Section 11: Summary of Important Findings

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Boston Harbor and Massachusetts Bay are the focus of an ongoing multidisciplinary scientific investigation to gain fundamental understanding about the transport and fate of contaminants introduced to coastal waters and to provide relevant and accessible information to state and federal managers responsible for managing the coastal environment. This investigation improves our ability to predict the fate of contaminants in coastal waters.

The coastal region off Boston is a particularly appropriate area for contaminant-transport investigations. In the late 1980s, Boston Harbor was among the most contaminated harbors in the nation, in part because of the discharge of sewage from the Boston metropolitan area to the harbor since colonial times (Section 1). A court-ordered program to clean up Boston Harbor mandated the cessation of sludge discharge to the harbor, upgrading sewage treatment to secondary, moving the location for sewage effluent discharge 15.2 km into Massachusetts Bay, and eliminating combined sewer overflows. This cleanup program initiated major changes in the quantity, quality, and location of sewage waste discharge to the coastal waters of Massachusetts. A comprehensive monitoring program was established, as a condition of the discharge permit, to assess the effects of the cleanup program, with emphasis on the effect of the new discharge in Massachusetts Bay. The cleanup and monitoring programs required improved knowledge of the circulation in Massachusetts Bay, distribution of bottom sediments, concentrations of contaminants in sediments in the harbor and bays, and an understanding of the transport and fate of contaminants and sediments in the coastal system.

Sediments 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. The mechanisms and rates by which sediments are resuspended, transported, buried, and bioturbated are critical factors in controlling the fate of particle-bound contaminants. Examining these processes fits the mandate and capabilities of the USGS to apply earth-science principles to environmental problems in coastal areas. The USGS multidisciplinary research program, focused on the transport and fate of particle-bound contaminants, began in Massachusetts Bay in 1989, building on a smaller effort in Boston Harbor initiated in 1977. This summary highlights results from sea-floor mapping, circulation and sediment-transport modeling, and geochemical investigations that were undertaken as part of this research program. The full bibliography of the project is available in appendix 1.

Sea-Floor Mapping

New maps of the sea floor were completed for much of western Massachusetts Bay, Stellwagen Basin, and the Stellwagen Bank National Marine Sanctuary (Section 2). They are based on a high-resolution multibeam echo-sounding survey that provided complete coverage of the topography and backscatter intensity of the sea floor at 10-m resolution. The new maps show the distribution of bottom sediment in relation to topography, and revealed for the first time the variability in sediment texture and sea-floor morphology over small spatial scales. The maps show the complex ridges in western Massachusetts Bay in the vicinity of the new outfall and anthropogenic features on the sea floor, such as mounds from disposal of dredged and other material. The survey, carried out after the new outfall was constructed, shows two parallel rows of mounds formed from material discarded on the sea floor from the shafts drilled to connect to the tunnel below. Sidescan sonar data revealed extensive marks from fishing trawls. Earlier versions of these maps were used to choose between alternative sites for the outfall diffuser and to select the most sensitive sampling sites for the outfall monitoring program. The maps continue to provide the geologic framework for commercial, scientific, and management activities.

Modeling Circulation, Sewage Outfall Plumes, and Sediment Transport

Knowledge of the circulation and sediment transport in Massachusetts Bay is critical to understanding the transport and fate of contaminants. As part of the USGS research program, long-term observations of currents and near-bottom processes were made at two locations in Massachusetts Bay (Section 3). These observations show that winter storms with winds from the northeast are the most important process that resuspend and transport sediments in this coastal region. To understand the spatial and temporal variability of currents in coastal areas that cannot be documented by measurements alone, numerical hydrodynamic models have been developed and implemented that have provided simulations of currents under seasonally varying conditions of insolation, wind stress, river runoff, and boundary conditions in the Gulf of Maine. Simulations of residual currents for winter (defined as November through February) and summer (June through August), averaged for the years 1990–1992, are quite consistent with the observed flow from limited field observations (Section 4). In summer

and winter, the residual flows in Massachusetts Bay are very slow, less than 0.05 m/s. A water particle originating near the Massachusetts Bay outfall in winter would be carried southeastward along the coast, reaching Cape Cod Bay in about 15 days.

Numerical circulation models of Massachusetts coastal waters have been used to address key management issues and to advance fundamental understanding of circulation and sediment transport. In developing the Boston Harbor cleanup plan, a major concern was that the new outfall in Massachusetts Bay would transfer the contaminated conditions in Boston Harbor offshore to Massachusetts Bay, Cape Cod Bay, and to the Stellwagen Bank National Marine Sanctuary, where endangered whales might be further threatened. The model was used to simulate the distribution of effluent originating from the existing harbor outfall and from the new Massachusetts Bay outfall. The simulations predicted that discharge through the bay outfall would greatly reduce effluent concentrations in Boston Harbor without significantly increasing concentrations in most of Massachusetts Bay (Section 5; Signell and others, 2000). Illustrations and animations of these predictions helped the public and decisionmakers understand and compare the fate of effluent discharged from the harbor and Massachusetts Bay outfalls. The predictions have since been verified by using the measured distribution of ammonium from the new outfall as an effluent indicator. Maps showing effluent distribution from the new outfall predicted by the model and determined by actual measurements are in good agreement (Section 5).

The circulation model also played a key role in the final design of the secondary sewage-treatment plant. Based on model predictions of effluent dilution, a smaller treatment system than originally planned was determined to be adequate to achieve the desired water quality in Massachusetts Bay. The construction of the smaller treatment system saved about $160 million (Section 5) with no adverse affect on the environment.

Massachusetts Bay has been a natural laboratory for development and assessment of a coupled hydrodynamic and sediment transport model. This model enables predictions of sediment erosion, transport, and accumulation under different oceanographic conditions (Section 6). The complex topography, variable sediment types, and the long-term oceanographic observations make Massachusetts Bay an ideal location to evaluate model performance. Simulations were carried out to explore the effects of northeast storms, identified by observations as a key transport process, on the distribution of sediments in Massachusetts Bay. The model simulations explored how a mixture of sediments (medium sand through medium silt) placed uniformly in a layer on the sea floor throughout Massachusetts Bay would be redistributed during a series of large northeast storms. The qualitative agreement between the model predictions and the observed present distribution of sediments is consistent with the hypothesis that sediment transport caused by northeast storms plays a key role in determining the sediment distribution in Massachusetts Bay. The model simulations showed that winds from the northeast cause particles originating at the mouth of Boston Harbor or from the new outfall site to be transported southeastward toward Cape Cod Bay and Stellwagen Basin. The simulated transport pathways of sediments from Boston Harbor during northeast storms are consistent with Boston being the long-term source of anthropogenic silver found in the surficial sediments of Cape Cod Bay and Stellwagen Basin.

Geochemistry of Sediments Influenced by Inputs and Post-Depositional Processes

Discharges of metals into Boston Harbor have declined in recent decades as the result of legislation that restricted both point and nonpoint sources. Major reductions in contaminant inputs resulted from the elimination of sludge discharge to the harbor in 1991 and from moving the outfall to its new location in Massachusetts Bay in 2000. The concentrations of silver, copper, and lead in the surface sediments in Boston Harbor have decreased by about 50 percent over the last 25 years. Concentrations of metals considered toxic to benthic organisms still remain buried beneath surface sediments and may provide a continuing source of contaminants to the environment (Section 7).

To assess the chemical impact of the new Massachusetts Bay outfall, the USGS determined concentrations of a suite of potentially toxic metals in suspended matter and in bottom sediments collected before and after outfall startup. In suspended matter, collected by sediment traps moored near the new outfall, the only constituents found to have higher concentrations in post-outfall samples than in pre-outfall samples were silver and *Clostridium perfringens*, a bacterial spore found in sewage (Section 7). Although elevated more than pre-outfall samples, the highest concentrations of silver in the trap samples were below the toxicity warning level. In fine-grained bottom sediments about 2 km west of the outfall, the average post-outfall concentrations were not different from pre-outfall values. The largest increase in concentrations of silver

and *C. perfringens* in the bottom sediment followed an exceptionally strong storm on December 11–16, 1992, that generated maximum significant wave height of 7.1 m in western Massachusetts Bay. The increased concentrations are attributed to transport of fine-grained sediment bearing silver, possibly from the harbor or winnowed from nearshore sediments, to this location by the northeast storm. The long-time series of baseline data that were collected prior to the outfall startup established the range of natural variability for metal concentrations at the site and improves our ability to interpret the cause of any changes that may occur as discharge from the outfall continues.

Geochemical studies of oxygen, radioactive isotopes, and metal cycling have been done to define the rates and processes that control the fate of metals after deposition on the seabed. Oxygen penetration depths and diffusive oxygen fluxes into sediments (calculated from O_2 depth profiles) were measured on sampling cruises from 1995 to 2005 (Section 8). Measurements of these quantities provide another test of the outfall's effect on local sediment chemistry. If organic matter deposition from the outfall on the sea floor was significant, O_2 penetration depths would decrease, and diffusive O_2 flux into the sediment would increase. A comparison of results collected by the in situ oxygen profiler before and after the outfall startup provides no evidence for a change in these quantities following discharge of treated sewage. Even a substantial (about 25 percent) nondiffusive O_2 flux, not detectable with the method used here, seems unlikely to alter this conclusion; however, a slow reaction rate for outfall-derived organic matter could delay the onset of detectable changes. Seasonal differences in O_2 penetration and flux into the sediment were observed. The measurements made during winter (February-March) indicated deeper O_2 penetration and lower O_2 flux than during later summer. Similar seasonal differences have been observed in other coastal environments in response to warmer temperatures and oxidation of organic matter added by the spring-summer bloom.

Depth profiles of radioactive isotopes of lead and plutonium (^{210}Pb and $^{239+240}$Pu) have shown evidence that material was removed from the sediment surface and redeposited a few centimeters below the surface. This process took place on a time scale of months to a couple of years (Section 9). This process is attributed to the feeding and defecation by benthic organisms, such as cirratulid polychaete worms, and results in bioturbation, or mixing, of the sediments. This interpretation contributes three main points to the understanding of contaminant additions to coastal sediments. First, an environmental benefit might be realized from bioturbation because the rapid mixing dilutes the new contaminant. Second, for contaminants that are dangerous at even low concentrations, the downward mixing could be an environmental detriment because it transports the contaminants below the zone of normal resuspension and subsequent transport away from the nearshore environment. Third, mixed surficial sediments may not accurately or sensitively record recent changes in contaminant deposition.

Studies of the cycling of metals in contaminated sediments and of the mechanisms and rates by which metals in sediments are released to overlying water have provided new insights (Section 10). Measurements of pore-water composition in sediment cores indicate that the cycling of silver (Ag), copper (Cu), and lead (Pb) between dissolved and solid phases is closely linked to the formation and dissolution of iron oxides and metal sulfides. These reactions occur within the top 10–20 cm of the sediment column, and sediment mixing by benthic animals can involve contaminated sediments from deeper, older sediment layers in these modern cycling processes. At the Massachusetts Bay site, Ag and Cu generally have higher concentrations in pore water than in overlying water. The difference in concentrations leads to the release of these metals into the overlying water. At the Boston Harbor site, the diffusion of these dissolved metals is higher in winter than in summer. Erosion experiments at both sites indicated that the resuspension of particles preferentially enriched in Ag, Cu, and Pb is an important mechanism by which particulate metals enter bottom waters. In addition, the particles have been shown to release dissolved metals (Ag and Cu) to the water in which they are suspended. The release of Cu from contaminated harbor sediments by diffusion and resuspension represents about 80 percent of the annual loading of Cu from all other sources. These metal-cycling studies highlight the importance of sediments as a lingering source of contamination to the coastal environment.

Future Work

This investigation is a federal/state/academic partnership that continues to address scientific and management questions concerning the transport and fate of contaminants in coastal waters. The next steps are to further synthesize, interpret, and publish the data collected in 2005 and 2006, refine and expand the application of sediment-transport models, and conduct additional experiments to define the release of metals from contaminated sediments to overlying water. The extensive new knowledge generated by this multidisciplinary investigation makes the coastal waters of Massachusetts a natural laboratory for continuing research on contamination that will have wide application in other coastal areas.

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