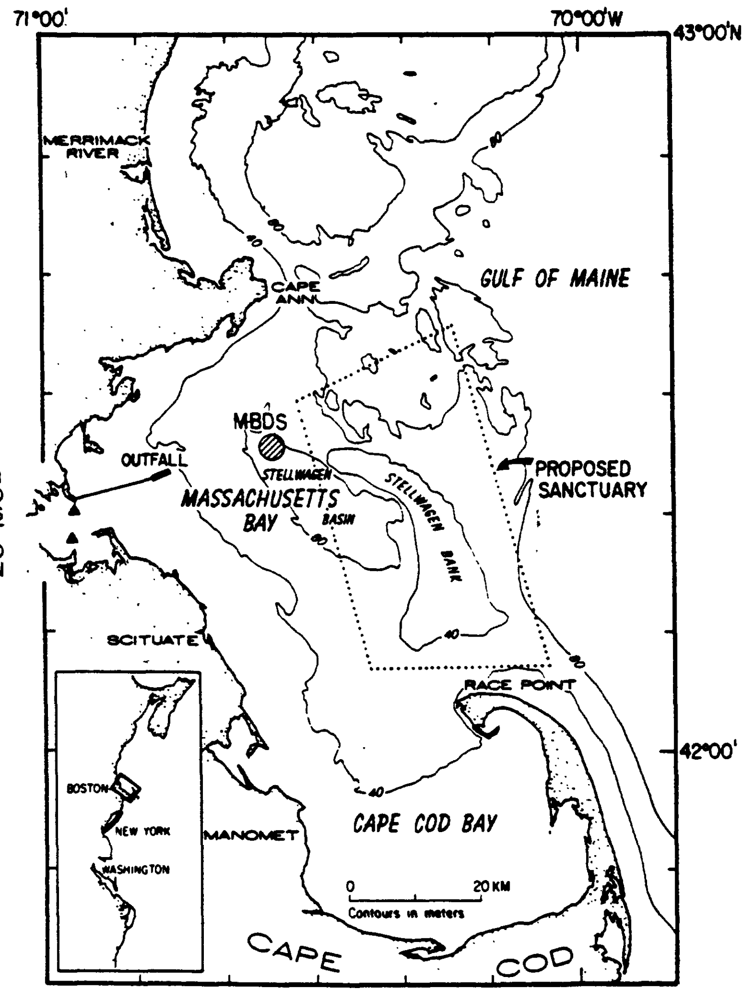
U.S. DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

CONTAMINANT TRANSPORT AND ACCUMULATION IN MASSACHUSETTS BAY AND BOSTON HARBOR: A SUMMARY OF U.S. GEOLOGICAL SURVEY STUDIES



Bradford Butman, Michael H. Bothner, John C. Hathaway, Harry L. Jenter,
Harley J. Knebel, Frank T. Manheim, and Richard P. Signell

U.S. Geological Survey Open-File Report 92-202

Woods Hole, Mass.
February 1992

TABLE OF CONTENTS

Any use of trade names or companies is for descriptive purposes only and does not imply endorsement by the U.S. Geological Survey.

EXECUTIVE SUMMARY

The U.S. Geological Survey (USGS) is conducting studies in Boston Harbor, Massachusetts Bay, and Cape Cod Bay designed to define the geologic framework of the region and to understand the transport and accumulation of contaminated sediments. The region is being studied because of environmental problems caused by the introduction of wastes for a long time, because a new ocean outfall (to begin operation in 1995) will change the location for disposal of treated Boston sewage from Boston Harbor into Massachusetts Bay, and because of the need to understand the transport of sediments and associated contaminants in order to address a wide range of management questions. The USGS effort complements and is closely coordinated with the research and monitoring studies supported by the Massachusetts Environmental Trust, the Massachusetts Bays Program, and by the Massachusetts Water Resources Authority. The USGS study includes (1) geologic mapping, (2) circulation studies, (3) long-term current and sediment transport observations, (4) measurements of contaminant inventories and rates of sediment mixing and accumulation, (5) circulation modeling, (6) development of a contaminated sediments data base, and (7) information exchange. A long-term objective of the program is to develop a predictive capability for sediment transport and accumulation.

Key results to date:

* Areas of sediment erosion and deposition have been mapped within Boston Harbor. Areas of deposition on the seabed are shallow subtidal flats and sheltered depressions where the tidal currents are weak. Contaminants most likely will accumulate in these areas. The shores of the mainland, where waves are relatively large, and harbor islands and the sea bed of constricted channels, where tidal currents are strong, are areas of erosion. Contaminants are not likely to accumulate in these areas of erosion.

* Detailed mapping of the western Massachusetts Bay sea floor in the region of the new Boston sewage outfall shows an extremely varied bottom that provides a wide range of biological habitats. Areas of coarse sand, gravel, and boulders lie adjacent to areas of finer sediments. The surveys have identified areas of fine-grained sediments that are likely sites of contaminant accumulations and candidates for long-term monitoring of environmental quality.

* Remote sensing mapping techniques are essential to adequately determine the complex spatial variability of the bottom morphology and sediment texture; accurate maps cannot be prepared from analysis of sediment grab samples alone.

* The concentrations of heavy metals (lead and silver for example) in fine-grained sediments of Massachusetts Bay near the new outfall site are higher than background concentrations, a condition common in marine areas adjacent to metropolitan centers that have received wastes for a long time. These elevated concentrations may make it difficult to detect changes in contaminant levels that might occur at the new outfall site. To accurately assess future changes caused by the outfall or by other sources, a carefully documented baseline of present contaminant levels is being established.

* To establish more accurate contaminant baselines for the Massachusetts bays and to address a wide range of questions, an intensive compilation of existing and new data on contaminated sediments from Boston Harbor and Massachusetts Bay has been undertaken in cooperation with the Environmental Protection Agency and the Massachusetts Bays Program. Data on more than 1,000 sediment samples revealed that the concentration of metals (copper, lead, cadmium, zinc, silver, nickel, chromium and others) in fine-grained sediments of Boston Harbor are higher than in natural, uncontaminated sediments. The most serious metal contamination in the harbor is caused by mercury; over 90% of the samples exceed the suggested National Oceanic and Atmospheric Administration criteria for low level toxicity.

* Concentrations of metals (copper, zinc, silver, cadmium, nickel and chromium), organic pollutants, and sewage contaminants are typically higher in surficial sediment than in deeper samples, both in the harbor and at the new outfall area.

* Two key processes have been identified which will incorporate contaminants into the bottom sediments. Major storms resuspend bottom sediment near the new outfall site and throughout much of western Massachusetts Bay. In winter, when the water column is mixed, particles are resuspended throughout most of the 30 m water column, providing a greater opportunity for particles to adsorb dissolved contaminants and transport them eventually to the bottom sediments. Bottom-dwelling organisms mix sediments and associated contaminants deposited on the surface into the sediments, potentially sequestering them from further resuspension and transport.

* The residual flow pattern in winter, spring, and summer is consistent with a weak residual counterclockwise flow around the bays, made up of southwesterly flow past Cape Ann, southward flow along the western shore, and outflow north of Race Point. The data suggest that this residual flow pattern reverses in fall. Fluctuations caused by wind and density variations are typically larger than the long-term mean.

* Numerical models are providing a mechanism to interpret the complex spatial flow patterns that cannot be completely resolved by field observations and to investigate key physical processes that control the physics of water and particle transport. The model will eventually form the basis of regional water quality and sediment transport models. The spatial complexity of the flow is typical of nearshore areas that have irregular coastal shorelines and topography and currents that are forced locally by wind and river runoff as well as by the flow in adjacent regions.

* More than 2 years of current measurements made near the new outfall site suggest that water and material discharged there are not swept away in a consistent direction by a well-defined steady current but are mixed and transported by a variety of processes, including the action of tides, winds, and river inflow. One-day particle excursions are typically less than 10 km. The outfall is apparently located in a region to the west of the basin-wide residual flow pattern.

INTRODUCTION

The U.S. Geological Survey (USGS) is conducting studies in Boston Harbor, Massachusetts Bay and Cape Cod Bay (Figure 1) designed to define the geologic framework of the region and to understand the transport and accumulation of contaminated sediments. The region is being studied because of environmental problems caused by the introduction of wastes for a long time, because a new ocean outfall (to begin operation in 1995) will change the location for disposal of treated Boston sewage from Boston Harbor into Massachusetts Bay, and because of the need to understand the transport of sediments and associated contaminants for effective environmental management of coastal waters. These problems are typical of those found off many large metropolitan areas, and thus, results and techniques developed in the Massachusetts bays study will be applicable to other regions. The USGS effort complements and is closely coordinated with studies supported by the Massachusetts Environmental Trust, the Environmental Protection Agency's Massachusetts Bays Program, and the Massachusetts Water Resources Authority to enhance the scope and accomplishments of the overall marine research and monitoring program in Boston Harbor and Massachusetts Bay.

The USGS program is designed to answer fundamental questions such as:

* What is the texture and morphology of the sea floor environment in the Massachusetts bays?
* How are water and materials transported throughout the system?
* Where do sediments and associated contaminants accumulate and at what rate?
* What are the present contaminant levels in the sediments and how will they change?

A long-term objective of the program is to develop a predictive capability for sediment transport and accumulation.

To address the issues of contaminant transport and accumulation in the Massachusetts bays, the USGS has developed and is carrying out a research and mapping program that consists of seven components. The seven components are:

1. Geologic mapping of sedimentary environments
2. Circulation in Massachusetts and Cape Cod Bays
3. Long-term current and sediment transport observations
4. Contaminant inventories and rates of sediment mixing and accumulation
5. Circulation modeling
6. Contaminated sediments data base
7. Information exchange

This report provides a brief summary of the objectives, rationale, fieldwork, results to date, and plans for 1992 for each component.

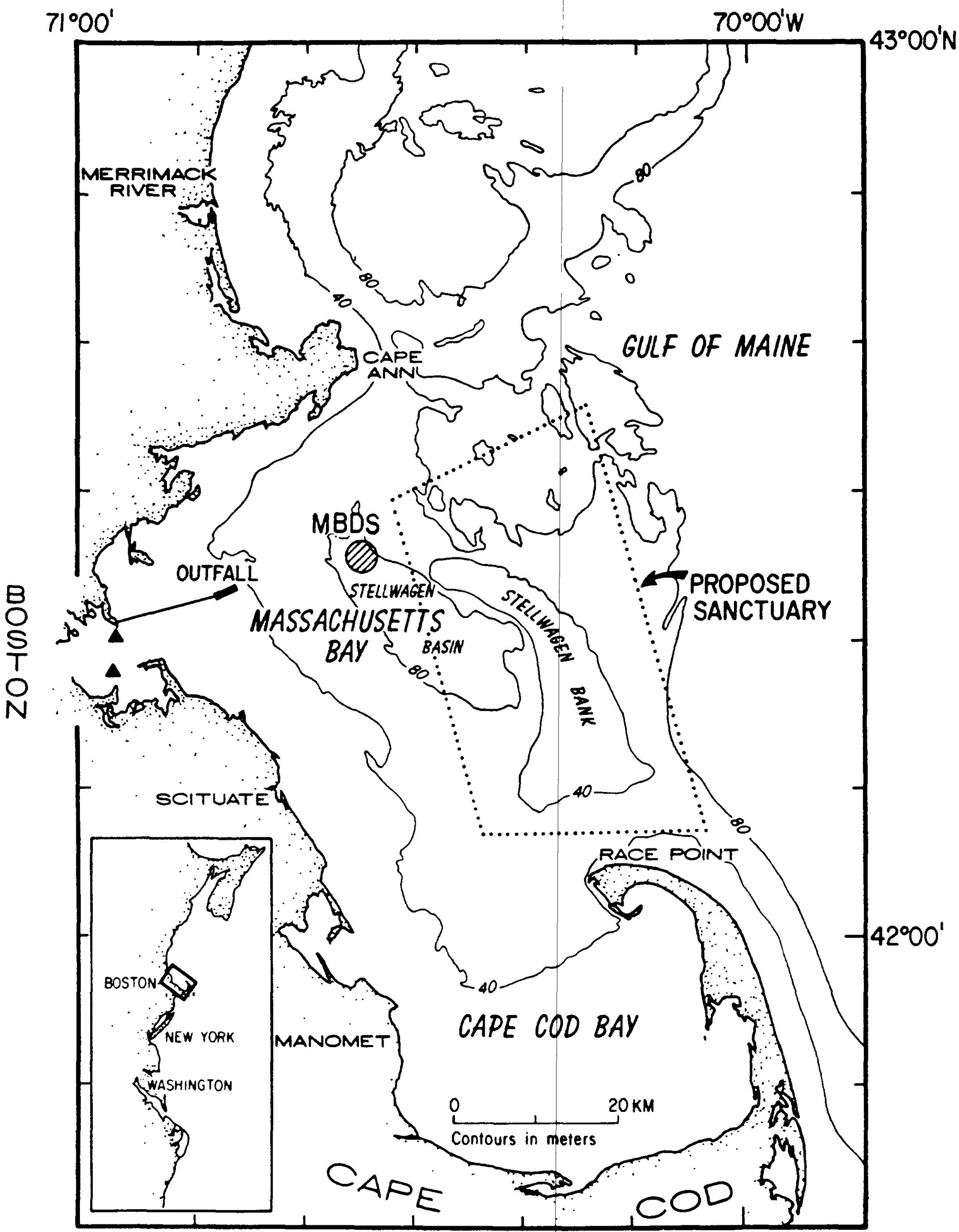


Figure 1. Bathymetric map showing Massachusetts and Cape Cod Bays, present sewage outfalls in Boston Harbor (solid triangles), location of new ocean outfall for treated Boston sewage in western Massachusetts Bay (average flow about 20 m^3/s), approximate boundary of the proposed Stellwagen Bank Marine Sanctuary, and the Massachusetts Bay Disposal Site (MBDS). The annual volume of river discharge from the Merrimack River is about 215 m^3/s and through Boston Harbor is about 10 m^3/s.

STUDY COMPONENTS

1. GEOLOGIC MAPPING OF MODERN SEDIMENTARY ENVIRONMENTS
(Principal USGS investigators: Harley J. Knebel and Michael H. Bothner)

Objective: Outline the regional distribution of sedimentary environments in Boston Harbor and Massachusetts Bay using side-scan sonar, high-resolution seismic reflection profiling, and sediment samples.

Rationale: Mapping of the sedimentary environments identifies areas where sediments and associated contaminants are most likely to accumulate, which potentially are sensitive sites for long-term monitoring. In addition, the mapping provides information useful in characterizing biological habitats.

Fieldwork: Detailed surveys were conducted in 1988 in Boston Harbor (fig. 2, region I, Rendigs and Oldale, 1990; Knebel et al., 1991) and in 1989 in western Massachusetts Bay (fig. 2, Region II, Bothner et al., 1990) using sidescan sonar, bathymetry, bottom photography and sediment sampling. In addition, this study component will utilize more than 1,200 line-km of sidescan sonar records that have been collected in areas I and III as parts of previous studies of Boston Harbor and western Massachusetts Bay (see Cooks et al., 1976; Fitzgerald et al., 1990; Knebel et al., 1991, 1992). Interpretations of the sonographs makes use of (1) subbottom profiles collected concurrently with the sidescan records; (2) grab samples, short cores, vibracores, and bottom photographs; and (3) available current and wave data, especially those collected during the long-term current and sediment transport study (see component 3 below).

Results: OUTFALL AREA (Region II, fig. 2) Maps showing the sediment texture and sea floor morphology have been completed in a 67 km^2 (4 X 5 nautical mile) area of western Massachusetts Bay. The maps and tabular data have been compiled for distribution on a CD-ROM (Bothner et al., 1992). This digital data storage and retrieval system includes: a bathymetric map; color bottom photographs; tabular data of sediment texture; a digital mosaic of sidescan sonar records covering 20% of the survey area (fig. 3); and a map of interpreted surficial geology (fig. 5). These detailed maps of the sea floor were used in selecting the outfall site for Boston's treated sewage effluent. In addition, because contaminants added to coastal waters are most likely to accumulate with the fine-grained sediments, the seafloor maps have been used in the design of environmental and monitoring studies in this region.

The maps demonstrate more fine-scale spatial variability on the sea-floor geology than was previously known (figs. 3, 4 and 5). The hills on the sea floor have the orientation and elliptical shape of drumlins and are typically armored by glacially derived gravel and boulders. The coarse gravel and boulders on these hills cover 23% of the survey area and are thought to represent the top of a glacial till deposit. Using seismic reflection profiles, this surface often can be traced as a strong acoustic reflector under the sediments that fill adjacent depressions. Surface sediments in depressions on the western side of the study area contain fine-grained sediment. These areas, which represent 6% of the survey area, may be preferential depositional sites for contaminants. The finest deposit is 60% silt and 15% clay. The most common sediment type (covering 42% of the area surveyed) consists of coarse sand and gravel that is located on slopes between hills, particularly on the eastern side of the survey area.

The remaining 29% of the area is characterized by a highly variable distribution of sediment types that changes from patches of sand and gravel to finer grained sediment within distances of 50 m or less. The fine-grained patches may be areas where contaminants preferentially accumulate. Their small size, however, makes them difficult targets for routine sampling for contaminant monitoring. Large sand ripples were observed in well-sorted sand; ripple crests are oriented north - south and have wavelengths of up to 4 m and estimated wave heights of about 0.5 m. Areas containing these well-defined bedforms constitute less than 5% of the survey area. The sand ripples probably are generated and maintained by oscillatory bottom currents from large storm swells approaching from the east or northeast. Such storm waves are the major cause of sediment resuspension in western Massachusetts Bay according to continuous observations of currents, waves, and suspended sediment concentrations at long-term instrumented moorings (see component 3 below; Bothner and Butman, 1990).

Results: BOSTON HARBOR (Region I, fig. 2) The shallow geologic framework of Boston Harbor and Massachusetts Bay has been mapped by Oldale and Bick (1987), Rendigs and Oldale (1990), and Knebel et al. (1992). These studies show that a wide variety of sedimentary units crop out or underlie the modern deposits on the sea floor. These units include Paleozoic bedrock, pre-Wisconsinan till, late Wisconsinan glacial drift and glaciomarine sediments, and Holocene channel-fill and marine deposits. The variable distribution of these texturally diverse rock types reflects the complex geologic history of this region, which includes periods of glaciation, crustal movement, and sea-level change.

Knebel et al. (1991) outlined the modern sedimentary environments in Boston Harbor from analyses of sidescan-sonar records supplemented by available bathymetric, sedimentary, subbottom, and bottom-current data (fig. 6). This study revealed where the modern wave and current regime has interacted with the complex topography and geometry of the harbor area to create environments of erosion, deposition, and sediment reworking atop the older sedimentary units. Areas of erosion (or nondeposition) appear on the sonographs either as patterns with isolated reflections or as patterns of uniform strong reflectivity. Erosional areas contain gravelly coarse-grained sediments and are found along mainland and insular shores, across the harbor entrance, within large constricted tidal channels and depressions, and over local topographic prominences where the waves and tidal currents are strong. Areas of deposition, on the other hand, appear as smooth featureless patterns of low reflectivity. These areas are blanketed by organic-rich muds that have accumulated over shallow subtidal flats and within broad bathymetric lows sheltered from strong tidal flow. Finally, areas of light and dark patches produced by variable reflectivity depict a combination of erosional and depositional processes in areas of reworked bottom sediments. Environments of sediment reworking have diverse grain sizes and are found in areas of variable bottom currents.

Plans for FY 92: Examination of the available sonographs from western Massachusetts Bay (fig. 2, Region III) reveals that this part of the New England glaciated shelf is characterized by sonograph patterns similar to those found in Boston Harbor. During FY 92, these patterns will be mapped across this part of the shelf extending from the coast to water depths of about 50 m. In compiling this map, the various previously collected data sets (Cooks et al., 1976) will be analyzed and integrated, and the resulting interpretations will be tied in with those in the harbor area. The detailed sonograph coverage within area II (fig. 2) will provide a calibration area for comparing sonographs obtained from various sources and for correcting navigational errors in the regional data set collected by Cooks et al. (1976).

A new set of sidescan-sonar images (1-2 km line spacing) will also be collected covering the deeper parts of western Massachusetts Bay and extending into parts of Stellwagen Basin (see region IV, fig. 2). This is a likely area of fine-grained sediment accumulation located just offshore of the proposed outfall site in region II. The new sonograph data set will incorporate sedimentary environments across the deeper parts of the shelf and should provide additional information concerning depositional sites and transport pathways of fine-grained sediments and contaminants.

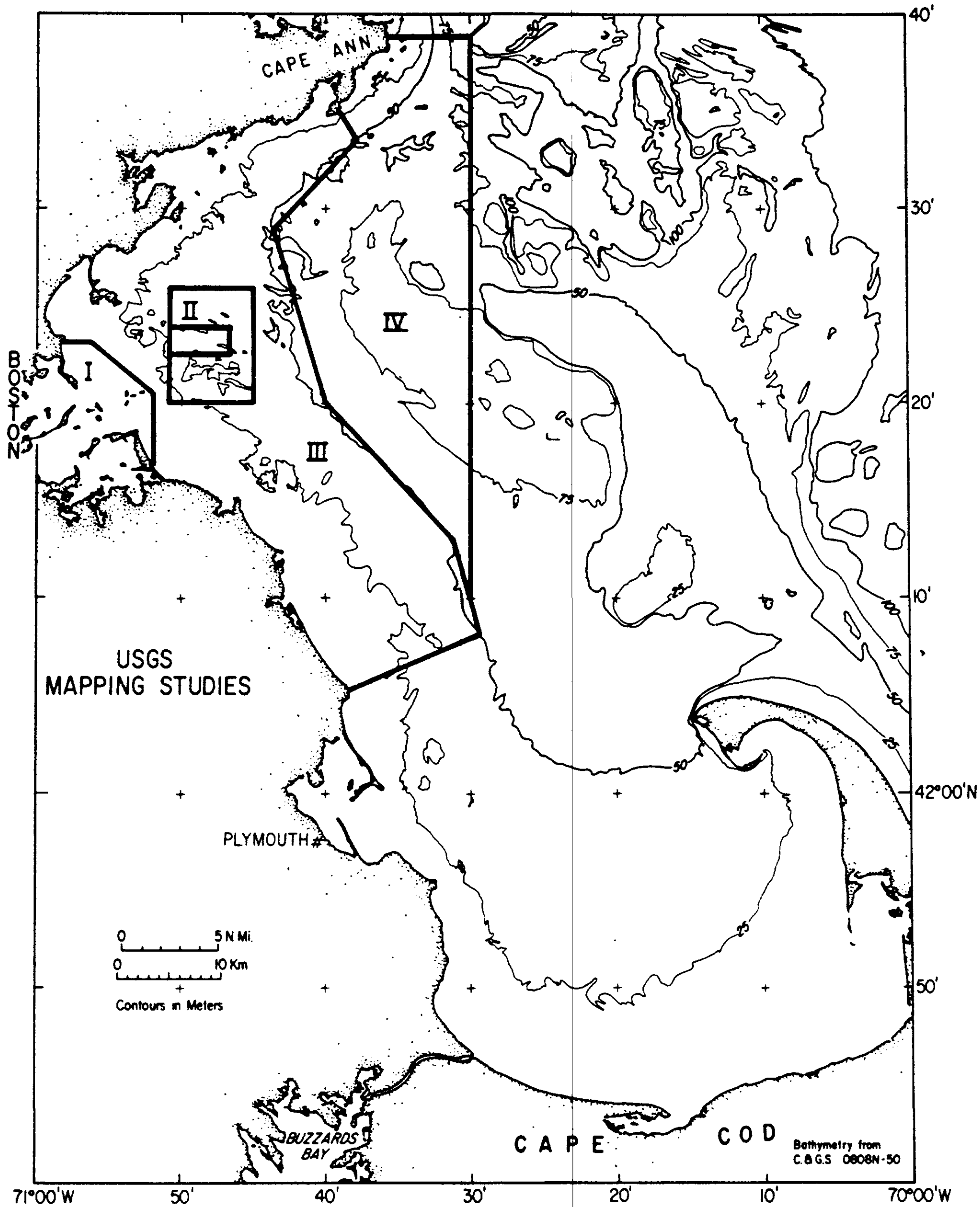
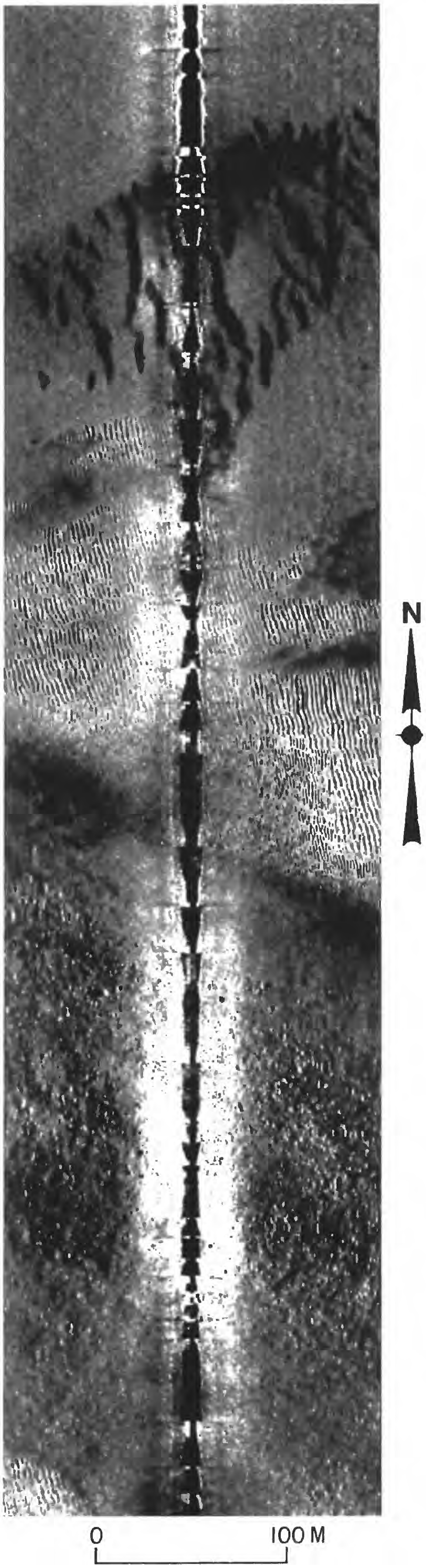


Figure 2. Location of USGS mapping studies designed to characterize the sedimentary environments of Boston Harbor and western Massachusetts Bay. Region I is a survey of sedimentary framework of Boston Harbor (Rendigs and Oldale, 1990, Knebel et al., 1991, 1992). Region II is the area surrounding the new ocean outfall (Bothner et al., 1990). The small box in region II is the boundary of the mosaic shown in figure 3. Region III is the area for which previously collected sidescan sonar records are being analyzed to map acoustic patterns and related sedimentary environments. Region IV is the proposed area covering the deeper sections of Massachusetts Bay and parts of Stellwagen Basin to be surveyed by sidescan sonar in FY 92.

Figure 3. Digital mosaic of sidescan-sonar images of the region surrounding the outfall area (see small box in region II, fig. 2) with bathymetry superimposed (contoured at 5 ft intervals in feet below mean low water). The mosaic shows a complex spatial pattern of bottom reflectivity, which indicates changes in sediment texture and roughness. The large rectangular box is the corridor for the diffusers for the new ocean outfall. The north-south-trending lines indicate the track of the sidescan fish. The blank gray stripes are areas of no data. In this image the areas of boulders are represented by the lightest tone and are typically found on the hills. The darkest areas represent deposits of fine-grained sediments, typically in topographic lows. The intermediate gray tone is sand with varying amounts of gravel. These interpretations are based on photography and samples. The small white box is the location of the image shown in figure 4. From Bothner et al., 1992.

Figure 4. A digitally processed sidescan sonar image from the mosaic shown in figure 3 at expanded scale. At the northern end, this figure shows elongated areas of finer grained material (darkest areas) within a sand and gravel deposit. In the center of the figure are large sand waves having wavelengths of up to 3 m. The sidescan pattern at the southern end of the figure is caused by boulders which cover a hill on the sea floor. Some of the individual objects seen in the sidescan image, presumed to be boulders, are 2-4 m in size. Note that the sediment type may change over a distance of 50 m or less; monitoring studies must be designed with this spatial variability in mind.



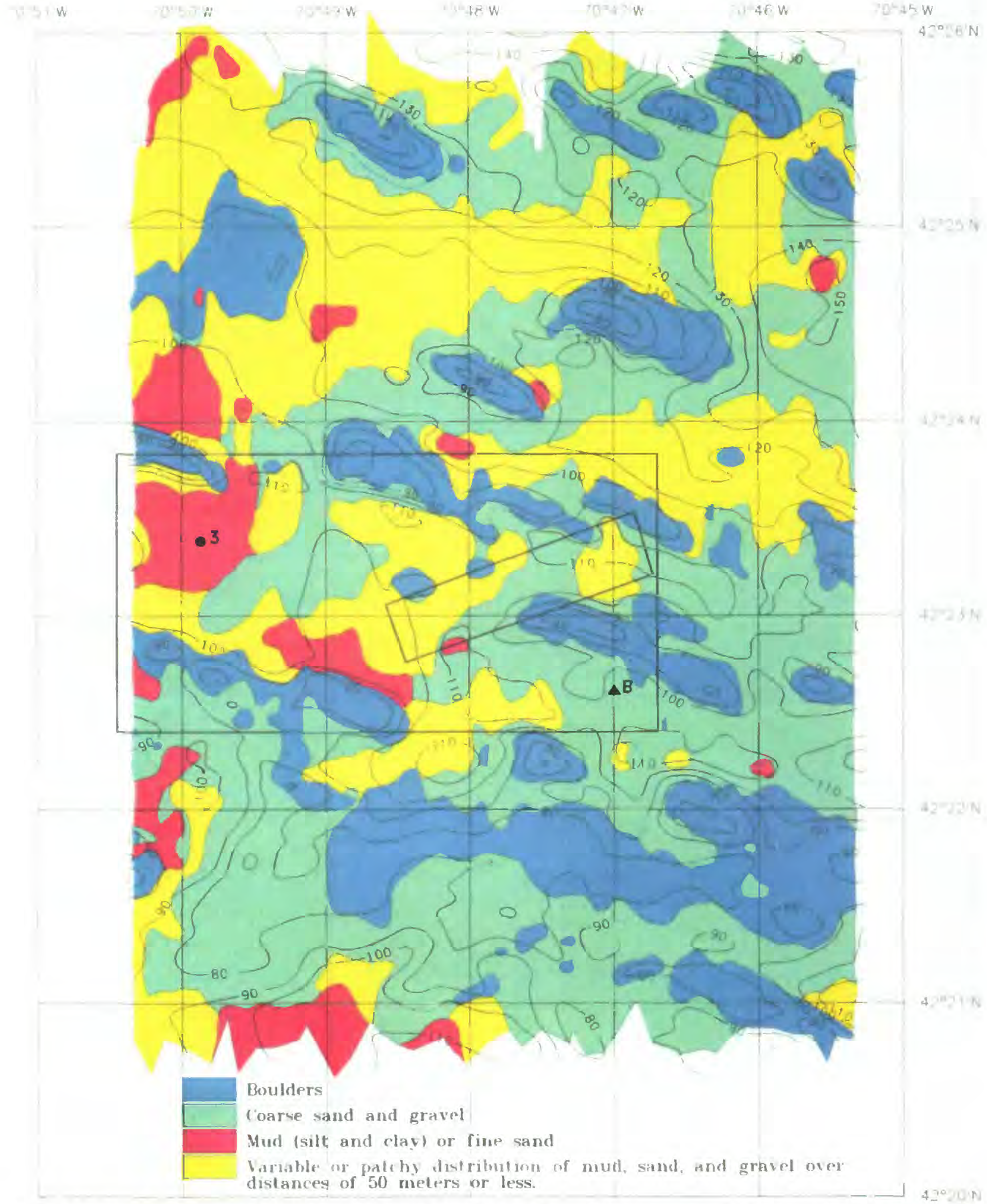


Figure 5. Geologic map for region II (see fig. 2) based on sidescan sonar images, video camera and textural analysis of surficial sediments. Bathymetry is superimposed with a 5 ft contour interval. B is the location of the long-term mooring; 3 is the location of sediment samples shown in figure 13. The smaller box will contain the diffusers for the new ocean outfall. The larger box is the area of the digital sidescan mosaic shown in figure 3. From Bothner et al., 1992.

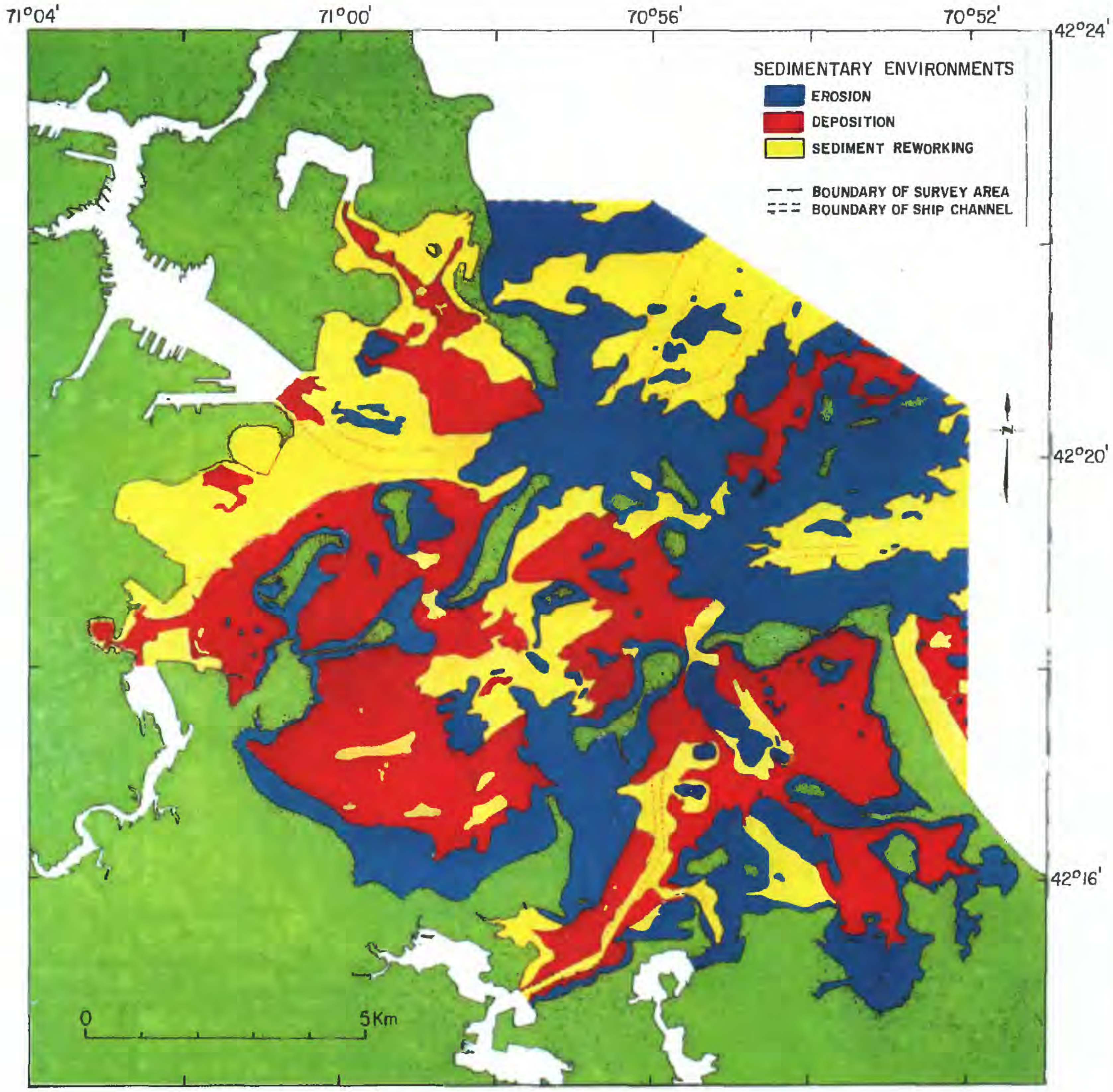


Figure 6. Map showing the distribution of sedimentary environments in Boston Harbor (fig. 2, Region I) based on analyses of sidescan-sonar records supplemented by available bathymetric, sedimentary, subbottom, and bottom-current data. Erosional areas (shown in blue) contain gravelly coarse-grained sediments and are found along mainland and insular shores, across the harbor entrance, within large constricted tidal channels and depressions, and over local topographic prominences where the waves and tidal currents are strong. Areas of deposition (shown in red) are blanketed by organic-rich muds that have accumulated over shallow subtidal flats and within broad bathymetric lows sheltered from strong tidal flow. Areas of reworked bottom sediments (shown in yellow) have diverse grain sizes and are found in areas of variable bottom currents. From Knebel et al. (1991).

2. CIRCULATION IN MASSACHUSETTS AND CAPE COD BAYS
(Principal USGS investigators: Bradford Butman and Richard P. Signell)

Objectives: Describe the baywide currents, transport, and exchange of water between the Massachusetts Bay and the Gulf of Maine on a seasonal basis. Provide a data set for testing of numerical models to form the basis of water quality models.

Rationale: A description of the baywide circulation on a seasonal basis is essential for understanding the transport of water, dissolved substances, and particles. Because horizontal and vertical transport is important to biological, chemical, and geological processes in Massachusetts and Cape Cod Bays, this physical oceanographic study will have broad application and will improve the ability to manage and monitor the water and sediment quality of the bays.

Field Studies: Between April 1990 and June 1991, a major field program was conducted to map the circulation and water properties in the Massachusetts bays on a seasonal basis. The experiment consisted of an array of moored instruments deployed in Massachusetts and Cape Cod Bays (fig. 7), detailed surveys of water properties, and a sequence of surface and bottom drifter deployments (Brown et al., 1992; Hotchkiss and Signell, 1991). Additionally, satellite data of sea-surface temperature were obtained, as well as coastal meteorology, sea level, and river run-off data. This physical oceanography experiment was initially conceived and crried out by a consortium of scientists at the University of New Hampshire (UNH), Woods Hole Oceanographic Institution (WHOI), and the University of Massachusetts at Boston (UMASS), and was augmented by scientists at the U.S. Geological Survey once initiated. The study was supported by the Massachusetts Environmental Trust, EPA's Massachusetts Bays Program, the Massachusetts Water Resources Authority, and the U.S. Geological Survey.

Results: The currents in the Massachusetts bays are driven by the tides, wind, changes in water density resulting from the local input of fresh water into Boston Harbor and from the Merrimack River, and low-salinity water from the Gulf of Maine. The flow patterns driven by these various forcing mechanisms are often complex because of the basin geometry, and they change rapidly with time and season in response to changes in wind forcing and river discharge. Typical daily water-particle excursions decrease with depth in the water column. In the western part of the bay daily water particle excursions are typically 5-10 km. The observations generally support the historical conceptual picture of counterclockwise flow (Bigelow, 1927; Bumpus and Lauzier, 1965), made up of southwesterly inflow south of Cape Ann and across Stellwagen Bank, southerly flow along the coast east of Plymouth and Scituate, and northeasterly outflow north of Race Point (fig. 7). However, this weak residual flow pattern is often altered by the wind and density changes and, except at U2 and Race Point, the fluctuations are typically stronger than the mean. In fall, the residual flow pattern appears to reverse (fig. 7d). The daily averaged currents are strongest in summer; although the winds are weak during this period, the water column is stratified so the frictional drag on the flow is reduced. Currents are weakest in the winter, even though the winds are strongest. A primary exit pathway for water leaving Massachusetts Bay is the channel north of Race Point at the northern tip of Cape Cod. Analysis of the moored array observations suggests that the flow patterns cannot be resolved completely by field measurements. Numerical models provide detailed information on the three-dimensional flow pattern caused by various forcings and thus greatly aid in the interpretation of the spatial flow patterns and in understanding the physics of water and particle exchange (see component 5 below).

<u>Plans for 1992:</u> An analysis report describing the results of the baywide measurement program will be completed by the consortium of scientists at UNH, WHOI, UMASS, and USGS. The analysis of these data has several objectives: (1) estimating the rates of water exchange between different parts of the bays and with the adjoining Gulf of Maine; (2) identifying and quantifying the physical mechanisms responsible for the observed motions and variations in water properties; and (3) providing a test of a three-dimensional numerical model being implemented by the USGS in cooperation with Hydroqual, Inc. and the MWRA to describe the physical transport in the bays.

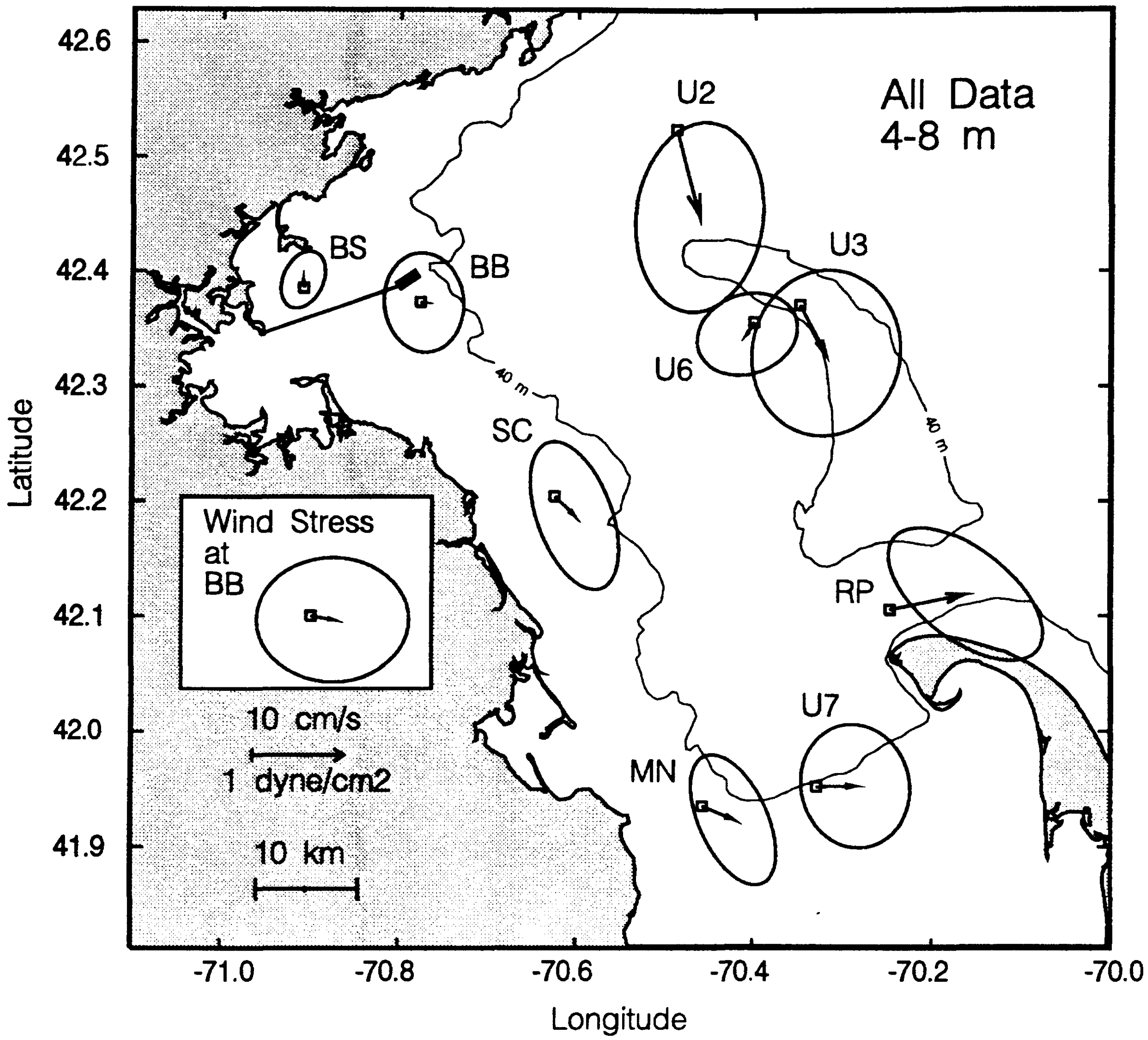


Figure 7a. Map showing the mean flow (solid arrow) and the low-frequency variability (shown as ellipses centered around the tip of the mean flow) for all near-surface (4-8 m depth) current measurements made from December 1989 to September 1991. Typically, the daily-averaged current originates at the station symbol and flows toward any location within the ellipse. The arrows and ellipses have been scaled to correspond to the distance a particle moving with that current would travel in one day. With the exception of station U2 and RP, the fluctuations are larger than the mean. The mean-flow pattern suggests weak flow into Massachusetts Bay from the north and across Stellwagen Bank, southeastward along-shore flow near Scituate and Plymouth, easterly flow in Cape Cod Bay, and outflow in the channel north of Race Point. Note that the area of the new ocean outfall is an area of weak flow compared to the outer bay and there is no strong preferred direction of flow; it is apparently located to the west of the stronger residual coastal current system. This means that water and material here are mixed and transported by a variety of processes rather than being swept in a consistent direction by well-defined steady currents. These data were collected by scientists at UNH (stations U2, U3, U6 and U7), WHOI (stations BS and SC), and USGS (stations BB, MN, RP and U6) as part the Massachusetts Bays Program (see text). Station BB is the long-term monitoring station.

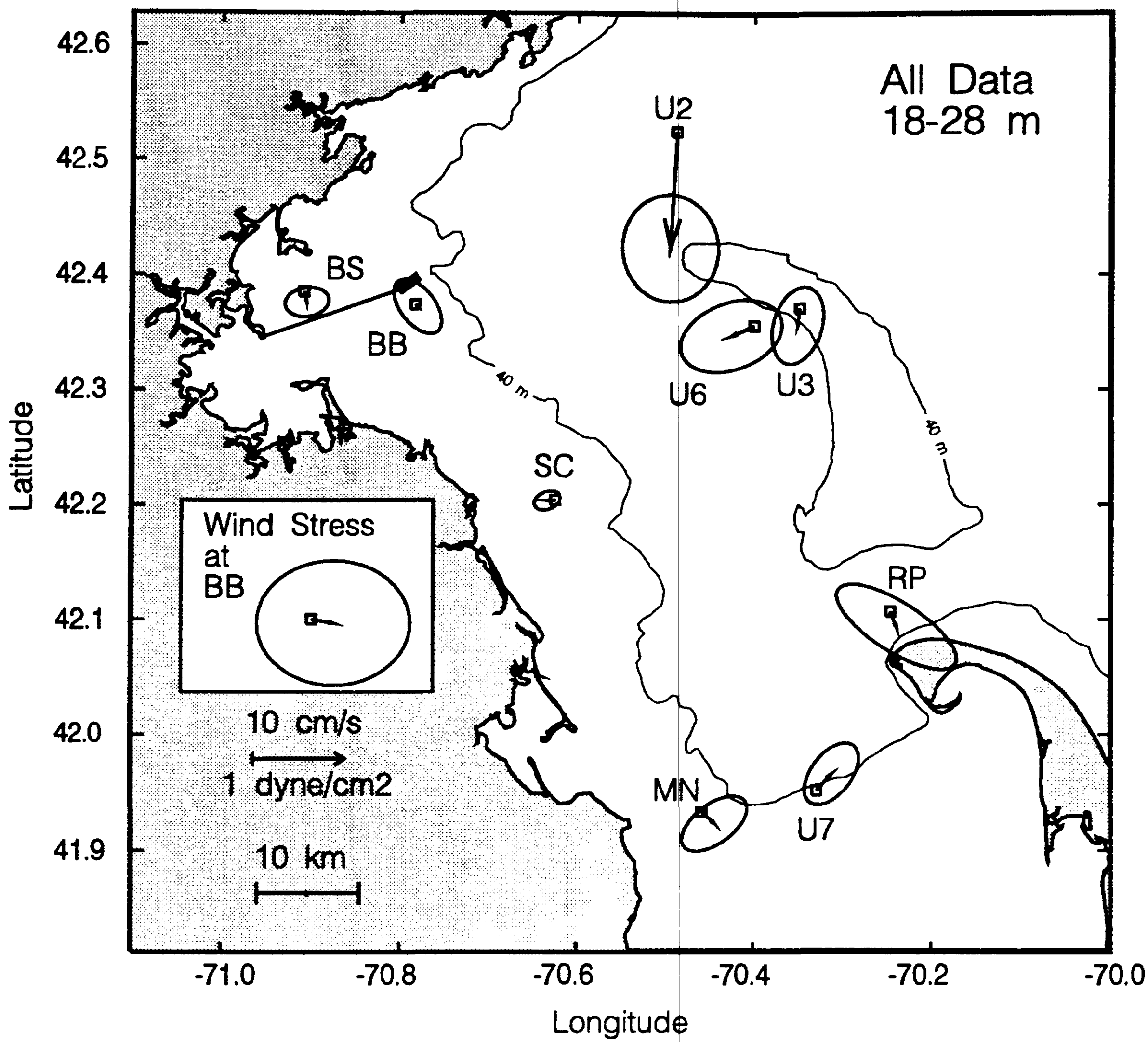


Figure 7b. Map showing the mean flow (solid arrow) and the low-frequency variability (shown as ellipses centered around the tip of the mean flow) at depths between 18 and 28 m from the surface for all current measurements made from December 1989 to September 1991. Typically, the daily-averaged current originates at the station symbol and flows toward any location within the ellipse. The arrows and ellipses have been scaled to correspond to the distance a particle moving with that current would travel in one day. At 18-28 m, the fluctuations are weaker than at 4-8 m from the surface (fig. 7a). Note that the strong flow to the east out of Massachusetts Bay at station RP at 4-8 m (fig. 7a) does not occur at 18-28 m. See figure 7a for information on the moored array.

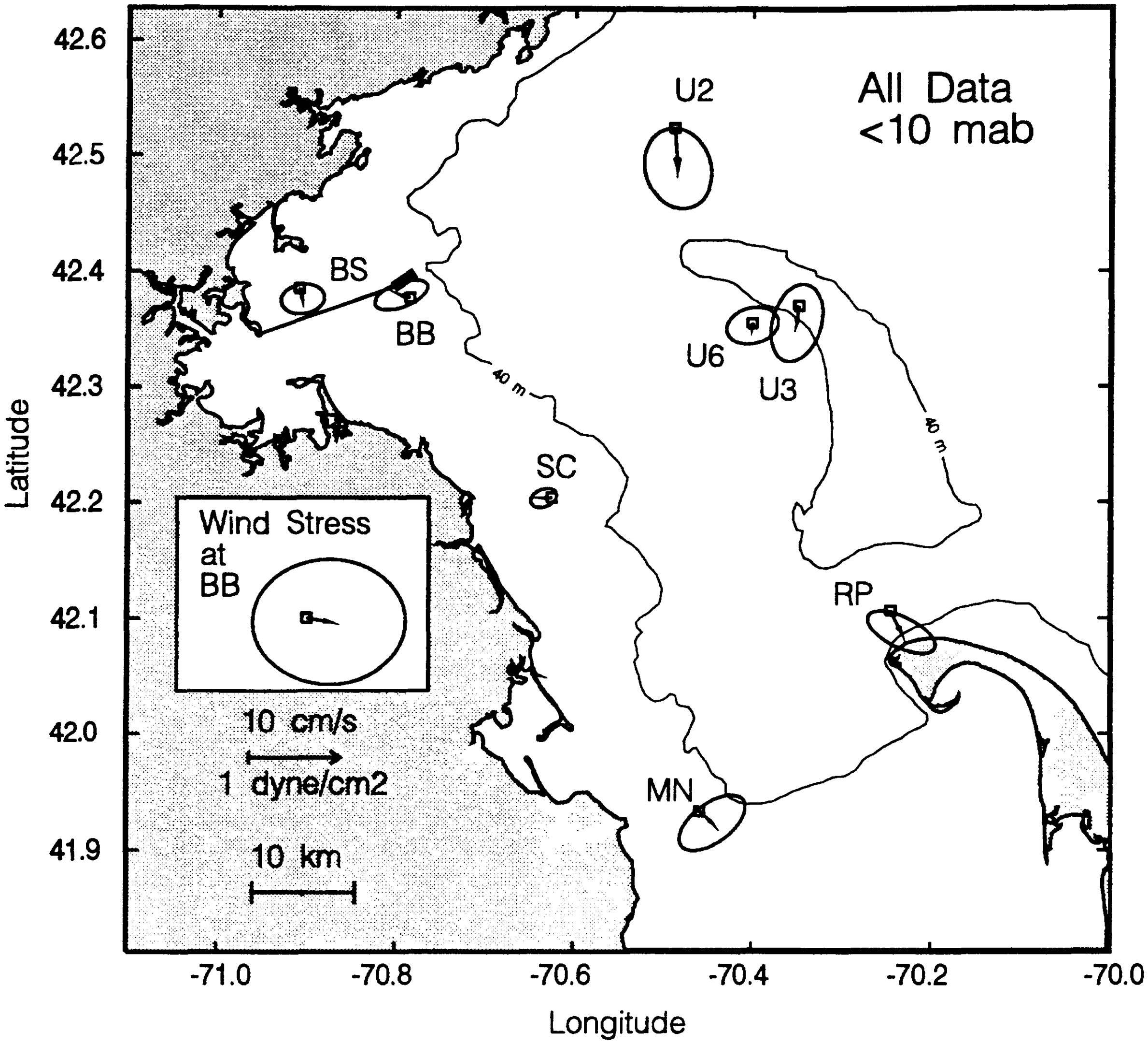


Figure 7c. Map showing the mean flow (solid arrow) and the low-frequency variability (shown as ellipses centered around the tip of the mean flow) at depths within 10 m of the bottom for all current measurements made from December 1989 to September 1991. Typically, the daily-averaged current originates at the station symbol and flows toward any location within the ellipse. The arrows and ellipses have been scaled to correspond to the distance a particle moving with that current would travel in one day. Note the very weak onshore flow near the bottom at Station BB and SC, suggesting coastal upwelling in the bottom layers. See figure 7a for information on the moored array.

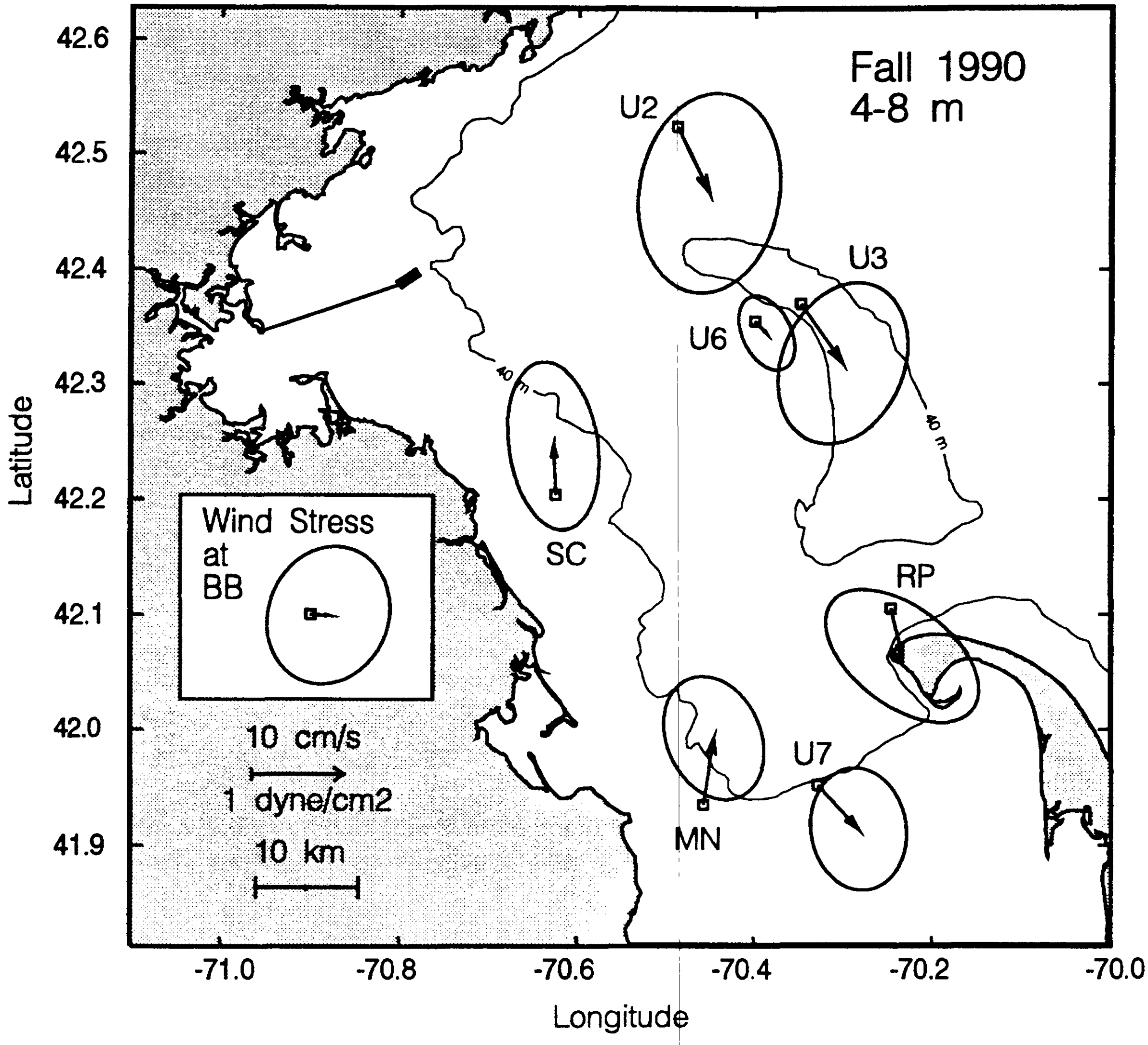


Figure 7d. Map showing the mean flow (solid arrow) and the low-frequency variability (shown as ellipses centered around the tip of the mean flow) for all near-surface (4-8 m depth) current measurements made during the fall of 1990 (September 1, 1990, to November 1, 1990). Typically, the daily-averaged current originates at the station symbol and flows toward any location within the ellipse. The arrows and ellipses have been scaled to correspond to the distance a particle moving with that current would travel in one day. The mean flow arrows suggest a reversal of the long-term near-surface flow pattern (fig. 7a), with westward flow north of Race Point, and northward flow along the western shore of Massachusetts Bay. Although not resolved by the available measurements, outflow probably occurs south of Cape Ann. See figure 7a for information on the moored array.

3. LONG-TERM CURRENT AND SEDIMENT TRANSPORT OBSERVATIONS
(Principal USGS investigators: Michael H. Bothner, Bradford Butman and Richard P. Signell)

Objectives: Document the long-term changes in currents, hydrography, and suspended-matter concentration and composition in western Massachusetts Bay. Investigate the importance of infrequent catastrophic events, such as major storms or hurricanes, to sediment resuspension and transport. Provide physical measurements to aid in interpretation of biological and chemical observations.

Rationale: Long-term observations are essential to document infrequent catastrophic events, such as storms or hurricanes that are major causes of sediment movement, and to define seasonal and interannual variability. The long-term physical observations near the outfall provide a framework for biological, chemical, and geochemical studies.

Field measurements: Maintain a long-term monitoring station at the Large Navigational Buoy (42° 22.6'N 70° 47.1'W, Station BB, see figures 5 and 7a) in western Massachusetts Bay. Observations include measurements of current, temperature, salinity, dissolved oxygen, light transmission, bottom pressure, waves, and suspended sediment concentration by means of a pumped sampler (fig. 8). A time-series sediment trap collects material from the water column sequentially over 9-day intervals. Logistical support for deployment and recovery of the long-term mooring is provided by the U.S. Coast Guard.

Results: Several key conclusions have emerged from the data collected at the long-term site which will help predict the fate of material discharged from the new outfall:

* More than 2 years of current measurements made near the outfall site suggest that water and material discharged there are not swept away in a consistent direction by a well-defined steady current but are mixed and transported by a variety of processes, including tides, winds, and river inflow. Typical 1-day particle excursions from the outfall are on the order of 10 km (fig. 9).

* Currents are strongest and most variable in the spring and summer due to the horizontal and vertical density gradients associated with the runoff of freshwater from Boston Harbor and the Merrimack River and the development of a strong seasonal thermocline that reduces the influence of bottom friction on the currents (fig. 10). Winds are the major forcing agent of the weak currents in winter.

* Storms periodically resuspend material on the sea floor at the outfall site (fig. 11). The ultimate fate of contaminants deposited on the sea floor near the outfall will depend on how they are mixed into the bottom sediments and whether they are resuspended and transported from the site by these events.

* Resuspension events provide an opportunity for resuspended matter to adsorb dissolved pollutants from seawater for eventual deposition onto the sea floor. During winter, the

sediment trap and transmissometer data indicate that sediments are resuspended to at least 5 m of the surface during storms; therefore the potential for adsorption reactions exists throughout most of the water column (30 m water depth) at this location.

* The rates of suspended sediment collection measured since December 1989 show a seasonal pattern (fig. 12). In general, the sediment collection rates display a maximum in spring, a minimum in summer, followed by increasing fluxes again in late summer and fall. Winter rates are highly variable. This seasonal pattern supports the hypothesis that fine-grained, organic-rich sediments accumulate on the bottom in western Massachusetts Bay during the tranquil summer months and then are resuspended and transported in response to storms at the end of the summer season. Understanding the timing and causes of this seasonal trend is important because the same processes may control the distribution of contaminants that are associated with fine-grained sediments.

<u>Plans for FY92:</u> Continue observations of current, temperature, light transmission, salinity, pressure, and suspended sediments at the long-term site. Instrumentation is recovered and redeployed 3 times per year.

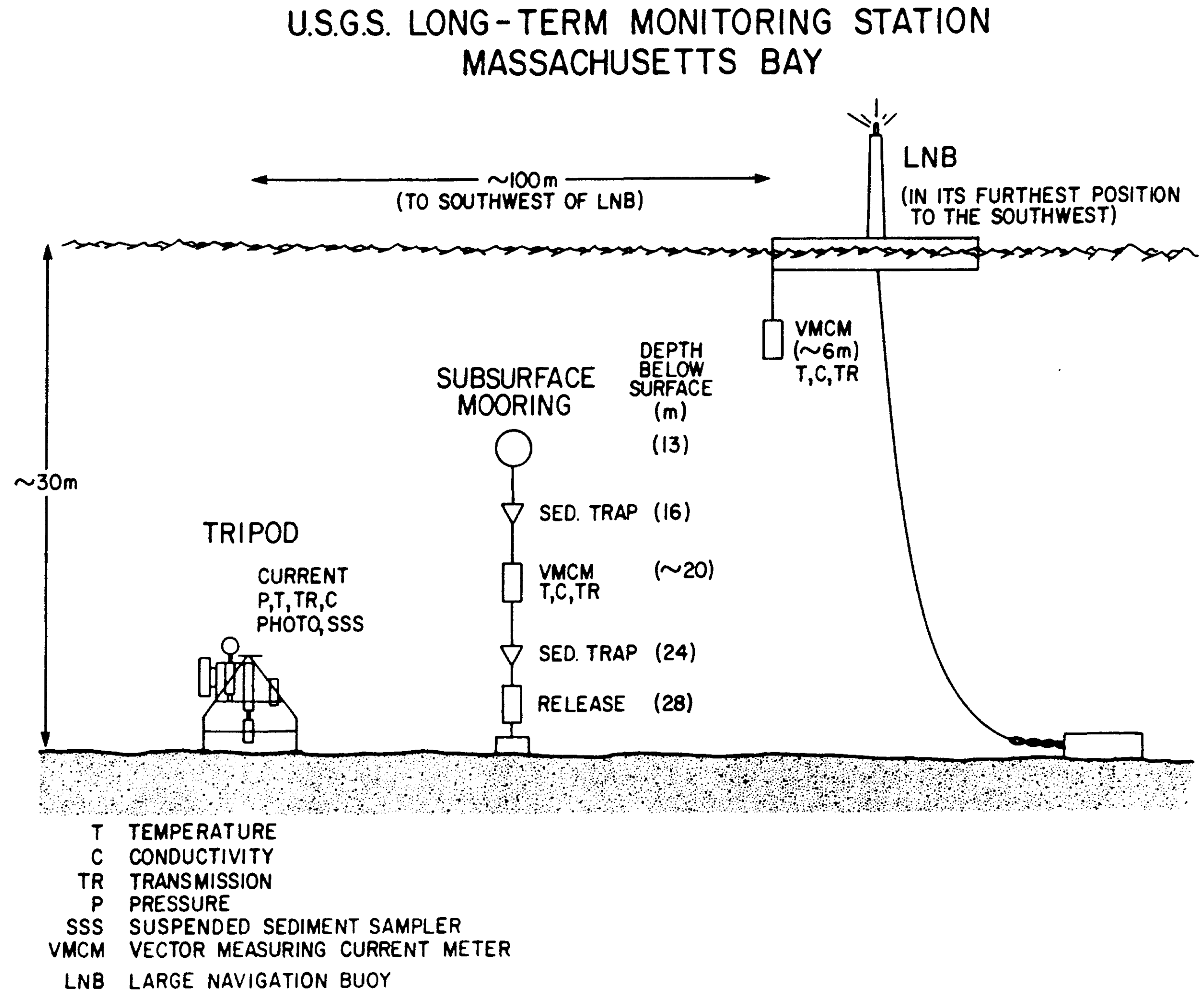


Figure 8. Schematic of the instrumentation deployed at the long-term monitoring site in western Massachusetts Bay (station BB, figs. 5 and 7a). This instrumentation provides measurements of current, temperature, salinity, and light transmission at 5 and 23 m and at the bottom. The bottom tripod also measures pressure and photographs the sea floor. Sediment traps collect samples of suspended matter at 16 and 24 m water depth and at the bottom. A pumped sampling system collects samples of suspended matter during selected events at the bottom. This station is an integral part of the baywide moored array experiment (fig. 7a) and will be maintained indefinitely to document infrequent catastrophic events as well as the seasonal and interannual variability. Logistical support for deployment and recovery of the long-term mooring is provided by the U.S. Coast Guard.

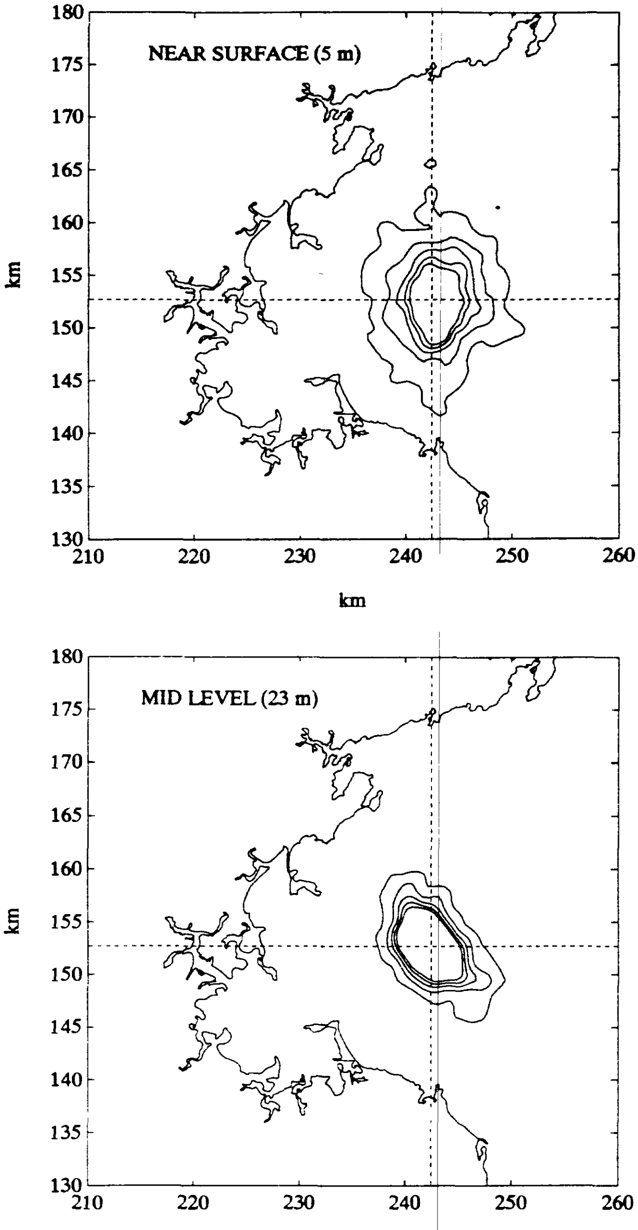


Figure 9. Simulation of the distribution of water particles released at 5 (top) and 23 m (bottom) at the new outfall site after 1 day. This distribution is based on the current observations at the long-term site (station BB, fig. 7a) from December 1989 to September 1991 and was developed by assuming particles are released into the flow each hour, calculating the 1-day particle trajectories, and contouring the distribution of end points of the trajectories. The calculation assumes that the flow measured at the long-term site is representative of the flow over the area of travel. For the 5-m observations, 87% and 40% of the 1-day excursions fall within the outer and inner contour, respectively. For the observations at 23 m, 96% and 73% of the 1-day excursions fall within the outer and inner contours, respectively. Note that there is no strong directional preference for the initial 1-day particle directions.

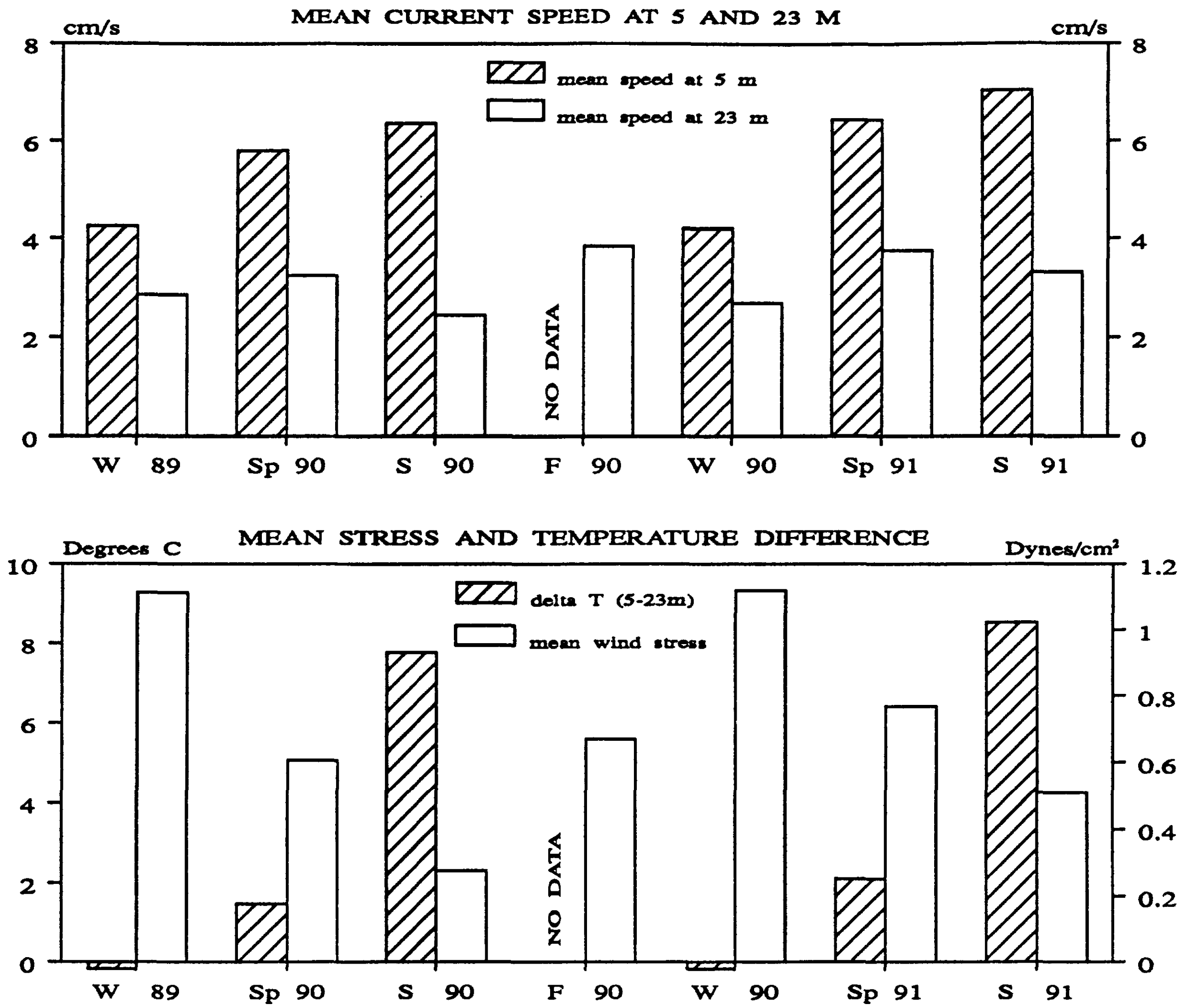


Figure 10. Top: Mean daily vector-averaged current speed at 5 and 23 m water depth obtained at the USGS long-term monitoring station (winter, November through February; spring, March through May; summer, June through August; fall, September and October). These current speeds can be used to estimate daily water-particle travel distances (approximately 0.9 km/day for each centimeter per second of speed). Bottom: Mean daily averaged wind stress amplitude at the Large Navigational Buoy and temperature difference between 5 and 23 m water depth at the long-term monitoring site. Wind stress is strongest in winter and weakest in summer; stratification (as indicated by the temperature difference between 5 and 23 m) is weakest in winter and strongest in summer. At 5 m, the current speeds increase from about 4 cm/s in winter to 6 cm/s in summer even though the winds are stronger in the winter. This suggests that stratification is more important than wind in determining the strength of the near-surface current at the new outfall site. Current speeds at 23 m remain between 2 and 4 cm/s and do not show a seasonal trend. No data was obtained in fall 1990.

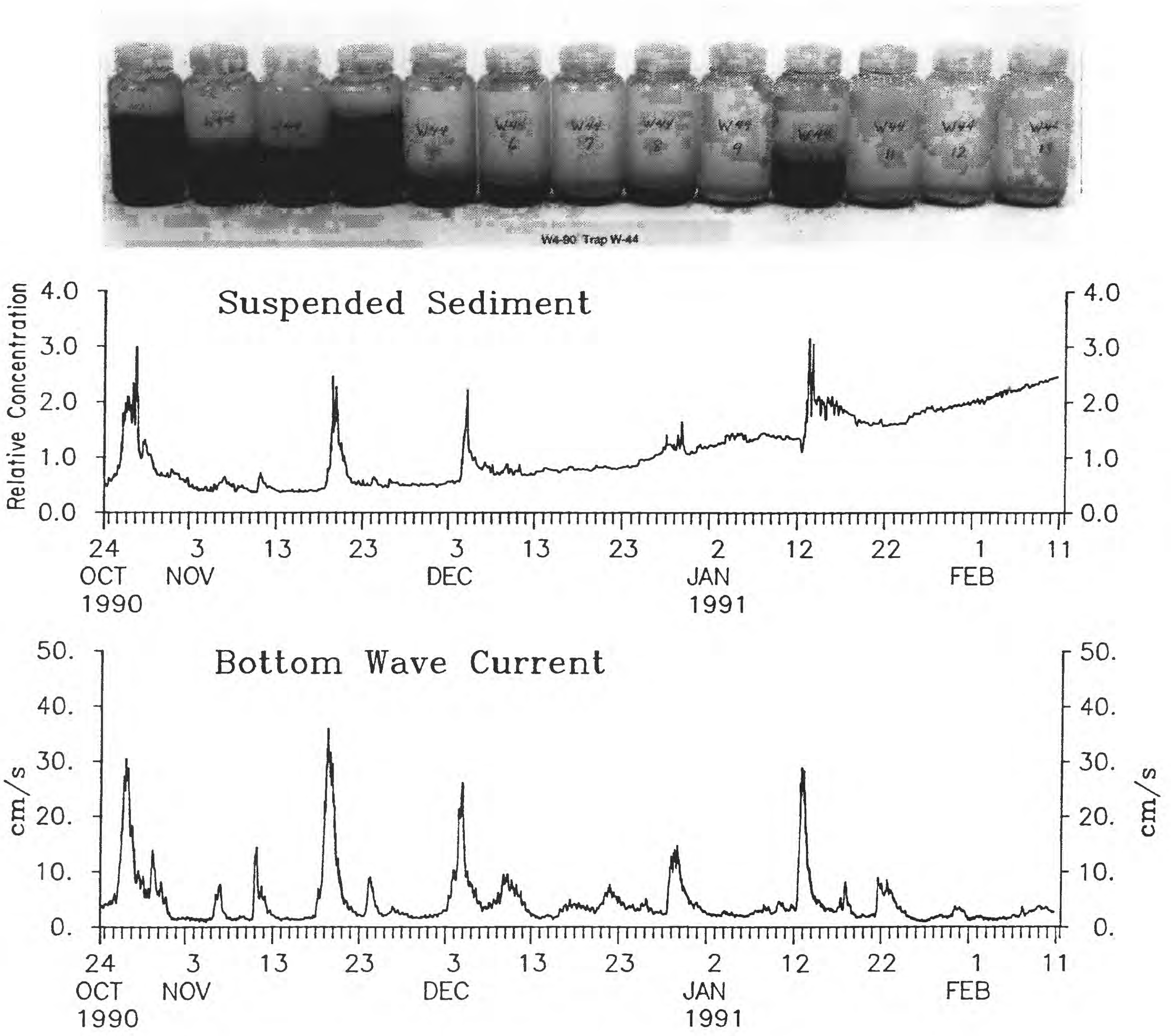


Figure 11. Photograph of the sample bottles (top) from the time-series sediment trap located 4 meters above the bottom at the long-term monitoring site shows the varying amount of material collected during approximately 9-day intervals from October 1990 until February 1991. The turbidity in the bottom water (second panel) is related to the concentration of suspended matter in the water (the upward sloping baseline starting in December is a result of biological fouling of the transmissometer optics used to make the measurements). The close correlation between the four periods of high turbidity in the water column and the four most intense periods of wave activity (bottom panel) indicates that waves are the major cause of resuspension; the rates of sediment collection in the sediment trap bottles also vary with the amount of resuspension. The samples provide an opportunity to measure the attributes (sediment characteristics, contaminant levels, etc.) of material in the water column during storm and nonstorm periods.

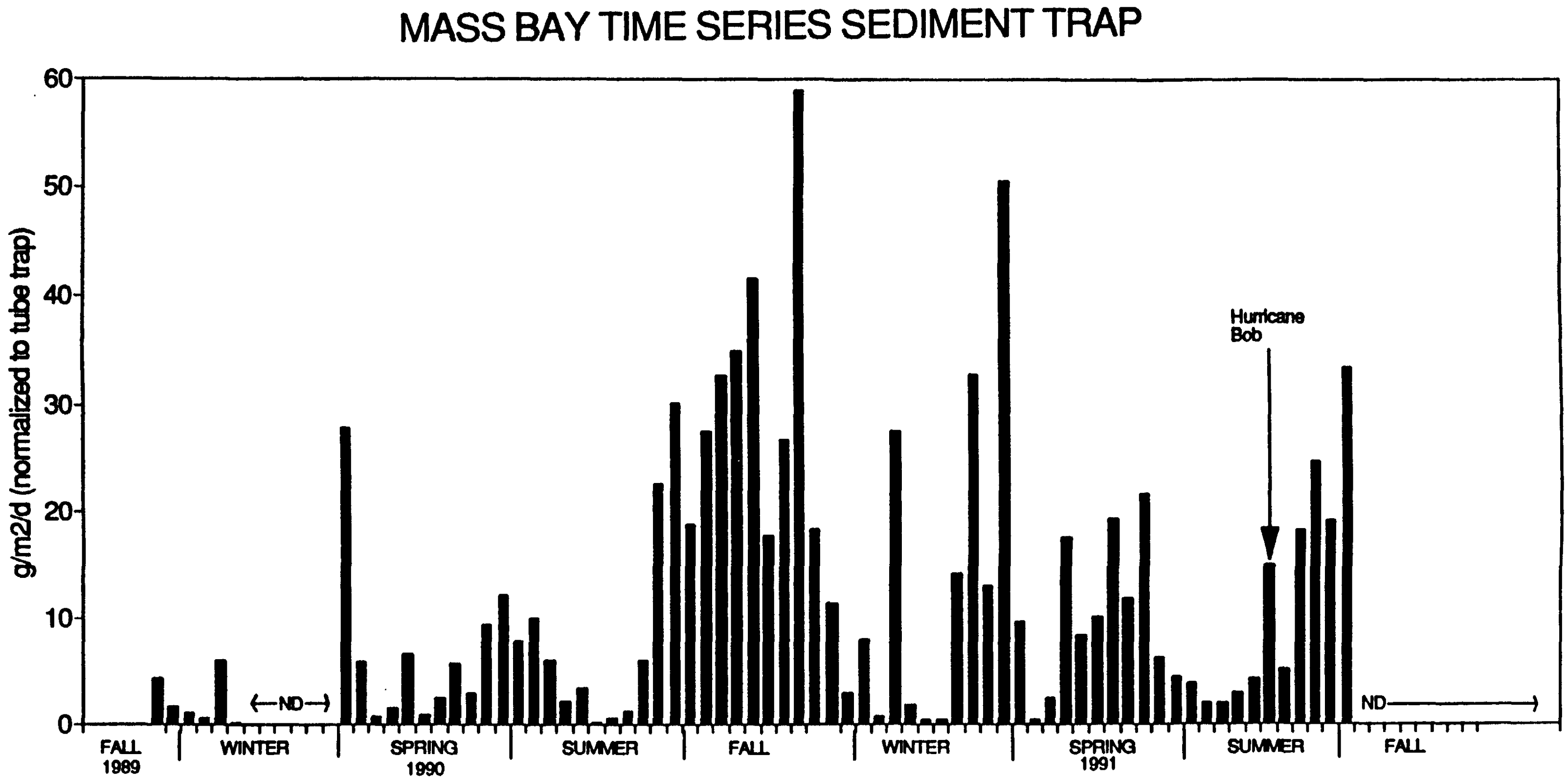


Figure 12. Sediment collection rates (in grams/m^2/day) from the time-series sediment trap at the USGS long-term mooring in western Massachusetts Bay between December 1989 and October 1991. No data was recorded (ND) in the winter of 1990. The collection rates vary in a similar pattern from spring to fall in each of the 2 years sampled. The minimum in collection (resuspension) rates during summer months followed by a rapid rise in rates during late summer and fall are consistent with the hypothesis that material collects on the sea floor of western Massachusetts Bay during the quiet periods of summer and is resuspended and transported during the subsequent period of more frequent and more intense storms. The deposition and transport of contaminants associated with particulates may follow a similar seasonal pattern. Note the increased collection rate during August 1991 associated with Hurricane Bob, which quickly passed through the region on August 19 with southwest winds of short duration. Wave and current data are being analyzed to explain the higher fluxes of trapped sediment during the weeks subsequent to Hurricane Bob.

4. CONTAMINANT INVENTORIES AND RATES OF SEDIMENT MIXING AND ACCUMULATION

(Principal USGS investigator: Michael H. Bothner)

<u>Objectives</u>: Document the levels of selected trace metals and other contaminants in sediments, estimate the rates of sediment mixing and accumulation, determine representative areas for monitoring long-term changes of contaminant levels in sediments.

<u>Rationale</u>: Knowledge of the present distribution of contaminants in surface sediments within the harbor and bays can be used to predict the transport and fate of new contaminants. The estimates of sediment mixing and accumulation rates will indicate how quickly and to what depth new contaminants can be mixed into the sediments, where they may be sheltered from further physical transport. A well-documented baseline of contaminant levels, including information on the seasonal and spatial variability, will be essential to evaluate any future changes related to the new ocean outfall and other activities.

<u>Field measurements</u>: Collect undisturbed samples of the surface sediments on a seasonal basis in a selected depositional area to evaluate the magnitude of seasonal changes in contaminant concentrations and mixing rates.

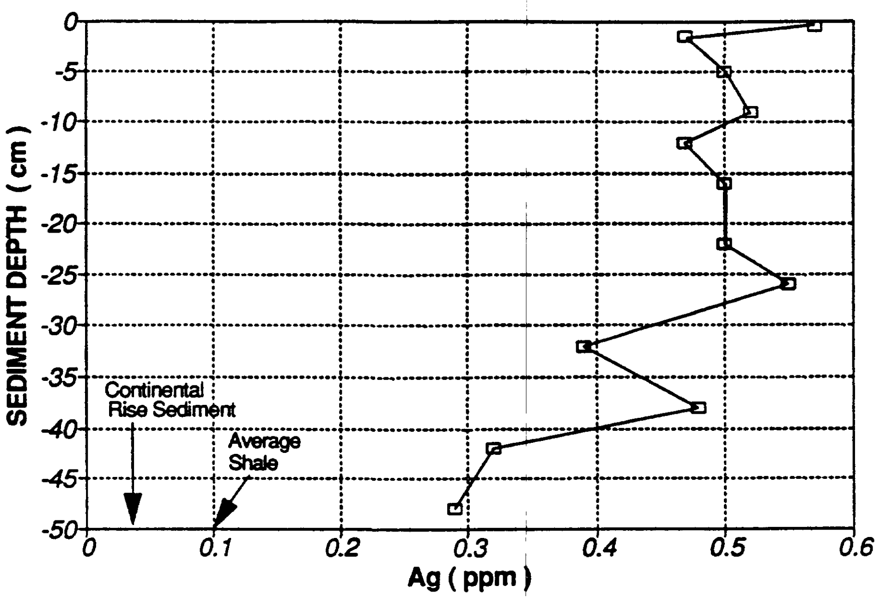
<u>Results to date</u>: The concentrations of some contaminants are already elevated above background. Analyses of sediment cores from the finest grained deposit in the vicinity of the proposed outfall (Station 3, fig. 5) show moderate elevations of contaminants that exist deeper in sediment than expected (fig. 13a, b). The concentrations of Pb and Ag are 100 and 0.5 ppm, respectively, over much of the top 40 cm in the core; these concentrations are up to 6 times higher than concentrations in world average shale. The concentrations of <u>Clostridium perfringens</u> (a bacterium spore characteristic of sewage sludge) are $5 \pm 2 \times 10^3$ spores per gram dry weight (S/g) over the top 80 cm of a gravity core from the same location (fig. 14). Background levels (<10 S/g) were found at depths of 100 cm and greater. These concentrations of <u>Clostridium</u> are surprising because they are as high as those at many stations in Boston Harbor and because they occur so deep in the sediments. The presence of lead-210 and plutonium-239-240 isotopes to depths of 44 cm suggests that mixing by benthic organisms may account for the deep occurrence of metals and <u>Clostridium</u>. The rates of mixing and accumulation will be estimated with the recently documented mixing model of Crusius (1992).

One complication in defining mixing of marine sediments near population centers using contaminant profiles is the possibility that previous dumping of solid wastes and dredged material has occurred with incomplete documentation. Glass shards, metal fragments, slag, old pill bottles, and leather gasket material have been found in these and other cores from this general area of Massachusetts Bay. Waste dumping and burial could also account for the deep contamination in sediments at this location.

The sediment trap samples from 4 mab (meters above the bottom: water depth is 29 m) contained lead concentrations of 82-100 ppm and median <u>C. perfringens</u> concentrations of 1×10^4 S/g. These concentrations are similar to those found in the fine-grained surficial sediments of the seafloor near the mooring location and are consistent with the hypothesis that much of the material collected in the traps is resuspended from the sea floor.

The geochemical analyses of bottom sediment and suspended matter will establish a baseline prior to discharge from the new ocean outfall. Quantitative information on the causes, frequency, magnitude and rates of the processes that control the transport and deposition of fine grained sediments will aid predicting the fate of future contaminants added to this coastal area.

Plans for 1992: Obtain undisturbed cores at approximately 8 locations throughout Massachusetts and Cape Cod Bays including one location east of Stellwagen Bank. This information will extend the coverage of sediment contaminant levels in depositional areas. Experiments will be conducted at the long-term site to measure the rates of particle mixing into the sediment column.



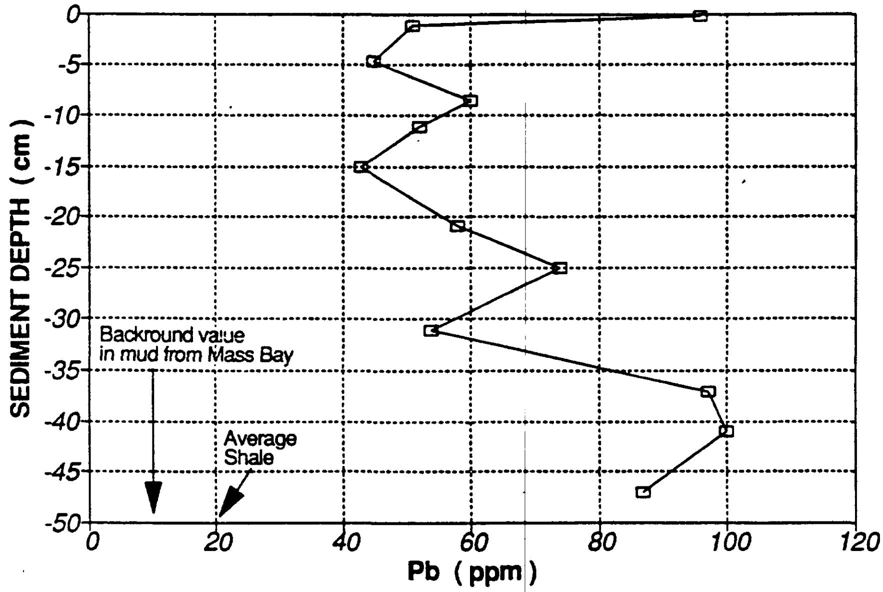


Figure 13. Top: Concentrations of silver vs. sediment depth at station 3 (fig. 5). Background concentrations of silver in muddy sediments from the Continental Rise are 0.04 ppm. The concentrations in world average shale is 0.1 ppm. The maximum concentrations of silver in this core (0.57 ppm) are 6 times higher than average shales and 14 times higher than sediments from the Continental Rise. Bottom: Concentrations of lead vs. sediment depth at station 3 (fig. 5). Background concentrations in fine-grained sediments from Massachusetts Bay are about 13 ppm. The subsurface concentration of lead (100 ppm) at 42 cm may be due to deep biological mixing or to direct dumping of waste material at this location. Glass fragments and slag have been found at depth in some cores from this location.

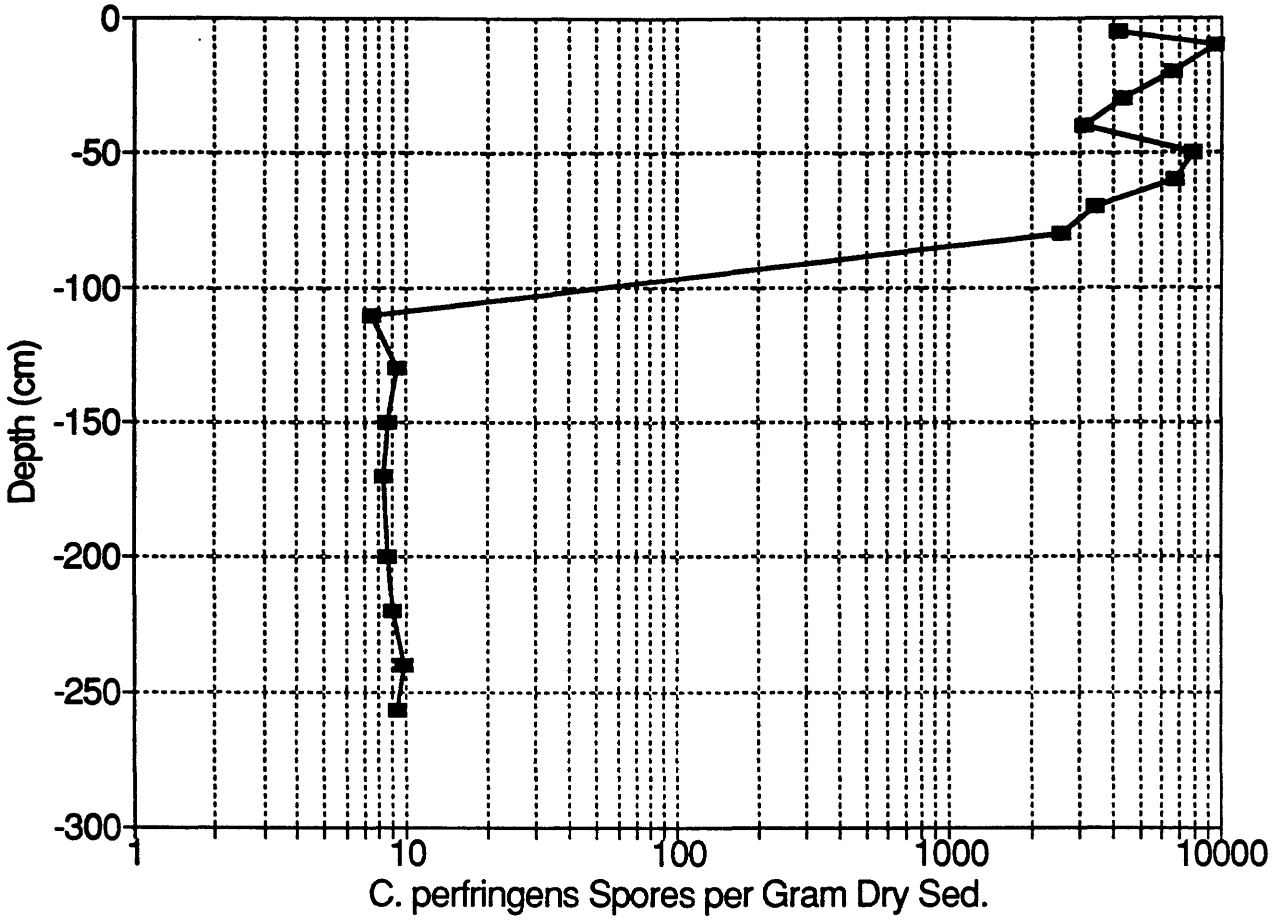


Figure 14. Concentrations of Clostridium perfringens, a bacterium spore indicative of sewage sludge, vs. sediment depth. Background concentrations reached in the longer gravity core are <15 spores per gram. Concentrations average 5 ± 2 X 10^3 spores per gram dry weight over the top 80 cm in the gravity core collected in October 1990. Slag and glass were observed at 70-80 cm in this core, suggesting that dumping of wastes may account for part of this deep C. perfringens distribution.

5. CIRCULATION MODELING
(Principal USGS investigators: Richard P. Signell and Harry L. Jenter)

<u>Objectives:</u> Develop computer models of circulation that may be used to address water quality and sediment transport issues in Boston Harbor and Massachusetts Bay. Use these models to aid in interpretation of field observations, to investigate key physical processes, and to form the basis for regional water quality and sediment transport models.

<u>Rationale:</u> Understanding the circulation of water in the bays is of critical importance for determining how nutrients, sediment, contaminants, and other water-borne materials are transported. The circulation varies over distances of several hundred meters in Boston Harbor and over several kilometers in the bays and is a complicated function of winds, tides, and river inflow. Direct measurements are providing essential information about circulation in the bay, but they cannot adequately represent the spatial scales of motion, and they represent only the conditions that existed during which the measurements were made. Numerical models can help bridge this gap by providing more complete spatial coverage, synthesizing the information from the measurements, and allowing different scenarios to be tested.

<u>Model Development:</u> The key dynamical influences on the circulation must be identified in a specific region before an appropriate model is developed: different models are appropriate for different regions. A vertically averaged model has been used in Boston Harbor, a tidally dominated embayment where the influence of vertical stratification is weak. This model was principally developed by Ralph Cheng of the USGS and Vincenzo Casulli of the University di Trento, Italy, and was adapted to Boston Harbor using a 200-m grid spacing. Acoustic Doppler current measurements obtained in the vicinity of President Roads indicate that the model does an excellent job at representing the strong spatial structure in the flow. In Massachusetts and Cape Cod Bays, where buoyancy forcing and stratification are important, a fully three-dimensional model is used that allows for river inflow, surface wind and heat flux, and turbulent mixing of the water column. This model was principally developed by Alan Blumberg of HydroQual, Inc., and was adapted to the bays using a variable size mesh that varies from 500 m in Boston Harbor to 5,000 m at the boundary offshore of Stellwagen Bank. The depth-averaged and the three-dimensional models are both fully nonlinear and allow the propagation of long surface waves.

<u>Results to date:</u> From the Boston Harbor model of the tides, it was discovered that at the two inlets to the harbor, the asymmetry between the flood and ebb tide gives rise to a net exchange of water, which acts over successive tidal cycles to flush the harbor (Signell, in press; Signell and Butman, submitted; fig. 15). The tidal flushing is very efficient at mixing water in the vicinity of the inlets over several tidal cycles, but efficiency decreases with time as "tidal mixing regions" (containing water from the harbor and the bay) form on either side of the harbor inlets. When wind forcing is included, the wind-driven currents act to remove water from the tidal mixing regions, providing new water to mix into the harbor and giving rise to more efficient flushing. In general, therefore, flushing is a two-step process: rapid exchange due to tides over a large region in the vicinity of the harbor inlets, then flushing of this region by wind-driven flow. The model also illustrates that flushing is not uniform over the entire harbor but occurs

rapidly in the deep tidal channels and slowly in the regions of weak tidal currents around the harbor periphery. Particle-release simulations from point sources also demonstrate that while the tides efficiently exchange material in the vicinity of the inlets, the exact nature of dispersion from point sources is extremely sensitive to the timing and location of the release and the distribution of particles is streaky and patch-like.

Three-dimensional modeling of Massachusetts and Cape Cod Bays is underway and is yielding important information regarding the basic processes which determine the circulation. Tidal runs have provided maps of maximum surface currents, maximum bottom currents (fig. 16), and have revealed clockwise tide-induced residual flow around Stellwagen Bank. Steady wind runs have allowed insight into the spatial structure of wind-driven flow in the bays that has proved crucial for interpretation of the moored current measurements. The wind-driven flow is very sensitive to stratification, and is particularly complex in western Massachusetts Bay.

Plans for FY92: Examine buoyancy-driven flow and the effect of stratification on tide- and wind-driven flow. Determine boundary conditions necessary for realistic simulation of mean southerly flow past the mouth of Massachusetts Bay. Conduct 1-year simulation of circulation for the period of intensive data collection (June 1990 to May 1991). This simulation will be used as the basis for a water-quality simulation over the same period.

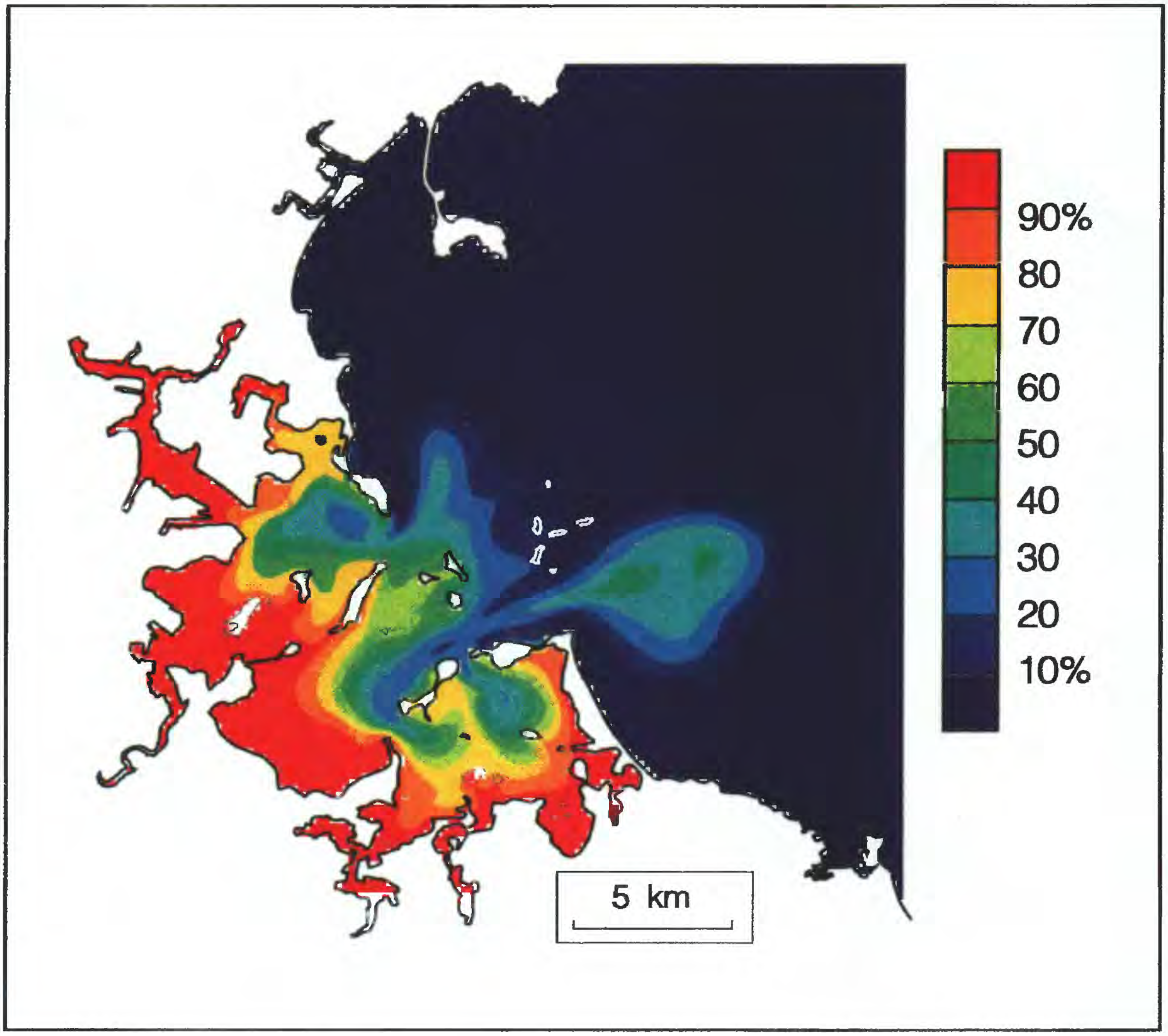


Figure 15. A computer simulation of tidal flushing of Boston Harbor in which water in Boston Harbor at high tide is initially dyed red, then tracked over successive tidal cycles as it is diluted by Massachusetts Bay water and exported from the harbor. Shown is the concentration of Boston Harbor water after 2.1 days (four complete tidal cycles). The concentration of Boston Harbor water is less than 50% in the vicinity of the harbor entrances, indicating efficient flushing by the vigorous tidal currents in these regions. Around the periphery of the harbor, however, the concentration of Boston Harbor water is greater than 90%, indicating relatively poor flushing due to weaker tidal currents. The strong gradients in concentration indicate that the dispersion of material released in Boston Harbor can be very sensitive to the exact location and time of discharge.

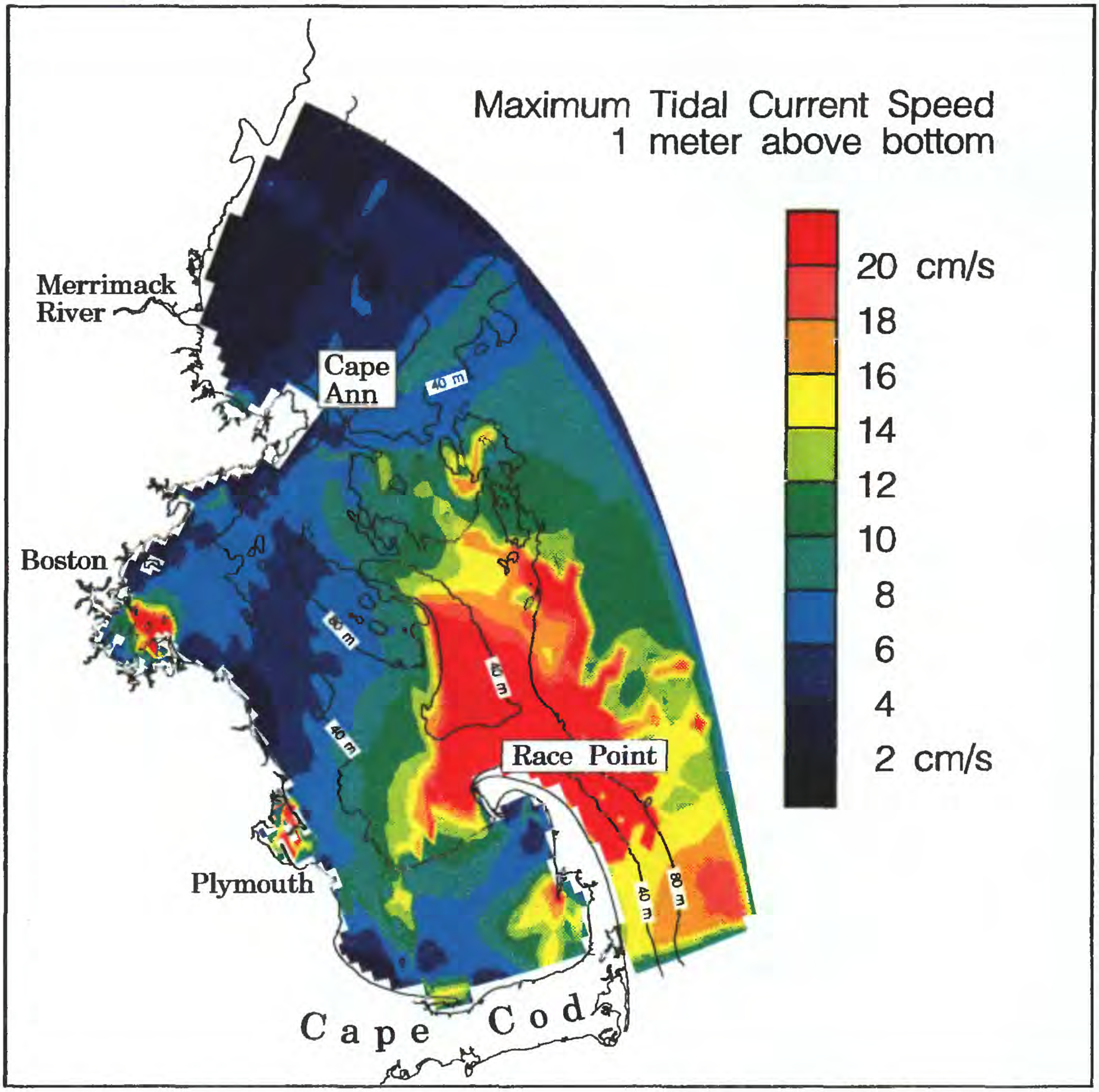


Figure 16. Maximum tidal current speed at 1 meter above the bottom from a three-dimensional circulation model of Massachusetts and Cape Cod Bays. The model can account for wind- and density-driven currents as well as tidal currents, and vertical mixing is dynamically coupled to the turbulence levels. This latter aspect is crucial in the Bays, since stratification strongly affects circulation processes. The model encompasses all of Massachusetts and Cape Cod Bays, as well as Stellwagen Bank and the Merrimack River, and will be used by the MWRA to provide transport information for a water quality model of the region. In this figure of tidal currents, the regions in red, where tidal currents exceed 20 cm/s, occur north of Race Point and at the constricted entrances to harbors.

6. CONTAMINATED SEDIMENTS DATA BASE
(Principal USGS investigators: Frank T. Manheim, John C. Hathaway, and Marilyn R. Buchholtz ten Brink)

Objectives: Develop a comprehensive inventory of available information on sediment contaminants, inorganic and organic, in cooperation with other agencies and organizations; place these and ancillary data in user-interactive form, readily interchangeable with cooperators and other organizations; assess the quality of available data; link contaminant concentration (potentially including sulfides) with available sediment texture and other key properties of bottom sediments; establish specific contaminant signatures and trace their relationships to time and locality; map contaminant distributions and pathways of dispersal outside Boston Harbor; and provide baselines for current and future monitoring studies. Incorporate all data on chemistry, sediment texture, and other properties in a documented format to facilitate display, analysis, and transfer to other users.

Rationale: Compilation of all available sediment data into a readily accessible database will provide a more extensive base for environmental mapping and pollutant distribution than previously available. Properly utilizing these data is less expensive than new sampling, will provide indication of sources of pollutants and changes with time, will help evaluate location of monitoring stations, and will serve as a baseline against which future conditions can be measured.

Methodology: Recompile and evaluate the Boston Harbor Data Management File (BHDMF), the most comprehensive source of compositional data on sediment and establish a form compatible with exchange and interaction with other organizations, using the INGRES database management software, as well as spreadsheet and other software; add all other useful and accessible data.

Results to date: In June of 1991, an agreement was reached with the U.S. Environmental Protection Agency that the USGS would complete the preparation of data in the former BHDMF and the EPA, Region I, would compile data of 1984 to present. These data would then be integrated into a single database. Both compilation efforts have been completed to the degree practicable, and integration is now in progress (fig. 17).

The BHDMF file contains approximately 7,000 records pertaining to sediment parameters. Our work confirms the earlier observations of Mason (1984), who concluded that the measurements in the BHDMF were valid and that uncertainties were related mainly to absence of information about analytical methods, and lack of information on or miscoding of locations. PCBs make up the most frequently analyzed organic contaminant in the BHDMF. About 53% of the samples analyzed fall above the National Oceanic and Atmospheric Administration's (NOAA) Overall Apparent Effects Threshold (OAET), roughly agreeing with the concentration range found in the most concentrated NOAA Standard and Trends (NS&T) monitoring sites (Long and Morgan, 1990). Frequency plots demonstrate striking lognormal distributions for metals (Manheim and Hathaway, 1991) that are characteristic for distributions reported in other polluted sediment environments in the U.S. and Europe (Lyman et al., 1987 and references cited therein). Copper represents one end member, where the majority of samples analyzed fall below the OAET threshold, roughly comparable to the earlier "high" toxic metals threshold cited in O'Connor (1990) and to recent Washington State and Massachusetts criteria for sediment toxicity. The majority of samples analyzed for mercury (fig. 18), on the other hand, exceeded the NOAA effects-based toxic thresholds, as well as values for NOAA Standards and Trends monitoring sites (Long and Morgan, 1990). More precise definitions of toxicity may take advantage of recent Environmental Protection Agency studies showing a quantifiable depressant effect on toxicities of some heavy metals by the relative concentration of acid-volatile sulfide (AVS) (DiToro, 1991).

The BHDMF data, along with the EPA Region I data (which aggregate many sources), and other unpublished data from the USGS will include about 1,300 discrete sediment samples. Validation and scientific editing of the set will yield perhaps the most intensive background control on bottom sediments of any environmentally impacted coastal area around the United States.

Plans for 1992. Next steps include (1) merging, validation and integration of the full data set with EPA Region I, and (2) beginning of comprehensive mapping, including integration of contaminant and available texture and pertinent sediment measurements with sidescan surveys of bottom sediment environments. Preparation of a CD ROM to provide wide access to all data as well as limited syntheses will begin.

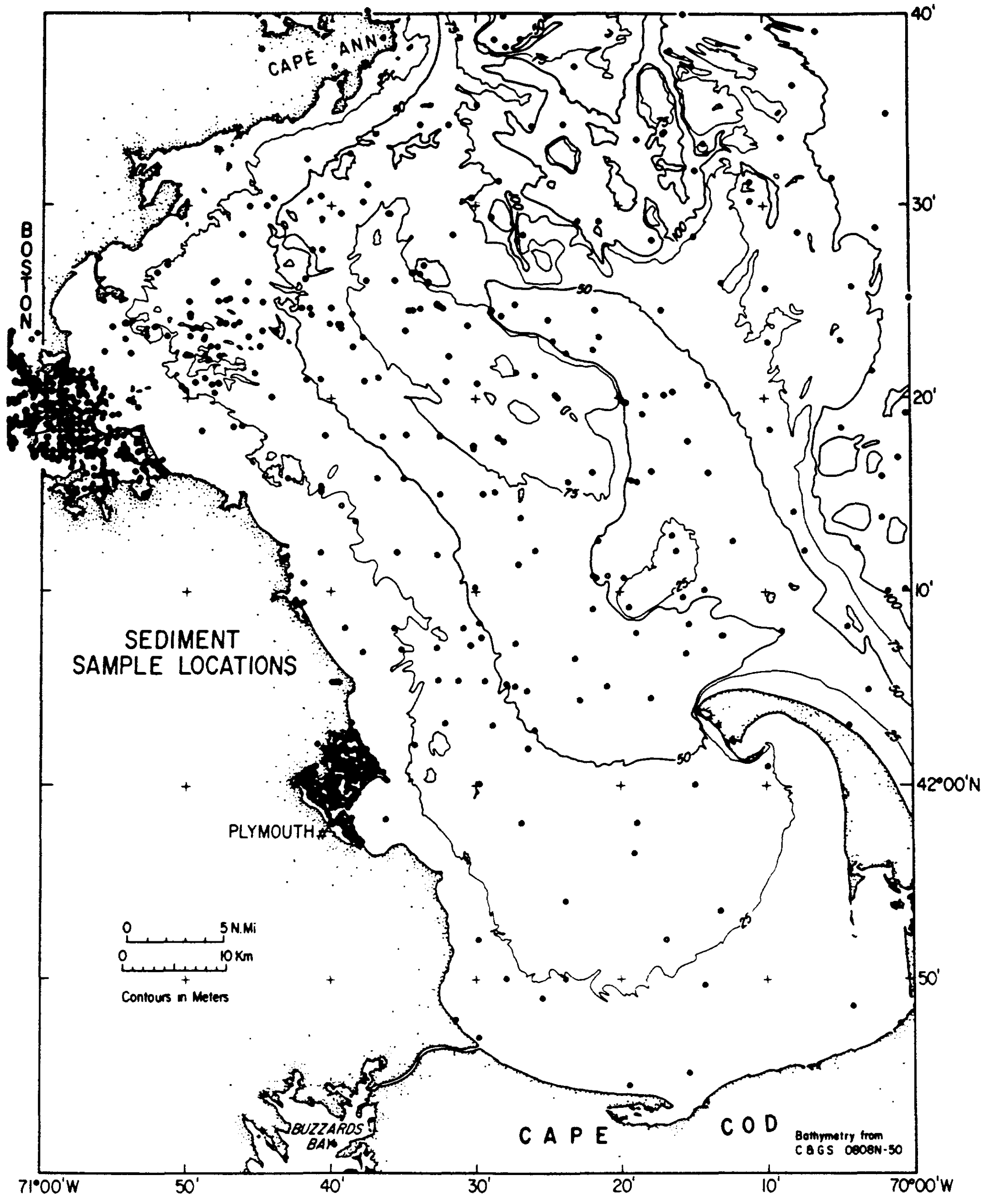


Figure 17. Locations of Boston Harbor, Massachusetts Bay and Cape Cod Bay sediment texture samples presently in the USGS data archive.

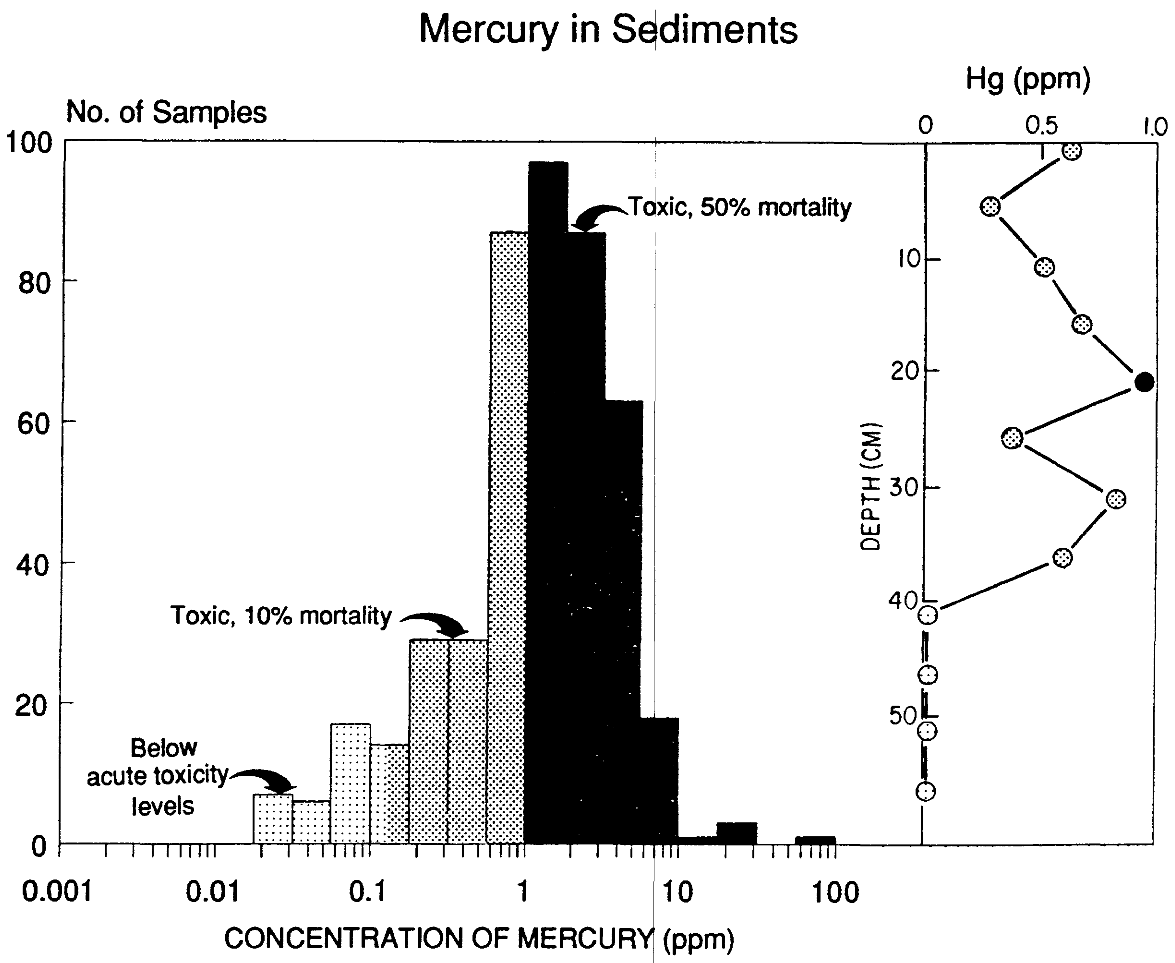


Figure 18. Histogram of the concentration of mercury in the surficial sediments in Boston Harbor. The Overall Apparent Effects Threshold of pollutant concentration (50% mortality) in sediment for consistent toxic effects on organisms is listed by Long and Morgan (1990). The profile of mercury in the sediment at one location in Boston Harbor (right panel) shows elevated concentrations in the upper 40 cm of the sediment column (data of M.H. Bothner).

7. INFORMATION EXCHANGE

Objective: Provide information to the public, managers, and other researchers working in the Massachusetts bays.

Results to date: Scientists at the USGS have presented results of the Boston Harbor and Massachusetts bays studies to citizens concerned with the outfall siting issue, provided briefings to the board of the MWRA, the EPA, the Massachusetts Office of Coastal Zone Management, and to the Executive Office of Environmental Affairs and have presented numerous talks and poster displays at the annual Symposium on Massachusetts Bay and Boston Harbor. USGS investigators sit on the Massachusetts Bays Management Committee (Michael Bothner), the Massachusetts Bays Technical Advisory Committee (Bradford Butman), and the Outfall Monitoring Subcommittee (Richard P. Signell). Data have been exchanged with other investigators. Results are published in U.S. Geological Survey reports and in the scientific literature.

ACKNOWLEDGEMENTS

Part or all of Geologic Mapping (component 1), Long-term Observations (component 3), Contaminant Inventories (component 4), and Circulation Modeling (component 5) are conducted under a Cooperative Agreement with the Massachusetts Water Resources Authority (Bothner et al., 1990). Logistical support for deployment and recovery of the long-term mooring (component 3) is provided by the U.S. Coast Guard; the able assistance of the captain and crew of the Buoy Tender WHITE HEATH is gratefully acknowledged. The Baywide circulation study (component 2) was conceived and carried out by a consortium of scientists, consisting of W.R. Geyer (Woods Hole Oceanographic Institution), W. Brown, (University of New Hampshire), J.D. Irish (Woods Hole Oceanographic Institution), N. Pettigrew (University of Maine), and G.B. Gardner (University of Massachusetts, Boston) and augmented by scientists at USGS. The circulation study was supported by the Massachusetts Environmental Trust, the Massachusetts Bays Program, as well as the U.S. Geological Survey. The modeling component is conducted cooperatively with A. Blumberg (Hydroqual, Inc.). The Polluted Sediments Data Base (component 6) is being developed in cooperation with the Massachusetts Water Resources Authority, the Environmental Protection Agency, and other organizations involved in the Massachusetts Bays Program. C. Parmenter constructed the digital side scan sonar mosaic in figure 3 and processed the sediment trap samples. A. Brown and R. Rendigs aided in the collection and processing of sediment samples. B. Strahle and M. Martini conducted and managed the field measurements made by the USGS as part of the moored array experiment as well as the measurements at the long-term station. F. Hotchkiss processed the USGS current and seabed drifter observations. J. Zwinakis and Dann Blackwood produced the graphics. This report benefitted by the reviews of F. Hotchkiss, J. Schlee, and P. Valentine.

REFERENCES CITED

Bigelow H.B., 1927, Physical Oceanography of the Gulf of Maine. U.S. Fisheries Bulletin 40, p. 511-1027.

Bothner, M.H. and Butman, B., 1990, Assessing pollutant transport and accumulation in the coastal ocean - a pilot study in Boston Harbor and Massachusetts Bay, in U.S. Geological Survey Year Book fiscal 1989, U.S. Government Printing Office, p. 52-54.

Bothner, M.H., Parmenter, C.M., Brown, A.B., and Signell, R., 1990, Studies of circulation and pollutant transport in Massachusetts Coastal Waters: U.S. Geological Survey Open-File Report 90-328, 32 p.

Bothner, M.H., C.M. Parmenter, D.C. Twichell, C.F. Polloni, and H.J. Knebel, 1992, A geologic map of the sea floor in western Massachusetts Bay, constructed from digital sidescan sonar images, photography, and sediment samples, U.S. Geological Survey Digital Data Series DDS-3, 1 CD-ROM, in press.

Brown, W.S., Butman, B., Gardner, G.B., Geyer, W.R., Irish, J., Pettigrew, N., and Signell, R.P., 1992, The Physical oceanography of Massachusetts Bay: An overview of the Massachusetts Bay Program Study, Seventh Annual Boston Harbor and Massachusetts Bays Symposium, February 10-11, 1992, Boston, Mass.

Bumpus, D.F. and Lauzier, L.M., 1965. Surface circulation on the continental shelf of eastern North America between Newfoundland and Florida. American Geographical Society Serial Atlas of the Marine Environment, New York, folio 7, 4 pp, 8 plates.

Cooks, D.O., Bell, D.L., Willett, C.F., Wilkins, R.L., and Jackimovicz, J., 1976, Surficial sediments and sand and gravel deposits of inner Massachusetts Bay: Maritime Sediments v. 12, p. 9-16.

Crusius, J.F., 1992, Evaluating the mobility of 137Cs, 239+240Pu, and 210Pb from their distributions in laminated sediments: Ph.D. Dissertation, Columbia University, 261p.

Di Toro, D., 1991, AVS. What is it, why was it missed?, Contaminated Sediment Assessment Methods Workshop, Galilee, R.I., U.S. Environmental Protection Agency (verbal report).

Fitzgerald, D.M., Smith, J.B., and Goodbred, S.L., 1990, Exploration and inventory of sand and gravel resources offshore of Boston Harbor: Boston University Technical Report 2, 177 pp.

Hotchkiss, F.P., and Signell, R.P., 1991, Average near-bottom currents in Massachusetts Bay and Cape Cod Bay measured with Woodhead drifters: Progress Report for drifters released Sept. 1990 through May 1991. U.S. Geological Survey Open-File Report 91-361, 14 p.

Knebel, H.J., Rendigs, R.R., and Bothner, M.H., 1991, Modern sedimentary environments in Boston Harbor, Massachusetts: Journal of Sedimentary Petrology, v. 61, p. 791-804.

Knebel, H.J., Rendigs, R.R., Oldale, R.N., and Bothner, M.H., 1992, Sedimentary framework of Boston Harbor, Massachusetts, in Fletcher, C.H., III, and Wehmiller, J.F., eds., Quaternary Coasts of the United States: Marine and lacustrine systems: Society of Sedimentary Geology (SEPM) Special Publication 48, (in press).

Long, E.R., and Morgan, L.G., 1990, The potential for biological effects of sediment-sorbed contaminants tested in the National Status and Trends Program, NOAA Technical Memorandum NOS OMA 52, 175 p and appendices; see also Anonymous, 1988, National Status & Trends Program for Marine Environmental Quality, Progress Report, NOAA Technical Memorandum NOS OMA 44, 15 p and appendices.

Lyman, W.J., Glazer, A.E., Ong, J.H., and Cons, S.F., 1987, An overview of sediment quality in the United States, Final Report for U.S. Environmental Protection Agency, Monitoring and Data Support Div., Washington, D.C. 109 p. and appendices.

Manheim, F.T. and Hathaway, J.C. , 1991, Polluted sediments in Boston harbor - Massachusetts Bay: Progress report on the Boston Harbor Data Management file, U.S. Geological Survey Open-File Report 91-331, 28 p.

Mason, C., 1984, Unpublished memorandum and correspondence with Office of Program Support, U.S. Environmental Protection Agency, Region I. (Courtesy, S. Curran, MWRA).

MWRA, 1988, Secondary Treatment Facilities Plan, Massachusetts Water Resources Authority, Charlestown, Mass., Chapter 2-42.

O'Connor, T.P., 1990, Coastal environmental quality in the United States, 1990, NOAA Oceanic and Atmospheric Administration, Special 20th Anniversary Report, 34 p.

Oldale, R.N., and Bick, J., 1987, Maps and seismic profiles showing geology of the inner continental shelf, Massachusetts Bay, Massachusetts: U.S. Geological Survey Miscellaneous Field Studies Map MF-1923, 4 sheets.

Oldale, R.N., and O'Hara, C.J., 1990, Maps showing the geology of the inner continental shelf, Cape Cod Bay, Massachusetts: U.S. Geological Survey Miscellaneous Field Studies Map MF-2118.

Rendigs, R.R., and Oldale, R.N., 1990, Maps showing the results of a subbottom acoustic survey of Boston Harbor, Massachusetts: U.S. Geological Survey Miscellaneous Field Studies Map MF-2124, 2 sheets.

Schlee, J., Folger, D.W., and O'Hara, C.J., 1973, Bottom sediments on the continental shelf off the northeastern United States - Cape Cod to Cape Ann, Massachusetts. U.S. Geological