# Analysis of Boston Inner Harbor Dye Study

submitted to

Massachusetts Water Resources authority

by

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Summary

During July 1992 a fluorescent dye study was conducted in Boston's Inner Harbor in support of MWRA's System Master Planning Combined Sewer Overflow (CSO) program. Approximately 500 pounds of 20% Rhodamine WT dye were released over a period of $5\frac{1}{2}$ hours into the Charles River just upstream of its entrance to the Inner Harbor at the Charles River Dam. Dye concentrations were recorded throughout the Inner Harbor over the following six days. After the first day, dye was reasonably well mixed laterally, but showed decreasing concentration with depth and distance toward the mouth. The mean residence time of Charles River water in the Inner Harbor, computed from the time variation of total dye recovery, was in the range of 3.5 to 4 days, suggesting that about half of the freshwater leaving the Inner Harbor during ebb tide returns during flood tide. Fecal coliform are often used as indicators of sewage pollution. Reported half lives of fecal coliform, determined by calibrating models to field measurements in Boston Harbor, fall in the range of 0.2 to 0.7 days—significantly shorter than the mean residence time. This suggests that most bacteria entering the Inner Harbor with the Charles River inflow, or from nearby CSOs, die by the time they reach the Outer Harbor.

Background

During July 1992 Aquatec, Inc., and MIT conducted a fluorescent tracer study in Boston's Inner Harbor. The survey was conducted in support of the Massachusetts Water Resources Authority's (MWRA) System Master Planning and Combined Sewer Overflow (CSO) program and was designed to improve understanding of residence times and flushing rates of Charles River water within the Inner Harbor. As such, the study was intended to complement recent field measurements collected on the smaller scale of Fort Point Channel (Adams and Stolzenbach, 1992) and several field studies (Kossik et al., 1986; Adams et al., 1987; Kelly, 1991; Sung, 1991; Shea and Kelly, 1992) and theoretical studies (Ketchum, 1951b; Hydroscience, Inc., 1973; Lee, 1990; Signell and Butman, 1992) conducted on the larger scale of Boston's Outer Harbor. Dye was released at the confluence of the Charles River and the Inner Harbor because the Charles is the major source of freshwater to the harbor (Menzie et al., 1991) and because the river contains high concentrations of pollutants (including CSO sources).

In order to maintain a near constant water level in the Charles River basin, freshwater is usually released by gravity to the Inner Harbor every tidal cycle for a period of time surrounding low tide. Both an upper and lower sluice gate are available at the dam for this purpose. During our survey, we released 501.2 pounds of 20% solution Rhodamine WT (specific gravity 1.03) into the forebay of the upper level sluice as freshwater was being released; see Figure 1. Dye was delivered at a constant rate from 20:35 on the evening of 22 July to 02:00 on the morning of 23 July. Low tide was at 23:37 on 22 July. The $5\frac{1}{2}$-hour release coincided as closely as possible with the release of Charles River water for this tidal cycle; i.e., we tagged all of the river water released during the tidal cycle. (The low level sluice was not used during this cycle.) Based on calibration curves supplied by N. Winter at the dam, we estimate that a near constant freshwater flow rate of 20 $m^3/s$ (700 cfs) was delivered during this interval, corresponding to a total of $3.9 \times 10^5 m^3$ of freshwater over the

$5\frac{1}{2}$ 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 our survey), and hence freshwater was not released through the sluices during the tidal cycles immediately prior to or following dye release. (Small quantities of Charles River water were discharged to the Inner Harbor, however, to operate the fish ladder.) Prior to the dye survey freshwater was last released through both sluices from 19:00 on 21 July to 02:30 on 22 July. The next release of freshwater following the dye survey was from 14:00 to 16:00 on 24 July. Hence there was an interval of about 18 hours with essentially no freshwater inflow prior to our experiment and an interval of about 36 hours with no freshwater inflow following our experiment.

A boat with a flow-through fluorometer was used to measure fluorescence, temperature, and conductivity (from which salinity and dye concentration were computed) at depth intervals of approximately one foot from surface to bottom at approximately 30 stations throughout the Inner Harbor (Figure 1). 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 also conducted to assess background fluorescence. Details concerning the measurements and calibration are contained in the appendix (Aquatec, 1993).

Data Presentation

Figure 2 displays longitudinal-vertical sections of dye concentration along a transect extending from Chelsea Creek to the Inner Harbor mouth. In this and subsequent discussion, dye concentration is represented in $\mu g/\ell$ of pure Rhodamine WT. Contouring was accomplished using SURFER software (Golden Software, Inc., Golden, Colorado) by first projecting measured concentration to a regular 600-foot (horizontal) by 1-foot (vertical) grid using inverse-distance-squared weighting and then fitting a 2-D quadratic surface. The vertical sections indicate that the dye is initially concentrated near the surface at the confluence with the Charles River and gradually spreads longitudinally and vertically. After six days the dye is nearly, but not completely, vertically well mixed.

Figure 3 displays horizontal contours of near-surface dye concentrations. Contouring was performed by hand. After a few surveys, the data indicate that dye is reasonably well distributed laterally, across the Inner Harbor and between Mystic River and Chelsea Creek upstream. A gradient of decreasing concentration toward the Inner Harbor mouth is also clearly seen.

For each survey, dye concentrations were integrated spatially to arrive at total dye mass within the Inner Harbor, which is plotted in Figure 4, as a function of time. Except for the first two surveys, where high concentration gradients probably precluded an accurate spatial interpretation, the mass showed the expected monotonic decrease over time. Note that the injected mass was 100.2 pounds.

## Interpretation

As demonstrated in Adams and Stolzenbach, 1992, the mean Inner Harbor residence time of dye (and hence of any conservative pollutants dissolved or suspended in the Charles River inflow under the survey conditions) can be found by extrapolating the dye recovery to zero at t = infinity and integrating over time, i.e.,

$$\tau = \frac{\int_0^\infty M(t)dt}{M_0} \qquad (1)$$

where M(t) is the mass of dye in the harbor as a function of time and $M_0$ is the initial dye mass (100.2 pounds). Using data in Figure 4 the estimated time is between about 3.5 and 4 days. (Using the piece-wise fit to the observed M(t), shown in Figure 5, the calculated value is 3.6 days.)

The observed residence time can be compared with the few other estimates available in the literature. Using the fraction freshwater method, Bumpus et al. (1953) measured Inner Harbor residence times for ten dates during 1951 and 1952. They found the time $\tau$ to increase with decreasing freshwater inflow ranging from a low of about 1.6 days to a high of about 10 days. Using their Figure 16 showing residence time versus total runoff to the Inner Harbor and their ratio of 1.33 relating total runoff to Charles River flow measured by the USGS in Waltham, one estimates $\tau \simeq 2.2$ days for an annual average Charles R. flow at Waltham of 8.6 $m^3/s$ (ave. of 1931 to 1992; USGS, 1992) and $\tau \simeq 4$ days corresponding to an average summertime flow of 3.4 $m^3/s$ at Waltham (average of July–September over the same time interval). Although the last value agrees nicely with our experiment, the fraction freshwater method would have to be considered very approximate due to unsteady inflow and the difficulty in accurately defining end member salinity in the Outer Harbor.

A theoretical residence time of 6 days was computed by Ketchum (1951b) for Inner Harbor waters between the Charles River and the mouth using the modified tidal prism technique (Ketchum, 1951a). This is a theoretical method which assumes complete mixing within harbor segments of length equal to the computed local tidal excursion. Another theoretical calculation which is often used as a lower bound estimate on residence time is the tidal prism method

$$\tau = \frac{VT}{P} \tag{2}$$

where V is 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 values of $V = 7.8\times10^7 m^3$ and $P = 2.2\times10^7 m^3$ (Bumpus et al., 1953)) yields a tidal prism residence time of 1.8 days. This value is a lower bound because it assumes concentrations within the whole Inner Harbor are well mixed and that none of the mass that leaves the harbor on ebb tide returns on the following flood tide. The measured time of 3.6 days suggests that about half of the dye exiting on ebb tide is returning on the following flood tide. The value of 50% is typical of return factors often found (or assumed) for tidal embayments (Sanford et al., 1992).

Other quantities of interest can also be calculated from these data. Because freshwater is generally released twice a day, it would appear nearly continuous to an observer at the mouth of the Inner Harbor. As such a flushing rate can be computed as

$$Q_f = \frac{V}{\tau} \tag{3}$$

where again V is the Inner Harbor high tide volume. Using $V = 7.8\times10^7 m^3$

$$Q_f \simeq 250 \ m^3/s$$

The flux of a pollutant out of the Inner Harbor is equal to the flushing rate times the average pollutant concentration. In an average summer (July–Sept.) freshwater flow at the Charles River Dam is about 4 $m^3/s$ (61-year average flow at Waltham of 3.4 $m^3/s$ (USGS, 1992) multiplied by estimated factor for low flows of 1.15 (CDM, 1976)). 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 $250/4 \simeq 60$.

The dye data can also be applied to the fate of a non-conservative substance by first computing the residence time distribution f(t), defined by

$$f(t) = \frac{-d\,M(t)}{M_0\,dt} \tag{4}$$

Using the piece-wise fit to the M(t) data shown in Figure 5, f(t) is computed as the solid line in Figure 6. Also shown as dashed lines in Figure 6 are first-order decay curves ($e^{-kt}$) corresponding to values of k = 1, 2, and 3 per day (half lives of 0.69, 0.35, and 0.23 days respectively). The values of k were chosen because calibration of mathematical models against field measurements of fecal coliform (Hydroscience, 1973; CDM, 1989; Adams et al., 1992) has suggested that the disappearance rate of fecal coliform in Boston Harbor is in the range of 1–3 per day.

The fraction of live bacteria that enter the Inner Harbor from the Charles River and exit alive to the Outer Harbor would be given by

$$F = \int_0^{\infty} e^{-kt} f(t) \qquad (5)$$

Using $k = 1$, 2, and 3 $d^{-1}$ yields values of $F \simeq 0.01$, 0.03, and 0.12. These low values are qualitatively consistent with the mathematical simulation of Adams and Zhang (1991) who found that the majority of the CSO impact on the Outer Harbor was due to the (nearby) Outer Harbor CSOs rather than the larger but more distant Inner Harbor CSOs. We are currently in the process of quantitatively comparing model predictions of dye concentration against the July 1992 measurements for purposes of additional model calibration and validation.

Acknowledgments

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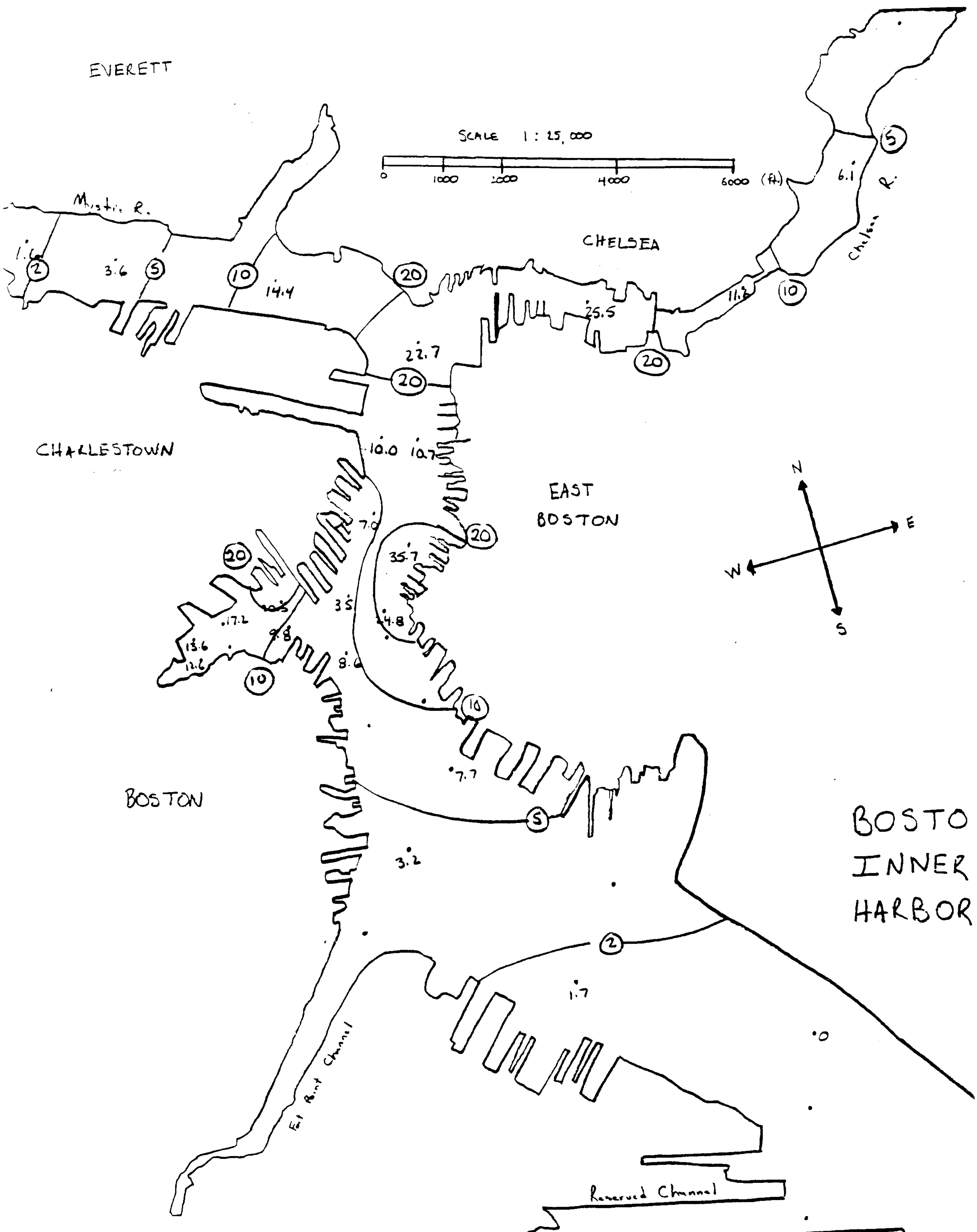
Figure 1 Location of Vertical Profile Stations

Figure 2. Horizontal contours of surface dye concentration ($\mu g/\ell$)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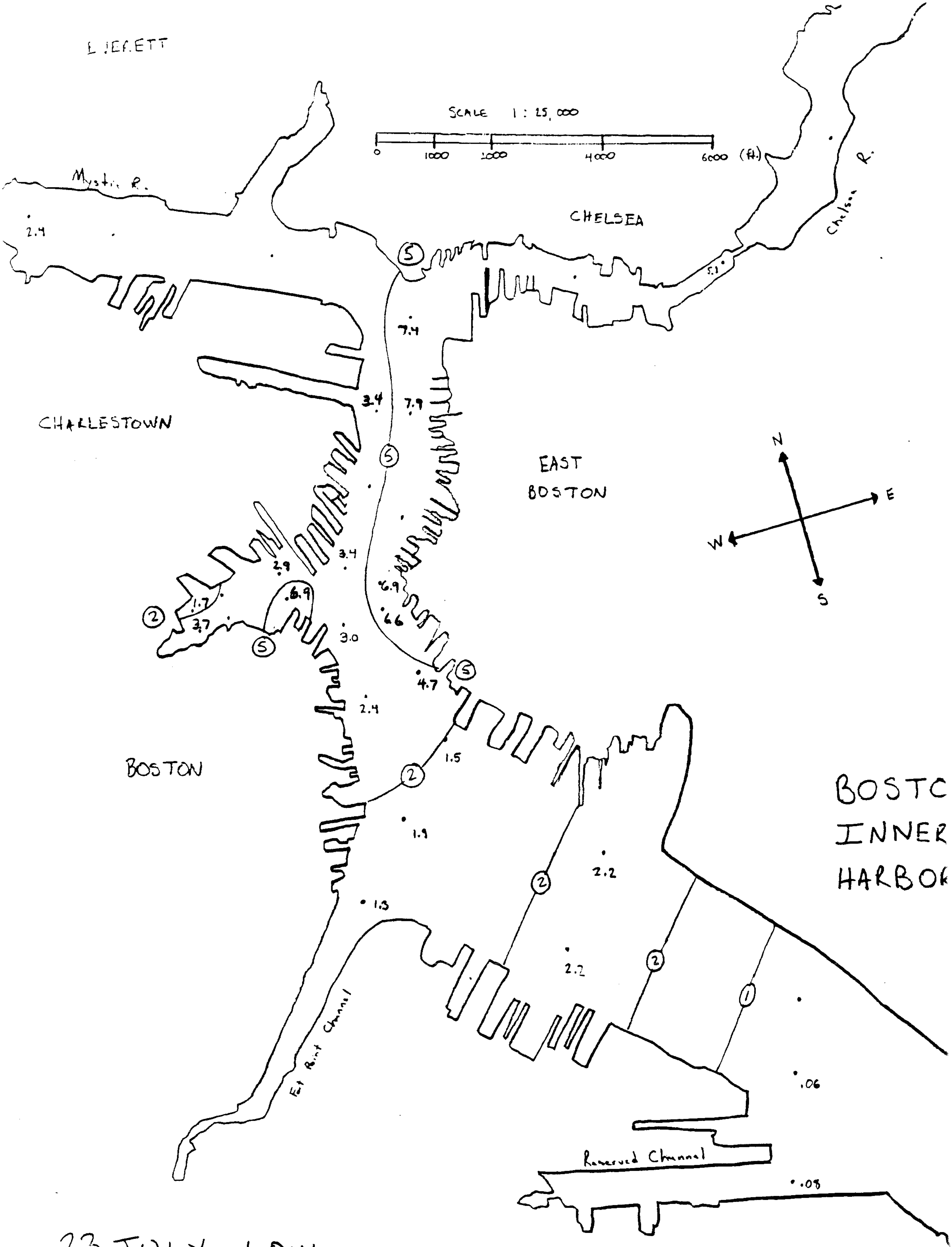
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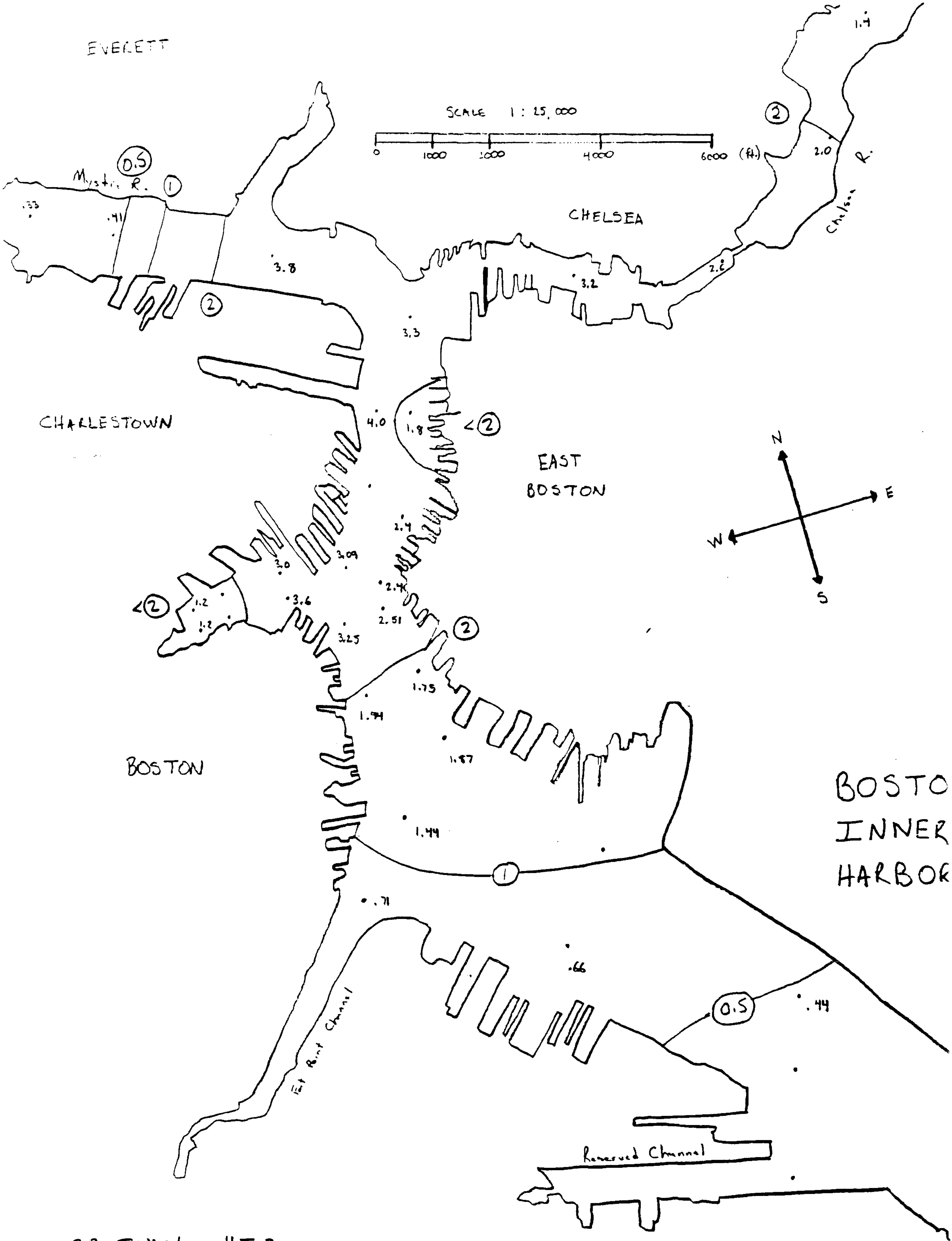

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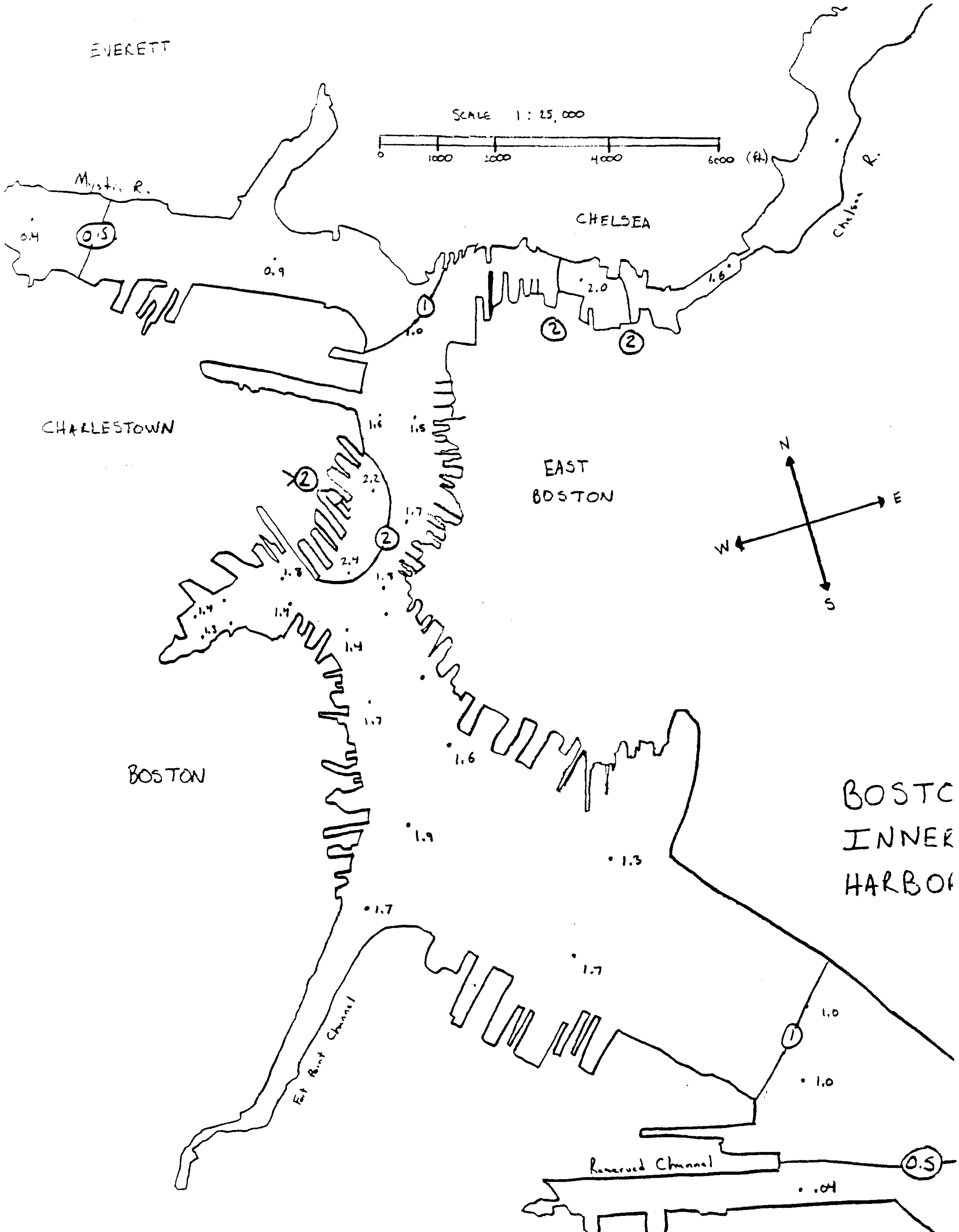
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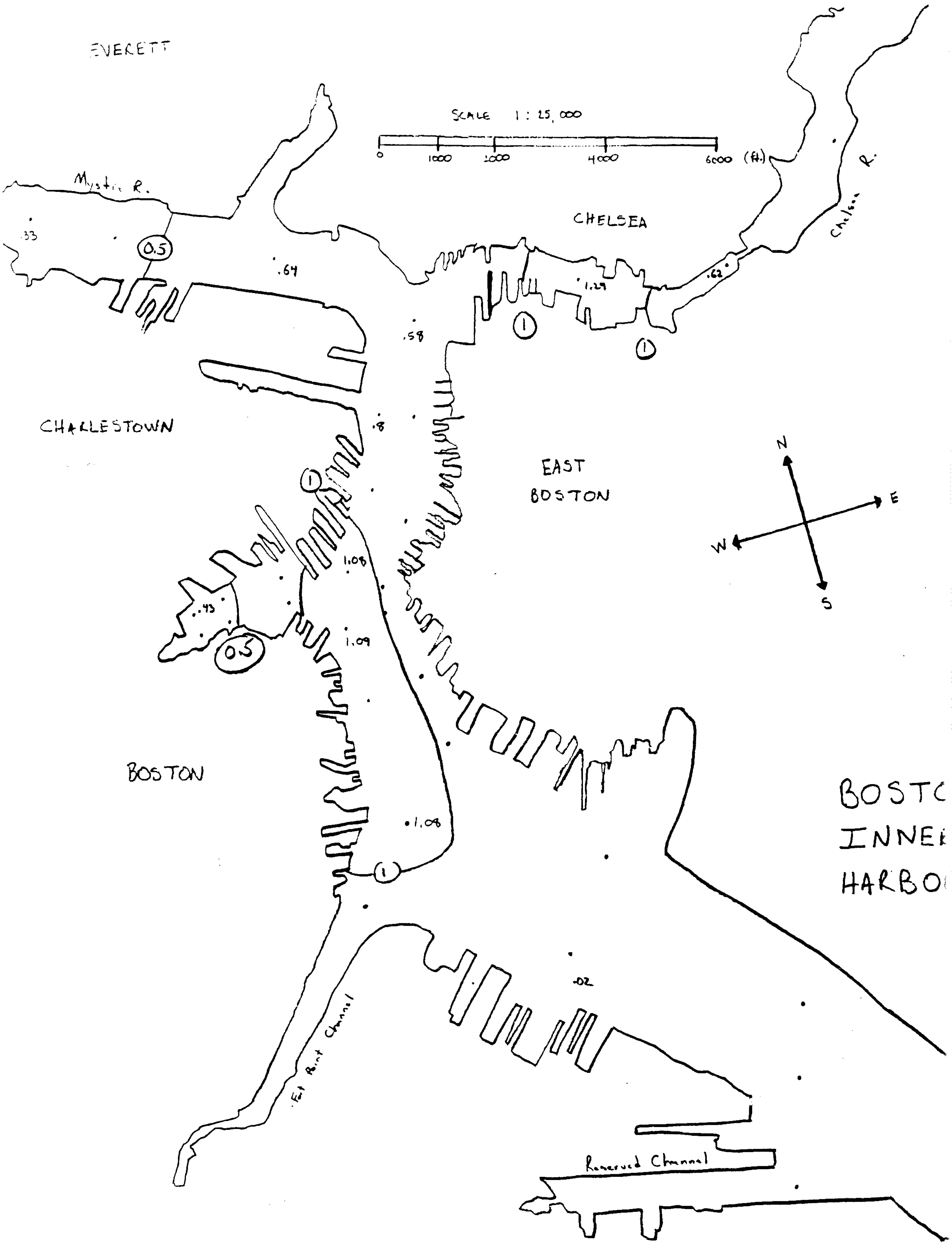
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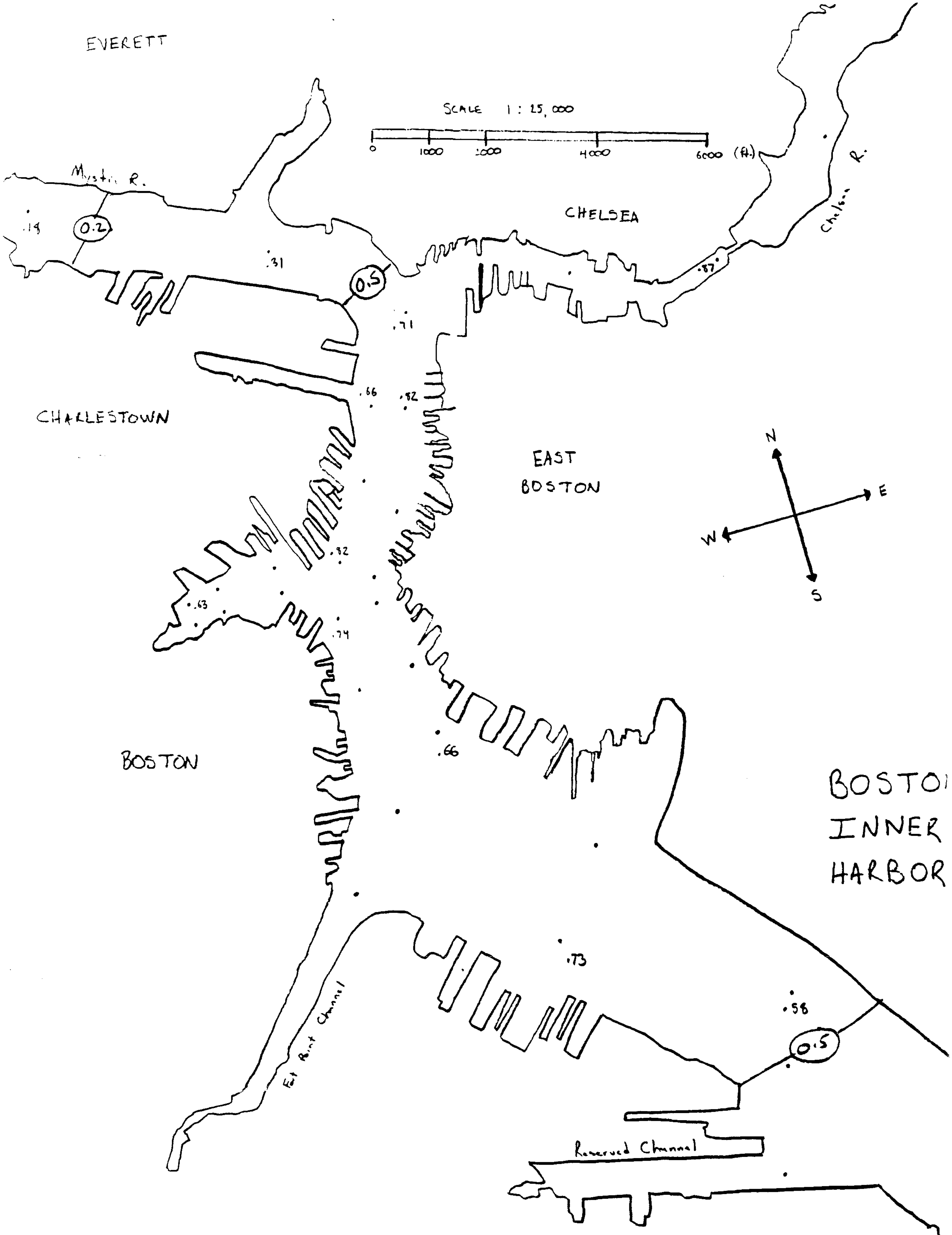
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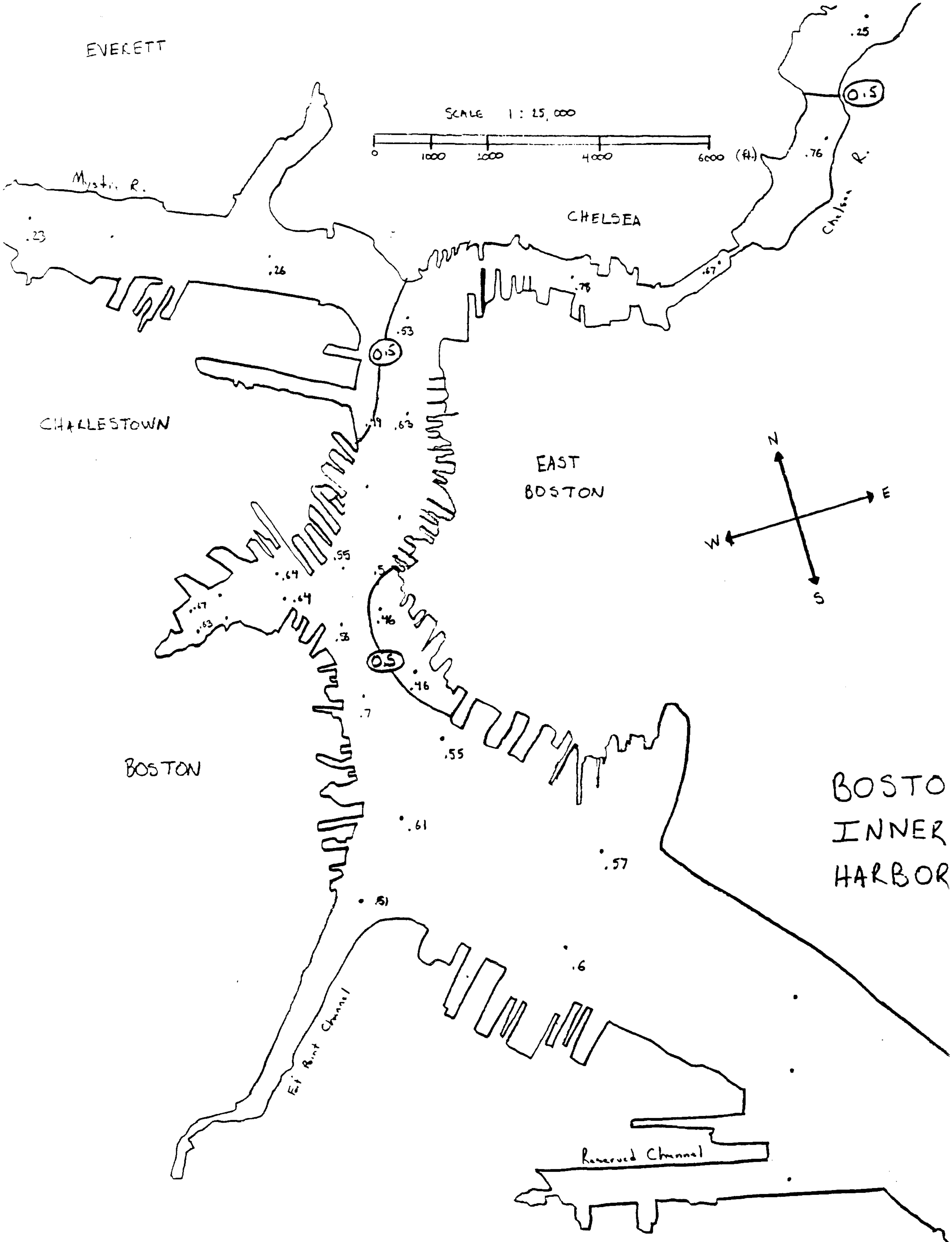
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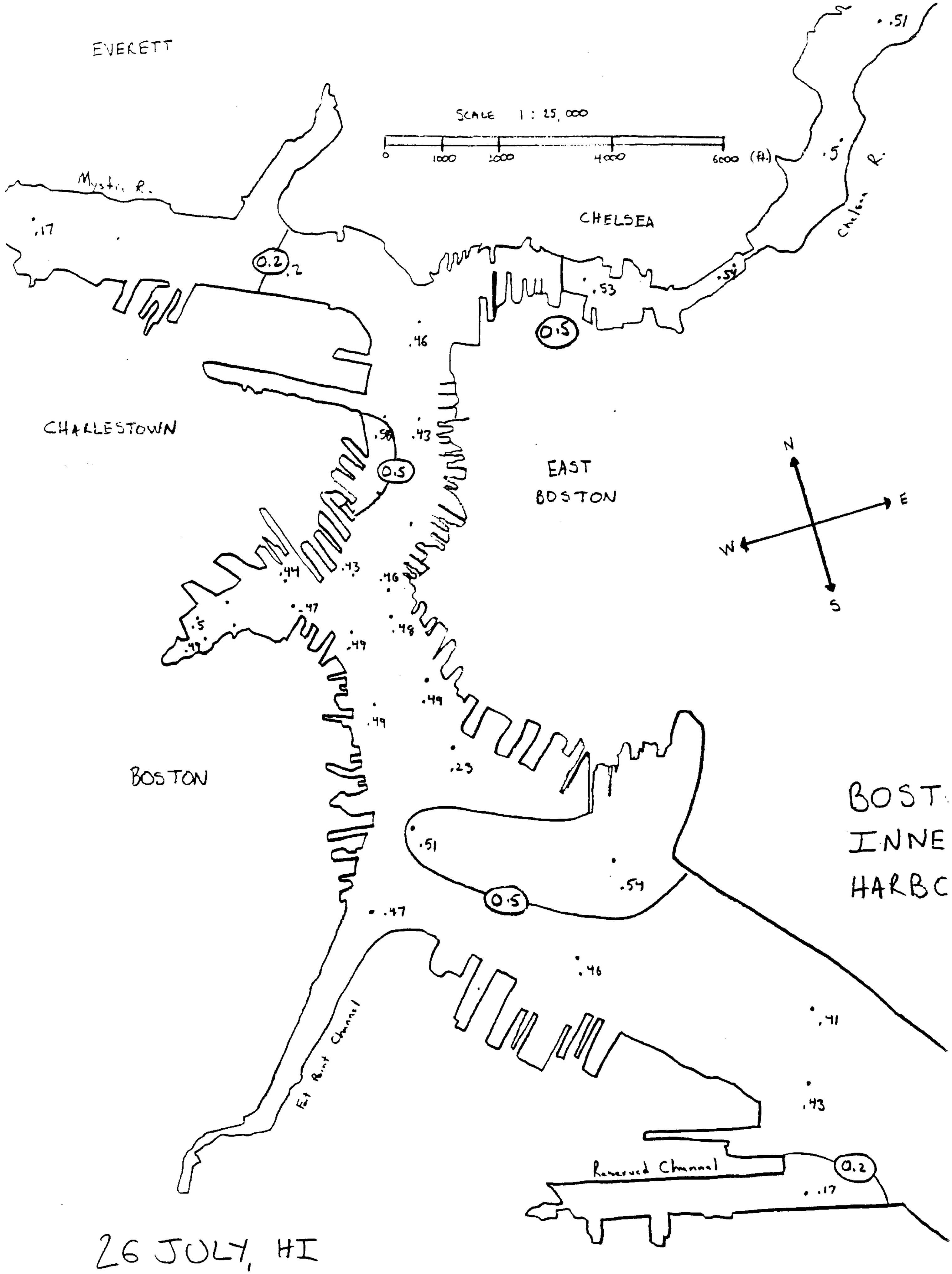
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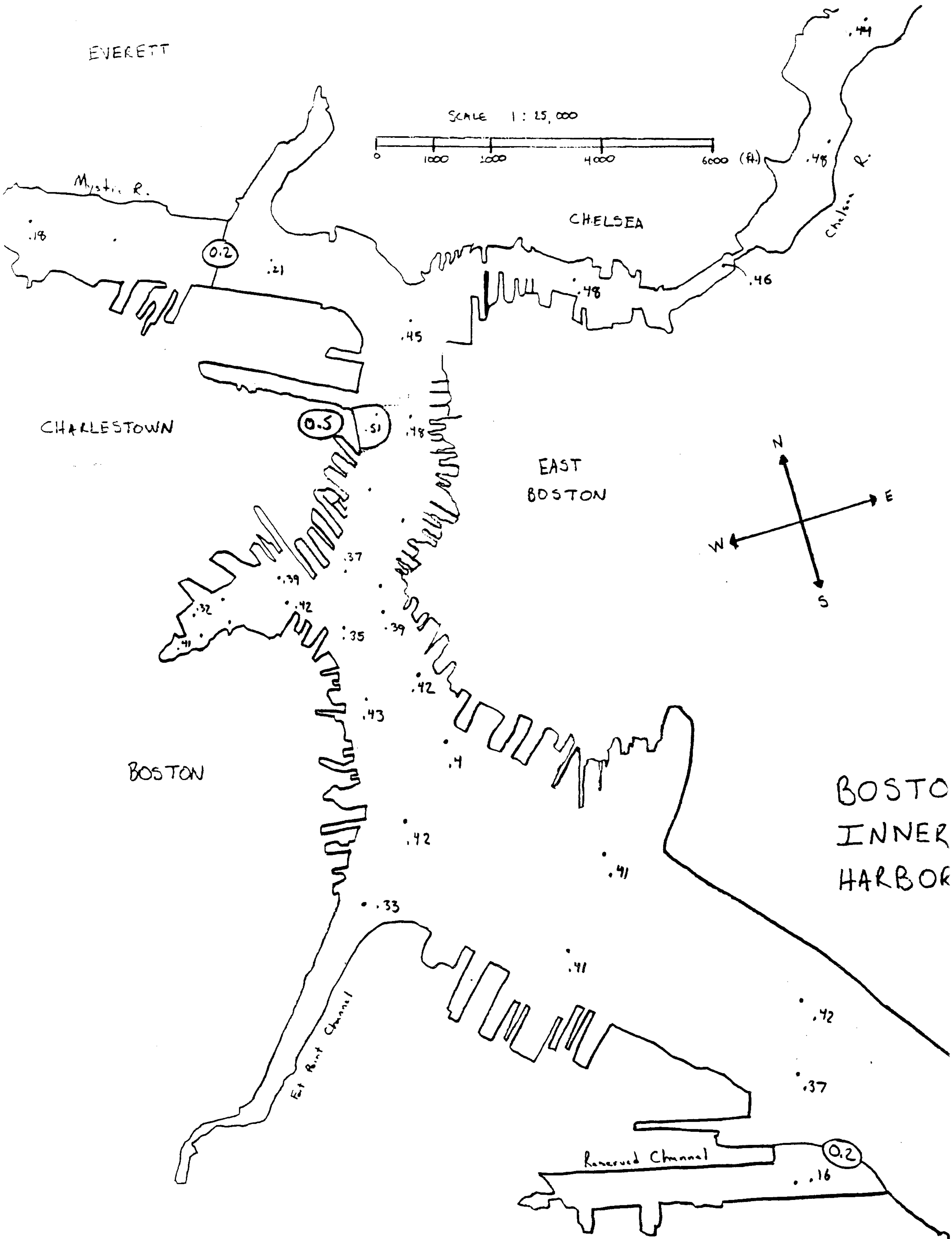
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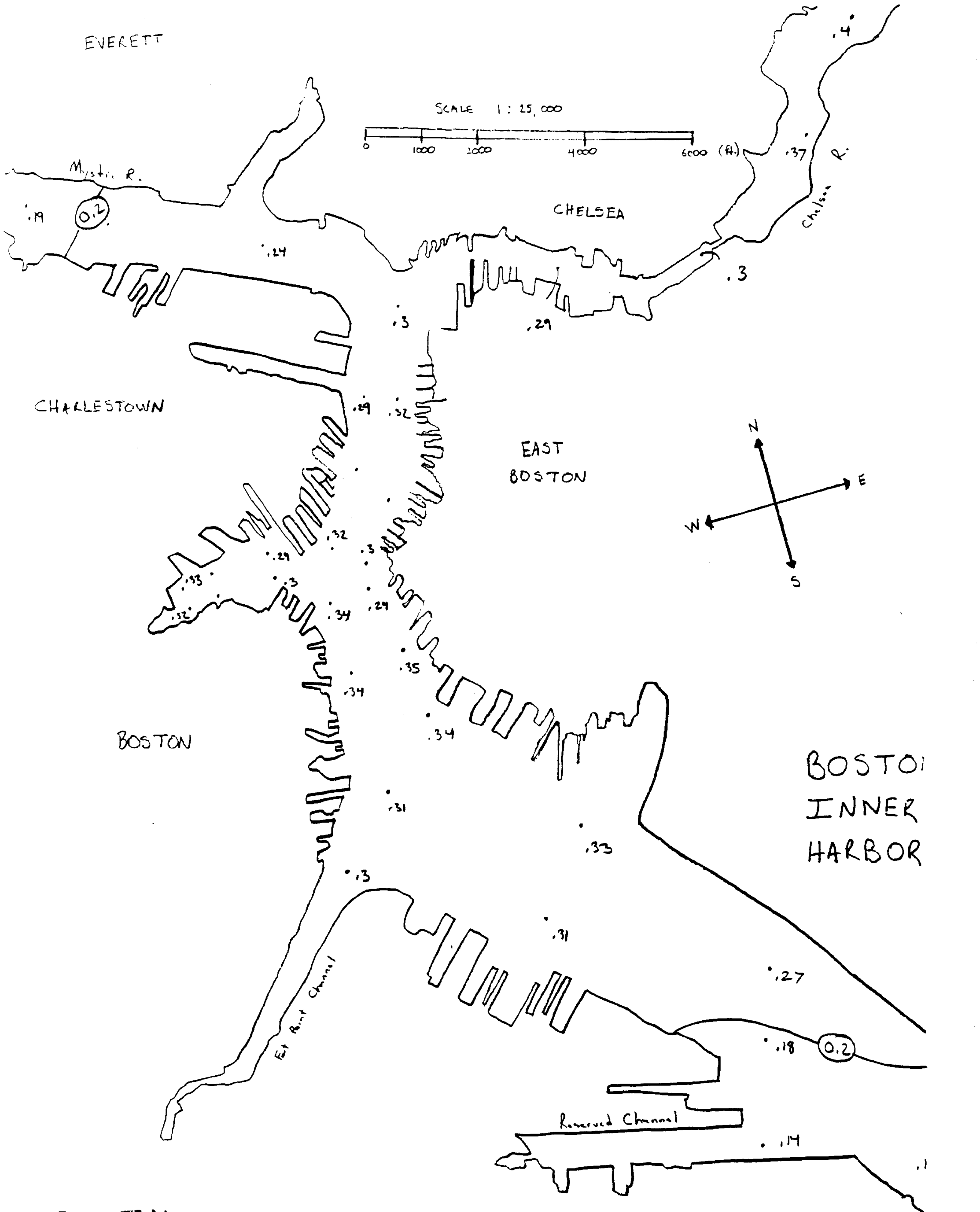
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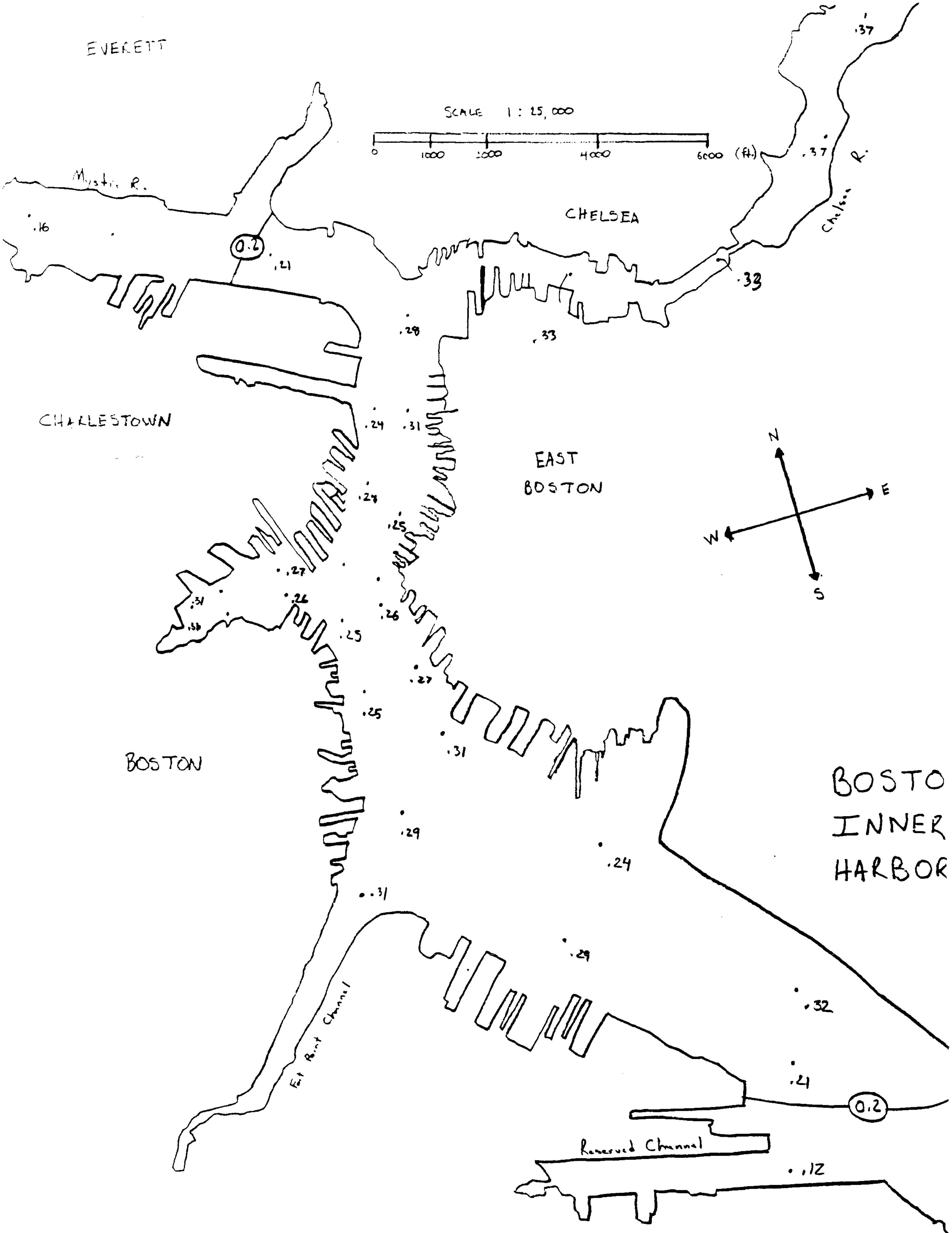
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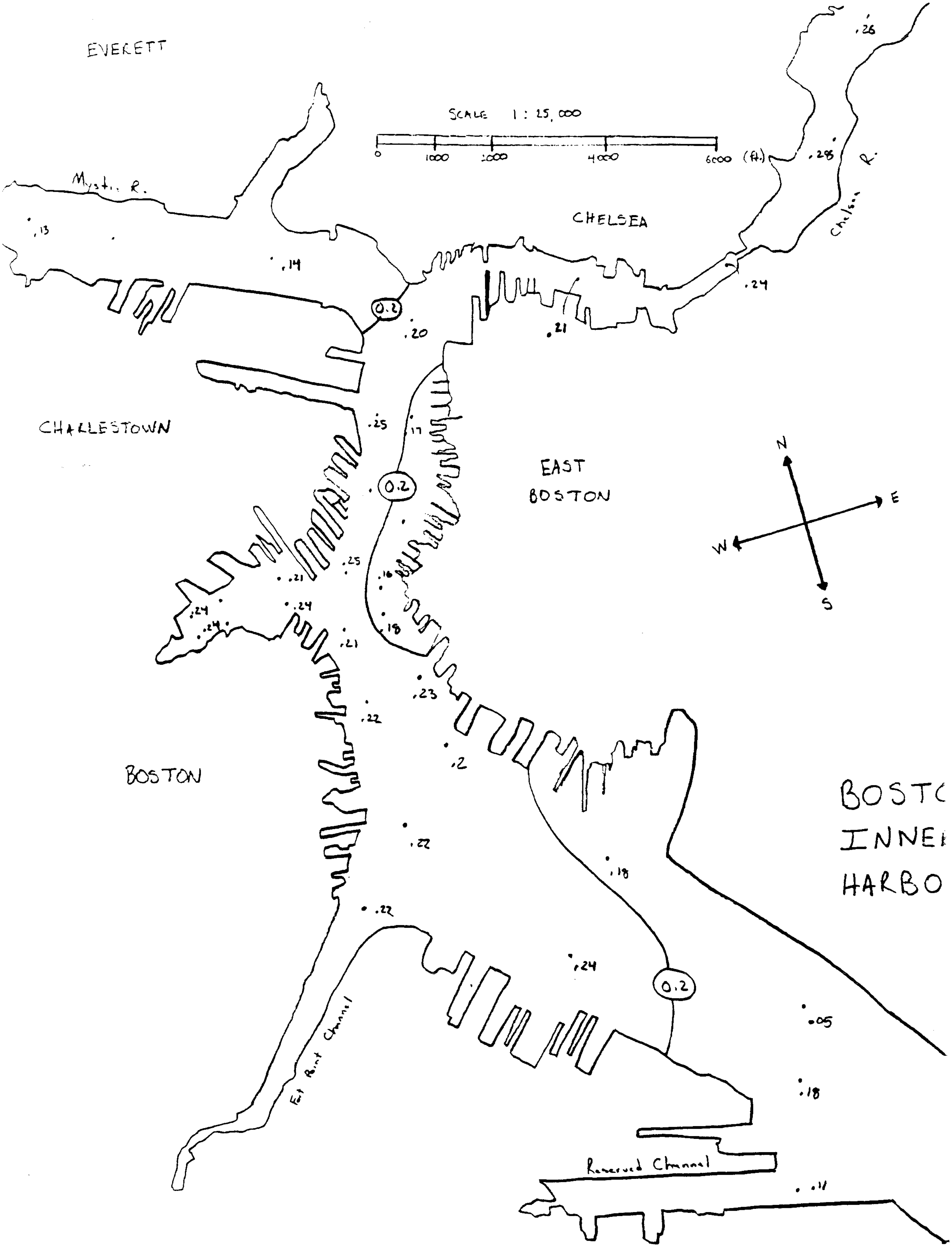

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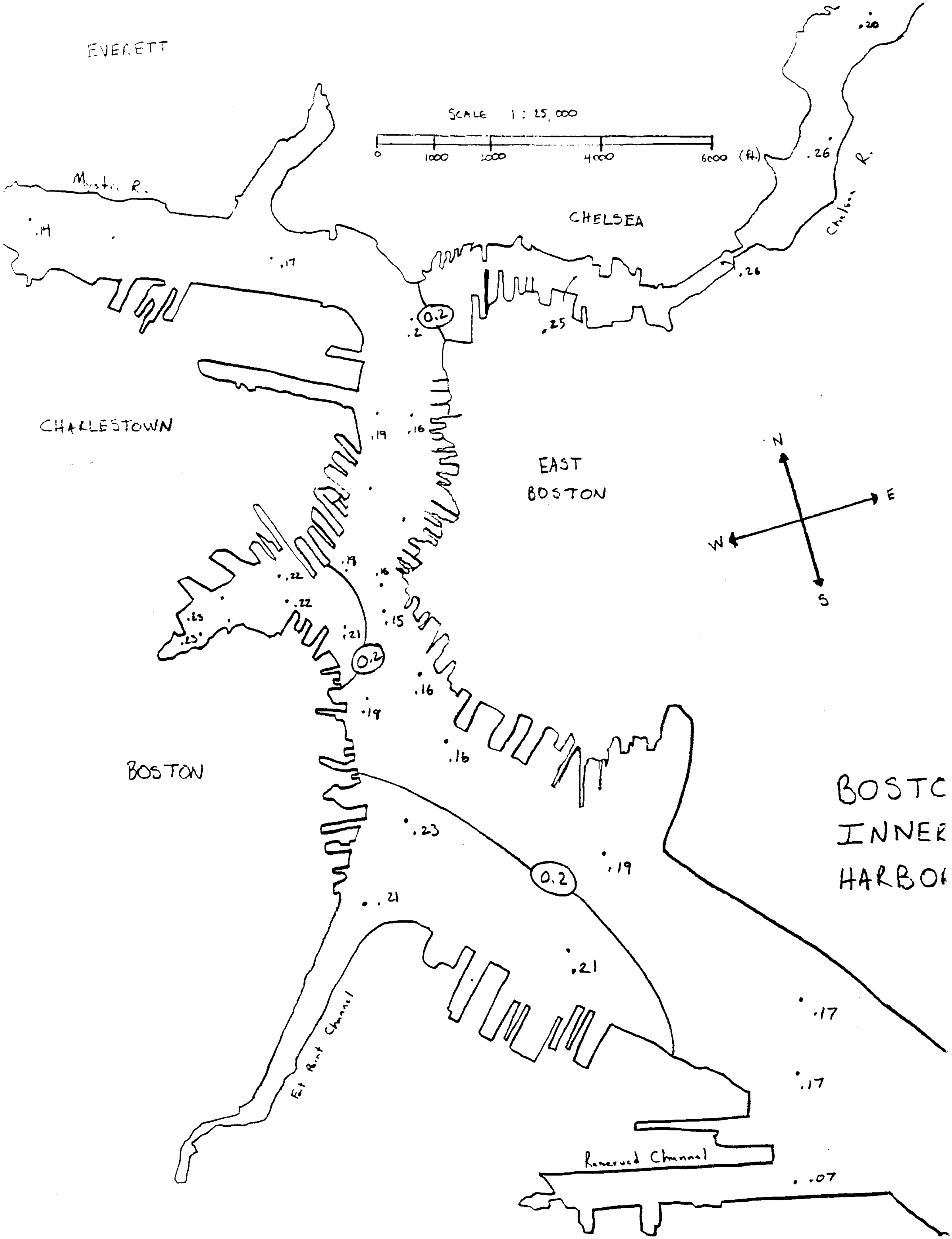
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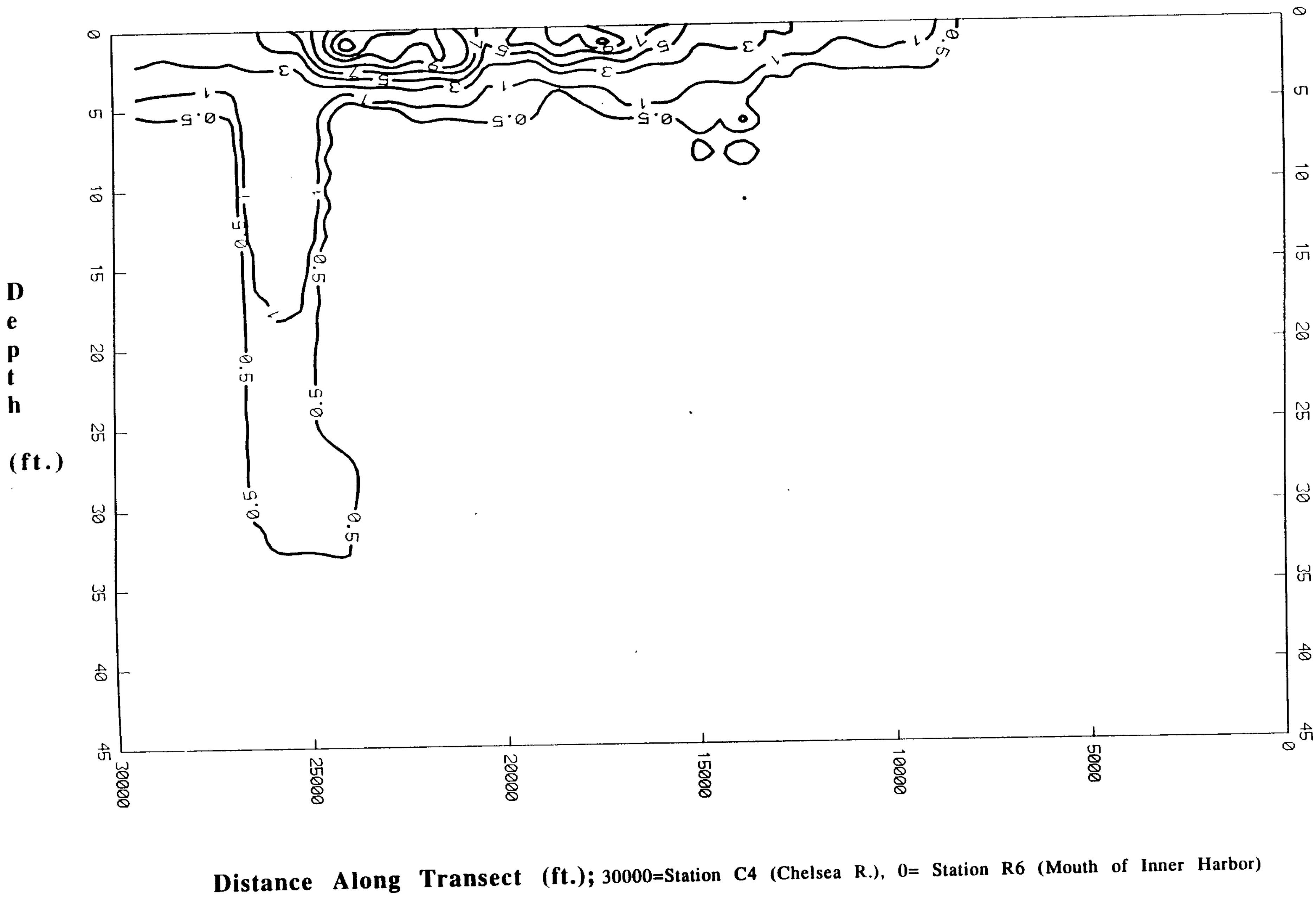
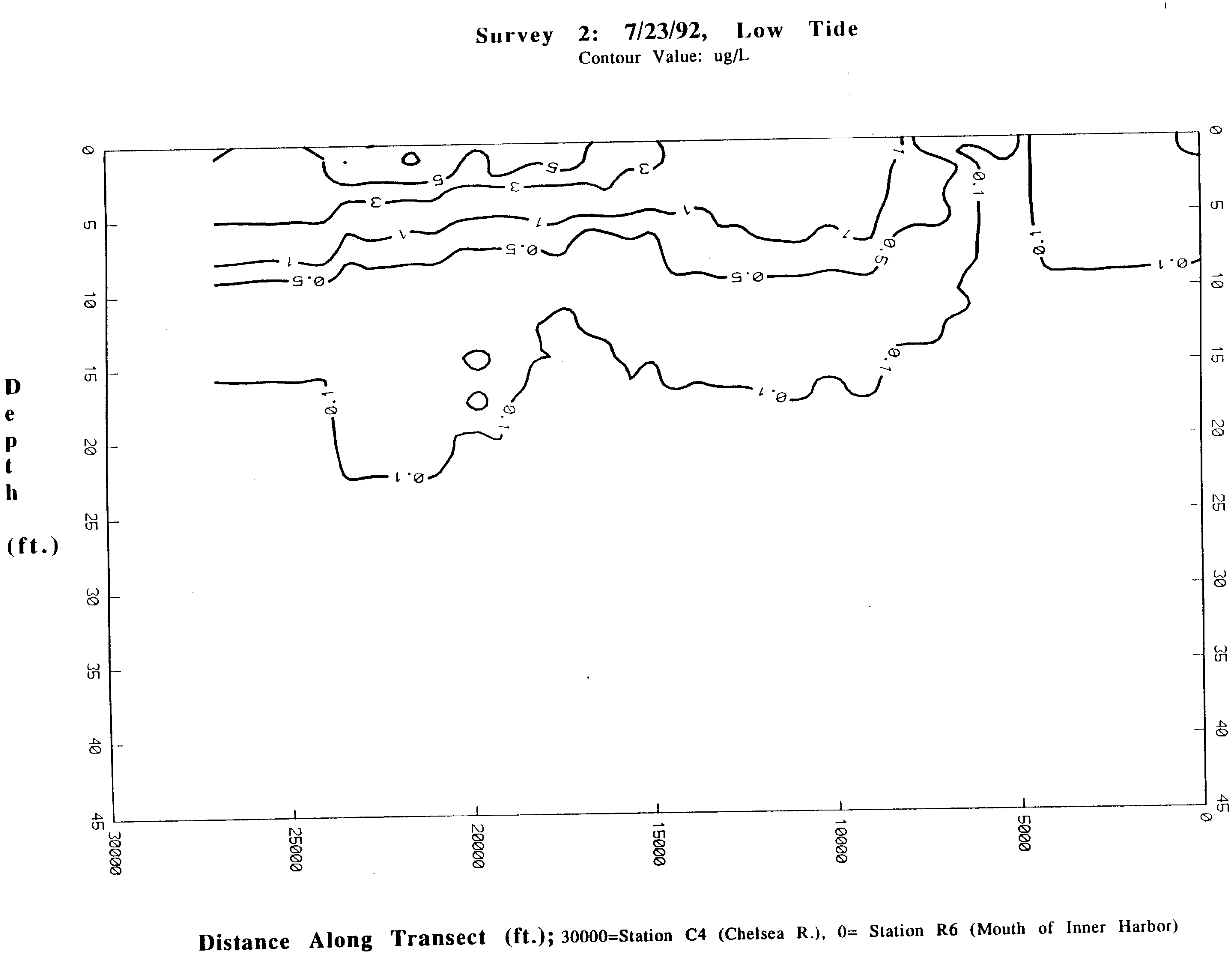
28 JULY LO

Figure 3. Longitudinal-vertical contours of dye concentration ($\mu g/\ell$) from Chelsea Creek to Inner Harbor mouth

Survey 1: 7/23/92, High Tide 1

Contour Value: ug/L

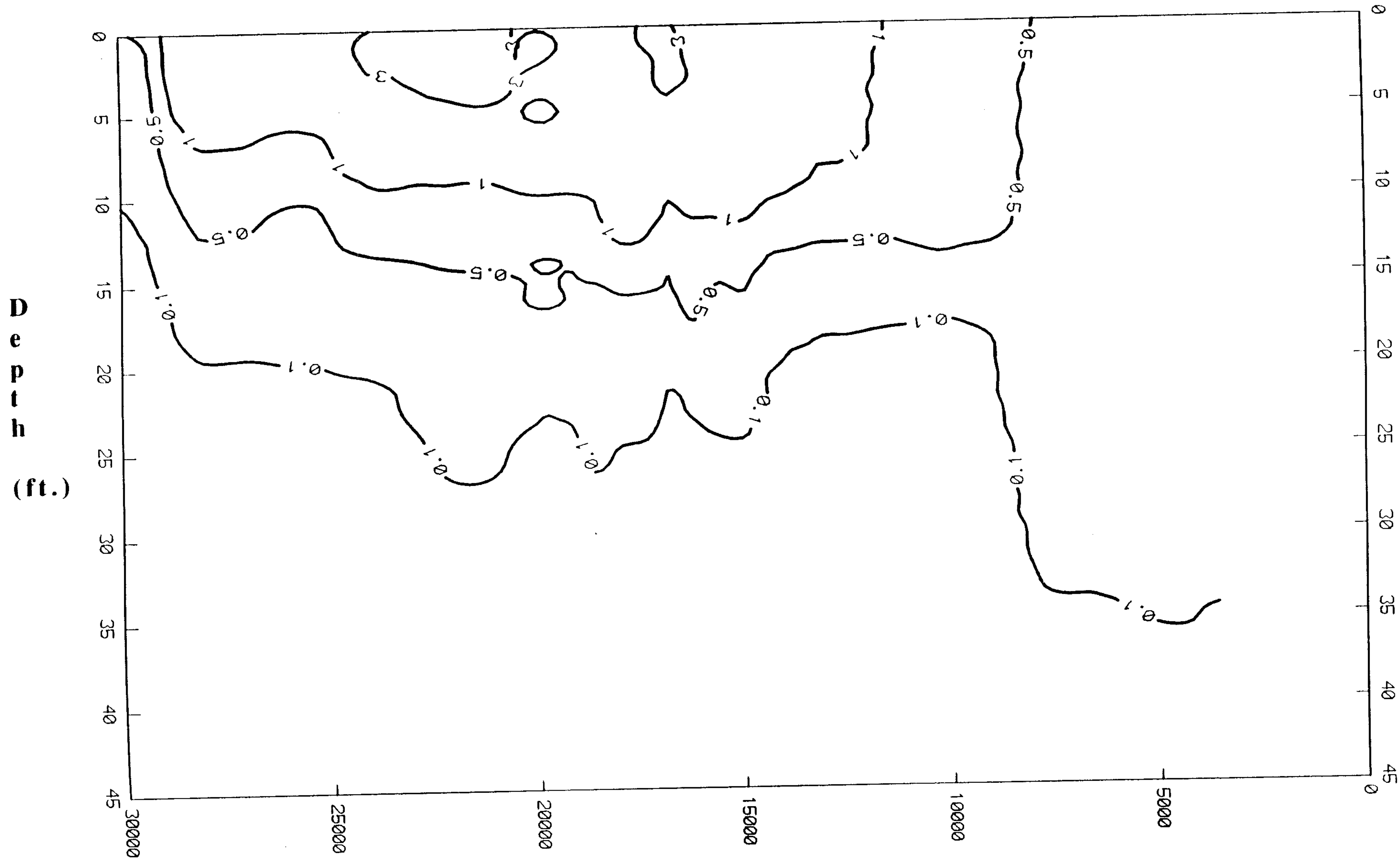




Survey 2: 7/23/92, Low Tide
Contour Value: ug/L
Depth (ft.)
Distance Along Transect (ft.); 30000=Station C4 (Chelsea R.), 0= Station R6 (Mouth of Inner Harbor)

## Survey 3: 7/23/92, High Tide 2

Contour Value: ug/L




Distance Along Transect (ft.); 30000=Station C4 (Chelsea R.), 0= Station R6 (Mouth of Inner Harbor)