Massachusetts Water Resources Authority
Effluent Outfall Dilution:
July 2001

Massachusetts Water Resources Authority
Environmental Quality Department
Report ENQUAD 2002-07

MASSACHUSETTS WATER RESOURCES AUTHORITY
EFFLUENT OUTFALL DILUTION
JULY 2001

Submitted to

Massachusetts Water Resource Authority
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EXECUTIVE SUMMARY

The Massachusetts Water Resources Authority (MWRA) is responsible for the operation and monitoring of the new sewage effluent outfall form the Deer Island Wastewater Treatment Plant, which began discharging into Massachusetts Bay on September 6, 2000. The outfall is regulated under a National Pollutant Discharge Elimination System (NPDES) permit issued by the U.S. Environmental Protection Agency (EPA) and the Massachusetts Department of Environmental Protection (EPA/MADEP 1999) with an effective date of August 19, 2000. Part I, Section 18.e of the permit requires that MWRA "field test and certify whether the outfall's minimum dilution is equal to, or greater than, the predicted minimum dilution" specified in a hydraulic study published in 1993 (Roberts and Snyder (1993a,b). MWRA addressed this permit condition in the summer of 2001 by conducting a Plume Tracking survey to 1) determine the initial dilution characteristics of the outfall and 2) track the longer-term location and mixing dynamics of the outfall plume. The certification of effluent plume dilution characteristics and far field transport evaluation was conducted using Rhodamine WT dye as an effluent tracer on July 16 and 17 and July 18 and 19, 2001, respectively.

The Plume Tracking Certification Survey was conducted by adding the Rhodamine dye at the MWRA Deer Island Treatment Plant to achieve a constant concentration in the effluent for at least six hours. The dye was traced offshore in Massachusetts Bay for three days. The certification study was conducted under treatment plant flows that were on the low side of typical summertime flows due to drought conditions experienced regionally in the summer of 2001. The treated effluent flow rate varied from 346 MGD at the start of dye injection decreasing to 254 MGD at the end of dye injection. The flow increased to approximately 550 MGD at mid morning during the offshore near field plume tracking study in response to ~0.3 inches of rain. Flow decreased to less than 380 MGD by noon on July 17.

Offshore, the dyed effluent exited from the diffusers into a water column that was moderately stratified with a sharp inflection in the pycnocline at approximately six meters depth. Water property (salinity, temperature, density) distributions during the survey were typical of summertime conditions. Hydrodynamic conditions were typical of summer conditions with respect to magnitudes of tidal and mean current velocities and direction, which reflected the relatively low wind vectors experienced during the study.

The water column in Massachusetts Bay was transported to the east-northeast at ~15 cm/s for the 8 hour period that the dye exited the diffuser, turning to the south and southwest at the end of the survey period as the tide turned. The current velocities were relatively similar and uniform with depth as the dye entered Massachusetts Bay. The net water column transport over the next two days was to the south and east at 2 to 6 cm/s. These are typical non-tidal velocities for Massachusetts Bay in the summertime. The dominant energy source influencing the vertical mixing of the dye field was the tidal motion due to low energy of the wind forcing during the survey period. Low winds are also typical of summertime conditions.

Effluent dilution based on the average dye concentration in the effluent (85.96 ppb Rhodamine) and in the receiving waters (0 to ~1.09 ppb based on instantaneous field data) found initial mixing of the effluent was completed very close to the diffuser line. The lowest dilution measured was ~ 50 very close to a riser. Dilution measured in the core of the dye field by an *in situ* sensor system ranged between 80 and 105. This range was observed on all three hydraulic mixing zone surveys conducted to characterize the dye field and estimate the spatial variability and distribution of effluent initial dilution.

The dye field was located between 5 and 25 meters depth during the hydraulic mixing zone surveys, with the core of the plume located between 10 and 15 m depth. The upper edge of the dye field extended to the base of the pycnocline.

The dye emerged from the diffuser just after the ebb tide began and was transported to the east throughout the near field (hydraulic mixing zone) study. During the period that the dye exited from the diffuser, the dye field spread laterally from ~150 m width at the west end of the diffuser line to over 1,500 m approximately 100 m east of the diffuser. The spread was due to the sustained ENE current field, which paralleled the diffuser line throughout the dye tracking effort on the near field day. The observed spread agrees extremely well with theoretical predictions.

The dye field was then transported to the south and east of the diffuser over the two days following release into Massachusetts Bay. The dye field was located at least 5 km offshore of Situate, MA between 10 and 23 meters depth 48 hours after dye release and became elongated in the north-south direction. The northern boundary of the plume had moved 6.5 km to the south and slightly east of the diffuser and increased in area from about 1.6 km^2 to 20 km^2 between July 17 and 18. This represents an additional ~10-fold increase in dilution over the 24-hour period or an increase in average dilution from ~ 100:1 after hydraulic mixing was completed to approximately 1000:1 on average one day after release. The spread and dilution was mostly in the horizontal direction as the thickness of the dye patch remained relatively constant between July 17 and July 19. The elongation of the dye patch in the north-south direction in the far field is consistent with the dominance of the north-south mean shear observed during the study. The dye data also allowed an estimate of the dispersion rate in Massachusetts Bay. A rate of 18 cm^2/s was derived and is similar to previously measured dispersion in the bay in the summer time.

The plume's dimensional characteristics and effluent dilution, estimated using the RSB model with input of the current velocities and direction measured during the certification survey were very consistent with measured results. Initial dilution estimates based on spatial low pass signal processing of the *in situ* dye data, resulted in an estimated average initial dilution of 102. This is slightly higher than the dilution estimated using discrete dye data (~94 fold). The dilution calculated using spatially averaged values are considered more representative than those derived from instantaneous sampling which may not capture short temporal and spatial fluctuations adequately. The time averaged initial dilution estimated by the RSB model gave an initial dilution of 104. The thickness of the dye field measured during the third hydraulic mixing zone survey (conducted just east of the diffuser) was about 20 m, the rise height to the top of the field was about 25 m, and the height of the minimum dilution about 15 m. This compares to the RSB model results of 18.8 m, 24.8, and 16.6 m for dye thickness, rise height, and height of minimum dilution, respectively. These results compare well with predictions from the original physical model study completed during the design of the diffuser system.

Water quality characteristics measured from discrete samples collected during the survey found small increases in metals, nutrients, and total suspended solids in the plume relative to background levels. Copper concentrations after initial mixing were ~60% higher than background levels measured east and north of the diffuser system. Ammonia and phosphate in the diluted effluent were ~ 5- and 1.5-fold over background levels, respectively. Total suspended solids increased as much as 1.2 fold in the core of the plume. *In situ* measurements of the particle field confirmed a localized increase in turbidity relative to background levels. In contrast, bacterial indictors were near or below the detection limits of the methods and did not display an increase relative to the background measured in Massachusetts Bay since outfall came on line in September 2000.

The water quality data from the plume demonstrated that state standards and federal marine water quality criteria were not exceeded. The highest measured copper concentration in the effluent plume was

0.69 µg/L. This compares to a marine water quality criterion of 3.1 µg/L. The *Enterococcus* levels were not detected in 16 samples and at 2 colonies per 100mL in two samples. Fecal coliform was measurable at 1 to 4 colonies per 100mL (MDL = 2 colonies/100 mL). These values compare to the state water quality standards for contact recreation of 200 fecal coliform colonies/100 mL and 35 *Enterococcus*/100 mL of sample.

The initial dilution and water quality characteristics for the summer plume tracking survey were similar to those observed during a spring plume tracking survey, which was conducted under weak water column stratification. While the net transport direction was different between the two surveys, measured plume thickness and dilution were very similar both surveys (plume thickness 22 vs 20m; initial dilution 88 to 95 vs 102; height of minimum dilution 17 vs 15m for spring and summer surveys, respectively). The modeled data were also similar (plume thickness 28 vs 17.6m; initial dilution 109 vs 104; height of minimum dilution 16 vs 15.7m for spring and summer surveys, respectively. The modeled rise height in the spring (24 m) was slightly greater than the summer period (23.5m) due to the shallower pycnocline. The plume dimensions 24 hours after dye release in the summer were substantially larger in the summer due to the local currents and shear at the time of the surveys. Plume dilution continued in the far field driven primarily by the shear that was present at the time of the dye addition. Far field dilutions were at least 200 to 400 fold based on measurements from the core of the plumes and much greater on average (~1000).

Conclusions

Both field and modeling results show the outfall is performing as expected. Measured dilution and other wastefield characteristics derived from the certification survey show excellent agreement with results derived from the RSB model using oceanographic conditions experienced during the dye addition. For this certification survey, an initial dilution of at least 94 was estimated from discrete dye samples collected in the core of the plume, which compares reasonably with the initial dilution of 102 derived from the instantaneous low band pass average dye concentration in the plume. The latter compares very well to the initial dilution predicted from the RSB model (104).

The results from the April (weakly stratified) and July surveys are similar with respect to key plume characteristics and show that initial dilution under typical effluent flows is similar.

Oceanographic mixing and dispersion further increased the dilution in the far field to over 200 fold with much of the measured dye patch showing greater than 400 fold dilution 48 hours after release of the dye. Average dilution in the far field plume was ~1000 fold 24 hours after dye release. These measured far field dilutions are consistent with dilution simulated using hydrodynamic models.

The two dye studies performed to document initial dilution at the MWRA's outfall in Massachusetts Bay demonstrate that the outfall is performing as designed (i.e., "outfall's minimum dilution is equal to, or greater than, the predicted minimum dilution") and that federal water quality criteria and state water quality standards are met well within the hydraulic mixing zone. Moreover, the agreement between field and modeled results under two distinctly different stratification conditions provide a high degree of confidence that the RSB model (and newer more sophisticated models) can be used in the future to accurately estimate initial dilution under a variety of effluent flows, oceanographic conditions, and stratification regimes.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

APPENDIX

1.0 INTRODUCTION

The Massachusetts Water Resources Authority (MWRA) is responsible for the operation and monitoring of the sewage effluent outfall (Figure 1-1) from the Deer Island Wastewater Treatment Plant (DITP), which began discharging into Massachusetts Bay on September 6, 2000. The outfall is regulated under a National Pollutant Discharge Elimination System (NPDES) permit MA0103284 issued by the U.S. Environmental Protection Agency (EPA) and the Massachusetts Department of Environmental Protection (EPA/MADEP 1999) with an effective date of August 19, 2000. Part I, Section 18.e of the permit requires that MWRA "field test and certify whether the outfall's minimum dilution is equal to, or greater than, the predicted minimum dilution" specified in a hydraulic study published in 1993 (Roberts and Snyder (1993a,b). Thus, the primary objective of the Plume Tracking Program is to determine the initial dilution characteristics of the outfall. The effluent plume dilution characteristics and transport assessment study was evaluated using Rhodamine WT dye as a tracer during winter (unstratified) and summer (stratified) conditions. The summer survey was specifically designed to address the permit condition. The winter survey was designed to ensure the approach to the plume tracking would result in effective data collection methods and obtain initial information on the dilution characteristics as described in the *Combined Work/Quality Assurance Project Plan for Plume Tracking: 2001* (Bruce *et al*. 2000) and reported in Hunt *et al.* (2002). The summer study is the subject of this report.

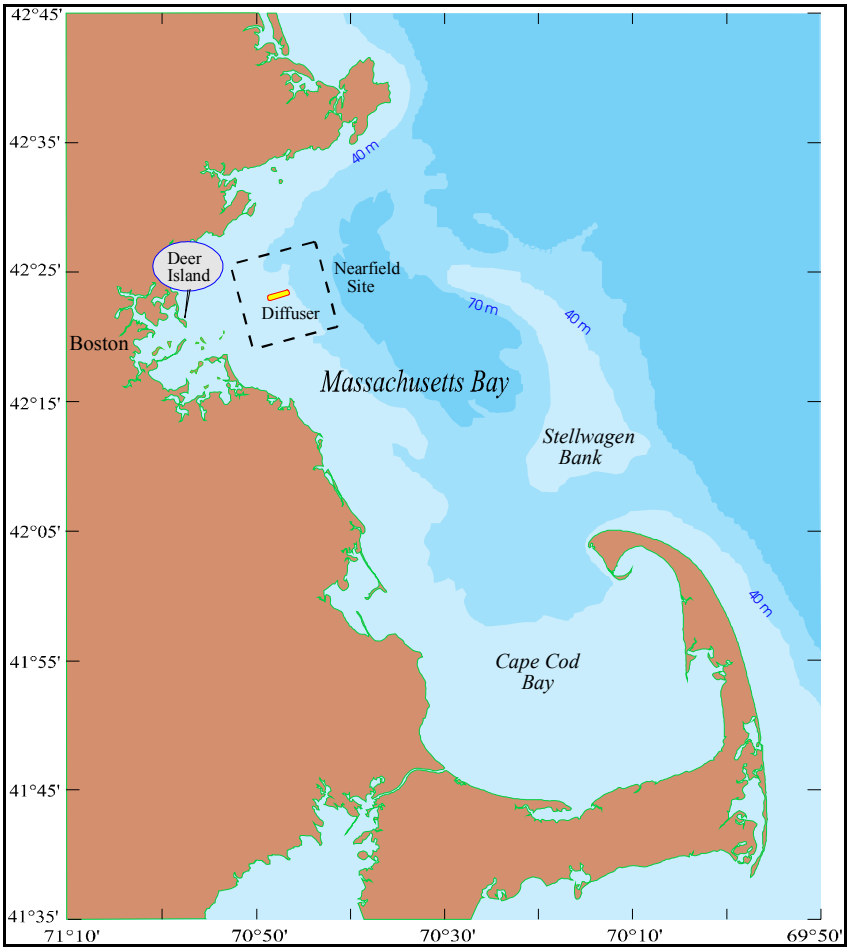

Figure 1-1. Location of the MWRA effluent outfall in Massachusetts Bay.

The summer plume tracking survey was designed to provide information on the effluent plume characteristics under stratified conditions (when the initial dilution characteristics are expected to be lowest) and to develop information to validate the initial dilution and performance of the diffuser in Massachusetts Bay. All aspects of the technical approach, including methods and equipment employed, data quality objectives, and quality assurance activities were developed in the planning process and are described in the (Bruce *et al.* 2000). Revisions and modifications to the CW/QAPP resulting from the April survey (Hunt *et al.* 2002) were incorporated into the survey plan prepared for the summer survey (Battelle 2001).

The Summer Plume Tracking survey was conducted at Deer Island Treatment Plant (DITP) and Massachusetts Bay from July 16 through July 19, 2001. Rhodamine WT dye was added at the MWRA Deer Island Treatment Plant (DITP) and traced offshore for three days. Data collected during the plume tracking exercise were used to determine the location of the effluent discharge plume as it exited the diffuser and mixed with ambient waters. The dilution performance of the outfall was evaluated and compared with results of the RSB model (Roberts and Snyder 1993a,b). Transport and dispersion in the far field was completed by evaluating the dye fields for two days following the completion of the dye addition.

Several laboratory studies associated with the plume–tracking surveys were conducted in 2001. These studies primarily addressed the stability of Rhodamine WT in chlorinated effluent and in seawater. The results of the studies can be found in (Hunt *et al*. 2002).

This report is organized into five major sections. Section 1.0 introduces the report and establishes the purpose and goals of the study. Section 2.0 summarizes the methods used during the plume tracking including the dye addition at Deer Island, field activities offshore, and discrete sample analysis methods. The results of the field measurement program, the discrete sample analysis, and physical oceanographic conditions during the survey including factors affecting the transport of the plume and its dispersion characteristics are presented in Section 3.0. Section 3.5 presents the results of the modeling study including comparison of model results to the field results. Section 4.0 provides a summary-level discussion of the findings. Section 5.0 presents the conclusions from the certifications study and compares initial dilution estimates from the summer and winter surveys.

2.0 METHODS

2.1 Dye Tracer Study

The data acquired in support of the 2001 Summer Plume Tracking survey were collected in three study components: 1) Ancillary dye studies and sensor calibration, 2) Deer Island Treatment Plant (DITP) and 3) the offshore field program. The ancillary dye studies addressed the stability of dye and dye fluorescence under the conditions found at the DITP or at sea. Additionally, robust calibrations of the sensors used on the survey were obtained under laboratory conditions (Hunt *et. al*. 2002). Activities conducted at DITP included dye addition, *in situ* effluent monitoring, and discrete effluent sampling. Figure 2-1 provides a summary of the DITP and offshore survey components, showing the juxtaposition of the activities in the tidal cycle. The general chronology of events is also is also presented in Table 2-1. Further details of the survey chronology are presented in the Summer Plume tracking Survey Report (Mansfield *et al*. 2001).

Four distinct survey activities comprised the offshore component:

1. Background survey
2. Pre dye emergence exploratory surveys
3. Three hydraulic mixing zone (HMZ)[1] surveys, and
4. Far field plume tracking survey (2 days).

The first three offshore activities occurred on day 1, July 17, 2001. The far field survey took place on the second and third field days. The *R/V Aquamonitor,* a 45-foot research vessel, served as the sampling platform during the offshore survey. Over the course of the offshore surveys, both *in situ* and discrete samples were collected. A summary of the methods of each of these components is presented below.

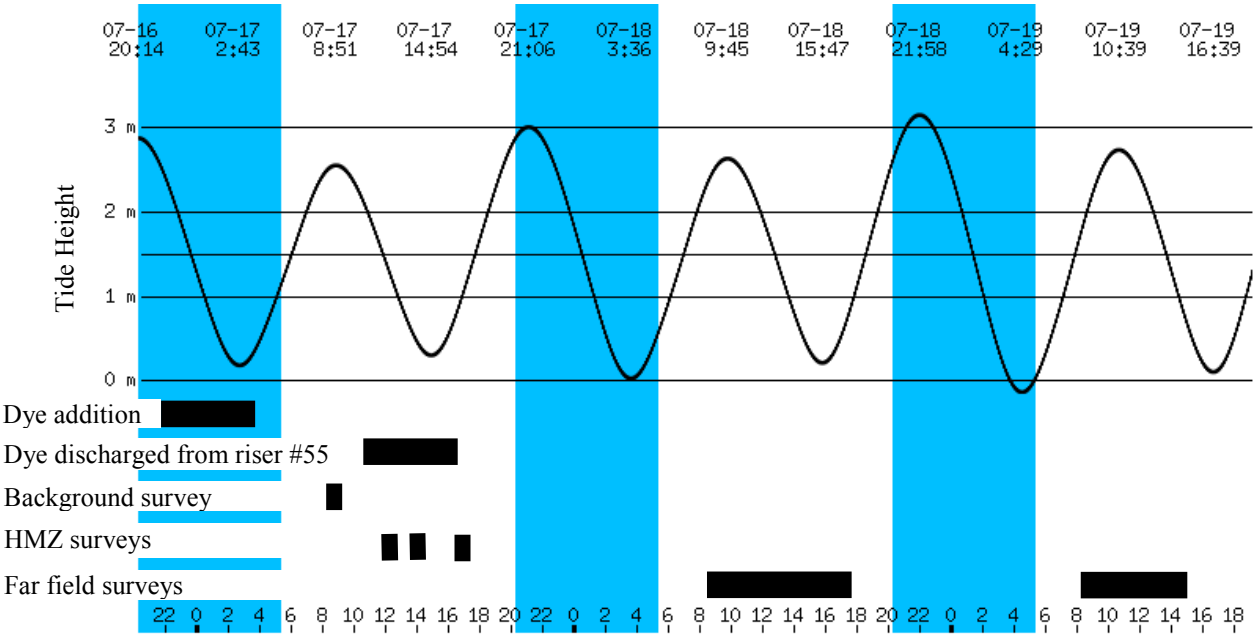

Figure 2-1. Timeline of the summer survey plume tracking activities showing juxtaposition with the tides (blue highlight indicated nighttime). Note times are EDT.

[1] Note: The term nearfield in this document refers to the general vicinity of the diffuser line. The term is not to be confused with the term near field used by plume modelers to mean the region in which mixing and dilution occur as a result of the turbulence generated by the discharge itself. This latter region is often referred to as the initial mixing zone. We will refer to the modeler's near field as hydraulic mixing zone or HMZ. The term far field is not to be confused with the modelers use of the term far field. The later is used to mean the region where plume mixing and dilution is due to oceanic turbulence. The far field surveys described herein will encompass the modeler's far field, as will most of the nearfield survey. It is the transition point between the hydraulic mixing zone and the far field that initial dilution is set. Sampling this location was the goal of the hydraulic mixing zone surveys.

Table 2-1. General survey chronology, summer plume tracking survey.

Date	Time (EDT)	Activity
July 13, 2001	All Day	Mobilization at DITP and marina, Hingham MA
July 16 - July 17, 2001	2124 - 0540	Dye monitoring at DITP
July 16 - July 17, 2001	2145 - 0345	Dye addition at DITP
July 17, 2001	0807 - 0929	Background survey
July 17, 2001	1032 - 1657	HMZ surveys
July 18, 2001	0817 - 1751	Far field survey day 1
July 19, 2001	0808 - 1505	Far field survey day 2

The plume tracking *Combined Work/Quality Assurance Project Plan* (Bruce *et al.,* 2000) and Survey Plan for the March 2001 plume tracking survey (Battelle 2001) contain additional details on survey/sampling methods. The summer plume tracking survey report (Mansfield *et al*. 2001) provides additional information the activities and accomplishments of the summer plume tracking survey before and after the summer plume tracking survey to address potential interferences on Rhodamine WT dye detection that may be encountered either at the DITP or in the offshore survey area. A critical element of these studies was development of accurate estimates of the response of dye as a function of changing temperature. These data were required to establish calibration coefficients for the *in situ* the sensors used to measure the dye concentrations during the survey. The potential interferences that were examined included background fluorescence, turbidity, temperature, photochemical decay, adsorption to particulate matter, pH, agitation, biodegradation, degradation by chlorine, and degradation by chlorine enhanced by bromine in seawater. The methods and results of these experiments were reported in a series of letter reports that are summarized in the (Hunt *et al*. 2002). Based on the results of these experiments the only data corrections required were temperature compensation for Rhodamine WT fluorescence. The study concluded that media specific temperature calibration coefficients were required for the 2001 plume tracking surveys. Table 2-2 lists the temperature calibration coefficient. These coefficients were applied to the winter and summer plume tracking data through post-survey processing. These coefficients were also applied to all of the data from the ancillary studies. Special studies associated specifically with the summer survey included background dye florescence and turbidity during the action field sampling and a photodegradation study. A small background fluorescence response was found in the effluent and offshore. Dye data has been corrected for this signal. Interference from turbidity was not found during the field program; therefore, no corrections were applied to the dye data. The photodegradation study (see Hunt *et al*. 2002 for the results) found no relevant degradation from the sunlight during the survey.

Table 2-2. Temperature correction coefficients.

Media	Slope	T_0 (Intercept) °C
Seawater	0.0250	4.876
Effluent	0.0231	5.365

2.1.1 DITP Field Activities

The primary activities occurring at DITP supporting the plume tracking survey included the addition of Rhodamine WT dye into the effluent stream and the *in situ* monitoring of the dye concentrations throughout the period it was being added. Additionally, discrete effluent samples were collected for the purpose of comparing laboratory-derived dye concentrations with *in situ* data, comparing dye concentrations in the west and east disinfection basins, and for determining the concentrations of selected parameters in the effluent. Dye was added to the effluent stream from 21:45 EDT July 16 to 03:45 EDT

July 17, 2001 (Table 2-1). Dye monitoring at DITP was conducted from 21:24 EDT July 16 to 05:40 EDT July 17, 2001 when dye concentrations returned to pre-addition levels.

Dye Addition -Rhodamine WT dye solution was added to the primary/secondary blended effluent channel at the Deer Island Treatment Plant downstream of the secondary clarifiers at a location near the riser shaft for clarifier B (Figure 2-2). At this location, the effluent undergoes vigorous mixing before the flow splits into the two streams that lead to the sodium hypochlorite dosing points, the hypochlorite mixers, and the two disinfection basins. The hypochlorite mixers blend the effluent with chlorine (as sodium hypochlorite (NaOCl); pre-diluted to ~500 mg/L). The target dye concentration was 75 µg/L (75 ppb).

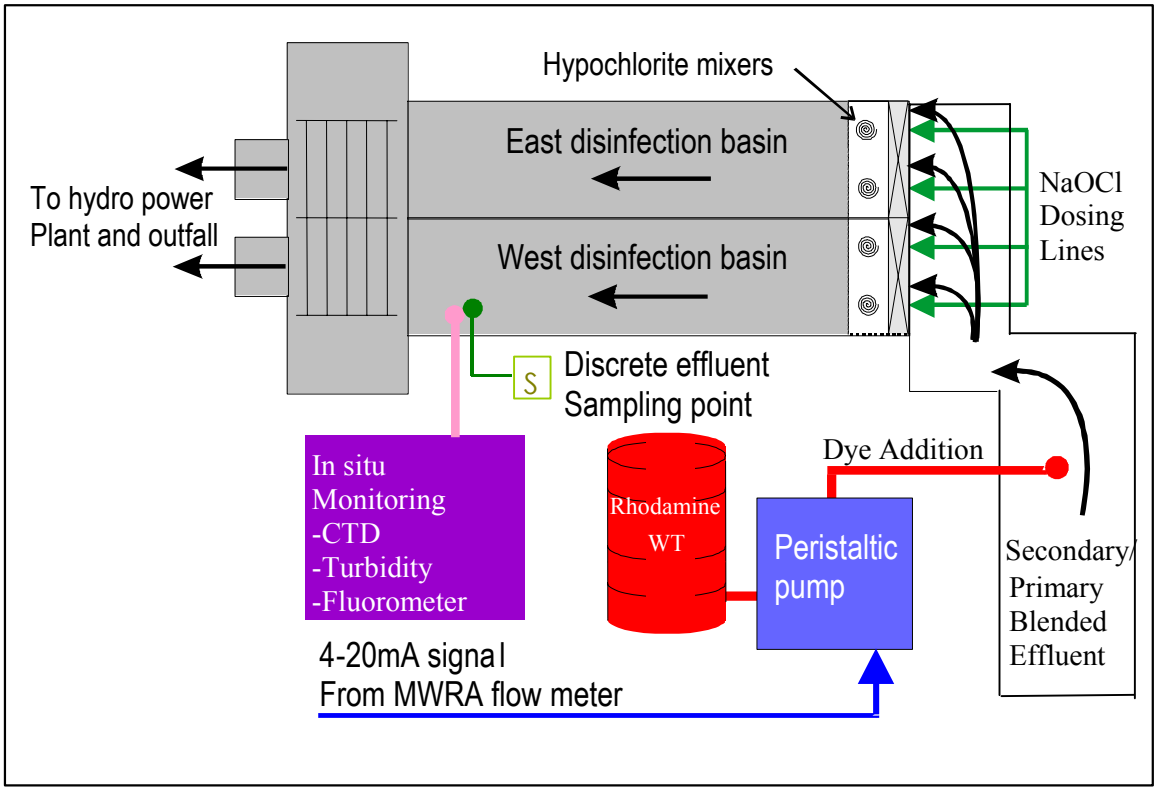

Figure 2-2. Schematic of DITP dye addition and sampling locations.

Rhodamine WT dye (assumed to be 20% wt/wt active ingredient), purchased from Keystone Aniline Corporation, Chicago IL, was metered directly into the primary/secondary blended effluent channel using a peristaltic pump. The pumping speed was proportional to the "official plant flow" measured by MWRA and derived as the sum of readings from flowmeters located in four parallel streams in the treatment plant. The pumping speed and plant volume were periodically monitored throughout the period of dye addition.

Dye Monitoring (*in situ* sampling) – The dye-dosed effluent was monitored with *in situ* instrumentation at the downstream end of the west disinfection basin. Fluorescence, temperature, conductivity, density, pH and turbidity were measured *in situ*. A Seapoint Rhodamine WT fluorometer, Seapoint turbidity sensor, and an Ocean Sensors OS200 CTD unit containing conductivity, temperature, pressure (depth), and pH sensors comprised the *in situ* sensor package. The fluorometer and turbidity sensors were powered by, and their analog signals were processed through, the CTD unit. The *in situ* data were collected and stored by the Battelle Ocean Sampling System (BOSS). The effluent was continuously monitored in the center of the west basin at approximately 2m below the surface. Additionally, vertical

profiles were conducted at three locations within in the west basin: 1) 5' from the west wall, 2) the center of the basin, and 3) 5' from the east wall. These profiles were conducted before dye addition began and again approximately 1 hour after the start of dye addition. These profiles were conducted to determine dye homogeneity throughout the basin. Results from the profiles revealed a homogeneous distribution of dye. Details of the DITP monitoring are provided in Mansfield *et al.* (2001).

Discrete Effluent Sampling – In addition to the continuous *in situ* monitoring of the effluent, discrete effluent samples were collected to verify the *in situ* data and provide additional information on the waste stream. Samples were obtained for analysis of Rhodamine WT, chloride, total suspended solids (TSS), ammonium (NH_4), phosphate (PO_4), silver (Ag), copper (Cu), and fecal coliform/*Enterococcus* (Table 2-3). These samples were collected prior to dye addition, periodically over the 6-hour period that the dye was released, and following dye addition and dye levels had returned to background levels. The discrete samples were collected as grab samples from the flow of a submersible pump that was placed near the *in situ* monitoring point in the west disinfection basin. Samples were also collected from the east basin for Rhodamine analysis only. These grab samples were collected along the western edge of the east basin ~1 m below the effluent surface. The discrete samples were analyzed by the either MWRA Deer Island Laboratory (DIL), Battelle, or University of Rhode Island (URI) as specified in Table 2-3. Total suspended solids (TSS) and nutrients were measured by both DIL and URI to allow comparison of standard-oceanographic to EPA-approved methods.

Table 2-3. Laboratory analysis of discrete samples collected at DITP and in the field.

Parameter	Units	Instrument	Reference	Sample source	Lab
Rhodamine WT	µg/L	Seapoint rhodamine fluorometer	Seapoint Rhodamine WT fluorometer manual	DITP & Offshore	Battelle
Chloride (Effluent only)	mg/L	Mettler autotitrator	MWRA (1997) SOP 10-ORNG-TAR-01.1	DITP	DIL
Total suspended solids	mg/L	Mettler 5-place balance (0.01 mg)	Battelle SOP 5-053	DITP & Offshore	URI
Total suspended solids	mg/L	Mettler 4-place balance (0.1 mg)	MWRA (1999) SOP 1012.0	DITP	DIL
Dissolved ammonium	µM	Technicon Autoanalyzer II	Lambert and Oviatt (1986); Solorzano (1969)	DITP & Offshore	URI
Dissolved ammonium	µM	Skalar autoanalyzer	MWRA (1998a) SOP 1005.0	DITP	DIL
Dissolved phosphate	µM	Technicon Autoanalyzer II	Murphy and Riley (1962)	DITP & Offshore	URI
Dissolved inorganic phosphorus	µM	Skalar autoanalyzer	MWRA (1998b) SOP 1006.0	DITP	DIL
Silver – total	µg/L	Inductively coupled plasma mass spectrometry (ICP-MS) or graphite furnace atomic absorption	EPA Method 200.8, 200.9 (EPA 1991); EPA Method 1638 and EPA 1640 Battelle MSL SOP I-022; Battelle MSL SOP I-029	DITP & Offshore	Battelle
Copper – total	µg/L	Inductively coupled plasma mass spectrometry (ICP-MS) or graphite furnace atomic absorption	EPA Method 200.8 , 200.9 (EPA 1991); EPA Method 1638 and EPA 1640 Battelle MSL SOP I-022; Battelle MSL SOP I-029	DITP & Offshore	Battelle
Fecal Coliform/ *Enterococcus*	#/100 mL	Microscope	MWRA (1996a) and MWRA (1996b)	DITP & Offshore	DIL
Chlorophyll a/phaeopigments	µg/L	Turner Designs fluorometer Model 10AU	Arar and Collins (1992); Battelle SOP 5-265	Offshore	UMD

2.1.2 Offshore Field Activities

A description of the planned offshore methods employed for this survey is presented the *Combined Work/Quality Assurance Project Plan for plume tracking: 2001* (Bruce *et al.* 2000) and are further elaborated in a survey plan prepared for the survey (Battelle 2001). During the first day of survey operations when dye was emerging from the diffusers, the survey focused on the environment in the immediate vicinity of the outfall. Additional monitoring of the plume at greater distances was conducted on the second and third days. The dye plume tracking was conducted using a second *in situ* sensor package deployed from the *R/V Aquamonitor* in the BOSS towfish. The BOSS towfish sensor package, in "towyo" mode (undulating depths), provided measurements of Rhodamine WT dye that indicated the vertical and horizontal distribution of the effluent. The data from the first survey day were used to develop contours of dilution over relatively small spatial scales (meters to 100s of meters) in the immediate vicinity of the outfall. Data collected during the far field survey day were used to demonstrate the dispersion of the plume over longer time scales. To support the interpretation of the dilution field and the transport of the plume, current velocities in the study area were measured using a downward looking Acoustic Doppler Current Profiler (ADCP) installed on the survey vessel. Density data were measured with a CTD throughout the study. The ADCP measurements documented the currents that affect the dilution and short-term trajectory of the plume. Onboard graphic displays of *in situ* temperature, salinity, and Rhodamine WT dye were used during the survey to guide field decision-making. Additional details of the equipment, methods, and final survey strategy can be found in Battelle (2001) and Mansfield *et al.* (2001).

The offshore surveys included the following four components:

- *Background survey* –This survey was designed to obtain measurements of background fluorescence in the environment prior to dye release at the diffuser and to obtain discrete background water samples from locations outside the region influenced by the effluent.

- *Exploratory surveys* –The objective of this exploratory survey was to determine the hydrographic gradients, current directions, and current velocities near the diffuser before dye emerged from the diffuser. Following dye emergence, exploratory surveys were continued to define the prevailing movement, location, and dispersion of the dye. These data guided the location and field approach to the hydraulic mixing zone surveys.

- *Hydraulic mixing zone (HMZ) surveys* –These surveys were designed to measure dilution within and outside the hydraulic mixing zone. The data were used along with modeling to determine compliance with the requirements of the MWRA NPDES permit. Discrete samples were collected during each HMZ survey.

- *Far field plume tracking survey* – The objective was to determine plume structure and behavior in the Far field by tracking the spread of the dye to dilutions of at least 1:1000.

The first three offshore activities occurred on July 17. Survey activities on July 18 and 19 were dedicated exclusively to the far field plume tracking (Table 2-1). During the offshore surveys, both *in situ* data and discrete samples (first day only) were collected to support dye tracking, dilution estimates, and hydrographic characterization. During the background and HMZ surveys, discrete samples were collected as a secondary measurement of dilution and to demonstrate the effectiveness of effluent treatment and dilution. A summary of the parameters measured in the discrete samples is presented in Table 2-3. Discrete sample locations were selected in the field based on the real-time towyo *in situ* data. Discrete sample collections were completed as the vessel drifted or was slowly powered through the

effluent plume. Discrete samples were collected using the BOSS pumping system which delivered a stream of seawater from depth to the *R/V Aquamonitor*'s shipboard laboratory. The depths where discrete samples were obtained included:

BACKGROUND

- One sample at each of 4 depths from a location outside of the effluent plume (see Section 3.2 for the location) for measurement of Rhodamine, TSS, NH_4, PO_4, and chlorophyll. The samples were collected to ensure background conditions at various depths were available for *in situ* sensor correction/calibration and calculation of dilution using discrete parameters measured.
- One sample at each of two (2) depths from a location outside of the effluent plume for silver and copper analysis.

HMZ1

- While nine (9) discrete samples were scheduled for collection during HMZ1, only 3 sample locations could be obtained due to the narrowness of the dye field and time available to the field crew. Samples for TSS, NH_4, PO_4, Rhodamine WT, chlorophyll and copper and silver analysis were obtained.

HMZ2 & HMZ3

- Discrete samples were collected at nine locations during each of the HMZ2 and HMZ3 surveys. These samples were obtained in the core of the dye field exiting the diffuser. Samples for TSS, NH_4, PO_4, Rhodamine WT, chlorophyll, copper and silver and fecal coliform and *Entercouccus* analyses were obtained.

While real-time survey data (both at DITP and offshore) were used to make decisions in the field, all survey (*in situ*) and laboratory data (discrete sample) were subsequently entered into the MWRA Environmental Monitoring and Management System and subjected to a quality assurance review before use in the plume tracking assessment. During data post-processing, the background fluorescence of seawater outside the direct influence of the outfall was subtracted from the fluorescence values obtained from the plume tracking surveys. Additionally, all fluorescence data were temperature corrected as described in Section 2.1.

The contouring and surface mapping software Surfer® was used to plot nearfield and far field data in this report. Grid files of dilution, depth and latitude or longitude, or dilution, latitude and longitude were created from data in the database. Gridding allowed the interpolation or extrapolation of data following the *inverse distance to a power* method (Golden Software 1999). The inverse power method was selected over kriging because the wide range of dye dilution values caused the kriging method to overshoot data during extrapolation. For horizontal plume dispersion plots the highest dye concentration from each towyo pass (up or down) was selected, and only those points were used in the grid data. For each gridded plot contained in this report the gridding search radius is identified.

The data collected during the plume tracking exercise were also used as input to the environmental discharge model RSB (described in Baumgartner *et al*. 1992). RSB was developed based on experiments on multiport diffusers in density-stratified currents. This model predicts the spread of the plume and calculates the minimum dilution and the flux-average dilution based on the physical characteristics of the outfall, diffuser flow rate, effluent density, ambient water density, and the current speed at one depth. The approach and results are presented in Section 3.5.

2.2 Physical Oceanographic Study

During the offshore surveys, data were also collected supporting a physical oceanographic study conducted to assess the forcing conditions, current regime at the vicinity of the outfall, and dye dispersion in support of the interpretation of dye dilution and transport assessments. Water properties were obtained from conductivity, temperature and depth profiles acquired from Battelle's BOSS profiler data (Table 2-4). Data on the current field were obtained in two ways. In addition to the currents obtained from the ship-mounted ADCP, which was deployed continuously during the three offshore survey days, continuous current data were obtained from the USGS (United States Geological Survey) bottom-mounted ADCP located near the Boston Buoy (latitude 42 22.72, longitude 70 46.84). The ship mounted ADCP provided real-time current measurements to the offshore survey crew at 0.5 m or 1.0-m vertical increments between 2.5-m depth and 26-m depth (in 30 m of water). The USCG ADCP provide data from ~1000m south of the diffuser. These data were obtained courtesy of Dr. Brad Butman from the web sites http://woodshole.er.usgs.gov/starbell/Scituate/Scituate.htm and http://woodshole.er.usgs.gov/starbell/Boston/Boston.htm.

Table 2-4. Summary of shipboard instrumentation.

Parameter	Lab	Units	Instrument	Reference
Rhodamine fluorescence	Battelle	µg/L (ppb)	Seapoint RWT Fluorometer	Seapoint manual (2000)
Conductivity	Battelle	mmhos/cm	OS200 CTD	Ocean Sensors CTD manual (1999)
Temperature	Battelle	C	OS200 CTD	Ocean Sensors CTD manual (1999)
Pressure	Battelle	m	OS200 CTD	Ocean Sensors CTD manual (1999)
Transmissometry	Battelle	m-1	Seatech 20-cm (660nm)	Seatech manual (1998)
Altitude	Battelle	m	Datasonic PSA-916	Datasonic manual (1997)
Bottom depth	Battelle	m	Furuno FCV-52	Furuno manual (1998)
Navigational position	Battelle	degrees	Northstar 942X	Northstar manual (1998)
Ocean current velocity	Battelle	cm/sec	RD Instruments ADCP WHM600-I-UG6	RD Instrument manual (2000)
Sigma-T*	Battelle	no units	OS200 CTD	Fofonoff and Millard (1983)
Salinity*	Battelle	PSU	OS200 CTD	Fofonoff and Millard (1983)

* Sigma-T and salinity are calculated from conductivity, temperature, and pressure.

The mooring data provided information on the general direction of the water column advection during the dye release and enabled a comparison of current conditions during the release relative to typical conditions during 2001. The data include hourly velocities from May 23 to October 23, 2001, at 2-m depth increments from 2-m to 24-m depth. The hourly data were filtered with the 33- hour "PL33" filter to render the tidally averaged velocities. Particular attention was focused on the data near 12-m depth, which is the average depth of maximum dye concentration observed during the study. Additionally, tidal information was obtained from the NOAA tidal predictions and wind data were obtained from the NOAA web site http://seaboard.ndbc.noaa.gov.

Dye dispersion during the far field surveys on July 18 and 19, 2001 was determined from the distribution of dye. The horizontal moments and the effective dispersion were evaluated. The magnitude of the dispersion was also assessed in context with previous observations and the forcing conditions in Massachusetts Bay. The analysis focused on the first far field survey, which came closer to fully mapping the dye distribution than the second far field survey. An initial attempt to use the decrease in

maximum dye concentration with time to estimate dilution was found to be ineffective because the dye concentrations were too variable and there was no broad "maximum". A second method, which is discussed in Section 3.4.4, estimated the dispersion by the more conventional approach of calculating the second moment of the dye distribution at a known time following the release. The approach used the change in size of the dye patch to estimate the dispersion coefficients in the two horizontal directions as

$$K_x = 1/2\ d/dt\ (X')^2$$
$$K_y = 1/2\ d/dt\ (Y')^2$$

where K_x is the horizontal diffusivity in the x direction, d/dt is the normal time derivative, and $(X')^2$ is the horizontal variance in the x direction, and likewise for the y direction. The x and y directions can picked arbitrarily. However it is most informative to rotate the coordinate system to directions of maximum and minimum variance, i.e., "along" the patch. After this rotation, the dye concentrations were vertically integrated, and the horizontal positions of the observations were shifted horizontally, based on trajectories derived from the shipboard ADCP velocity measurements at the mid-depth of the dye (12-14 m). This removed apparent displacements due to the finite time of the survey. The distribution of the dye following the dye injection into Massachusetts Bay was then estimated. The time derivative was based on the change in the second moment between 1700 EDT on July 17 and the same time on July 18, 2001.

2.3 Cooperative Studies

The United States Environmental Protection Agency (EPA) in cooperation with the National Oceanic and Atmospheric Administration (NOAA) has been conducting studies of effluent dilution in the marine environment using acoustic and *in situ* measurement approaches. During the offshore components of this July plume survey, the EPA and NOAA coordinated several offshore survey activities with the MWRA. The EPA/NOAA survey used instrumentation similar to that used by the MWRA team (towed dye and CTD sensors) except the EPA/NOAA sensor suite was towed at fixed depths in contrast to the towyo operations used by the MWRA team. The acoustic system on board the EPA survey vessel (a downward looking ADCP) has the additional capability of evaluating acoustic backscatter (a measure of particle fields) thus was able to perform a high resolution study of the particle fields in the vicinity of the diffuser before and during the dye emergence from the diffuser as well as in the far field. During the survey several activities were conducted to cross calibrate the various measurement systems including a side-by-side vertical hydrocasts conducted within 75 m of each other and various towed transects conducted either in parallel or perpendicular to each other or sequentially along the same trackline. This provides robust set of data for intercomparison, although such comparisons are not made in this report.

3.0 RESULTS

3.1 Dye Addition – DITP

Rhodamine WT dye was introduced into the effluent stream at DITP from 2145 EDT July 16 to 0345 EDT July 17, 2001. The DITP effluent flow rate varied from 346 MGD at the start of dye injection, to a peak of ~370 MGD at midnight before decreasing to 254 MGD at the end of dye injection (Figure 3-1). The flow increased to approximately 550 MGD at mid morning during the plume tracking study in response to ~0.3 inches of rain. Flow decreased to less than 380 MGD by noon on July 17 and varied for the remainder of the period that the dye was being tracked offshore on the 17th.

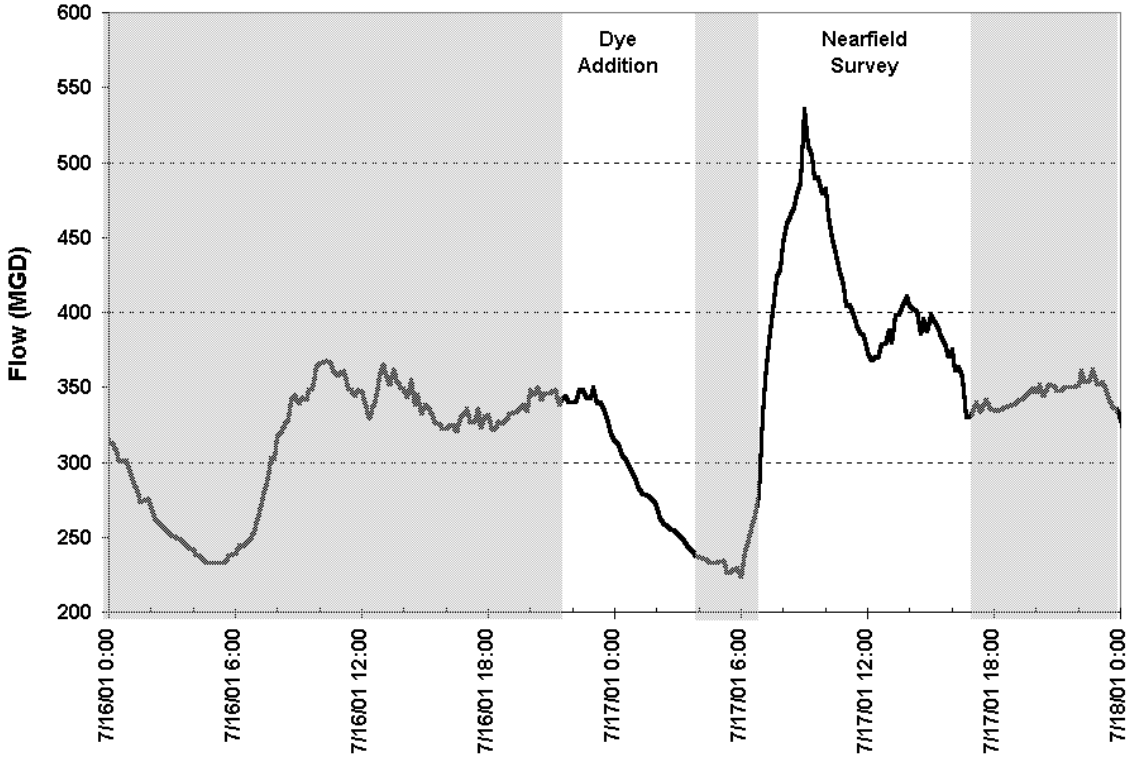

Figure 3-1. DITP flow rates during the survey period[2]. Times are EDT.

The DITP dye concentration measured by the *in situ* fluorometer in the west disinfection basin showed that the dye concentration was extremely uniform once the dye concentration had stabilized in the disinfection basin and remained so until dye injection was discontinued (Figure 3-2). Vertical profiles conducted at three locations within in the cross section of the west basin demonstrated that dye concentrations were uniform across the effluent channel. Discrete dye sample concentrations from each basin were also constant after the dye reached a constant concentration (Table 3-1). As observed in the April Survey (Hunt *et al*. 2002), the east disinfection basin had slightly higher discrete sample values relative to the west basin data.

[2] Data provided by MWRA

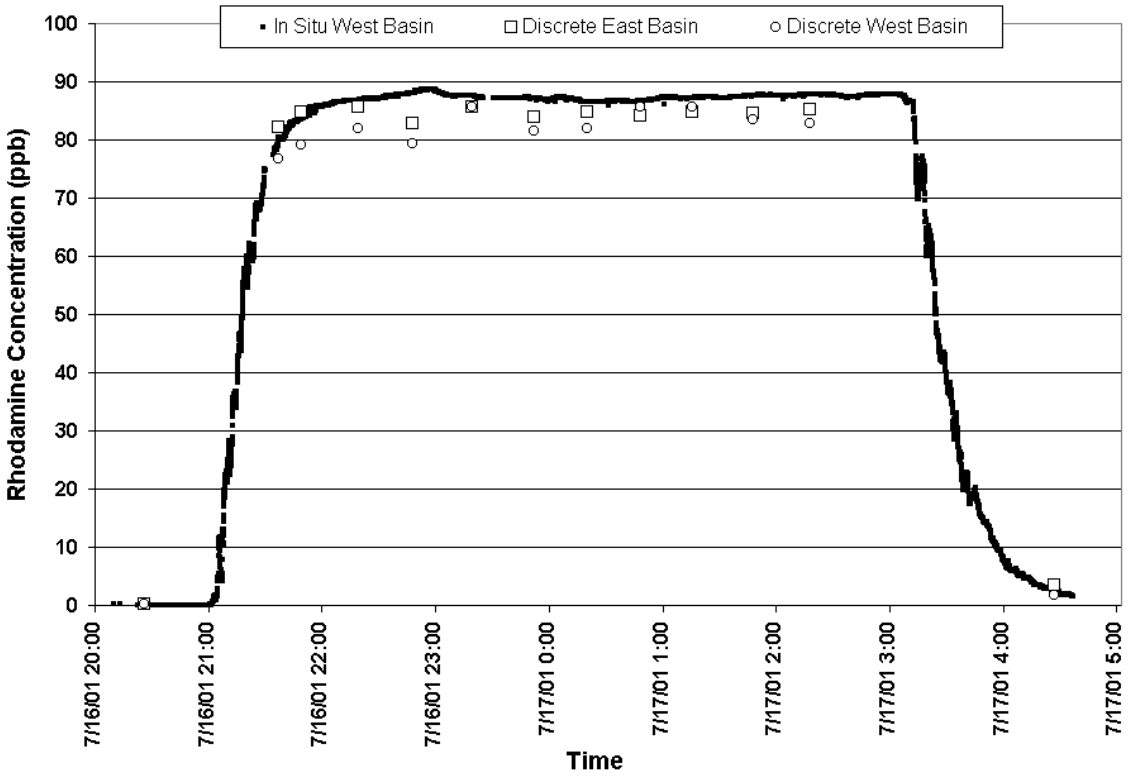

Figure 3-2. DITP *in situ* and discrete dye concentrations. Note times are EST.

Table 3-1. Dye concentrations (mg/L) in the East and West disinfection basins (highlighted samples are not included in the means).

Sample ID		Time of Collection	Dye Concentration (ppb)			
West Basin	East Basin	EST	West Basin *In Situ*	West Basin Discrete	East Basin Discrete	DITP Grand Mean
P012A032	P012A033	7/16/01 20:35		0.12	0.13	
P012A03B	P012A03C	7/16/01 21:47		76.77	82.13	
P012A042	P012A043	7/16/01 21:59		79.06	84.81	
P012A048	P012A049	7/16/01 22:29		82.06	85.74	
P012A04C	P012A04D	7/16/01 22:58		79.42	82.84	
P012A050	P012A051	7/16/01 23:29		85.64	85.36	
P012A057	P012A058	7/16/01 24:02		81.48	83.99	
P012A05B	P012A05C	7/17/01 00:30		82.02	84.83	
P012A060	P012A05F	7/17/01 00:58		85.56	84.16	
P012A063	P012A064	7/17/01 01:26		85.71	84.8	
P012A067	P012A068	7/17/01 01:58		83.45	84.55	
P012A06B	P012A06C	7/17/01 02:28		82.81	85.25	
P012A075	P012A076	7/17/01 04:37		1.77	3.48	
Mean			87.27[A.]	82.72[B]	84.63[B]	**85.96**[C.]
Std.Dev.			0.592	2.42	0.85	

A. Range 84.0 to 88.77, n = 7,871
B. Highlighted samples not representative of stable dye concentration and not included in mean
C. Average of the West Basin mean *in situ* data and the mean of the East Basin discrete values

The DITP dye monitoring strategy (continuous *in situ* monitoring in the west disinfection basin only), was developed under the assumption that dye concentrations would be the same in both the east and west disinfection basins. However, as noted above, discrete samples collected concurrently from the two basins showed small differences (within 10% of each other) with the east basin having consistently higher values. The average concentration between the two basins was within 3 % not including the highlighted values that were not included as they represent increasing or decreasing dye concentration rather than stable dye concentrations. Thus, these data indicate that while each of the disinfection basins represent very nearly 50% off the total plant flow as well as 50% of the total dye flow, the unequal mixing must be accounted for in the final estimate of effluent average dye concentration. Note also in Figure 3-2 the slightly lower discrete sample concentrations relative to the *in situ* sensor data. The cause of the small differences could not be identified.

Because the dye concentration in the effluent is a critical value in the determination of offshore dilution, several approaches were evaluated to determine the initial concentration. As done for the April survey (Hunt *et al*. 2002), the mean *in situ* dye concentration from the west basin and the mean dye concentration from the discrete sample analyses from the east basin were averaged together as the most defensible approach. This method provided the largest number of data points from the west basin, while incorporating the available data from the east basin, thus achieving the most accurate mean concentration that accounts for subtle variations throughout the stable dye period. The resulting overall mean dye concentration in the effluent is 85.96 ppb (Table 3-1). This is the initial concentration (C_0) used for the calculation of dye dilution in the plume tracking and far field surveys.

3.1.1 Weight of Dye Used

The accuracy of the average dye measurement was evaluated independently to validate the initial dye concentration (C_0) calculations. This was accomplished using the mass of dye added to effluent divided by the volume of effluent to which the dye was added to estimate an average dye concentration. Four 30-gallon (capacity) barrels of Rhodamine WT dye were purchased and available for the dye addition. Of the four dye barrels, two were from Keystone lot #566 and two were from lot #209 (only the barrels from lot #209 were used during the dye addition). Each barrel was assigned a number (1-4), which was written on the side and top. On Monday, July 16, 2001 each of the four dye barrels was weighed at DITP. Each of the barrels was again weighed at DITP on November 7, 2001. Table 3-2 lists the initial and final weights of the dye barrels as well as the total weight added to the effluent stream from each barrel. The total weight of Rhodamine WT dye added to the effluent during the dye addition was 288.5 lbs. This compares closely with the total mass accounted for based on a flow weighted integration of the i*n situ* dye concentrations in Figure 3-2, which resulted in an estimated addition of 286.7 pounds of dye. These independently derived weights increase the confidence that the average concentration of dye measured in the effluent is highly accurate.

Table 3-2. Weight of Rhodamine dye barrels.

	Lot #566		Lot #209	
Barrel #	**1**	**3**	**2**	**4**
Initial weight (lbs)	270	269	275	269
Final weight	270	269	137	118.5
Weight of dye added	0	0	138	150.5

3.2 Offshore Dye Tracking –Plume Tracking

In situ dye fluorescence, as well as the fluorescence of the discrete samples analyzed after the survey, was measured with the same rhodamine fluorometer. The concentration of dye in the plume or discrete sample (C_{plume}) measured directly in ppb using the *in situ* rhodamine fluorometer was used to determine dilution (S):

$$S = \frac{C_o}{C_{plume}}$$

where C_o is the concentration of dye in the effluent at the Deer Island Treatment Plant and C_{plume} is the concentration of dye in the plume in the ocean. The C_0 value calculated from the DITP data was 85.96 µg/L as active dye ingredient (Table 3-1). All dye values were compensated for the temperature effect described in Section 2.1.

3.2.1 Background Survey

The objective of the background survey was to obtain measurements of background fluorescence in the environment prior to dye release at the diffuser and to obtain discrete background water samples from locations outside the region influenced by the effluent. The background survey was conducted prior to dye emergence from the outfall diffusers. The tracklines of the background survey are shown in Figure 3-3. Upon arriving near the western end of the diffuser, a towyo trackline was conducted from west to east directly down the diffuser line (labeled "A" in Figure 3-3). This trackline was conducted to collect *in situ* background values within the effluent plume area and to determine the direction of currents in the area. Section "B" of the background transect was a towyo operation conducted away from the diffuser in a direction opposite to the current direction observed in the onboard ADCP data. The direction was established because currents were slightly to the west and the tide stage was approaching high flood. Section "C" of the background survey was the location for collection of discrete background samples and is in an area outside of the effluent plume. Confirmation of this is presented in the discussions on turbidity and discrete background data.

The mean background fluorescence of seawater outside the direct influence of the outfall, measured with the *in situ* sensor during the vertical profile prior to discrete samples collection (location "C" in Figure 3-3) was 0.0158 ppb. During post-survey processing, this value was subtracted from all *in situ* fluorescence measured during the nearfield and far field plume tracking exercises to correct for the background contribution.

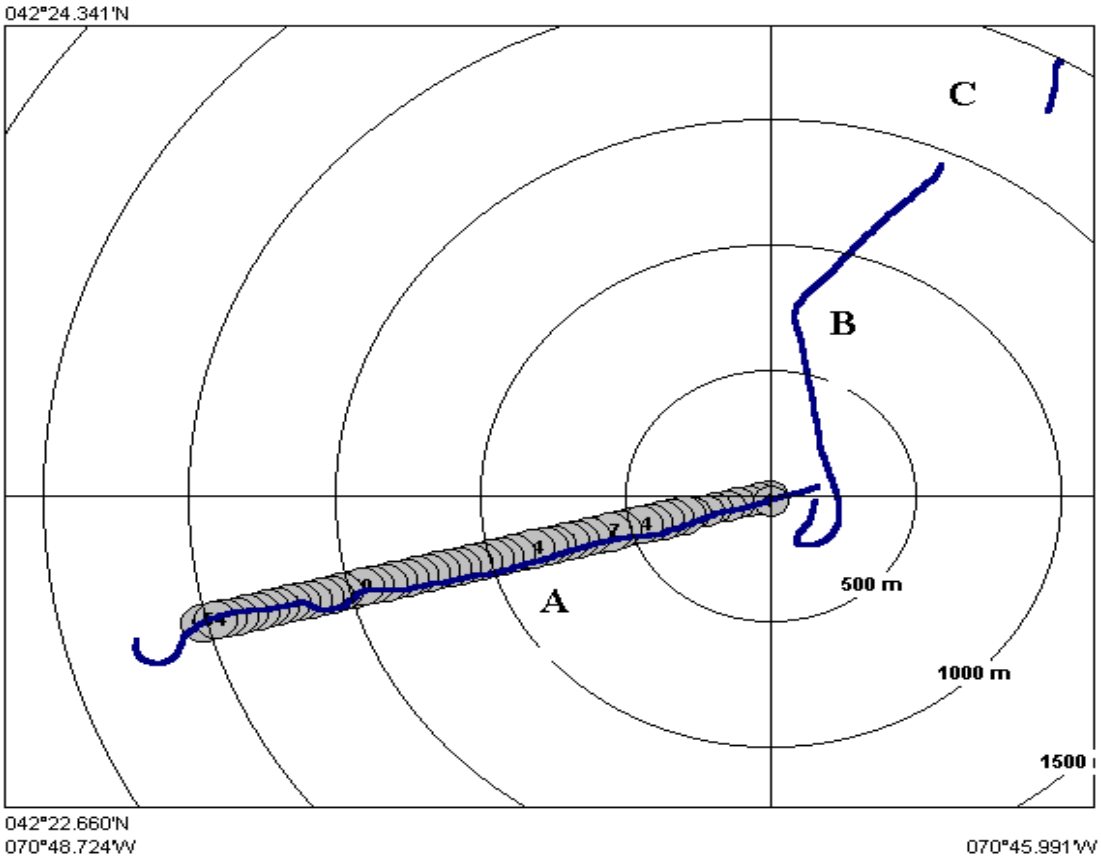

Figure 3-3. Locations of background survey transects and background discrete sample collections.

Two *in situ* methods were used to independently measure the particle concentrations in the water during the offshore surveys. The first measures transmissivity (percent transmission of light over a given path length in water) and is reported as beam attenuation in inverse meters (m^{-1}). The second measures turbidity by detecting light scattered from suspended particles in a small volume of water (within 5cm of the sensor).

Figure 3-4 shows a vertical profile of beam attenuation and turbidity at the background station. Because the response of these two instruments is very similar (Figure 3-5, $r^2 = 0.84$), only beam attenuation is used as a measure of the particle field in this report. The correspondence between beam attenuation and TSS for all discrete sample locations was not as good with the $r^2 = 0.52$ (Beam = 0.455TSS + 0.464)[3].

[3] The correspondence improves substantially for samples from HMZ2 where Beam = 0.379TSS + 0.625 $R^2 = 0.918$

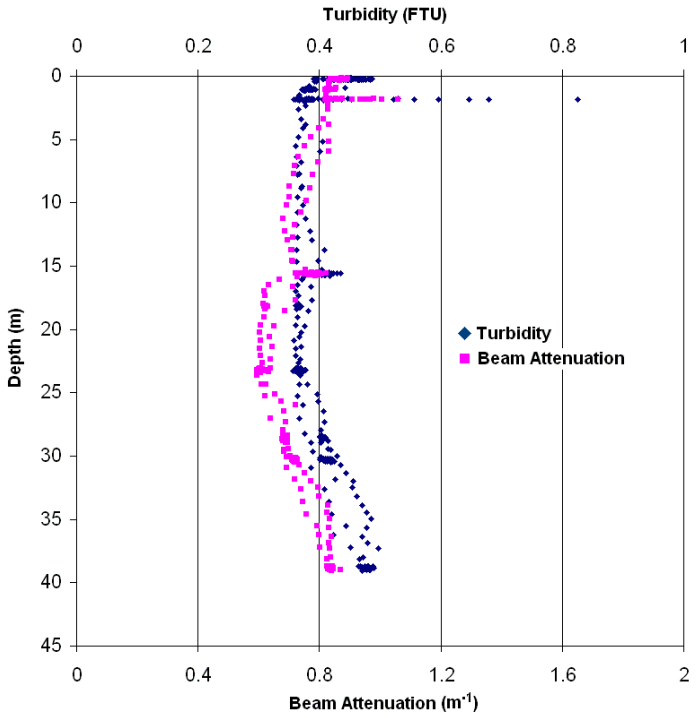

Figure 3-4. Background beam attenuation and turbidity profile (including downcast and upcast data).

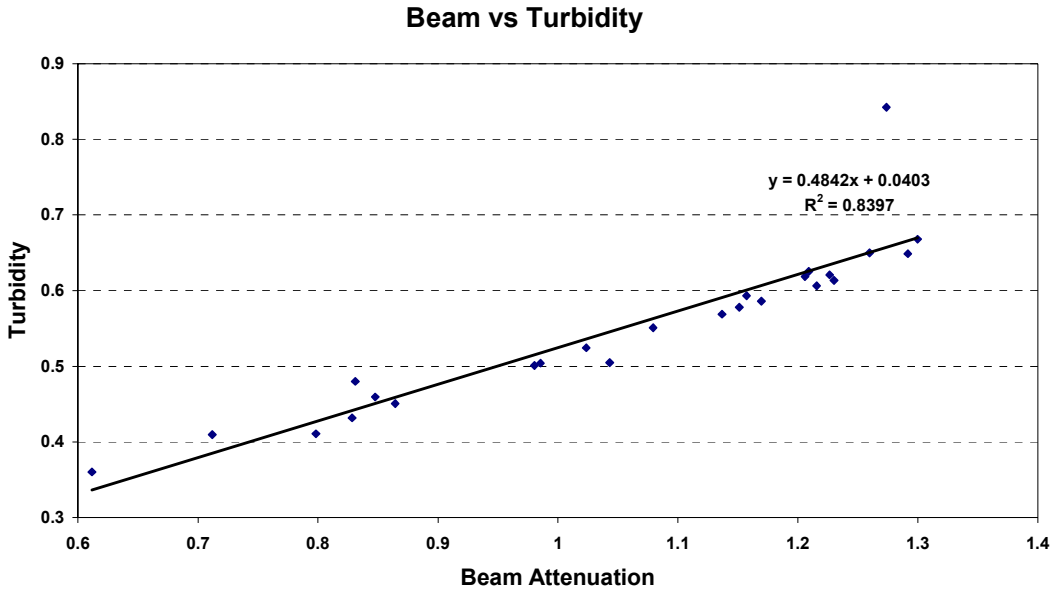

Figure 3-5. Correspondence between beam attenuation versus turbidity measured concurrently during discrete sample collections on July 17, 2001.

The two primary sources of particles in coastal water are biogenic material (plankton or detritus) and suspended sediments. Beam attenuation measured in the background water column vertical profile ranged ~0.6 to 0.85 m^{-1} with higher values at the surface and at depth in the profile. These values are consistent with the relatively low values of particulate matter in the water column. Background TSS ranged from ~0.61 mg/L at 31 m depth to 1.2 mg/l at ~16 m depth (see Section 3.3).

Comparison of these background particle concentrations with the particle field measured along the diffuser prior to dye emergence at depths between 5 and 15 m and the transect run to the northeast off the eastern end of the diffuser between 5 to 10 m clearly show higher beam attenuation than at the background station (Figure 3-6). Along the diffuser, beam attenuation ranges from 0.85 to 1.26 m^{-1}, with some variability near the mid point of the diffuser. The beam attenuation generally decreases from the mid point of the diffuser system towards the east (offshore and up current at this point in the survey). The beam attenuation decreases to values between 0.6 and 0.83 m^{-1} at ~10 m depth along the trackline run towards the northeast. Given that the currents had been directed towards the west prior to and during the data collection, the results suggest particle concentrations along the diffuser line and likely in waters to the west of the diffuser were affected by the effluent. This is evaluated further in Section 3.2.3.

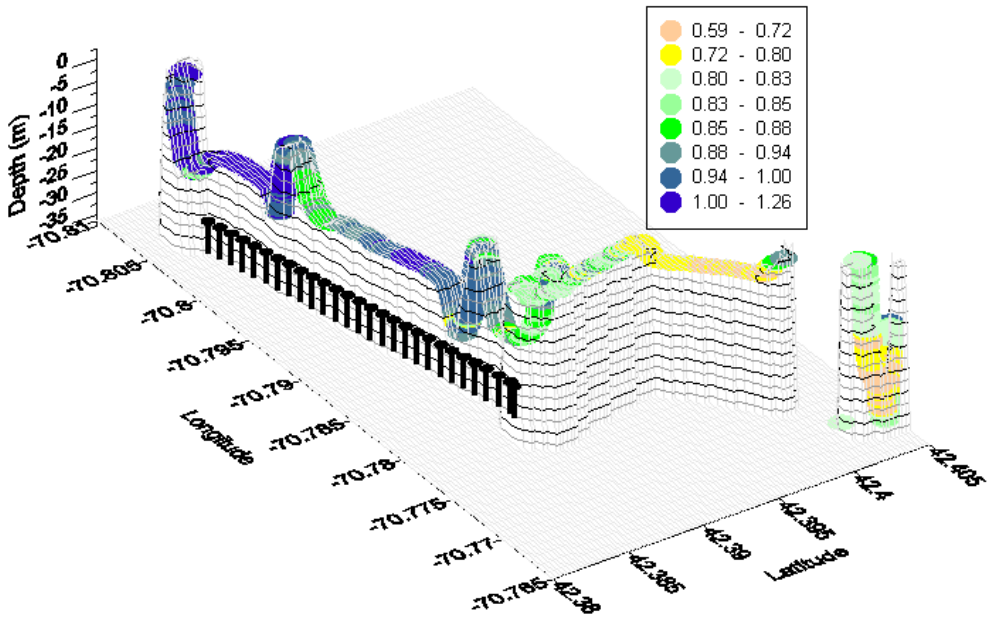

Figure 3-6. Beam attenuation (m^{-1}) measured along the path of the sensor unit adjacent to the diffuser prior to dye emergence from the diffuser.

3.2.2 Pre-dye Emergence Exploratory Survey

Prior to dye emergence: Exploratory transects were conducted before the dye emerged from the first riser to define the hydrographic gradients in the water column near the diffuser line and current direction and velocity (Figure 3-7). Once dye was detected, additional exploratory transects were conducted to define the behavior of the dye and dye field. Transects were conducted west of, and perpendicular to, the diffuser line before dye emerged from riser #55 (the furthest inshore).

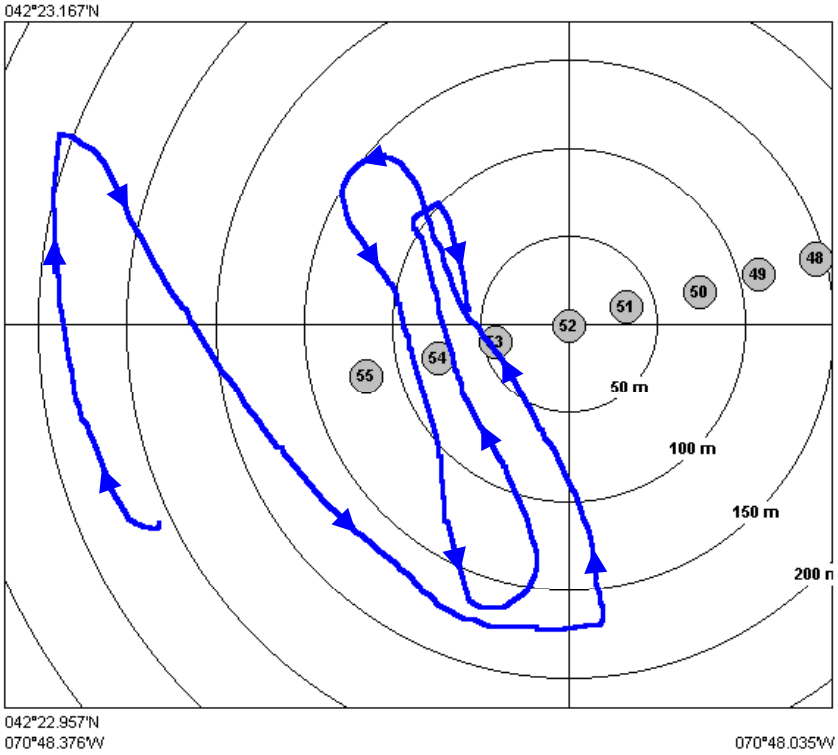

Figure 3-7. Pre-dye exploratory transects.

Figure 3-8 shows a profile of the water column from the all of the pre-dye exploratory transects. The data presented includes the initial detection of dye at 10:27 AM (EDT) over riser #55. Moderate stratification (change in sigma-t = ~1.5), typical of Massachusetts Bay early summer conditions, was observed between 5 and ~7 meters depth in the water column in the vicinity of the diffuser. Even though the data were collected from within the effluent plume (as evidenced by the initial dye emergence), the density data show little influence of the effluent field on the salinity and density. Note that the pycnocline was mostly temperature driven. Temperatures in the surface waters were ~15.5° while waters below 10 m were generally less than 8°C.

During dye emergence: Once dye began to emerge from the diffuser, perpendicular transects were continued between risers 55 and 51 at the west end of the diffuser. These transects allowed 1) time for the dye emergence to reach a steady state (~45 minutes after initial emergence) and 2) and provided a general characterization of the dye plume and dimensions of the dilution field prior to conducting the HMZ transects and sample collection. These transects were conducted in the dye (thus effluent) field and perpendicular to the diffuser line at both fixed depths and under towyo operations. Figure 3-9 shows the post-dye emergence exploratory transects and a general indication of the early plume dispersion; the start time of each trackline is included. The transects were conducted using towyo methods; the dye concentrations shown are from variable depths. Figure 3-10 shows a profile of the water column from the combined post-dye exploratory transects. As the emerging dye increased in concentration, its vertical movement was constrained by the pycnocline; peak dye concentrations were measured between 15 and 20 meters deep. The on board data from these initial transects were used to determine the location, duration and direction of the HMZ transects. No discrete samples were collected during the exploratory transects.

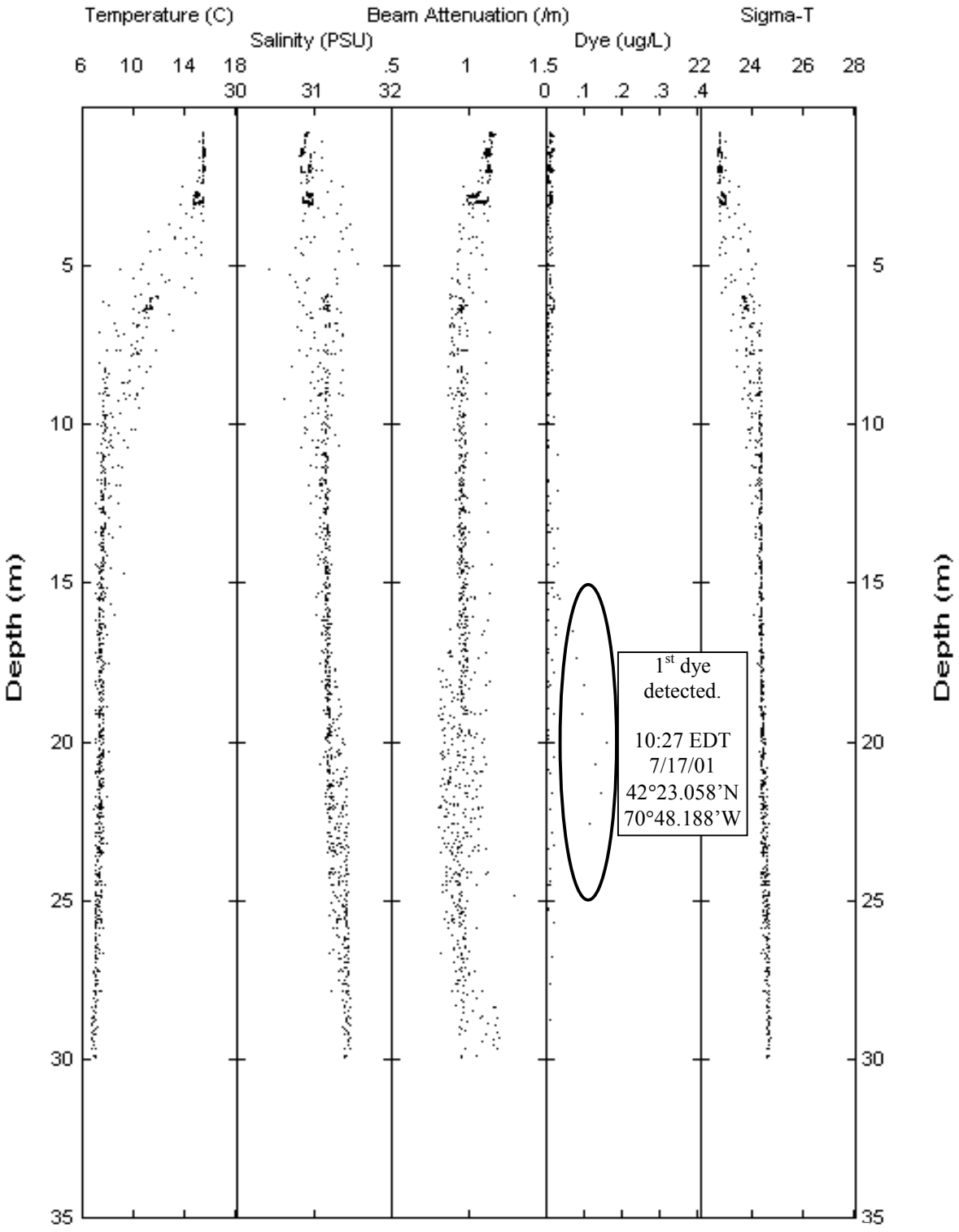

Figure 3-8. Vertical Hydrographic Characteristics from the Pre-Dye Emergence Exploratory Survey Tracklines.

(Start time of each transect is shown. Color scale indicates dye concentration range)

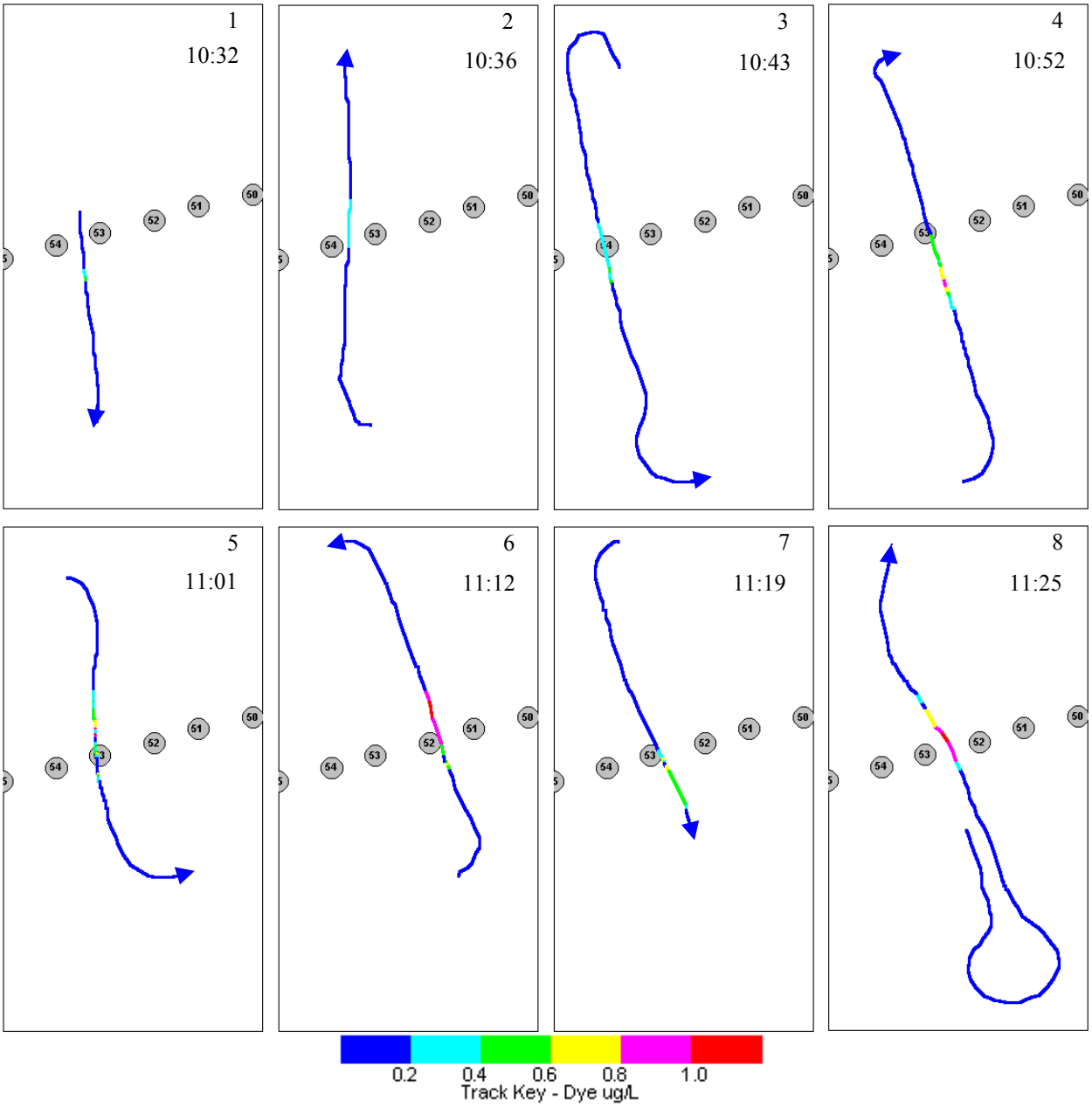

Figure 3-9. Post-dye exploratory survey transects showing dye concetration ranges measured with the *in situ* sensor.

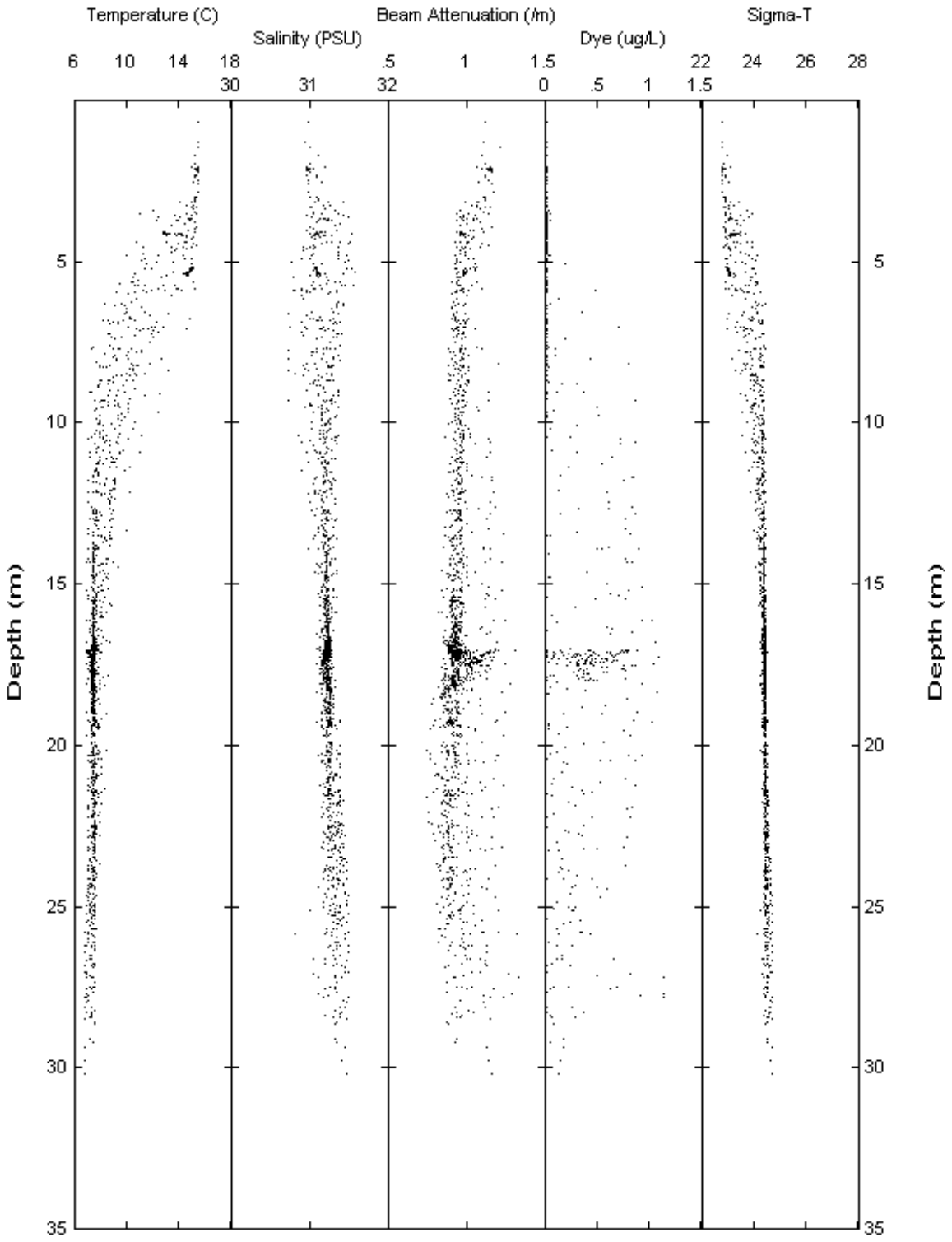

Figure 3-10. Post-dye emergence exploratory hydrographic characteristics.

Residual pre-dye particle fields: The pre-dye emergence data were collected after the tide began to ebb. Thus, particle fields in the water column in this region of the bay could have been affected by previous contact with the effluent as the flooding tide transported the water column to the west over the diffuser and past its western terminus. If this water, containing an elevated particle signature relative to the background levels observed northeast of the diffuser, returned back over the diffuser on the ebbing tide, the particle field measured within in the dye field would reflect the concentrations associated with the dyed effluent plus a residual signal from the previous effluent release. This process could also affect the levels of other constituents measured from the discrete samples. This potential was considered by examining the beam attenuation data from the pre- and immediate post-dye emergence survey tracking lines.

In Figure 3-8 the vertical structure of the particle field in the water column shows relatively constant beam attenuation (~0.9 to 1.0 m^{-1}) between 5 and ~17 m. The beam attenuation at these depths is slightly higher than the values observed at these depths at the background station (Figure 3-4). Above 5 m, the beam attenuation increases to ~1.2 m^{-1}, reflecting higher particle concentrations in the near surface water possibly due to phytoplankton biomass. Between 17 and 25 m, the depth range at which the dye was first detected, beam attenuation tends to show more scatter than observed between 5 and 17 m and at the background station. Immediately after the dye emerged from the diffuser beam attenuation values ranged between 0.9 and 1.3 $m^{-}1$ between ~7 and 17 m depth and 0.7 to 1.3 below 17m (Figure 3-10). This depth corresponds to the depths that dye concentrations ranging up to 0.9 ppb were detected, and reflects an increase in beam attenuation of 0.15 to 0.4 m^{-1} relative to the values observed outside of the dye field.

This was evaluated further by examining the horizontal variability in the pre dye towyo beam attenuation data. This proved difficult due to the nature of the tracklines and changing depths of the exploratory towyo lines. Figure 3-11 shows beam attenuation along the sensor unit's path at the western end of the diffuser prior to dye emergence. The beam attenuation in this figure is plotted on the same scale as shown in Figure 3-6. Evident in the data is generally higher beam attenuation between 5 and 30 m than observed at these depths at the background station. The beam attenuation at these depths (0.85 to 1 m^{-1}) is slightly lower than the 1 to 1.26 m^{-1} measured at the western end of the diffuser at high slack tide on the initial background survey (Figure 3-6). Also evident in the data is the higher beam attenuation in the surface 5 m, which consistently ranged between 1.0 and 1.26 m^{-1}.

The data from these two evaluations suggest there may be a small contribution of particles in the dye field from effluent discharged before that associated with the dye. Thus, the data from the pre dye emergence exploratory survey suggest that the effluent associated with the initial dye signal was discharged into a variable and slightly elevated particle field possibly resulting from previous discharge of the effluent on the flooding tide. Whether the discharge of dyed effluent continued into a residual effluent waste field can only be speculated. However, if it did occur, the influence of the previously discharged effluent on the measured values appears to be small.

3.2.3 Hydraulic Mixing Zone (HMZ) Surveys

The objectives of the HMZ surveys were to collect *in situ* data and discrete samples at or just outside of the boundary of the hydraulic mixing zone to determine initial dilution after the hydraulically driven mixing was complete and to evaluate compliance with the requirements of the NPDES permit.

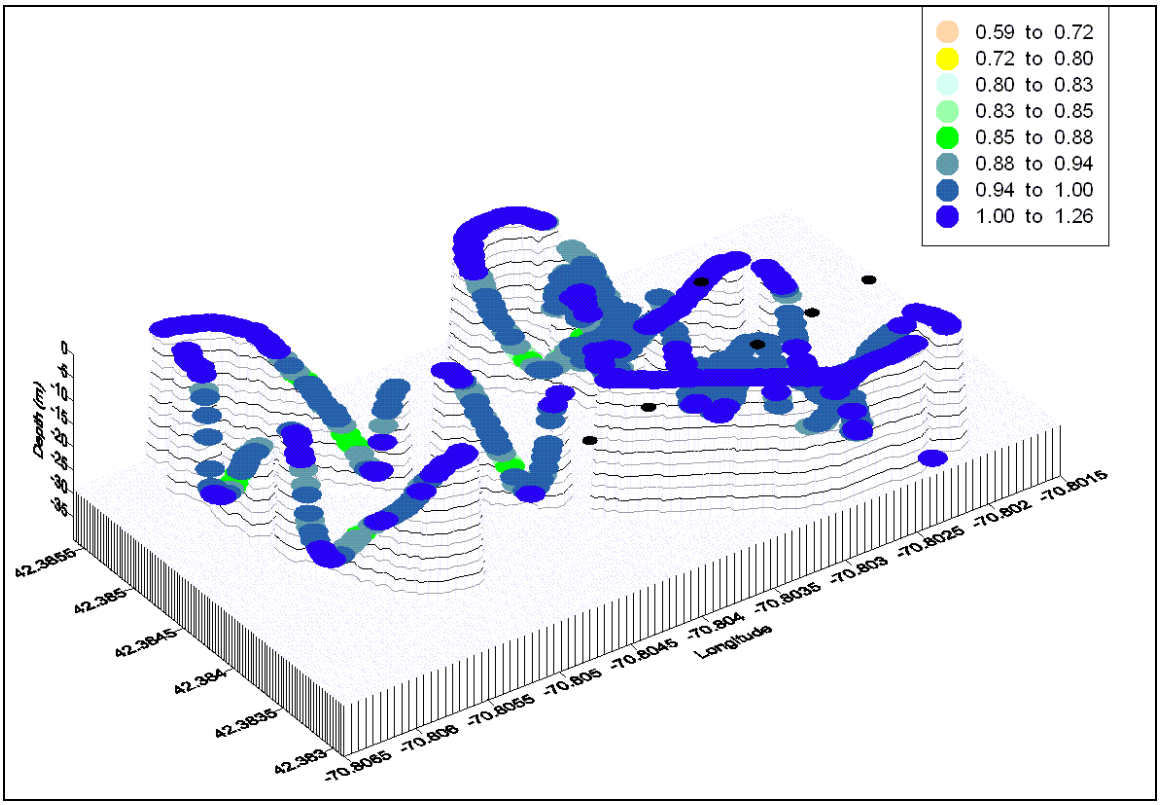

Figure 3-11. Beam attenuation measured along the path of the sensor unit during the pre dye emergence transects at the western end of the diffuser.

Because the currents were essentially parallel to the diffuser line (Section 3.4) and the dye emerged over two hours into the ebb tide, it was determined by the field team that the HMZ surveys should be conducted at least three locations along the diffuser[4]. The decision was predicated on the fact that the flow down the diffuser would cause a laterally spreading plume that ultimately would extend beyond the east end of the diffuser line. Roberts and Snyder (1993a, 1993b) describe plume behavior under this type of current regime. HMZ1 was conducted at the west end of the diffuser between risers 51 and 52 beginning at 11:56 AM EDT, approximately one hour after dye emerged. The second HMZ was conducted midway down the diffuser line between risers 25 and 26 as the tide continued to ebb, approximately 3.5 hours after initial dye emergence. The third HMZ survey was conducted approximately 110 meters east of the eastern terminus of the diffuser approximately 6 hours after initial dye emergence. The tide had turned and was in an early flood stage during this HMZ. Discrete samples were collected during each of the HMZ surveys.

3.2.3.1 HMZ1

Prior to collecting discrete samples, two transects were conducted perpendicular to the diffuser line to assess the dimension of the dye plume and identify ideal sampling locations (Figure 3-12). This figure shows the HMZ1 tracklines, ranges of dye concentrations along the sensor path, and discrete sample locations (arrows pointing to the third trackline). At this location, the plume was

[4] The original plan was to sample two locations with repetition of one or both locations depending on available survey time.

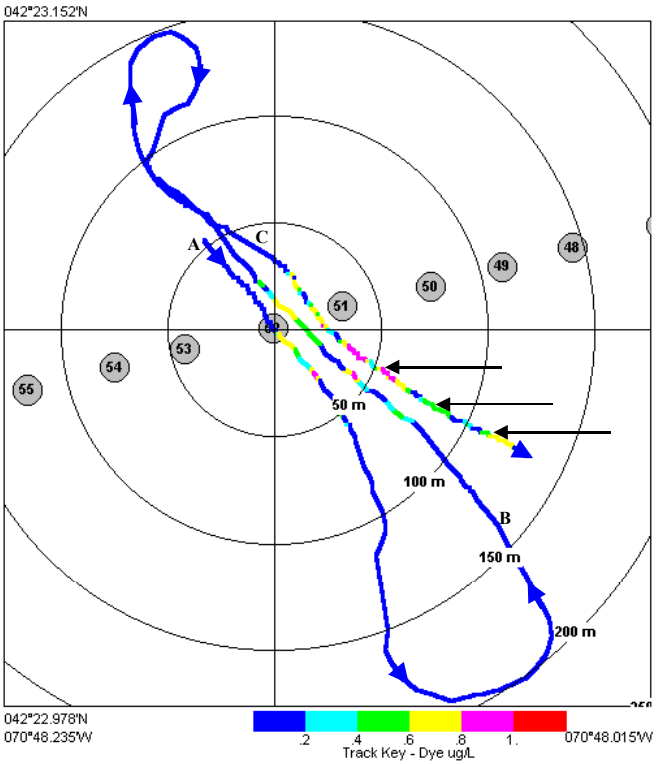

Figure 3-12. HMZ1 Trackline and Discrete Sample Locations (arrows). (Labeled Transects Refer to Figure 3-15)

approximately 150 meters wide and centered around the diffuser axis with slight tendency to set to the south. The maximum dye concentration observed in the dye plume during these transects was 0.92 µg/L. In Figure 3-13 and Figure 3-14, respectively, the dye concentration and dilution were plotted against depth and distance from the diffuser axis using Surfer® contouring software to provide a vertical 2-D view of the plume. This image represents a composite cross-section of the plume incorporating all data during these three transects. Negative values on the x-axis represent the southern side of the diffuser, so that the image is viewed as if looking towards the west along length of the diffuser. For this presentation, the Surfer® program interpolated the data by the inverse distance to a power method across an area of 30m horizontally by 3m depth. Figure 3-13 also includes the position of the towyo sensor in the water column. Locations where discrete samples were obtained during HMZ1 Transect C are also shown on these figures.

The core of the plume (highest concentrations) was found between 15 and 20 meters depth with more dilute portions observed between 5 and 10 m depth. The great majority of the dye plume is submerged below the surface although there was an occasional surfacing. This is most probably isolated puffs in the centers of the turbulent plumes briefly reaching the water surface. At the 15 to 20 m depth, the lowest dilution measured ranged between 90 and 100 (Figure 3-15), as calculated from measured dye concentrations. The highest dye concentration (lowest dilution) was found 22m south of the diffuser at 17 meters depth, where a 93.4 fold dilution was observed. The slight southern set of the dye plume is evident in Figure 3-12, Figure 3-13, and Figure 3-14 and is revealed further in Figure 3-15 where each of the HMZ1 transects is shown independently. These transects were conducted over the course of 45 minutes. Transect "A" took 12 minutes to complete, "B" took 10 minutes, and the combined transect and discrete sampling of "C" took 23 minutes. Note that the sparse data collection points in these individual transect figures results in greater extrapolation of the data compared to Figure 3-13 and Figure 3-14.

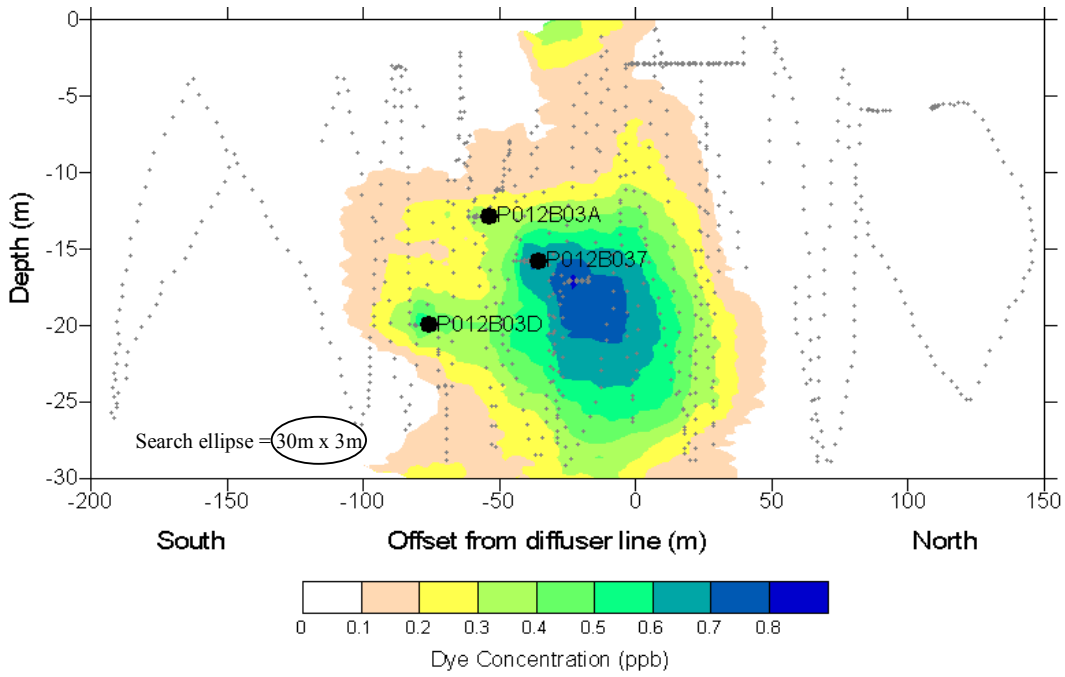

Figure 3-13. Contour plot showing dye concentrations in a composite cross-section of all HMZ1 Towyo Transects. Dotted lines indicate the Towyo Tracks. Sample locations are identified by large dots and Sample ID#.

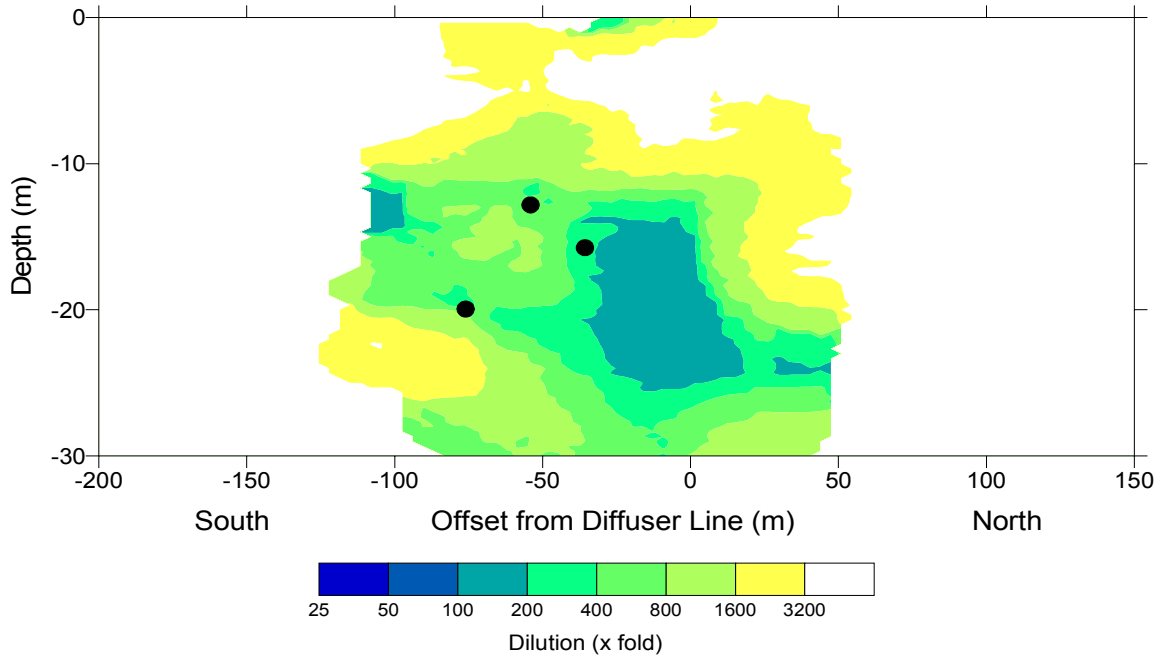

Figure 3-14. Dilution values in the cross-section of all HMZ1 Towyo Transects.

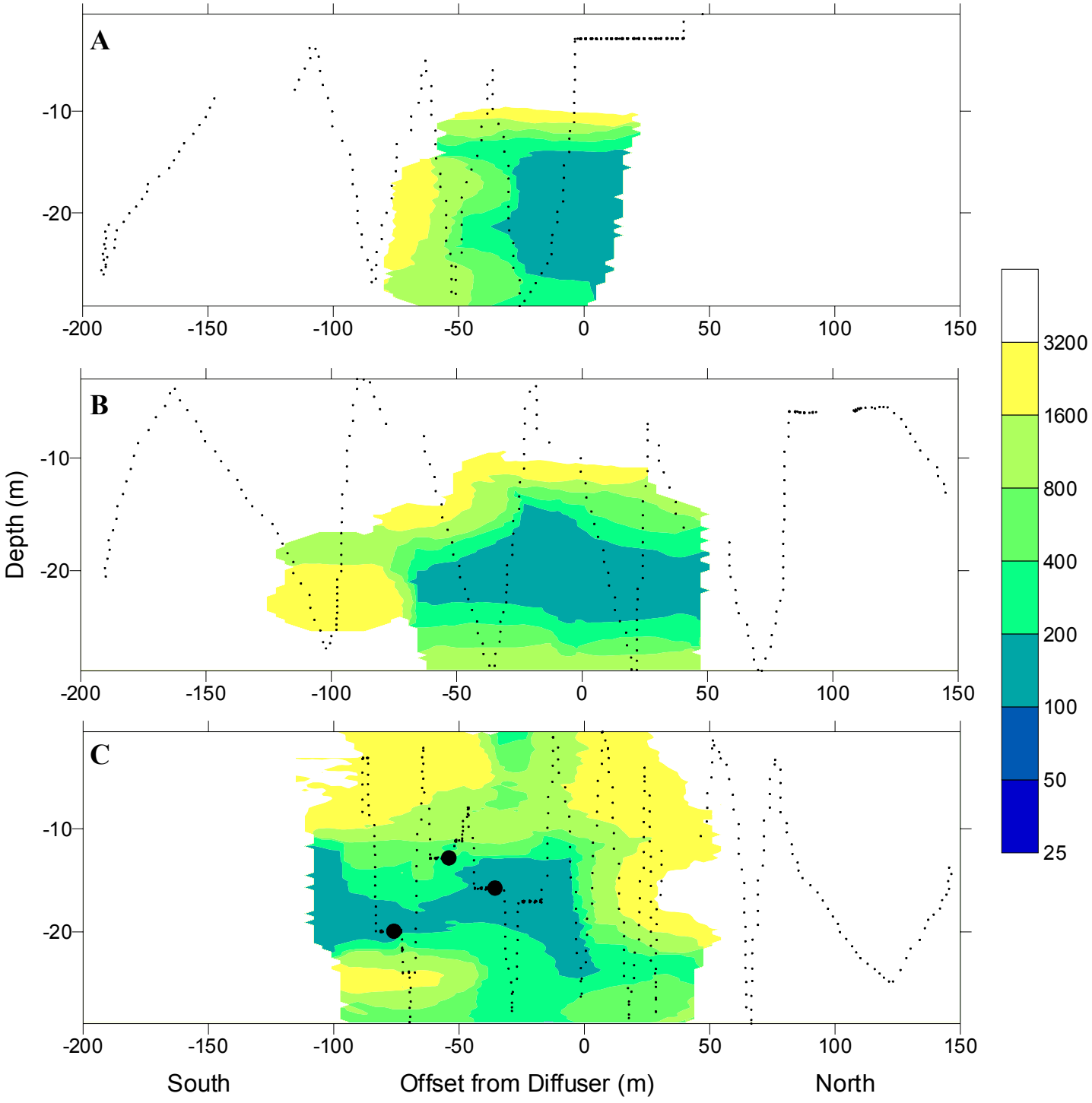

Figure 3-15. Dilution in each of the HMZ1 Transects (as labeled in Figure 3-12).

A composite transect of the beam attenuation data from HMZ1 is plotted in Figure 3-16. The same contouring parameters were used as in Figure 3-13 through Figure 3-15. The effluent plume as represented with beam attenuation is nearly identical in shape to the dye plume and shows the core of the plume (beam attenuation >1.2 m^{-1}) between 15 and 25 m depth. The lateral spread of the plume core was about 50 m with an overall spread above background values of about 150m. Unlike the dye composite contour plot, elevated beam attenuation was measured at depths shallower than 10m. These higher values are consistent with observations during the background surveys and likely result from natural ambient particles (chlorophyll) at these depths.

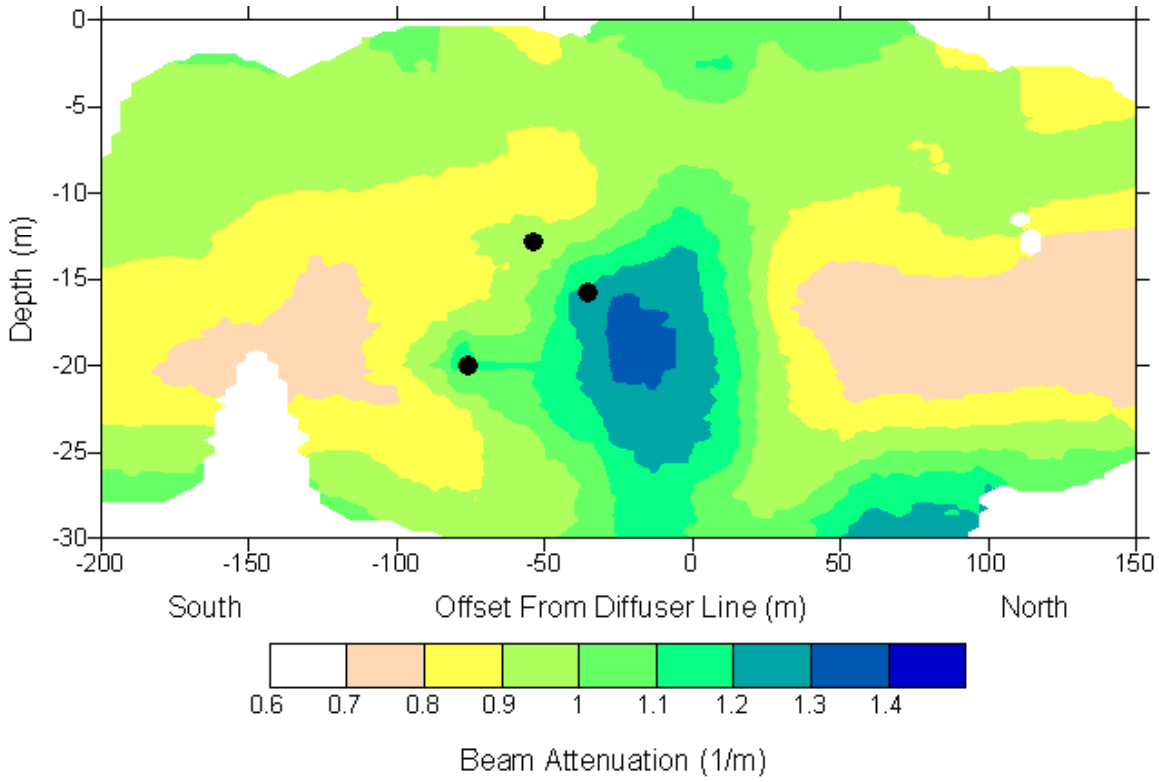

Figure 3-16. Composite beam attenuation contours obtained from HMZ1 showing the locations of discrete sample collection.

3.2.3.2 HMZ2

The second hydraulic mixing zone survey was conducted near the center of the diffuser line between risers 25 and 26 beginning at ~1PM EDT. Prior to collecting samples, two transects were conducted perpendicular to the diffuser line to assess the dimension of the dye plume and identify ideal sampling locations. Figure 3-17 shows the HMZ2 tracklines, approximate dye concentrations, and discrete sample locations. At the center of the diffuser line, the plume was approximately 700 meters wide, more than four times wider than during HMZ1 at the west of the diffuser. Dye concentrations measured during these transects revealed a tendency for the dye field be slightly to the north with the plume centered about 100 meters to the north the diffuser axis. The maximum dye concentration observed in the dye plume during these transects was 1.7 µg/L, approximately a 50 fold dilution. This concentration was found deep in the water column (26.6m) just above a diffuser head (the tops of risers 25 and 26 are ~30.5m deep). The dye values varied widely in this vicinity, thus data appear to be from within the area of rapid mixing or hydraulic mixing zone. In Figure 3-18 the calculated dilution is plotted against depth and offset from the diffuser axis. The contouring parameters were the same as for HMZ1. Typically the areas of the highest dye concentration (lowest dilution) were located in a band between 14 and 24m deep extending

from just south of the diffuser to approximately 300m to the north and 100 m to the south of the diffuser. As observed in HMZ1 the majority of the dye plume was submerged below the surface an occasional surfacing observed which are likely related to centers of the turbulent plumes along the active diffuser briefly reaching the water surface.

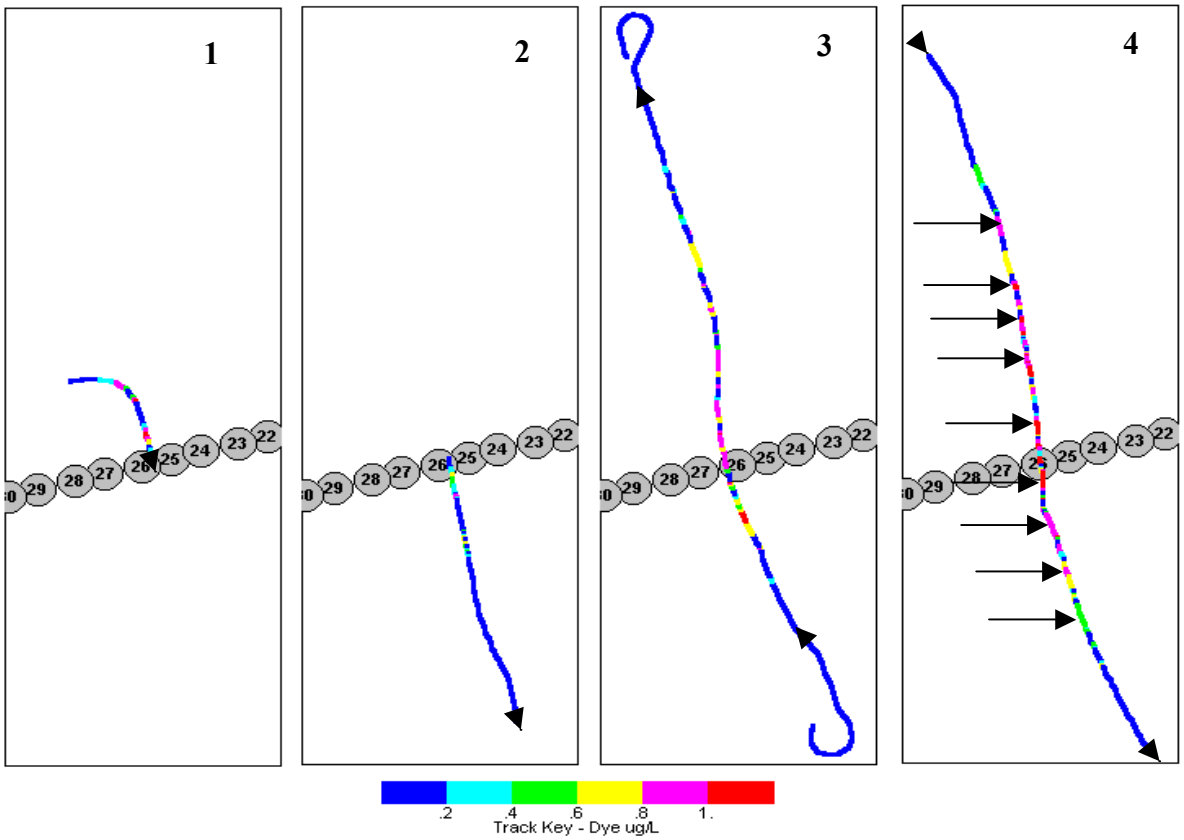

Figure 3-17. HMZ2 Trackline and discrete sample locations (arrows).

The composite beam attenuation cross-section during HMZ2 reveals basically the same plume characteristics as the dye dilution data (Figure 3-19). As observed during HMZ1, the core of the plume was found between 14 and 24m deep and extended ~300m to the north and 200 m to the south of the diffuser axis. Elevated beam values (>1.2 m^{-1}) are seen closer to the risers and at depth in the water column. Similar to the HMZ1 cross-section, the beam attenuation at HMZ2 shows higher values above 5 m depth.

The correspondence between the dye concentration and beam attenuation for HMZ2 (Figure 3-20) was similar to that observed during the April plume study (Hunt *et al.* 2002). The July data show that at low dye concentrations the beam attenuation is close to background levels (0.85 to 1 m^{-1}), while the highest dye concentrations had systematically higher beam attenuations values ($r^2 = 0.70$). The dye concentrations above 1.3 ppb were obtained from within 3 m of the diffuser line at 32 m depth. The slightly higher beam attenuation values at low dye concentrations were obtained from depths below 25 m and may reflect either bottom resuspension or remnant effluent.

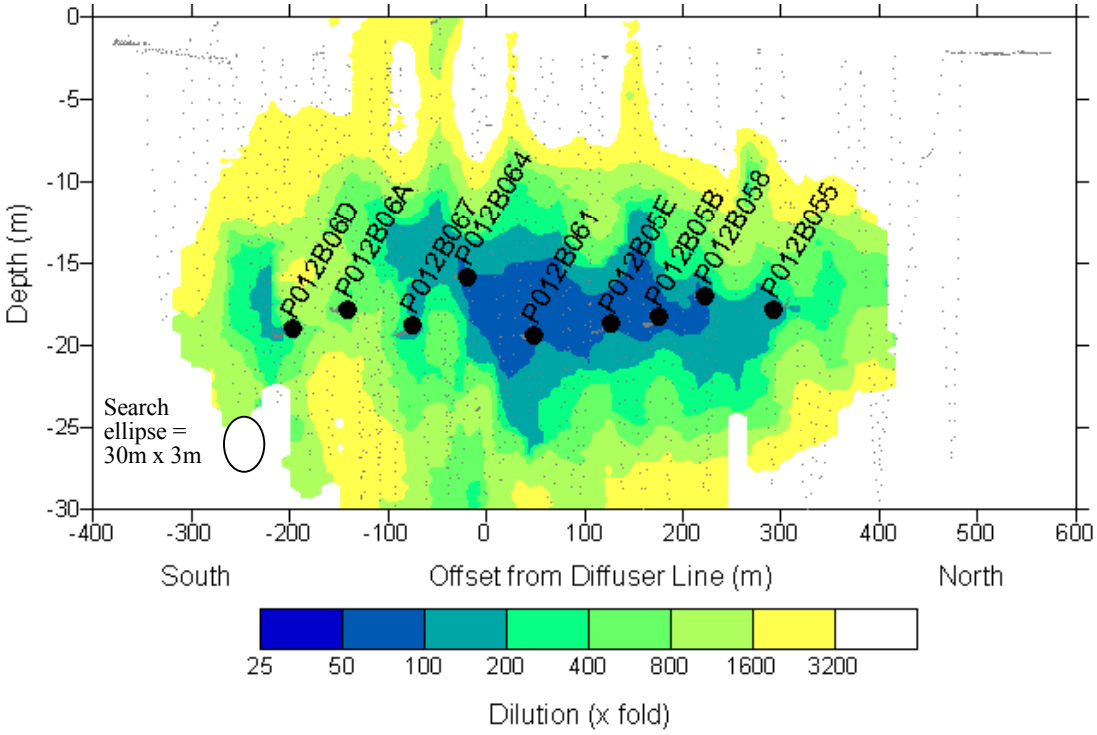

Figure 3-18. Dilution values in the cross-section of all HMZ2 Towyo Transects. Dotted lines indicate the Towyo Tracks. Discrete sample locations are identified by Sample ID#.

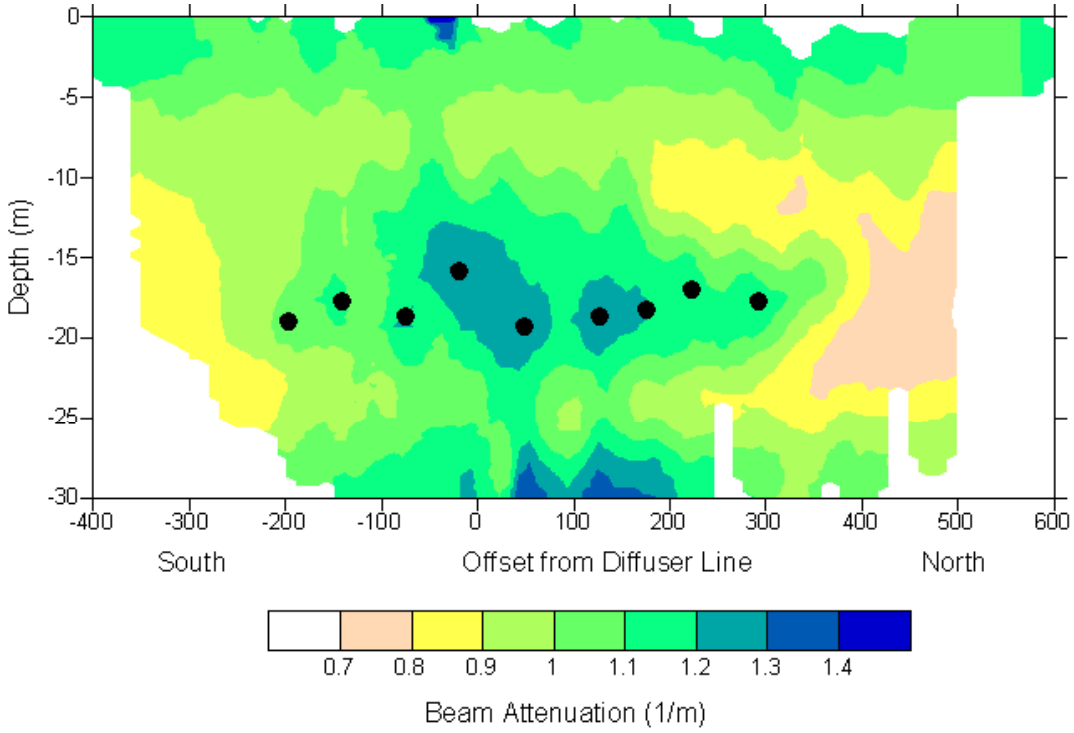

Figure 3-19. Beam attenuation during HMZ2 (approximate center of diffuser length).

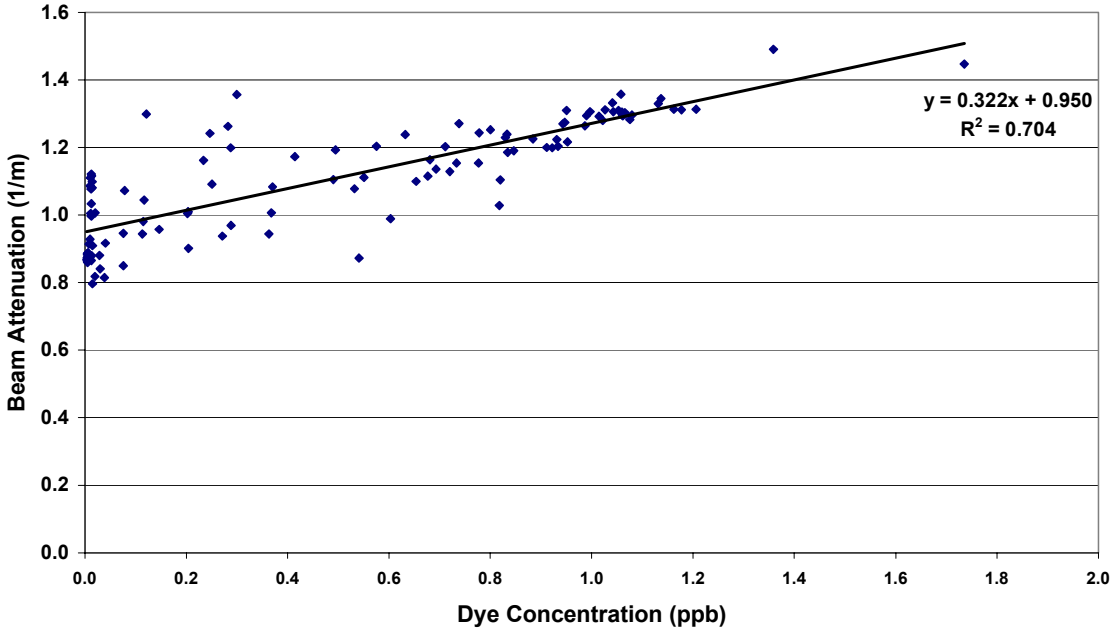

Figure 3-20. Beam attenuation versus dye concentration from HMZ2. Data shown are from within 20 meters of the diffuser.

3.2.3.3 HMZ3

The third hydraulic mixing zone survey was conducted east of the diffuser array. Prior to collecting samples, two transects were conducted perpendicular to the diffuser line to assess the dimension of the dye plume and identify ideal sampling locations. Figure 3-21 shows the HMZ3 tracklines, approximate dye concentrations, and discrete sample locations. The first transect extended from the centerline of the diffuser to the north. This transect was used to define the northern extent of the dye plume. The second extended to the south and includes panels 2 and 3 of Figure 3-21. This north-south transect may describe an exaggerated plume width as the tide cycle was shifting from ebb to flood and local currents began driving the plume towards the south. As a result, this north-south transect "chased" the moving plume to some extent and does not represent an instantaneous plume width. The third trackline (panel 4 Figure 3-21) was run from south to north, against the current direction. The dye values along this transect are more likely to represent the plume width, although the trackline run in this direction may have resulted in some compression of the apparent plume width. This transect was used for the collection of discrete samples and was conducted by heading towards the plume at a fixed depth of ~15 m (plume core) until dye was detected. Once detected towyo procedures were followed to ensure that the plume could be fully mapped and discrete samples collected at the appropriate depths.

Figure 3-22 shows the composite dilution contour plotted against depth and offset from the diffuser axis (projected as a straight line past the true end of the diffuser). Figure 3-23 shows the same view but only includes data collected during the south-north discrete sample collection transect. The comparison of Figure 3-22 and Figure 3-23 provides an indication of the exaggerated plume width resulting from the changing current field. The contouring in Figure 3-22 and Figure 3-23 was calculated across a search radius of the 100m wide by 3 meters deep. The search radius for these transect data was widened relative to the other HMZs to accommodate the spreading plume and the elongated transects.

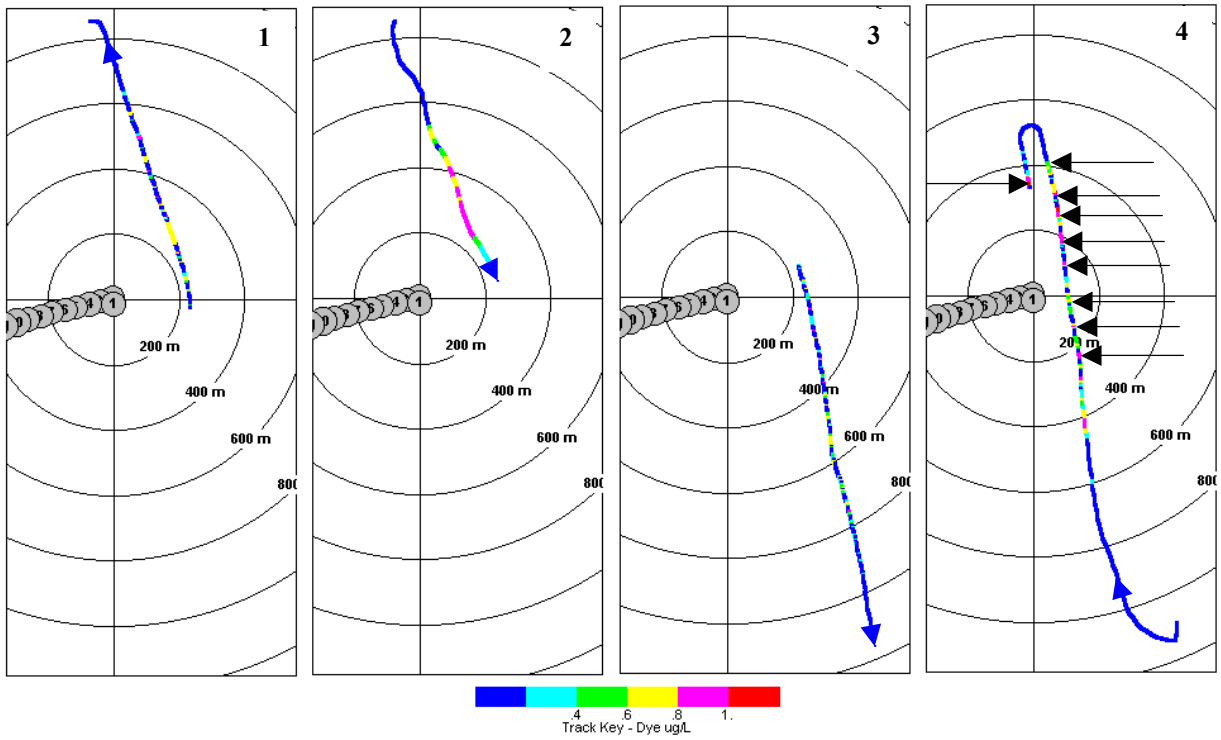

Figure 3-21. HMZ3 Trackline and discrete sample locations (arrows).

The dye east of the diffuser was detected in a plume that exceeded 1,500m in width. This is more than twice the width of the plume at the middle of the diffuser, and ten times wider than at the west end of the diffuser. The maximum dye concentration observed in the dye plume during these transects was measured at 14m depth and 315 m north of the diffuser axis at 1.1 ppb, or ~79 fold dilution. The core of the plume (50 to 100 fold dilution) was centered on the diffuser axis (projected past the actual east end of the diffuser), and extended in a band 400m in either direction at a depth between 12 and 18m deep.

Beam attenuation during the HMZ3 did not maintain the same relationship to dye concentration and dilution that was found during the other HMZ transects (Figure 3-24). The contouring parameters were the same as those used to develop Figure 3-22. The composite beam attenuation cross section for HMZ3 did not show a distinct area of elevated particles plume, rather the particle field measured during the HMZ is more dispersed (maximum values measured ~1.0 to 1.1 m^{-1}) with an area of low beam attenuation (<0.9 m^{-1}) at depths below 15m north of the diffuser. This reflects the southern westerly movement of the plume after the tide turned and the transport of water with lower background particle levels from the northeast towards the diffuser. Note the region in Figure 3-24 with the highest beam attenuation is coincident with that of high dye in Figure 3-22 even though the particle field is less distinct than the dye field.

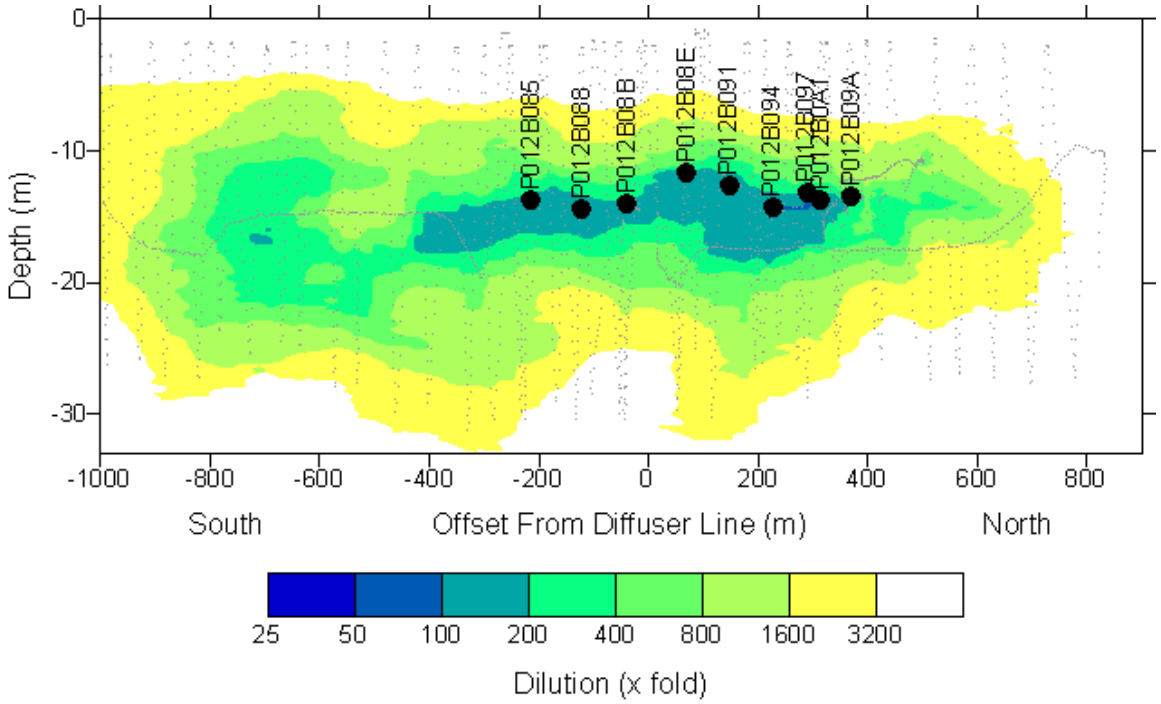

Figure 3-22. Composite cross-section contour of dilution using all HMZ3 Towyo Transects. Dotted lines indicate the Towyo Tracks. Discrete sample locations are identified by large dots and Sample ID#.

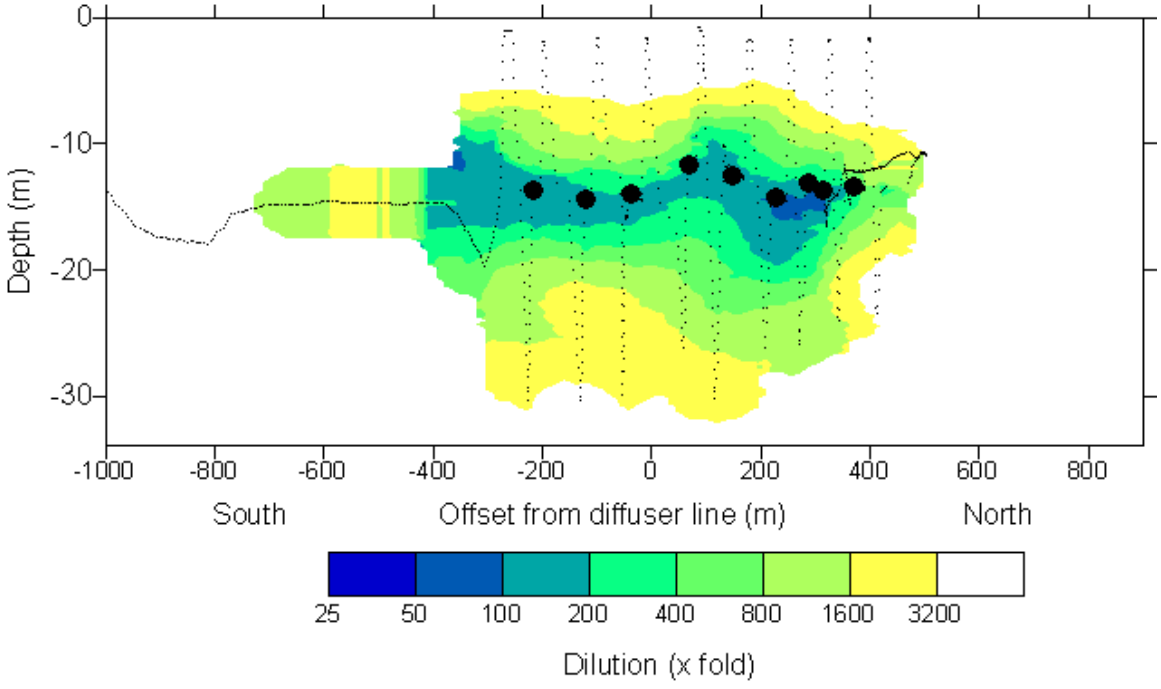

Figure 3-23. Dilution values in the cross-section of HMZ3 discrete sampling Towyo transects.

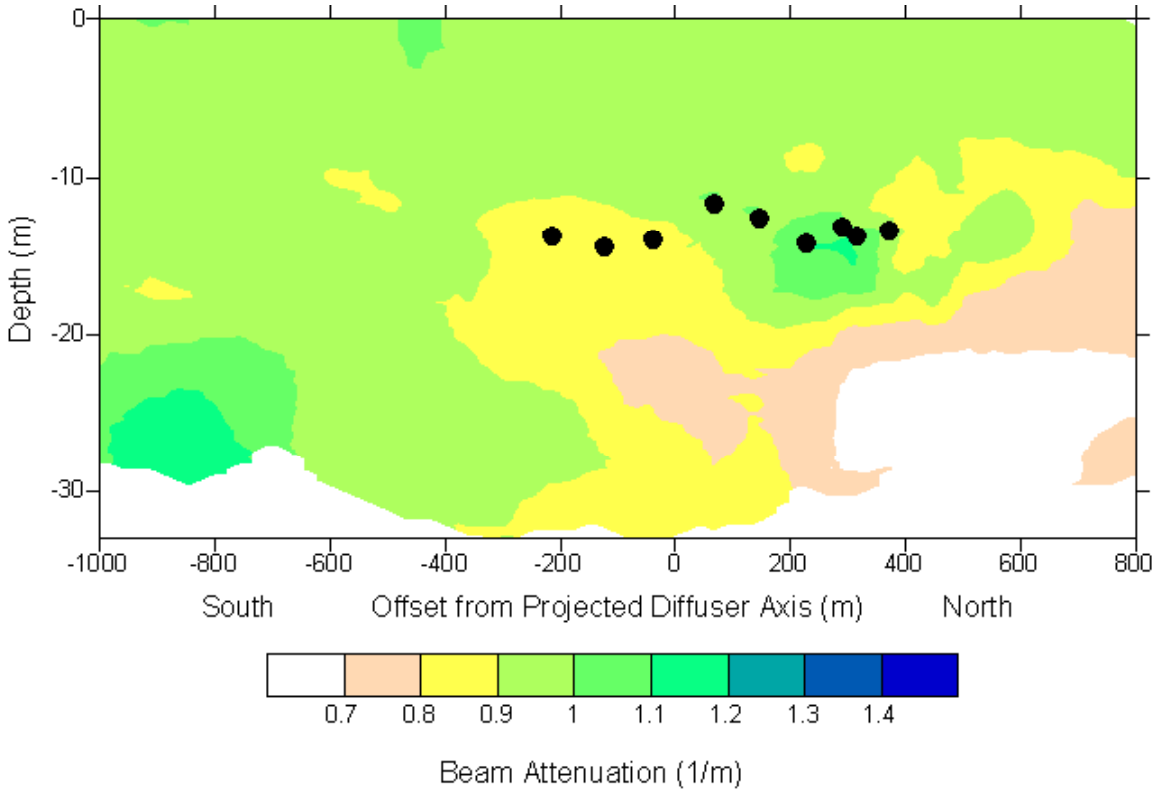

Figure 3-24. Composite beam attenuation during HMZ3 (East of the diffuser array).

The relatively less distinct particle field present on this HMZ may reflect the relatively small changes in beam attenuation and the interactions within the contouring program or the transition from ebb to flood tide. The correspondence between the beam attenuation and dye concentrations at depths between 7 and 30 meters where the dye plume was detected on this HMZ (Figure 3-25) showed a general trend of higher beam attenuation when dye was high. However, the variability in the turbidity at low dye concentrations was high, as was observed in the other HMZ studies. In addition, the beam attenuation data displayed large variability at the higher end of the dye concentrations. Thus the relationship between these two parameters in this depth interval on this HMZ was not as distinct as that observed near the diffuser (see for example Figure 3-20) on HMZ2.

3.2.3.4 HMZ Survey – Overview of Results

The dye plume was successfully tracked from the west end of the diffuser to ~100m beyond the east end. No attempt was made on the nearfield day to identify the overall boundaries of the plume[5]. Because dye was emerging throughout the survey period and conditions were changing rapidly as currents forced the plume to the east, plume boundaries (especially east-west) would have been difficult to define and would have been representative of only a brief window in time. The north-south boundaries of the plume were identified to some extent and are included in the discussion of each of the individual HMZ surveys. However these conditions were rapidly changing and the boundary locations should be considered in the

[5] The EPA survey track lines ranged over greater distance scales. However, the data from the EPA survey is not evaluated or compared in this report.

context of the hydrographic forcing influences discussed in Section 3.4. Despite the above caveats, it was clear that the plume was spreading as currents drove the dye down the diffuser line from west to east. Factors causing the spreading are discussed in Section 3.5.

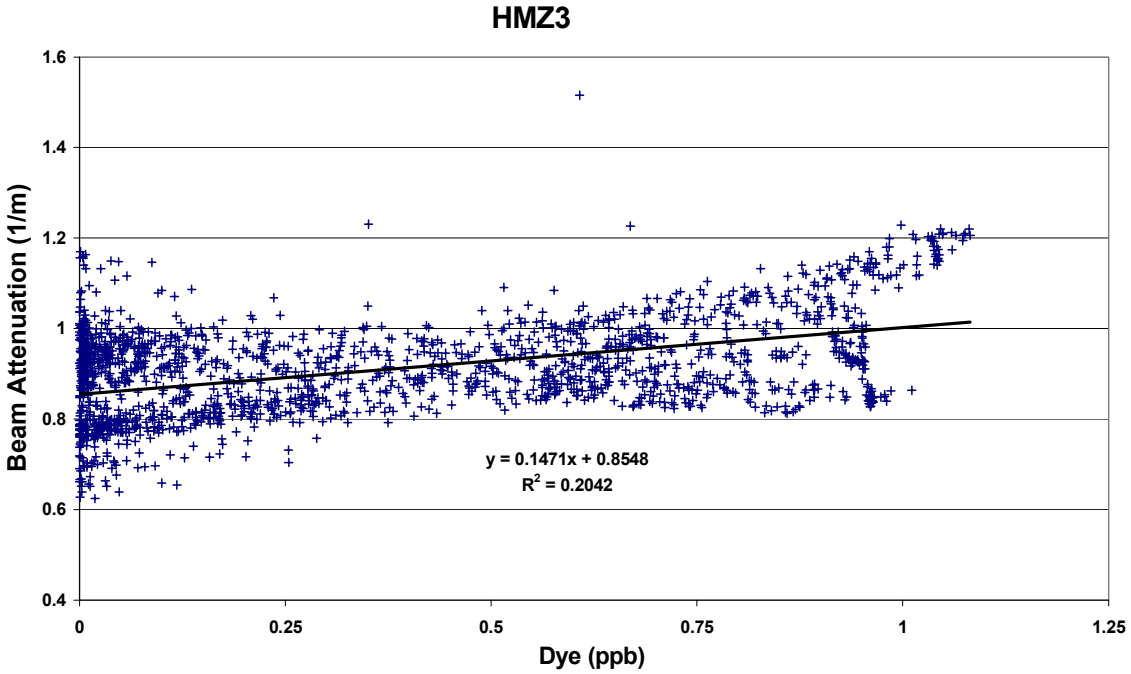

Figure 3-25. Correspondence between dye concentrations and beam attenuation between 7 and 30 m depth from HMZ3.

The HMZ dye data also show the plume was trapped below the pycnocline with the upper edge of the dye field coincident with the sharp change in density observed between 5 and 7 m depth. The core of the plume was located approximately 12 m below the water surface. Plume thickness was generally 20 to 25 m.

The data show the plume spread from approximately 150 m in width at the west end of the diffuser to over 1,500 m beyond the eastern end of the diffuser. Moreover, the southward forcing of the dye field as the tide transitioned from ebb to flood is reflected in the northern and southern extent of the dye field as shown in Figure 3-26. This figure also provides an overview perspective of the plume spread and spatial scales.

Figure 3-27 provides another view of the influence of the effluent on particle concentrations near the diffuser. In this figure the beam attenuation is shown as a function of depth for all data that was collected within 20 m of the diffuser axis, which was extrapolated for selecting HMZ3 data. The HMZ3 data thus did not go through the core of the plume east of the risers. These data clearly show the increase in particle concentrations and the fact that the tide had turned just before HMZ3 was conducted moving water with lower particle concentrations into the extrapolated region.

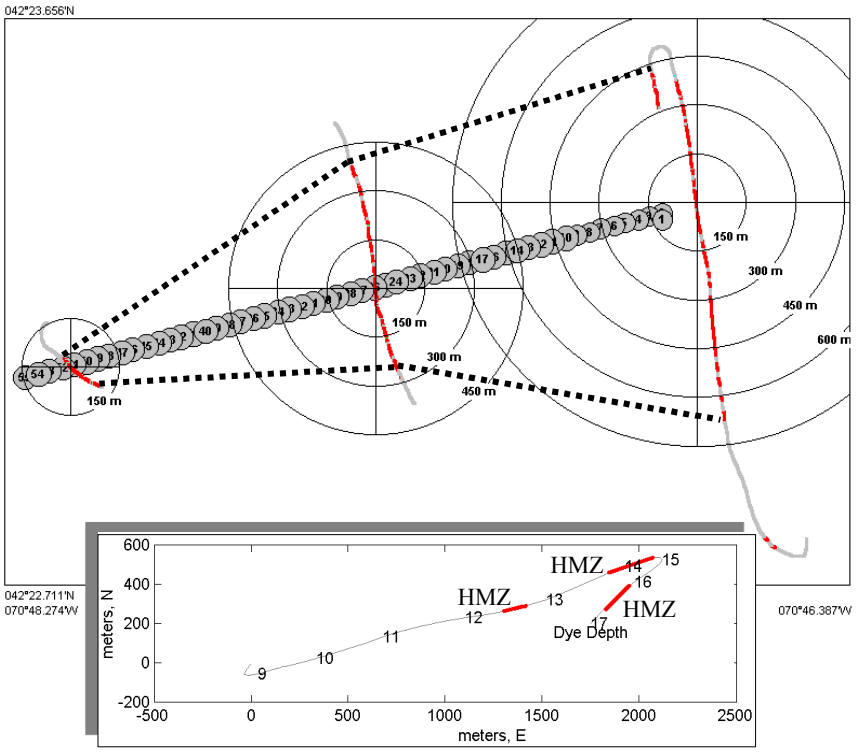

Figure 3-26. Dye spread during the plume tracking showing the southerly movement after the tide began to flood. The numbers refer to the time of day (EDT) in the insert showing water displacement from the ADCP data.

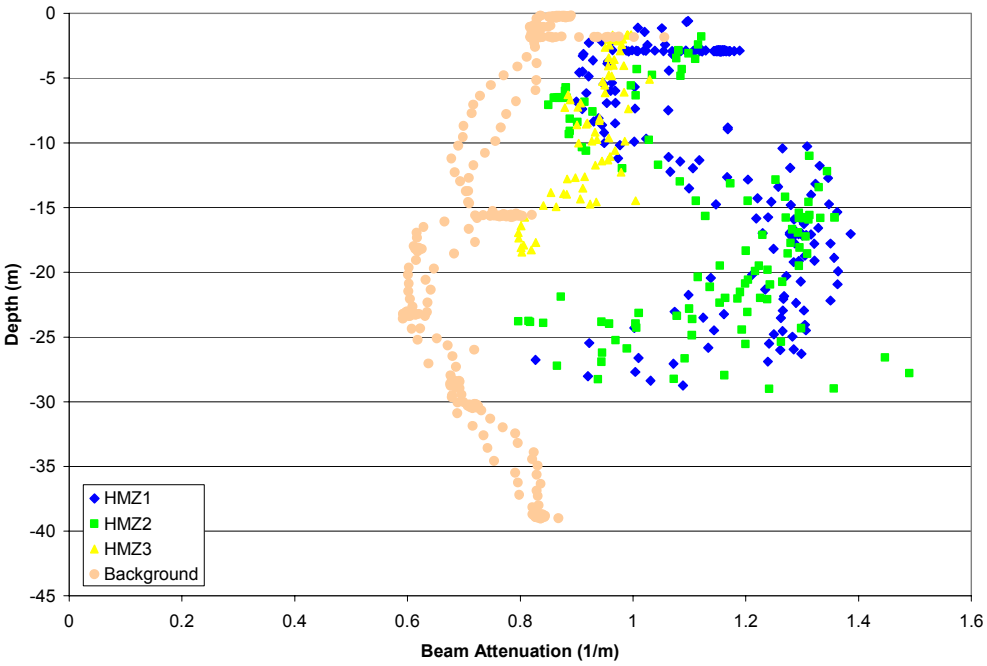

Figure 3-27. Beam attenuation in the background and ± 20 m from the diffuser axis during each of the HMZ surveys.

3.2.4 Far field Surveys

3.2.4.1 Far field Day 1

The objective of the far field survey was to determine plume structure and transport beyond the period of initial mixing. The dye plume was tracked in the far field over the course of two days, July 18 and 19, 2001. The far field surveys were entirely conducted in towyo mode and discrete samples were not collected during these surveys. Far field survey tracklines were intended to characterize the three dimensional structure of the plume, as well as its net movement. The data was also used to evaluate dispersion rates of the dye to place the far field transport and dilution of the plume within the context of dispersion rates for Massachusetts Bay (see Section 3.4.4). Tracklines from the each of the survey days can be seen in Figure 3-28 and Figure 3-30.

On Wednesday, July 18, 2001 the survey vessel transited directly to the MWRA outfall diffuser area. More than 12 hours had passed since the end of the nearfield survey on July 17 when the vessel arrived at the diffuser. The EPA vessel *OSV Peter W. Anderson* had remained in the diffuser area overnight and maintained contact with the dye plume during the majority of this time. Based on information from the *Anderson*'s crew, tide state, and ADCP current data from the previous day, it was assumed that the dye plume would be found near the diffuser line and likely to the east. Recognizing that the shift in current direction at the end of the nearfield day might have brought the dye back towards the southwest, tracklines expanding away from the center of the diffuser were planned.

Upon arrival at the center of the diffuser array, the sensors were placed in the water and a towyo transect was driven approximately parallel to and just to the north of the diffuser line. Dye concentrations up to ~0.25 ppb, were detected 190m northeast of riser #2 at ~12 m depth. This initial trackline continued to a location over 1500 m east end of the diffuser, although dye extended only ~350m east of riser #2. After reaching the east end of this trackline the vessel was turned and a parallel line was run 500 m north of the original line. No dye was detected during this entire 3.3 km transect. A trackline was then run 500m south of the first trackline. Dye was found along a large portion of this transect. The initial tracklines on the first far field day showed the plume extending primarily to the south of the diffuser and not to the north.

As a result transect lines were continued, under towyo operations, south of the diffuser line with the lines run parallel to the diffuser (Figure 3-28). Each transect was conducted approximately 500m south of the previous line. Transects were extended well beyond the last location of measurable dye concentration to ensure that the entire plume was being mapped. This mapping protocol was continued for 10 transects and found that the plume extended over 4.5 km to the southeast of the diffuser. Dye concentrations were >0.5 ppb this far from the diffuser. Due to time constraints, the field team became concerned that the entire dye plume could not be mapped during the day and increased transect spacing to 1000 m to capture as much of the plume as possible. Two transects were conducted at this spacing, bringing the southern-most survey line some 7.2 km south and east of the diffuser. The dye sensor was still in contact with the dye field at this location. Therefore, a decision was made to follow trackline to the approximate center axis of the plume, and to commence a "zigzag" transect towards the SSE to capture the southern extent of the dye plume. The zigzag transect was conducted due to concern that currents were driving the dye plume towards the SSE more quickly than could be captured by the east/west transect pattern. Contact with the dye plume was lost on this transect 10.8 km SSE of the diffuser. Because the final zigzag pattern did not allow the eastern and western boundaries of the plume in this area to be measured, estimates of the plume boundary locations were made[6] during post survey data processing. These are shown as pluses in Figure 3-28 and are an estimate of the eastern edge of the southern extent of the dye field.

[6] The boundary location was estimated from the location of the boundary observed to the north and estimated transport of the plume by the currents measured during this portion of the survey.

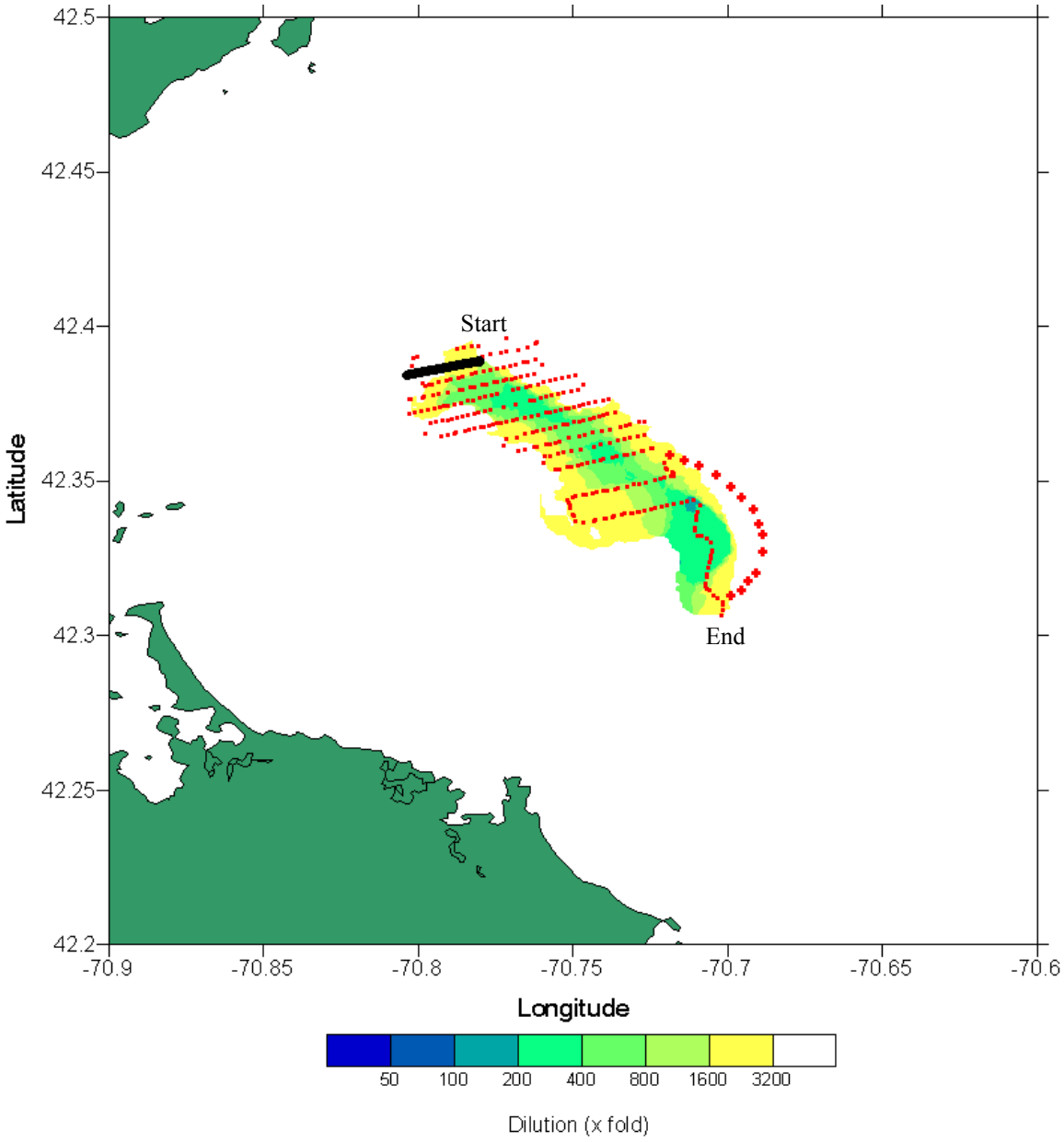

Figure 3-28. Dye dilution measured during the first far field survey day, July 18, 2001.

Once the southern edge of the plume was identified, a towyo transect was conducted towards the north (not shown). The northern boundary of the plume on this transect was found approximately 2000 m to the south of the location of the northern dye field boundary nine hours earlier (the diffuser itself is useful for scale, being 2020m long). Based on this shift, it may be assumed that the entire plume depicted in Figure 3-28 could be exaggerated as much as 2000m in length relative to the actual size at a given time.

The vertical and horizontal structure of the plume on far field day 1 showed a relatively intact plume with smooth gradients in the dye field with depth (Figure 3-29). As shown in these representative cross sectional data, the upper surface of the dye field fluctuated between 7 and 10 m depth, while the bottom of the dye field extended to depths of 20 and 24 m. This gave rise to a dye field that varied between 10

and 15 m thick in the most northerly transect conducted early in the day to as much as 20 m thick near the center of the dye field as represented in Figure 3-28. The transect ran towards the southwest near the end of the day showed a much thinner plume (~10 m thick) towards the south. The spatial scale of the plume was on the order of 9 km in the north-south direction and 4 km in the east-west direction. Typically, the areas with the highest measured dye concentration had dilutions of at least 200 fold with much of the measured dye patch showing dilutions greater than 400 fold. The lowest measured dilution on the first far field day was 92 approximately 8 Km south of the diffuser at 11 m depth.

3.2.4.2 Far field Day 2

The second far field survey day also required that the dye plume be located. This required "fishing" for a dye signal. To guide the fishing effort, the movement of the plume on the previous day and the onboard ADCP was used to estimate the dye movement. In this search the vessel was initially driven towards the southern most plume location found on far field day 1. A trackline was then run towards the northwest through the dye plume (Figure 3-30). Once this line was completed, a series of tracklines were conducted throughout the area to capture the boundaries of the plume in all directions[7]. Greater emphasis was placed in the survey pattern on obtaining data to describing the southwestern boundary of the plume, as this represented a shoreward movement. The dye levels measured on the second far field day were fairly low (<0.4 ppb) and were spread over a large area. The data also suggested the dye field was breaking into patches that were no longer contiguous. This created difficulty in defining whether the entire dye plume was in fact mapped on far field day 2. Because of the uncertainties and high dilution found on the second far field day, the third scheduled far field plume-tracking day was not conducted.

The spatial extent and patchy nature of the plume measured two days after dye release is depicted in Figure 3-30. The lowest dye dilution measured on this day was 206. The majority of the dye data showed the dilution was well above 400 fold (Figure 3-31). The dye field was located at least 5 km offshore of Situate, MA between 10 and 23 meters depth. The northern boundary of the plume had also moved 6.5 km to the south and slightly east of the diffuser in the 2 days following the dye release.

The data from the two far field days are combined in Figure 3-32. Note this graphic does not portray the extent of the plume field at any given time. The plume distribution and movement depicted in this figure shows the general locations the dye plume traveled through after release. The path followed by the plume and the dilutions realized are consistent with modeled plume trajectories and dilution (Signell *et al,* 1996). The transport and dispersion of the plume in the far field and the factors causing the movement are considered further in Section 3.4.

[7] Rationale for each of the transect courses is described in Mansfield *et al*. 2001)

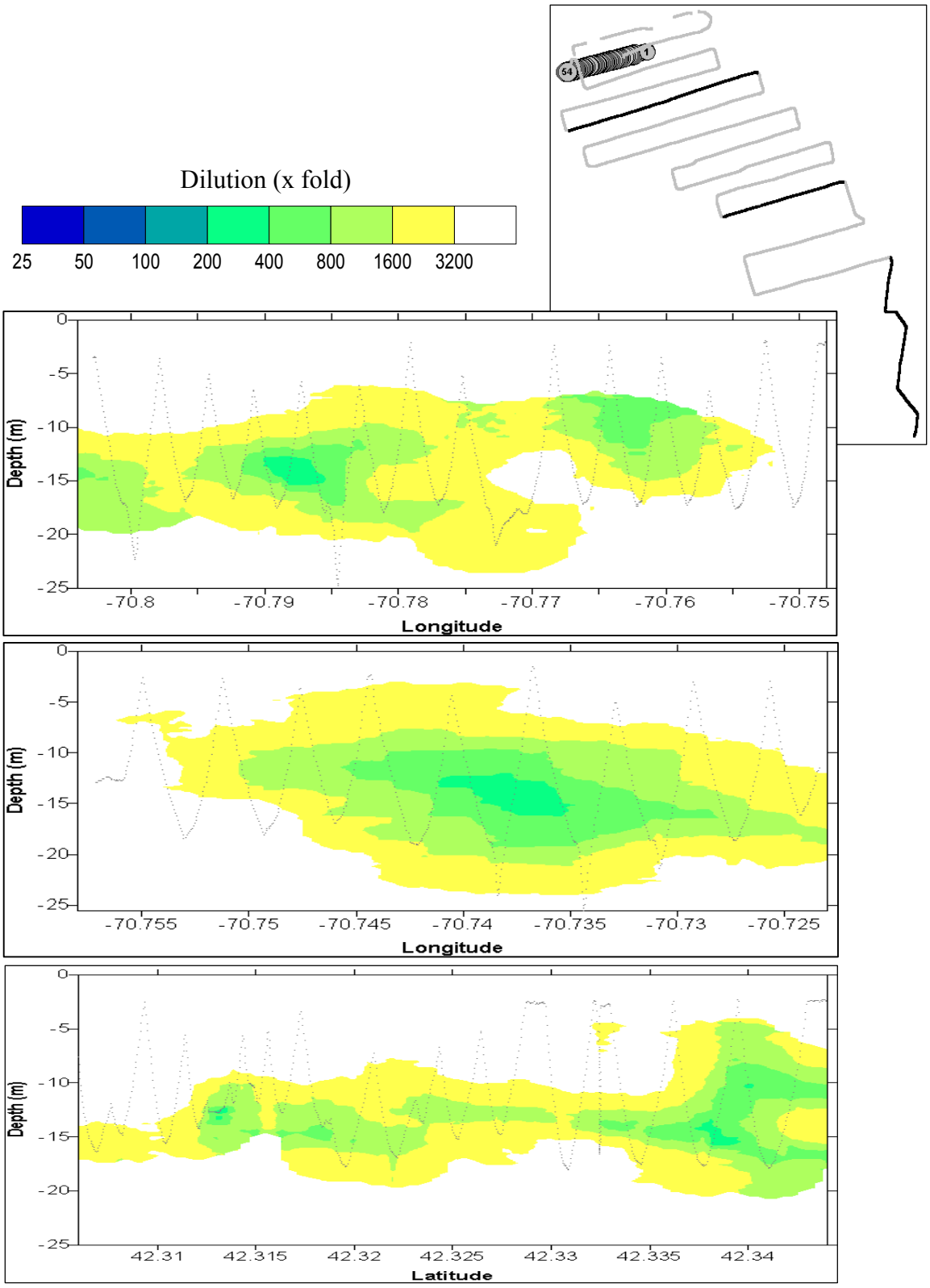

Figure 3-29. Vertical structure of 3 far field transects (as highlighted on inset map). Note that the top 2 panels are plotted against longitude while the bottom panel is latitude.

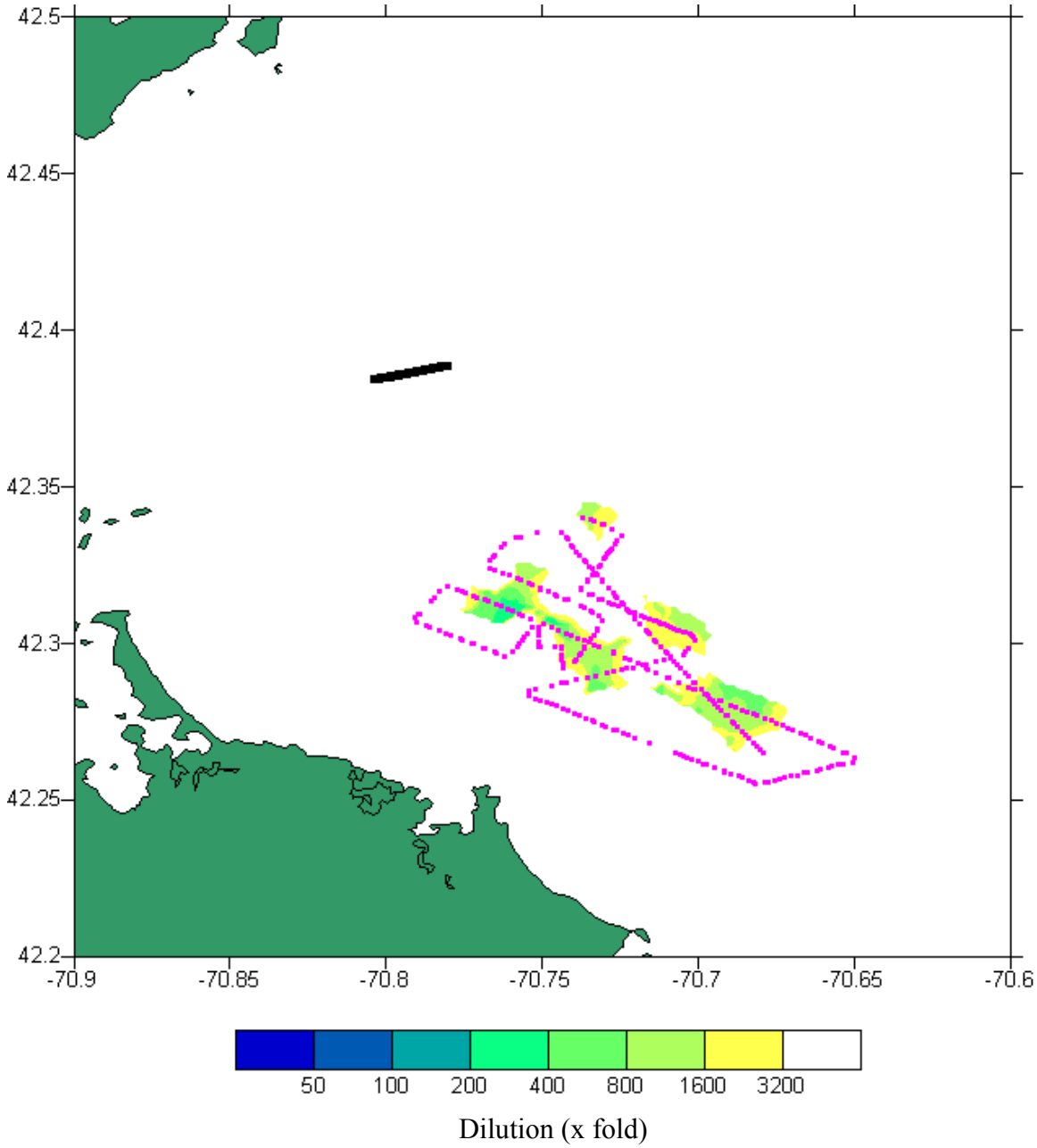

Figure 3-30. Dye dilution measured during the second far field survey day, July 19, 2001.

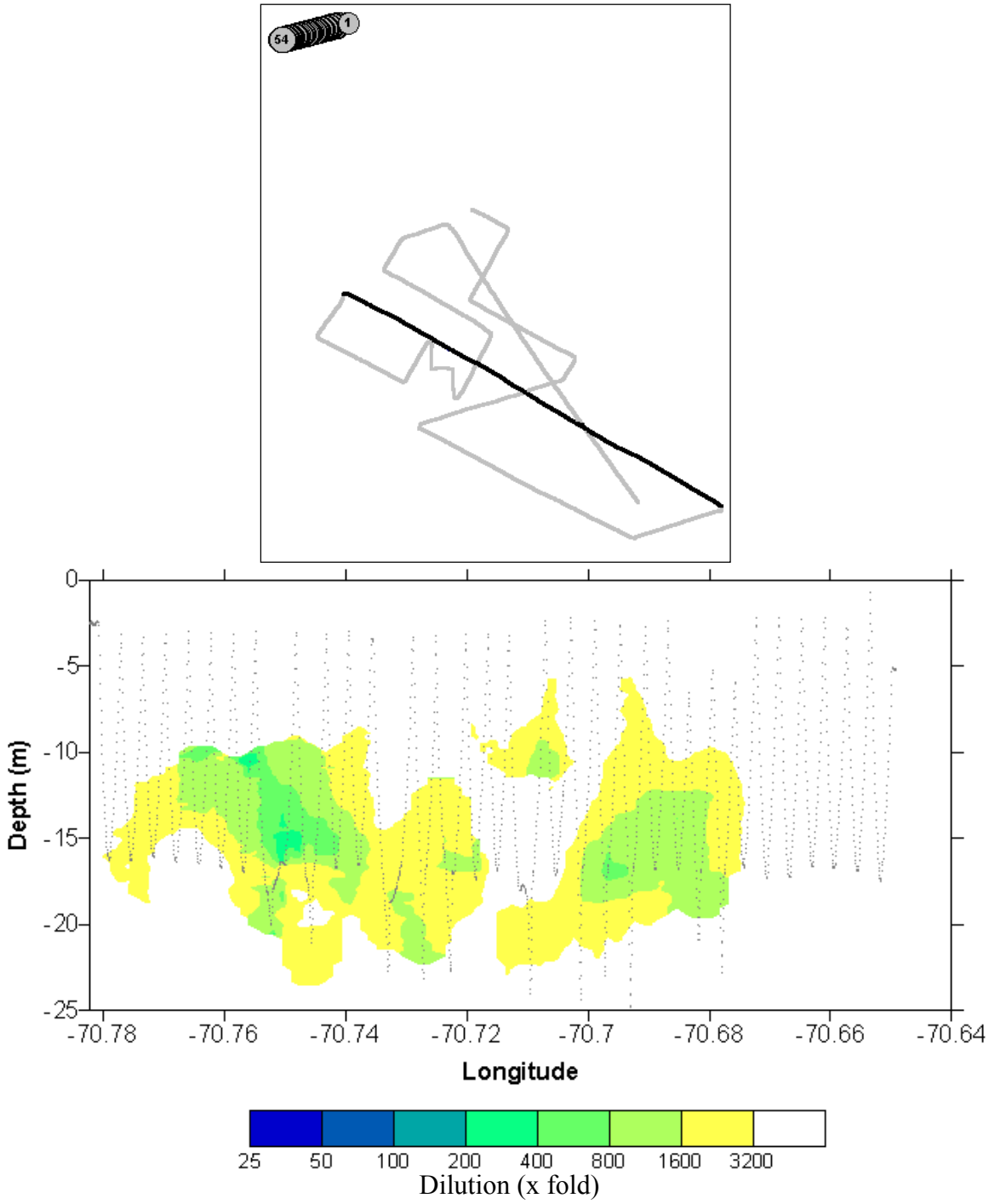

Figure 3-31. Vertical structure of the center far field day 2 transect (as highlighted on inset map). Note: plotting by longitude compresses the trackline somewhat because it is diagonal.

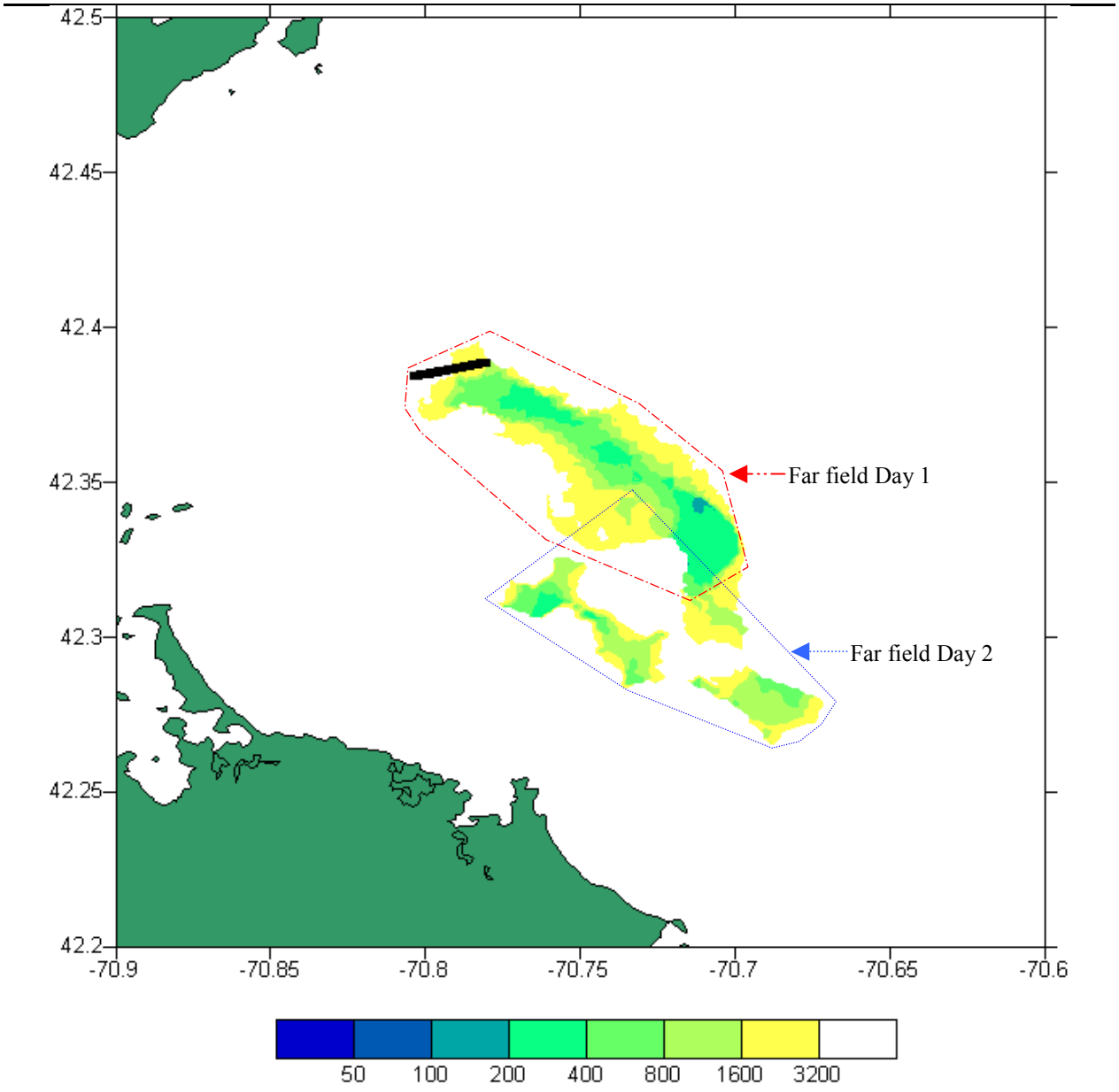

Figure 3-32. Dye dilution measured over the course of two far field survey days. (Note: Boundaries represent overall plume transport rather than the total area of the plume at any given time)

3.3 Discrete Sample Data

As discussed in the April plume tracking report (Hunt *et al.* 2002), discrete sample data obtained from the effluent and offshore environment provide information on effluent characteristics and the dilution at the outfall. These data were obtained to provide information on the concentration and variability of these parameters over the dye addition period and from which additional dilution estimates can be made. A more complete set of discrete sample data was collected during the July survey than the April survey to provide information on concentrations of the selected parameters away from the direct influence of the plume (background) and within the plume after initial dilution was completed. Background measurements were required to enable adjustment of the concentrations measured in the plume when estimating dilution (e.g., metals, nutrients). These background samples also provide limited data for comparison to historic data for parameters not routinely measured under the MWRA ambient monitoring program (e.g., selected metals) or that are not measured during initial mixing (nutrients, TSS, bacterial indicators). These data, coupled with the dye study enabled an extrapolation of the dye results to other water quality measures and an evaluation of whether marine water quality standards were exceeded.

As in April, the study design included an inter-laboratory comparison of standard-oceanographic methods to EPA-approved methods for ammonia, phosphate, and TSS in the MWRA effluent. University of Rhode Island's Marine Ecosystems Research Laboratory and the MWRA Central Laboratory performed these measurements.

This section first examines the results of discrete samples in the effluent and the laboratory inter-comparison. The ambient offshore results are then considered. The background data are compared with historical data, while the data from within the effluent plume are compared with federal and state water quality standards. The last section presents estimates of dilution based on nutrients and metals and compares these to estimates derived from the dye.

3.3.1 Effluent Discrete Sample Results

The effluent data obtained from the discrete samples during the dye addition (Table 3-3) are generally consistent with results generated during MWRA's routine effluent monitoring and corresponds to about 3 percent seawater. The chloride measured in the effluent (~590 ppm) is typical of levels routinely measured in the effluent. The concentrations are slightly higher than observed in April 2001 and reflect a slightly higher contribution of seawater to the effluent, probably due to the slightly lower effluent flow, (350 decreasing to 225 MGD in July compared to 390 to 330 MGD in April) during the July dye addition. The chloride concentrations tended to decrease as the flow decreased.

The abundance of both bacterial indictors measured in the effluent was variable with possible decreases over the course of the dye addition (Table 3-3). Fecal coliform counts at the sampling point for the dye study ranged from 70 to 995 colonies/100mL. *Enterococcus* levels were ~9 times higher on average (2850 per100 mL) than measured fecal coliform levels.

The concentrations of the two metals measured in the effluent were low and relatively constant. Total copper was less than 10 ppb (average 8.3 ppb). Total silver was measured at <0.48 ppb (average 0.36 ppb). As in April the silver data tended to be more variable than Cu (42 versus 13.0 percent coefficient of variation). The metals concentrations did not vary with flow.

Table 3-3. Results from the discrete samples collected from the MWRA effluent during the July 2001 MWRA plume tracking survey.

Sample Time (EDT)	Dye east basin[a] ppb	Dye west basin[a] ppb	Ammonia (MWRA) μM	Ammonia (URI) μM	Phosphate (MWRA) μM	Phosphate (URI) μM	TSS (MWRA) mg/L	TSS (URI) mg/L	Chloride mg/L	Copper μg/L	Silver μg/L	Enteroccus #/100 mL	Fecal Coliform #/100 mL
7/16/01 20:35	0.13	0.12	1,664	1,927	69.68	72.1	12.5	13.42	596	7.13	0.21	2,700[b]	515
7/16/01 21:47	82.1	76.8	1,614		70.32		11.3		638			3,000[c]	
7/16/01 21:59	84.8	79.1	1,629	1,914	70.32	72.37	10.7	13.9	587	7.30	0.22	2,800[b]	995
7/16/01 22:29	85.7	82.1	1,629		71.94		11.3		566			3,300[c]	
7/16/01 22:58	82.8	79.4	1,621	1,843	72.26	73.49	12.0	13.5	573	7.53	0.27	2,900[b]	90
7/16/01 23:29	85.6	85.6	1,614		72.9		12.7		571			4,200[c]	
7/16/01 24:02	84.0	81.5	1,593	1,847	72.26	63.79	13.0	15.5	545	8.18	0.34	3,100[b]	300
7/17/01 0:30	84.8	82.0	1,600		74.84		13.0		501			3,600[c]	
7/17/01 0:58	84.2	85.6	1,564	1,851	75.48	69.4	13.5	15.7	477	8.68	0.4	2,500[b]	65
7/17/01 1:26	84.8	85.7	1,593		75.81		14.0		468			2,600[c]	
7/17/01 1:58	84.6	83.5	1,579	1,843	75.16	70.72	14.0	17.0	483	9.34	0.63	1,900[b]	95
7/17/01 2:28	85.3	82.8	1,600		76.45		14.5		438			2,500[c]	
7/17/01 4:37	3.48	1.77	1,600	1,797	74.84	75.37	17	18.8	424	10.1	0.48	2,000[b]	70
MEAN	**84.7**	**82.7**	**1,608**	**1,860**	**73.3**	**71.0**	**13.0**	**15.4**	**528**	**8.32**	**0.36**	**3151[d]**	**304**
STDEV	**0.85**	**2.4**	**25.3**	**45.1**	**2.3**	**3.7**	**1.7**	**2.0**	**67**	**1.10**	**0.15**	**600[d]**	**347**
CV%	**1.0**	**2.9**	**1.58**	**2.42**	**3.16**	**5.24**	**12.7**	**13.0**	**12.7**	**13.3**	**41.8**	**19.1[d]**	**114**

a. Highlighted samples are not included in statistics. See section 3.1.
b. EC24 data
c. EC48 data
d. Based on EC48 data

The parameters that were measured at two laboratories showed generally good agreement. However, the agreement was not as good as observed in April, especially for ammonia and TSS (Table 3-4). The precision of the measurements within the two laboratories was excellent for ammonia and phosphate (<5 percent CV), while TSS showed generally higher variability (12.7 and 13 %CV, respectively for MWRA and URI laboratories). Ammonia levels throughout the dye addition were constant at ~1609 and 1860 μM, depending on the analytical laboratory (Table 3-4). The overall phosphate data was very consistent between the two laboratories (73.3 versus 71.0 μM). The paired ammonia data returned average values of 1607 and 1860 μM ammonia. Paired phosphate concentrations were 73.7 and 71.0 μM with overlapping standard deviations for the two laboratories. Phosphate concentrations tended to increase slightly as the flow decreased. The paired data returned average values of 13.0 and 15.4 mg/L TSS. The average concentration using the data both from laboratories was 13.9 mg/L. The MWRA data is consistent with weekly and monthly averages generally achieved by the treatment plant (Werme and

Hunt 2001). The daily average TSS in the effluent from late June to late August 2001 was 10 mg/L (Dave Duest, MWRA, Personal communication, February 2002).

The factors that caused the differences in ammonia concentrations between the two laboratories were not identified. They may be related to the dilutions required under the URI method. Regardless of cause, the data were pooled together to develop a grand mean ammonia concentration of 1696±128 μM (%CV = 7.5). The grand mean for the phosphate was 72.5±3 μM (%CV = 4.1) and for TSS 13.9±2.1 mg/L (%CV = 15.1).

Table 3-4. Laboratory intercalibration data for ammonia, phosphate and total suspended solids.

Sample Time (EST)	Ammonia (MWRA) μM	Ammonia (URI) μM	Phosphate (MWRA) μM	Phosphate (URI) μM	TSS (MWRA) mg/L	TSS (URI) mg/L
7/16/01 20:35	1,664	1,927	69.7	72.1	12.5	13.4
7/16/01 21:59	1,629	1,914	70.3	72.4	10.7	13.9
7/16/01 22:58	1,621	1,843	72.3	73.5	12.0	13.5
7/16/01 24:02	1,593	1,847	72.3	63.8	13.0	15.5
7/17/01 0:58	1,564	1,851	75.5	69.4	13.5	15.7
7/17/01 1:58	1,579	1,843	75.2	70.7	14.0	17.0
7/17/01 4:37	1,600	1,797	74.8	75.4	17.0	18.8
MEAN	**1,609**	**1860**	**73.0**	**71.0**	**13.2**	**15.4**
STDEV	**32**	**45**	**2.5**	**3.72**	**2.0**	**2.0**
CV%	**2.0**	**2.4**	**3.4**	**5.2**	**14.9**	**13.0**

3.3.2 Ambient Discrete Sample Results

As discussed in previous sections, the Rhodamine dye concentrations in the effluent plume after initial mixing was completed were generally <1.0 ppb. The background fluorescence signature was not detected in the discrete samples collected northeast of the diffuser before the dye exited the diffuser system (Table 3-5). As determined in April, the background station location in July demonstrated that the station was essentially free of any influence of previously discharged effluent. The background ammonia and phosphate concentrations, which were less than 4.9 and 1.4 μM, respectively, were typical of values measured in the Bay previously at these depths and time of year. The values are also typical of those measured in areas outside of the influence of the effluent plume during MWRA's mid summer water quality monitoring surveys (Libby *et al*. 2002). In addition, the total copper concentrations (0.38 μg/L) are the same as those measured in August 1994 and September 1996 by Christian Krahforst, (MACZM, personal communication, December 2001). His total copper results, summed from separate measures of the dissolved and particulate phases, range from 0.34 to 0.35 μg/L. In contrast, total silver concentrations in Massachusetts Bay reported by Krahforst range from 0.002 to 0.004 μg/L. As in April, the background total silver concentrations (~0.017 μg/L) measured in July were higher than the 1996 data by a factor of 4 to 8. Thus, the silver data from the plume tracking study may not represent background levels typically found in Massachusetts Bay. The difference in values is likely related to sampling artifacts. TSS concentrations at the background stations (0.87 to 1.28 mg/L) were also indicative of Massachusetts Bay waters not influenced by the effluent plume. Monthly MWRA surveys to sample and measure bacterial indicators in Massachusetts Bay, including data from adverse condition surveys conducted in 2001, have not detected fecal coliform (MDL = 1 colony /100mL) in the receiving water near the outfall (K. Coughlin, MWRA, personal communications, February 2002). The extracted chlorophyll concentrations were low, decreasing from 2.5 μg /L at 16 m depth to 0.35 μg /L at 39 m depth. Thus, the

background samples were obtained in waters unaffected by the ongoing discharge and the chlorophyll levels were typical of the mid summer period.

Table 3-5. Background and HMZ Vertical Profile Discrete Sample Data Summary.

Study element	Depth (m)	Dye Concentration (ppb)	Ammonia µM	Phosphate µM	TSS mg/L	Copper µg/L	Silver µg/L	Enterococcus[a] #/100 mL	Fecal Coliform #/100 mL	Chlorophyll *a* µg/L	Phaeophytin µg/L
Back ground	39.44	0	3.84	1.41	0.87	0.38	0.019	NA	NA	0.350	0.297
	30.86	0	3.5	1.31	0.61			NA	NA	0.490	0.323
	23.81	0	2.2	1.16	1.28			NA	NA	0.678	0.438
	16.25	0	4.9	0.84	1.25	0.38	0.017	NA	NA	2.515	0.932
HMZ1	16.27	0.796	21.4	1.08	1.58	0.69	0.024	NA	NA	2.181	0.695
	13.22	0.415	14.0	0.93	1.17			NA	NA	2.692	0.595
	20.55	0.611	19.5	2.01	1.49	0.61	0.026	NA	NA	2.152	0.590
HMZ2	18.11	0.829	30.8	1.72	1.49			0	0	3.066	0.829
	17.58	0.956	24.5	1.89	1.38	0.58	0.022	0	3	1.553	0.511
	18.77	0.963	24.9	1.91	1.57			0	1	2.132	0.529
	19.11	0.919	25.4	2	1.59			0	1	2.643	0.510
	19.86	1.015	22.2	2.05	1.78			0	1	2.378	0.802
	16.23	1.023	26.1	2.18	1.75			0	2	2.555	0.813
	19.12	0.866	23.0	1.81	1.55	0.64	0.031	0	51	2.466	1.106
	18.36	0.785	21.5	1.78	1.62			0	1	2.555	0.696
	19.29	0.537	18.0	1.71	1.34	0.62	0.033	0	0	3.105	0.611
HMZ3	14.28	0.947	24.0	1.89	0.99			0	3	1.759	0.644
	14.77	0.817	21.6	1.83	1.00			0	2	1.484	0.928
	14.75	0.583	15.9	1.55	0.97	0.48	0.022	0	0	2.289	0.631
	12.22	0.891	22.2	1.44	1.72			0	3	2.398	0.863
	12.97	0.901	22.3	1.44	1.10	0.54	0.023	2	2	2.378	0.587
	14.75	0.953	24.3	1.59	1.23			0	0	2.555	1.456
	13.7	0.843	19.3	1.32	0.88	0.68	0.023	2	2	2.427	0.592
	14.0	0.621	16.9	1.17	0.97			0	1	2.191	1.176
	14.13	1.044	26.8	1.69	1.39			0	4	1.936	0.887

[a]EC24 data

The background concentrations of the parameters measured from the discrete samples in the bay were substantially lower than measured in the effluent: Ammonia ~470 times; PO_4 ~60 times; TSS ~10 to 14 times (depending on depth); and Cu and Ag each ~20 times.

Within the effluent plume, the discrete sample data (Table 3-5) showed measurable increases relative to the background data with the exception of the bacterial indicators where measurable levels in the dye plume were not present except in one sample. Because the discrete samples were collected at relatively constant dye concentrations (notable exception HMZ1) [8], the discrete data were relatively constant but

[8]Note: The sample collection depths during the HMZ surveys are shown in Figure 3-13, Figure 3-18, and Figure 3-22 for HMZ1, HMZ2, and HMZ3, respectively.

higher than measured at the background station. The relative increase in concentrations in the plume after initial dilution estimated from the discrete samples was~ 5 times for ammonia, ~ 1.5 times for phosphate, ~1.2 times for TSS and 1.5 times for copper and silver. Note the increase is estimated based on the background sample collected at ~16 meters. The increase in TSS ranged from 1.2 to less than 1 indicating very little change in the particle concentrations based on this parameter. Also, the data from the three samples collected during HMZ1 were in the lower range of those measured during HMZ2 and HMZ3, as was the dye concentrations.

Regression of the discrete TSS data against *in situ* beam attenuation (Figure 3-33) and turbidity data showed a strong correlation to TSS for the combined discrete HMZ sample sets (R^2 = 0.60, slope = 0.397 m^{-1} per mg TSS/L; intercept 0.578 m^{-1}). The regression data indicate the beam attenuation data discussed in the previous sections are indicative of the general particle concentrations in the plume.

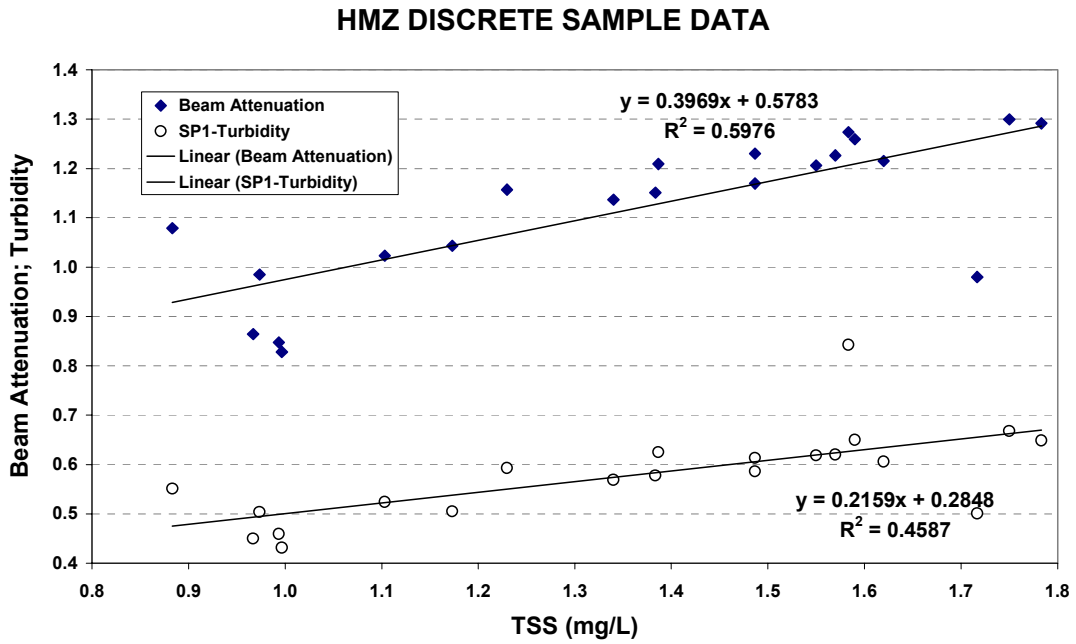

Figure 3-33. Correspondence between discrete TSS data and the paired *in situ* beam attenuation and turbidity data for all discrete samples collected.

Measured increases in the discrete parameters sampled after initial mixing was complete were ~19 µM for ammonia, 0.5 to 1.1 µM for phosphate, and <0.25 mg/L for TSS. Copper and silver levels increased by ~60 percent (~0.23 µg/L and ~0.009 µg/L, respectively). Variably among the metal sample results is relatively high, making a definitive conclusion on the measured increase difficult to draw. The chlorophyll and phaeophytin levels remained similar in background levels within the plume.

From a water quality perspective, the plume data demonstrate that state standards and federal marine water quality criteria are not exceeded after the initial mixing of the plume is completed. As observed from the April plume tracking study, copper provides evidence that the design of the diffuser and achieved dilutions effectively reduce the already low levels of contaminants in the secondary treated effluent levels to well below those considered harmful. The highest measured copper concentration in the effluent plume was 0.69 µg/L. This compares to a marine water quality criterion of 3.1 µg/L. Thus, after initial dilution this metal is about 5 fold lower the applicable marine water quality criteria.

The fecal coliform and *Enterococcus* levels were also at acceptable levels immediately after initial dilution is completed. *Enterococcus* was found at two colonies/100 mL (EC24) in each of two samples (MDL = 1 colony per 100 mL) and was not detected in any of the other 16 samples collected. Fecal coliform colonies were measurable at 1 to 4 colonies per 100mL (MDL = 2 colonies/100 mL) in all but one sample, which had a value of 51 colonies/100 mL. Detection of these indicators at or slightly above the detection limit is expected and is not considered consequential to water quality. These values compare to the state water quality standards for contact recreation of 200 fecal coliform colonies/100 mL and 35 *Enterococcus*/100 mL of sample.

3.3.3 Dilution estimates from discrete samples

The data from the discrete sample collection effort were used to estimate effluent dilution (Table 3-6) for comparison to that determined by the dye itself as well as the dilution modeling (see Section 4). For the calculations, the average concentration of each parameter measured in the effluent after the dye concentration stabilized was calculated. The dye concentration used for the effluent was that developed in Section 3.1. For ammonia and phosphate the mean of the samples analyzed at URI was used for the calculation. This data was chosen to ensure internal consistency in the methodology for these parameters. In contrast the grand mean of the TSS data from both laboratories was selected for TSS as it better represents the long-term TSS concentration measured in the effluent. The dye, ammonia, phosphate, and TSS concentrations for each HMZ were based on the mean values measured in plume after some samples were removed based on low discrete dye data, which indicated the removed samples were not collected in the core of the dilution field. These included data associated with HMZ2 sample dye = 0.537 ppb and HMZ3 samples with dye = 0.583 and 0.621 ppb. All metals data were used for the dilution calculation. All of three HMZ1 samples were used even though the data clearly suggest the samples were outside of the region of initial dilution.

To calculate the dilutions from the discrete samples, the measured concentration in the effluent plume offshore must was adjusted to reflect "new" input. This adjustment was done based on the average concentrations measured at the background station. Except for metals, four values were included in the background mean. The background silver and copper averages are based on only two samples.

These calculations gave estimated dilution from these samples from 23 to 444 across all parameters and HMZ's (Table 3-6). Among the three HMZ studies, HMZ1 shows consistently high dilutions for dye ammonia, phosphate. The data for the TSS and two metals was more consistent across the HMZ surveys, although the calculated dilutions were considerably lower than estimated using the dye, ammonia, and phosphate. Consideration of the data from HMZ2 and HMZ3 only show fairly good agreement for the initial dilution between the dye and ammonia with estimates ranging between 88 and 96. Dilution based on phosphate is similar to the ammonia and dye derived initial dilution for HMZ2 but substantially higher (169 vs 94) for the HMZ3. The data for the TSS and metals considerably underestimate the dilution relative to the dye.

Table 3-6. Estimates of effluent dilution based on discrete data results from the July plume tracking survey.

Parameter	Units	Effluent	SW Background	HMZ 1	HMZ 2	HMZ 3	Initial Dilution		
							HMZ 1	HMZ 2	HMZ 3
Dye	ppb	86.0	0.00	0.61	0.92	0.91	142	94	94
Ammonia	µM	1860	3.61	18.3	24.7	22.9	127	88	96
Phosphate	µM	71.0	1.18	1.34	1.92	1.60	444	96	169
TSS	mg/L	13.9	1.00	1.41	1.59	1.19	34	24	75
Copper	µg/L	8.3	0.38	0.65	0.61	0.61	31	35	36
Silver	µg/L	0.364	0.018	0.025	0.029	0.023	52	34	73

Of the five parameters in Table 3-6 ammonia gives the closest estimate of dilution to that measured with the dye. The dilution estimate based on ammonia and dye from HMZ2 and HMZ3 also agree well with the overall modeling results (Section 3.5).

The poor prediction of the dilution using the TSS and metals is most likely due to analytical variability as observed from the April survey (Hunt *et al*., 2002) and small changes that occur relative to the background levels after initial dilution. The other possible explanation is that the background values do not reflect entrainment of previously discharged plume, which would cause the difference for the "newly" discharged concentration to decrease. However, the scenario is unlikely based on the ammonia, which has the largest potential concentration change. That is, if the selected background values were low the ammonia results would not approximate the dye results as well as they do in this study. As in April, silver is problematic in that the background and plume values do not agree with silver concentrations measured in the mid-1990's.

3.4 Oceanographic Forcing Conditions during July 2001 Plume Tracking Study

This section summarizes the external forcing variables and oceanographic conditions in the vicinity of the outfall and dye dispersion in support of the interpretation of dye dilution and transport assessments during the Plume Tracking Study conducted on July 17–19, 2001. Tidal information was obtained by the NOAA tidal predictions. Wind data were obtained from the NOAA web site http://seaboard.ndbc.noaa.gov. Water properties and current data were obtained as describe in Section 2.2.

3.4.1 External Forcing Variables

The principal external forcing variables affecting the dye trajectory are the tides and winds. Tidal conditions were determined by predicted tidal heights at Boston, as shown in Figure 3-34. The tides were mid-way from the neap to the spring part of the fortnightly cycle during the dye release, thus the advection and mixing associated with the tides was moderate. Survey activities on each of the three survey days (indicated in shading) started close to high tide, continued through the ebb, and finished during the rising tide.

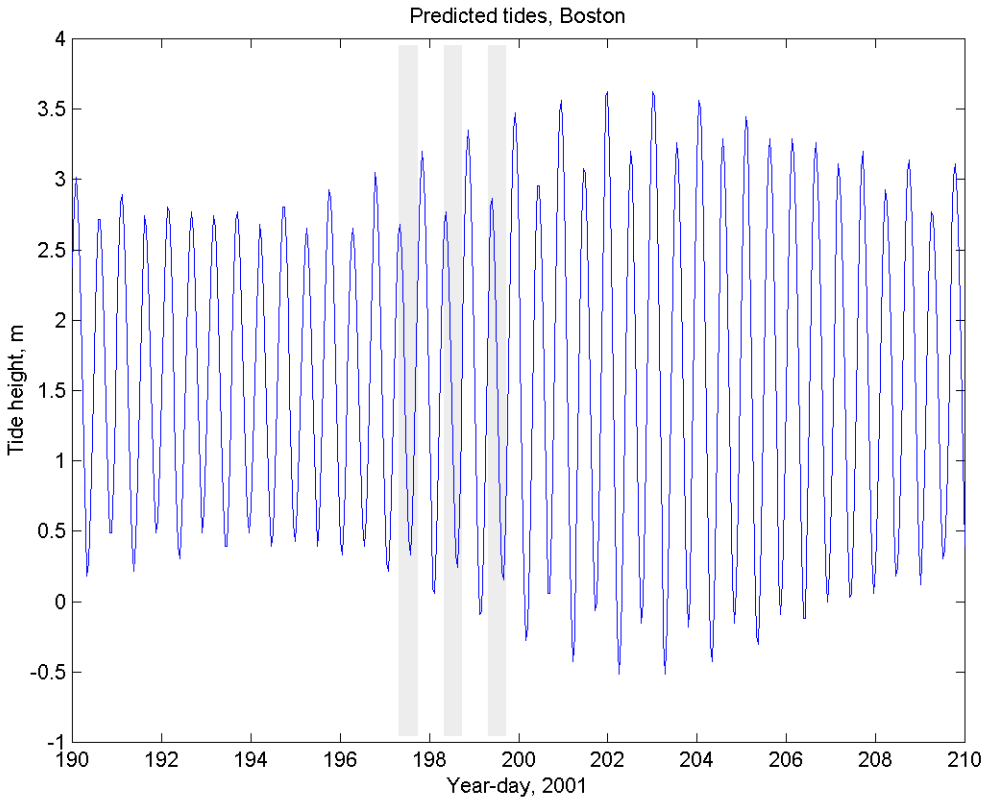

Figure 3-34. Tidal height at Boston Harbor, based on NOAA predictions. The shaded bands indicate the periods of shipboard measurements. The observations between neap and spring tidal conditions.

Wind conditions (shown in Figure 3-35) were moderate from the South at the beginning of the first survey, but they switched to northerly during the early part of the first survey day. The winds were variable during the interval between the first and second survey, and then the northerly winds resumed during the second and third surveys. The wind velocities were weak (maximum 4 m/s or 8 knots), typical of summertime conditions, throughout the interval.

3.4.2 Oceanographic Conditions

Vertical profiles of water properties (temperature, salinity and density) are shown in Figure 3-36, with data from each of the survey days superimposed. A strong thermocline is evident, extending from near the surface to about 15-m depth. Salinity also shows a gradient over this depth interval, but the density gradient is mostly due to temperature. Below the thermocline there is a slight increasing density gradient extending to the bottom, although it is much weaker than the stratification in the thermocline. There is no evidence of a bottom mixed layer in any of the profiles.

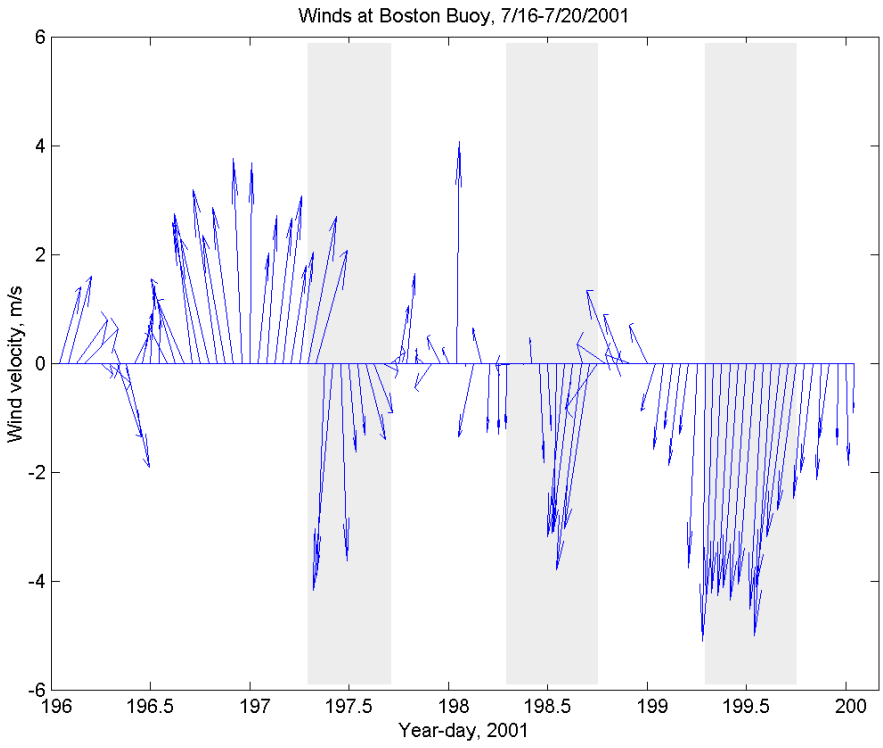

Figure 3-35. Wind vectors during the July dye study measured from the Boston meteorological buoy in western Massachusetts Bay. The shaded bands indicate the intervals of shipboard measurements.

Vertical profiles of velocity are shown in Figure 3-36, Figure 3-37, Figure 3-38 and Figure 3-39. These profiles were constructed from harmonic analysis of the raw ADCP data, in order to obtain a temporally continuous representation of the raw observations, which had numerous time gaps in them. The duration of the observations was approximately 0900 to 1700 on July 17, 1030 to 1730 on July 18, and 1000 to 1500 on July 19. None of the observations was long enough to resolve the tidal cycle, so the influence of tides and other factors (such as wind forcing) could not be separated.

The east-west component of velocity showed the barotropic (depth-independent) variability due to the tides, which tended to produce eastward motions for most of the observations, due to the timing of the surveys. There appeared to be a net eastward motion in addition to the tides, which was also evident in the displacement of the dye patch. The east-west velocity showed more vertical shear near the surface on July 18 and 19. This shear may be in response to the wind forcing, although the record is too short to provide a definitive analysis. This near-surface shear probably had little influence on the dye dispersion.

The north-south component had more vertical variability than the E-W component, with some suggestion of internal tidal fluctuations on July 17. The deeper water indicated a persistent southward velocity, typically in the range of 5-10 cm/s. It was probably the result of the regional response to the northerly wind regime, which results in a generally southward flow in western Massachusetts Bay. This southward motion is consistent with the net southward drift of the dye patch.

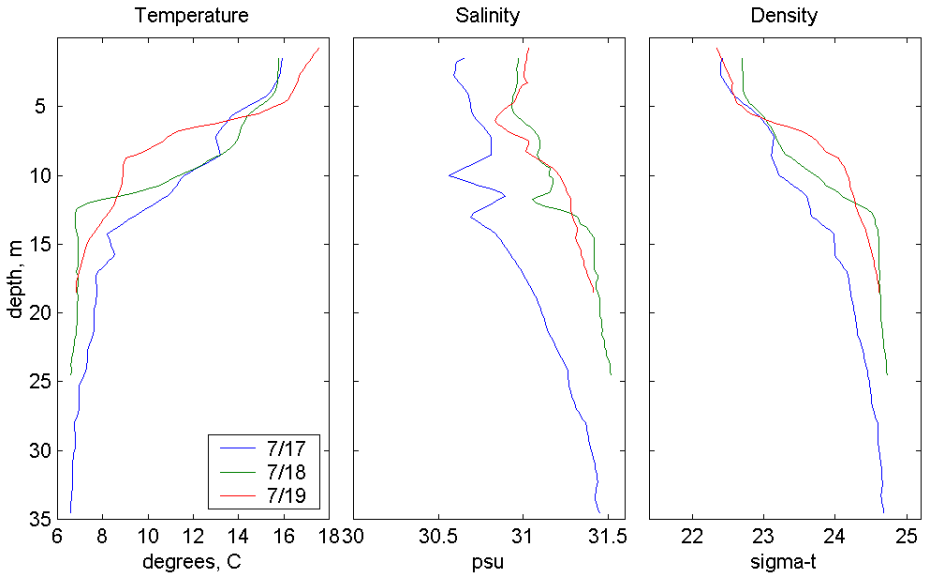

Figure 3-36. Temperature, salinity and density profiles from the far-field observations using the BOSS profiler, obtained at the beginning of each of the three survey days in July, 2001 (around 0800 local time).

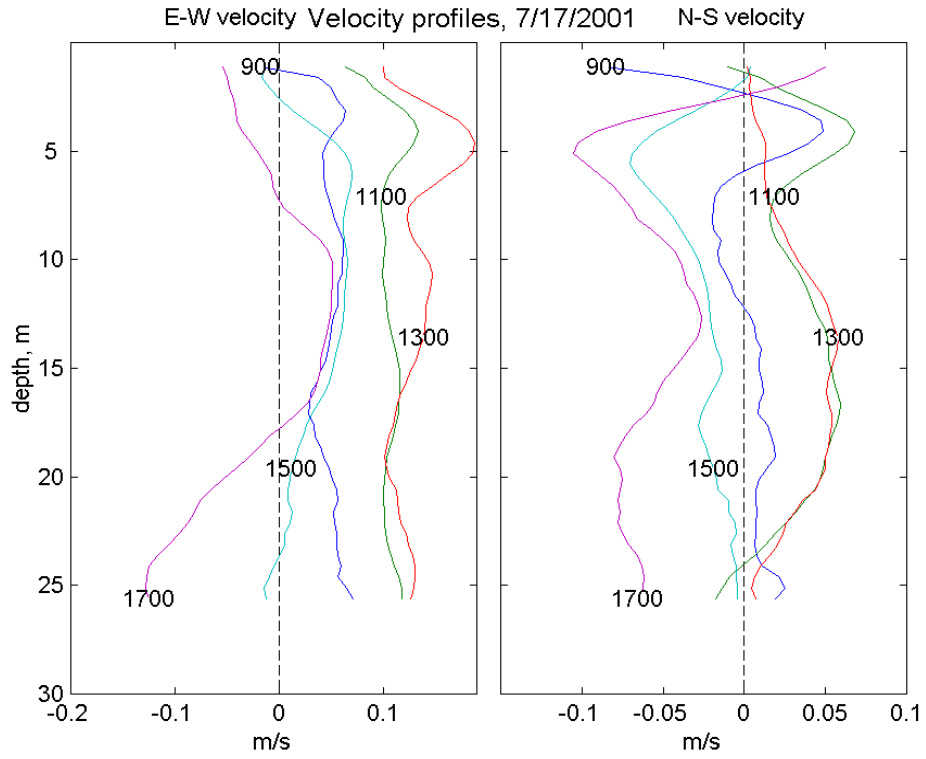

Figure 3-37. East-west and north-south velocity profiles from the shipboard ADCP at 2-hour intervals on July 17, 2001.

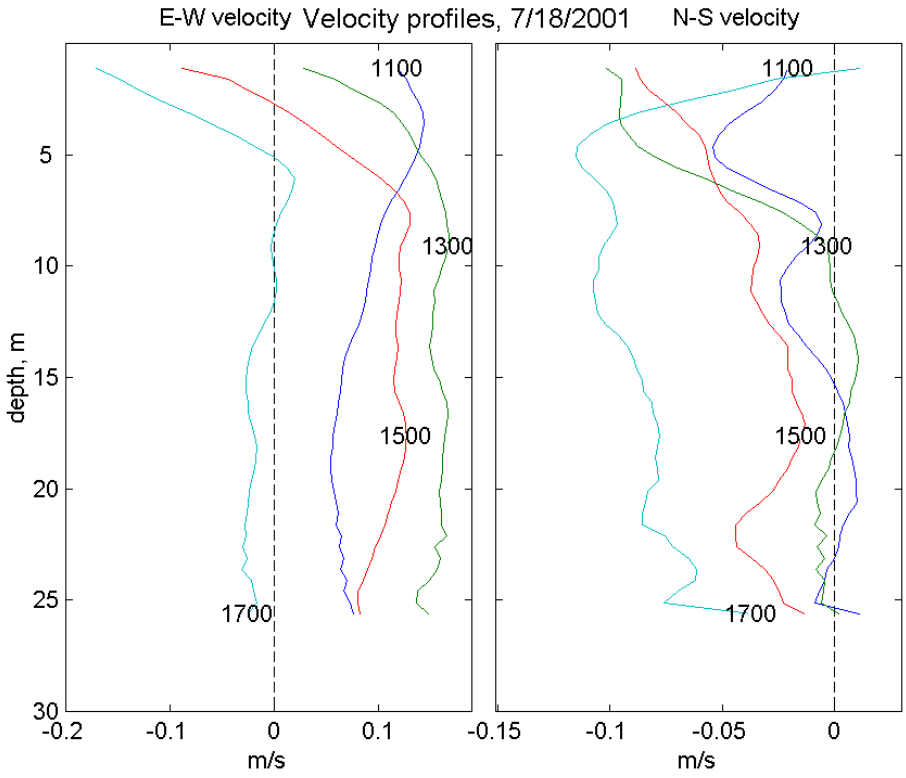

Figure 3-38. East-west and north-south velocity profiles from the shipboard ADCP at 2-hour intervals on July 18, 2001. Times are EDT.

The net influence of these currents on the displacement of water parcels was estimated by constructing progressive vector plots in Figure 3-40. The displacements of near-surface (1-5 m) and "dye-depth" (19-24 m) water parcels were determined by integrating the harmonically analyzed velocity data in time. The resulting displacements would correspond to actual water displacements if there were no spatial variations in the currents. They should be a reasonable approximation of actual displacements for timescales of several hours. The strong eastward trajectories are mostly due to tidal motions. The net southward displacement only amounts to slightly over 1 km over the observation period, which is considerably smaller than the actual southward displacement of the dye patch of about 7 km. This difference is due to the motion that occurred between observations, particularly during the night between July 18 and 19. The southward currents were increasing rapidly at the end of the observations on July 18, and this southward motion probably accounts for most of the displacement of the dye patch between July 18 and 19.

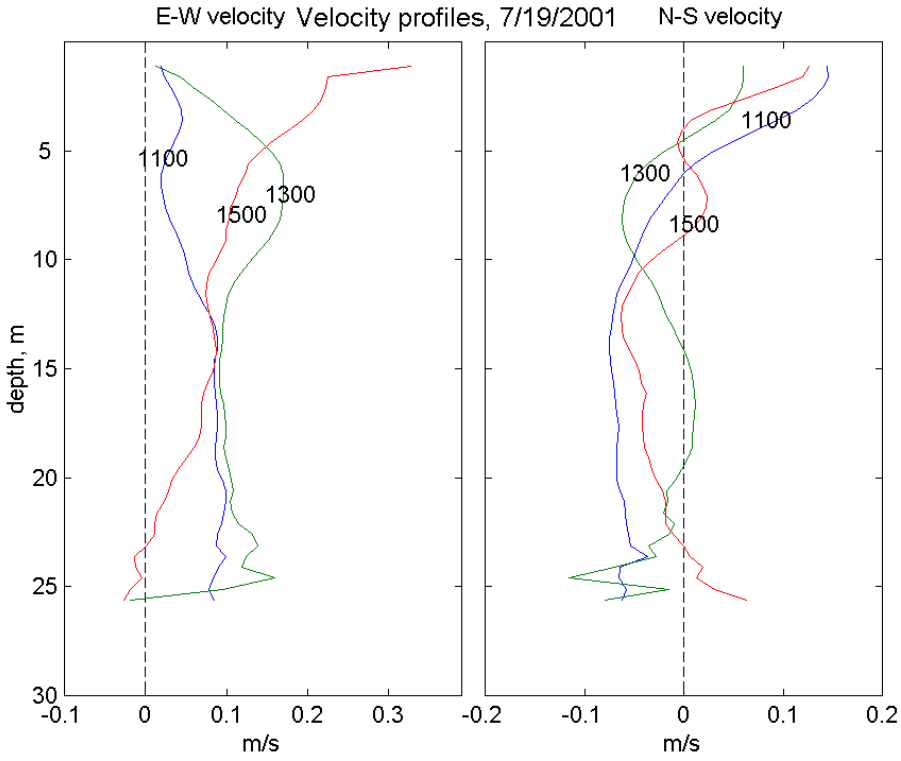

Figure 3-39. East-west and north-south velocity profiles from the shipboard ADCP at 2-hour intervals on July 19, 2001.

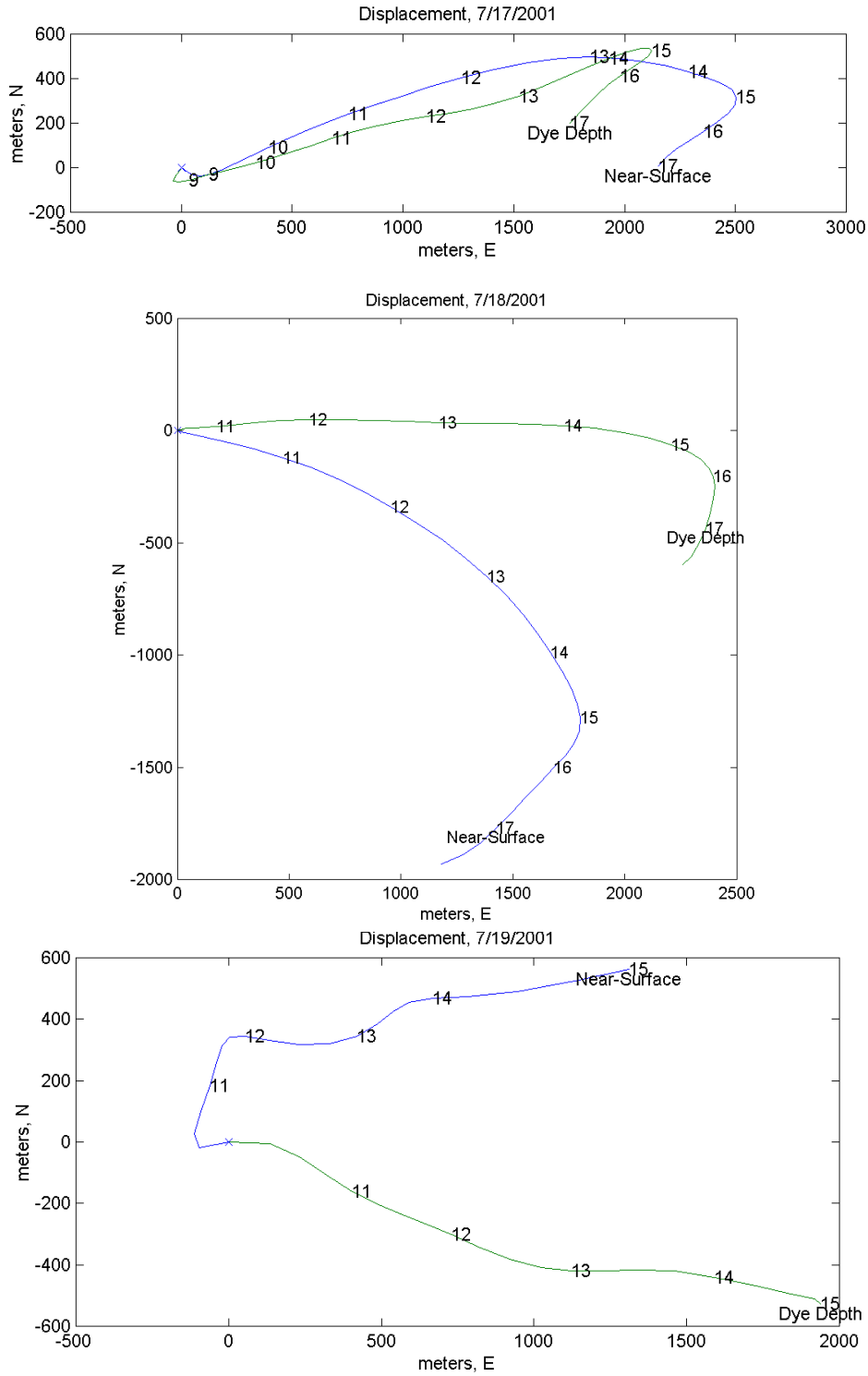

Figure 3-40. Progressive vector plot of near-surface and "dye depth" water parcels on each of the survey days, based on integration of the shipboard ADCP data. The numbers indicate hours (local time) during the day.

3.4.2.1 USGS Current Velocity Analysis

Low-pass filtered data over the entire record length at 12-m depth at the Boston Buoy (Figure 3-41) indicate typical non-tidal velocities of ±5 cm/s, with no preferred direction. During the dye release, there was a relatively strong net eastward component (4-6 cm/s) and a moderate southward component (3-5 cm/s). These results are consistent with the shipboard ADCP observations obtained during the dye tracking study.

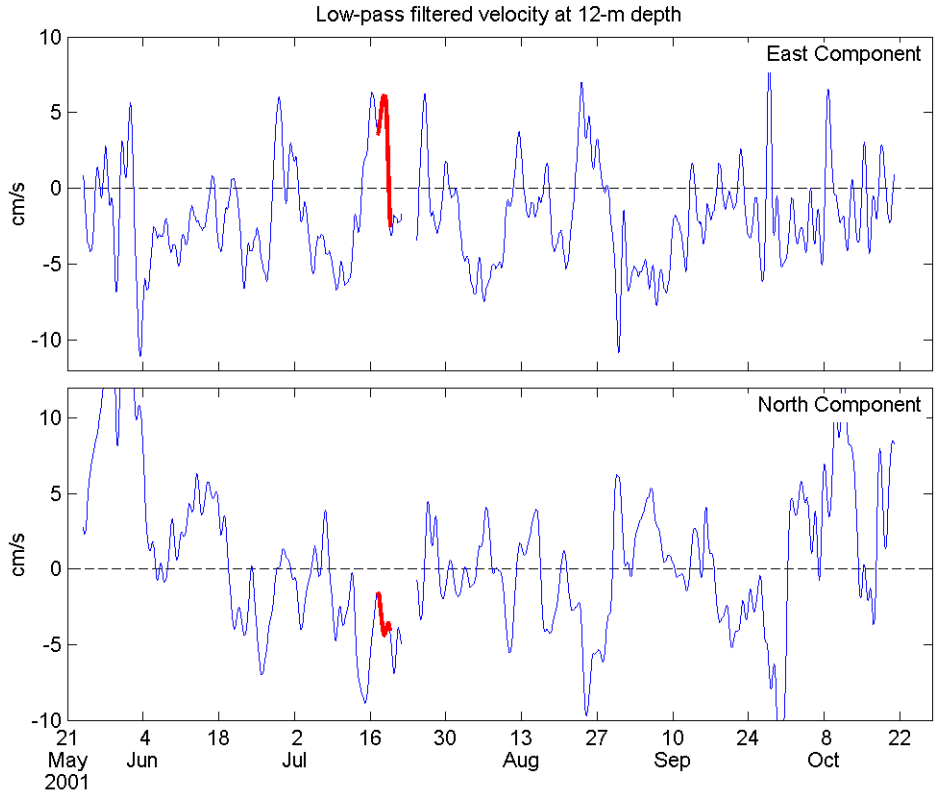

Figure 3-41. Low-passed velocity data from the ADCP at the Boston Buoy location, at 12-m depth (the level of the maximum dye concentration). The red highlighted segment indicates the period of dye release and dye tracking.

The USGS ADCP data were used to determine the magnitude of the shear in the depth range of the dye, because the shear is the main source of energy for vertical mixing outside the zone of initial dilution, and the shear also provides the most important mechanism for horizontal dispersion. Figure 3-42 shows the time-series of RMS shear (upper panel) and non-tidal (i.e., low-pass filtered) shear (lower panel). The RMS velocity difference across the dye level ranged from 6 to 14 cm/s during the study. This is within the range of typical summertime conditions. This indicates that the energy for vertical mixing was typical of Massachusetts Bay during this period. The non-tidal velocity difference (lower panel) ranged from 2 to 6 cm/s is also typical of summertime conditions. The non-tidal shear is an important factor in the horizontal dispersion—these observations indicate that the conditions influencing horizontal dispersion were representative of summertime conditions during the study.

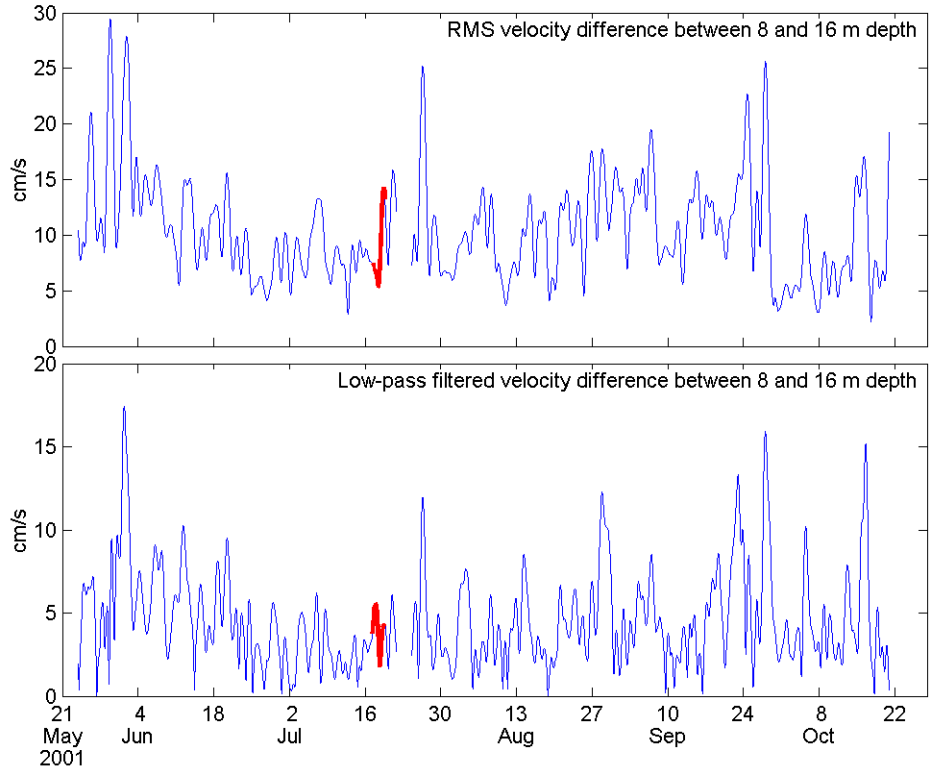

Figure 3-42. Upper panel: RMS velocity difference between 8- and 16-m depth over the deployment period, with the period of the dye release highlighted. Lower panel: low-pass-filtered (i.e., non-tidal) velocity difference between 8 and 16-m.

Vertical profiles of the time-averaged velocities (Figure 3-43) indicate that the North-South shear was the strongest shear component. This mean shear probably explains the elongation of the patch in the N-S direction.

The USGS data were further analyzed to determine the net trajectory of the dye patch, to determine whether its observed trajectory was consistent with the observations. Figure 3-44 shows the estimated position of the dye at three times within the survey, based on the progressive vector analysis. Each of the lines corresponds to the hypothetical position of the dye at different depths, from 8- to 20-m. The water was moving faster at 8-m depth, so the positions are farther eastward and southward for the near-surface displacements than the deep displacements. Vertical mixing mitigates this tilting of the patch. Based on these displacements, the center of mass of the dye should be southeast of the geographic center of the dye patch.

The USGS also maintained an ADCP near Scituate, MA, approximately 20 km south of the outfall. Comparison of the Scituate and Boston data indicated little correlation between the two. In fact, during the period of the dye study, the Scituate instrument indicated northerly flow during the whole period, in contrast to the southward tendency at the Boston Buoy. The Scituate measurements appear to be in a different regime, associated with the along-coast flow of western Massachusetts Bay. The trajectory of the dye seems to be more closely related to the conditions at the Boston Buoy.

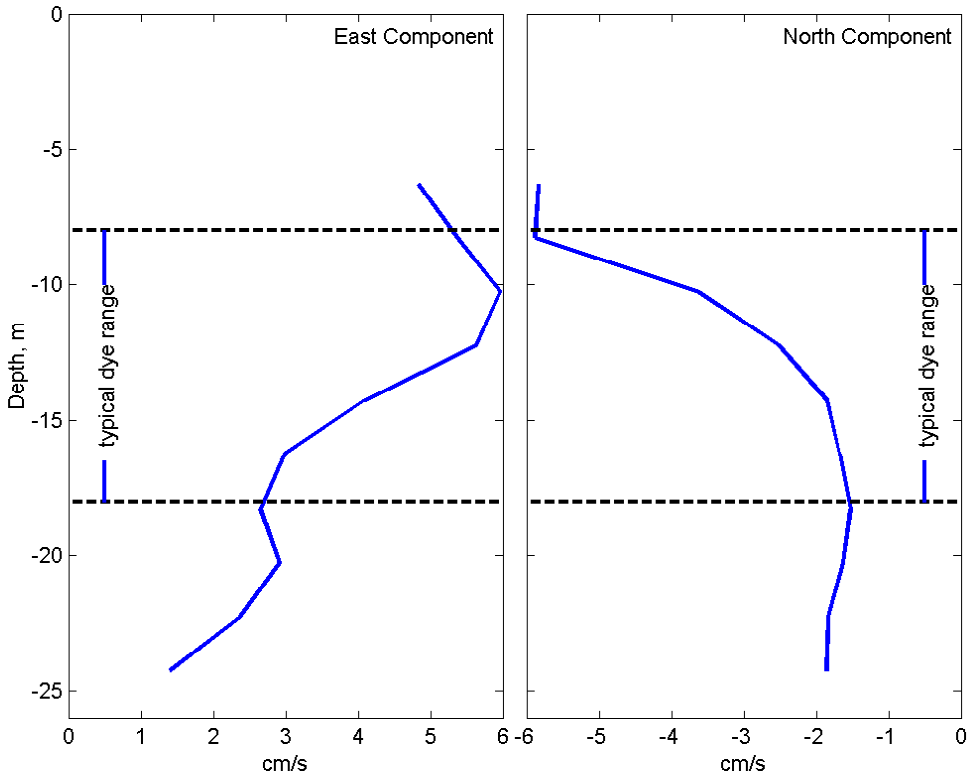

Figure 3-43. Velocity profiles of east and north component, averaged over the first 24 hours after dye emerged from the diffusers. The strongest shears were in the N-S direction, which probably explains why the dye patch was elongated in the N-S direction.

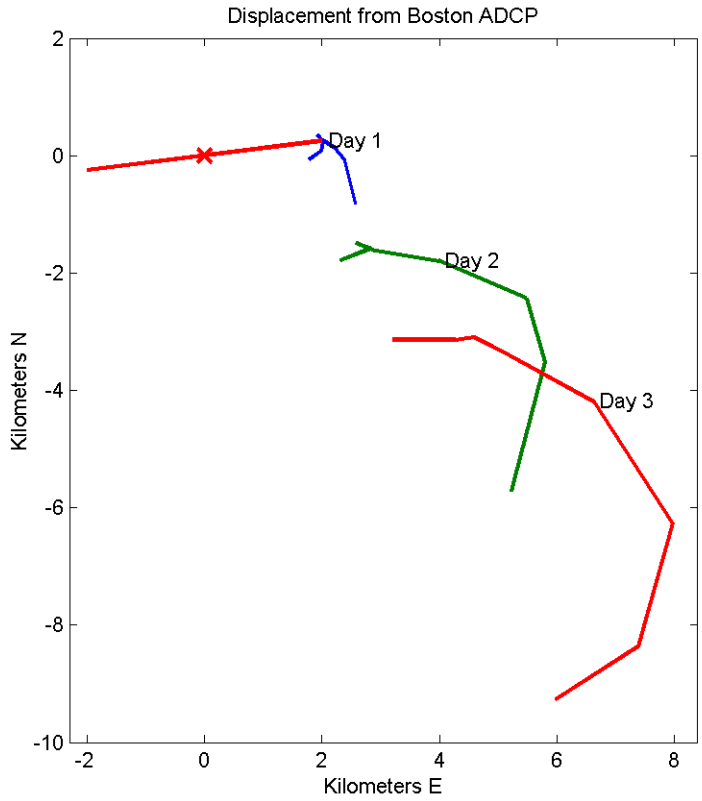

Figure 3-44. Estimated position of the centroid of the dye, based on the ADCP velocity data across the depth range of the dye, for 3 time intervals: the last survey on July 17, 2001, the mid-point of the first far-field survey (July 18, 2001) and the mid-point of the second far-field survey (July 19, 2001).

The lines for each prediction correspond to the end-point of the elapsed trajectory for each depth, from 8 to 20 m below the surface. The currents at 8-m were moving more than twice as fast as those at 20-m, so the near-surface trajectories extend further southward. The Outfall diffusers are depicted as a straight red line. The origin of all of the trajectories is the "x" at the center of the Outfall.

3.4.3 Overall Assessment of Transport

The water properties distribution was typical of summertime conditions, and the velocity forcing conditions were also typical, at least with respect to magnitudes of tidal and mean velocities. The northerly winds were somewhat atypical of summertime conditions, and the resulting southward drift in the vicinity of the Outfall is not the "normal" regime. However, the non-tidal motion at this site has no preferred direction, so the observed trajectory should be considered as one realization of a random process. Because of the low energy of the wind forcing during this time, the dominant energy source influencing the vertical mixing of the dye was the tidal motion, which was typical of summertime conditions. Strong meteorological forcing is rare during the summer months, so the general forcing conditions should be considered representative of the summer regime.

The analyses of the USGS velocity data confirmed the general southeastward trajectory of the dye. The elongation of the dye patch in the north-south direction is consistent with the dominance of the north-south mean shear during the dye study. The ambient flow conditions during the dye study are within the

typical range for the summertime regime, based on a comparison of the dye release with the rest of the data between June and October.

3.4.4 Dispersion

The dye started coming out of the diffusers early in the ebb tide on July 17. The currents were directed eastward, and over the 6-hour period of the dye release there was approximately 2-km eastward displacement due to the current. The diffusers extend approximately 2-km in the E-W direction, so even without current, the dye patch would have at minimum a 2-km E-W extent. The combination of the current and the diffuser geometry produced a dye patch approximately 4-km long near the end of the dye discharge on July 17th. The final near-field survey (HMZ3) was taken just to the east of the outfall, roughly in the middle of the patch at that time. This survey indicated that the patch extended about 800 m in the N-S direction. Without a detailed analysis of the Day 1 distribution, the second moment can be approximated by $X' \approx 1/4 L_x$, where L_x is the overall length of the patch. Based on this approximation, the apparent dispersion rates for the first 6 hours are

$$K_x = 23 \text{ m}^2/\text{s}$$
$$K_y = 0.9 \text{ m}^2/\text{s}$$

Where K_x corresponds to E-W dispersion and K_y corresponds to N-S dispersion. For this short timescale, neither component of dispersion is due to "ambient" forcing. The E-W "dispersion" is due mostly to advection and outfall geometry, and the N-S dispersion may be strongly influenced by the dynamics of the outfall itself, as indicated by Roberts' analysis. The dispersion between July 17 and July 18 provides more of an indication of the ambient dispersion processes.

The July 18 moments were calculated directly from the observations, as described above. The patch was oriented 10º to the east of north, so the estimates of dispersion were based on a rotated coordinate system. However the terms "North" and "East" are still applied to these directions. The results are shown in Table 3-7.

Table 3-7. Moments and dispersion from first far field survey day.

	X' or Y'	L_x or L_y	K_x or K_y
North component (major axis)	1,900 m	7.6 km	18 m^2/s
East component (minor axis)	750 m	3.0 km	3 m^2/s

To put these quantities in perspective, the dye patch increased in area from about 1.6 km^2 to 20 km^2 between July 17 and 18. This represents in approximately ten-fold dilution over the 27-hour period associated with horizontal spreading. If the average dilution in the Hydraulic mixing zone is 100:1, the average dilution after one day increases to approximately 1000:1.

The magnitude of horizontal dispersion is comparable to that observed in the 1993 dye study (Geyer and Ledwell, 1994)[9]. During that study, the dispersion rate increased from approximately 3 m^2/s to 18 m^2/s as

[9] The dispersion value is also consistent with parameterization of horizontal mixing using the Smagorsky formulation, which led to dispersion rates of 5 to 20 cm/s in a comparison of plume behavior using the far field circulation model of Massachusetts Bay to derived using the near field ULINE model results (Blumberg *et al*. 1996).

the patch increased in size over several days. This increase in dispersion may be due in part to changes in forcing, but it is also due to an increase in the size of the patch, which tends to increase the dispersion rate. In the outfall dye release, the dispersion rate reaches a high value of 18 m^2/s on the first day of spreading, although the horizontal extent of the patch is still limited. The higher initial dispersion is probably due to the larger vertical distribution of dye coming from the outfall (approximately 10-m vertically) compared to the patch release in 1993, which had a 5-m vertical extent. The larger the vertical extent, the more influence the vertical shear has on horizontal spreading of the dye.

In conclusion, this study indicates a large horizontal dispersion rate, which produces rapid dilution of the dye due to the influence of the ambient shear.

3.5 Modeling

The field results described in the preceding sections were also evaluated through modeling of the effluent dilution. The measurements and the modeling were partly conducted to satisfy the conditions of the Boston MWRA NPDES permit that requires comparison of the field operation of the diffuser with the physical model studies on which the riser and diffuser design were based (Roberts and Snyder, 1993a,b). In this section, the results of the near field observations are compared to the original physical model studies and to predictions of a mathematical model.

3.5.1 Field Study Summary

Fluorescent dye (Rhodamine WT) was added at the Deer Island Treatment Plant at a variable rate to match the wastewater flow rate so that the final effluent concentration remained approximately constant (Section 2.1.1). The wastewater flow variation is shown in Figure 3-1 and the effluent dye concentration in Figure 3-2. The wastewater flow varied from about 250 to 370 MGD during dye addition, and about 300 to 550 MGD during the near field survey. The dye concentration was 86.0 ± 0.5 ppb for the duration of the tests. The mean value of c_0 = 86.0 ppb was assumed for the purpose of computing dilutions.

The offshore survey activities are described in Section 2.1.2. The survey included measurements of ocean currents with a downward-looking Acoustic-Doppler Current Profiler (ADCP) attached to the survey boat. Ocean currents were measured by the ADCP are shown in Figure 3-45. Because plume behavior and dilution are affected mostly by deeper currents, the depth-averaged currents (below 10 m) are shown as vectors and speed magnitudes in Figure 3-46. Dye was first detected around 10:30 EDT. From 10:30 to about 14:00, the depth-averaged speeds ranged from 11 to 16 cm/s. From 14:00 EDT to the end of the surveys at 17:00 EDT, the speeds slowed to 5 to 10 cm/s, and the direction rotated clockwise to the SW.

Density profiles were measured by STD (Salinity-Temperature-Depth) profiling. The profiles of salinity, temperature, and density that were obtained in the vicinity of the diffuser on the near field day are shown in Figure 3-47. The water column was stratified, due to both temperature and salinity variations. The total difference in density over the water column was about 2.0 sigma-t units. Most of this density change occurred in the surface layer, which was about 10 m thick. Below this layer (the region of the water column that most affects the plume behavior), the change of density with depth is much less. The density profile there was approximately linear, with a buoyancy frequency, $N = \sqrt{\frac{-g}{\rho_o}\frac{d\rho}{dz}} = 0.0157\ s^{-1}$, where g is the acceleration due to gravity, ρ the seawater density at height z above the bottom, $\rho_o \approx 1.0$ g/cc is a reference density. This value of N is very close to that observed during the April field tests (Hunt *et al*. 2002).

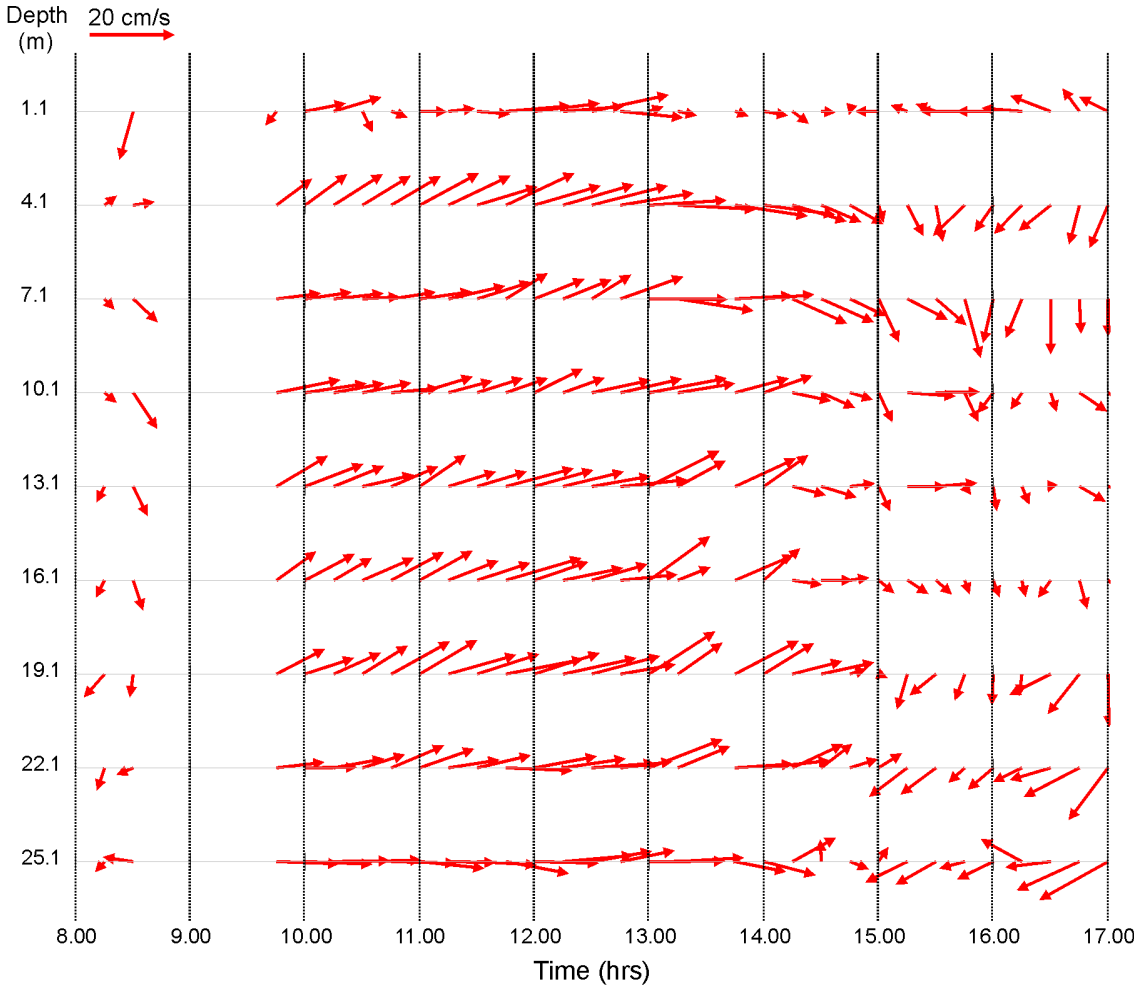

Figure 3-45. Variations in current speed and directions over depth measured by the ADCP.

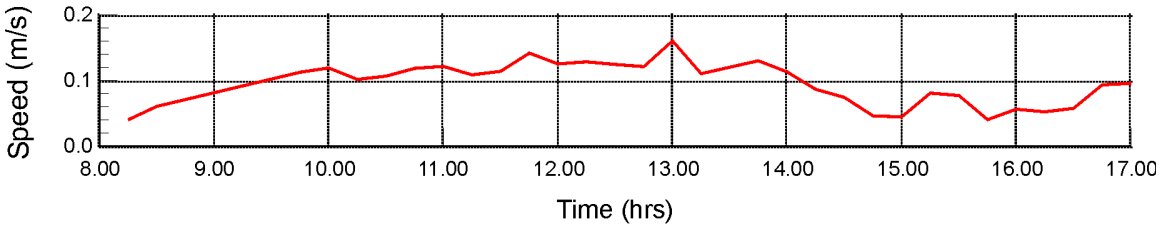

Figure 3-46. Depth-averaged current speed (below 10 m) currents.

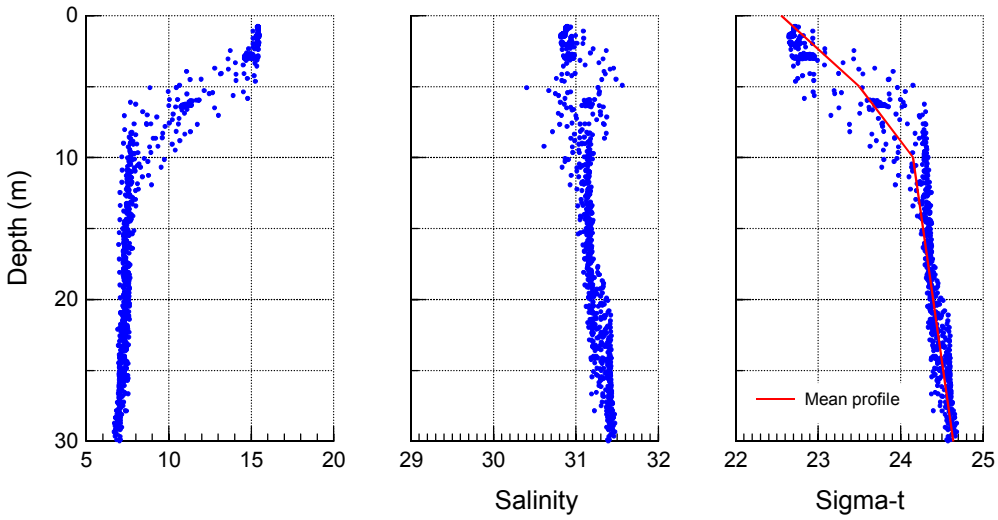

Figure 3-47. Vertical temperature, salinity, and density profiles measured near the diffuser on July 17, 2002.

The field test conditions are summarized in Table 3-8.

Table 3-8. Summary of near field test conditions, July 17, 2001.

Effluent dye concentration	86.0 ppb
Wastewater flow rate	300 – 550 MGD
Current speeds	4 – 16 cm/s
Current directions	Generally to ENE
Stratification	About 2.0 sigma-t units over water column

The predominant current direction was almost exactly parallel to the axis of the diffuser. Under these conditions, the wastefield spreads laterally as a dynamical density current (Roberts *et al*., 1989). The dye transects were therefore conducted perpendicular to the diffuser axis beginning at the onshore end as shown in Figure 3-48. Three Hydraulic Mixing Zone (HMZ) tracklines were run, labeled HMZ1, HMZ2, and HMZ3.

The tracklines for HMZ1 extend about 200 m on each side of the diffuser between riser numbers 51 and 52, i.e., about 150 m from the inshore end of the diffuser. HMZ2 is between riser numbers 25 and 26, i.e., roughly midway along the diffuser. HMZ3 is beyond the offshore end of the diffuser, about 100 m to 200 m from riser number 1. The tracklines and dye concentrations for each HMZ are shown in Figure 3-48; vertical dye concentration profiles for each HMZ are shown in Figure 3-49.

The lateral and vertical variations of dye concentrations are shown in normalized (as c/c_o) three-dimensional form in Figure 3-50a. It can be seen that the data are quite "spiky," with large fluctuations. These are probably due to internal waves, active near-field mixing, and advection of patches of water with

different dye concentrations past the sampling instrument (see Roberts *et al*., 2001, for further discussion of this phenomenon).

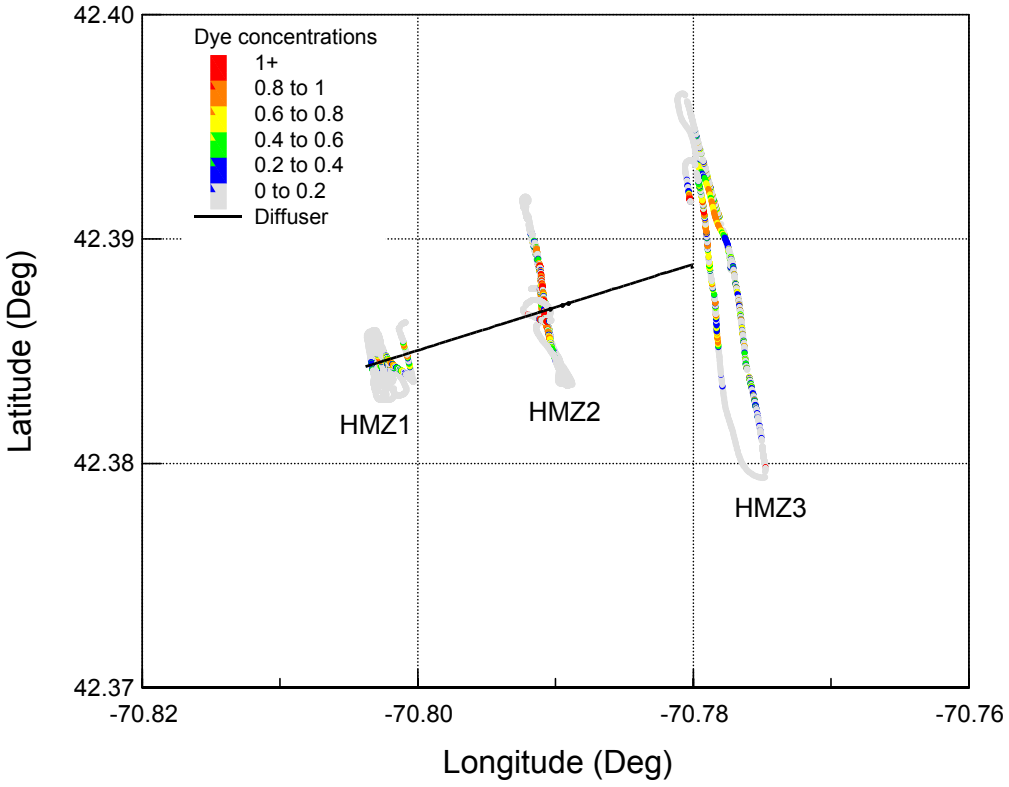

Figure 3-48. Vessel tracklines and dye concentrations measured during lateral HMZ transits perpendicular to the MWRA diffuser.

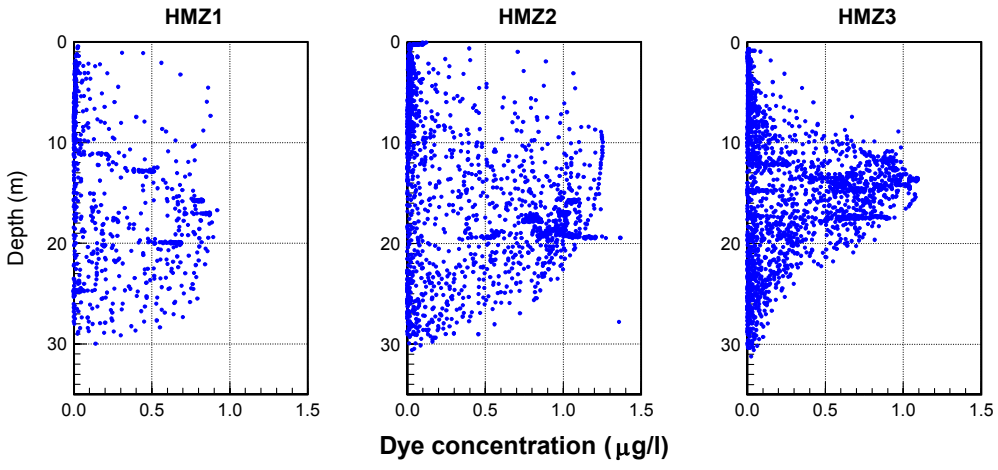

Figure 3-49. Vertical dye profiles measured during lateral HMZ transects perpendicular to the MWRA diffuser.

The dilutions obtained from physical or mathematical models are time-averaged, with temporal fluctuations removed. For the most effective comparisons to the models, field dilutions should also be time-averaged, and comparisons with instantaneous values measured in the field may not provide the best comparative information. However, field logistics are such that without *a priori* knowledge of the length of the dilution field and magnitude of local currents at the time of the survey, positioning a system to collect time-averaged data at the appropriate depth at several locations along the diffuser would jeopardize the study. The towyo data obtained during the survey provided highly resolved information on both the location and magnitude of the dye concentrations. These data were used to estimate time-averaged results by applying a low-pass filter to the spatial data. This spatial filter removed the high frequency fluctuations, providing a better estimate of the average concentrations at each HMZ. The resulting filtered data are shown in Figure 3-50b. The lateral variations of the measured instantaneous dye concentrations (Figure 3-49) within ±400 m from the diffuser axis are superimposed on overhead (plan) views of the filtered data in Figure 3-51. It can be seen that the instantaneous measurements can often greatly exceed average values.

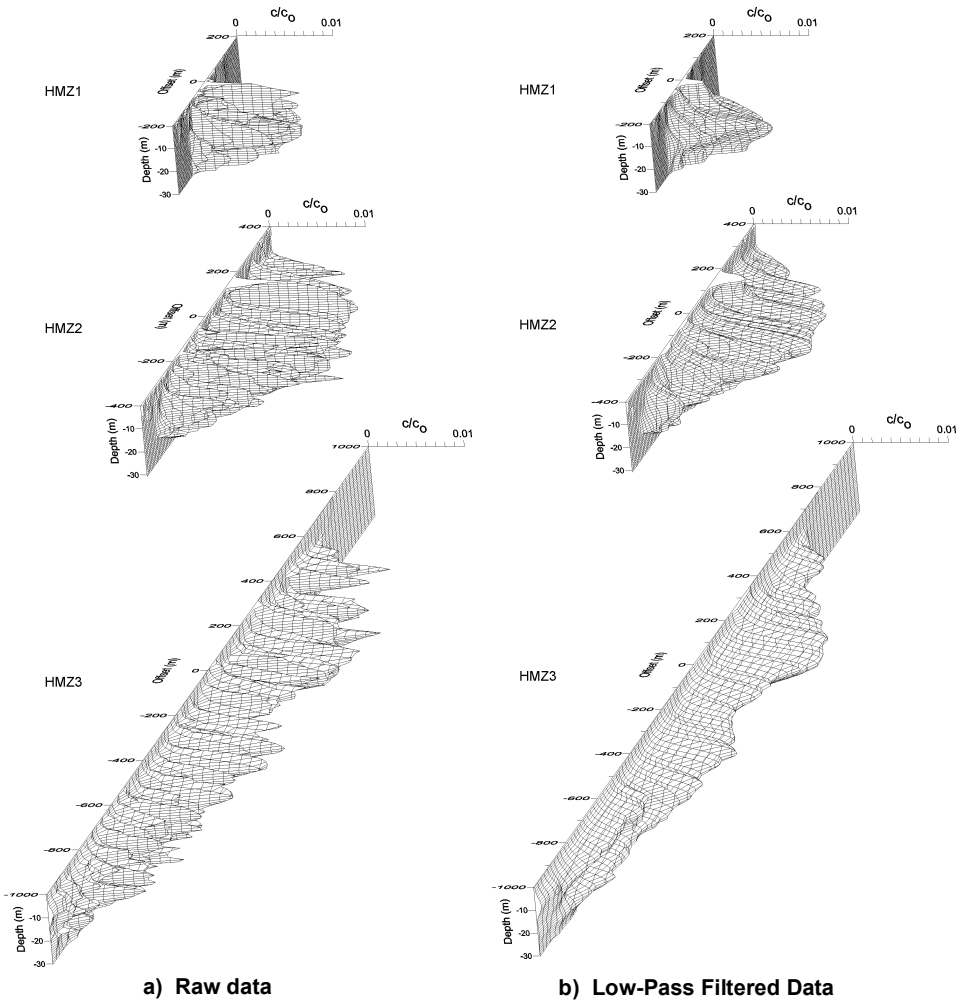

Figure 3-50. Horizontal dye profiles measured during lateral HMZ transects perpendicular to the diffuser axis.

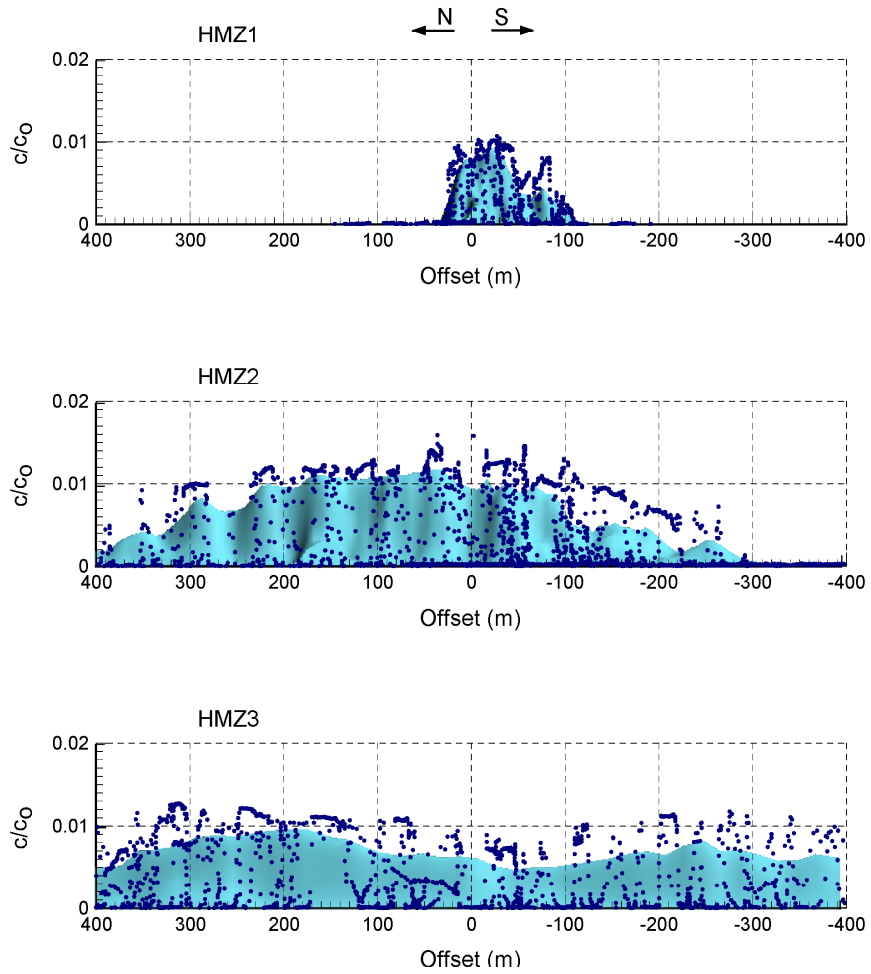

Figure 3-51. Plan views of low-pass filtered dye profiles and instantaneous measured dye concentrations.

Because of the variability of the conditions throughout the sampling periods, and because of the temporal and spatial variability of the measured dye concentrations, even at nearby locations, the computation of dilution requires some judgment.

Consider the measurements at HMZ3, which is downstream and beyond the end of the diffuser. The highest concentration, *c,* in the filtered data is 0.845 µg/l. The source concentration, c_o = 86.0 µg/l, thus, the dilution, S = 86.0/0.845 = 102. Spatially averaged values could also be used. The highest dye concentrations occur between 13 and 17 m depth. The spatial average in this depth range between ±400 m (the range of highest dye concentrations), is 0.745 µg/l, which implies a dilution of 115, between ±300 m is 0.731 µg/l, which implies a dilution of 118, and between +150 m to +250 m, (the broad lateral peak that occurs to the north of the diffuser), is 0.919 µg/l, which implies a dilution of 94. Thus, estimates of near field dilution computed with various assumptions range from 94 to 118, with a value of 102 computed from the spatially filtered data.

The top of the wastefield at HMZ3 (Figure 3-49) occurs at about 5 m depth. Occasional surfacing can be seen in Figure 3-50. This is most probably isolated puffs in the centers of the turbulent plumes briefly reaching the water surface, however; the great majority of the wastefield is submerged. The bottom is at

about 25 m depth. The wastefield thickness is therefore about 20 m. The maximum dye concentration (corresponding to the minimum dilution) occurs at about 15 m depth. The port depths range from 31.5 to 33.9 m with an average of 32.8 m. Taking the average port depth, the rise height to the top of the wastefield is about 28 m, and the height of the minimum dilution about 18 m.

Dilutions were also estimated for HMZ2. The maximum concentration observed there was 1.735 µg/l, but this was directly over the diffuser. Excluding this value, peak dye concentrations in the near field (assumed to extend ±60 m from the diffuser) were typically 1.37 µg/l. Beyond this distance, peak concentrations in the laterally spreading are around 1.11 µg/l, implying dilutions of about 78. Again, however, these are instantaneous peaks that are not representative of time-averaged values. The highest concentrations outside of the near field occur between 60 to 230 m north of the diffuser. The spatially filtered peak in this range is 0.960 µg/l, implying a dilution of 90. The peak concentrations occur over depths from 13 to 18 m. The spatially averaged concentration over this depth and offset range is 0.924, implying a dilution of 93.

3.5.2 Physical Modeling Studies

The original physical model studies (Roberts and Snyder, 1993a,b) were carried out in a large density-stratified towing tank at scales of 52:1 to 87:1. Conditions tested included flows of 390, 620, and 1270 MGD. The current speeds were zero, 12, and 25 cm/s, mostly perpendicular to the diffuser, although some were parallel to the diffuser. Three density stratifications were tested: "Winter" (homogeneous), "Early Summer" (total density difference of 3.3 sigma-t units over the water column), and "Late Summer" (total density difference of 3.7 sigma-t units over the water column). The modeled profiles are shown in Figure 3-52, along with the mean assumed profile from Figure 3-47. (The mean measured profile has been shifted to have the same density at the port depth as the modeled profiles, as it is only the density *differences* over the water column that affect plume behavior).

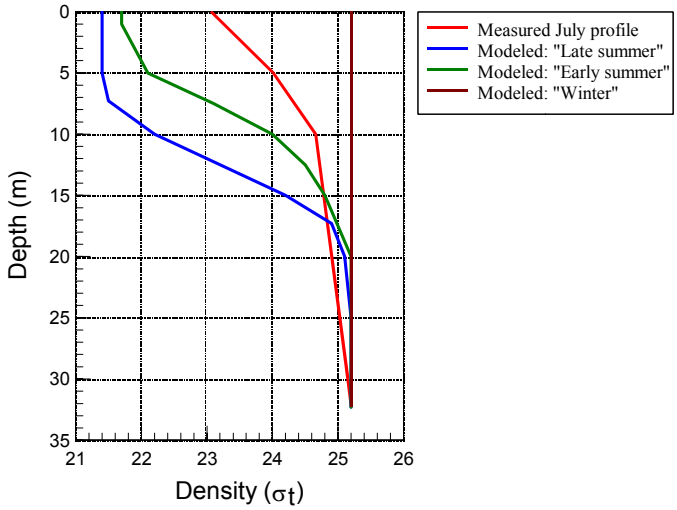

Figure 3-52. Density profiles modeled by Roberts and Snyder (1993 a,b) compared with the mean assumed profile from the July 2001 plume tracking study.

Both of the modeled summer profiles are much stronger than those actually observed in July. The model conditions closest to those observed in the field are a test with a parallel current at 12 cm/s, flow rate of 390 mgd, Early Summer stratification. Only four risers were modeled due to length limitations of the test tank. For this test (see Table 3 of Roberts and Snyder, 1993b), the measured dilution was 105, height to top of wastefield 20.3 m, and thickness 11.0 m. In comparison, the results at HMZ3 were: dilution 102, height to top of wastefield 28 m, and thickness 20 m. The higher rise height and thicker wastefield observed in the field relative to the model are consistent with the sharper and deeper thermocline of the Early Summer modeled profile. Because of the difference in the density profiles and unsteadiness of the currents and flow rates during the field surveys more exact comparisons are not possible, but the results of the field and physical model studies appear to be generally consistent.

3.5.3 Mathematical Modeling

The field results were compared with predictions of the mathematical model RSB. RSB is available in the U.S. EPA Visual PLUMES interface (Frick *et al*., 2001) and also as a separate Windows program RSBWIN. The model is described in Roberts (1999), where a version (called NRFIELD) that was recoded to use long time series of oceanographic data. RSB is based on the extensive experiments on multiport diffusers in density-stratified currents of arbitrary direction reported in Roberts *et al*. (1989). It uses semi-empirical formulations based on the relative magnitudes of the dominant length scales of the problem. The model output consists of the plume characteristics (dilution, rise height, and wastefield thickness) at the end of the near field. Predictions of RSB were also compared to the original physical model study results (Roberts and Snyder, 1993b, Table 5), with generally good agreement. The RSB predictions for the late summer conditions were always conservative, i.e., they underestimated the measured dilutions, by 4 to 22%.

As previously discussed, the oceanic conditions were variable during the near field sampling. The depth-averaged currents (below 10 m) were in the range of 4 to 15 cm/s (Figure 3-46) with a direction almost exactly parallel to the diffuser. The wastewater flow rate ranged from 300 to 550 MGD (13.1 to 24.1 m^3/s).

The most important dynamical parameter governing the dynamics of the diffuser flow in the near field is a type of Froude number, F (Roberts *et al*., 1989):

$$F = \frac{u^3}{b} \qquad (1)$$

where u is the current speed and b is the buoyancy flux per unit length equal to $g\frac{\Delta\rho}{\rho}\frac{Q}{L}$ where g is the acceleration due to gravity, $\Delta\rho$ is the density difference between the wastewater and seawater at the port level, ρ the seawater density at the port level, Q the total wastewater flow, and L the diffuser length. According to the experiments of Roberts *et al*. (1993a,b), the current exerts little or no effect on mixing and dilution for $F < 0.1$. The conditions for each HMZ survey are summarized in Table 3-9, along with the value of the Froude number. The Froude number ranged about 0.03 to 0.79 so the current may have some effect on dilution. The effect in this range for a current parallel to the diffuser is quite small, however (Roberts *et al*., 1989).

RSB was run for the assumed conditions shown in Table 3-9 along with the non-linear mean density profile shown in Figure 3-47. The predictions and comparisons with the field data for HMZ3 are shown in Table 3-10. Dilution, rise height, and thickness are very closely simulated. It should be noted, however, that it is not clear which oceanic conditions should be used. The depth-averaged current speeds varied during the field tests from about 12 cm/s initially to 4 cm/s during the HMZ3 measurements. The drift time for wastewater to be advected the length of the diffuser is about 5 hours at 12 cm/s, thus the

parcels of fluid that were measured during HMZ3 could have been formed 5 hours earlier when the current speed was higher. If this higher current speed is assumed, RSB would predict a minimum dilution of about 132.

Table 3-9. Summary of conditions for each HMZ survey.

Period:	**HMZ1**	**HMZ2**	**HMZ3**
Time (EDT)	11:56 to 12:41	13:02 to 14:57	15:06 to 16:57
Flow (MGD)	368 to 439	380 to 411	330 to 399
Average flow (MGD)	394	397	367
Currents:			
Average speed (m/s)	0.12	0.09	0.04
Average direction	76°	77°	194°
Direction relative to diffuser	0°	1°	62°
Froude number, $F = u^3/b$	0.79	0.33	0.03

Table 3-10. Comparison of Field Measurements and RSB Predictions (HMZ3).

	Field measurements	**RSB predictions***
Near field dilution	102	104
Thickness of wastefield (m)	20	18.8
Height to top of wastefield (m)	28	24.8
Height of minimum dilution (m)	118	16.6
Length of near field (m)	Not measured	~13
*Assuming five ports open per riser		

3.5.4 Lateral Spreading

The wastefield in a stratified parallel current spreads laterally as a density current. This is a dynamical spreading that is not related to lateral turbulent diffusion. Discussion of this phenomenon is given in Roberts *et al*. (1989) along with experimental results. Roberts *et al*. (1989) predict that the wastefield will spread linearly, in a V-shape according to:

$$\frac{w}{x} = 0.70F^{-1/3} \quad (2)$$

where w is the wastefield width a distance x from the leading edge, and F is the Froude number defined in Eq. 1. Eq. 2 can be written in terms of the internal spreading angle Θ:

$$\Theta = 2\tan^{-1}\left(0.35F^{-1/3}\right) \quad (3)$$

Eq. 3 is plotted on Figure 3-53 assuming a current speed of 12 cm/s and a flowrate of 394 mgd (17.3 m^3/s). This yields a Froude number (Eq. 1) $F = 0.78$, and a spreading angle (Eq. 3) $\Theta = 41°$. Although flow and current speed varied somewhat during the HMZ transects, the agreement with the plume extent inferred from the dye concentration data is remarkable.

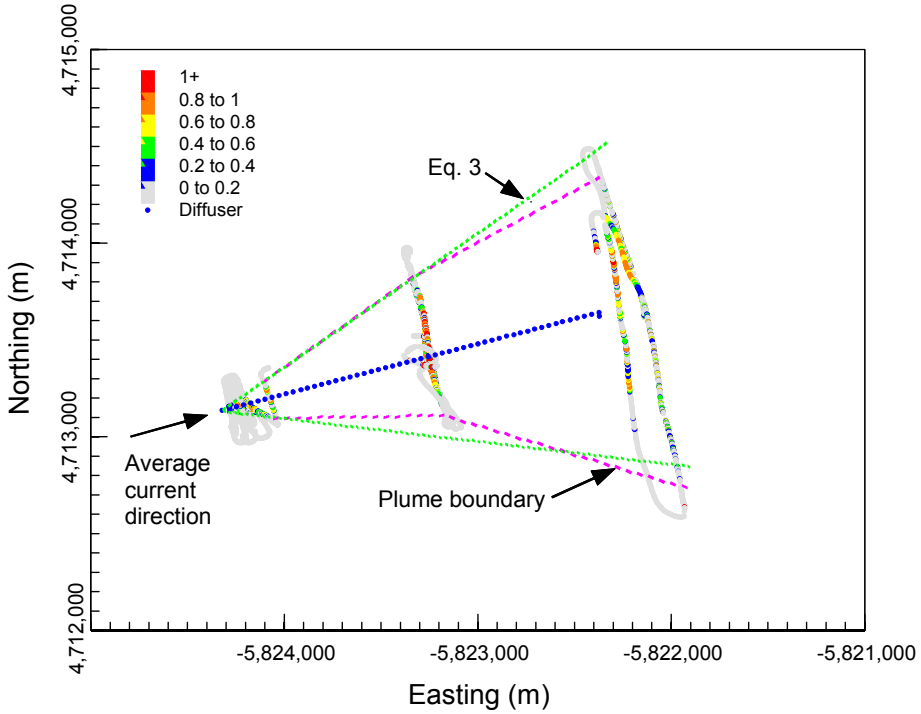

Figure 3-53. Observed plume boundary and comparison with buoyant spreading equation.

3.5.5 Conclusions

Comparisons of the near field measurements of the plume observed on July 17, 2001, with the original physical model studies (Roberts and Snyder, 1993a,b) and predictions of the mathematical model RSB are reported. The current on July 17 was flowing almost exactly parallel to the diffuser axis for most of the sampling period. Some of the physical model tests were also done with parallel currents. The results of the physical model tests with conditions closest to those on July 17 were consistent with those observed in the field.

The field results were also compared to predictions of the mathematical model RSB. The near field dilution, plume rise height, and wastefield thickness were closely simulated. The wastefield width increased along the diffuser axis due to dynamical spreading; Eq. 3 closely predicted the spreading angle.

It is concluded that the outfall is behaving as expected. Measured dilutions and other wastefield characteristics show good agreement with results from both the original physical model studies and also with predictions of the mathematical model RSB.

4.0 SUMMARY

4.1 General

The Plume Tracking Certification Survey conducted in July 2001 was extremely successful and all study objectives were met. The dye added to the treatment effluent at Deer Island was traced offshore in Massachusetts Bay for three days. The dyed effluent exited from the diffuser into a water column that was moderately stratified with a sharp infection in the pycnocline at five to seven meters depth. Water property (salinity, temperature, density) distributions during the survey were typical of summertime

conditions as were hydrodynamic conditions with respect to magnitude of tidal and mean current velocities and direction. These conditions reflected the low wind vectors experienced prior to and during the study.

The water column in Massachusetts Bay was transported to the east-northeast at ~15 cm/s for the 8 hour period that the dye exited the diffuser, turning to the south and southwest at the end of the survey period as the tide turned. The current velocities were relatively similar and uniform with depth as the dye entered Massachusetts Bay. The net water column transport over the next two days was to the south and east at 2 to 6 cm/s. These are typical non-tidal velocities for Massachusetts Bay in the summertime. The dominant energy source influencing the vertical mixing of the dye field was the tidal motion due to low energy of the wind forcing during the survey period. Low winds are also typical of summertime conditions.

Effluent dilution based on the average dye concentration in the effluent (85.96 ppb Rhodamine) and in the receiving waters (0 to ~1.09 ppb based on instantaneous field data) found initial mixing of the effluent was completed very close to the diffuser line. The lowest dilution measured was ~ 50 very close to a riser. Dilution measured in the core of the dye field by the *in situ* sensor system ranged from 80 to 105. This range was observed on all three hydraulic mixing zone surveys conducted to characterize the dye field and to estimate the spatial variability and distribution of effluent initial dilution.

The dye field was located between 5 and 25 meters depth during the hydraulic mixing zone surveys, with the core of the plume located between 10 and 15 m depth. The upper edge of the dye field extended to the base of the pycnocline. These characteristics were maintained throughout the following 2 days.

During the dye addition the plume was transported to the east by the currents and spread laterally from ~150 m at the west end of the diffuser system to over 1,500 m east of the diffusers due to the sustained ENE current direction which paralleled the diffuser line throughout the dye tracking effort on the near field day.

The dye field was transported to the south and east of the diffuser over the two days following release. The dye field was located at least 5 km offshore of Situate, MA between 10 and 23 meters depth 48 hour after dye release and elongated in the north south direction. The northern boundary of the plume had moved 6.5 km to the south and slightly east of the diffuser and increased in area from about 1.6 km^2 to 20 km^2 between July 17 and 18. This represents an ~10-fold dilution over the 24-hour period or an increase in average dilution from ~ 100:1 after hydraulic mixing was completed to approximately 1000:1 on average one day after release. The spread and dilution was mostly in the horizontal direction as the thickness of the dye patch remained relatively constant between July 17 and July 19. The elongation of the dye patch in the north-south direction in the far field is consistent with the dominance of the north-south mean shear observed during the study. The dye data also allowed an estimate of the dispersion rate in the Bay in Massachusetts Bay. A rate of 18 cm^2/s was derived and is similar to previously measured dispersion in the bay in the summer time.

The plume's dimensional characteristics and effluent dilution, estimated using the RSB model and current velocities and direction measured during the certifications survey were very consistent with measured results. Initial dilution estimates based on spatial low pass signal processing of the *in situ* dye data, resulted in an estimated average initial dilution of 102. This is slightly higher than the dilution estimated using discrete dye data (~90 fold). The dilution calculated using spatially averaged values are considered more representative than those derived from instantaneous sampling which may not capture temporal and spatial fluctuations adequately. The time averaged initial dilution estimated by the RSB model gave an initial dilution of 104. The thickness of the dye field measured during HMZ3 was about 20 m, the rise height to the top of the field was about 25 m, and the height of the minimum dilution about 15 m. This

compares to the RSB model results of 17.6 m, 23.5, and 15.7 m for dye thickness, rise height, and height of minimum, dilution, respectively. These results compare well with predictions from the original physical model study completed for during the design of the diffuser system.

Water quality characteristics measured from discrete samples collected during the survey found small increases in metals, nutrients, and total suspended solids in the plume relative to background levels. Copper concentrations after initial mixing were ~60% higher than background levels measured east and north of the diffuser system. Ammonia and phosphate in the diluted effluent were ~ 5- and 1.5-fold over background levels, respectively. Total suspended solids increased as much as 1.2 fold in the core of the plume. *In situ* measured of the particle field confirmed a localized increase in turbidity relative to background levels. In contrast, bacterial indictors were near or below the detection limits of the methods and did not display an increase relative to the background measured in Massachusetts Bay since the outfall came on line.

The water quality data from the plume demonstrated that state standards and federal marine water quality criteria were not exceeded after initial mixing. The highest measured copper concentration in the effluent plume was 0.69 µg/L. This compares to a marine water quality criterion of 3.1 µg/L. *Enterococcus* levels were not detected in 16 samples and at 2 colonies per 100mL in two samples. Fecal coliform was measurable at 1 to 4 colonies per 100mL (MDL = 2 colonies/100 mL) except for one sample at 51 colonies per 100mL. These values are well below Massachusetts water quality standards for contact recreation of 200 fecal coliform colonies/100 mL and 35 *Enterococcus*/100 mL of sample.

4.2 Comparison of Winter and Summer Results

The plume tracking surveys conducted as part of the MWRA plume tracking studies were completed under two under different oceanographic regimes in offshore Massachusetts Bay and flow conditions at the Deer Island Treatment Plant (Table 4-1). During the spring survey, the water column was weakly stratified and currents were to the north due to a local wind event that occurred in the days immediately preceding the survey. The summer water column was moderately stratified (reflecting early summer conditions) and nontidal currents were to the south and east at about 2-6 cm/s. Summer currents as the dye left the diffuser were slightly lower than in the spring. Shear was the predominate force driving dilution after the initial dilution caused by the momentum of the effluent entering the ocean had dissipated. The measured dilution was not influenced by wind events over the course of the two studies. Effluent flow varied within the two surveys but was typical of the non-rain impacted flows, thus characteristic of the normal flows experienced by the treatment plant. The spring base flow tended to be slightly higher than the summer flow, reflecting the mild drought at the time of the summer survey.

Table 4-1. Comparison of summary of field conditions, April and July 2001 plume tracking surveys.

Characteristic	Spring	Summer
Effluent dye concentration (ppb)	59.7	86.0
Wastewater flow rate (MGD)	420 – 470	300 – 550
Current speed (cm/s)	1 – 20	4 – 16
Current direction	Variable, generally to North	Generally to ENE
Stratification	~ 0.9 sigma-t units over water column	About 2.0 sigma-t units over water column, sharp pycnocline at ~6 m)

Even though the water column characteristics were dissimilar during the two surveys, the plume characteristics derived from the field program and modeling were not greatly different. Plume thickness and initial dilution predicted by the RSB model were very similar for both surveys (Table 4-2). Plume thickness of 22 and 20m were measured for the spring and summer surveys, respectively, with predicted thickness slightly less than measured and the spring plume thicker than the summer plume. Initial dilutions estimated from the field data were 88 to 95 vs 102, while the model predicted 109 and 104, for the spring and summer, respectively, with 275 ports open. The height of minimum dilution was very consistent at 15 to 17 m based on both field and model results. Similarly the measured and simulated rise heights were nearly identical both within and across the two surveys. Slightly higher rise height in the spring was likely due to the shallower pycnocline and possibly effluent higher flow rates. The last characteristic compared in Table 4-2, the length of the near field or hydraulic mixing zone, was derived from the model results only. The length is very short being less than 15 m in the spring and ~14 m in the summer. This result indicates initial mixing is completed very close to the risers and explains why the field program obtained little data from within the hydraulic mixing zone.

Table 4-2. Comparison of plume measurements and RSB predictions from the April and July 2001 plume tracking surveys.

	Spring		Summer	
	Field measurements	**RSB predictions**	**Field measurements[b]**	**RSB predictions**
Near field dilution	88-95[a]	109	102	104
Thickness of wastefield (m)	22	18	20	17.6
Height to top of wastefield (m)	28	24	25	23.5
Height of minimum dilution (m)	17	16	15	15.7
Length of near field (m)	Not measured	~15	Not measured	~14

[a]Based on instantaneous *in situ* data; discrete samples gave an initial dilution estimate of ~93
[b]Based on low band pass filtered instantaneous *in situ* field data

Both surveys also obtained samples from within the plume for key water quality characteristics. The water quality data from both surveys demonstrated that federal criteria and standards were met even before the initial mixing had been completed. Bacterial indicators were at or below the detection limits on both surveys; copper and silver concentrations, while higher than background values, were well below applicable standards. Other parameters such as nutrients and total suspended solids showed elevated concentration in the plume, as expected. However, measured concentrations were consistent with the initial dilution measured by the dye. The subsequent dilution as the plume is transported through the far field brings the concentrations of these parameters to background levels in less that a day.

5.0 CONCLUSIONS

Both field and modeling results show the outfall is performing as expected under moderately stratified conditions. Measured dilution and other wastefield characteristics for this certification survey showed excellent agreement with results derived from the RSB model using conditions experienced during the

dye study. For the certification survey, an initial dilution of 94 was estimated from discrete dye samples collected in the core of the plume, which compares to an initial dilution of 102 derived from the average dye concentration in the plume. The latter compares very well to the initial dilution predicted from the RSB model using the hydrgraphic conditions and currents measured during the survey (104).

The results from the April (weakly stratified) and July surveys are similar with respect to key plume characteristics and show initial dilution under typical effluent flows is within predicted values.

Oceanographic mixing and dispersion further increased the dilution in the far field to 200 fold with much of the measured dye patch showing greater than 400 fold dilution 48 hours after release of the dye. Average dilution in the far field plume was ~1000 fold 24 hours after dye release. These measured far field dilutions are consistent with dilution predicted by hydrodynamic models.

The two dye studies performed to document initial dilution at the MWRA's outfall in Massachusetts Bay demonstrate that the outfall is performing as designed (i.e., "outfall's minimum dilution is equal to, or greater than, the predicted minimum dilution") and that federal water quality criteria and state water quality standards are met well within the hydraulic mixing zone. Moreover, the agreement between field and modeled results under two distinctly different stratification conditions provide a high degree of confidence that models can be used in the future to accurately estimate the initial dilution under a variety of effluent flow, oceanographic flows, and stratification regimes.

It is concluded that the outfall is behaving as designed and that MWRA permit condition Part I, Section 18e is met.

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Appendix A

Matlab m-file to calculate dispersion rate

Appendix A: Matlab m-file to calculate dispersion rate

```
load ctd_array
 [dyem,ng]=meang(dyen,1);
 dz=zn(1)-zn(2);
 dyem=dyem.*ng*dz;
 %a=find(jdn<198);
a=find(jdn>198&jdn<199);
%a=find(jdn>199);
[x,y]=meters(latn,lonn);
clf;showvar2(x(a),y(a),dyem(a)*10,1:length(a));aspect(1)

thetarot=-11;
%   rotation of -11 degrees minimizes eastward variance
load corrected_positions        %  this comes from adcp analysis
[xg,yg]=meshgrid(-2:.5:3,-10:.5:1.5);  % even grid
[xdum,ydum,dd]=griddata(xr2,yr2,dyem(a),xg,yg);   % interpolate onto grid
[xr,yr]=rot(xr2,yr2,thetarot);
showvar2(xr,yr,dyem(a))      %  plot out
 hold on;

[xgr,ygr]=rot(xg,yg,thetarot);
contour(xgr,ygr,dd)
aspect(1)

[dye_total,nn]=meang(dd(:));
[x_dye,nn]=meang(dd(:).*xgr(:));
[y_dye,nn]=meang(dd(:).*ygr(:));
x_dye=x_dye/dye_total;
y_dye=y_dye/dye_total;
[xx_dye,nn]=meang(dd(:).*(xgr(:)-x_dye).^2);
[yy_dye,nn]=meang(dd(:).*(ygr(:)-y_dye).^2);
xx_dye=xx_dye/dye_total;    %  second moment
yy_dye=yy_dye/dye_total;    %  second moment

Kx=xx_dye*1e6/1.2/86400/2  % dispersion coef
Ky=yy_dye*1e6/1.2/86400/2 % dispersion coef
dye_total=dye_total.*nn*500*500/1e6  % check on total mass of dye (in kg)
```

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