The Mixing Zone for Combined Sewer Overflows: Testing the Concept as a Basis for Regulation

Models and approaches to applying the concept of mixing zones to the coastal zone require further refinement in order to meet water quality standards for resource areas.

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Under the provisions of current federal and state clean water acts, discharges of pollutants into coastal and inland waters in the United States are to be controlled or eliminated. To achieve this goal, state and federal agencies have been empowered to regulate both point and nonpoint source discharges. The regulations that are being promulgated are based on a wide range of criteria: some are linked to technological solutions, some to biological toxicity and some to the water quality conditions in the receiving water. One concept now being developed that is integral to the receiving water criterion is that of a *mixing zone.* The mixing zone, also called a *dilution zone,* is defined as a "limited area or volume of water where initial discharge takes place; and where numeric water quality criteria can be exceeded but acutely toxic conditions prevented from occurring."[1]

The concept of mixing zone has been further refined in policy and guidance documents by specifying additional constraints. These constraints may include ones that stipulate that mixing zones will not be allowed to extend into areas with critical resources, and/or it shall be small enough to allow adequate passage for motile organisms.

Initially, the concept of mixing zones was developed for regulating discharges into rivers and streams, and individual states have been empowered to set their own criteria for the size of the mixing zone. At present, 30 states have regulations for discharges into rivers, streams or lakes based on a mixing zone. Recently, however, the mixing zone concept is also being considered as a criterion for discharges into coastal areas. As of 1988, the states of Florida and Hawaii, and the District of Columbia, had formalized mixing zone criteria for estuaries and coastal areas.[2]

A significant source of pollution to the coastal zone are discharges that occur from combined sewer overflows (CSOs).[3-5] These discharges occur because many municipalities, especially those along the eastern seaboard, have sewer systems that also collect storm runoff. Most of these sewer systems cannot carry the combined flows of sewage and stormwater during heavy rains, and the excess is discharged into the nearest body of water, the coastal zone in this instance. Now that the direct discharges from wastewater treatment plants are in the process of being controlled in the United States, CSO discharges are coming under closer regulatory scrutiny.

Since the mixing zone concept is currently in use for discharges into lakes and rivers, it is also being considered as a basis for regulating CSO discharges into the coastal zone. This approach is attractive from an engineering point of view because it would reduce the need for expensive technical solutions at the point of discharge by, *de facto,* lowering the water quality standards in the immediate vicinity of the discharge, as long as coastal resources are not impacted. Dilution by the receiving waters would become part of the treatment process for meeting water quality criteria.

The use of the mixing zone concept in regulating CSOs, however, assumes that a method or a model for estimating the size of the mixing zone exists, and that the water quality standards will actually be met within a reasonable distance of the discharge point. It is further assumed that the mixing zone will not extend into nearby resource areas. These assumptions, however, need to be tested in the coastal zone before the approach becomes widely accepted as a basis for drafting regulations. If analyses show that water quality standards are not consistently met in resource areas, then the mixing zone concept would not be useful as a basis for determining regulations.

Initial studies have indicated that discharge plumes from CSOs can travel large distances without adequate mixing,[6] and there is a concern that the aforementioned basic assumptions are not usually met. The plume of a CSO discharge will almost always impact a nearby beach, shellfish bed or natural resource before it is adequately diluted to meet water quality standards.

The study described here was undertaken to determine whether the mixing zone concept provides any flexibility in regulating CSO discharges in two coastal areas. If the size of the mixing zone always includes resource areas, then the concept would not provide any flexibility in the design of a mitigation approach. The regulatory decision would be that no discharge is permitted. The results of a dye study in New Bedford, Massachusetts, to assess the size of the mixing zone from a CSO discharge, and attempts to use models for determining the size for CSO discharges in Lynn, Massachusetts, are reported here.

Measuring Mixing Zones in New Bedford

During the period between February 15 and May 12, 1989, a series of six dye studies at five of the 38 combined sewer overflows in New Bedford were performed as part of a CSO facilities plan.[7] Only the results from two batch release dye studies done at one CSO (Number 004 at the north end of Clarks Cove — see Figure 1 for its location) are reported here, since that CSO provided the best test of the mixing zone concept. The other four dye studies were complicated by technical problems such as a plugged CSO, the termination of flow and discharge under docks, which prohibited establishing an accurate picture of the mixing zone.

The details of the methods used for the dye studies are described in the CSO facilities plan,[7] and only a summary is presented here. Approximately ten liters of a 20 percent aqueous solution of Rhodamine B dye were dumped into the CSO discharge. The CSO discharge was pumped through the hurricane barrier at a rate of 55,000 gallons per minute, and a total of approximately 600,000 gallons were discharged during each of the two studies.

The dispersion and dilution of the dye released into the CSO discharge was mapped for

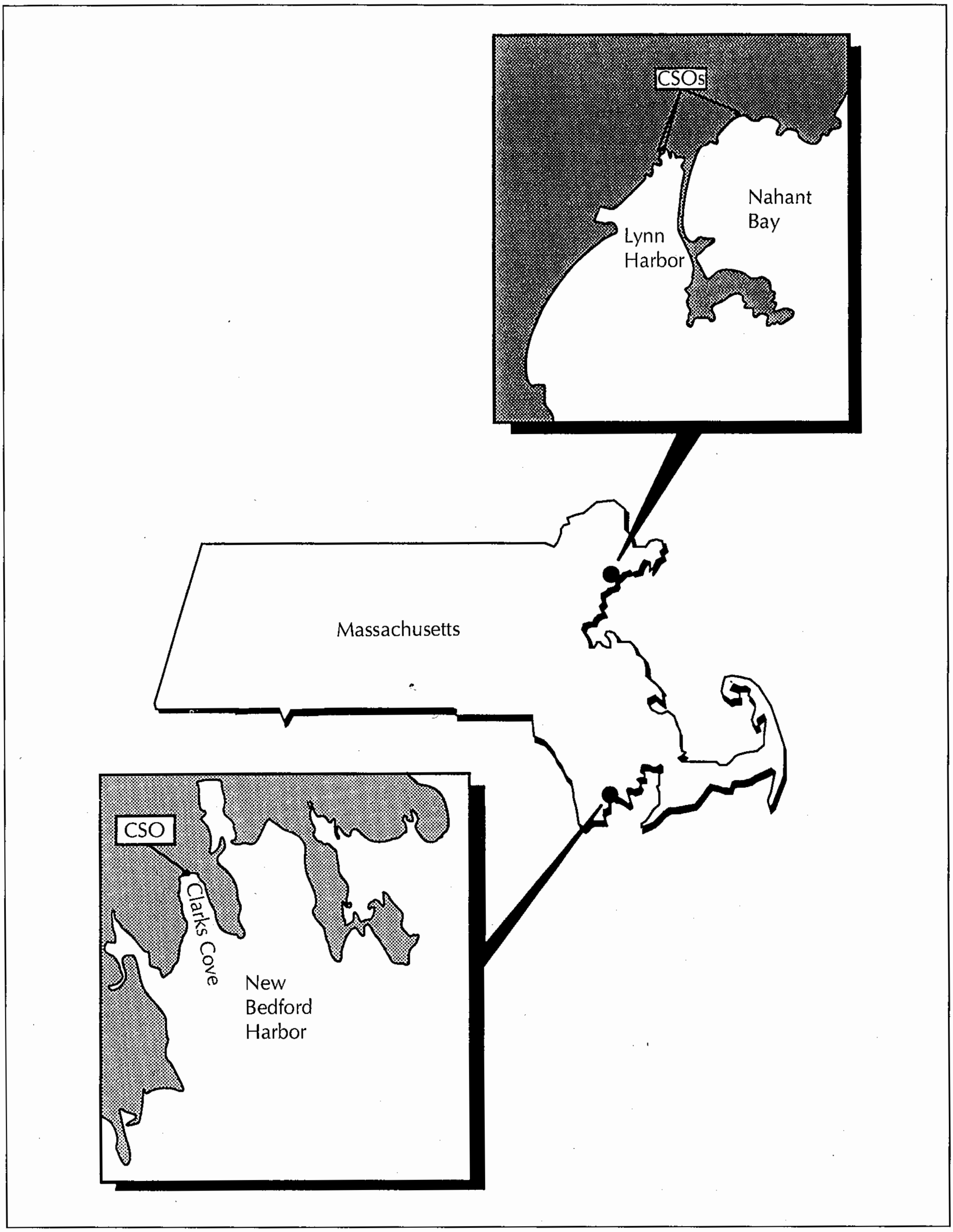

FIGURE 1. Location of CSOs in Lynn and New Bedford, Massachusetts.

six hours using a flow-through fluorometer mounted on a vessel. Horizontal positioning of the survey vessel was provided by using an electronic positioning system. Dye concentrations and the size of the plume were mapped at hourly intervals by recording dye concentrations along perpendicular transects that crossed the plume. Vertical profiles of dye concentration, salinity and temperature were also performed at regular intervals along the transects.

Modeling the Mixing Zone

The mixing zone of discharges from waste treatment plants is often estimated by modeling the dilution and dispersion of the discharge plume in the receiving water. With outfalls located offshore, in deep water, two-dimensional models are often sufficiently accurate to be used.[8] The major factors that influence the mixing zone are the relative buoyancy of the discharge and the velocity of the currents in the area.

In coastal waters, however, two-dimensional models do not provide enough detail to completely predict the dilution and transport of a CSO discharge. Factors such as wind-induced surface currents, tidal eddies, the density difference between a surface discharge of freshwater and the underlying salt water all interact to affect the mixing. Furthermore, most models available at present use a deterministic approach in order to model pollutant transport. CSO discharges, however, are stochastic, and the pollutant mixing and transport is not easily characterized by deterministic models.[9]

Some of these problems can be overcome by developing three-dimensional deterministic models that can incorporate most factors. Such models exist, or are under development, but they are extremely complicated and expensive because they attempt to model stochastic events using a deterministic approach. Their cost quickly becomes prohibitive given the number of CSOs that need to be modeled in coastal areas.

Because two-dimensional models do not completely characterize the three-dimensional nature of the mixing from a freshwater CSO discharge into saline coastal waters, four different models were used to provide an estimate of the size of the mixing zone for three CSOs in Lynn (the locations of the CSOs modeled are shown in Figure 1). The first model simply considers dilution based on the volume of the discharge and the volume of the receiving water. The second and third models are two-dimensional estuarine models, and the fourth is a density flow model. None of these models accurately describe all aspects of mixing when a CSO discharges because each model takes into account only a few of the many factors that influence plumes. The models were used together, however, in order to outline the scope of the problem and to provide a preliminary estimate of the size of the mixing zone.

Dilution Model. A first-order estimate of the size of the mixing zone can be made by determining the volume of the receiving waters that is needed in order to provide the level of dilution required to meet water quality standards, based on the pollutant loadings in the discharge. The area represented by the volumes of water needed to dilute discharges from different storms can be plotted and areas where the mixing zone impinges on important resources can be identified.

Estuarine Flow Models. A dynamic estuarine model (DEM) was used to predict the size of the mixing zone in Lynn Harbor, while the Tidal Embayment Analysis/Eulerian Lagrangian Analysis model (TEA/ELA) was used in Nahant Bay. Both of these models incorporate tidal flows and the intermittent nature of the discharge in the modeling. Both models can address wind effects, albeit crudely. They do not, however, include the density differences between the discharge and the ambient water. The description of the models and their use for the Lynn discharges is given in one section of the facilities plan.[10] Briefly, the models were calibrated with oceanographic data that were collected in the field, and then the discharge from the two-week and five-year storms were modeled using average tidal conditions.

Density Flow Model. The two estuarine models used, DEM and TEA/ELA, do not take into account any stratification that may occur. This aspect of the mixing dynamics was investigated using an expert system computer program for mixing zone analyses of waste discharges.[11,12] The expert system predicts the dilution that can be achieved for submerged discharges that have a different density than the receiving water. The model that is derived from this analysis takes into account density differences between the discharge and the receiving water, the velocity of the discharge and the local currents that can move the plume. It does not, however, model any wind-induced mixing that may occur.

Results of the Dye Studies in New Bedford

The procedure for estimating the mixing zone from the dye studies was to determine the estimated dilution achieved in the plume as a function of time and next to map the distance traveled by the plume in that time. A detailed description of the results and their analysis is given in the final facilities plan.[7] Figure 2 presents a graphical summary of the path of the dye plume on April 20, and the concentrations of dye at different times. On March 30, the plume traveled to the western shore and was contained within the shallow waters within one kilometer of the discharge.

By relating the peak concentration of dye with the time since discharge, it is possible to estimate the dilution rate of the discharge. Figure 3 presents the dilution of dye as a function of time for the two studies. The dilution rate initially seems to be linear. In the first study (on March 30), the dilution rate was 2.5/hour *(i.e.,* the concentration of dye decreased by a factor of 2.5/hour). In the second study, the dilution rate was 10/hour. The significant difference in dilution rates can be attributed to the observation that on March 30 the plume was pushed against the western shore of the bay and held there by the wind. On April 20, the plume was moved along the shore, and in waters that were 20 feet deep, thus permitting better mixing.

The distance traveled by the plumes was most closely correlated with wind direction and velocity. On the average, the plume moved at approximately one to 2.5 percent of the wind speed as measured at the New Bedford Hurricane Barrier, depending on the proximity to shore. Tidal currents in Clarks Cove are very small, and the average tidal excursion is less than one kilometer.[7]

Based on these observed dilution rates, it was possible to estimate the time that would be needed for the CSO discharge to meet water quality standards. The average concentrations of the two most concentrated pollutants (measured during the field studies undertaken for the facilities plan), copper and coliform bacteria, were utilized in order to obtain estimated mixing times.

Initially, the mean concentration of fecal coliform bacteria in the discharge was 156,000/100 milliliter (ml), and that of copper was 0.11 milligram/liter (mg/l).[7] Based on a dilution rate of between 2.5 to 10 per hour and assuming that the 90 percent of the bacteria die within 24 hours (T_{90} of 24 hours), it is estimated that the beach standard for total coliform in Massachusetts (200 fecal/100 ml) would be met in 21 to 32 hours. The shellfish standard for fecal coliform, which is stricter (14 fecal/100 ml), would be met in 42 to 54 hours. Copper, which is assumed to be a conservative pollutant that remains in the water column, will take four to 16 hours to reach water quality standards (2.9 μg/l).

Shellfish beds are found throughout Clarks Cove in New Bedford Harbor,[13] and beaches are found along both shores of Clarks Cove. During the dye studies, the discharge plume reached the beaches within four hours of discharge, and were over the shellfish beds almost immediately. Given the time needed to meet water quality standards for coliform bacteria, the mixing zone *(i.e.,* the area where water quality standards are not met) extended into the resource areas. Based on a detailed analysis of 40 years of wind data, it was found that water quality standards for coliform bacteria will be violated throughout most of Clarks Cove over 30 percent of the time a discharge occurs through this CSO.[7]

Modeling

The four aforementioned models were used to estimate the size of the mixing zone for CSOs in Lynn. Of the six major CSOs in Lynn, the discharges from three were analyzed: two that discharge into Lynn Harbor and are combined in the calculations, and one that discharges into Nahant Bay (see Figures 1 and 4). The flow characteristics from these CSOs are summarized in Table 1, and are based on the data collected for the Lynn CSO facilities plan.[10] The marine resources that can be impacted from the CSO discharges are summarized in Figure 4. These resources include shellfish beds, beaches and lobstering areas.

Dilution Model. Using National Oceano-

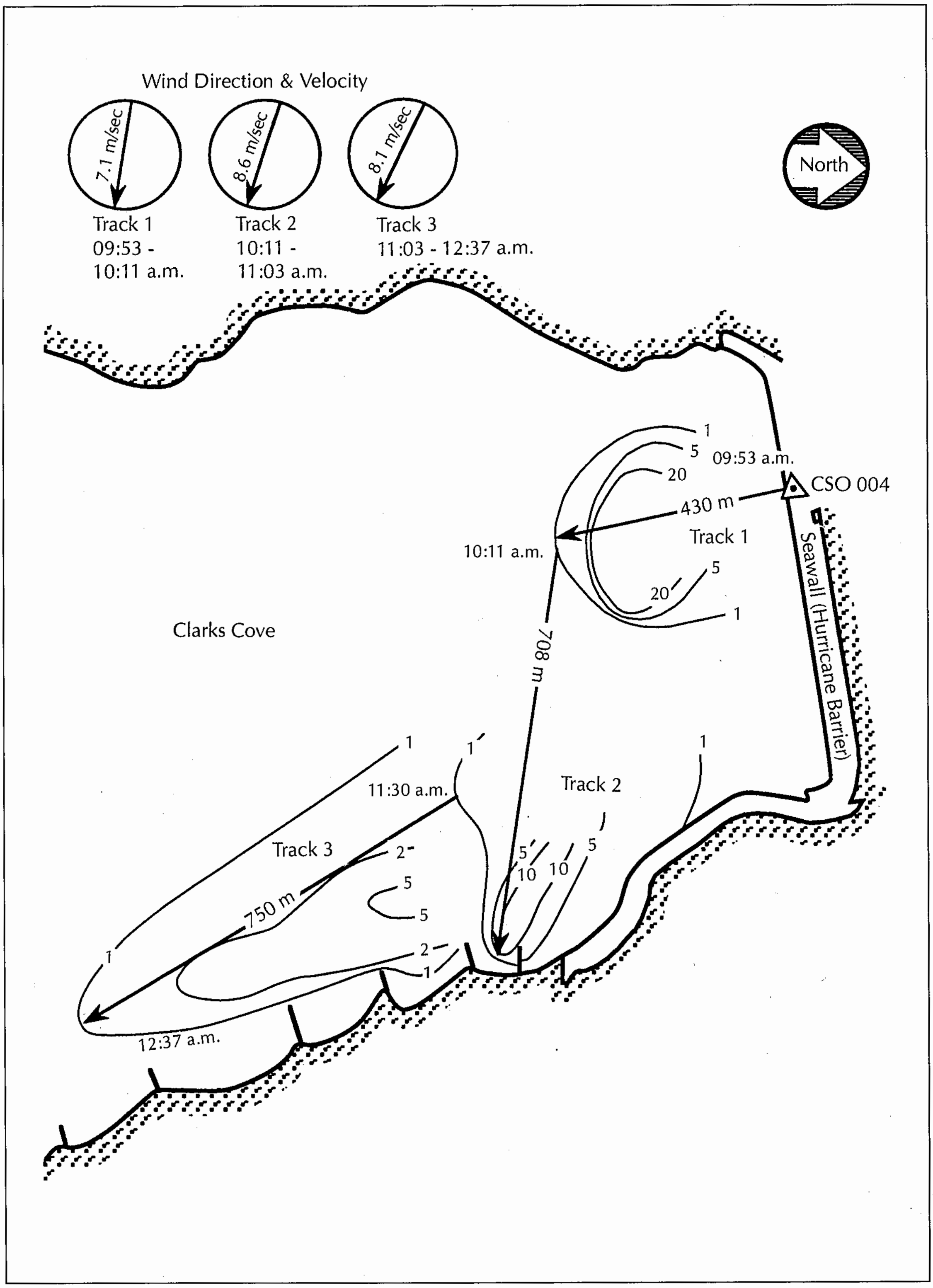

FIGURE 2. Leading edge of dye plume from a CSO discharge on April 20, 1989, in Clarks Cove, New Bedford Harbor. Contours represent dye concentrations in parts per billion.

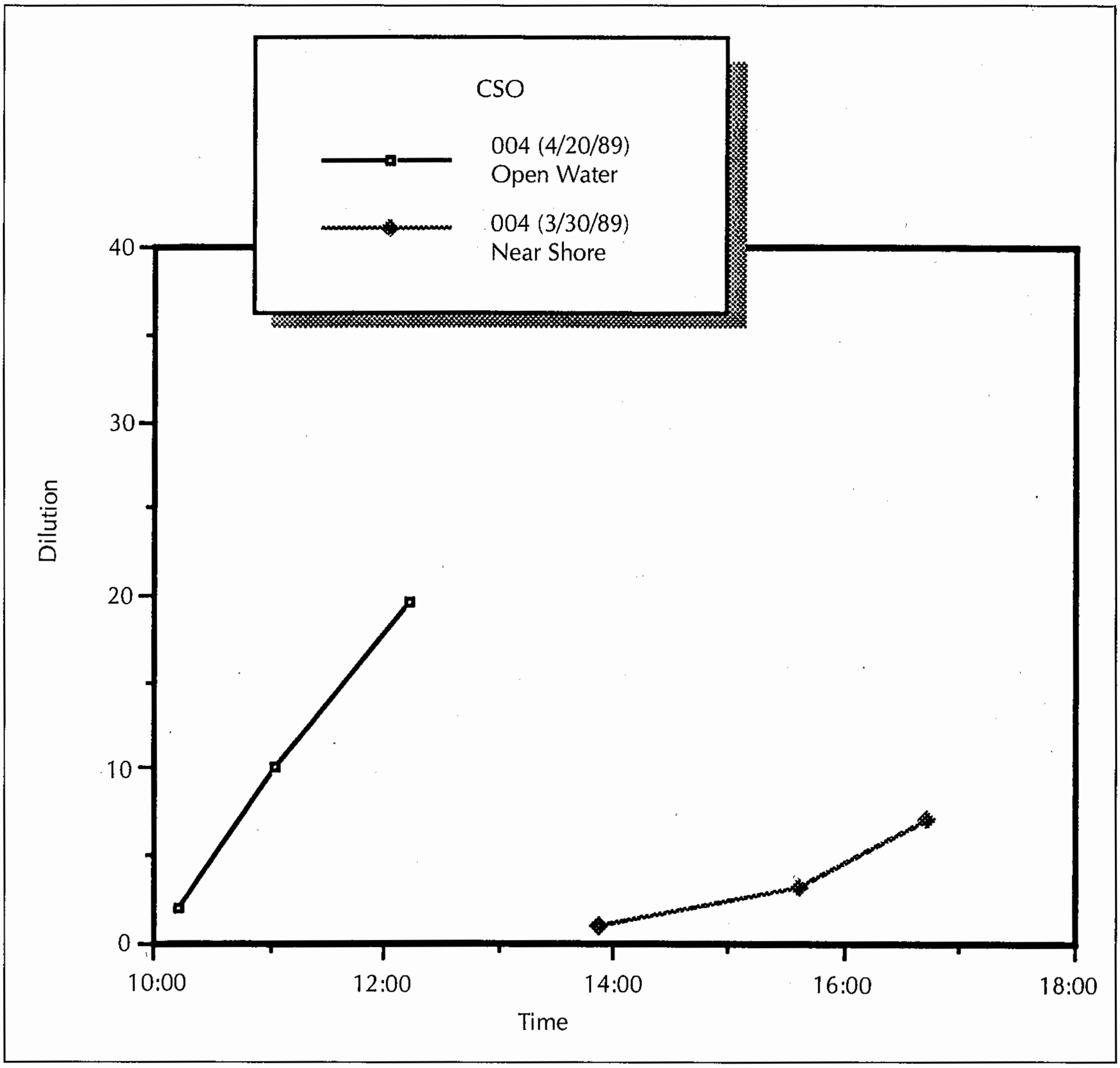

FIGURE 3. Dilution of CSO discharge in New Bedford Harbor as a function of time.

graphic and Atmosphere Administration (NOAA) chart #13275 of Lynn Harbor and Nahant Bay, it is estimated that there are approximately 150 million gallons of water in Lynn Harbor at low tide in the area extending between the north end of the harbor and its mouth (a line running east of the Nahant Peninsula). In Nahant Bay, the estimated volume is 19,000 million gallons between the two points that span the bay.

Copper and coliform bacteria are two pollutants needing the highest dilution in the CSO discharges into Lynn Harbor. The average fecal coliform count is 200,000/100 ml and the copper concentration is 60 parts per billion (ppb).[10] To achieve the state shellfish standard of 14/100 ml, therefore, a dilution of approximately 14,000 is needed. If the less rigorous standard of 88/100 ml is used in areas for restricted shellfishing, a dilution of approximately 2,300 is needed. To achieve the U.S. Environmental Protection Agency (EPA) water quality standard of 2.9 ppb for copper,[14] a dilution of approximately 20 to one is required.

With a two-week storm discharging 0.6 million gallons, and a five-year storm discharging 11.7 million gallons through the two CSOs, volumes of 1,380 and 26,900 million gallons, respectively, are needed to dilute the discharge in order to meet the less stringent coliform stan-

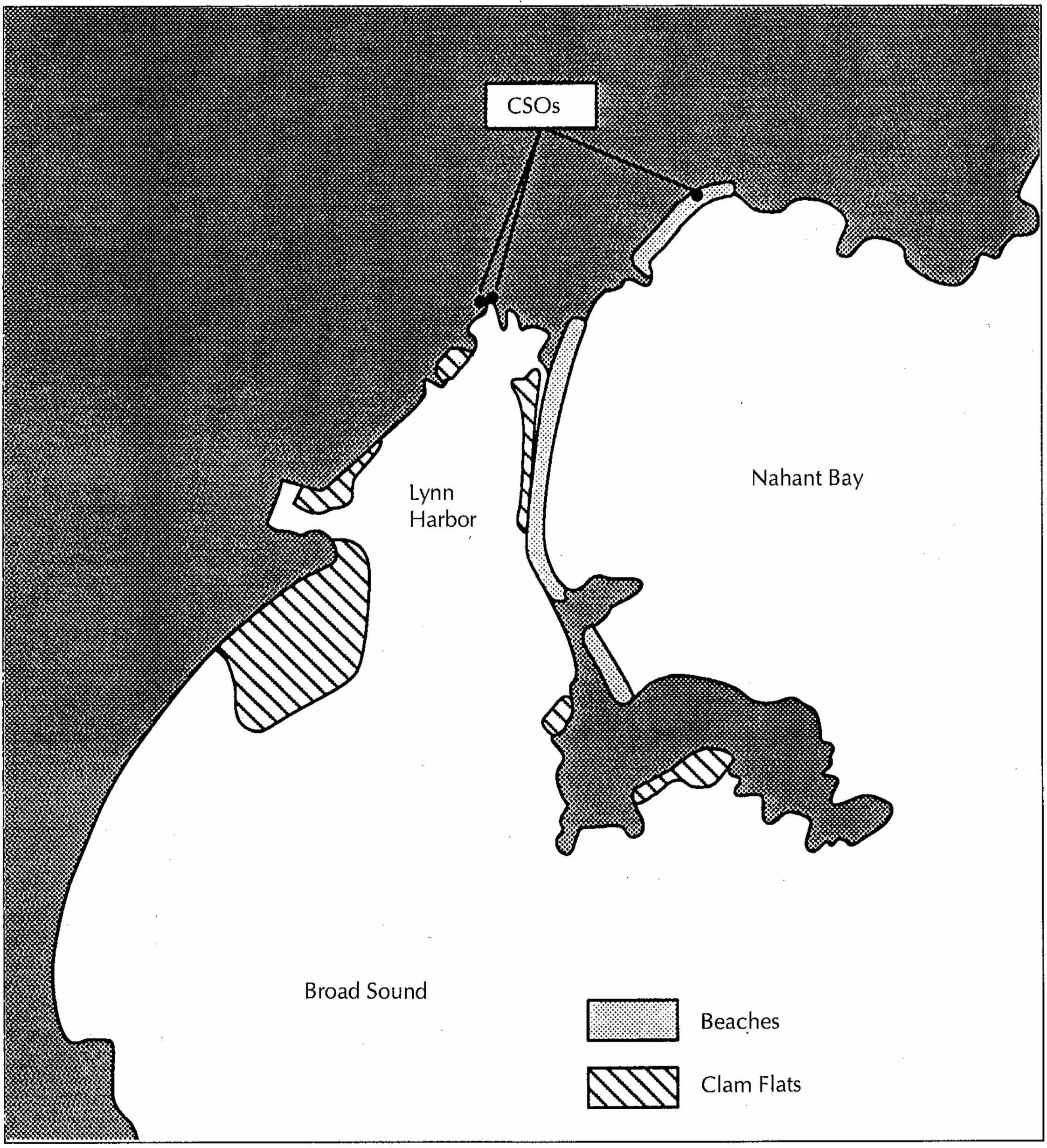

FIGURE 4. Lynn Harbor and Nahant Bay showing the locations of CSOs and critical resources that may be impacted by the discharges.

dards. For copper discharges, the volumes of the receiving waters needed are 12 and 234 million gallons, respectively, for the two storm conditions.

The CSO discharging into Nahant Bay has fecal coliform concentrations of approximately 260,000/100 ml, but it does not have any measurable levels of copper.[10] Since there are no shellfish beds in Nahant Bay, the only water quality standard for coliform bacteria that needs to be met is that for beaches (200/100 ml). Thus, a dilution of 1,300 to one is needed in the bay in order to meet the standard. By comparing the estimated size of the receiving waters with the dilutions needed to meet water quality criteria, neither the harbor nor the bay is large enough to adequately dilute the discharges from a five-year storm, and Lynn Harbor is

TABLE 1
Characteristics of CSO Discharges into Lynn Harbor and Nahant Bay

Location of CSO Discharge	Average Flow 2-Year Storm (Million Gallons)	Average Flow 5-Year Storm (Million Gallons)	Dilution Needed to Meet Minimum Coliform Standard*	Dilution Needed to Meet Copper Standard*
Nahant Bay	2.3	42.0	1,300:1	none
Lynn Harbor	0.6	11.7	2,300:1	20:1

* The dilutions noted are those needed to meet water quality standards based on the concentrations of the pollutants as measured in the discharge.

even too small to adequately dilute coliform bacteria during a two-week storm.

This estimate is crude, since it does not take into account the duration of a storm nor the tidal flushing that takes place. It can be used, however, in order to provide a computationally simple first-order approximation of the mixing zone where water quality standards are not met from the CSO discharges. The comparison of the potential mixing area with the resources in the area (compare Figures 4 and 5) shows that resources are impacted by the discharges, even if the estimate is wrong by a factor of two or more. Thus, the mixing zones of the CSOs in Lynn Harbor and Nahant Bay as they are estimated from a "dilution" model will almost always impact some critical resource.

Estuarine Flow Models. The results from the DEM and TEA/LEA models, summarized in Figure 5, show that by adding a time factor, the dilution of the effluent is improved relative to the simpler model described previously. The figure illustrates the dilutions 24 hours after an overflow began. The results from these models, however, still indicate that water quality criteria would not be met by the time the plume from a five-year storm reaches critical resources. In Nahant Bay, the plume reaches the beaches before a 1,300 to one dilution is achieved. In Lynn Harbor, shellfish beds are subject to a plume that is diluted only by a factor of 100 to one, not the 2,300 to one needed in order to meet the criteria.

Density Flow Model. Since coastal CSOs discharge freshwater into salt water, the density difference between the two may result in the formation of a lens of effluent that does not mix immediately with the receiving waters. Measurements of dispersion in actual plumes have shown that the density differences may significantly enlarge the mixing zone. In Jamaica Bay, New York, plumes of effluent were still measurable more than one mile from the discharge point.[6]

In order to use the expert system, which requires submerged discharges, the site of the CSO discharge in Nahant Bay was changed to a hypothetical offshore location at a depth of five meters. When the conditions for a two-week storm were modeled, using the field measurements of ambient currents, temperature and salinity,[10] the model indicated that the plume would extend over two kilometers before a dilution of 100 to one is achieved. These results again suggest that the discharge would not be mixed well enough in order to meet water quality criteria at the beaches.

Conclusions

There are several key factors that extend the size of the mixing zone in coastal areas:

- The relatively small volume of receiving waters;
- Strong tidal currents;
- Wind; and,
- The density difference between discharged waters and the receiving waters.

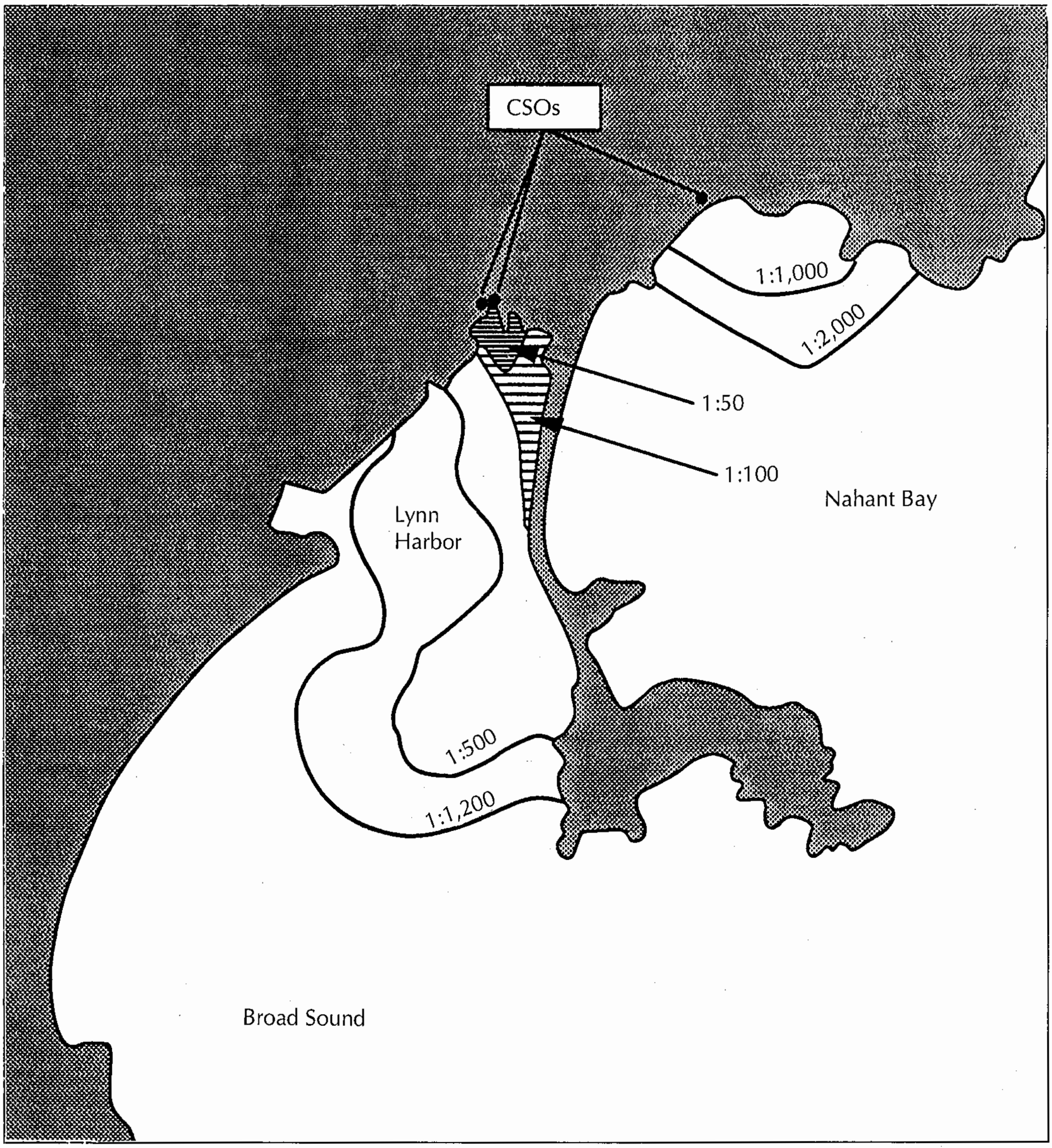

FIGURE 5. Dilutions for a five-year storm as predicted by DEM and TEA/LEA for Lynn Harbor and Nahant Bay.

In the example of the CSO discharge in New Bedford, the mixing zone extended well beyond the nearest beaches and shellfish beds. In Lynn, all four modeling approaches indicated that the mixing of discharges would not be sufficient in order to meet water quality standards for nearby resources. Since the other coastal communities in the Northeast such as Boston, New Bedford, Salem and Gloucester, all have CSOs discharging into shallow constricted bays, similar problems can be expected in these cities. The mixing zone of the discharge would extend to nearby resource areas for these communities.

All of these observations suggest that the concept of mixing zone for regulatory purposes may not be very useful for CSO discharges into coastal areas. Important resources will almost always be within the zone where water quality standards are not met, and the basic regulatory conclusion would be that no CSO discharges are to be permitted. Therefore, regulations based on the mixing zone concept in the coastal zone would not provide the needed flexibility for developing the appropriate remediation that would meet both environmental and economic needs.

The size of a mixing zone can be reduced by some form of treatment before discharge. Such an assumption was not made in this analysis because only the concept of mixing zones as a general approach to regulations was explored. Treatment at the point of discharge becomes a very site specific problem because each effluent has different pollutant characteristics and has different amounts of dilution available in the receiving waters.

If the concept of mixing zones is not readily applicable to CSO discharges, do other options for developing regulations exist? One idea being considered by regulators in Massachusetts is to limit the number of discharges. The assumption is that every discharge from a CSO would cause a water quality violation and impact some resource. The impacts on the coastal environment would be reduced by limiting the discharges to only a few per year. This approach makes technical control measures more feasible, since there is no need to design systems to handle extreme storm conditions that occur infrequently. The unresolved question with this approach is whether a few "pollution" events per year is an acceptable environmental compromise.

CSO regulations are still in their embryonic stage, and now is the time to explore different concepts. It is hoped that the summary of these experiences in trying to apply the concept of the "mixing zone" in New Bedford and Lynn will stimulate discussion of the issue. In the future, there is a need to explore other concepts in more detail, including the feasibility of using the "permitted violations" concept. In addition, there is a need to develop an empirical model for assessing the size of CSO plumes in different coastal environments.

ACKNOWLEDGMENTS — *The data for this study were collected as part of CSO facilities plans for the cities of New Bedford and Lynn, Massachusetts. Oceans Systems, Inc., was the subcontractor for the dye studies. The DEM was developed by Camp Dresser & McKee (CDM) and the TEA/ELA model was developed by the Parsons Laboratory at the Massachusetts Institute of Technology. Most of the modeling using TEA/ELA and DEM was performed by Mitchell Heineman and Robert Kapner of CDM. Joanne Barker of CDM did the volume estimates of Lynn Harbor and the CSO loadings. A Turner Model 10 fluorometer and the Racal "Micro-Fix" electronic positioning system were employed in the New Bedford site study. CORMIX1 was the expert system used for analyzing the mixing zone.*

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