Technical Report

THE RESIDENCE TIME OF FRESHWATER IN BOSTON'S INNER HARBOR

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Abstract

Two field tracer studies and some numerical model experiments were used to analyze the residence time of freshwater in Boston's inner harbor, and thereby help evaluate water quality impacts of combined sewer overflows. An exponential filter was used to modify the fraction freshwater approach for variable freshwater inflow and to re-analyze data from Bumpus *et al.* (1953). Results showed an inverse relationship between residence time and inflow rate, with times ranging from 2 to 10 days. An instantaneous dye study gave a residence time of 3.75 days, consistent with the freshwater measurements for conditions of summertime low flow. A 3-D numerical model applied to a schematized domain was able to reproduce trends observed in both the freshwater and dye studies.

1. Introduction

The mean residence time of a water body defines the average length of time a contaminant from a particular source remains within the water body (Officer, 1976; Fischer *et al.*, 1979). It is an important determinant of water quality because, in comparison with rates of chemical reaction, boundary loss, internal decay or die-off, it determines the biogeochemical fate of the contaminant.

The focus here is Boston's inner harbor. The Boston area is currently planning for the control of its combined sewer overflows (MWRA, 1994, 1996), many of which are located deep within the commercial inner harbor or along tributaries to the inner harbor. Meanwhile the outer harbor is home to many beaches and shell fishing areas whose uses have historically been jeopardized by high bacteria counts, much of which results from CSOs. By comparing the hydrodynamic residence time of CSO water with the disappearance rate of indicator bacteria, one can quickly determine the approximate impact of inner harbor pollution sources on the outer harbor. Residence time also provides a convenient integrated measure of transport which can be used to validate more sophisticated water quality analyses based on 3-D numerical models.

In this paper, residence time is evaluated using three approaches--two sets of field tracer experiments and a numerical model study. These approaches include: (1) re-analysis of data from Bumpus *et al.* (1953) using freshwater as a continuous tracer and modified to account for variable freshwater inflow rate; (2) analysis of data from an instantaneous fluorescent dye study; and (3) schematic numerical experiments with a 3-D model designed to simulate the dye test, and to explore the sensitivity of residence time to freshwater inflow rate and the discharge sequence (e.g., continuous vs intermittent).

2. Study area

As indicated in **Figure 1**, Boston's inner harbor extends from the confluence of Mystic R. and Chelsea Cr. to it mouth at the entrance to the outer harbor, which in turn discharges to Massachusetts Bay. The volume of the inner harbor is approximately 7.8 x $10^7 m^3$ (high tide) and 5.6 x $10^7 m^3$ (low tide), while the depth is nearly constant at about 10 m MLW (Bumpus *et al.*, 1953; Alber and Chan, 1994). Tides are semi-diurnal with an average range of about 2.9 m (NOS, 1991).

The inner harbor receives freshwater from the Charles R., Mystic R. and Chelsea Cr. whose respective drainage areas represent 82, 17 and 1 percent of the total drainage area (Alber and Chan, 1994). Except during extreme flow conditions, flow from the Charles and Mystic Rivers enters the harbor by gravity through sluice gates at dams (indicated by dashes in Fig. 1) that can be opened for several hours surrounding low tide, while flow from the smaller Chelsea Creek is unregulated. The Charles is by far the largest freshwater source with an annual average flow (1931-1992) at the USGS gage in Waltham of 8.6 m^3/s. The corresponding summertime average (July through September) at the same gage is 3.4 m^3/s (USGS, 1992). Using a scaling factor of 1.27 to extrapolate to the entire drainage area (Alber and Chan, 1994), these flows scale to 10.9 and 4.3 m^3/s, respectively.

Nearly once a week, during times of moderate to heavy rainfall, up to 35 CSOs discharge a combination of storm water plus raw and partially treated sewage directly to the inner harbor (Fig. 1). As of 1992, the annual freshwater load from these sources was about 3.5×10^6 m^3 (MWRA, 1994). In addition, CSOs as well as other wet and dry weather sources contribute pollution to the rivers, which discharge to the inner harbor. As part of the CSO planning it is important to understand how these pollutants are diluted within the harbor, what their residence time is, and how the residence time varies with magnitude and timing of the freshwater inflow.

3. Calculation of residence time from tracer measurements

Residence time can be calculated from measurements resulting from either an instantaneous or a continuous release of a conservative tracer.

3.1 Instantaneous tracer release

This approach is based on the time-varying mass, m(t), remaining after an instantaneous release of mass m_o; m(t) is found from spatial integration of measured concentrations. The rate of mass loss (flushing) provides the distribution of residence times:

$$r(t) = -\frac{1}{m_o}\frac{dm}{dt} \tag{1}$$

By definition, the mean residence time is

$$\tau = \int_0^\infty r(t)t\,dt \tag{2}$$

which can be written alternatively as

$$\tau = -\frac{1}{m_o}\int_0^\infty \frac{dm}{dt}t\,dt = \frac{1}{m_o}\int_0^\infty m(t)\,dt \tag{3}$$

Thus τ is the first moment of r(t) or the zeroeth moment of m(t). Eq. 3 is used below to analyze the results of the instantaneous dye study. If the water body can be approximated as spatially well-mixed, the flushing is first order such that:

$$\frac{dm}{dt} = -k_f m \tag{4}$$

where the removal (flushing) rate, $k_f = rm_o / m$, and $m = m_o e^{-k_f t}$. Starting with the first equality of Eq. 3,

$$\tau = \int_0^\infty k_f e^{-k_f t} t dt = k_f^{-1} \tag{5}$$

3.2 Continuous release under steady and unsteady conditions

A continuous tracer can also be used to determine residence time. The most common tracer is freshwater, and the (fraction freshwater) approach is usually applied under the assumption of steady state conditions. Although an expression for residence time can be derived from temporal integration of the instantaneous source result above, it is more intuitive to begin with a steady state control volume analysis.

At steady-state, freshwater inflow to the control volume is balanced by flushing of freshwater, characterized by an effective flushing rate Q_{eff}:

$$Q_f = Q_{eff} \bar{f} \tag{6}$$

where $\bar{f}$ is the freshwater fraction defined in terms of the average salinity of the water body $\bar{S}$ and the ocean salinity S_{ocean} as

$$\bar{f} = \frac{S_{ocean} - \bar{S}}{S_{ocean}} \tag{7}$$

The residence time is defined as the volume of freshwater, V_f, divided by the inflow rate, or

$$\tau = \frac{\bar{f}V}{Q_f} = \frac{V}{Q_{eff}} \tag{8}$$

where V is the volume of the water body.

If the inflow rate Q_f (hence $\bar{f}$ and V_f) are not constant, then

$$\frac{d}{dt}V_f = Q_f(t) - Q_{eff}\bar{f}(t)$$

or

$$\frac{d}{dt}V_f = Q_f(t) - \frac{V_f}{\tau} \tag{9}$$

Q_f is often reported as a time series based on stream gauge measurements recorded at daily (or other time) intervals. Treating V and V_f (hence τ) as constants, the value of V_f resulting from a step change in Q_f at time t = 0 is

$$V_f(t) = V_f(o) + \tau[Q_f(t) - Q_f(0)]\{1 - \exp(-\frac{t}{\tau})\} \tag{10}$$

From Eq. 10 the response to an infinite series of step changes in Q_f, each lasting for time Δt, is

$$V_f(t) = \{1 - \exp(\frac{-\Delta t}{\tau})\}\tau\sum_{n=0}^{\infty} Q_f(t - n\Delta t)\exp(\frac{-n\Delta t}{\tau}) \tag{11}$$

It is easy to show that Eq. 11 converges to the correct steady state solution since, for constant Q_f, $V_f = Q_f\tau$, consistent with Eq. 8. The residence time in Eq. 11 can thus be written in the form:

$$\tau = \frac{V_f}{< Q_f >} \tag{12}$$

where $<Q_f(t)>$ is the value of the time series $Q_f(t)$ passed through an exponential filter defined by

$$< y(t) > = (1 - \alpha)\sum_{n=0}^{\infty} y(t - n\Delta t)\alpha^n \tag{13}$$

where α is a filter parameter equal, in the present context, to $\exp(-\Delta t / \tau)$. The filter weights α^n sum to one and provide decreasing weight to values of y (Q_f) as $n\Delta t$ increases. When the time series does not extend infinitely far back in time, the series sum may be approximated by terms going back to time t - $N\Delta t$, or

$$V_f(t) = \tau \frac{\sum_{n=0}^{N} Q_f(t - n\Delta t)\exp(\frac{-n\Delta t}{\tau})}{\sum_{n=0}^{N} \exp(\frac{-n\Delta t}{\tau})} \tag{14}$$

where the sum in the denominator of Eq. 14 replaces $[1 - \exp(\Delta t / \tau)]^{-1}$ in Eq. 11, guaranteeing that the filter weights sum to 1.

Properties of the exponential filter are discussed in standard textbooks (e.g., Koopmans, 1974) and use of exponential filters to interpret the transient response of first order systems such as cooling ponds is discussed in Adams and Kossis (1980), which also describes extensions to account for non-linear effects--in this context given by the fact that τ is technically time-varying.

4. Tracer Studies in Boston's Inner Harbor

Two field studies have been conducted to estimate the residence time of freshwater in Boston's inner harbor. One used freshwater as a tracer, whereas the more recent one used an instantaneous dye release.

4.1 Freshwater study (1951-52)

Bumpus *et al.* (1953) used the fraction freshwater method to estimate the residence time of freshwater within Boston's inner harbor on 10 dates in 1951 and 1952. On each date water samples were collected from three or four depths at six stations. Salinities were determined by the Knudsen method to compute freshness f, which was spatially integrated to determine the freshwater volumes of the inner harbor, V_f. See **Table 1**. Q_f was calculated using data from the Waltham gage on the Charles River, extrapolated to account for the additional drainage area downstream from the gage plus drainage areas associated with the Mystic and Chelsea Rivers. As indicated in **Figure 2**, the daily average flow rates were not steady during most of the studies; a cumulative method was used to determine the average flow rate $\overline{Q}_f$ during the indicated residence time. This is tantamount to computing τ through solution of:

$$V_f(t) = \int_{t-\tau}^{t} Q_f(t')dt' \tag{15}$$

Average flow rates $\overline{Q}_f$ and computed residence times τ from Eq. 15 are indicated in Table 1.

As an alternative, we also present in Table 1 the exponentially filtered flow rates $\langle Q_f \rangle$, and associated residence times from Eq. 12. Results from both calculations are similar, yielding residence times of about 2 to 10 days as freshwater inflow decreases from about 34 m^3/s to less than 2 m^3/s. τ versus $\langle Q_f \rangle$ is plotted in **Figure 3**, and has been fit with a linear inverse relationship, using $\langle Q_f \rangle$ in m^3/s and τ in days:

$$\tau = 1.158 + 12.88/\langle Q_f \rangle \qquad (r^2 = 0.94) \tag{16}$$

By contrast, r^2 for the corresponding relationship between τ and $\overline{Q}_f$ was 0.90, suggesting a slight preference for use of the exponential, rather than the average, filter to treat the variable inflow. Theoretically, the exponential filter is appropriate for well-mixed water bodies, while the average filter apply to plug flow. Spatial distributions of dye concentration associated with the instantaneous dye release (described below), suggest that the harbor is neither well mixed nor plug flow, but the associated residence time distribution suggests the harbor flushes more like a well-mixed water body, further supporting use of the exponential filter.

For comparison, Asselin and Spaulding (1993) used measurements of both instantaneous and continuous tracer concentration to analyze the effect of freshwater inflow on the residence time of the Seekonk and Providence Rivers. Assuming steady inflow, they found the following exponential fit for data on the two rivers combined:

$$\tau = 9.02 \exp(-0.0217\, Q_f) \qquad (r^2 = 0.89)$$

An exponential fit to the Boston Harbor data gave

$$\tau = 5.01 \exp(-0.0393 \langle Q_f \rangle) \quad (r^2 = 0.57)$$

4.2 Dye study (1992)

During July 1992 Aquatec, Inc. (Colchester, VT) and MIT conducted a fluorescent tracer study to monitor the transport of Charles River water in Boston's inner harbor (Aquatec, Inc., 1993; Adams *et al.* 1993). 501 pounds (227 kg) of 20% solution of Rhodamine WT (specific gravity 1.03) were released into the forebay of the upper level sluice at the Charles River Dam as freshwater was being discharged. Both dye and freshwater were released at constant rates for 5.5 hours surrounding low tide which occurred at 23:37 on 22 July. Based on sluice calibration curves, a total of 3.9×10^5 m^3 of freshwater was released over the about 5.5 hours. This was a dry period of time (Charles River flow was approximately 2 m^3/s at the Waltham gauge immediately prior to and during the survey), and no other freshwater was released from about 18 hours prior to the start of dye release until about 36 hours after the end of dye release. Freshwater discharges from the Charles and Mystic Rivers during the study are indicated in **Figure 4**.

A boat with flow-through fluorometer measured fluorescence, temperature and conductivity (from which salinity and dye concentration were computed) at depth intervals of 30 cm at about 30 stations throughout the inner harbor. Thirteen surveys were conducted of approximately two hours' duration each surrounding daytime low and high tides over the six-day period of 23-28 July. Two earlier surveys were conducted to assess background fluorescence.

Horizontal contours of dye concentration showed that, after 40 hours, the dye was laterally mixed across the harbor. Longitudinal-vertical contours showed that the dye was initially concentrated near the water surface at the dam, but gradually spread longitudinally and vertically.

After six days, dye concentrations in the longitudinal direction showed a monotonic decrease from head to mouth and were nearly, but not completely, vertically well-mixed.

For each survey, dye concentrations were integrated spatially to arrive at total dye mass within the inner harbor, m(t), which is plotted in **Figure 5**. Except for the first two surveys, where high concentration gradients precluded accurate spatial integration, m(t) decreased monotonically. Although the dye was not completely mixed in either the vertical or longitudinal direction, the shape of m(t) approximated a declining exponential, suggesting that removal occurred as if the dye were in fact well-mixed. m(t) was extrapolated to large times by fitting a declining exponential to data starting 59 hours after initial tracer release and the extrapolated data were integrated using Eq. 3 to give a residence time of 3.75 days. This point is plotted on Fig. 3, using a freshwater inflow of 3.9 m^3/s, computed as the Charles River flow averaged over the six days following the dye release, and divided by 0.82 to account for the combined drainage area. The residence time of 3.75 days is close to the corresponding value from Bumpus *et al.*.

4.3 Additional discussion

The residence times computed from the tracer studies can be compared with theoretical estimates. Ketchum (1951b) calculated a residence time of 6 days for inner harbor water between the Charles River and the mouth using his modified tidal prism technique (Ketchum, 1951a). This is a theoretical method which assumes complete mixing within harbor segments of length equal to the local tidal excursion. Another residence time estimate, often used as a lower bound, is the simple tidal prism method

$$\tau = \frac{VT}{P} \tag{17}$$

where V is taken as the high tide volume of the inner harbor, P is the intertidal or tidal prism volume of the inner harbor, and T is the tidal period (12.4 hr). Using $V = 7.8\times10^7$ m^3 and $P = 2.2\times10^7$ m^3 yields a tidal prism residence time of 1.8 days. This is a lower bound because it assumes that the dye is well mixed over the inner harbor volume and that none of the dye that leaves the harbor on ebb tide returns on the following flood tide (Sanford, et al., 1992).

An effective flushing rate $Q_{eff} \cong 250$ m^3/s was computed from Eq. 8 using V = 7.8x10^7 m^3. The transport of a continuously discharged contaminant equals the flushing rate times the average pollutant concentration. In an average summer (July-Sept.) freshwater flow at the Charles River Dam is about 4.3 m^3/s. Therefore mixing within the inner harbor can be expected to dilute the average concentration of a conservative substance entering with the Charles River inflow by a factor of about 250/4.3 $\cong$ 60. Applying the same analysis to the freshwater data using Eq. 16 yields an expression for inner harbor dilution, S, as a function of freshwater flowrate (m^3/s)

$$S = \frac{780}{Q_f + 11.1} \tag{18}$$

For conditions studied by Bumpus *et al.*, Eq. 18 indicates that inner harbor dilution decreases from about 60 to about 17 as freshwater inflow increases from about 2 m^3/s to about 34 m^3/s.

The dye data can also be applied to the fate of non-conservative substances by first computing the residence time distribution r(t) from the mass distribution m(t) using Eq. 1. Because m(t) based on individual surveys is "noisy", r(t) has been computed in **Figure 6** from an exponential fit to the data in Fig. 5 following the third survey. Also shown as broken lines on Fig. 6 are first-order decay curves [exp(-kt)] corresponding to k = 1, 2 and 3 per day (half lives of 0.69, 0.35 and 0.23 days, respectively). These values were chosen because model calibration against field measurements of fecal coliform (Hydroscience, 1973; CDM, 1989; Adams *et al.*, 1992) has suggested that the disappearance rate of fecal coliforms in Boston Harbor ranges from 1-3 per day. The fraction of fecal coliform which enter with the Charles and survive passage through the harbor is

$$F = \int_0^\infty e^{-kt} r(t)dt \tag{19}$$

Using k = 1, 2 and 3 per day yields values of F = 0.01, 0.03 and 0.12. These values support the mathematical simulations of Adams and Zhang (1991) who found that the major CSO impact on the outer harbor was from (nearby) outer harbor CSOs rather than the larger but more distant inner harbor CSOs.

5. Numerical model study

To better understand the transport of freshwater in the inner harbor, the 3-D finite difference model ECOMsi was employed (Blumberg and Mellor, 1987; HydroQual, Inc., 1991). The model was first used to simulate the 1992 dye study, and then used to simulate effects of variable freshwater inflow rate and timing (continuous vs. intermittent). Model application and results are briefly summarized below with more information available in Chan (1995).

5.1 Model description and results

ECOMsi solves the primitive equations of motion along with equations for temperature, salinity and passive tracer concentration using a sigma coordinate transformation in the vertical. Hydrostatic pressure is assumed and vertical diffusion coefficients are calculated using the Mellor and Yamada (1982) second order closure scheme as modified by Galperin *et al.* (1988).

Figure 7 shows the schematic prismatic grid, set-up to capture the essential features of Boston's inner harbor, and enough of the outer harbor to allow for a realistic return of dye during flood tide. The domain shape was half of a "T" with the full "T" having length, depth and width equal to corresponding average dimensions in the inner harbor. Use of half a "T" reduced computational time, requiring that Coriolis forces be omitted, and that freshwater and tracer loading be reduced by 50%. (For clarity, however, all reported flows and loads correspond to the full domain.) The open boundary at the top of the "T" was forced with a constant M_2 tide with 1.5 m amplitude, and uniform phase. All other boundaries were closed and there no surface wind stress was applied.

Model simulations were run for 168 hours using a time step of one minute. Forcing functions were ramped to steady-state using a time constant of 90 minutes. The non-dimensional bottom friction coefficient (one-eighth of the Darcy-Weisbach friction factor) was 0.0025, the bottom roughness coefficient was 0.003 m, and the horizontal diffusivity was 2 m^2/s. A constant value of background vertical diffusivity (5×10^{-5} m^2/s or about 50 times molecular) was added to the closure model-predicted diffusivity during calibration (see following discussion). Freshwater from the Mystic and Charles Rivers were simulated. Each was assumed to have zero salinity and ambient temperature. (Initial temperature and salinity distributions were uniform.) The Mystic River discharge was delivered to the surface layer at the upstream portion of the grid, while the Charles River discharge was delivered to the surface layer near the modeled dam. See Fig. 7.

Table 2 summarizes 9 simulations. The base case simulated the actual intermittent Charles River discharge experienced during the dye study (Fig. 4). The model was started from rest and allowed to run for about 1.7 tidal cycles before the initial 5.5 hour freshwater release of 20 m^3/s began at a model time of 20.7 hours. A conservative tracer of concentration 117 μg/l was included with this initial freshwater injection. This first discharge corresponded to 4×10^5 m^3 of freshwater and 46 kg of pure dye, and the average freshwater flow during the 147 hour model simulation was 3.2 m^3/s.

For each run the total tracer mass in the inner harbor, the outer harbor and the total domain were calculated every 8 hours and plotted versus time. **Figure 8** shows results for the base case. Mass in the inner harbor declined nearly monotonically, with shape similar to observed mass decline which has been overlain. Mass in the outer harbor showed a corresponding increase with time, indicating that total mass was conserved. Residence times were calculated from Eq. 3 and are summarized in Table 2.

5.2 Calibration of background diffusivity

The only parameter varied for purposes of model calibration was the background diffusivity, which was selected in consideration of simulated vertical structure and residence time. **Figure 9** compares measured vertical dye concentration profiles 34 hours after the start of tracer injection with model predictions using background diffusivities of 5 x 10^{-5} m^2/s and 7.5 x 10^{-5} m^2/s. The solid lines represent average measured concentrations from three or four adjacent locations, while the dashed and dash-dot lines represent model output at the nearest grid point. Fig. 9a) suggests that the model underestimates total mass somewhat above the Charles River, and does not produce the subsurface concentration maximum apparently caused by freshwater overriding the denser, diluted, tracer. The remaining parts of Fig. 9 suggest that the model-data comparison improves with distance down the harbor, although there appears to be too much vertical mixing.

Table 2 summarizes the computed residence times. With the base case background diffusivity of 5 x 10^{-5} m^2/s , the model gave a somewhat shorter residence time (3.26 d) compared with the dye data (3.75 d). Increasing background diffusivity to 7.5 x 10^{-5} m^2/s resulted in longer residence time (3.95 days), but overpredicted vertical mixing even more, while lower values of background diffusivity underpredicted both residence time and vertical mixing. The base case diffusivity of 5 x 10^{-5} m^2/s was thus chosen as a compromise between matching observed residence time and vertical mixing.

5.3 Model sensitivity

Rather than discharging freshwater intermittently, freshwater could theoretically be released at high tide or continuously. One run was performed for a high tide release and five simulations were carried out with continuous releases. The high tide scenario released freshwater periodically during the 2 hours surrounding every high tide. The flow rate during each two hour release was 20.0 m^3/s such that the average flow rate during the simulation was 3.2 m^3/s, the same as the base case run. Tracer was added to the first high tide release, and residence times were referenced to the beginning of the tracer release. The continuous releases involved steady releases of freshwater from t = 21 hours until the end of the simulation. Flow rates ranged from half of the base case to ten times the base case (1.6 to 32 m^3/s), and tracer was added over the first 5.5 hours of the freshwater release. Table 2 indicates that discharging freshwater at high tide reduces the residence time, as expected, but the difference in residence time between the low tide and high tide release (0.07 days) is small. Discharging continuously results in a further slight decrease in residence time, presumably because of increased vertical stability leading to lower vertical diffusivity and faster flushing. However, again the difference is not of practical significance.

Simulated residence times for runs with continuous flow are plotted in Fig. 3 in comparison with field measurements. The model reproduces the trend of decreasing residence time with increasing flow indicated by the freshwater measurements, though it underpredicts residence time at low flows.

Table 2 indicates that computed residence times are sensitive to background diffusivity which calls into question the turbulence closure model. To explore whether the turbulence model produces enough mixing in the near-surface layers, the vertical profiles of vertical diffusivity (K_h, without any added background diffusivity), longitudinal velocity (u) and tracer concentration (c) were examined at several locations. **Figure 10** indicates that modeled K_h is much greater than background at t = 8 hours, before any discharge of Charles River water has occurred; under these conditions background diffusivity is overshadowed by the closure model-predicted diffusivity. At t = 80 hours, this is still the case in the lower portions of the water column, but in the upper portions of the water column (which have maximum salinity and concentration gradients) the modeled K_h were near zero. It appears that the closure model predicts diffusivities that are several orders of magnitude smaller than background at the critical depths which govern vertical transport of freshwater and tracer. To the extent that a constant background diffusivity is added to the closure model-predicted diffusivity, model sensitivity to changing freshwater flow may not be truly predictive. This may also explain the somewhat milder than observed dependence of model residence time on flow rate.

6. Conclusions

Two field tracer studies and a series of numerical model experiments have been used to analyze the residence time of freshwater in Boston's inner harbor. The following conclusions have been reached:

- Use of an exponential filter with time-variable freshwater inflow provides a rational way to apply the fraction freshwater approach under transient conditions. Re-analysis of data from Bumpus *et al.* (1953) using the modified fraction freshwater approach showed residence time and filtered freshwater inflow rate to be inversely related (Eq. 16), with residence times decreasing from about 10 days to less than 2 days as (filtered) freshwater inflow rates increased from less than 2 m^3/s to about 34 m^3/s. Similar inverse relationships have been found for other water bodies.

- Analysis of an instantaneous fluorescent dye study, conducted under summertime low flow conditions, gave a residence time of about 3.75 days, consistent with results of the modified fraction freshwater approach. Under these conditions, conservative contaminants contained in the freshwater would be diluted by a factor of 50-60 as they are transported through the inner harbor. The concentrations of fecal coliforms, indicator bacteria used to assess compliance with swimming and shell fishing standards, would be reduced further through die-off and/or settling. Assuming first order disappearance rates of 1-3 per day, based on previous numerical model calibrations, results in fractional disappearance of 99 to 88%, suggesting that high fecal coliform counts historically found in the outer harbor are most likely due to local (rather than inner harbor) sources. While measurements indicated that the dye was not uniformly distributed in either the vertical or longitudinal direction, the residence time distribution suggested that flushing could approximated as if the inner harbor were in fact well-mixed.

- A three-dimensional numerical model was used to simulate the transport of freshwater plus a conservative tracer in a schematized domain representing the inner and outer harbors. After modest calibration of the background vertical diffusivity, the model was able to reproduce reasonably well the distribution of vertical dye concentration and residence time found in the summertime dye study. Simulations with different steady freshwater inflow rates showed similar dependence on freshwater inflow rate as indicated by the data of Bumpus *et al.*, though the modeled times were shorter than observed during low flow. However, because the background value of vertical diffusivity was only calibrated under one flow condition, model predictions may not be truly predictive for widely different flow. Simulations showed only modest sensitivity to the timing of the freshwater release, suggesting slightly shorter residence times for water released at high tide vs. low tide, and slightly shorter residence times still for freshwater released continuously, as opposed to intermittently at either high or low tide.

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Table 1

Analysis of measurements from Bumpus *et al.* (1953)

Date	V_f ($m^3 x 10^6$)	$\overline{Q}_f$ (m3/s)	$\langle Q_f \rangle$ (m3/s)	τ[1] (day)	τ[2] (day)
May 1951	2.28	13.9	14.2	1.9	1.9
June 1951	2.08	11.4	11.4	2.1	2.1
Aug 1951	1.66	6.6	6.5	2.9	3.2
Sept 1951	1.83	4.2	3.7	5.1	4.9
Nov 1951	4.05	24.7	24.9	1.9	1.9
Feb 1952	3.73	18.8	18.7	2.3	2.3
Apr 1952	4.63	33.6	33.5	1.9	1.9
July 1952	1.12	2.9	2.9	4.4	3.9
Aug 1952	1.50	4.0	4.6	4.3	3.9
Oct 1952	1.64	1.9	1.5	10.2	10.5

[1] computed from average filter (Eq. 15).

2 computed from exponential filter (Eq. 12).

Table 2

Summary of model simulations and calculated freshwater residence times.

Discharge scenario	Ave. Charles River flow rate (m^3/s)	Background vertical diffusivity (m^2/s)	Residence time (days)
low tide	3.22	5×10^{-5}	3.26
low tide	3.22	2.5×10^{-5}	2.41
low tide	3.22	7.5×10^{-5}	3.97
high tide	3.22	5×10^{-5}	3.19
continuous	1.61	5×10^{-5}	4.22
continuous	3.22	5×10^{-5}	3.12
continuous	6.43	5×10^{-5}	2.54
continuous	16.1	5×10^{-5}	2.04
continuous	32.1	5×10^{-5}	1.62

List of Figures

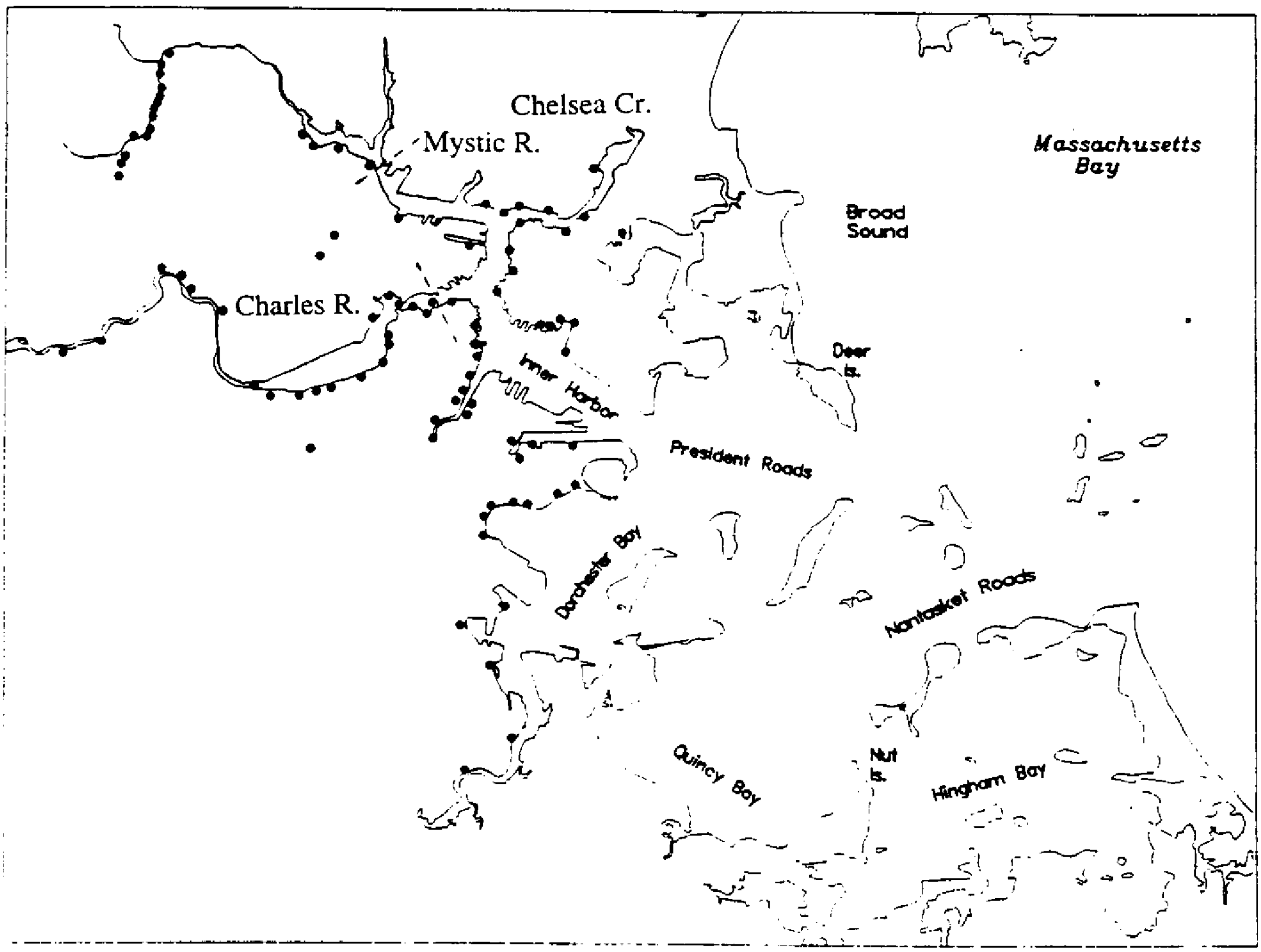

Chelsea Cr.
Mystic R.
Massachusetts Bay
Broad Sound
Charles R.
Deer Is.
Inner Harbor
President Roads
Dorchester Bay
Nantasket Roads
Quincy Bay
Nut Is.
Hingham Bay

Fig 1

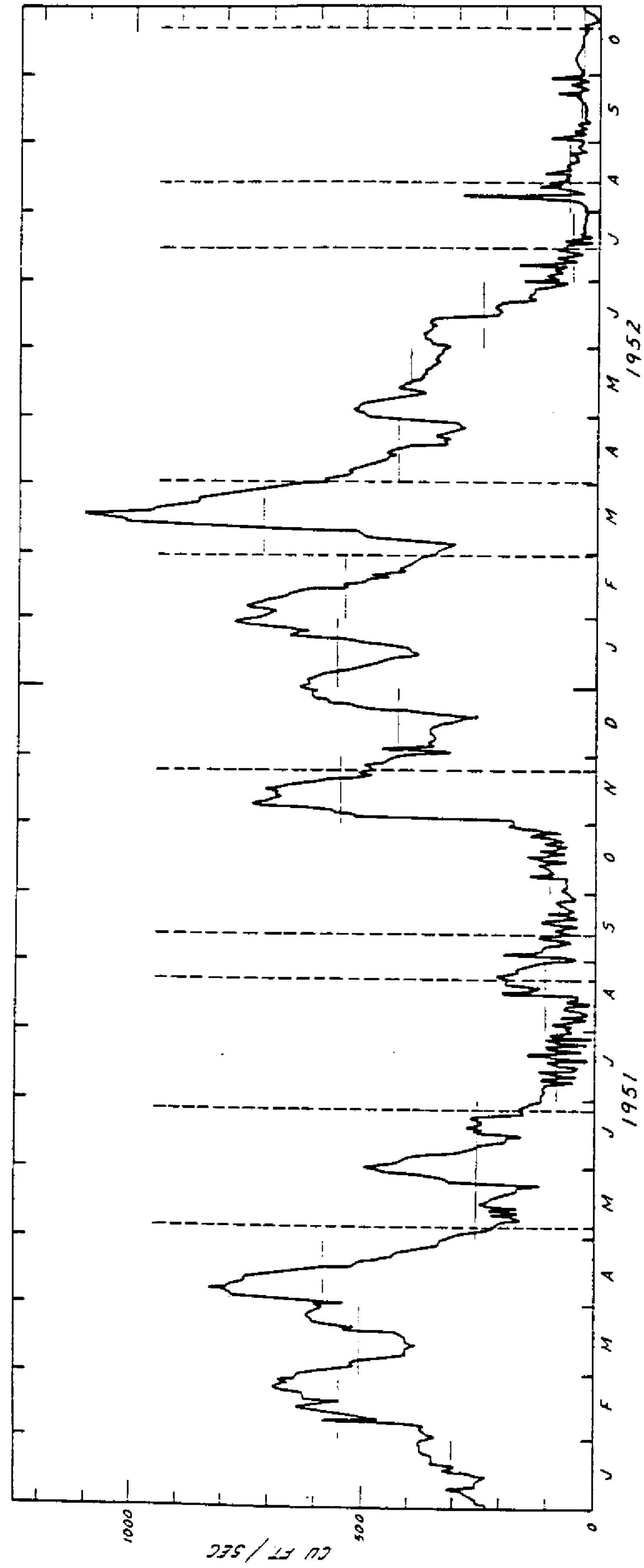
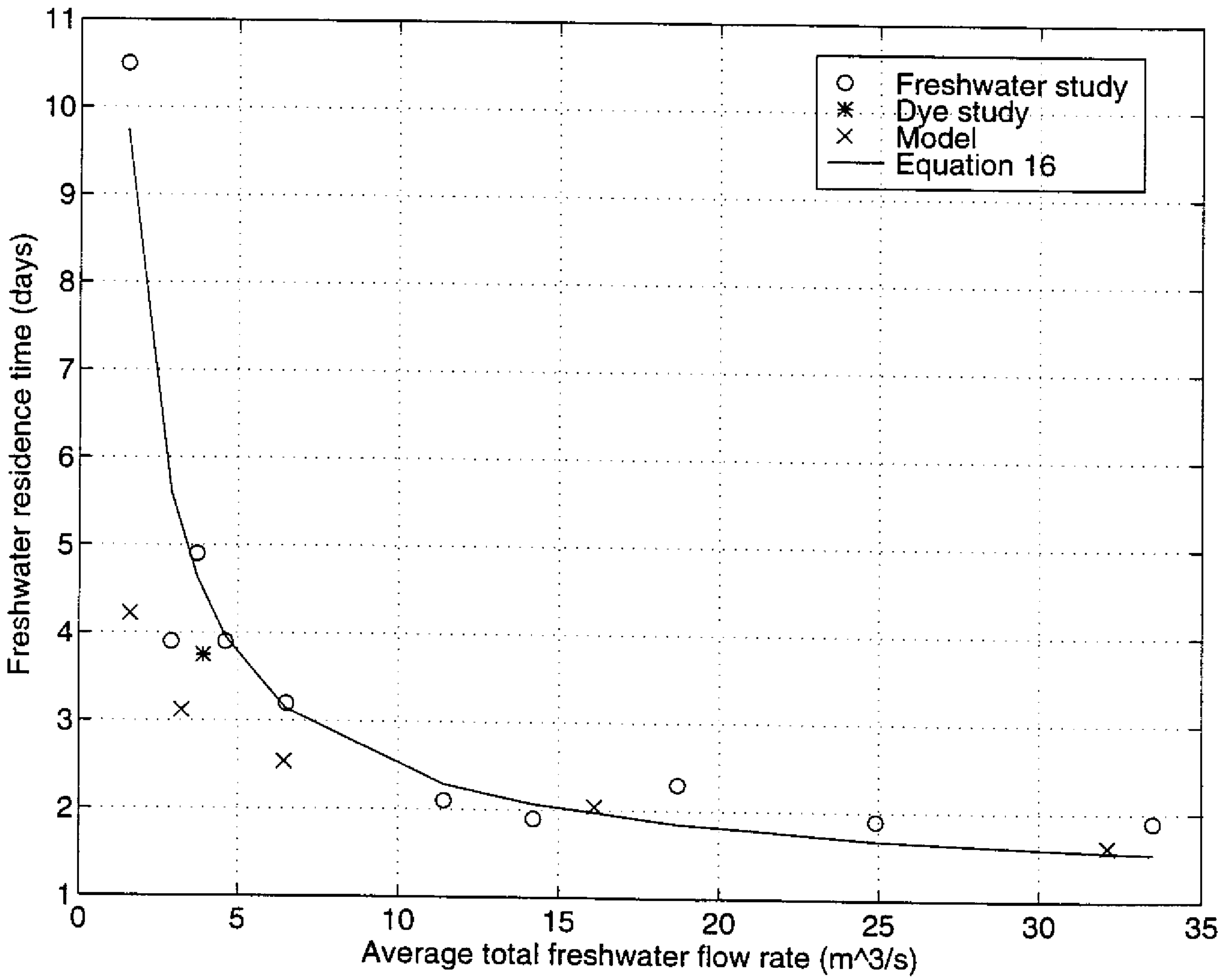
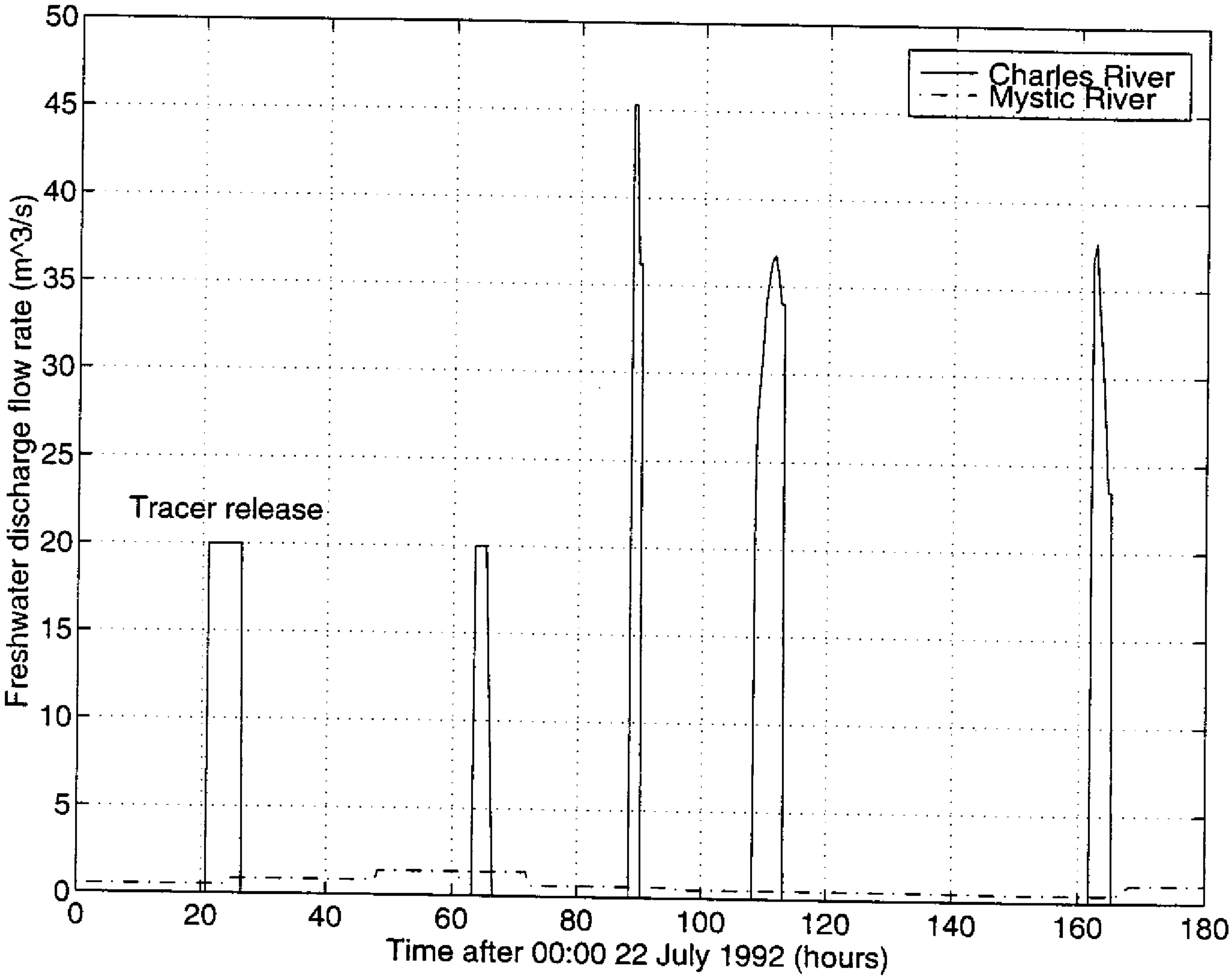


Fig 2



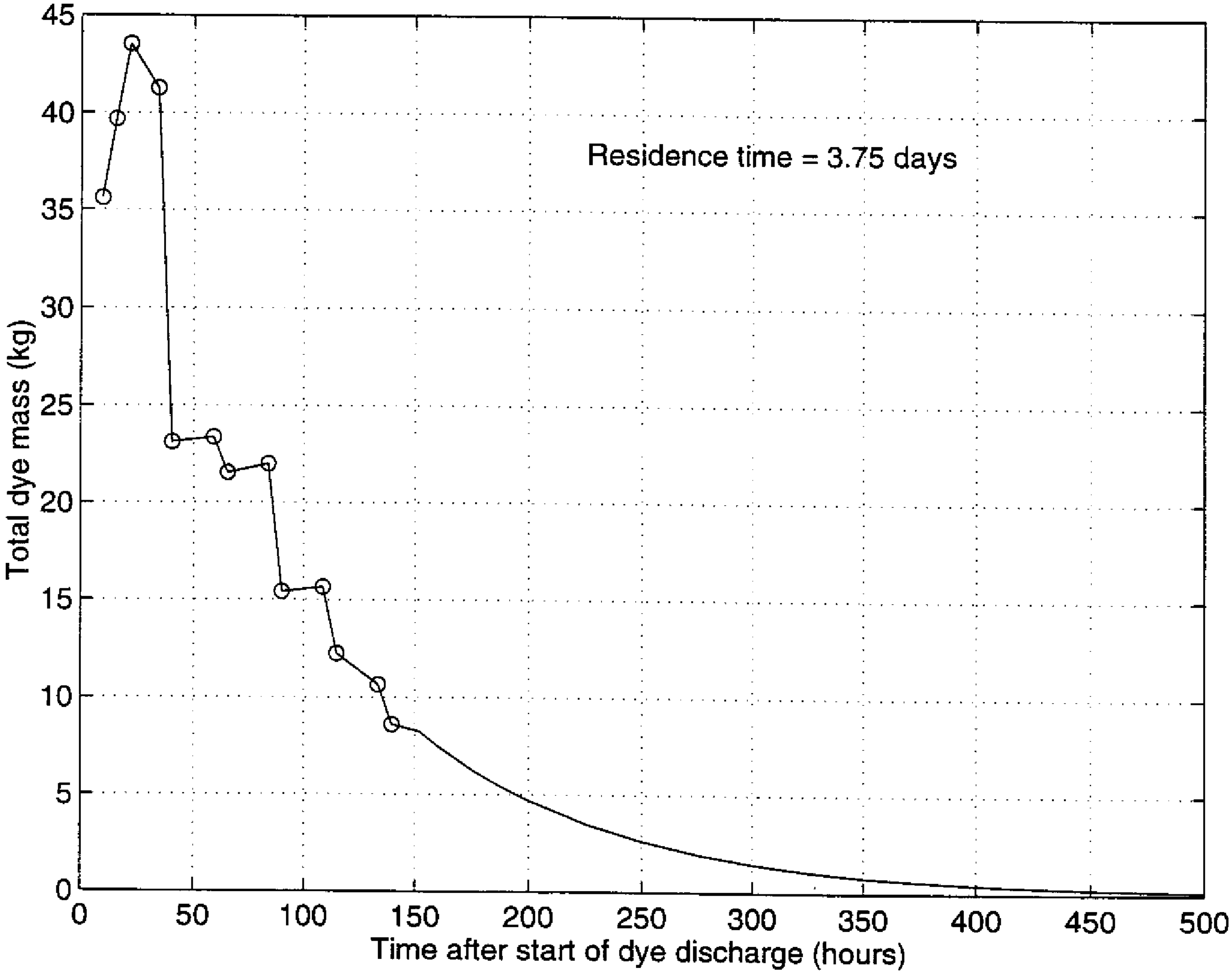
Freshwater study
Dye study
Model
Equation 16
Freshwater residence time (days)
Average total freshwater flow rate (m^3/s)
11
10
9
8
7
6
5
4
3
2
1
0
5
10
15
20
25
30
35

Fig 3



Charles River
Mystic River
Tracer release
Freshwater discharge flow rate (m^3/s)
Time after 00:00 22 July 1992 (hours)
0
5
10
15
20
25
30
35
40
45
50
0
20
40
60
80
100
120
140
160
180

Fig 4



Residence time = 3.75 days
Total dye mass (kg)
Time after start of dye discharge (hours)
0
5
10
15
20
25
30
35
40
45
0
50
100
150
200
250
300
350
400
450
500

Fig 5

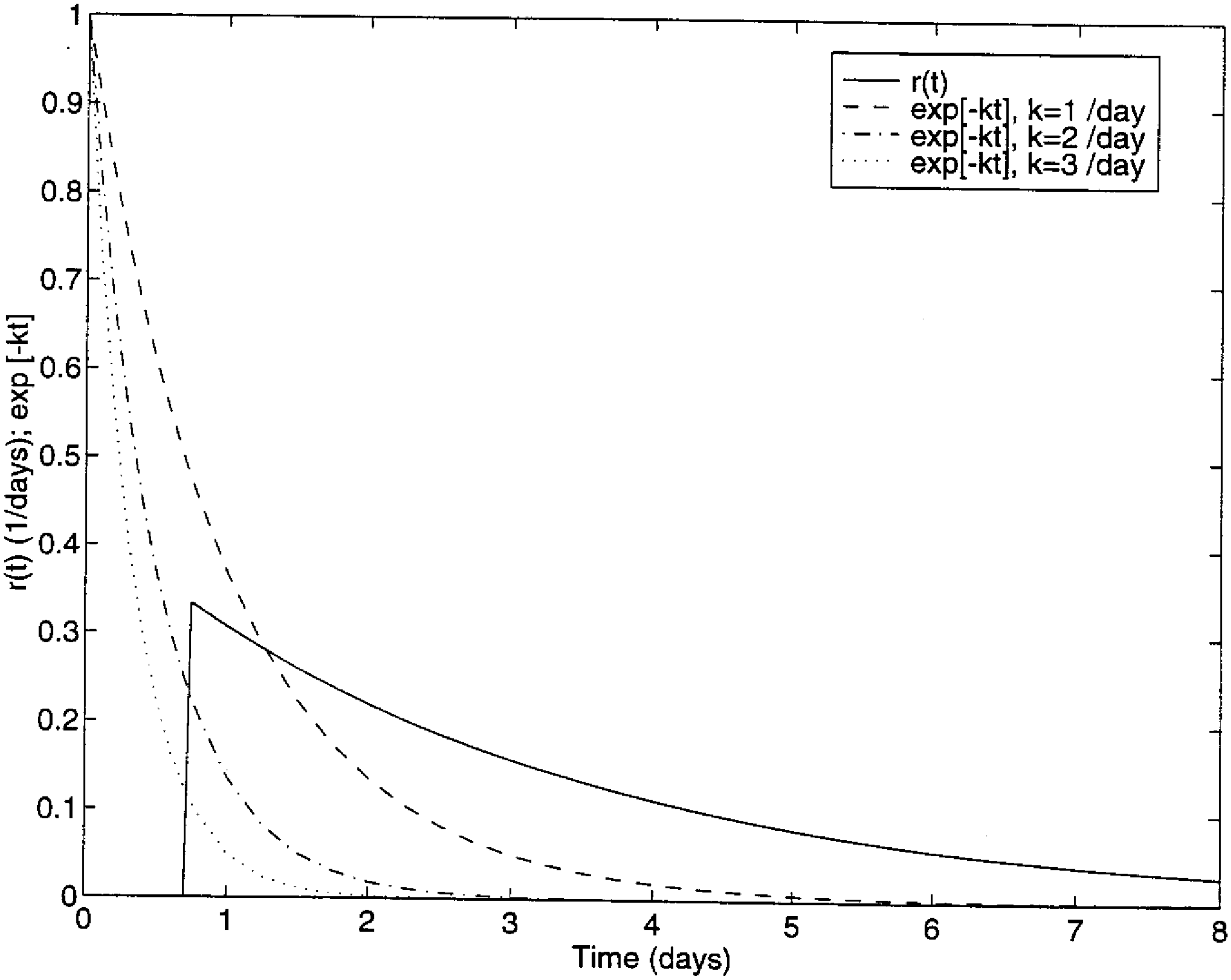

r(t)
exp[-kt], k=1 /day
exp[-kt], k=2 /day
exp[-kt], k=3 /day
r(t) (1/days); exp [-kt]
Time (days)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
2
3
4
5
6
7
8

Fig 6

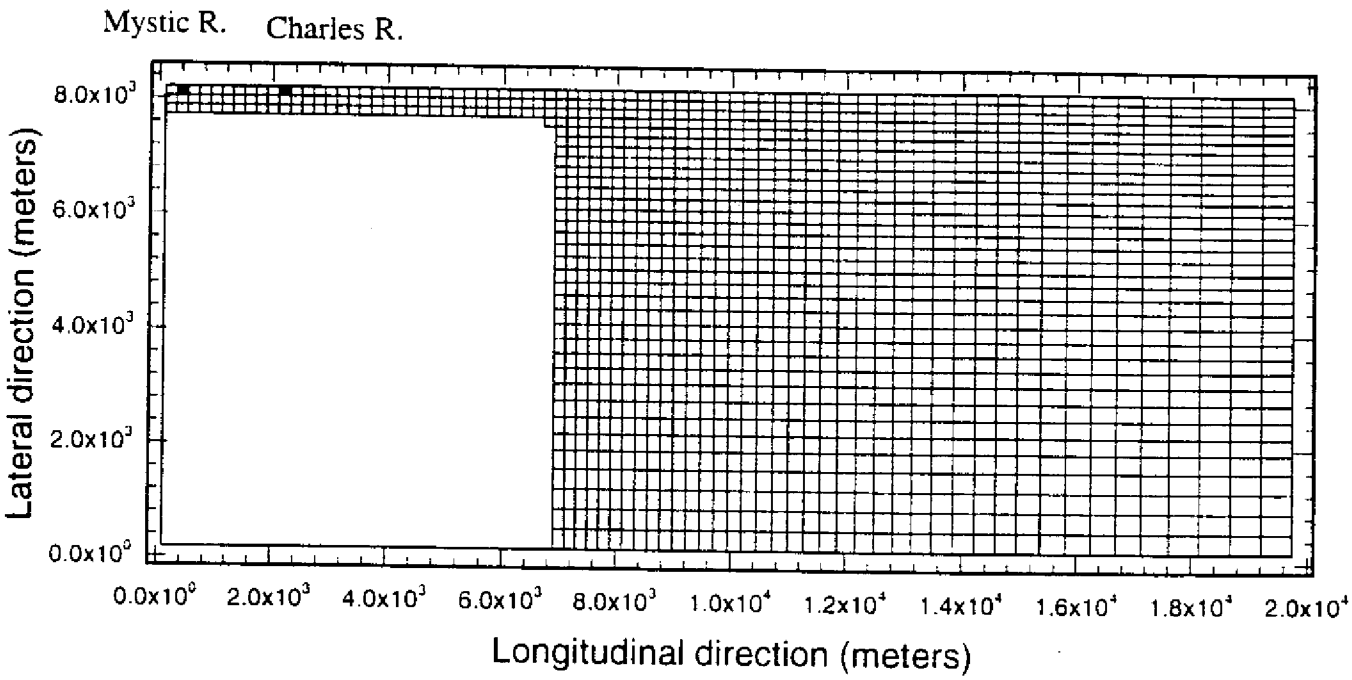
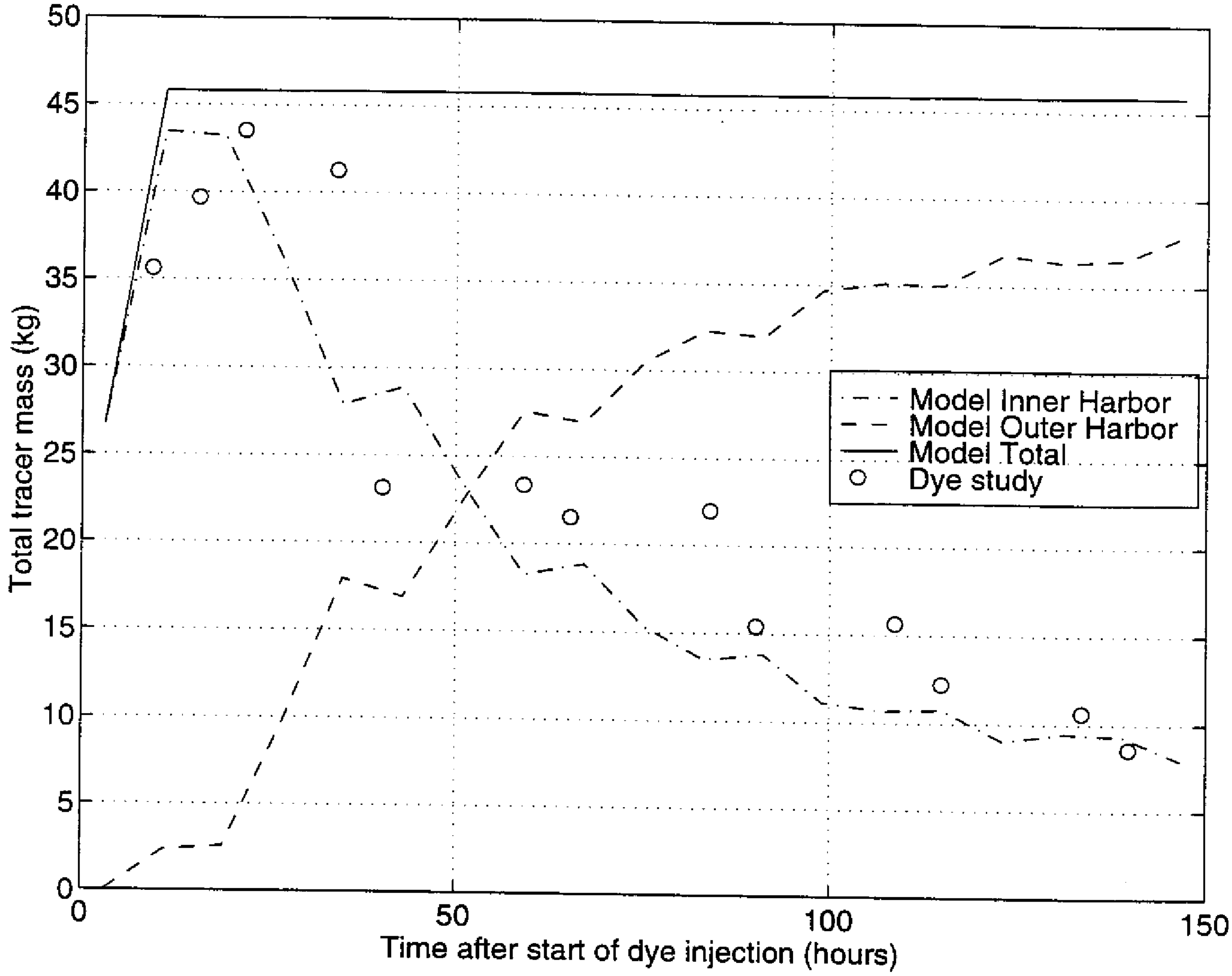

Mystic R.
Charles R.
Lateral direction (meters)
8.0x10³
6.0x10³
4.0x10³
2.0x10³
0.0x10⁰
0.0x10⁰
2.0x10³
4.0x10³
6.0x10³
8.0x10³
1.0x10⁴
1.2x10⁴
1.4x10⁴
1.6x10⁴
1.8x10⁴
2.0x10⁴
Longitudinal direction (meters)

Fig 7



Model Inner Harbor
Model Outer Harbor
Model Total
Dye study
Total tracer mass (kg)
Time after start of dye injection (hours)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150

Fig 9

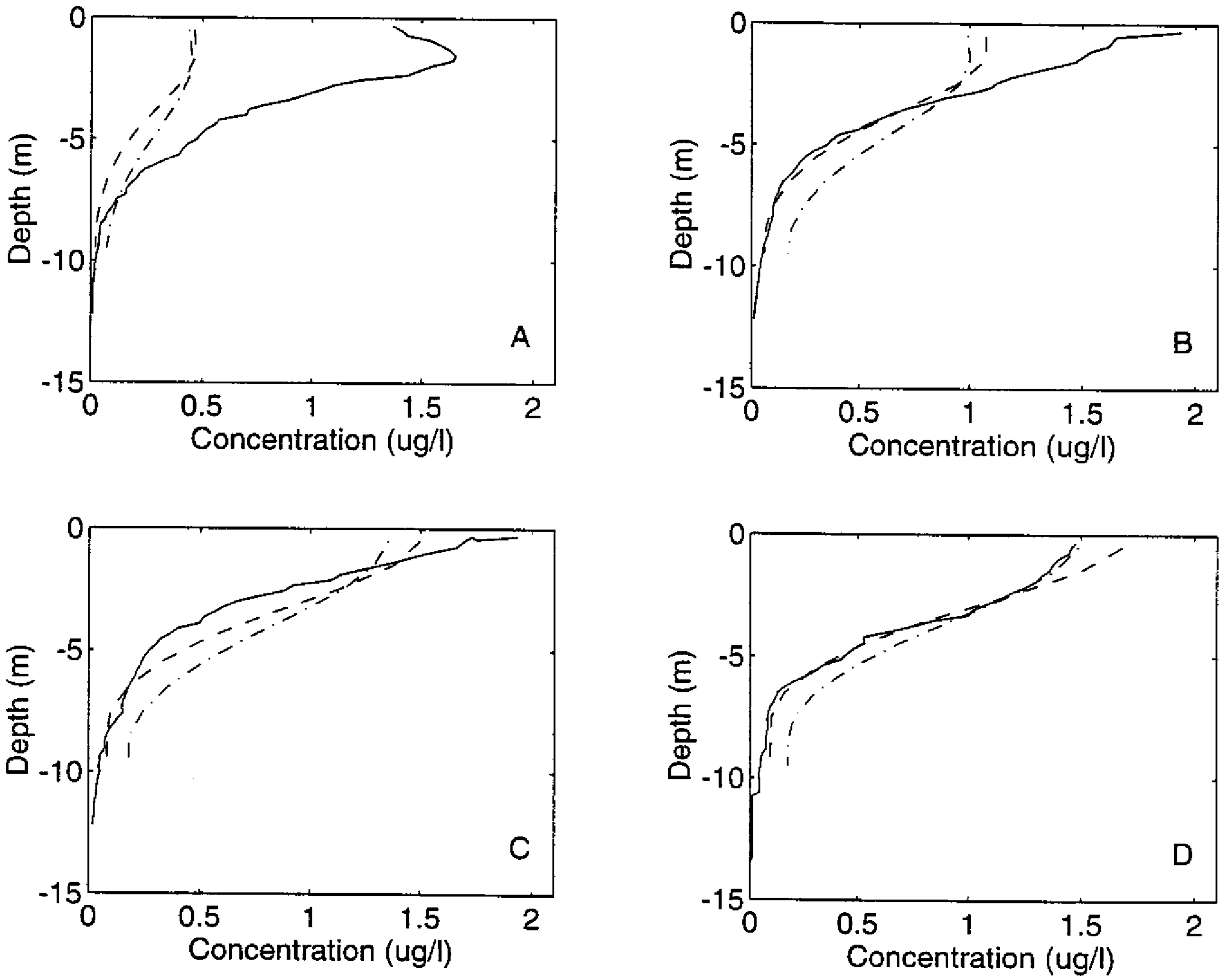


Fig 9

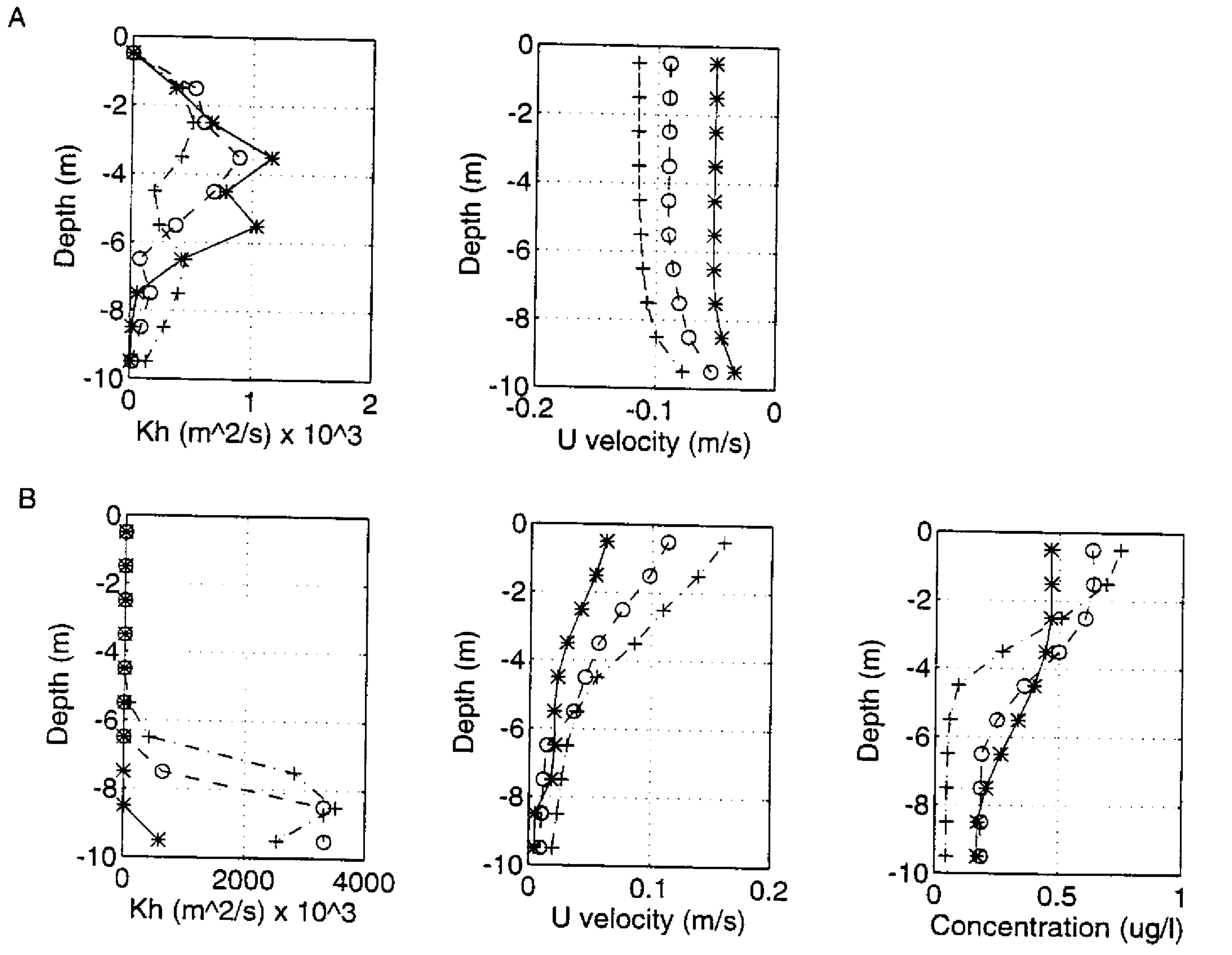

A
Depth (m)
Kh (m^2/s) x 10^3
Depth (m)
U velocity (m/s)
B
Depth (m)
Kh (m^2/s) x 10^3
Depth (m)
U velocity (m/s)
Depth (m)
Concentration (ug/l)

Fig 10