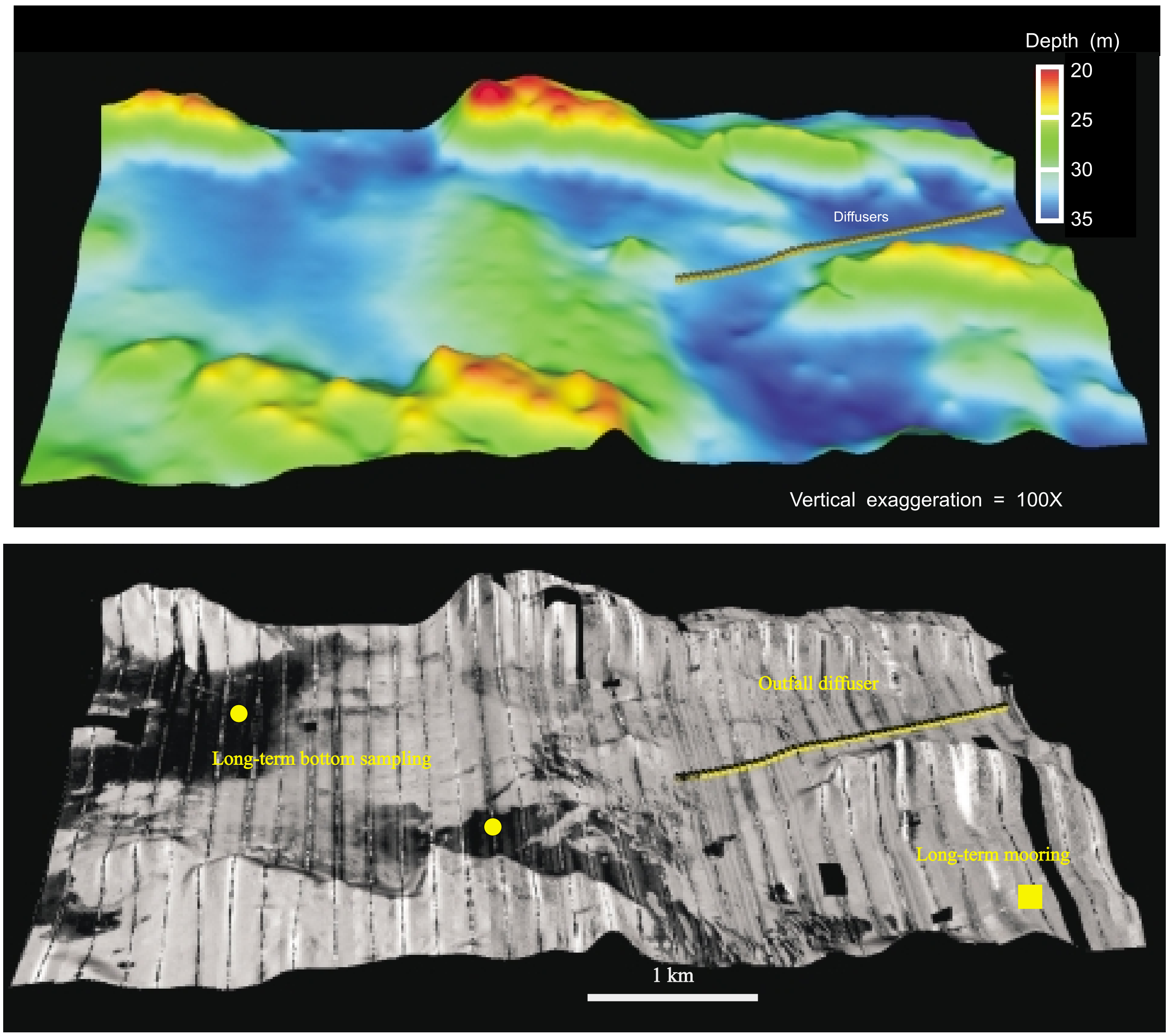


Figure 2. Top: Sea-floor topography in the region of the future ocean outfall. The submerged hills (tops about 20 m from the surface and shown capped in red) in this region are similar in size and shape to the harbor islands. They formed during the last glaciation and submerged during the rise in sea level after the glaciers melted. **Bottom:** Reflectivity of bottom sediments, measured by sidescan sonar and superimposed on the bathymetry, showing a complex pattern that indicates differences in the sea-floor environment. Areas of boulders are represented by the lightest tone and are typically found on the crests of the small submerged hills. The intermediate gray tone is sand with varying amounts of gravel. The darkest areas represent deposits of fine-grained sediments, often in the topographic lows between the hills. Long-term sampling of the sediments is conducted in two areas of fine-grained sediments. Currents and suspended sediments are monitored at the long-term mooring site. The stripes represent the ship track and are about 150 m apart. (See Bothner and others, 1992.)

Contaminant Accumulation in the Boston Harbor-Massachusetts Bay Sedimentary System

Boston Harbor, Stellwagen Basin, and Cape Cod Bay are long-term sinks for fine-grained sediments and associated contaminants. The regional pattern of sedimentary environments in the Boston Harbor-Massachusetts Bay sedimentary system is a result of the basin geometry, the supply of sediment, and oceanographic processes (fig. 3). Fine sediments accumulate in the Boston Harbor estuary because of its restricted flushing and low-wave climate. The inner shelf along the western shore of Massachusetts Bay (water depths shallower than 40–50 m) is covered by deposits of gravel, coarse sands, and bedrock. Fine sediments do not accumulate here because storm currents resuspend and remove them from the bottom. The deepest part of the system, Stellwagen Basin, is generally a tranquil environment where fine-grained sediments accumulate.

Contaminants discharged into Boston Harbor are sequestered in the sediments of Boston Harbor, Massachusetts Bay, and Cape Cod Bay. Contaminant levels in sediments decrease offshore from Boston Harbor. Silver is a key element in tracing the distribution of sewage-derived particles. Because of silver's use in photography, sewage particles contain silver at concentrations often 1,000 times higher than found in natural, uncontaminated sediments. The concentration of silver in the surficial sediments and the total amount of silver in the sediments are highest in Boston Harbor and lowest in the western Gulf of Maine (fig. 4). Elevated concentrations of silver (and other contaminants) occur in the small patches of fine sediments near the future outfall site and in the depositional areas of Massachusetts and Cape Cod Bay. The relatively high amounts of silver in Cape Cod Bay suggest preferential accumulation of sewage-associated contaminants in this region.

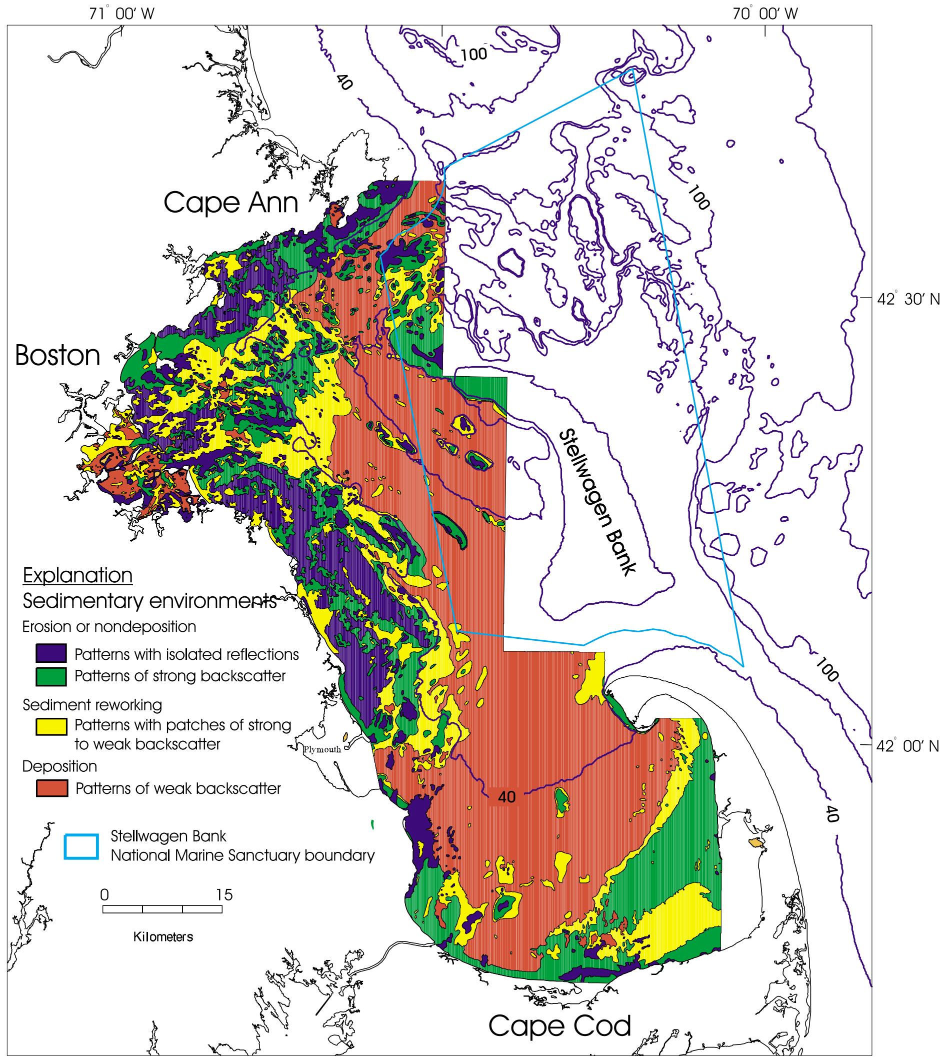


Figure 3. Distribution of sedimentary environments in the Boston Harbor-Massachusetts Bay sedimentary system. The map shows areas of sediment deposition (typically fine-grained muddy sands and mud in red), two areas characteristic of sediment erosion or non-deposition (areas of boulders or bedrock in blue; areas of gravel and medium to coarse sand in green), and areas of sediment reworking (typically patches of gravelly sand, sand, and mud in yellow). (See Knebel and Circe,1995; Knebel and others, 1996.)

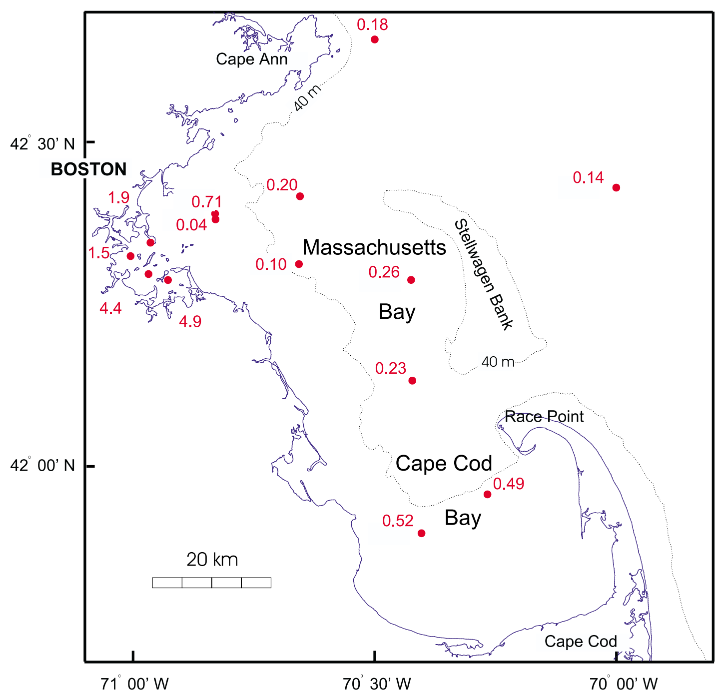


Figure 4. Concentration of silver in surficial sediments (in micrograms per gram of dry sediment). Silver is a key element in tracing the distribution of sewage particles in the coastal ocean. (Bothner and others, 1993.)

Circulation in Massachusetts Bay

The mean current typically flows southerly through Massachusetts Bay and turns offshore into the Gulf of Maine (fig. 5). During much of the year, this weak counterclockwise circulation persists in Massachusetts and Cape Cod Bays, principally driven by the southeastward coastal current in the Gulf of Maine. The current proceeds southwesterly into the bay south of Cape Ann, southward along the western shore, and easterly out of the bay north of Race Point, typically at a strength of about 5 cm/s (0.1 knot). This flow pattern may reverse in the fall, especially near the western shore, because preferential cooling of the shallow water creates denser water near the shore. Fluctuations of the current caused by wind and density variations alter this simple flow pattern on any day (figs. 5 and 6). In most of Massachusetts Bay, the flow-through flushing time for the surface waters ranges from 20 to 45 days. In western Massachusetts Bay near the new outfall site, mixing and transport of water and material into the regional mean flow pattern are accomplished by a variety of processes, including the action of tides, winds, and river inflow. The distance that particles travel in a day is typically less than 10 km. The future outfall is located in a region generally to the west of the basin-wide residual flow pattern.

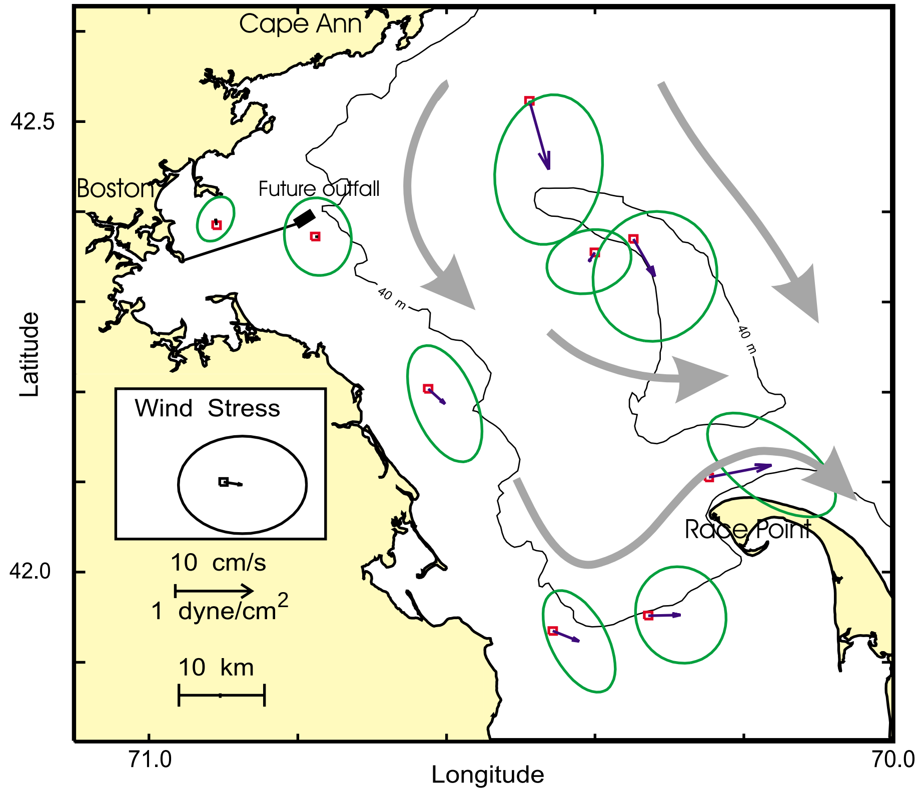


Figure 5. Observed mean flow (small blue arrows) and the variability (shown as a green ellipse centered around the tip of the mean flow arrows) for near-surface currents (4–8 m below sea surface) measured between December 1989 and September 1991. Typically, the daily-averaged current originates at the station symbol (red squares) and flows toward any location within the ellipse. In general, the fluctuations are larger than the mean. The bold gray arrows indicate the overall direction of the residual drift. The mean wind during this period was from the west at about 0.1 dyne/cm^2 as measured at the Boston buoy. (See Geyer and others, 1992.)

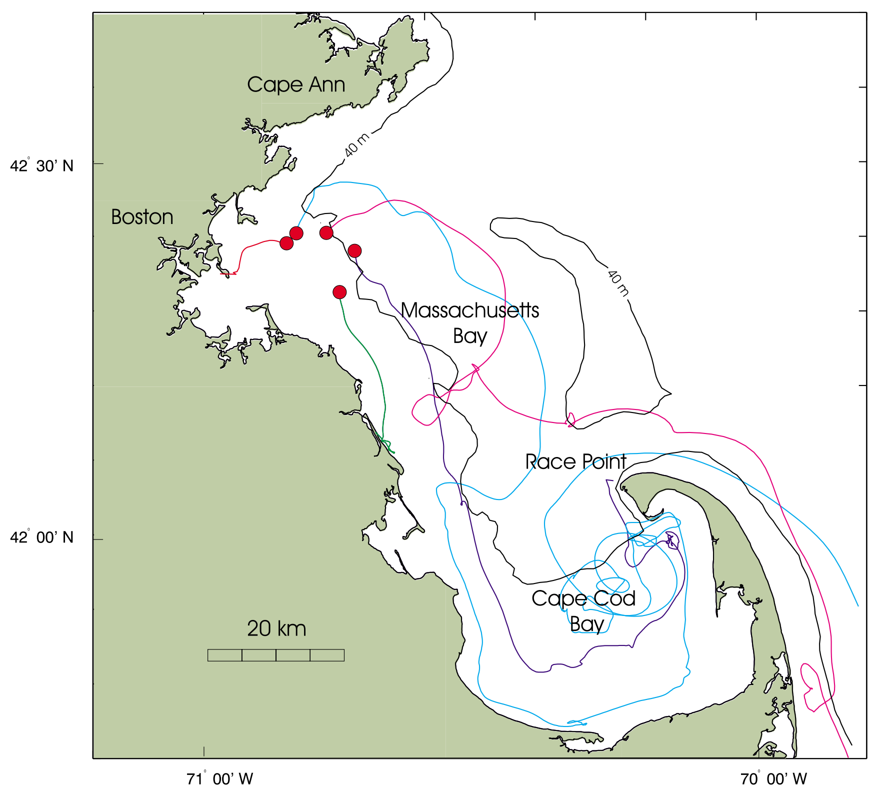


Figure 6. Paths of a few of the drifters released in May 1990 illustrating the variability of the surface currents in Massachusetts Bay. Drifters (surface floats attached to an underwater drogue) were released (initial locations at the red dots) and tracked via satellite until they either left the bay or grounded ashore. For drifters set out during various times of the year as part of a field experiment carried out in 1990–91, traveltimes from western Massachusetts Bay to Cape Cod Bay ranged from 4 to 7 days and from western Massachusetts Bay to Race Point ranged from 7 to 50 days. (Geyer and others, 1992.)

Sediment Transport by Storms

Strong storms with winds from the northeast resuspend fine sediments from western Massachusetts Bay and transport them offshore and toward Cape Cod Bay. Northeasters, with winds that blow across the Gulf of Maine, generate large waves that enter Massachusetts Bay from the east. The oscillatory currents associated with these waves cause resuspension of the bottom sediments in water depths less than 40 to 50 m over areas exposed to the northeast, principally along the western shore of Massachusetts Bay (fig. 7). Typically only a few millimeters of sediment are resuspended from the seabed during each storm. The currents driven by winds from the northeast flow southeastward parallel to the coast (with an offshore component near the bottom) and carry the suspended sediments toward Cape Cod Bay and offshore into Stellwagen Basin (figs. 8 and 9). Sediments settle to the sea floor along this transport pathway following each storm.

Sediments that reach the sea floor in Cape Cod Bay or Stellwagen Basin are likely to remain there. In this coastal system, currents caused by surface waves are the principal cause of sediment resuspension. Cape Cod Bay is sheltered from large waves by the arm of Cape Cod, and waves are rarely large enough to resuspend sediments at the seabed in the deep Stellwagen Basin. Thus, once sediments reach Stellwagen Basin or Cape Cod Bay, carried either by the mean flow or transported by storms, it is unlikely that they will be resuspended and transported again by waves.

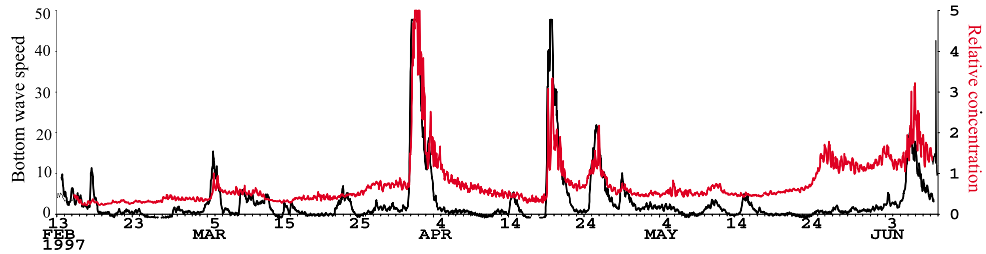


Figure 7. Above: Plot of the relative strength of the wave-induced current (black line) and suspended sediment concentration (red line) at the bottom at the long-term monitoring station near the site of the future outfall. Increased sediment concentrations occur in the water whenever wave-induced currents are large. **Below:** Sequence of bottom photographs taken before, during, and after the April 1, 1997, storm. During the storm (middle photograph), material in suspension obscures the sea floor from view. By the end of the storm, several of the large cobbles on the sea floor have moved (the frame holding the camera also moved during the storm, slightly changing the field of view).

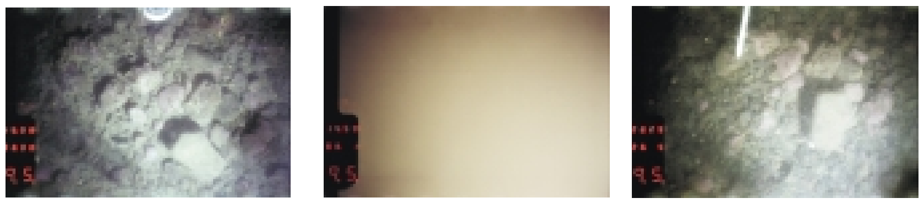
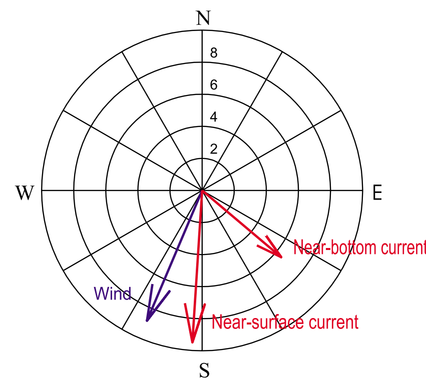


Figure 8. Mean wind (in m/s) and currents (in cm/s) measured near the future outfall site during strong storms that resuspend and transport bottom sediments. Winds from the northeast drive near-surface currents at this location to the south toward Cape Cod Bay and near-bottom current to the southeast offshore toward Stellwagen Basin.



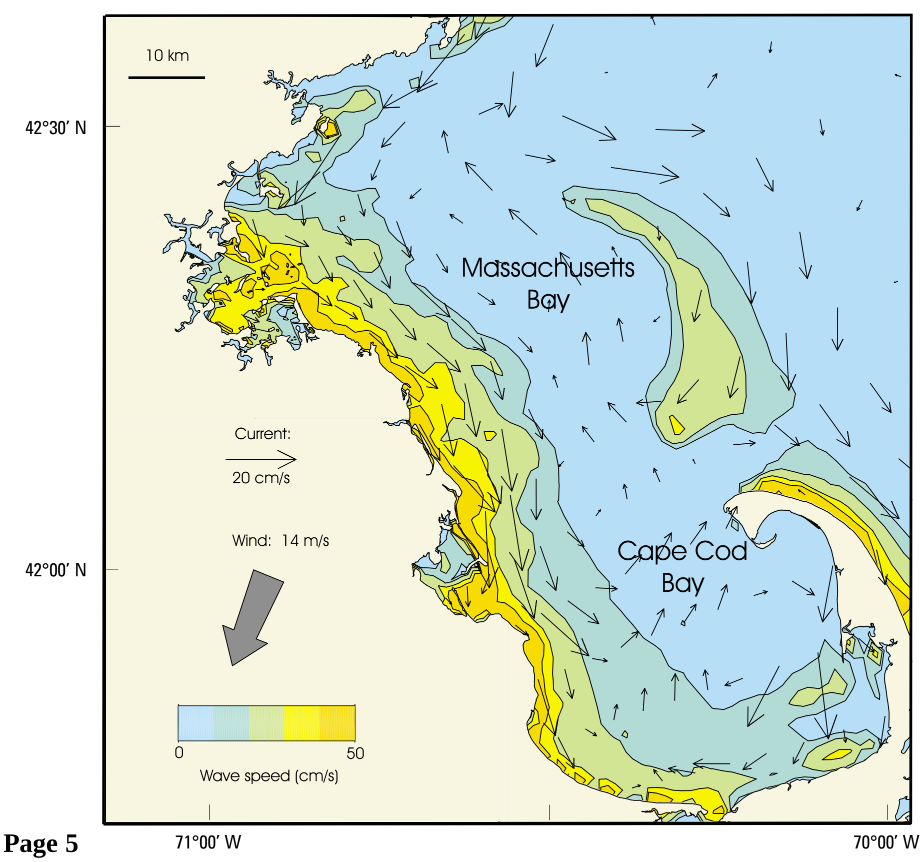


Figure 9. Modeled wind-induced currents (arrows) and contours of near-bottom wave current speed driven by a northeasterly wind of 14 m/s (28 knots). Near-bottom wave speeds in excess of about 10 cm/s are sufficient to resuspend fine-grained sediments. During major northeasters, fine sediments along the western shore of Massachusetts Bay are resuspended by the wave currents and transported by the wind-driven flow to the southeast toward Cape Cod Bay, where they settle. They are protected from the influence of subsequent storms by water depth and basin geometry. The numerical circulation models provide predictions of the basinwide storm response, which would be very difficult to observe directly.

Implications for Management

Understanding the long-term fate of sediments and associated contaminants has influenced management decisions and guided long-term monitoring of Massachusetts and Cape Cod Bays. For example:

- Detailed geologic maps were used in selecting the location of the future outfall. The maps identified areas of the sea floor used for fishing and regions where boulders on the sea floor would make construction of the diffuser risers difficult.

- Long-term monitoring for contaminants in sediments in the region close to the outfall (the near field) has been established at two sites identified by the geologic maps. These sites are likely to accumulate fine-grained sediments and associated contaminants and thus are sensitive locations for assessing environmental change.

- Long-term monitoring for contaminants in sediments in the region distant from the outfall (the far field) has been established in depositional sites downstream from the source of contaminants and at control stations. The geologic maps show that this modest number of stations characterizes and represents the sedimentary environments of large areas of Massachusetts and Cape Cod Bays. The geologic maps provided the framework for the design of a sensitive and efficient monitoring program for assessing environmental change.

- Observations of the natural processes that transport sediments (storms, for example) will help determine whether changes in contaminant levels are due to anthropogenic or natural causes.

- The observation that a modest fraction of the total amount of contaminants introduced into the Massachusetts Bay system is sequestered in the bottom sediments suggests that dilution is not the best long-term solution for disposal of toxic substances in this coastal system. Instead, reducing the input of toxic substances is the best strategy to ensure the long-term environmental quality of the sediments. The Massachusetts Water Resources Authority is aggressively pursuing source reduction.

Partnerships for Coastal Ocean Science

Coordination of efforts by Federal, State, and academic partners is essential to effectively address complex coastal environmental issues. USGS studies of sediments are part of a coordinated effort to understand the environment of Massachusetts Bay and complement multidisciplinary programs supported by the Massachusetts Environmental Trust, the Environmental Protection Agency, the National Oceanic and Atmospheric Administration (NOAA), the MWRA, and others. Parts of the USGS effort are co-funded by the MWRA and NOAA and carried out with at-sea support from the U.S. Coast Guard. USGS studies have been conducted cooperatively with scientists at the Woods Hole Oceanographic Institution, the University of New Hampshire, the University of Massachusetts, the Massachusetts Institute of Technology, and the University of New Brunswick.

Continued Monitoring

The USGS will continue to monitor environmental change in Massachusetts Bay. In cooperation with the MWRA, the USGS will continue long-term observations of sediment-contaminant levels and currents in western Massachusetts Bay after the new ocean outfall begins operation in 1998. These observations will provide a unique data set to document environmental change and to assess whether change is caused by natural or anthropogenic processes. A long-term goal of the USGS is to develop similar capabilities in a variety of coastal environments.

Further Reading

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