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Transport of Contaminated Sediments in Boston Harbor

Massachusetts Water
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BOSTON HARBOR STUDY OF SOURCES AND TRANSPORT OF HARBOR SEDIMENT CONTAMINATION

PART I: TRANSPORT OF CONTAMINATED SEDIMENTS IN BOSTON HARBOR

Summary Final Report

submitted to
Massachusetts Water Resources Authority

by

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EXECUTIVE SUMMARY

Four interrelated sub-projects were conducted as part of this study.

1. Fluorescent tracer studies of water column transport and initial particle deposition

Several tracer studies were used to quantify the transport of contaminated sediments from shoreline sources (e.g. CSOs) in Boston Harbor. The studies, described in more detail by Adams et al. (1992), involved the simultaneous release of two fluorescent tracers into a CSO at the head of Fort Point Channel, a tributary of Boston's Inner Harbor. The first tracer, red Rhodamine WT dye, is designed to follow dissolved pollutants; the second, yellow Day Glo paint (a suspension of 0.1 to 5 micron diameter paint pigment), is designed to track suspended matter. Samples were collected for a period of about one week following tracer injection and were analysed for tracer concentration, salinity, fecal coliform, suspended solids, and the presence of trace metals. The dye measurements indicated a mean hydrodynamic residence time in the channel of 1–2.6 days depending on tidal amplitude and phase (at the time of tracer release) and freshwater inflow. Rates of particle deposition, determined by comparing the disappearance rates of paint and dye were in the range of 0.25 to 1 per day. Assuming that sewage particles settle at least as fast as paint, one concludes that upwards of half of suspended sewage particles, and their associated toxic chemicals, are being trapped in the channel before reaching the outer harbor. The inferred rates of paint deposition substantially exceed the range calculated for discrete settling or found in laboratory column tests conducted with varying initial concentrations and solvents; these observations suggest that the channel bed may play a critical role in scavenging particles from the water column, as suggested by Newman et al. (1990b) and Stolzenbach et al. (1992). Measurements in Boston Harbor of fecal coliform, used as an indicator bacteria for establishing beach closures, suggest disappearance rates of 1 to 3 per day. Combined with the hydrodynamic residence times, one predicts that anywhere from about 50 to about 98 percent of the bacteria are lost within the channel before they have an opportunity to contaminate downstream beaches or shellfishing areas. Tracer experiments were also conducted near the Nut Island sludge discharge, but the duration of measurement was too short to assess the rate of particle deposition.

2. Metal concentrations in sediment cores and overlying water

Six sediment cores were collected down the axis of Fort Point Channel and were analyzed for deposition rate using Pb-210, metal concentration, etc. (Wallace et al., 1992). The core nearest the CSO discharge (BOS070) was in an erosional area; deposition rates of 0.7 to 6.3 cm/yr were inferred from the other five cores. These rates are an order of magnitude greater than rates characterizing the outer harbor and a factor of 6 greater than the calculated rate assuming all suspended sediment from Fort Point Channel sources deposits uniformly within the channel. Similarly, the annual deposition of copper exceeds the reported channel input by a factor of 12 and, in fact, accounts for over 10% of the estimated total copper input into Boston Harbor. Our observation of deposition rates and metal inventories are consistent with previous measurements collected in Fort Point Channel. Collectively they support the conclusion from the tracer study that the channel is highly depositional and suggest further that most of the contaminated sediments have been imported.

3. Measurements of the surficial strength of marine sediment using the MIT fall cone

Once deposited, a major question concerning contaminated sediments is whether they are "strong" enough to resist mobilization by waves, currents and tides. If not, then shear stresses in excess of a critical value will cause erosion and subsequent transport of the contaminants. For cohesive soils, erodibility is very difficult to assess; hence the purpose of this task was to develop a device capable of measuring the surficial strength (undrained shear stress) of extremely weak cohesive sediments and to relate this strength to the critical bottom shear stress governing erodibility. The device is an automated fall cone, whose precise depth of penetration into a cored section can be (inversely) correlated with the undrained shear stress of the surface sediment. Although fall cones have been used for more than a decade, their traditional use is in foundation engineering where soil strength is much greater than in marine waters; hence a new lightweight device was needed. Such a device was developed in the initial phase of this project and its development, testing and calibration are described in Zreik (1991). Since then, the fall cone has been used to determine three strength profiles from two cores collected on different sides of Peddock's Island in Boston Harbor. Despite the different hydrodynamic environment of the two sites, the strength profiles were substantially similar. The undrained shear stress of a soil is generally about three orders of magnitude greater than the threshold erosional shear stress. We are conducting follow-up experiments to better quantify this relationship by replicating the kaolinite sediment beds used by Mehta et al (1982) in their hydrodynamic experiments of critical erosional stress in an annular flume. Samples of Mehta's sediment have been obtained, and the design of an experimental flume is proceeding.

4. Numerical model studies of ultimate deposition

A two-dimensional depth-averaged model (TEA) was used to compute the time-varying distribution of bottom shear stress in Boston Harbor and Broad Sound due to tidal currents. Regions of erosion and deposition were identified by comparing the distribution to a specified constant critical shear stress τ_c. By comparing the regions of simulated erosion and deposition with regions inferred from sediment characteristics (e.g., Knebel et al., 1991), the value of τ_c is on the order 0.3 to 1.0 N/m^2, well within the range reported in the literature. This distribution indicates that only a small portion of the harbor, and none of the inner harbor, is erosional and that most of the harbor is depositional. The transport of cohesive sediment was modeled by incorporating the computed shear stress distribution into a modified version of the transport model ELA. The model had been previously calibrated to field measurements using sewage tracers and was run using estimated sediment loadings from riverine, shoreline, and outfall sources. A base-case simulation used $\tau_c = 0.3$ N/m^2, dispersion coefficient $D = 75$ m^2/s, settling velocity $w_s = 10^{-5} m/s$, and an erosion rate $M = 0.04$ g/m^2-s. Modeled water column concentrations averaged about 0.8 mg/ℓ, a factor of 3–10 smaller than typically observed concentrations. Similarly, simulated accumulation rates averaged about .02 cm/yr, about an order of magnitude less than Fitzgerald's (1980) measured accumulation rates [also compare with Gordon's data]. Because the model only considers riverine, shoreline, and outfall sediment sources, these observations suggest that the majority of deposited sediments are imported. Model results suggest that about 34% of the input solids are ultimately deposited within the harbor. This estimate is only slightly larger than corrected estimates from Fitzgerald, after accounting for differences in assumed depositional area. When only treatment plant sources are considered, the percent deposited in Boston Harbor drops to about 25%; accounting for near shore sources only the percent deposited increases to about 50%.

Summary

Based on the results of these four studies, in combination with previous information, we can summarize the sediment regime of Boston Harbor.

- In all regions of the harbor except for President Roads and Nantasket Roads the heaviest fraction of waste particles are probably deposited within about 100 to 1000 meters from the source.
- The semi-enclosed regions of the Inner Harbor such as Fort Point Channel have residence times on the order of one to several days. On the basis of the observed

deposition of tracer particles and sediment cores it is estimated that at least half of the particle load discharged to the inner harbor may be retained in these regions and never participate in the harbor-wide particle transport regime.

- Particles (other than the heaviest fraction) discharged directly into the outer harbor or escaping the inner harbor enclosed regions are fairly well dispersed by tides throughout the harbor as a whole and deposit wherever resuspension is negligible. On the basis of the calculated bottom stress distribution due to tidal currents and observed sediment characteristics it is estimated that about 80% of the harbor, including the entire inner harbor, is depositional. This large area, coupled with the efficient dispersion of particles within the harbor, insures that particles from different sources may be deposited together throughout the harbor and that attribution of contamination to a particular source will be difficult. (We note that the factor of 80% is an upper bound because wave-induced bottom stress contributes to additional areas of erosion.)
- Of the particles participating in the harbor-wide transport roughly 25% to 50% will be retained in the harbor depending on their source location. The higher percentage will characterize particles emanating from the inner harbor and shoreline areas and the lower number will characterize particles discharged from the treatment plant outfalls in the outer harbor.
- The accumulation of "natural" particles, i.e., those imported from outside the harbor, appears to exceed the average rate of deposition of waste particles by a factor of up to 10. Likewise, the rates of sediment deposition and trace metal accumulation in Fort Point Channel exceed the respective sediment and metal loadings to the channel by a factor of up to 10. This latter observation, if borne out in other regions of the inner harbor, has important implications for future CSO control: control of a particular CSO (e.g., BOS070 at the head of Fort Point Channel) may not, by itself, significantly reduce the build-up of contaminants in the nearby sediments.

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On February 24, 1992, a workshop was held at MIT Sea Grant concerning Contaminated Sediment in Boston Harbor. A rough draft of this report was presented. We would like to than the participants of the workshop for their many helpful comments on the oral and written versions of the report.

Table of Contents

I. INTRODUCTION

This report summarizes the results of the interdisciplinary study "Boston Harbor Study of Sources and Transport of Harbor Sediment Contamination: I—Transport of Contaminated Sediments in Boston Harbor" which has been conducted by researchers from the Massachusetts Institute of Technology and the University of Massachusetts at Boston. The second half of the study, II—Sediment-Water Exchange of Contaminants in Boston Harbor, is to be reported on separately. The objectives of the research are:

- To quantify water column dispersion in near-shore areas.
- To determine the spatial and temporal extent of initial settling of contaminated particles.
- To infer the areas of ultimate deposition of contaminated particles.

In pursuit of these objectives the following sub-studies were conducted:

- Tracer studies near outfalls led directly to estimates of water column dispersion and provided information about the process of initial particle deposition. Five separate tracer studies were performed: three in Fort Point Channel and two at the Nut Island sludge discharge off of Long Island. The detailed results of these studies are contained in a report entitled "Transport of Contaminated Sediments in Boston Harbor: Fluorescent Tracer Studies" by Adams et al. (1992).
- Measurements of suspended solids and particle-bound constituents in the water column were obtained synoptically with the tracer studies, and Pb^{210} and trace metal analysis of sediment cores throughout the Harbor were used to infer long-term depostion rates and inventories of contaminants.

- A fall cone device was modified to make possible the determination of resistance to stress typical of the surficial sediments found in Boston Harbor. Extensive laboratory testing of the modified fall cone on model sediments and on samples of Boston Harbor sediments are reported in a Masters Thesis by Diana Zriek entitled "Determination of the Undrained Shear Strength of Very Soft Cohesive Soils by a New Fall Cone Apparatus" (Zreik, 1991). Additional estimates of surficial shear stresses from undisturbed box cores obtained in the Harbor are reported in Section II of this report.

- The transport and deposition of sediment from all known sources within Boston Harbor was simulated using two-dimensional numerical models for water movement and contaminant transport that have been previously calibrated to Boston Harbor [Kossik et al., 1986; Adams et al., 1987]. The model simulations enabled estimates of the areas of ultimate deposition within the harbor and the rate of contaminated sediment transport to Massachusetts Bay. The model predictions, including a sensitivity study of the effect of parameters regulating sediment dispersion, deposition, and resuspension, are contained in a Masters Thesis by Jeng-Jong Lee entitled "Contaminated Sediment Transport in Boston Harbor" (Lee, 1990).

Section II of this report summarizes each of the above sub-studies and presents appropriate conclusions pertaining to that sub-study. Section III of this report then synthesizes these results, along with information from other studies, to address the overall objectives of the study as described above.

II. SUMMARIES OF SUB-STUDIES

2.1 Fluorescent Tracer Studies of Water Column Transport and Initial Particle Deposition

Fluorescent tracer studies were performed to better understand water column dispersion in near shore areas and to quantify the rate of initial deposition. During our project five separate studies were performed: three in Fort Point Channel and two in the Nut Island sludge discharge off of Long Island (see Figure 2.1). We also performed some settling column tests in the laboratory and analyzed results of an earlier dye study performed as part of the Combined Sewer Overflow (CSO) Facilities Plan (described in Section 3.1.3).

2.1.1 Fort Point Channel surveys

The majority of our effort was concentrated in Fort Point Channel. This site was emphasized, in part, because the CSO at the head of the channel (BOS070) is the largest discharging directly to Boston Harbor. Fort Point Channel is also part of the inner harbor (hence several miles from beaches and shellfishing areas), and it it critical to future CSO planning to understand how dissolved and particle-bound pollutants discharged in the inner harbor are transported to the outer harbor. Finally, the channel geometry and bridge crossing allow for easy sampling. On the other hand, BOS070 is perhaps the most complicated CSO because it receives combined sewerage from a number of different regulators as well as some storm water runoff. As such, direct monitoring of the aggregate overflow rate is very difficult and was not attempted.

Table 2.1 summarizes the three studies conducted in Fort Point Channel. During each study, fluorescent tracer(s) were discharged at the head of Fort Point Channel (mouth of BOS070 culvert) over a period of about two hours and monitored throughout the channel for about one week. Although dye injections were all made in the morning, the phase of the tide varied for the three surveys. Monitoring was conducted by collecting discrete samples from bridges and the channel banks during intervals of about one to two hours surrounding low slack tide. During the first two to three days of each study, surveys were conducted at each low tide, while during the latter phases, surveys were conducted at greater intervals. Figure 2.2 shows typical horizontal positions used for tracer sampling and also provides an indication of typical channel depths (in feet at MLW). Generally surface samples were collected at each station while vertical samples (1.5 m, 3 m, and 5 or 6 m) were also collected at the central stations.

For the first survey, the only fluorescent tracer was Rhodamine WT (a 20% solution of dissolved red dye, specific gravity $\simeq$ 1.13) and concentrations were detected using a Turner model 10 filter fluorometer with light source and emission and excitation filters appropriate for Rhodamine WT. During the second two surveys a mixture of Rhodamine WT dye and Saturn Yellow Day-Glo fluorescent paint was used and concentrations of the two tracers were detected using a fluorescence spectrometer (Perkins-Elmer). The paint is a 50% solution of suspended AX-17 pigment particles (specific gravity of solution = 1.19; particle diameters range from 0.1 to 5 microns); settling and aggregation characteristics of the particles have been documented in Newman et al. (1990a).

As shown in Table 2.1, several other tracers were monitored at times of low tide, including salinity (using a YSI model 33 SCT meter and the Seabird package aboard the UMass/B RV *Neritic*), fecal coliform and *Enterococcus* (by MWRA), and total suspended solids and metals concentration (by UMass/B personnel, described in Wallace et al., 1992, and summarized in Section 2.2). In addition, during the third study, surface and near-bottom measurements were taken near the channel mouth to better understand what fraction of pollution transported from the channel to the inner harbor on ebb tide returns with the following flood tide.

2.1.1.1 Analysis of channel flushing using dye data

Although dye patterns differed somewhat for each study, maximum concentrations were always found at the water surface between the head and the middle of the channel (depending on tidal phase at the time dye was released). After the first tidal cycle, concentrations were fairly uniform laterally and decreased with depth and with distance down the channel near the mouth. These patterns were generally similar to those of freshwater (based on salinity measurements) except that pockets of low salinity were sometimes observed at the channel mouth. These pockets of freshwater likely came from the Charles River whose average freshwater release is about 200 times that of the Fort Point Channel CSO.

The total mass of dye in the channel was computed for each sampling interval by integrating dye concentration over the channel volume. Figure 2.3 shows normalized dye mass versus time for the July 1991 study. The mean residence time for the dye, as determined by the time-varying mass distributions, is summarized for each study in Table 2.2. The residence times vary from about 1 day to about 2.5 days with the variation attributed to 1) the phase of the tide at the time of release (e.g., discharge during high or ebb tide gives the dye a "head start" leading to more rapid flushing than a discharge at low tide); 2) the range of the tide (more rapid flushing expected for greater tidal ranges); and 3) the extent of freshwater (more rapid flushing expected due to estuarine-type circulation associated with greater freshwater inflow). The importance of each factor has been substantiated by analytical calculations in Adams et al. (1992).

2.1.1.2 Analysis of initial deposition using paint data

Paint concentrations were analyzed in a similar manner as dye and Figure 2.4 shows a plot of normalized paint mass versus time for the July 1991 study, in analogy with Figure

2.3 for dye. Several curves are given, reflecting our uncertainty in background concentration (the uncertainty was greater for paint than for dye). However, it is clear that the mass of paint declined more rapidly than the mass of dye, with the difference attributed to deposition. For example, for this study, the rate of decrease in paint mass is about 2 d^{-1} while the corresponding rate for dye (reciprocal of the dye residence time) is about 1 d^{-1} (based on Figure 2.4), suggesting a net deposition rate of about 1 d^{-1}. For the May 1990 study the net deposition rate was between about 0.25 and 0.5 d^{-1}.

The inferred rates of deposition (0.25 to 1.0 d^{-1}) are considerably faster than expected on the basis of discrete settling. As evidence, five laboratory settling columns were used to measure settling rates for paint suspensions having different concentrations (10^{-1} to 10^{-7} on a weight basis) and using different solvents (distilled water and ambient channel water). No significant difference in settling among the columns was observed. Average results, depicting the decline in normalized concentration vs. time, are shown as closed circles in Figure 2.5. For comparison, computed results for Stokes settling based on the particle size distribution measured by Newman (1990a) are shown as asterisks. Considering the particle size range of nearly two orders of magnitude, the difference is small, and one concludes that the paint particles in the laboratory settle by discrete settling. Figure 2.5 also shows results for the field studies. Although sample variability and uncertainty in background may affect these data, the indicated rates (0.25 to 1 d^{-1}) are greater by a factor of 7 to 30 than the corresponding laboratory rates. Because the laboratory data showed no dependence on particle concentration or solvent (suggesting no particle-particle interaction within the water column), we suspect that interaction between paint particles and the sediment bed may be significant as suggested by Newman (1990b) and Stolzenbach et al. (1992).

2.1.1.3 Particle retention and residence time distributions

To the extent that Fort Point Channel can be treated as spatially well mixed, the fraction of particles escaping through the channel mouth and the fraction retained in the channel through deposition are given by

$$\text{fraction escaping} = \frac{1}{1 + \tau k} \tag{2.1a}$$

$$\text{fraction retained} = \frac{\tau k}{1 + \tau k} \tag{2.1b}$$

where k is the effective deposition rate and τ is the residence time. Because the inferred deposition rates ($k = 0.25$ to $1\ d^{-1}$) are comparable with the reciprocal of the hydrodynamic residence times ($\tau^{-1} = 0.4$ to $1\ d^{-1}$), Eqs. (2.1a) and (2.1b) suggest that approximately half of the paint is depositing in the channel and half is being flushed.

This comparison can be formalized, without the assumption that the channel is well mixed, by developing residence time distributions f(t). Such distributions describe the rate at which dye leaves the channel, as determined from the decline in the mass curves, and are indicated in Figure 2.6 for the three studies. Note that the area under each curve is one (all the dye ultimately leaves) and the center of mass of each curve is the channel residence time. Superimposed on the residence time curves are three declining exponential curves (e^{-kt}) which describe the fraction of material remaining in the channel as a function of time, assuming first-order loss processes characterized by $k = 0.5$, 1.0, and 2.0 d^{-1}. The fraction of material discharged to the channel that escapes and the fraction that is retained are given by

$$\text{fraction escaping} = \int_0^\infty e^{-kt} f(t)\,dt \tag{2.2a}$$

$$\text{fraction retained} = 1 - \int_0^\infty e^{-kt} f(t)\,dt \tag{2.2b}$$

For example, using the residence time curve for the May 1990 study, and exponential curves corresponding to deposition rates of 0.25 d^{-1} (not shown) and 0.5 d^{-1}, results in a deposition of 44 to 64% of the discharge flux. Using the residence time curve for the July 1991 survey with the decay curve corresponding to a deposition rate of 1.0 d^{-1} yields a retention of 52%. In both cases we conclude that about half of the paint particles are retained. Because sewage particles are significantly "stickier" than the paint pigment (Newman, 1990a), we'd expect a somewhat greater retention for sewage particles, and their associated contaminants.

Similar analysis can be used to estimate the percentage of bacteria that are flushed from the channel. Analysis of fecal coliform measurements conducted as part of this research and for previous studies suggest disappearance rates of $k = 1$ to 3 d^{-1}. Using a middle rate of 2 d^{-1} with the residence time curve for the May 1990 study would give a flux of 7% of the initial loading, suggesting that 93% disappear within the channel. Using a range of $k = 1$ to 3 d^{-1} independently with the residence time distribution for each of the three studies suggests that between 2 and 48% of the bacteria exit from the channel alive.

We can note that, if the channel were well mixed, the residence time distribution would be given by $f(t) = e^{-t/\tau}/\tau$ and Eqs. (2.1) and (2.2) would be identical. In general the shape of the residence time curves in Figure 2.6 suggest mixing patterns between completely well-mixed conditions (given by a declining exponential) and plug flow (given by a spike at $t = \tau$). Hence, the actual retention rate will be greater (and the escaping rate smaller) than predicted by Eqs. (2.1), with the difference increasing with increasing value of k (i.e., the difference is greater when applied to the disappearance of bacteria than to the deposition of solids).

2.1.1.4 Conclusions from fluorescent tracer studies

Based on experience at Fort Point Channel we can draw the following conclusions concerning the transport of contaminants from sources (e.g., CSOs, storm drains) located in similar semi-enclosed regions of the inner harbor.

- Transport is governed by the amplitude and the phase of the tide as well as by density differences caused by freshwater inflow.
- CSO effluent remains concentrated on the surface and exhibits residence time distributions intermediate between those characterizing plug flow and well-mixed conditions.
- The sub-basins are effective at trapping contaminants with half or more of the suspended solids likely settling and between 50 and 98% of the bacteria disappearing before the effluent leaves the channel mouth.
- The rate of particle deposition is substantially greater than found in laboratory settling column tests, suggesting that the sediment bed may be playing a critical role in scavenging particles from the water column.

2.1.2 Nut Island sewage plume

Two fluorescent dye studies were conducted in the President Roads shipping channel adjacent to the Nut Island sludge outfall during July 1990 and October 1990 (Adams et al., 1992). The purpose of these experiments was to quantify the deposition of sludge particles by comparing their concentration in the water, relative to dye, as a function of time (i.e., using "real" particles in place of paint). Unfortunately several difficulties were encountered concerning the timing of sludge release and the duration of observation.

Hence, although information was learned about the plume shape, little could be inferred about the rates of deposition.

2.2 Metal Concentration in Sediment Cores and Overlying Waters

2.2.1 Sediment Deposition Rates in FPC

Six cores were collected during the May 1990 survey and analyzed for ^{210}Pb. Assuming no bioturbation, the average deposition rate from four cores (eliminating the highest and lowest values) was found to be 3.6 cm/yr. This rate is qualitatively consistent with measured profiles of metal concentration reported for the Central Artery Project (CDM, 1991) which indicates generally high sediment concentrations down to a level of about 4 ft. and low concentration below a depth of about 7 ft. (No data are reported at intermediate depths). Based on the fact that the channel was last dredged in 1952 (personal communication, USACE, Waltham, Mass.), or about 39 years prior to the measurements in 1991, and assuming that the channel was dredged to below the depth of any significant contamination, we estimate a deposition rate of 3 to 5 cm/yr. As an additional check, we will be trying to detect the yellow paint used in our initial deposition studies described in Section 2.1.

Assuming a bulk dry sediment density of 1200 kg/m^3, and a channel area of $2.3 \times 10^5 m^2$, the deposition rate of 3.6 cm/yr corresponds to the deposition of $9.9 \times 10^6 kg$ of sediment per year. This is almost 6 times greater than the estimated existing sediment load to Fort Point Channel of $1.7 \times 10^6 kg/yr$ (TM5-1, Table 2, CH_2M-Hill, 1988). And it is about 35 times larger than the estimated CSO load to the channel under Future No Action conditions (CDM, 1989b). While this last estimate reflects anticipated reduction in CSO loading due to treatment plant improvement, recent indications are that solids loading to the channel may already be even less than the predicted future no action condition

(BWSC, 1991). The total channel deposition of 9.9×10^6kg/yr also represents about 11% of the estimated existing sediment load *to the entire harbor* of 8.5×10^7kg/yr (CH_2M-Hill, 1988). Using our estimate that 34% of these sediments are ultimately deposited in the harbor (Lee, 1990), the measured deposition in the channel is about one-third of the estimated deposition from known sources in the entire harbor. These calculations clearly support the notion that most of the deposited sediments are imported from outside the harbor.

2.2.2 Metal Inventories

Metal concentrations found in the surface sediment of Fort Point Channel were high in comparison with the known source loadings. For example, using an average copper concentration of 0.45 mg/g in the upper layer of the channel cores, and assuming a sediment density of 2.5 g/cm^3, a channel area of $2.3\times10^5m^2$ yields an annual rate of copper deposition of 9.3×10^3kg/yr. This is approximately 12 times the estimated channel loading of 750 kg/yr under existing conditions (CH_2M-Hill, 1988), and 43 times the predicted CSO loading of 215 kg/yr under future no action conditions (CDM, 1989b). The rate is about 11% of the estimated existing copper loading of 8.1×10^4kg/yr from all sources into Boston Harbor (CH_2M-Hill, 1988).

The metal concentrations measured in Fort Point Channel sediments are in reasonable agreement with those assembled for the Central Artery Project (CDM, 1991); on the other hand, metals data collected by the Army Corps of Engineers for Reserved Channel, Mystic R., and Chelsea Creek show concentrations that are quite a bit lower (5 to 10 times). If metal-laden sediments are being imported to these sub-regions as well, they must be from a different (lower concentration) source than those being imported to Fort Point Channel. Or it may be that H_2S, resulting from anoxic conditions in the surficial sediment of Fort Point Channel, results in greater sequestration of metals in the channel. A third possibility would be an additional (illegal) metal source, but this is unlikely because measured concentration profiles are relatively uniform with depth; thus in the absence of significant bioturbation, such an additional source would have to be continuous.

2.3 Measurements of the Surficial Strength of Marine Sediment using the MIT Fall Cone

2.3.1 Introduction

In trying to understand the long-term transport of contaminated sediments, one must understand which sediments are "strong" enough to withstand the action of waves, currents and tides. Once the shear stress exerted by the water above the sea bottom exceeds a critical or threshold value, the sediments will be eroded (i.e., mobilized).

It is generally accepted that the critical condition for mobilization (erosion) of the bottom sediments is closely related to their surficial strength. For cohesive soils, erodibility is very difficult to assess. This is due to the large number of variables involved and also to the lack of techniques for measuring the surficial strength of very weak sediments. In the literature, critical bottom shear stress values equal to 1/100 to 1/1000 of the undrained shear strength values are reported. It is believed that the critical bottom shear stress pertinent to the present problem is of the order of 1 Pa (about 0.01 g/cm^2).

The purpose of the work was to design an apparatus capable of measuring the surficial strength of extremely weak cohesive sediments and then to try to relate this strength to the critical bottom shear stress and to the erodibility of the sediment. The layer of interest consists of the top 10 cm of the sediment.

The fall cone test was found to be best suited to fulfill the requirements of the new apparatus. It can be easily performed on board a ship in order to avoid any degradation of samples that might occur with time. Also, it allows testing on samples that are still in the coring tubes or barrels. This is most important for samples that cannot stand under their own weight as is the case for the top 10 cm of the harbor bottom. Another important advantage of the fall cone is its low depth of resolution meaning that only a thin layer of soil is needed in order to measure the strength. The thickness of this layer can be minimized by using the appropiate cone, i.e., by reducing the weight and increasing the angle of the cone. This technique will enable the strength determination of extremely weak soils and its variation, at intervals of about 0.5 cm, over a depth of only 10 to 15 cm.

2.3.2 The Automated MIT Fall Cone Device

The fall cone test consists of a cone positioned to touch the surface of the soil sample. The cone is then released and penetrates the surface of the soil sample under its own weight. By adjusting the tip angle and the weight of the cone, depending on the strength of the soil, the depth of penetration can be limited to a few millimeters. The conventional fall cone was found unsuitable for testing weak soils since it cannot use low enough weights. Thus, a new fall cone device capable of measuring shear strength values as low as 0.03 g/cm^2 (2.9 Pa) was constructed. The new fall cone is composed of five major parts:

1. The fall cone apparatus is mounted on an adjustable height stand and has a displacement transducer, a sensor with a light signal to determine the exact location of the soil surface, and three different cones (plexiglas with a 60° angle, brass with 60° and plexiglas with 90°). The weight of the cone can be controlled by a frictionless pulley mechanism which allows the use of any weight between 1 g and 70 g. A set of 1, 2, 5, and 10-g weights was manufactured in order to obtain any required combination. An electromagnetic clamp prevents the cone from dropping under its own weight.

2. A power supply provides the required voltage to the transducer.

3. A voltmeter reads the voltage going in and out of the transducer and that of the power supply.

4. An accurate electronic timer which is connected to the electro-magnetic clamp on the cone apparatus can be programmed to open the clamp hence dropping the cone for a preset period of time. It was set during the experiments to operate for a period of five seconds.

5. A computer-controlled data acquisition system records the voltage coming out of the transducer versus time. The program is set to read 500 points in five seconds.

An additional feature of the fall cone device is its ability to test at different depths inside a container with the use of two 15-cm extensions that can be attached to the cone. The experimental setup is shown in Figure 2.7 and the new fall cone apparatus is shown in Figure 2.8.

2.3.3 Results on Boston Blue Clay

Before testing samples from Boston Harbor, some testing was carried out on Boston Blue Clay (BBC) in order to get a better understanding of the new device. Boston Blue Clay has been extensively tested at MIT since the 1930s.

The remolded BBC used has the following index properties:

Specific gravity $G_s = 2.78$
Liquid limit $w_l = 43\%$
Plastic limit $w_p = 23\%$
Plasticity index $PI = w_l - w_p = 20\%$

The liquid limit is determined by measuring the water content and the number of blows required to close a specific width groove for a specified length in a liquid limit device like the Cassagrande cup. The plastic limit is determined by measuring the water content of the soil when a thread of the soil, 1/8" in diameter, begins to crumble. The water content (w) of a soil is the ratio of the weight of water to the weight of dry soil grains. The liquidity index (IL) is defined as $IL = (w-w_p)/PI$.

Oven-dried samples of BBC were mixed thoroughly with distilled water at different water contents ranging from 30% to 110% approximately. The paste was then placed in airtight plastic containers and cured for a period of at least 24 hours. Testing on those samples was performed using both the "new" and the "old" fall cone. Also, some lab vane tests were carried out. It should be noted that the lab vane is not capable of measuring the shear strength of very weak soils and is incapable of giving the resolution of strength versus depth achievable with the fall cone.

The versatility of the new apparatus permits the use of different cone weights. Therefore, weights of 1 g, 2 g, 5 g, 10 g, 15 g, 20 g, and 30 g were used on different soil samples according to their consistency. Most tests were performed with the 60° plexiglas cone; for soils with high liquid content, the 90° plexiglas cone was also used. Results of the tests are tabulated in Table 2.3. The table shows results of several tests of the strength values obtained by using the different cones are shown with their standard deviation. The shear strength values, c_u, are calculated using $c_u = 100\ KW/d^2$ where c_u is the undrained shear strength in g/cm^2 (it is the custom in geotechnical engineering to use the term "weight" in lieu of "mass" and to express the shear strength in units of g/cm^2 where $1\ g/cm^2 = 98.1\ N/m^2$); K is the cone factor (a K value of 0.29 is used for the 60° cones whereas a K of 0.12 is used for the 90° cones. These values were obtained from empirical correlations performed on K values reported in the literature); W is the weight (mass) of the cone in g, and d is the penetration distance in mm.

Figure 2.9 presents the water content versus the shear strength curves for both the old and the new devices. As seen from the results in Figure 2.9, the new fall cone always measures lower strengths than the "old" fall cone, especially at high water content. This means that the new device is measuring higher cone penetrations at the same water content. This is explained by the fact that the new device is providing closer conditions to the ideal theoretical free fall, i.e., friction losses accompanying the shaft movement in the old device are eliminated because the new device does not have a shaft. The displacements are measured from the electromagnetic field changes due to the transducer core movement. In the "old" cone, the displacements are measured by a mechanical connection between the shaft and a dial gage. The difference between the two curves is larger at high water content since the 26-g cone used with the old device has a very large penetration at high moisture contents and the device is at the limit of its readability.

In Figures 2.10 and 2.11, the liquidity index versus shear strength curves are plotted for the old and the new fall cone respectively. These figures also show data for lab vane (LV) tests for comparison. For $IL < 1$ the lab vane results fall close to the new fall cone curve and for $IL > 1$ they fall close to the old fall cone curve. This is due to the fact that, at low liquidity index, the lab vane is much more reliable than at high liquidity index ($IL > 1$).

2.3.4 Results on Boston Harbor Mud

In April 1990, samples for fall cone testing were collected near UMass/Boston. At low tide, mud samples were collected using three open-ended plexiglas cylinders manufactured at UMass, and two Shelby tubes. The cylinders and tubes were pushed in by hand. X-rays on the Shelby tubes showed the mud to be filled with shells throughout its depth. Therefore, fall cone tests could not be performed (once a cone hits a shell it stops penetrating).

In June 1990, a boat expedition in Boston Harbor was organized in order to get more representative undisturbed samples. Two box samples (50 cm by 50 cm by 50 cm) were taken southeast of Peddocks Island under 8 m of water using the gravity driven technique. One of these box core samples was subsampled immediately using two of the same open-ended plexiglas cylinders, 16.5 cm in diameter and 16 cm in depth. The cylinders were pushed into the top surface by hand and then sealed immediately by placing on airtight top caps. Then, one of the box sampler sides was removed and the cylinders' bottom caps were pushed into place. Finally, the cylinders were cleaned and transported to the humid room for storage. To avoid any effect of the storage time on the shear strength of the soil, Sample 1 was tested about 24 hours after sampling and Sample 2 after 48 hours.

In order to get a profile of the strength versus the depth, the cylinders were tested in five layers of 3 cm each, numbered 1 to 5 from the top down. On each layer, six tests were performed using the 60° plexiglas cone with three different weights. Shear strength results, at each layer, are tabulated in Tables 2.4 and 2.5 for Samples 1 and 2, respectively. Missing data correspond to locations at which meaningful results could not be obtained (e.g. due to the presence of a shell or a void full of water). Figure 2.12 presents the strength profile of the Boston Harbor Mud based on the combined strength of Samples 1 and 2, with the standard deviation. This combined strength is taken as the mean, for each layer, of all the strength values recorded for both samples.

Trials to classify the material according to soil mechanics properties were unsuccessful due to its very high organic content. The mud could not really be classified as a soil but, rather, it could be better described as a mixture of a cohesive soil with a high proportion of organic matter at different stages of decomposition.

Moisture content could not be determined because of unknown amounts of other liquids and organic compounds which evaporated with the water. Although it is believed that at

105° C only the water evaporated, the water contents measured according to the standard ASTM procedure has here been called "liquid" contents (LC) instead. Liquid content values at each layer are also presented in Tables 2.4 and 2.5. A profile of the liquid content with depth is provided, with its standard deviation, in Figure 2.13. The liquid content decreases from the top to the bottom of samples. The two profiles in Figure 2.13 are very close and since Samples 1 and 2 were located on a diagonal in the sampling container, it is concluded that the liquid content across the box sample is homogeneous.

In September 1991, a second trip to Boston Harbor was undertaken aboard a small boat. The objective was to take samples from all around the harbor in order to obtain contours of the harbor bottom shear strength. Also, a comparison of the shear strength values at the different sites with the fluid shear stress values computed by numerical modeling was intended. The sampler used was a hand operated device, newly acquired by UMass that proved to be defective. When lowered in the water, the gravity weights resting on its sides fell off due to the strong currents, and the device became nonoperational. Only one sample (15 cm by 15 cm by 15 cm) was collected west of Peddocks Island (Sample 3) and tested with the fall cone in layers of 2 cm each. Figures 2.14 and 2.15 show the liquid content and shear strength profiles for Samples 1, 2, and 3. Although Sample 3 came from a different location than the box core from which Samples 1 and 2 were subsampled, the liquid content and shear strength profiles show amazing agreement. Also, it should be noted that the variation between Sample 3 and the box core was of the same order of magnitude than the variation within the box core.

According to Figure 9 in Knebel et al. (1991), Samples 1 and 2 were taken from an erosional environment, while Sample 3 was taken in between a depositional and an erosional environment. Also, according to Figure 4.8 in Lee (1990), the values of the bottom shear stress are smaller southeast than west of Peddocks Island (the southeast of the island is in between regions of $\tau < 0.05$ N/m^2 and 0.05 N/m$^2 < \tau < 0.3$ N/m^2, while the west is in between regions of $0.05 \text{ N/m}^2 < \tau < 0.3 \text{ N/m}^2$ and $0.3 \text{ N/m}^2 < \tau < 1 \text{ N/m}^2$). These differences in the physical characteristics of the two locations were not apparent from the shear strength profiles which were essentially the same southeast and west of the island.

2.4 Numerical Model Studies of Ultimate Deposition

Following initial deposition, one of three things can happen to a sediment particle discharged into Boston Harbor. First, if no resuspension ever occurs at the site of initial deposition the particle will remain there. Second, if resuspension does occur, the particle may be transported to a site with no resuspension where it will remain. Third, a resuspended particle may be transported out of Boston Harbor without ever reaching a site of ultimate deposition. Thus the ultimate fate of particles within the harbor depends upon the location of the particle source (particles discharged closer to depositional areas will tend to be retained and those discharged closer to erosional areas and to the entrance to the harbor will be more likely to leave the harbor), the rates of dispersion and deposition (as discussed in the preceding sections), and the distribution of erosional and depositional regions within the harbor. Lee (1990) examined these possibilities in the fourth component of our project.

2.4.1 Regions of erosion and deposition in Boston Harbor

Sediment resuspension is determined by the properties of the sediment and by the shear stress exerted on the bottom by local water movements caused by currents or waves. In general, resuspension will occur whenever the shear stress exceeds a critical value τ_c. In some formulations, deposition will occur only when the shear is below a critical value that may be less than the critical value for erosion. For a given current velocity or wave condition, the bottom shear stress may generally be determined theoretically with reasonable accuracy. However, the critical shear stress (or stresses) are a complex function of the sediment characteristics that are in turn determined by physical (particle size and density), chemical (particle surface chemistry), and biological (generation of mucus, particle packaging, etc.) influences. Because of the difficulty in replicating sediment conditions in the laboratory, reliable measurements of τ_c are probably obtainable only by in situ measurements of some type.

Regions of erosion and deposition within Boston Harbor have been estimated by computing the distribution of bottom shear stress from a numerical prediction of tidal current velocity using the two-dimensional model TEA (Westerink et al., 1988). See Figure 2.16. Meanwhile Knebel et al. (1991) estimated the regions of deposition and erosion on the basis of observed sediment characteristics (Figure 2.17). By comparing these figures, it is possible to deduce that the critical value for erosion for Boston Harbor sediments is on the order of 0.3 to 1.0 N/m^2 (Figure 2.18) which is well within experimentally observed values. This distribution indicates that approximately 80% of the harbor, including all of the inner harbor, is depositional. Approximately 20% of the harbor, plus substantial regions in the channel entrances just east of the harbor, are erosional in the sense that erosion is predicted to occur during at least part of the tidal cycle. Lee's calculation did not include the effect of waves in shallow shoreline regions that are evident in Knebel's plot.

2.4.2 The Ultimate Fate of Sediment in Boston Harbor

Lee (1990) utilized the above quantification of erosional and deposition processes in numerical models for water movement (TEA) and particle transport (a modification of ELA; Baptista et al., 1984) for the purpose of estimating the ultimate fate of waste particles discharged into the harbor. His simulations included particle loadings from all known waste streams as given in CH_2M-Hill (1988). For the semi-enclosed regions of the inner harbor, sources were located at the mouths of the cove or channel. Modifications of his loading values to reflect more current estimates, or the fact that some particles are retained in the semi-enclosed regions, would affect the absolute values of predicted quantities but would have relatively little effect on the distribution of particle fates (e.g., what percentage are retained in the harbor).

The base case (Case 1) simulation had the following parameter values, chosen to reflect the best estimates available:

- w_S = particle deposition velocity = 10^{-5}m/sec
- τ_C = critical erosion and deposition stress = 0.3 N/m^2
- M = erosion rate = 0.04 g/m^2/sec
- D = dispersion coefficient = 75 m^2/sec

The computed distribution of suspended sediment concentration at one tidal stage (representative of all others) and the long term rate of deposition for the base case are shown in Figures 2.19 and 2.20. Concentrations within the harbor vary from 0.1 mg/l to 3 mg/l except for values as high as 5 mg/l in the upper reaches of the inner harbor. The net sedimentation rate is between 100 and 500 g/m^2/year at most locations throughout the harbor except the non-depositional regions in President Roads and Nantasket Roads and in the inner harbor where deposition exceeds 500 g/m^2/yr. About 34% of the sediment discharged to the harbor is retained.

These results evoke a picture of suspended sediment relatively well dispersed throughout the harbor and provide motivation for a conceptualization of the harbor as a well-mixed basin. For Lee's simulations the magnitude of the total sediment source was 6.6×10^7kg/yr (4.5×10^7kg/yr from the treatment plants and 2.1×10^7kg/yr from shoreline sources). Assuming that deposition occurs over an effective area A equal to 80% of the harbor area of $108 \times 10^6 m^2$ (Menzie et al., 1991), the average accumulation rate of the 34% of solids that deposit in this region is:

accumulation rate = $(6.6 \times 10^7 kg/yr \times 0.34)/(0.8 \times 108 \times 10^6 m^2) \simeq 260\ g/m^2/yr$

To achieve this rate of accumulation with a deposition velocity of 10^{-5} m/sec the suspended sediment concentration must be:

suspended sediment concentration = $(260\ g/m^2/yr)/10^{-5} m/sec \simeq 0.82\ mg/l$

These values are consistent with the spatial distributions shown in Figures 2.19 and 2.20.

The well-mixed model may be extended further to calculate an effective flushing rate for the harbor:

flushing rate = $Q = (6.6 \times 10^7 kg/yr \times 0.66)/0.82\ mg/l \simeq 1.5 \times 10^8 m^3/day$

Assuming that the harbor volume is about $6 \times 10^8 m^3$, the residence time associated with the above flushing rate is:

residence time = $6 \times 10^8 m^3/1.5 \times 10^8 m^3/day \simeq 4.2$ days

These results are consistent with the sediment box model (now applied to the entire harbor) represented by Eqs. 2.1a and b, which can be re-written

$$\text{percent retained} = \left[1 + \frac{Q}{w_s A}\right]^{-1} \tag{2.3}$$

The parameter Q/w_sA represents the relative importance of flushing compared to deposition. For the base case $Q/w_sA \simeq 2$ indicating that flushing is twice as important as deposition, but that deposition is not negligible.

Calculations made separately for shoreline and treatment plant sources reveal that, although the shoreline sources represent only about a third of Lee's total sediment load, they were retained more efficiently (about 50% remain in the harbor vs. 25% for the treatment plant solids). Thus the shoreline and treatment plant loads contributed about equally to the simulated total suspended concentration and to sediment deposition. More recent estimates suggest shoreline sources represent about 16% of a total sediment loading of about 101×10^6kg/yr (Menzie et al., 1991). Extrapolating Lee's calculation to these new estimates would suggest that about one-quarter of deposited solids have come from shoreline sources while three-quarters have come from the treatment plants. The higher retention percentage for the shoreline sources is associated with a smaller effective flushing rate ($0.8 \times 10^8 m^3$/day) and a longer calculated residence time (8.2 days) than the treatment plant discharges ($2.3 \times 10^8 m^3$/day and 2.7 days). These differences reflect the relative positions of these sources within the harbor with the treatment plant discharges being exposed to the larger tidal volumes typical of the outer harbor.

Lee (1990) also investigated the sensitivity of the base case results to the parameter magnitudes:

- Reduction in the dispersion coefficient to a value $D = 45\ m^2/sec$ raised the percentage of total sediment retained from 34% to about 40%. This is consistent with predictions of Equation 2.3 assuming that the flushing rate Q is roughly proportional to the dispersion coefficient D. Flushing is then reduced by a factor of about $45/75 \simeq 0.6$, $Q/w_sA \simeq 1.3$, and the calculated percentage of sediment retained to about 43%.

- A two order of magnitude increase in the erosion rate M has almost no effect upon the fate of sediments within the harbor. This is because even the smallest value $M = 0.04\ g/m^2/sec$ results in about 1800 g/m^2 of erosion per 12.4-hour tidal cycle which is much greater than the average deposition of 0.3 g/m^2 corresponding to the average deposition rate of 200 $g/m^2/yr$. Thus where erosion is occuring, even for a fraction of a tidal cycle, all deposited sediment is removed and the rate of removal becomes irrelevant to the result.

- Variations in the critical erosion shear stress τ_c alter the areal pattern of deposition somewhat but have relatively little effect on the net retention of sediments in the harbor. This is because for the base case most of the harbor area is depositional. An increase to $\tau_c = 1.0$ N/m^2 produces a modest increase in the area of deposition and a slight increase (to 36%) in percentage of sediments retained. A decrease to $\tau_c = 0.05$ N/m^2 does make a large part of the outer harbor non-depositional but the total area of deposition decreases only by about a third; the percent retained decreases to about 23%. With the reduced area $Q/w_sA \simeq 3$ (flushing becomes more important) and the percent retained calculated using Equation 2.3 is about 25%.

- Clearly the most important parameter in the calculation is the effective deposition velocity w_s. An order of magnitude decrease to $w_s = 10^{-6}$m/sec ($\sim$ 0.1 m/day) reduces the percentage retained to about 7%, roughly in agreement with Equation 2.3 which predicts about 5%. In contrast, an increase to $w_s = 10^{-4}$m/sec (10 m/day) only increases the percentage retained from 34% to about 58%. This value is less than predicted by Equation 2.3 (83%), probably because much of the treatment plant particle load discharged from Deer Island on ebb tide is deposited outside the harbor without ever entering the harbor. This may be interpreted as an effectively larger flushing rate.

Thus it appears that Lee's calculations of sediment fate are fairly robust even in the face of substantial uncertainty about parameter values. As long as most of the harbor is depositional (as indicated theoretically and by the data of Knebel et al. (1991)), the residence time for water is on the order of several days to a week, and the effective deposition velocity is within an order of magnitude of 10^{-5} m/sec then the percentage of sediment retained in the harbor (of that which participates in the harbor-wide transport) will range between 10% and 50%. This percentage will be higher if a substantial percentage of the particles discharged by shoreline sources, particularly in the inner harbor, have rapid settling velocities and thus never get out of regions like Fort Point Channel. Section 3.3 extends Lee's analysis by examining experimental settling velocity distributions as a function of particle source (raw sewage, effluent, and sludge).

III. SYNTHESIS OF CONTAMINATED SEDIMENT TRANSPORT IN BOSTON HARBOR

In this section the results of the separate sub-studies and of other studies are used to address the general objectives summarized in the Introduction. A case is made that particle transport in Boston Harbor is characterized by the following features:

- The heaviest waste particles, discharged from sources other than those in President Roads, initially settle and are retained in regions within 100 to 1000 meters from the point of discharge.

- Slower-settling particles or those initially depositing in areas where resuspension is probable become fairly well dispersed throughout the Harbor as suspended solids. The majority of these particles are ultimately transported out of the Harbor by tidal flushing; the remainder settle in regions where resuspension is rare or where deposition is enhanced by processes such as bottom scavenging.

- The accumulation of "natural" particles, i.e., those imported from outside the harbor, exceeds the average rate of deposition of waste particles by a factor of 5 to 10, even in areas where the deposition of waste particles is heavy—such as Fort Point Channel.

The following sub-sections discuss the quantitative evaluation of particle transport processes leading to the above conclusions.

3.1 Water Column Dispersion in Near-Shore Areas

In this context water column dispersion refers to the transport of dissolved or suspended material in excess of the transport resulting from intra-tidal water movement. For purposes of this discussion the advective water movement in Boston Harbor is assumed to be predominantly tidal and to result in little net transport. Dispersive transport caused by non-tidal water movement or by small residual tidal motion regulates not only the spreading of a mass of constituent about its center of mass but also the flushing of constituents from sub-regions of the harbor and from the harbor to Massachusetts Bay. Because of the relatively shallow water depths all net transports are regarded as essentially horizontal (excepting deposition on the bottom).

Dispersion may be parameterized in several ways. The most general parameter is a dispersion coefficient D which may be used analytically to describe lateral spreading about the center of mass, or as a coefficient in a differential formulation of mass conservation that is solved numerically. Where a sub-region of the water body is defined, the dispersive transport may also be parameterized by a residence time τ or as an equivalent first-order flushing rate $k_f \simeq \tau^{-1}$.

In the following sections estimates for dispersion parameters are discussed for Boston Harbor as a whole, for sub-regions such as Fort Point Channel, and for small-scale areas.

3.1.1 Boston Harbor

The flushing of Boston Harbor has been studied theoretically and experimentally by a number of previous investigators who used residence time to parameterize the dispersive action of the tides. A summary of available studies is included as Table 3.1.

The experimental studies have all utilized the principle that the mean residence time of a continuously discharged conservative tracer can be determined by dividing the steady-state inventory in the water column (i.e., average concentration times volume) by the mass input rate. The fraction-of-freshwater method refers to the specific application of this technique using freshwater as the tracer. As with other techniques, the computed residence time will depend on the tracer source location with shorter times expected for sources located near the harbor mouth, which serves as a sink. The technique is obviously sensitive to errors in estimating water column concentrations and loadings. For example, to the extent that VHOC loadings were underestimated in analyses by Kossik et al (1986) and Adams et al (1987), their estimates of residence time would be too high. Similarly, if average metal concentrations in the harbor were underestimated by Sung (1991), then his estimate would be too low.

Four theoretical studies are also indicated. The tidal prism technique computes the residence time, in multiples of the tidal period, as high tide volume divided by tidal prism. Because this presumes complete mixing within the harbor and no return of material lost in the previous ebb tide, it is obviously a lower bound on residence time. The modified tidal prism method (Ketchum, 1951a) attempts to correct for this deficiency by dividing the harbor into well-mixed segments with length equal to the local tidal excursion. Despite some theoretical inconsistencies with the approach, it is frequently used; comparison with data has shown good agreement in many cases and poor agreement in others.

Signell's (1991) calculations simulate residence time directly using a depth-averaged numerical model subject to tidal and wind forcing. The initial fluid in Boston Harbor is uniformly marked and the flushing rate is calculated from the simulated decrease over time of marked fluid within the harbor. The residence time is taken as the reciprocal of the flushing rate. If there were complete mixing throughout the harbor, this definition would correspond to the mean residence time of all marked particles. Since mixing is not uniform, the mean residence time is approximated by the time necessary for mass to have declined to 37% (1/e) of its initial value. The greater flushing rate at short times is due to the more efficient flushing of material located near the mouth. We estimate that the equivalent flushing rate of particles released at the two treatment plants would be between the indicated rate for the first cycle (~ 3 days) and the average rate (~ 17 days).

Results in Table 3.1 are for no wind. Simulation with a steady wind reduced the average residence time to between about 9 and 12 days for most wind directions, but substantially increased residence time (to about 30 d) for the case of a SW wind. To the extent that other processes, such as vertical exchange, are omitted, Signell's calculation represents an upper bound on residence time; the neglected processes are expected to be most significant in the inner harbor and near-shore areas which reflect the longer time scales of dispersion.

Lee's (1990) residence times were derived indirectly through a different numerical exercise (see Section 2.4.2). In his case the simulated inventory of suspended solids in Boston Harbor was divided by the input mass rate to calculate residence time.

In the numerical model used by Lee, net tidal circulation was less resolved than in Signell's model, and the unresolved transport was parameterized using a horizontal dispersion coefficient calibrated to field measurements. Kossik (1986) and Adams et al. (1987) found that dispersion coefficients ranging from $D = 45\ m^2/sec$ to $D = 75\ m^2/sec$, along with an M_2 tide, best reproduced the measured distribution of halocarbons in sewage effluents. These values are consistent with earlier work by Hydroscience (1973) which found that coefficients ranging from 30 to 180 m^2/s reproduced the observed salinity distribution in a steady-state model; because the steady-state model did not include the tide the somewhat large coefficients are to be expected. We can compare these model calibrations with experimental residence time estimates. Considering that a typical horizontal scale of the harbor is about $L = 5$ km (approximate distance from the mouth of the Inner Harbor to the mouth of the Outer Harbor) to 10 km (square root of the harbor surface area), a dispersion coefficient of $D = 75\ m^2/s$ (Kossik et al., 1986) corresponds to flushing times $\tau \simeq L^2/D$ between 4 and 15 days which bracket most estimates in Table 3.1.

3.1.2 Dispersion in Sub-Region

Whereas all of the information in Table 3.1 pertains to the entire Boston Harbor, some limited efforts have been conducted on smaller scales. For example, the CSO Facilities Plan used bacterial measurements to calibrate their transport model (CDM, 1989a). A best fit between measurement and prediction was obtained with a value of horizontal dispersion coefficient of 10 m^2/s. Since this study focused on the Inner Harbor and the nearshore region of the Outer Harbor, typical space (offshore direction) and time scales associated with this study would be of order 1 km and 1 day, respectively.

In the present study we measured the dispersive flushing of dissolved and suspended constituents from Fort Point Channel during three separate field studies using fluorescent dye as a tracer (Adams et al., 1992); summarized in section 2.1 of this report. The residence time calculated for Fort Point Channel from these data varied from $\tau = 1.0$ to about 2.5 days. The larger residence time was measured on two of the field studies during periods of normal tidal range and relatively low freshwater flow. The smaller residence time (faster flushing) is attributed primarily to a larger tidal range during the survey and is consistent with a theoretically supported quadratic dependence of flushing on tidal range. Calculations also indicate that density-induced flows associated with the high freshwater dischage during this survey could have contributed to the increased rate of flushing. On the basis of tidal volumes it is estimated that a value of $\tau = 1$ day probably represents an upper limit on the rate of flushing by tidal action; more rapid rates of flushing would require much higher freshwater flows than measured during the surveys.

Our residence times for Fort Point Channel can be converted into an approximate dispersion coefficient using the relationship $D \simeq L^2/\tau$. Using $L = 1650$ m and $\tau = 2.5$ d yields $D \simeq 13\ m^2/s$, consistent with the calibrated value from the CSO study.

3.1.3 Small-Scale Dispersion

The flushing rates discussed in the foregoing two sections are relevant to regions with a spatial scales greater than about 1000 m and time scales greater than about one day. Dispersion of constituents on smaller scales may be important in the initial transport of a constituent away from a source. Short-term (order of 6-hour) dye studies conducted near CSO outfalls by CH_2M-Hill (1990), and analyzed by Adams et al. (1992) resulted in estimated dispersion coefficients ranging from $D = 0.3$ m^2/sec to $D = 7$ m^2/sec. The space and time scales associated with these small-scale measurements are 100s of meters and hours respectively. These values are consistent with the "puff" dispersion coefficient $D =$ 1 m^2/sec used in ELA to simulate the early stages of effluent dispersal from sewage outfalls in Boston Harbor.

Although very approximate, the above data suggest a variation of dispersion coefficient with time scale as indicated in Figure 3.1.

3.2 Initial Deposition of Contaminated Particles

The initial deposition of contaminated particles will be determined by the relative rates of horizontal transport and particle deposition by settling or other processes. In this context it will be assumed that the primary mode of horizontal transport is dispersive at typical rates discussed in the preceding sections. Spatial and temporal distributions of initial deposition may be determined by calculations based on assumed rates or by inference from tracer studies or contaminant inventories in the sediment.

3.2.1 Estimates of Deposition Rates

The rate of deposition of anthropogenic and natural particles is difficult to determine a priori because of the potentially wide distribution of particle sizes and associated settling velocities w_s, methodological errors in measuring either the particle size or settling velocity distributions, dynamic changes in these distributions within the water column, and the possible importance of deposition mechanisms other than settling, such as boundary scavenging as proposed by Newman et al. (1990b) and Stolzenbach et al. (1992). Settling column tests on sewage and sludge suspensions indicate that typical particles associated with these waste streams may have sizes ranging from 1 to 100 μm and settling velocities ranging from less than $w_s = 10^{-7}$m/sec to $w_s = 10^{-3}$m/sec (Wang, 1988). The distribution of particle mass within this range is known to depend at least upon the total particle concentration and the time history of the fluid shear to which the particles have been exposed. Wang (1988) defines fast sinking particles as those that have settling velocities greater than 10^{-4}m/sec or about 10 m/day. The fraction of particle mass that is fast sinking ranges from less than 10% in effluent and uncoagulated sludge to between 50 and 100% in coagulated sludges. The lower values are those determined by holography and thus may be more credible than the higher values determined by conventional settling column tests. Wang found $w_s = 10^{-5}$m/sec to be a typical value for the median (on a mass or volume basis) settling velocity for the effluents she measured. A summary of Wang's settling rates and those compiled by others for particles of different types is given in Table 3.2.

Newman et al. (1990b) and later Stolzenbach et al. (1992) hypothesize that fine particles may be scavenged from the water column by filtration in a porous layer at the sediment-water interface. On the basis of measured inventories of fluorescent particles released in Salem Sound and recovered in bottom sediment samples, Newman et al. estimate an equivalent velocity of deposition of about 3×10^{-6}m/sec which is greater than the discrete settling velocity of the particles ($\sim 10^{-6}$m/s). In other words, this mechanism would establish a minimum effective settling rate for sewage particles in the field which is greater than the minimum laboratory values (i.e., those reported in Table 3.2). Newman et al. speculated that, because the introduced particles are known to have a low coagulation efficiency, the observed rate of deposition may be a lower bound on the actual deposition of anthropogenic or natural particles and that more typical rates of deposition by boundary scavenging may be at least 10^{-5}m/sec. Further evidence of this mechanism is found in our data from Fort Point Channel described in Section 2.1.1: assuming a channel depth of 6 m, our observed deposition rate of order 0.5 d^{-1} corresponds to a deposition velocity of 3×10^{-5} m/s. The fact that this rate is higher than the rate found in Salem Sound could be attributed to the greater efficiency of tidal flushing in Fort Point Channel which promotes more contact between suspended solids and the bottom sediments.

The range of settling velocities discussed above can be combined with the dispersion parameters displayed in Figure 3.1 to provide an order-of-magnitude estimate of initial deposition for a water body such as Boston Harbor (Table 3.2). If the water depth is assumed to be about $H = 10$ m, the largest particles ($w_S = 10^{-3}$m/s) will settle to the bottom in a time $T = H/w_S = 10^4$sec $\simeq$ 3 hours. This time scale is well within the range governed by the small scale dispersion coefficient $D = 1$ m^2/sec (Figure 3.1); hence over a period of three hours the particles would spread horizontally over a distance no greater than about $L \simeq [DT]^{\frac{1}{2}} \simeq 100$ meters. Particles with a somewhat smaller but still "fast" deposition velocity of $w_S = 10^{-4}$m/sec would settle over a time of 10^5s or about 1 day. Using $D \simeq 10$ m^2/s for this time scale, they would be deposited over a distance of about $[DT]^{\frac{1}{2}} = 1000$ m, comparable in scale to Fort Point Channel. Lighter fractions of sediment ($w_S = 10^{-5}$m/s) will reach the bottom in a time $T \simeq H/w_S \simeq 10^6$ seconds or about 10 days for a water depth of 10 meters. The corresponding scale of deposition is 10 km, comparable with the dimensions of Boston Harbor.

From this analysis, we can conclude that the fast settling particles ($w_S \gtrsim 10^{-4}$m/s) will initially settle close to their sources whether they are discharged to semi-enclosed areas of the harbor or directly to the outer harbor. The fate of finer particles will depend on their source location. In Fort Point Channel we found that fine tracer particles settled at a rate of $w_s \simeq 3\times10^{-5}$m/s. Using a channel depth of 6 m and a residence time of 2.5 days, Eq. 2.1b suggests that 50%–60% of these particles were retained. If the coagulation-induced deposition of contaminated particles is greater than that of the tracer particles because of a higher sticking efficiency, the initial retention of particulates in the channel may be even higher. For example, if the effective deposition velocity is 10^{-4}m/sec (10 m/day), only about 20% of the particles will leave the channel.

Fine particles discharged directly to the outer harbor, such as the effluent and former sludge discharges, may not be sequestered in a region of intermediate size such as Fort Point Channel. Assuming an effective value of $w_s = 10^{-5}$m/s for these particles suggests (Table 3.3) that they will participate in the harbor-wide circulation as simulated by Lee (1990).

3.3 Ultimate Deposition of Sediments in Boston Harbor

Lee's (1990) calculations of ultimate deposition, summarized in Section 2.4, may be compared with the study by Fitzgerald (1980). Two of Fitzgerald's findings are relevant. First, he used ^{210}Pb profiles to deduce that the sediment accumulation rate in the Harbor is on the order of 0.2 cm/yr. This rate is an order of magnitude larger than the long-term accumulation of sediment. For example, Knebel et al. (1991) cite rates of 0.01 to 0.03 cm/yr based on depths of accumulation over the past 5600 to 5850 years. Fitzgerald speculates that contemporary rates of deposition may have been accelerated by coagulation processes that are in turn aided by the presence of waste particles. Using a bulk sediment density of 1.2 g/cm^3 his rate of sediment accumulation of 0.2 cm/yr is equivalent to a mass deposition rate of about 2400 g/m^2/yr or about 9 times the amount attributed by Lee (1990) to waste particles of all types. (The factor is 6 if Lee's calculations are revised based on the newer Menzie et al. (1991) sediment loading of 101×10^6kg/yr.) If Fitzgerald's deposition rates are correct, then most sediments deposited in the harbor are imported from sources outside the harbor. (Fitzgerald would have concluded this himself had not a numerical error intervened on page 147 of his thesis, resulting in a (re)calculated rate of 0.14 cm/yr instead of the correct value 0.014 cm/yr.) This is consistent also with observed values of suspended sediment concentration in Boston Harbor which are generally in the range 1 to 10 mg/ℓ, i.e., an order of magnitude larger than Lee (1990) calculates for waste particles alone. It is also noted that a suspended particle concentration of about 5 mg/l and a deposition rate of 2000 g/m^2/yr implies an effective deposition velocity of about $w_s \simeq 10^{-5}$m/sec.

Fitzgerald's results, corrected for numerical errors, also imply that only about 3% of the waste particles discharged to the harbor from the treatment plants are retained in the sediments. He makes this calculation by comparing the inventory of particle-associated metals in the depositional area of the harbor with an estimate of the total metal mass discharged. He used a depositional area of about 1.7×10^7m^2. This is in contrast with Lee's simulation showing that deposition occurs throughout the harbor over an area of about 9×10^7m^2. If Fitzgerald's results are extrapolated by a factor of $0.9/0.17 \simeq 5$, the total percentage retained increases to about 15% which is within the range indicated by Lee's sensitivity study, particularly for treatment plant sources. It should be noted that Fitzgerald's estimate of the metal inventory is also tied to his estimated total sediment deposition rate. If the true rate is smaller, e.g., because of bioturbation, the implied percentage retained would be comparably smaller.

Lee's estimates of total deposition did not distinguish between the different effluent sources in terms of their particle size distribution and the associated potential for solids to be retained near the source. These considerations are embodied in the approximate calculations made in Table 3.4. Here the total solids discharged to the harbor is assumed to be composed of either diluted raw sewage from shoreline sources; sludge; or effluent with annual loadings of 16, 23, and 62×10^6kg/yr respectively (Menzie et al., 1991). The sludge loadings refer to the recent historical period before the discharge of sludge to the harbor was stopped (December 1991) and the shoreline figure includes rivers (4×10^6kg/yr), stormwater runoff (5×10^6kg/yr), and CSOs (7×10^6kg/yr). Estimates of the percentage of particles retained in the harbor assume that all particles with settling velocities above 3×10^{-5}m/s deposit locally, while those with slower settling velocities follow Lee's results (i.e., 50% of the remaining shoreline particles and 25% of the effluent and sludge particles settle in the harbor). The fraction of particles with different settling velocities are determined from representative data in Table 3.2. The calculations in Table 3.4 indicate that approximately 85% of the shoreline sources, 55% of the sludge, and 30% of the effluent deposits in the harbor. Based on relative loadings, the weighted average is 45% implying that historically a little less than half of all discharged solids have been retained in the harbor.

3.4 Summary of Findings

Our results support the following overview of the transport of waste particles in Boston Harbor:

- In all regions of the harbor except for President Roads and Nantasket Roads the heaviest fraction of waste particles are probably deposited within about 100 to 1000 meters from the source.

- The semi-enclosed regions of the inner harbor such as Fort Point Channel have residence times on the order of one to several days. On the basis of observed deposition of tracer particles it is estimated that at least half of the particle load discharged to the inner harbor may be retained in these regions and never participate in the harbor-wide particle transport regime.

- Particles (other than the heaviest fraction) discharged directly into the outer harbor or escaping the inner harbor enclosed regions are fairly well dispersed by tides throughout the harbor as a whole and deposit wherever resuspension is negligible. On the basis of calculated bottom stress distribution and observed sediment characteristics it is estimated that all of the inner harbor and most of the outer harbor is depositional. This large area, coupled with the efficient dispersion of particles within the harbor, ensures that particles from different sources may be deposited together throughout the harbor and that attribution of contamination to a particular source will be difficult.

- Of the particles participating in the harbor-wide transport between 10% and 50% will be retained in the harbor depending upon sources location and the effective rate of deposition. For particles discharged into regions of the inner harbor such as Fort Point Channel, the percentage will be higher (50–90%). Historically, about half of the particles discharged to the harbor are estimated to have been retained in the harbor

- The accumulation of "natural" particles, i.e., those imported from outside the harbor, exceeds the average rate of deposition of waste particles by a factor of 5 to 10, even in areas where the deposition of waste particles is heavy such as Fort Point Channel.

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List of Tables

Table 2.1

Fort Point Channel Surveys

Date of discharge	Nov. 29, 1989	May 5, 1990	July 14, 1991
Time of discharge	0720–0850	0800–1000	0340–0555
Time of nearest high tide (phase during delivery)	1128 (flood)	0905 (high slack)	0124 (ebb)
Tidal range (m)	3.0	2.6	4.1
Rainfall at Logan Airport (36 hrs through discharge)	0.11"	0.72"	0.52"
No. surveys/duration	11 over 6 days	9 over 10 days	9 over 6 days
Tracers			
dye	×	×	×
paint		×	×
salinity	×	×	×
bacteria (MWRA)	×	×	×
SS (UMass/B)		×	×
metals (UMass/B)		×	×

Table 2.2

Summary of Residence Times

	Nov. 1989	May 1990	July 1991
Time τ (days)	2.5	2.6	1.0
Tidal range $2a_0$ (m)	3.0	2.6	4.1
Tidal phase	flood	high	ebb

Table 2.3

Results from the New Fall Cone

Test name	w (%)	IL	c_u (g/cm^2)	$c_{u\text{-}av}$ (g/cm^2)
30gP60	32.9	0.50	120.23	
35gP60			82.39	104.6
40gP60			111.19	sd=19.7
30gP60	43.4	1.02	29.08	
35gP60			26.15	28.77
40gP60			31.07	sd=2.47
5gP60	51.7	1.43	8.84	
10gP60			8.71	
20gP60			13.19	10.96
15gB60			14.92	sd=2.67
20gB60			11.44	
30gB60			8.64	
5gP60	60.3	1.86	4.32	
10gP60			3.74	
15gP60			3.69	
20gP60			3.80	3.81
5gB60			4.32	sd=0.35
10gB60			3.58	
15gB60			3.32	
20gB60			3.71	
1gP60	70.6	2.38	2.19	
2gP60			1.34	
5gP60			1.47	
10gP60			1.51	1.73
15gP60			1.38	sd=0.42
5gP90			1.71	
10gP90			1.67	
15gP90			2.54	
1gP60	79.2	2.81	1.05	
2gP60			1.33	
5gP60			0.77	0.95
1gP90			0.85	sd=0.24
2gP90			0.75	

Table 2.3 (cont'd)

Test name	w	IL	c_u	$c_{u\text{-av}}$
1gP60	80	2.85	1.29	
2gP60			1.31	
5gP60			1.15	
10gP60			1.02	1.18
5gP90			1.25	sd=0.12
10gP90			1.01	
15gP90			1.26	
20gP90			1.20	
1gP60	91	3.40	0.47	
2gP60			0.54	
5gP60			0.41	0.47
1gP90			0.66	sd=0.12
2gP90			0.38	
5gP90			0.34	
1gP60	110.5	4.37	0.47	
2gP60			0.44	
5gP60			0.49	
1gB60			0.44	
2gB60			0.46	0.49
1gP90			0.63	sd=0.06
2gP90			0.51	
5gP90			0.45	
10gP90			0.50	
15gP90			0.53	

Table 2.4

Results of Liquid Content and Shear Strength for Sample 1 of BHM

Layer	Depth (cm)	I (%)	W (g)	c_u (g/cm^2)	$c_{u\text{-av}}$ (g/cm^2)
1	0 - 3	208.3	5	3.75	
			5	3.75	
			10	3.98	3.27
			10	2.92	sd=0.63
			15	2.81	
			15	2.44	
2	3 - 6	155.8	5	4.29	
			5	2.88	
			10	5.64	4.92
			10	4.49	sd=1.35
			15	5.41	
			15	6.81	
3	6 - 9	129.5	5	6.76	
			5	7.52	
			10	8.27	8.35
			10	9.02	sd=1.03
			15	9.27	
			15	9.27	
4	9 - 12	125.0	10	9.52	
			10	7.4	
			15	10.92	9.35
			15	10.75	sd=1.45
			20	9.66	
			20	7.88	
5	12 - 15	107.9	10	15.76	
			10	19.16	
			15	23.64	20.79
			15	29.35	sd=5.74
			20	16.06	
			20	—	

Table 2.5

Results of Liquid Content and Shear Strength for Sample 2 of BHM

Layer	Depth (cm)	I (%)	W (g)	c_u (g/cm^2)	$c_{u\text{-}av}$ (g/cm^2)
1	0 - 3	210.8	5	3.22	
			5	2.92	
			10	2.34	2.79
			10	1.89	sd=0.55
			15	3.08	
			15	3.29	
2	3 - 6	153.9	5	5.40	
			5	7.19	
			10	4.60	5.04
			10	4.54	sd=1.14
			15	4.38	
			15	4.13	
3	6 - 9	129.6	5	10.88	
			5	6.32	
			10	5.92	8.43
			10	9.18	sd=1.96
			15	9.81	
			15	8.51	
4	9 - 12	123.2	10	14.45	
			10	13.53	
			15	—	13.0
			15	14.02	sd=2.09
			20	9.32	
			20	13.68	
5	12 - 15	110.7	10	—	
			10	28.14	
			15	13.29	18.62
			15	11.46	sd=6.6
			20	20.11	
			20	20.11	

Table 3.1

Boston Harbor Residence Time Estimates

Investigator	Technique	Source location	Res. time (τ) = flush rate^{-1} (d)	Comments
EXPERIMENTAL				
Bumpus et al. 1953	fraction freshwater	rivers	2d	calculation for inner harbor only; very sensitive to assumed salinities
Kelly 1991	fraction freshwater	rivers (1/3),TPs (2/3)	10.5d	very sensitive to assumed salinities
Kossik et al. 1986	meas. inventory of VHOC/$\dot{m}$	TPs	~8d	τ may be high if $\dot{m}$ is low
Adams et al. 1987	meas. inventory of VHOC/$\dot{m}$	TPs	~10d	τ may be high if $\dot{m}$ is low
Sung 1991	meas. inventory of Cu, Zn /$\dot{m}$	TPs	~3d	τ may be low if $\dot{m}$ is high (harbor concentration considered only dissolved phase; $\dot{m}$ included particulate)
Shea and Kelly 1992	meas. inventory of various metals/$\dot{m}$	TPs	~3-8d	τ would be higher if deposition were included
THEORETICAL				
numerous	tidal prism	no discrimination	1.3d	lower bound estimate for τ
Ketchum 1953	mod. tidal prism method	Chas. R. mouth to Deer Is.	9.5d	
		Neponset R. mouth to Deer Is.	5.6d	
Signell 1992	numerical sim. driven by M_2 tide	uniform over harbor	2.8d (first cycle)	indicates strong spatial variation of effective flushing
			16.7d (32 cycles)	later times may be high due to neglected processes
Lee 1990	sim. inventory of susp. solids/$\dot{m}$	all sediment sources	4.2d	model calibrated to Kossik et al. 1986
		river	8.2d	very sensitive to dispersion coefficient (lower coefficient yields higher τ)
		TP (President Roads only)	2.7d	

Table 3.2

Summary of Settling Velocities
(percent settling faster than indicated value)

W_s (m/s)	EPA (1982)		Wang (1988) Holography		Wang(1988) Column	Faist ('76,'80)	Ozturgut and Lavelle (1984)	Lavalle et al. (1988)	McCave and Grass (1991)
	Prim Effl	Raw	Effl[1]	Sludge[1]	Sludge[2] [4]	Sludge	Effl[3]	Sludge[4]	Nat sed
10^{-2}	--	5	--	--	--	--	--	--	
10^{-3}	5	40	--	--	0-25	0-5	--	10-20	
10^{-4}	20	60	~3	~3	10-60	5-40	5-25	25-30	10
10^{-5}	50	85	~10	~30	30-75	25-70	50-60	50-80	40-45
10^{-6}	--	--	~20	~60	45-85	50-80	~70	95-100	100

---

[1] Holography
[2] Column
[3] Computed
[4] Range for sludge reflects coagulation; highly coagulated samples settle faster

Table 3.3

Order of Magnitude Space and Time Scales of Initial Particle Deposition
(assumes $H = 10$ m)

W_s (m/s)	$T = H/W_s$ (s)	D (m^2/s)	$L = [DT]^{\frac{1}{2}}$ (m)	Geographic region
10^{-3}	10^4 (3h)	1	100	near source
10^{-4}	10^5 (1d)	10	1000	scale of Fort Point Channel
10^{-5}	10^6 (10d)	100	10^4	scale of Boston Harbor

Table 3.4

Percent of Solids Retained in Boston Harbor from Different Sources

Source	Percent of total solids discharged to harbor	Percent of those solids with settling velocity greater than 3×10^{-5}m/s	Est. percent retained in harbor
Raw sewage (rivers, stormwater and CSOs)	16	70	85
Sludge	23	40	55
Effluent	61	7	30
weighted average			45

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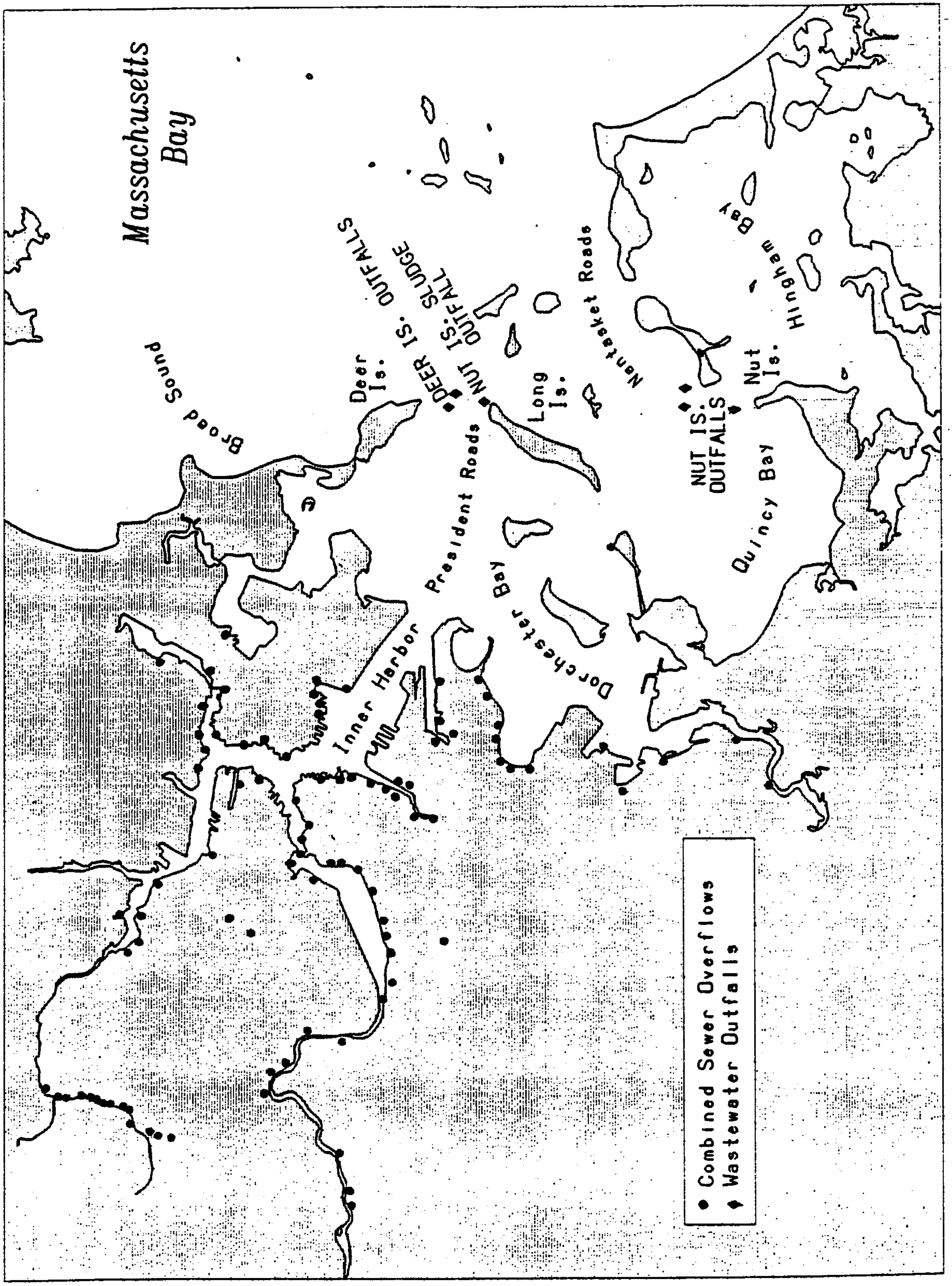

Figure 2.1. Map of Boston Harbor (after Rex et al., 1992)

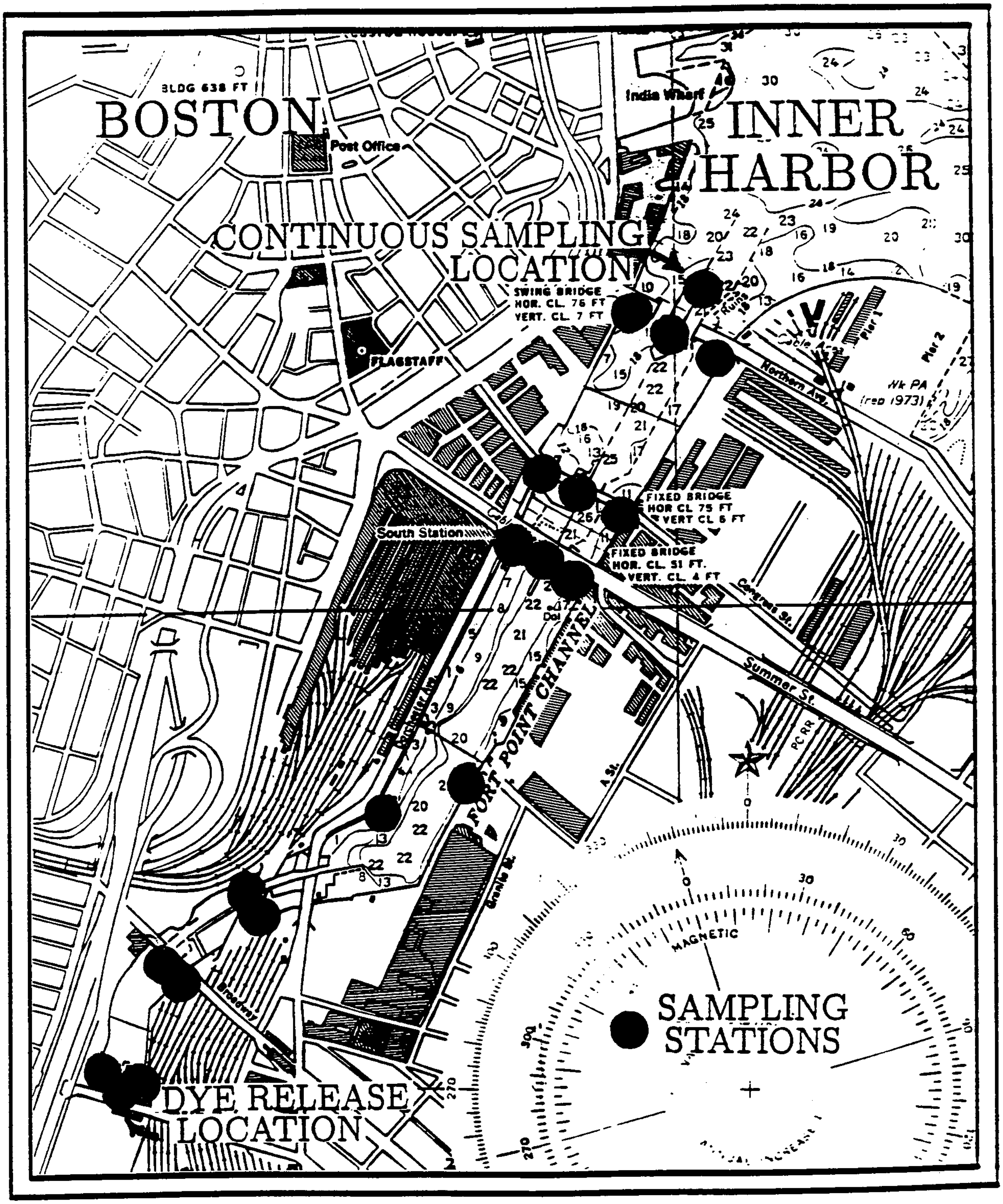

Figure 2.2. Plan view of Fort Point Channel showing typical sampling locations. Tracers were discharged to head of channel at BOS070 culvert in SW corner

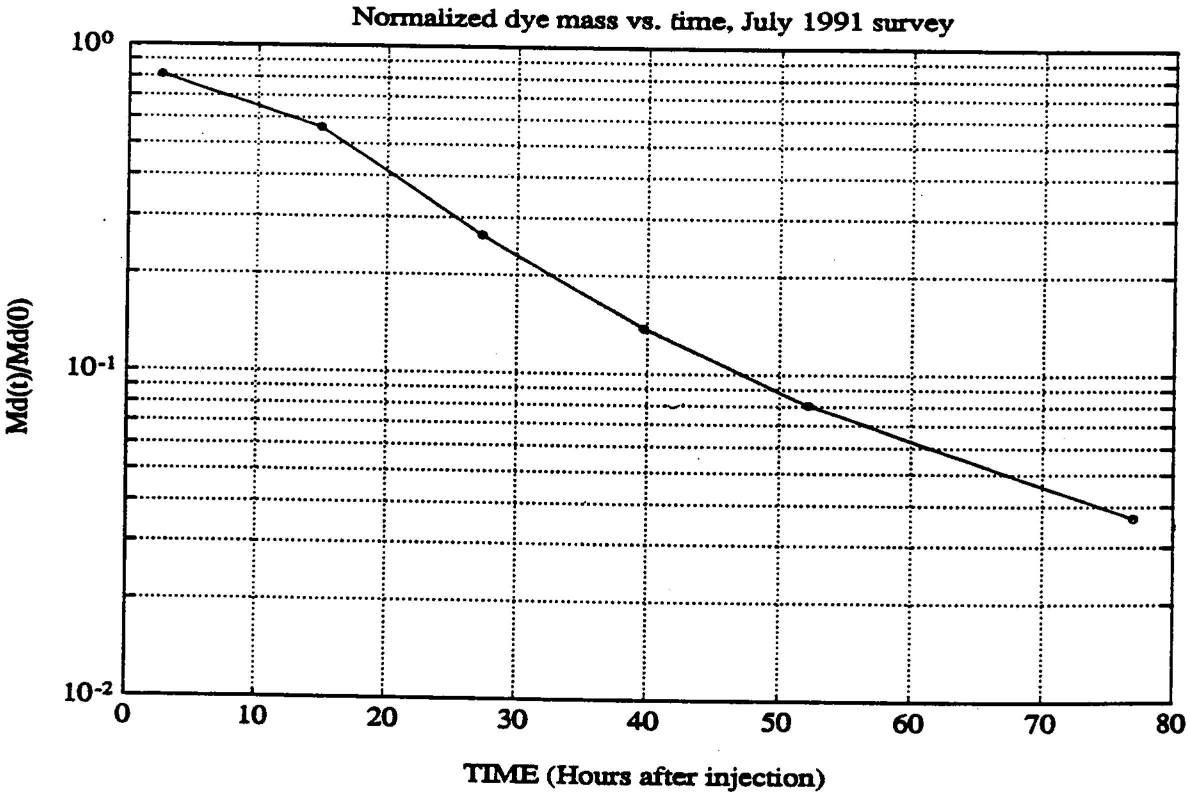

Figure 2.3. Normalized dye mass vs. time, July 1991 survey

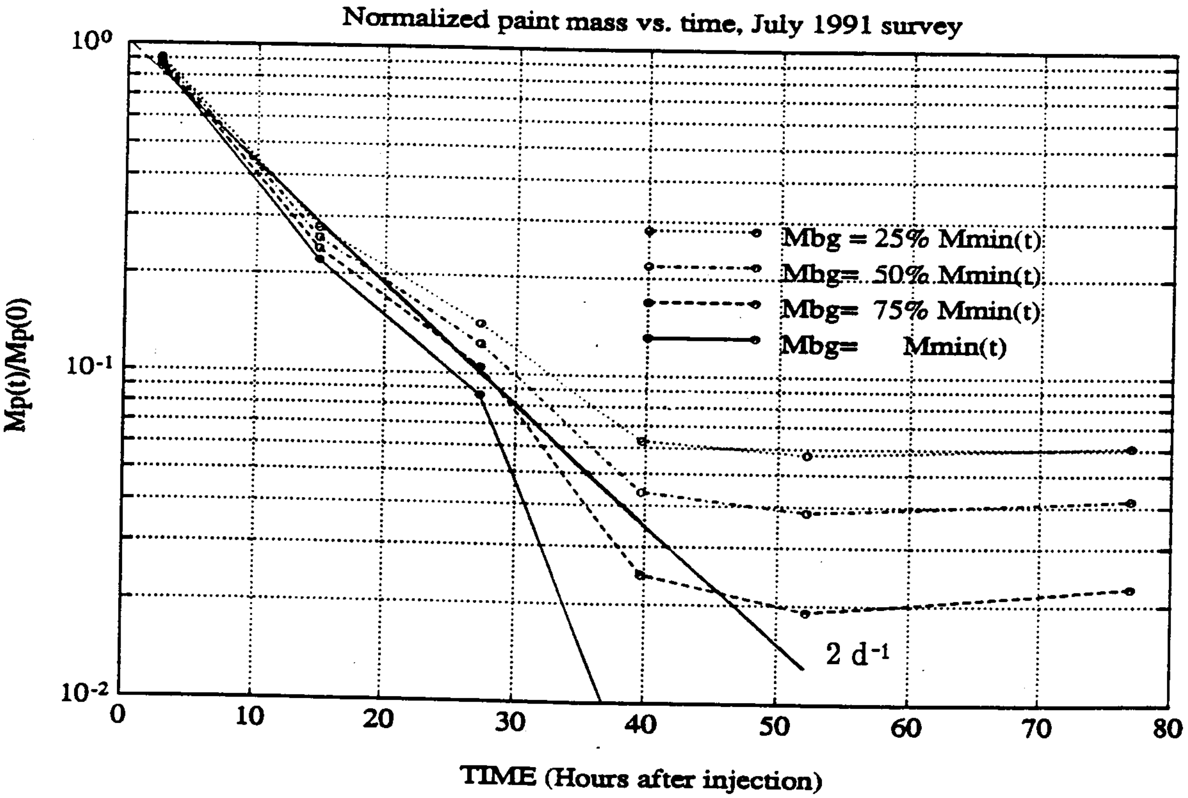

Figure 2.4. Normalized paint mass vs. time, July 1991 survey
M_p = mass of paint in channel
M_{bg} = estimated background mass of paint
M_{min} = mass of paint corresponding to minimum measurement

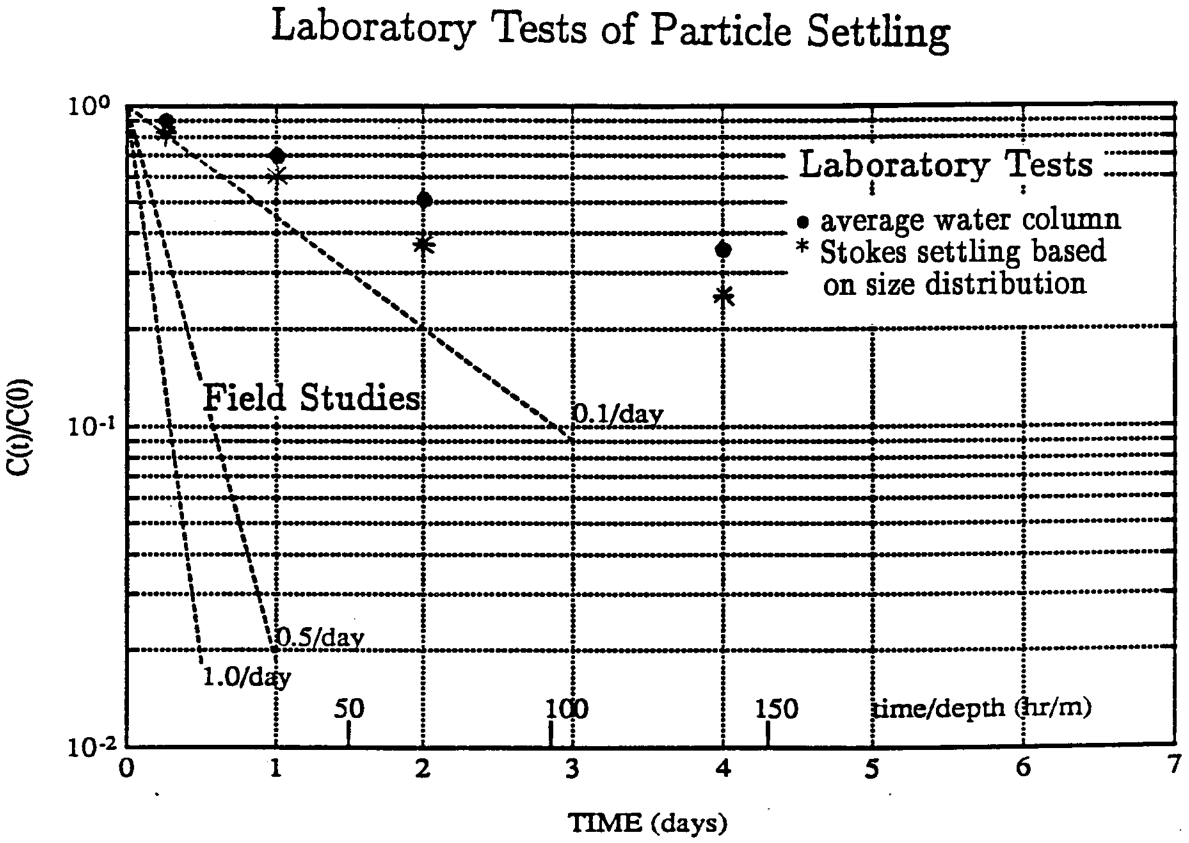

Figure 2.5. Suspended paint concentrations vs. time for laboratory settling tests

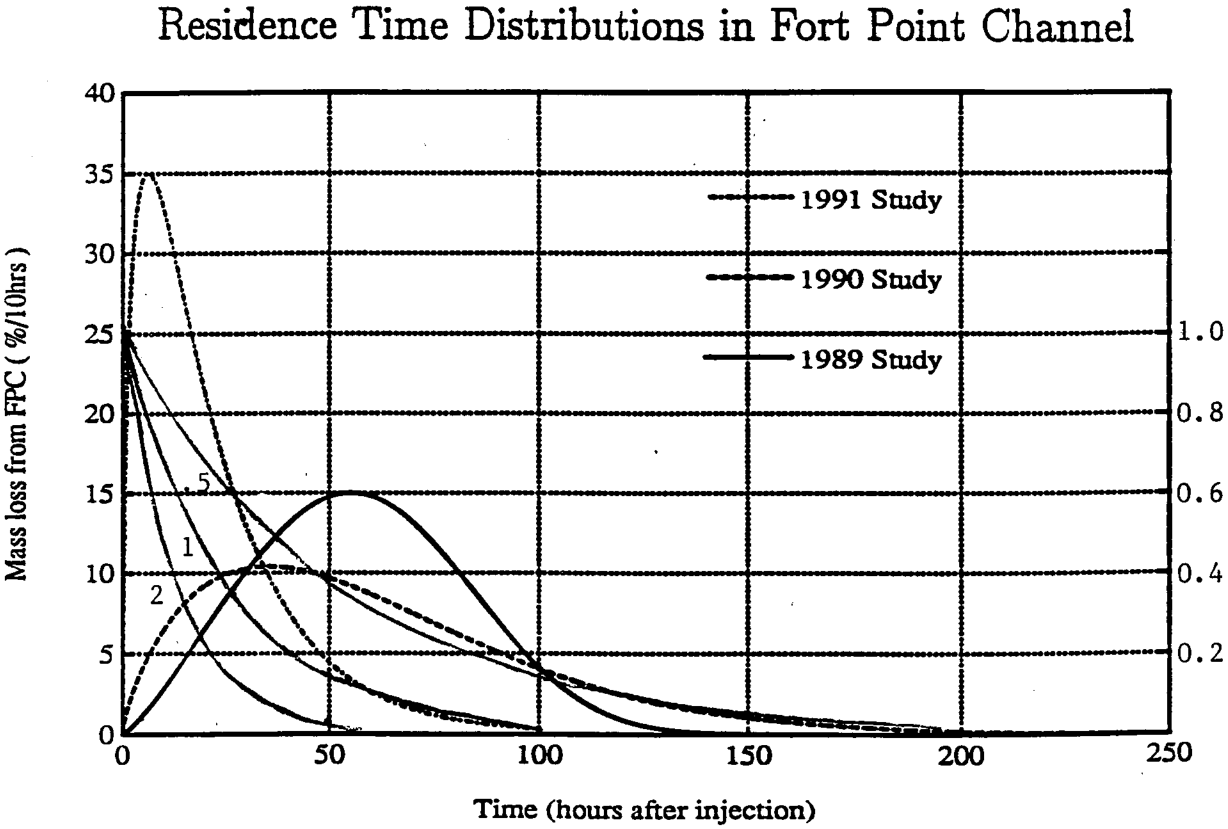

Figure 2.6. Residence time distributions in Fort Point Channel (left ordinate). First order (exponential) decay curves for rates of 0.5, 1.0 , and 2.0 d^{-1} (right ordinate)

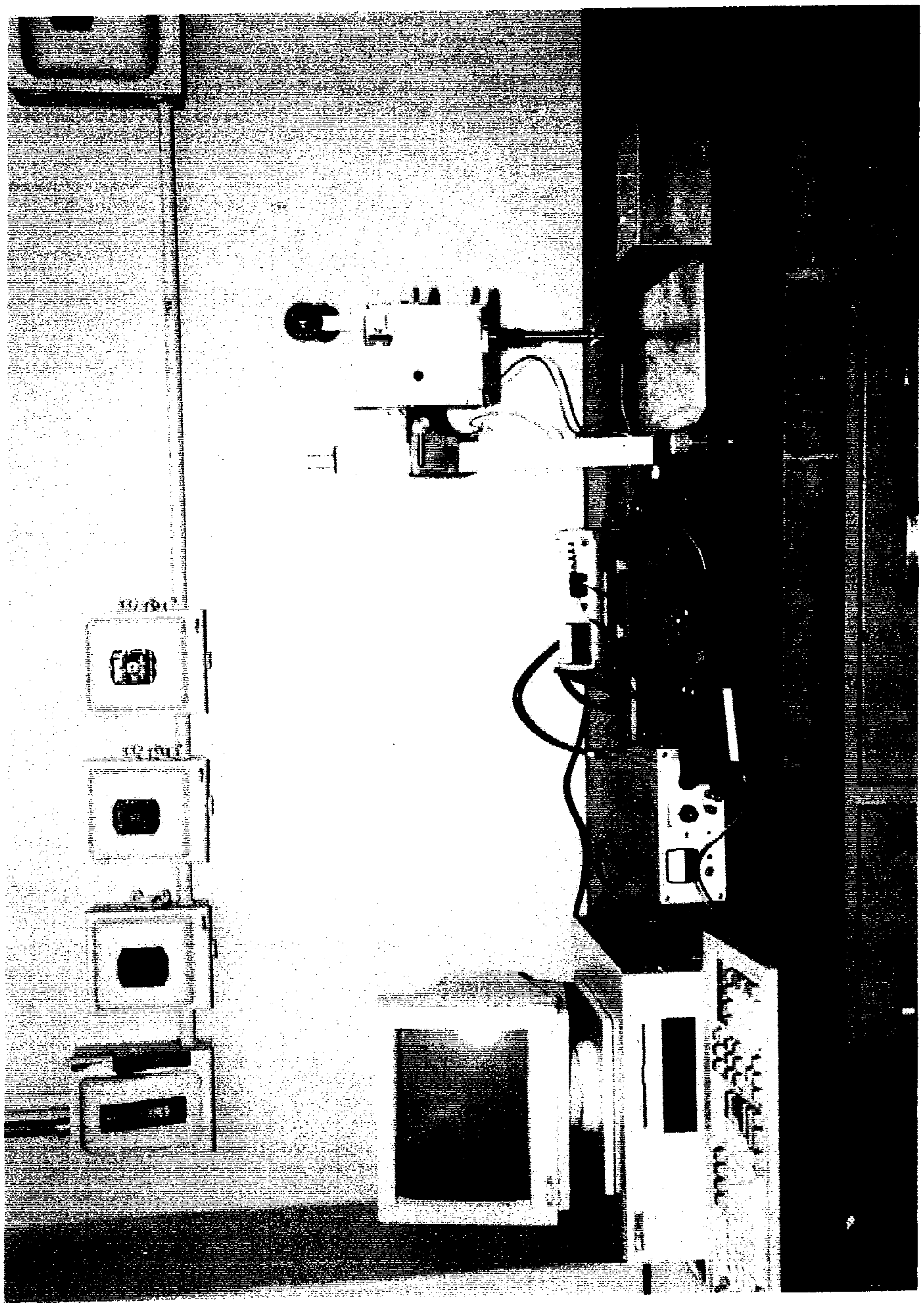

Figure 2.7. Automated MIT Fall Cone Device composed of the fall cone apparatus, a power supply, a voltmeter, an electronic timer, and a computer for data acquisition

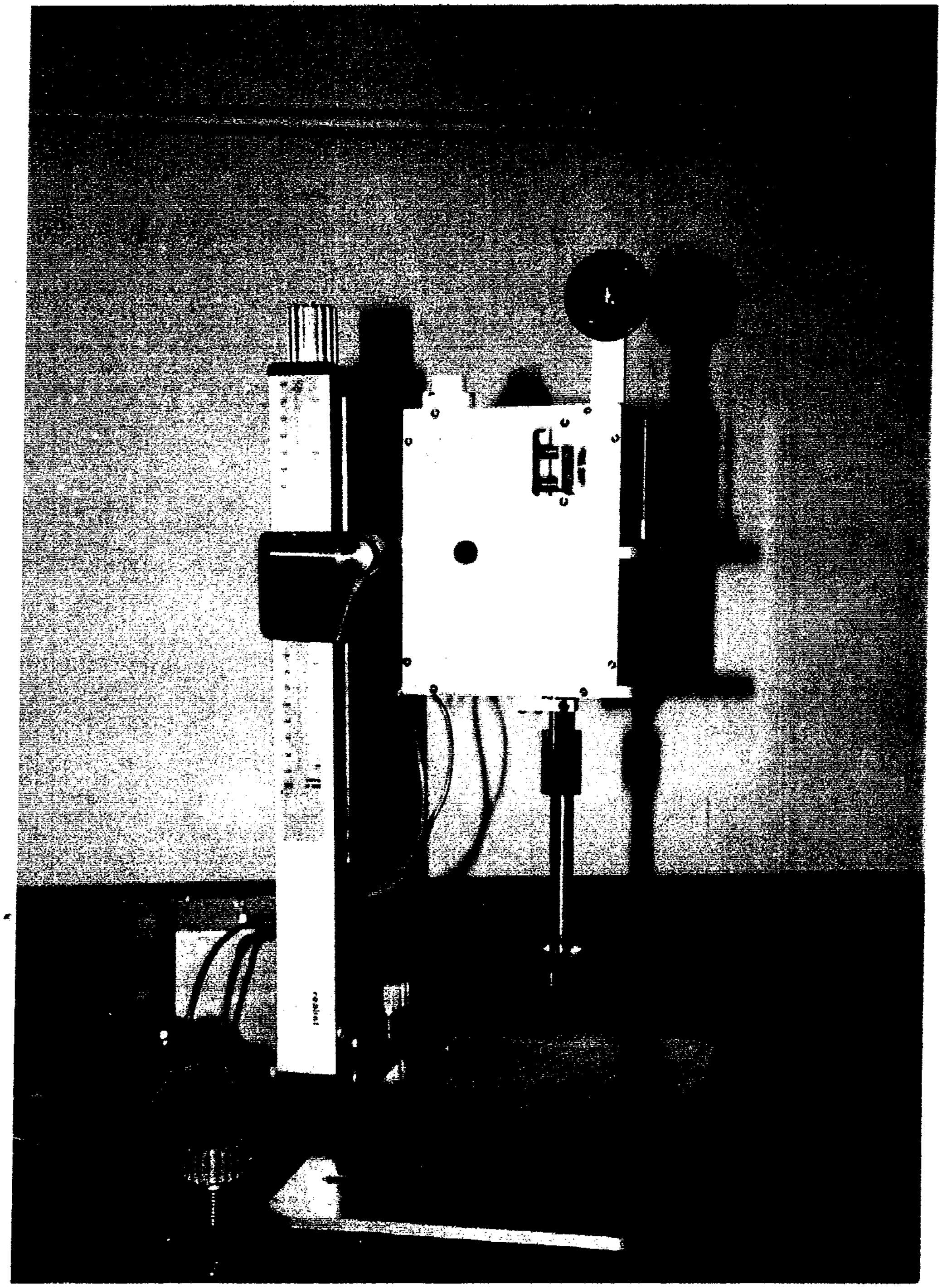

Figure 2.8. Fall cone apparatus showing: adjustable height stand, depth sensor with light signal, electro-magnetic clamp, frictionless pulley, and 60° plexiglas cone

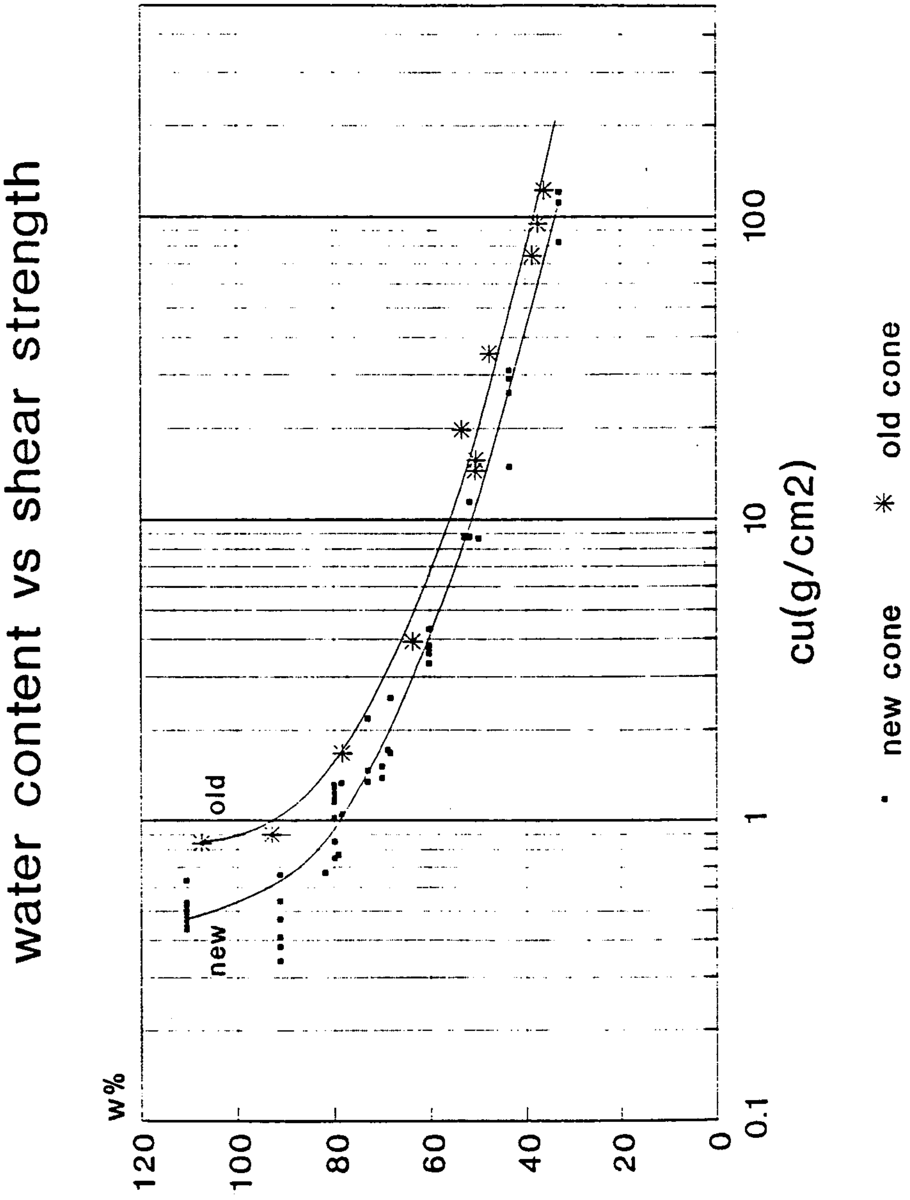

Figure 2.9. Water content versus shear strength for remolded BBC with old and new fall cone (semi-log plot)

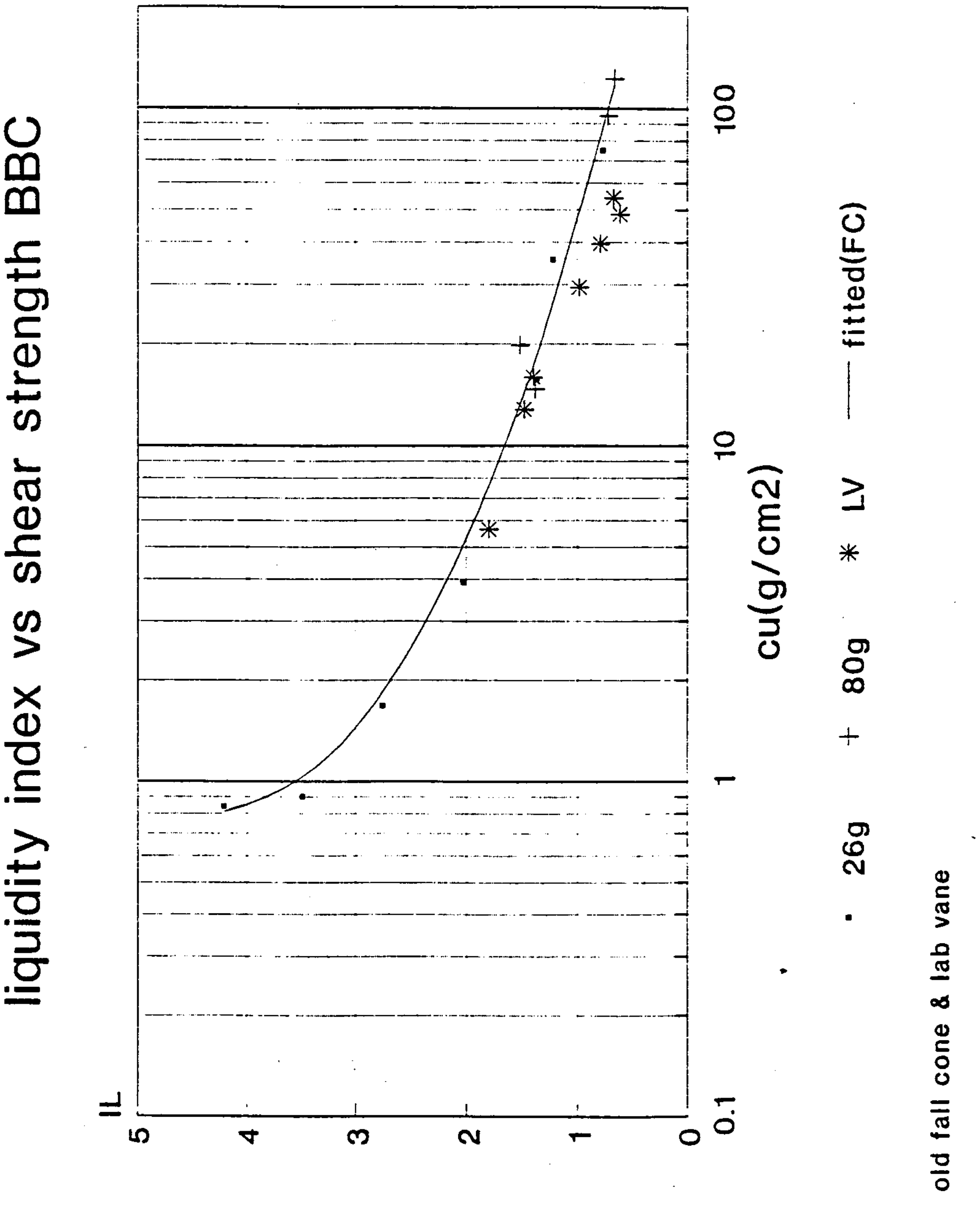

Figure 2.10. Liquidity index versus shear strength for remolded BBC with old fall cone and data from lab vane (semi-log plot)

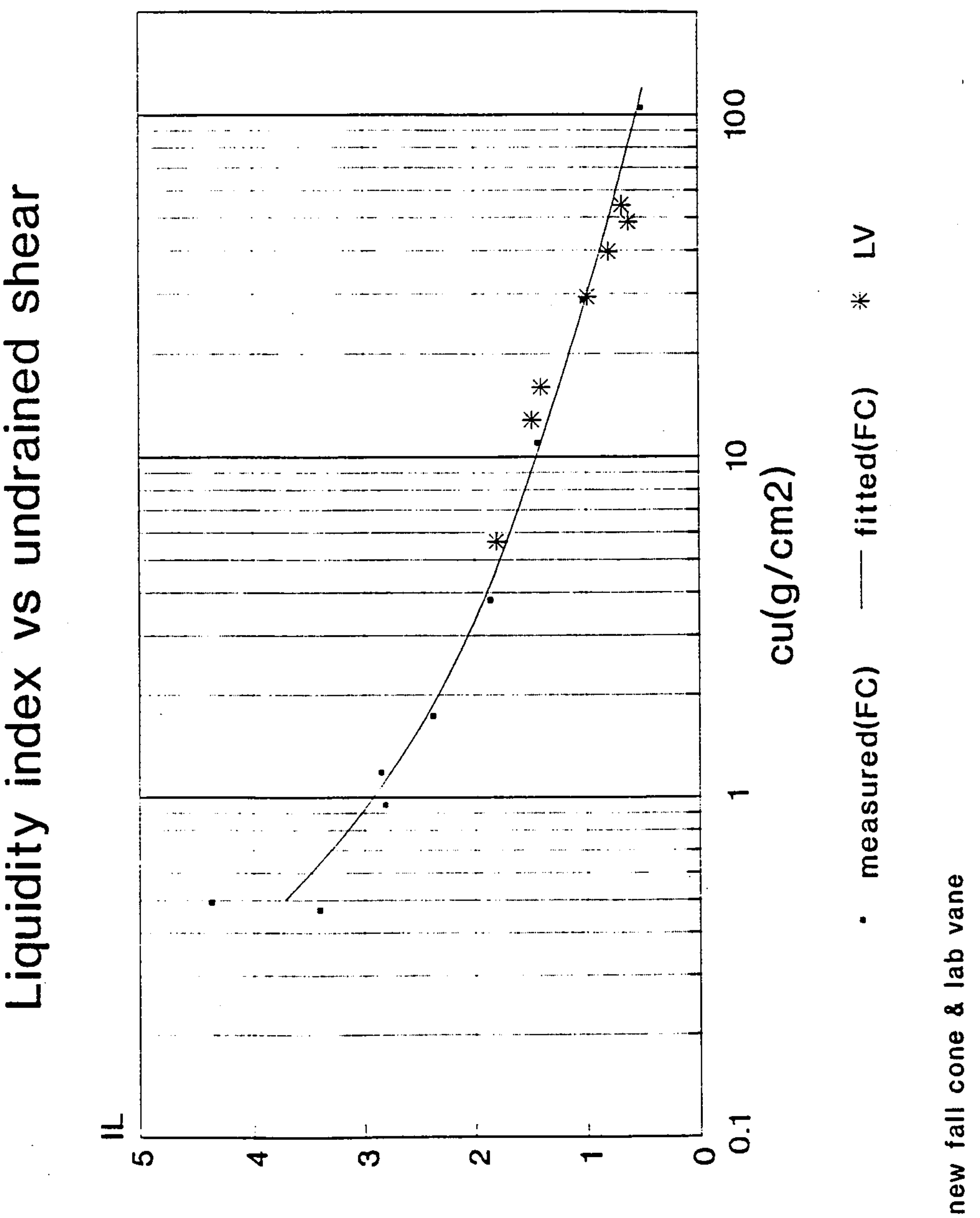

Figure 2.11. Liquidity index versus shear strength for remolded BBC with new fall cone and data from lab vane (semi-log plot)

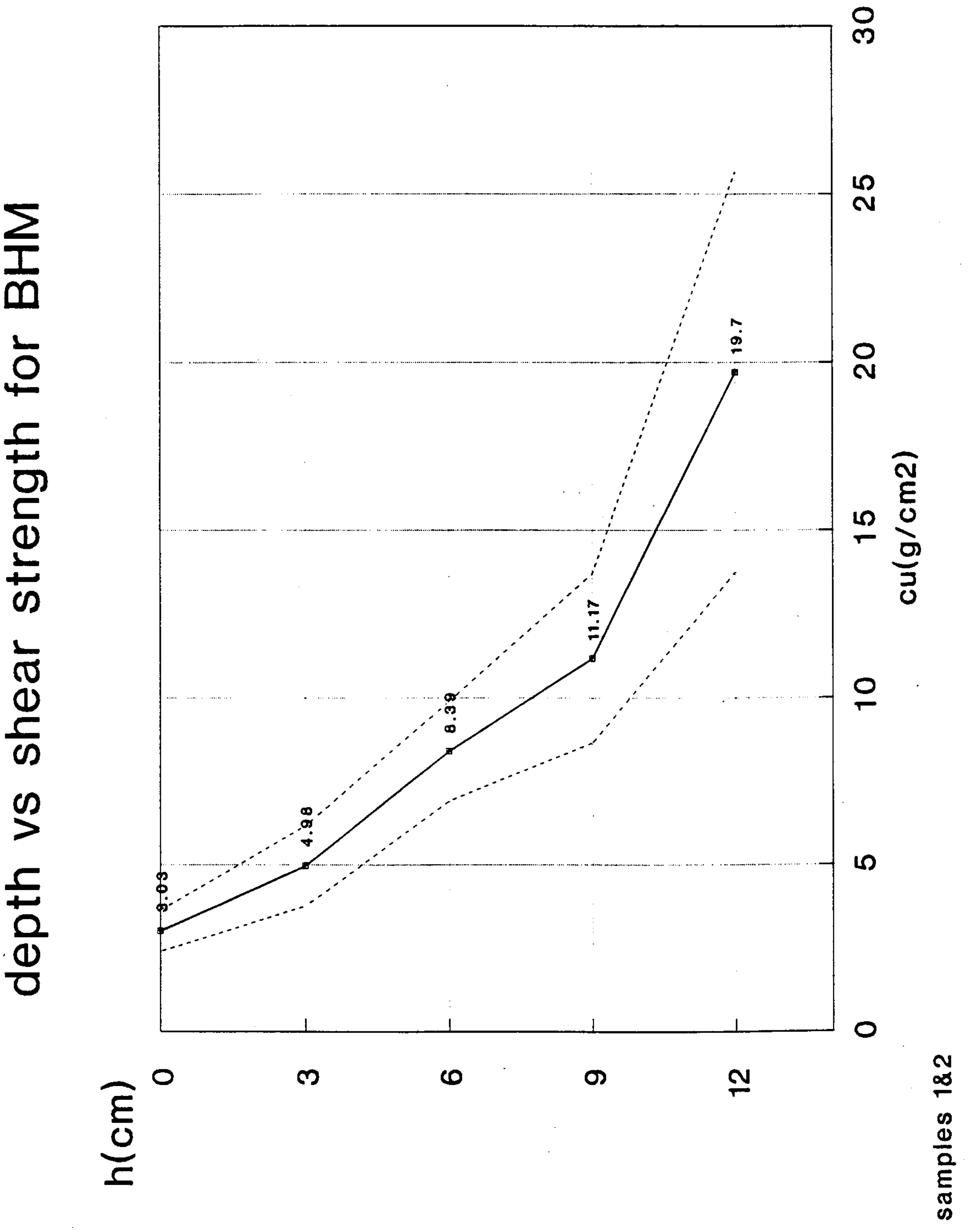

Figure 2.12. Shear strength profile for the upper 12 cm of the bottom southeast of Peddocks Island (combined values from Samples 1 and 2 shown with their standard deviation)

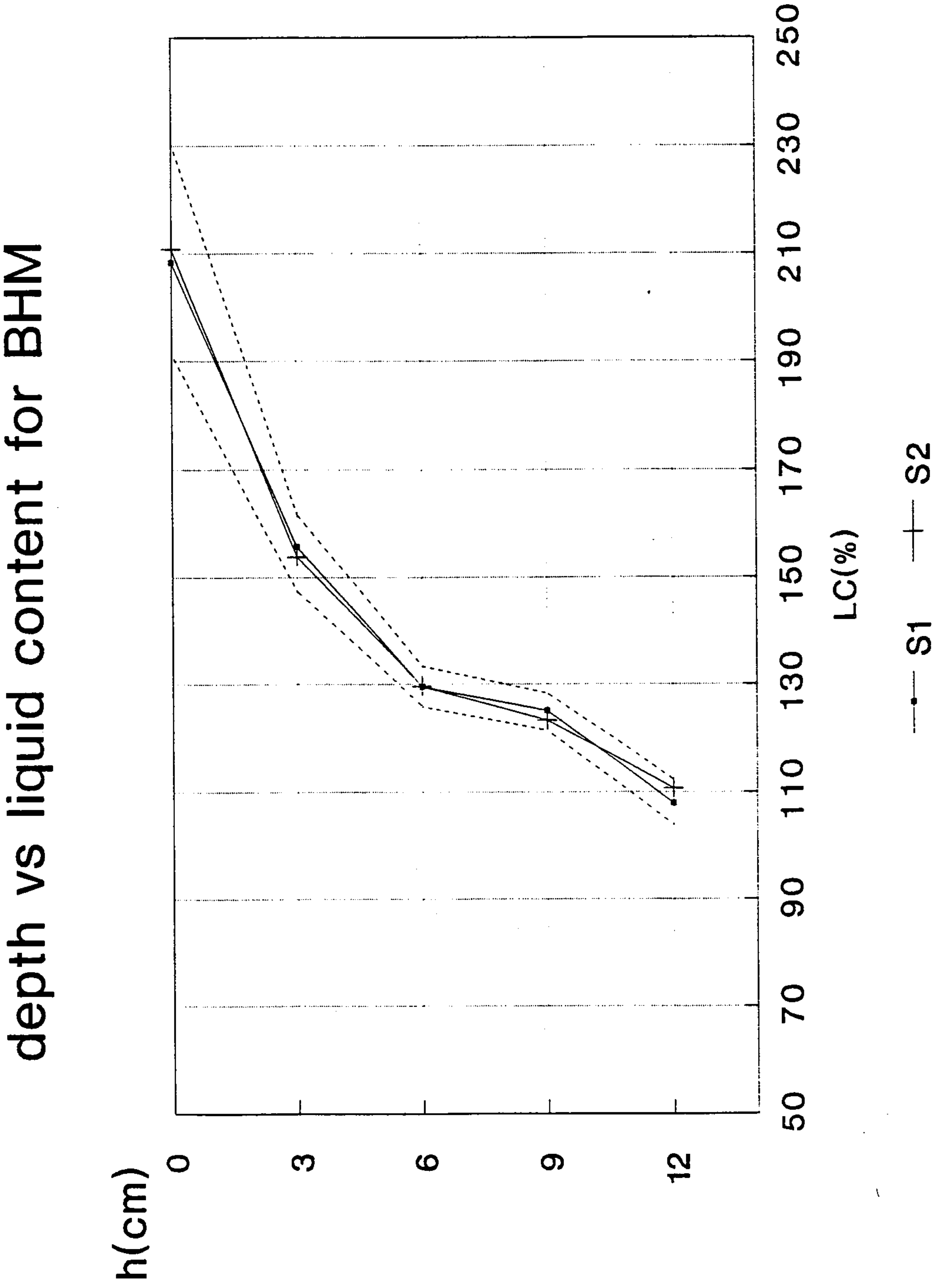

Figure 2.13. Liquid content profile for the upper 12 cm of the bottom southeast of Peddocks Island (values from Sample 1 and 2 separately with their standard deviation)

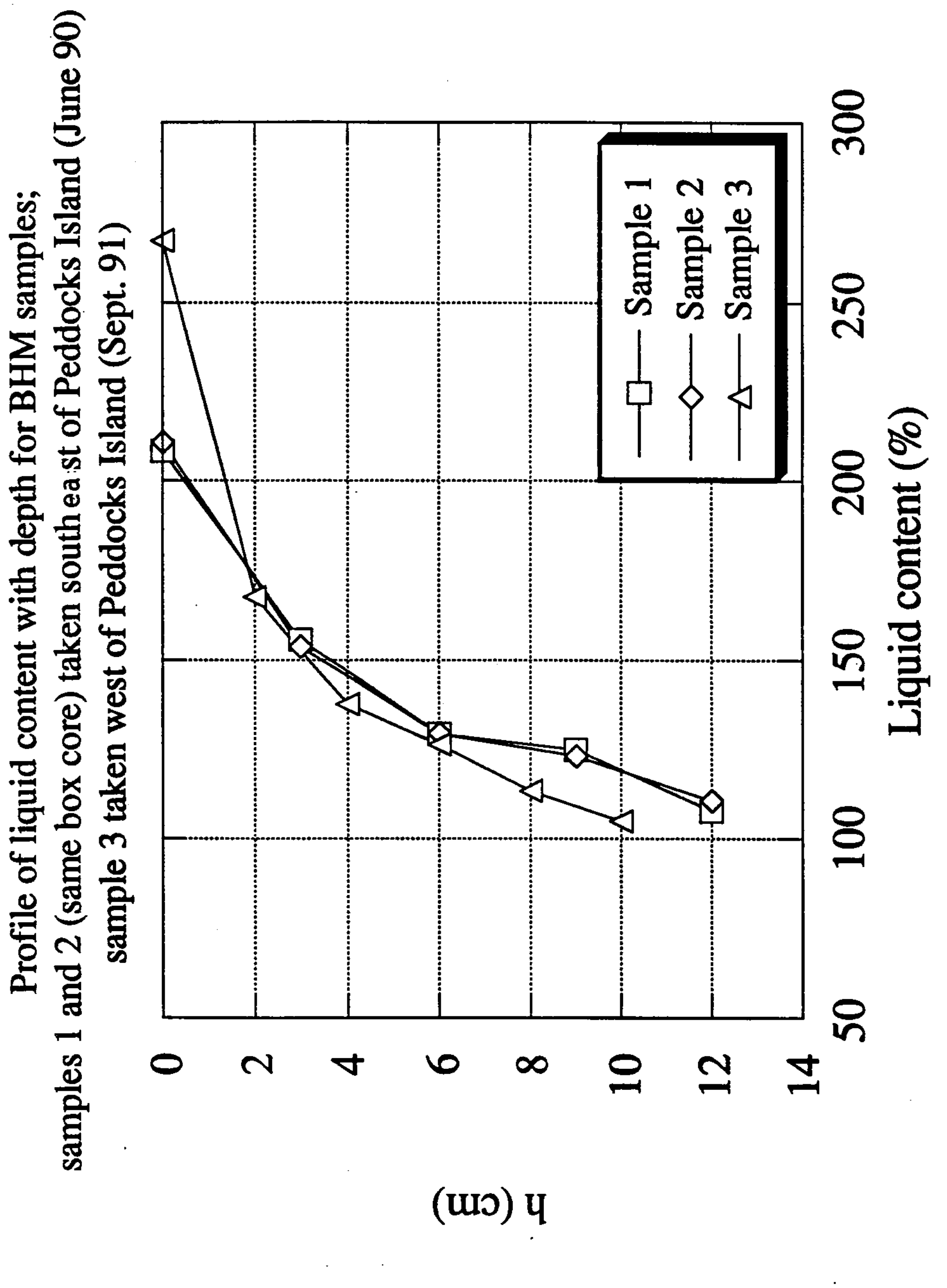

Figure 2.14. Liquid content profile for the upper 12 cm of the bottom around Peddocks Island (Samples 1, 2, and 3)

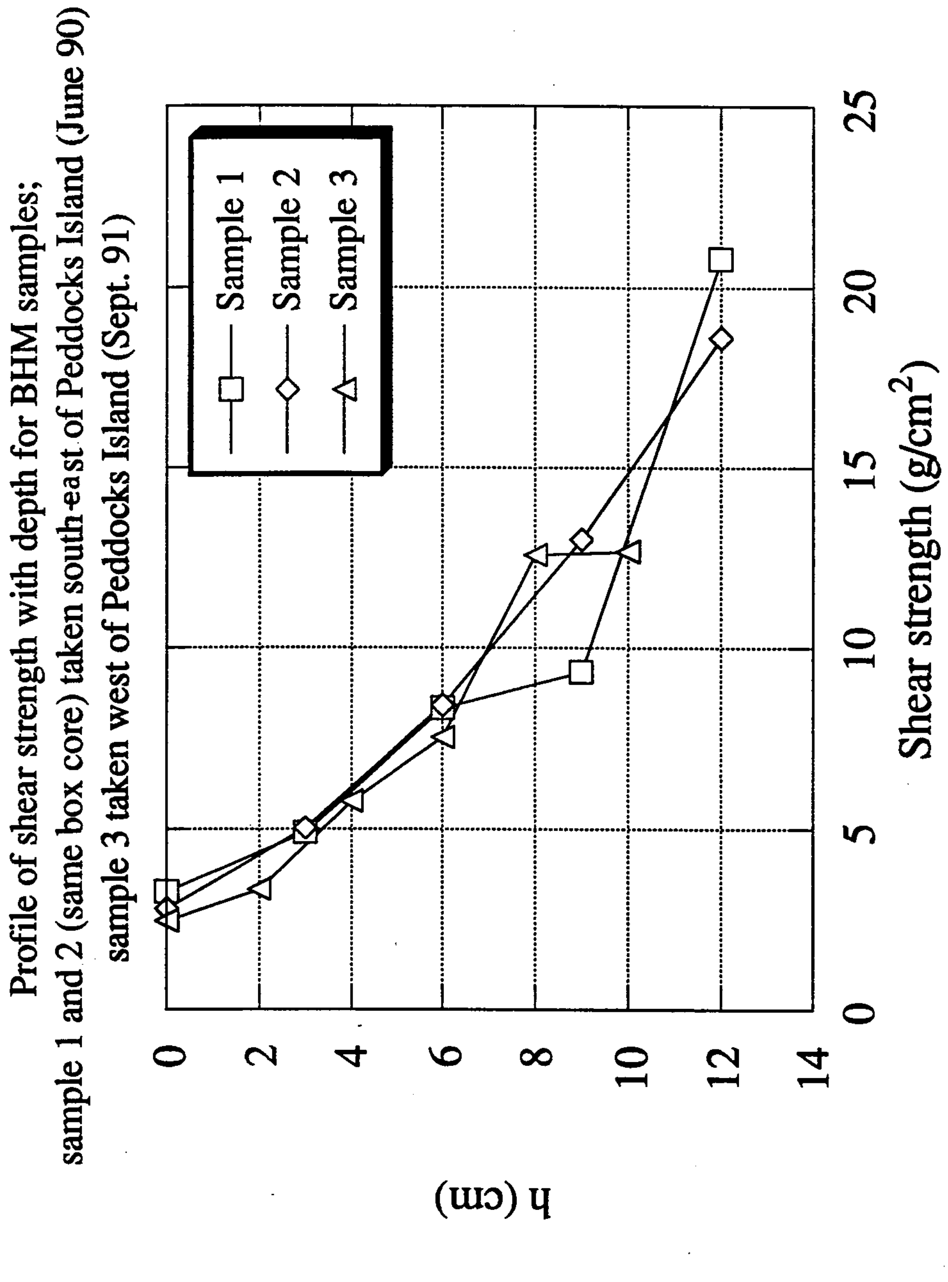

Figure 2.15. Shear strength profile for the upper 12 cm of the bottom around Peddocks Island (Samples 1, 2, and 3)

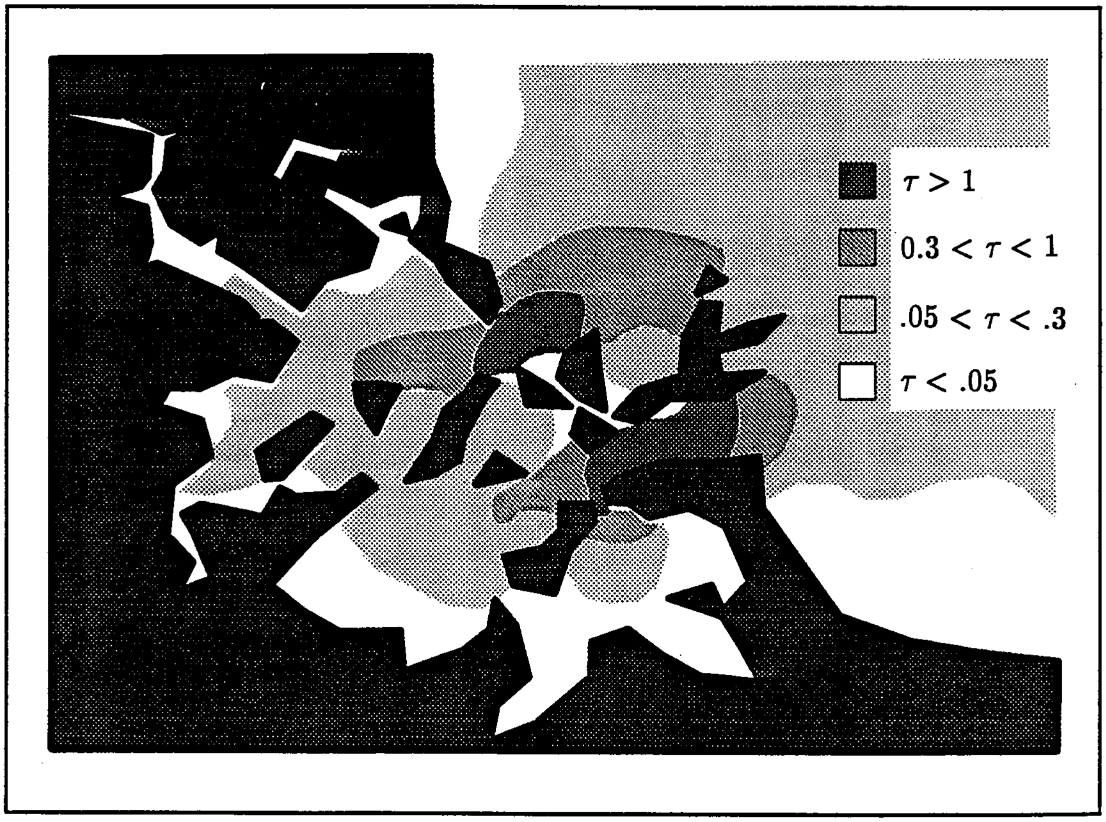

Figure 2.16. Bottom shear stress (N/m^2) at flooding tide

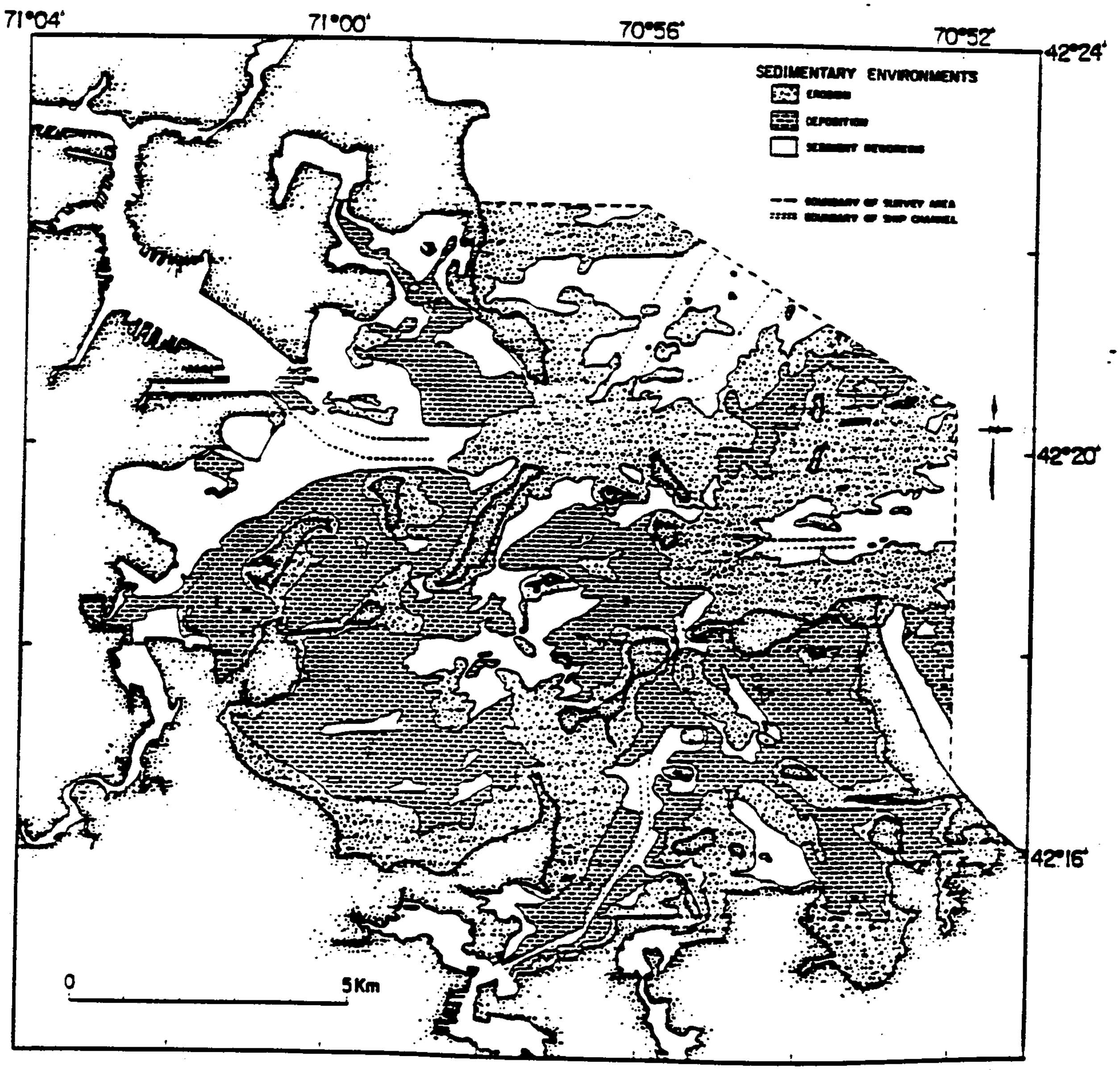

Figure 2.17. Map of erosion and deposition in Boston Harbor (Knebel et al. 1991)

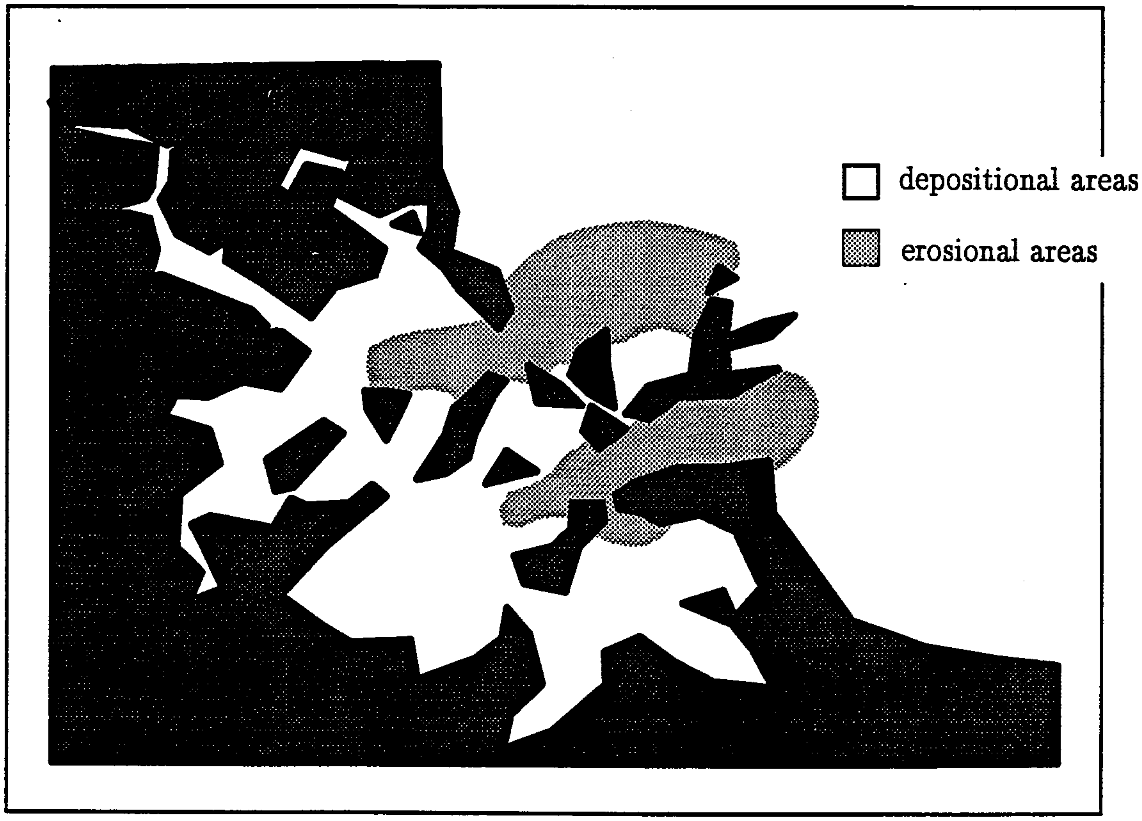

Figure 2.18. Delineation of erosional and depositional areas based on Case 1 with $\tau_c = 0.3\ \mathrm{N/m^2}$

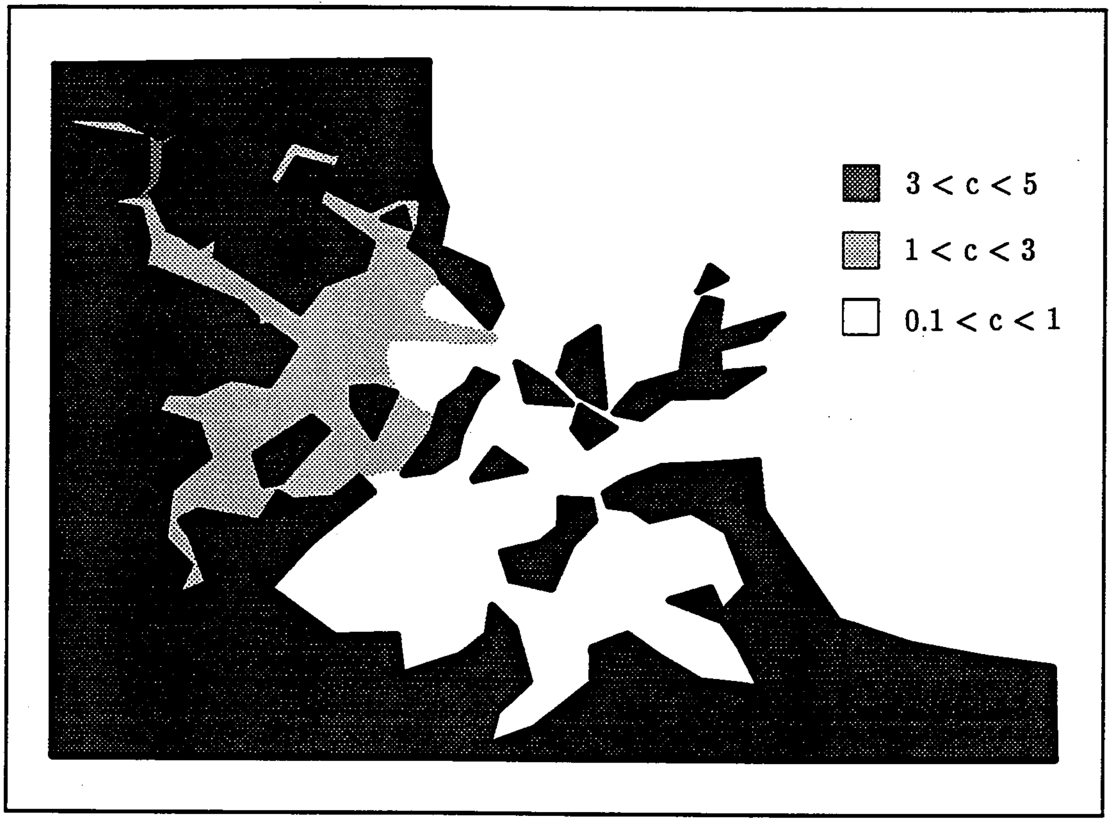

Figure 2.19. Case 1: Simulated suspension concentration (mg/l) in Boston Harbor at high water slack

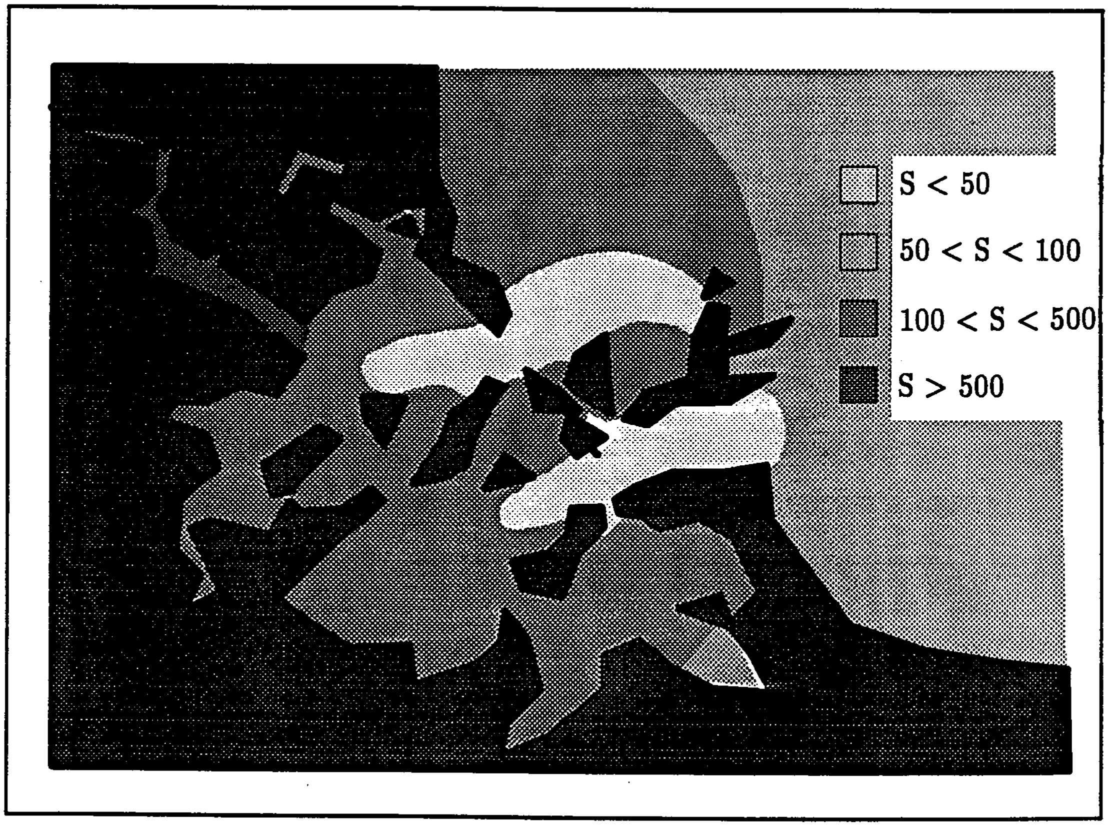

Figure 2.20. Case 1: Simulated sedimentation pattern (g/m²/yr) in Boston Harbor

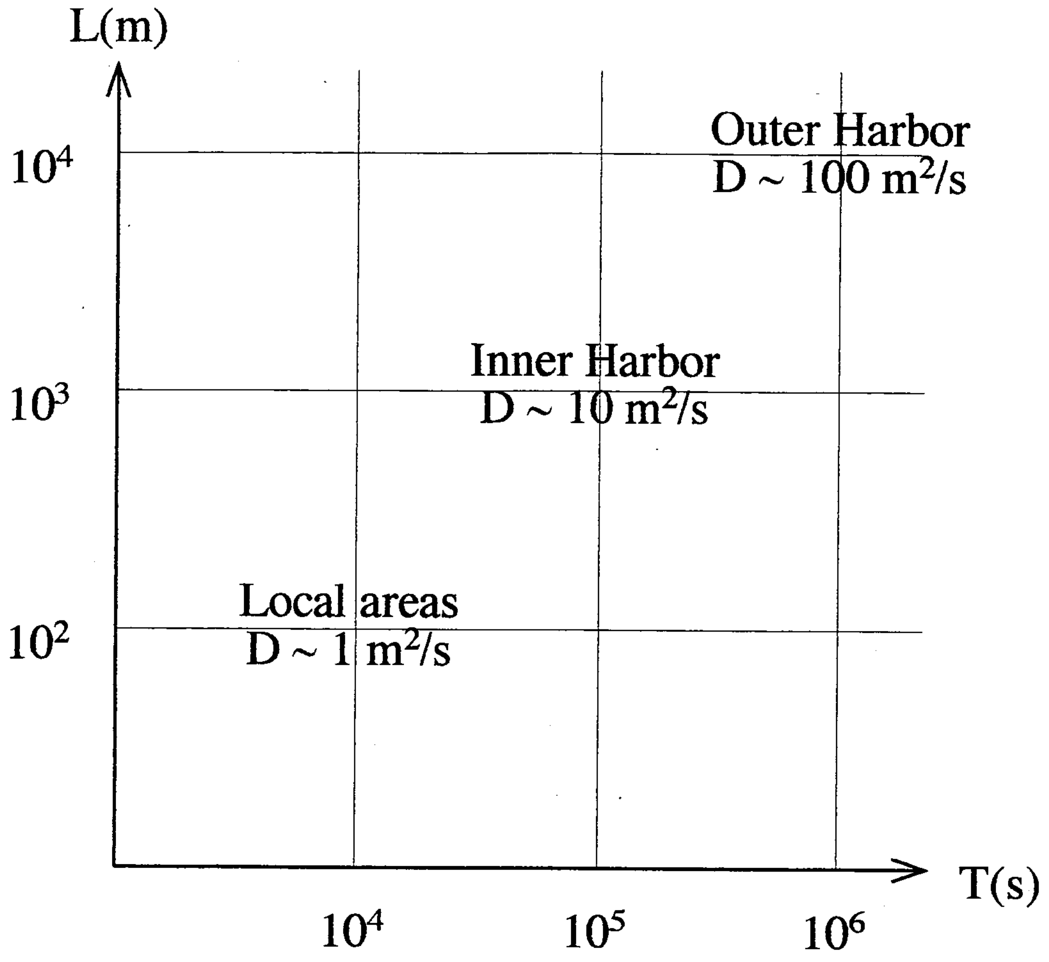

Figure 3.1. Order of magnitude relationship of space and time scales in Boston Harbor. L indicates spatial extent of mixing which occurs during time T. Dispersion coefficient $D \sim L^2/T$ increases with both L and T reflecting greater mixing at increasing space and time scales.

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