Section 5: Effluent Dilution Simulations in Massachusetts Bay: An Evaluation of Relocating Greater Boston's Sewage Outfall

By Richard P. Signell

For nearly two decades after enactment of the Clean Water Act of 1972 mandating secondary treatment of sewage, Boston Harbor continued to receive direct discharge of metropolitan Boston's sewage sludge, primary-treated effluent, and raw sewage combined with stormwater during storms. By the early 1980s, bottom-dwelling animal communities had disappeared from many locations in the harbor, beaches were frequently closed to swimming, and fish were diseased. In 1985, the MWRA was ordered by a federal court to meet the Clean Water Act requirements. They began a cleanup project that included elimination of sludge discharge, upgrading to secondary sewage treatment, and control of combined sewer overflows. One aspect of the project, however, created substantial controversy—the relocation of the sewage outfall from the mouth of Boston Harbor to a site 15.2 km offshore in Massachusetts Bay. There was concern that the new outfall might turn Massachusetts Bay into the next Boston Harbor and thus adversely affect whales and other marine species in the region, which includes the Stellwagen Bank National Marine Sanctuary.

A broad goal of the USGS Coastal and Marine Geology Program is to improve understanding of geologic factors that support the preservation of environments in their natural state. Toward this goal, the USGS has been a key player in the development of an integrated system of wave, circulation, and sediment transport models that can be used to study the movement of contaminated material in coastal waters. These models, when properly configured and validated with observational data, are often the best tools for evaluating management scenarios in the coastal ocean. One of the first steps in the development of such a model was implementation of a three-dimensional circulation model in Massachusetts Bay, a prototypical region of interest. Although developed to support sediment transport studies in the bay, the timing was perfect to help Boston address a major environmental issue—the cleanup of Boston Harbor.

The model used for the effluent dilution simulations was a modified version of the Estuarine and Coastal Ocean Model (ECOM) originally developed by George Mellor and Alan Blumberg at Princeton University (Blumberg and Mellor, 1987). The model simulates currents and water properties in three dimensions (and time), driven by wind, river runoff, offshore discharges of freshwater, surface heating and cooling, tides, and sea-level fluctuations in the open ocean. In Massachusetts Bay, the model was used to study the flushing characteristics of Boston Harbor, to provide input for a baywide water-quality model, and to assess the effect of possible chlorination failure at the new outfall location, as well as to predict effluent dilution.

The ECOM model was configured to encompass all of Massachusetts and Cape Cod Bays, with a resolution that varied from approximately 1 km in western Massachusetts Bay to about 6 km in the open ocean outside Massachusetts Bay. The 3-year period from 1990 to 1992 was simulated, including an 18-month period from January 1990 to July 1991 of intense oceanographic data collection by the USEPA-funded Massachusetts Bays Estuary Program (Geyer and others, 1992).

Comparing simulation results to measured oceanographic data showed that the model reproduced the development of seasonal stratification in the bay and the statistics for currents responsible for effluent transport in western Massachusetts Bay (Blumberg and others, 1993; Signell and others, 1996). The model was therefore judged to be appropriate for use in simulating effluent fields produced by continuous discharge in this region. Comparative dilution simulations for the existing outfalls and for the new outfall (figs. 5.1 and 5.2) projected that effluent concentrations in Boston Harbor would be greatly reduced by using the new outfall site, without significantly increasing concentrations in most of Massachusetts Bay (Signell and others, 2000). Thus, the model simulations supported relocation of the outfall from Boston Harbor to the site 15.2 km offshore.

These effluent dilution simulations were used to defend the construction of the outfall tunnel during a lawsuit claiming that the new outfall would endanger right whales in the Stellwagen Bank National Marine Sanctuary. The suit was unsuccessful, and construction of the outfall pipe was completed. The model results also helped MWRA evaluate and gain approval for downsizing the planned secondary sewage-treatment plant. It is estimated that the downsizing saved Boston area ratepayers about $160 million. In addition, the animated displays of model results have been used frequently as educational and outreach tools in public forums.

By utilizing data collected as part of the Massachusetts Bay monitoring program (1992–2004), it has been possible to use the measured concentration of ammonium (NH_4^+) in seawater as a proxy for the dilution of effluent that was predicted by the computer model. This approach, first used by Mickelson and others (2002), showed that NH_4^+ was an effective tracer of sewage effluent over time scales of several days.

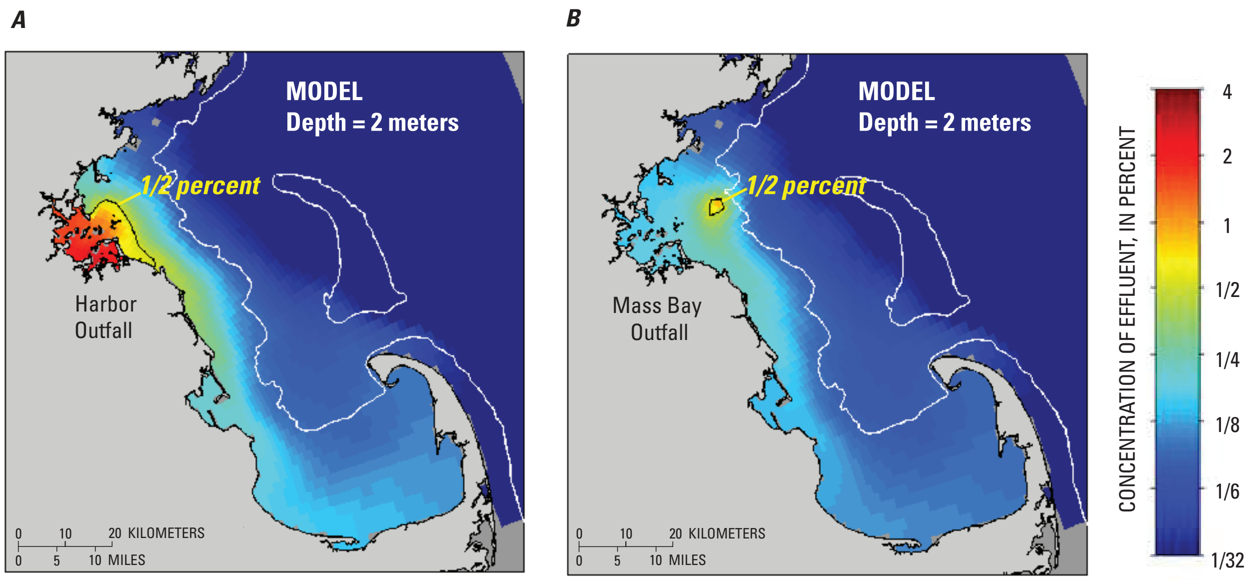

Figure 5.1. Modeled winter (1990–1992) near-surface (2-m depth) effluent concentrations for discharge from *(A)* the harbor sewage outfalls, and *(B)* the Massachusetts Bay outfall. The black line indicates a concentration of ½ percent (200-fold dilution of effluent), which is approximately the percentage at which nutrient levels released in the effluent are comparable to background variability. For discharge through the harbor outfalls, high effluent concentrations are within Boston Harbor and along the coastline immediately south. For discharge from the Massachusetts Bay outfall, high concentrations are only within a few kilometers of the outfall and are dramatically lower in Boston Harbor. Concentrations in most of Massachusetts Bay (including the region near Stellwagen Bank) are not significantly changed from their previous low values. The location of Stellwagen Bank is shown by the closed (white) 40-m depth contour about 50 km east of Boston.

The measured effluent concentrations of NH_4^+ at the treatment facility and in the field were divided into pre- and post-discharge groups around the outfall startup date, September 6, 2000, and averaged by season. Maps of effluent were created by dividing the average field concentrations by the average concentration discharged in the effluent (figs. 5.3, 5.4). The maps of ammonium concentration mimic the numerical simulations. There is good agreement between the simulation results (figs. 5.1 and 5.2) and the field measurements (figs. 5.3 and 5.4).

Because of the complexity of driving forces and topography in Boston Harbor and Massachusetts Bay, computer models have played, and continue to play, a critical role in managing these coastal waters. The ECOM model used for the effluent dilution simulations was also used as the basis for a full water-quality model of the region (Hydroqual and Normandeau, 1995), and it continues to be used for regulatory purposes by the University of Massachusetts in collaboration with the MWRA (for example, Jiang and Zhou, 2004). The ECOM model has since been replaced in the sediment-transport modeling system used by the USGS with an even more powerful three-dimensional model, the results of which are described in Section 6.

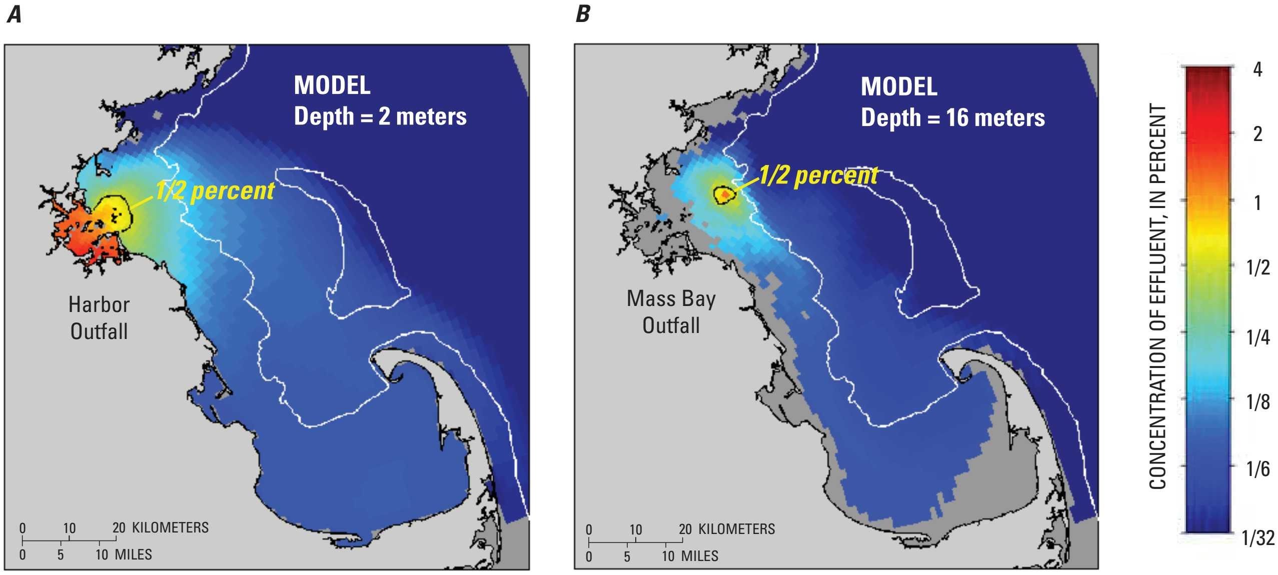

Figure 5.2. *(A)* Modeled summer effluent concentrations at near-surface (2-m depth) for discharge from the harbor sewage outfalls, and *(B)* modeled summer effluent concentrations at mid-depth (16-m depth) for discharge from the Massachusetts Bay outfall. At the Massachusetts Bay outfall, effluent is trapped at mid-depth during the summer beneath the warm surface layer, whereas effluent from the harbor outfalls remains near the surface. In summer, the areal extent of high effluent concentration is smaller at the Massachusetts Bay outfall than at the harbor outfalls, as it is in winter (see fig. 5.1). In addition, because nutrients from the Massachusetts Bay outfall are trapped in waters that are already nutrient rich, the effect of sewage-borne nutrients is decreased.

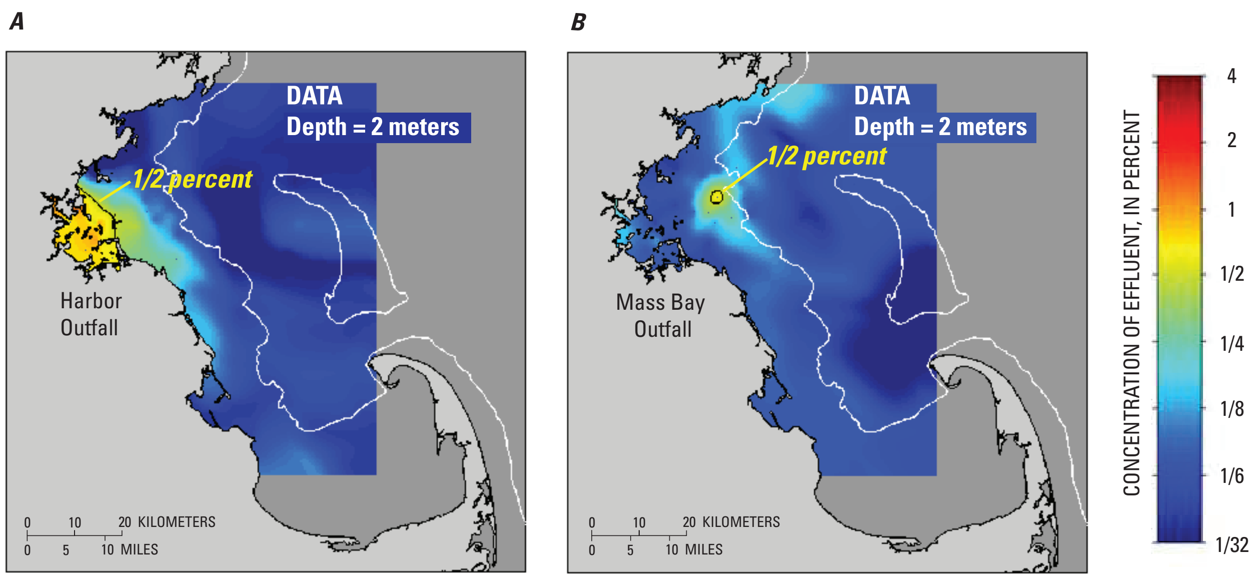

Figure 5.3. Comparison of winter near-surface (2-m depth) effluent concentrations calculated from observed NH_4^+ concentrations for discharge from *(A)* the harbor sewage outfalls, and *(B)* the Massachusetts Bay outfall. The black line indicates an effluent concentration of 1/2 percent (200-fold dilution). The line encloses an area where NH_4^+ concentrations are above background concentrations. As in the model simulation for the harbor outfalls (fig. 5.1A), high effluent concentrations are found within Boston Harbor and along the coastline immediately south. As in the model simulation for the Massachusetts Bay outfall (fig. 5.1B), high concentrations are found only within a few kilometers of the outfall, and concentrations are dramatically lower in Boston Harbor. Concentrations in most of Massachusetts Bay (including the region near Stellwagen Bank) are not significantly changed from their previous low values.

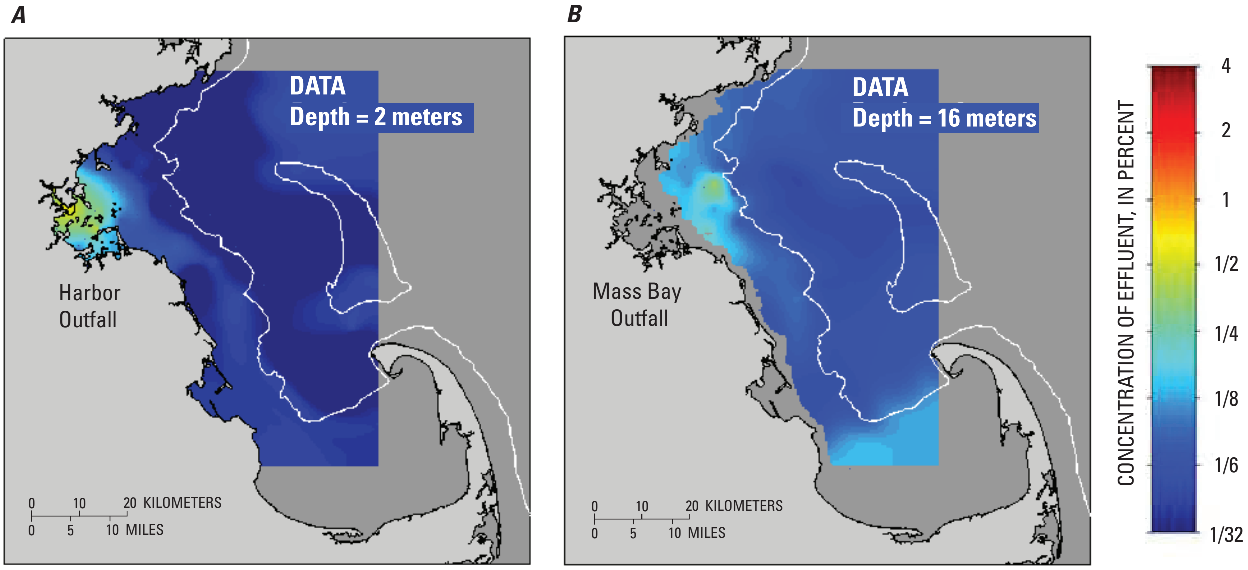

Figure 5.4. *(A)* Comparison of summer effluent concentrations calculated from observed NH_4^+ concentrations at near-surface (2-m depth) for discharge from the harbor sewage outfalls, and *(B)* summer effluent concentrations at mid-depth (16-m depth) for discharge from the Massachusetts Bay outfall. As in the model simulations at the Massachusetts Bay outfall (fig. 5.2B), effluent is trapped at mid-depth during the summer beneath the warm surface layer. In summer, the areal extent of high effluent concentration is smaller at the Massachusetts Bay outfall than it is at the harbor outfalls, as it is in winter (see fig. 5.3). The low values observed in the surface water are most likely due to biogeochemical processes in addition to physical dilution. The higher values in Cape Cod Bay at 16 m also were observed in the data for the harbor outfall (not shown) and thus are not due to outfall relocation.