3/24/09 PRESENTA- TION: EPA CRUISE SHIP DILUTION STUDY

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3/24/09

Cruise Ship Stationary Dilution Study Presentation

Senate Finance Committee
March 24, 2009

Department of Environmental Conservation
Division of Water
Cruise Ship Program

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What is a dilution factor?

- A dilution factor is a measure of the dye concentration in the marine water relative to the concentration of the dye in the ship's treated wastewater.

- If the concentration of a dye in the ship's treated wastewater is 100 and the measured concentration of the dye in the receiving water is 5, then the dilution factor is 20.

What is a dilution factor important?

- DEC must evaluate both the pollutant sample results and the dilution of the wastewater in the environment to estimate whether wastewater would exceed Water Quality Standards (WQS) in marine waters.

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Dilution of Wastewater while Vessel is Moving

- Wastewater is subject to a tremendous amount of dilution when cruise ships are moving.

- Based upon field studies, Science Advisory Panel estimated a conservative dilution factor of 50,000.

(min speed of 6 knots and discharge at 200 cubic meters/hour)

Dilution of Wastewater while Vessel is Stationary

- DEC partnered with EPA to collect field data to examine the dilution factors (mixing) for a stationary cruise ship.

- This study collected field data in order to calculate the dilution that occurs to wastewater when it is discharged under worst case conditions -- from a stationary cruise ship into a confined receiving environment with limited flushing.

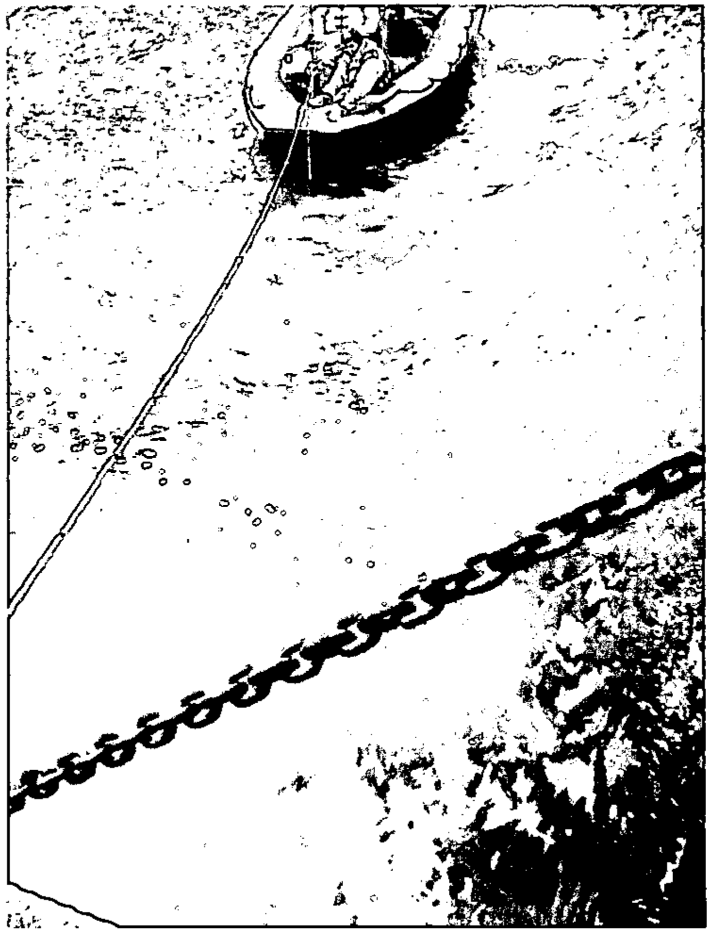
Methods Used to Collect Dilution Data for Stationary Cruise Ships

- This is a near field dilution study.
- Measurements were taken in the receiving water between the hull of the vessel at intervals up to 15 meters (49 feet; 1 meter = 3.28 feet) away.
- Six cruise ships volunteered to participate.

Methods Used to Collect Dilution Data for Stationary Cruise Ships

- A fluorescent dye (Rhodamine WT) of a known concentration was injected into the treated sewage and graywater discharges on each cruise ship.
- Outside of the vessel, a small boat with a fluorometer recorded the concentration of the dye in the receiving water.

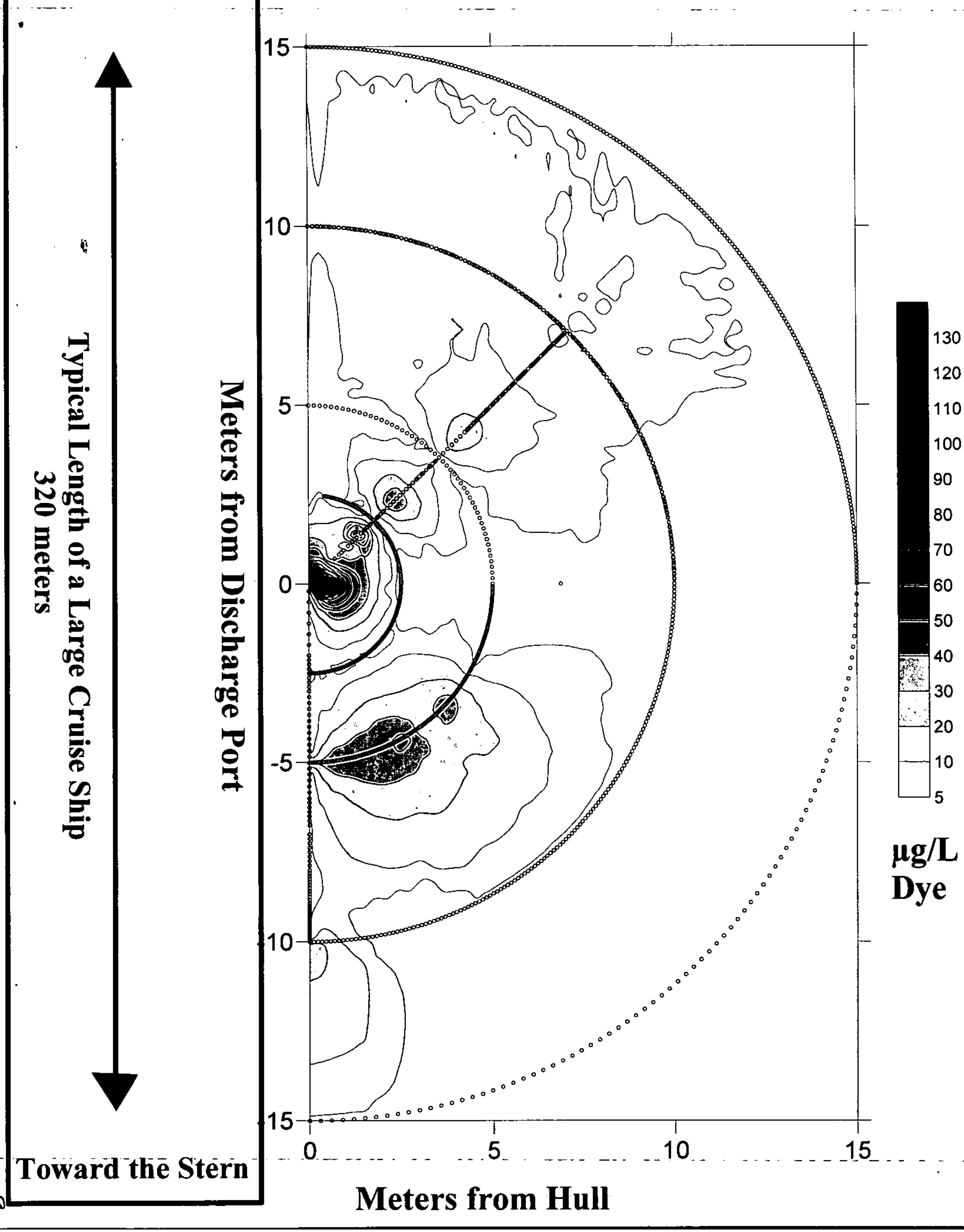
Release of dye from cruise ship and measurements being taken in receiving waters



Results

- Enormous and complex data set that fills >1,400 pages.
- Summary of a complex data set.
- "Time Lapse" plot of plume on Norwegian Star

Norwegian Star - July 16, 2008



How do you apply the dilution results to cruise ship sample data to determine where Water Quality Standards are met in the harbor?

- The cruise ship general permit requires that the discharges must meet the Alaska Water Quality Standards at the point of discharge.
- Ships meet most standards but are not able to consistently meet this stringent requirement for ammonia, copper, nickel and zinc.

How do you apply the dilution results to cruise ship sample data to determine where Water Quality Standards are met in the harbor?

- A standard scientific approach to a complex data set is to look first at the potential worst case scenario. If there is no exceedance in Water Quality Standards from the worst case scenario, then you will be confident that Water Quality Standards will be met in other situations.

- Skagway + max conc of pollutants + lowest dilution factor = worst case scenario

Dilution Factor at 2.5 meters from Ship

- The dilution factors ranged from about 4 to 12
- When the maximum pollutant concentration detected for ammonia, copper, nickel, and zinc for all ships during the 2008 season is divided by a factor of 4 (i.e. worst case dilution), the pollutants will exceed Water Quality Standards in the receiving water.

Dilution Factor at 2.5 meters from Ship

- If we divide the maximum pollutant concentrations by the highest (best case dilution) of 12, nickel and zinc will meet the WQS in the receiving water. However, the concentration of ammonia and copper found in the harbor will still exceed Water Quality Standard at 2.5 meters. (See Table 3 of DEC Draft Report for pollutant concentrations.)

Dilution Factor at 15 meters from Ship

- The lowest dilution factor (i.e. the least dilution or “worst case”) was 28.
- The highest dilution factor (i.e. best case – most dilution) was 63.

Dilution Factor at 15 meters from Ship

- If you apply the highest dilution (e.g. best case) to the maximum concentration (e.g. worst case), all four parameters will meet WQS at 15 meters.
- A worst case combination of a maximum pollutant concentration for ammonia and copper with the minimum dilution (28) will exceed the Water Quality Standards in the receiving water at 15 meters.

Comparison with Interim Limits in Cruise Ship Permit

- If a similar procedure is used to divide the interim limits in the current permit for ammonia, copper, nickel, and zinc concentrations by the worst case dilution factor (4), they will exceed Water Quality Standards for all four parameters at 2.5 meters.

Comparison with Interim Limits in Cruise Ship Permit

- If we applied this same procedure using the worst case dilution found in this study, all four parameters will meet Water Quality Standards at 15 meters.

- Based upon the data from the four ships in this study, a ship whose wastewater complies with the interim limits will meet the Water Quality Standards at 15 meters (49 feet).

Validation of the Computer Models

- DEC compared the observed dilution to what was estimated by computer modeling software.
- In the near field (0 – 15 meters) that the computer models were fairly accurate at predicting the dilution factor.
- The models actually estimated a lower dilution factor (i.e. less dilution) than was observed.

3/24/09

An Assessment of the Cruise Ship Plume Dilution Study Performed in Skagway, Alaska, July 2008

Alaska Department of Environmental Conservation

March 24, 2009

DISCLAIMER: This report is a work in progress and is still being finalized.

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Executive Summary

This report describes a plume dilution study conducted as a partnership between the Alaska Department of Environmental Conservation (DEC) and the U.S. Environmental Protection Agency (EPA). The study was conducted by EPA's Ocean Survey Vessel *Bold* in July 2008. It was designed to characterize the near-field dilution that occurs to wastewater that is discharged from a stationary cruise ship.

The dilution factors in this study were calculated by taking the known concentration of a pollutant in the pipe before discharge and dividing it by the concentration measured in the receiving water. For example, if a value of 100 concentration units was determined in the pipe and a concentration of 5 was measured after the wastewater was discharged into the receiving water, the dilution factor would be 100 / 5 which equals 20.

None of the vessels that visited Alaska in 2008 could consistently meet the State of Alaska Water Quality Standards for ammonia and selected metals at the point of discharge.

After undergoing turbulent mixing in the first 2.5 meters, plumes remained relatively intact to a distance of 15 meters.

In order to determine where cruise ship effluent would be diluted to the point where it would meet water quality standards in the receiving water, DEC divided the maximum reported concentrations for ammonia, copper, nickel, and zinc effluent levels from all ships that discharged in Alaska during the 2008 season by the highest dilution factor of 63 found at 15 meters. In this case water quality standards would be met in the receiving water for ammonia, copper, nickel, and zinc. When you take the most conservative approach of dividing the maximum concentration of pollutants by the lowest dilution factor of 28, ammonia and copper concentrations in the receiving water would exceed water quality standards at 15 meters.

We then looked at the interim limits that are currently in the cruise ship permit. If a similar procedure is used to divide the interim limits in the current permit for ammonia, copper, nickel, and zinc concentrations by the worst case dilution factor, they will exceed Water Quality Standards for all four parameters at 2.5 meters. If we applied this same procedure using the worst case dilution found in this study, all four parameters will meet Water Quality Standards at 15 meters.

Based upon the data from the four ships in this study, a ship whose wastewater complies with the interim limits will meet the Water Quality Standards at 15 meters (49 feet).

DEC also compared the near field dilution factors that were predicted by the PLUMES and CORMIX computer dilution models to the observed dilution. The maximum dye concentrations that were measured were in fair agreement with the modeled values in the 5 – 15 meter range. The modeled values were conservative and predicted higher maximum plume concentrations compared to those that were observed in the field. This means that the models are more protective of the environment. However, the PLUMES and CORMIX models diverged greatly when attempting to predict dilution factors beyond 15 meters and may not be appropriate for determining far-field dilutions.

Introduction

The Alaska Department of Environmental Conservation (DEC) has had the regulatory responsibility of protecting the waters of Alaska through the Cruise Ship Program since 2001. DEC provides detailed information about the Cruise Ship Program at the following web page:

http://www.dec.state.ak.us/water/cruise_ships/index.htm

As a part of the Cruise Ship Program DEC has completed and participated in studies that have provided information on the impacts that cruise ship discharges have on water quality. In 2001, DEC participated in a study of the dilution of wastewater discharge plumes from large moving cruise ships (Cruise Ship Wastewater Science Advisory Panel, 2002). The Science Advisory Panel concluded that very high dilution factors of 1/50,000 would conservatively be achieved behind a moving vessel.

In 2004, DEC used computer models to estimate the concentration and distribution of cruise ship discharges at three Alaska harbors; Juneau, Ketchikan and Skagway (DEC, 2004). The input conditions to the models in that study assumed the ships were stationary, and that normal tidal and hydrographic conditions existed. Individual characteristics such as discharge pipe diameter, flow rates and temperature of the discharge were based on individual data from eighteen vessels. DEC used the EPA approved computer modeling packages PLUMES and CORMIX to estimate the expected dilutions from each individual ship. Concentrating only on the modeling that was reported for the conservative conditions in Skagway harbor, the dilution factors achieved in the first 2 meters ranged from 1/10 to 1/20. At a distance of 5 meters the dilution factors were between 1/24 and 1/60.

In July 2008, DEC worked in partnership with the United States Environmental Protection Agency (EPA) on a study in Skagway harbor to directly measure the dilution of waste water discharge plumes from stationary cruise ships. The study was performed by DEC and EPA personnel and supported by the crew of the EPA research vessel *Bold*. Discharges from six cruise ships were tested between July 7, 2008 and July 17, 2008. Discharges from two of the ships were sampled twice so that a total of eight visits were completed. The purpose of this study was to measure the real world dilution factors that exist in the marine waters in order to assess whether the Alaska water quality standards are currently being met, and in addition, to compare these actual dilutions to the values predicted by the computer models.

Over the years, the cruise ship industry has, in general, worked to continually reduce the concentration of pollutants through major upgrades to advanced treatment systems onboard the vessels. There have been reductions in the levels of fecal coliform bacteria, biological oxygen demand (BOD), total suspended solids (TSS), pH (a measure of acidity) and chlorine. In 2008, however, four parameters continue to exceed the water quality standards that are mandated by law to be met at the point of discharge. The four parameters are ammonia, copper (Cu), nickel (Ni) and zinc (Zn). This report will focus on these parameters when assessing compliance with water quality standards.

Figure 1 provides a detailed map of the study area in Skagway harbor. It depicts the three areas where large cruise ships dock, the Ore Terminal, Broadway, and Railroad docks. The locations of the Alaska Marine Highway System Ferry dock and the City of Skagway domestic waste water outfall are also shown.

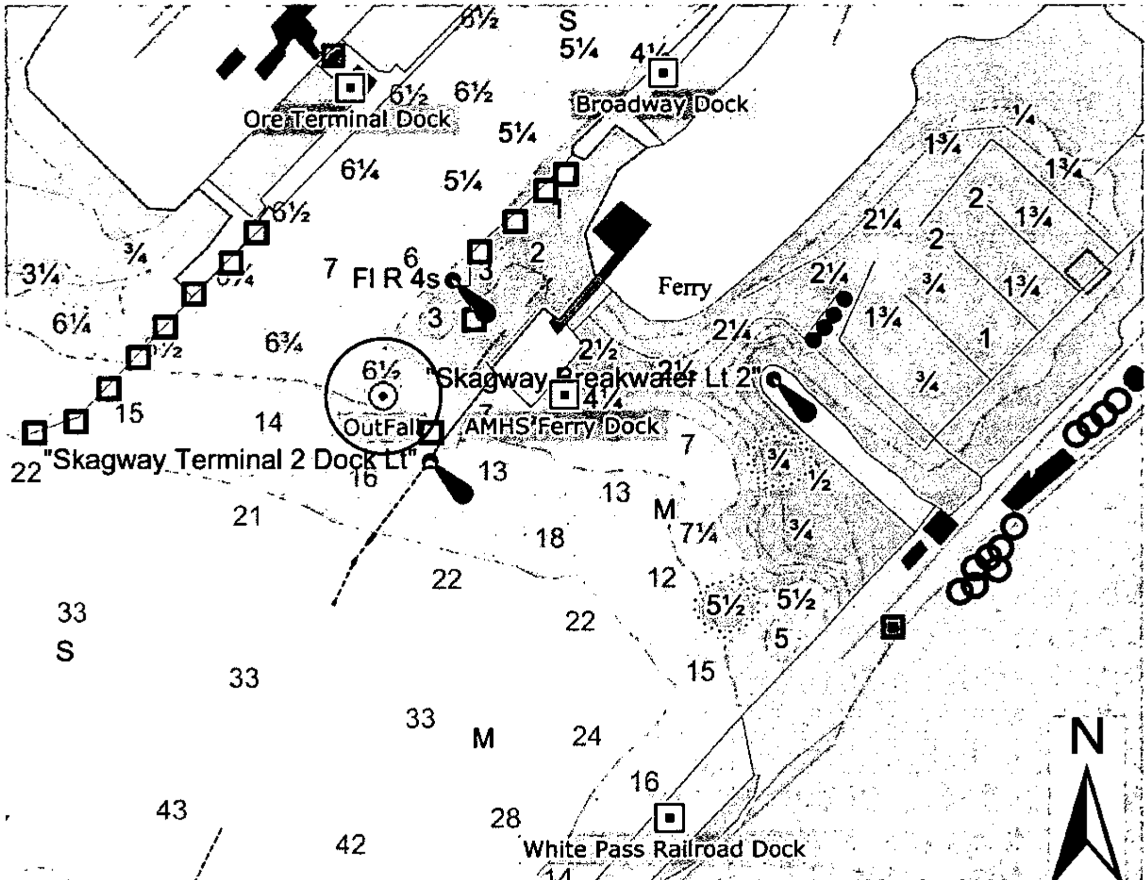

Figure 1 Skagway Harbor Showing Cruise Ship Sampling Sites.

Methods

Criteria for selecting the ships that were tested.

DEC acknowledges the tremendous cooperation and support that this project received from the officers and crew members on the vessels that were sampled during this work. One of the main criteria for selection in the project was that the ship volunteered to participate. Another important factor was that, as far as possible, DEC tried to include ships that were studied in 2004. Of the six ships that were sampled, four had been included in the previous study. While the ships were not selected randomly, DEC also attempted to select ships with a wide variety of treatment systems.

The following section provides a summary of the methods that were followed in introducing dye into the individual cruise ship wastewater streams and then in tracing the resultant dye plumes that formed in the receiving water. This summary of the methods used is based on the US EPA report entitled "Sampling

Episode Report Cruise Ship Plume Dilution Study, Skagway, Alaska", February 25, 2009. That report should be consulted for further sampling details and to locate all the raw data that was gathered during the plume dilution study.

Pre-Sampling Activities

Visits to each of the six ships were conducted during the week prior to the start of the sampling episode to establish ship contacts, communications, and safety and emergency procedures, and to inspect sampling ports and associated fittings.

Dye Injection Methodology

A variable speed peristaltic pump was used to inject the fluorescent dye, Rhodamine WT, into the waste discharge stream at a point downstream of the wastewater treatment system. The flow in the pipe was monitored using an ultrasonic flow meter. The in-situ concentration of the dye was calculated from the known input concentration, the discharge flow rate, and injection rate. In addition, the concentration of the dye was measured directly downstream using a calibrated fluorometer. This instrument was used successfully in three of the four surveys where plume distributions were mapped outside the ships. Usable data was not obtained in the other cases due to instrument failures.

Vessel	Target Concentration µg/L	Used by DEC µg/L
Star Princess	420	420
Coral Princess	1050	1050
Ryndam	754	700
Millennium	663	573 ± 218
Norwegian Star	893	606 ± 140
Volendam	918	787 ± 100

Table 1 Target Concentrations and actual Measured Concentration.

DEC used the measured concentration to calculate the dilution factors. Table 1 lists the concentration of dye that DEC used as the maximum in-pipe concentration for each ship surveyed. The value used for the Star Princess, Coral Princess and Ryndam was based on the calculated target concentration. For the Millennium, Norwegian Star and Volendam the maximum input was based on the mean value measured by the fluorometer and the standard deviation.

Plume Monitoring Methodology

A Sea-Bird SBE-19 CTD (conductivity, temperature, and depth) was deployed to provide detailed measurements of the ambient hydrographic conditions. In addition, this instrument package, which is pictured in Figure 2, was outfitted with a fluorometer and turbidimeter to measure the dye concentrations and possible interferences. Conductivity was an important parameter because it is used to calculate salinity which is a measure of the amount of dissolved salts in the seawater. This parameter along with temperature is used by the models to calculate density of the water and predict the behavior of the plumes. All of the parameter readings were measured two times a second and transmitted by cable to a laptop computer. It is important to note that the sensors and seawater intake hoses are located at the bottom of the instrument. In the case of the vessel Star Princess this feature prevented characterization of the surface plumes that formed.

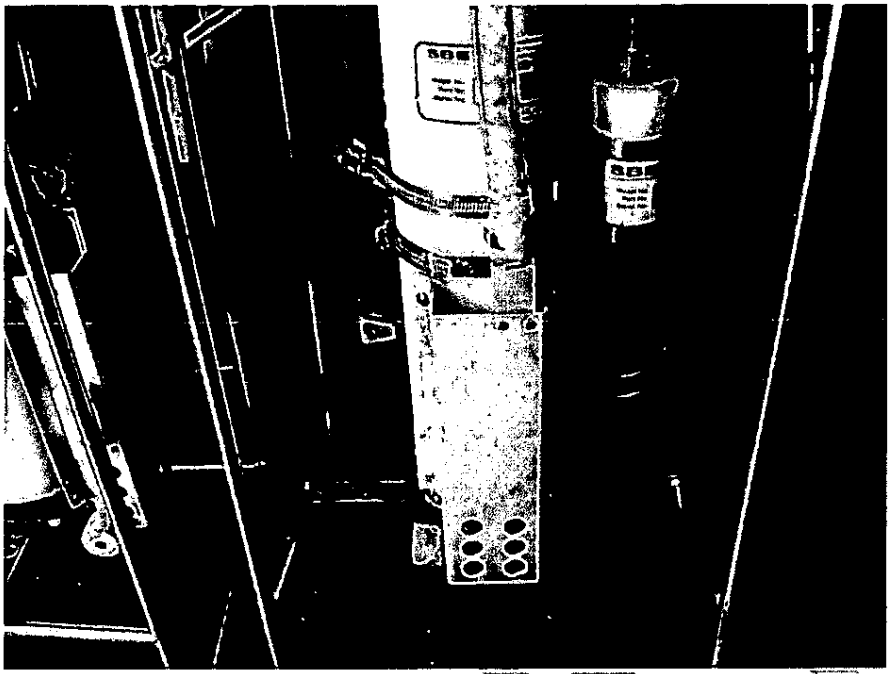

Figure 2. Sea-Bird SBE-19 CTD Sensor with Integrated SCUFA® Fluorometer

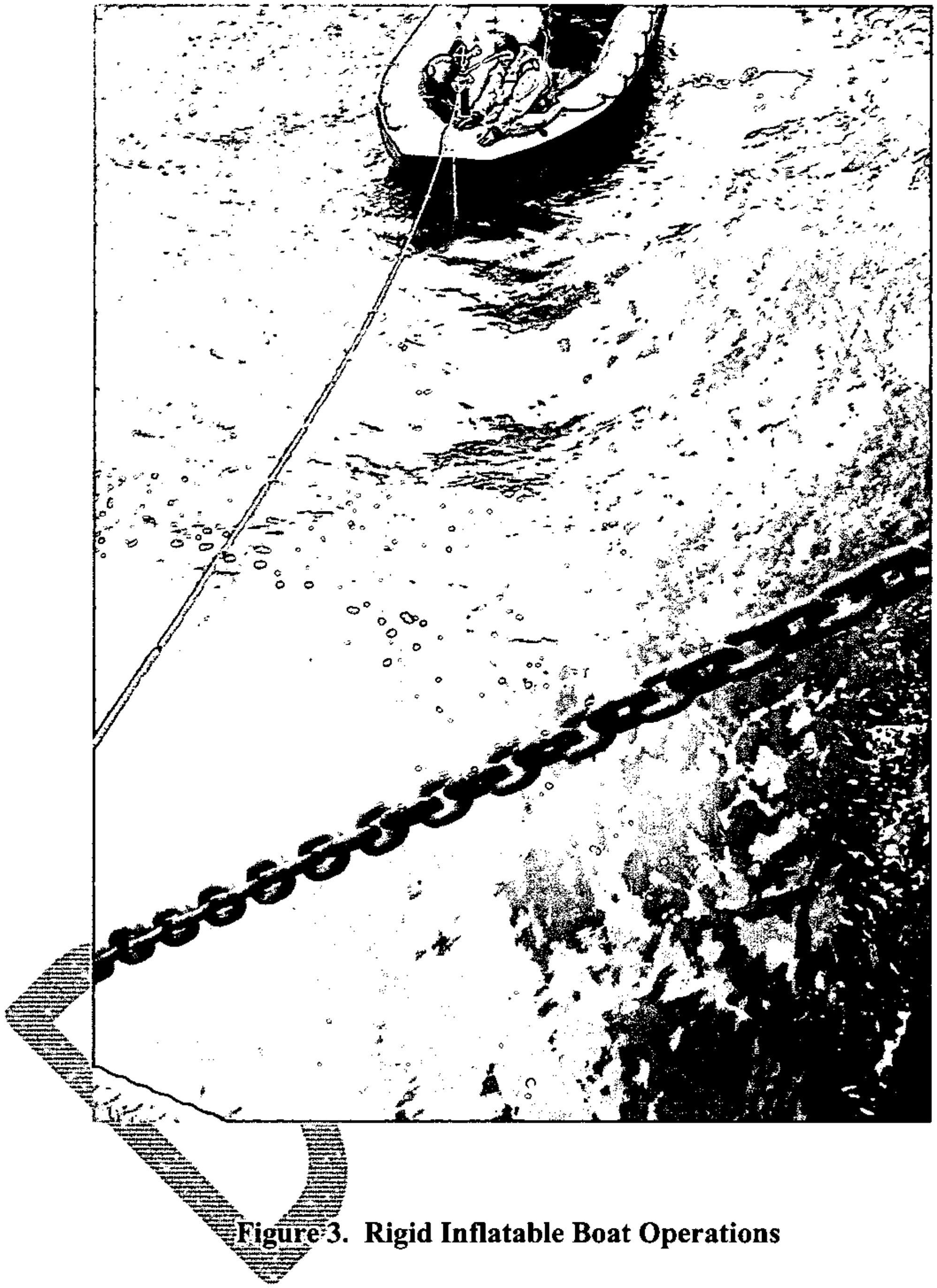

Figure 3. Rigid Inflatable Boat Operations

The CTD was deployed from the bow of a rigid inflatable boat (RIB). At times the CTD was lowered and raised at a stationary position to provide a vertical profile of the water column. In order to track the plume concentration distributions a series of arc transects were performed. To accomplish these, a hull magnet was first attached above the discharge port. The RIB then traversed a semicircle path at the nominal distances of 2.5, 5, 7.5, 10 and 15 meters away from the port. This pattern was repeated with the CTD held at the nominal depths of 1.5, 3, 5 and 7.5 meters deep.

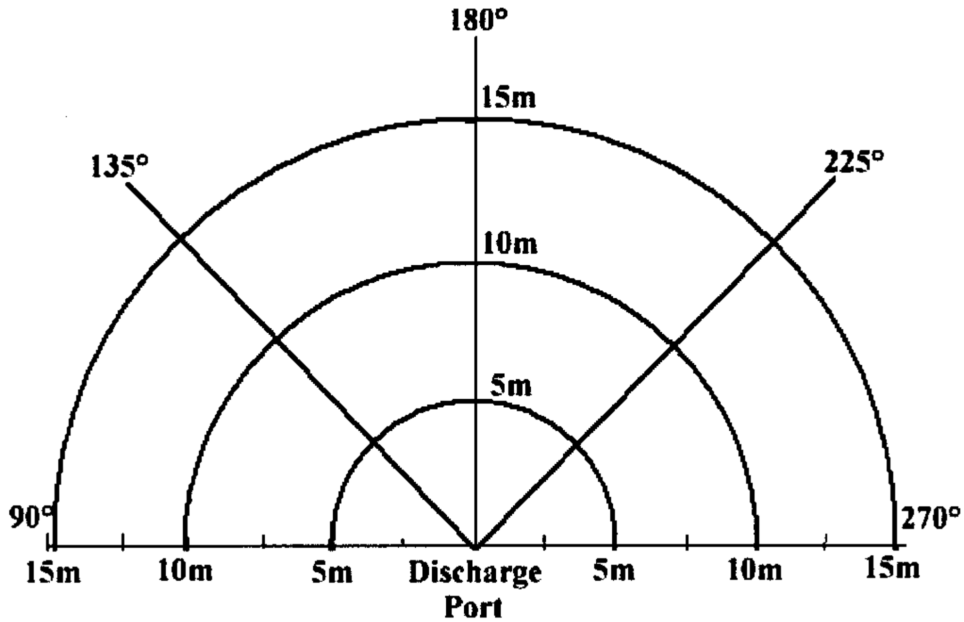

Figure 4 Sampling transect pattern used to locate dye plumes

Another type of transect was performed in order to maximize the definition of the plume distribution is shown in figure 4. The RIB was directed either toward or away from the discharge port along a straight course at constant depth where the plumes were expected to have the least dilution and greatest concentration of dye, i.e. in the center of the plumes.

Current and Weather Measurements

Current meters were used to record the major currents in the vicinity of the discharge port during the plume surveys. They were deployed at 1, 3 and sometimes 5 meters.

Personnel on the OSV Bold recorded weather conditions during the surveys.

DEC methods

The fluorometers used to quantify the concentration of Rhodamine WT dye both in the discharge and in the open waters adjacent to the vessels hulls were individually calibrated using a series of dilutions of known concentrations of dye. For the two fluorometers that were integrated into the CTD instrument packages, the dilutions were prepared in a clean, large plastic waste container. The entire CTD was then immersed in the dye solution. All of the calibrations produced curves with very low variability.

Raw data from the transects were first converted to the equivalent concentration of dye in micrograms / Liter (µg/L) using the calibration curves described above. The position of the instruments was estimated for each arc and linear transect by apportioning the angle to the ship based on the total time of the transect (assuming that the motion of the RIB was relatively constant). These positions were then converted from polar to rectangular coordinates and the dye distributions were plotted for a given depth using the commercially available software, Surfer8. Since the CTD/fluorometer instrument package was recording data for conductivity, depth, temperature and dye concentration at an interval of once every ½ second, the sampling coverage for defining the extent of the plumes appears to have been adequate. The resulting plots are a time average, not a snapshot of where the plumes were found, since the individual plumes were moving at speeds of about 10cm/sec and the entire process of mapping the area next to the ships out to a distance of 15 meters took up to ½ an hour.

Results

General

The initial attempts to characterize the dye plumes from the cruise ships were made on July 7, 2008 on the Millennium and July 9, 2008 on the Norwegian Star. In both cases no usable plume data was obtained.

After modifying procedures, dye plumes were detected during the sampling of the Star Princess on July 10, 20008. The plumes were observed at the surface moving away from the discharge port at an angle of 225° and directly along the ship's hull at about 270°. When the CTD is used at the surface the actual depth of the seawater that is sampled is about 0.8 meters. This configuration prevented the determination of plume values that were between the surface and 0.8 meters. A maximum plume value of 48 µg/L was detected at 1.3 meters depth at a distance of 10 meters from the discharge port. It is possible that higher concentrations were present nearer to the surface. No arc transects were completed for this sampling.

Coral Princess

For most of the sampling effort during the July 11, 2008 survey of the Coral Princess, the discharge was extremely intermittent. Near the end of the sampling period the Rhodamine WT dye concentration was increased to approximately 1050 µg/L and substantial plumes were detected at a depth of about 3.6 meters and a distance of 5 meters from the ship. Concentrations that were >158 µg/L were found at angles of 180°, 220°, from 235° to 240°.

Ryndam

The vessel Ryndam was sampled on July 12, 2008. Figure 5 provides a time-averaged mapping of the plume concentrations. The nominal depth for this plot is 3 meters. Extensive transects were also performed at depths of 1.5, 2.5, and 4.5 meters without detecting plumes. Using an arbitrary convention for compass rose direction, zero is looking directly at the discharge port and the angle increases clockwise such that 90 is to the stern, 180 directly away from the ship and 270 to the bow. See Figure 4. The plume is primarily distributed along an angle of 135° from the hull. The semi-circular arcs that are shown on the plot give the position of the CTD instrument at the ½-second interval sampling frequency. While the plot is not an instantaneous snapshot of the plume locations, it does represent a useful tool to compare the plume density between the different sampling events.

In this plot the ship is on the left axis with the direction toward the stern at the top and direction toward the bow and Northeast is at the bottom. The plume distribution is very different from the smooth and continuously varying results that both model s predict. The empirical data show that outside a distance of 5 meters from the ship the plumes are defined by roughly circular zones of high dye concentration that appear to be advected away from the ship. There is very good agreement between the 135° angle of the plume train and the direction of the 4 cm/sec tidal current that was measured at 3 meters depth.

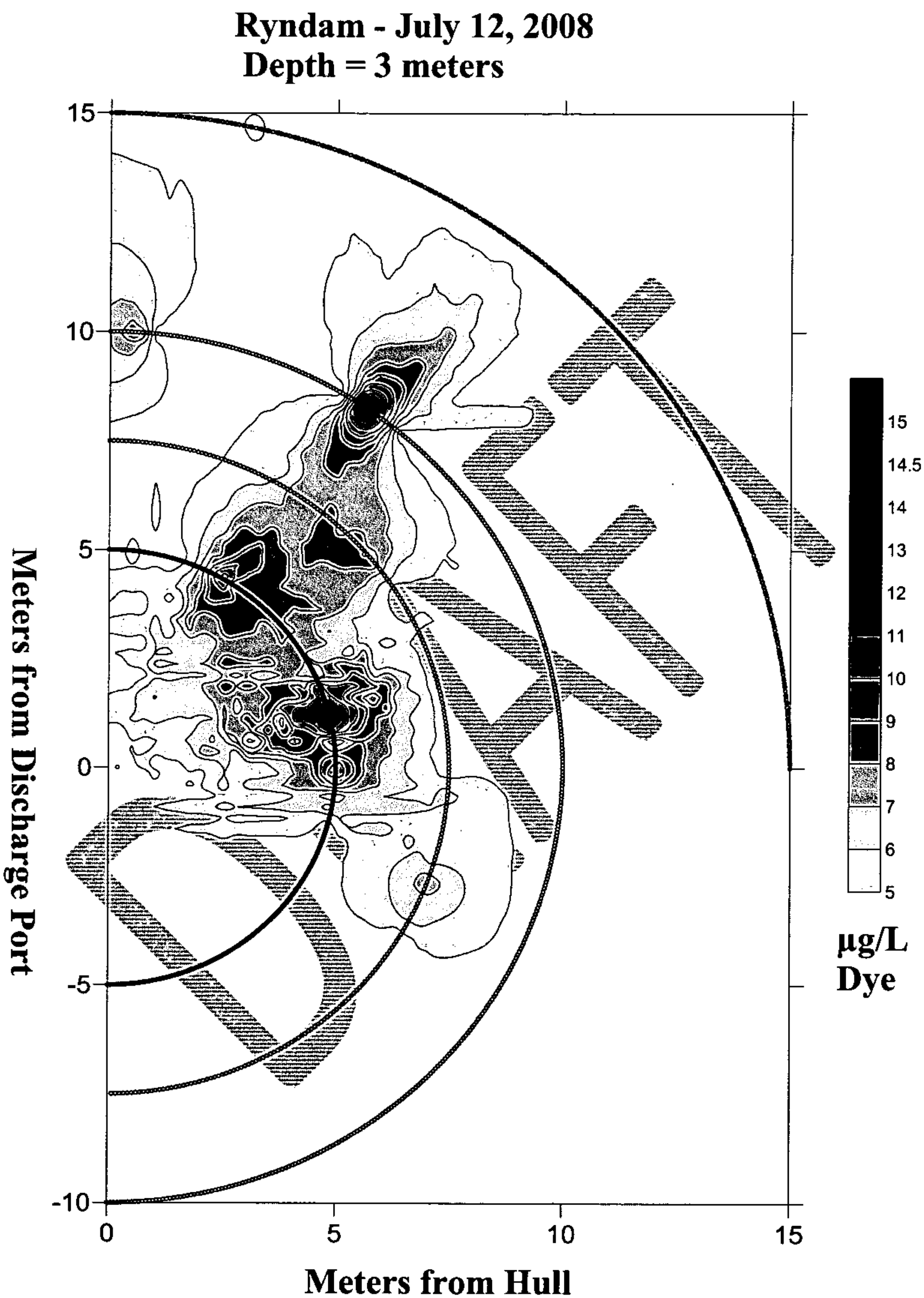

Figure 5 Plume distributions near the Ryndam at 3 meters depth

Figure 6 is a plot of the comparison between the measured value for the plume maximum concentration and the values predicted by the CORMIX and PLUMES computer models. The modeling was evaluated at 5, 10 and 15 meters from the discharge port. The average modeled dilution factor for the 5 to 15 meter range away from the discharge port is about 1/30. If the measured value at 7.5 meters is included the actual dilution factor is found to be 1/50. In this case, the models are predicting less dilution than was actually observed. In figure 6 the error bars that are plotted for the measured values are based on the variation of the input dye concentration that resulted from the variation in flow in the waste water.

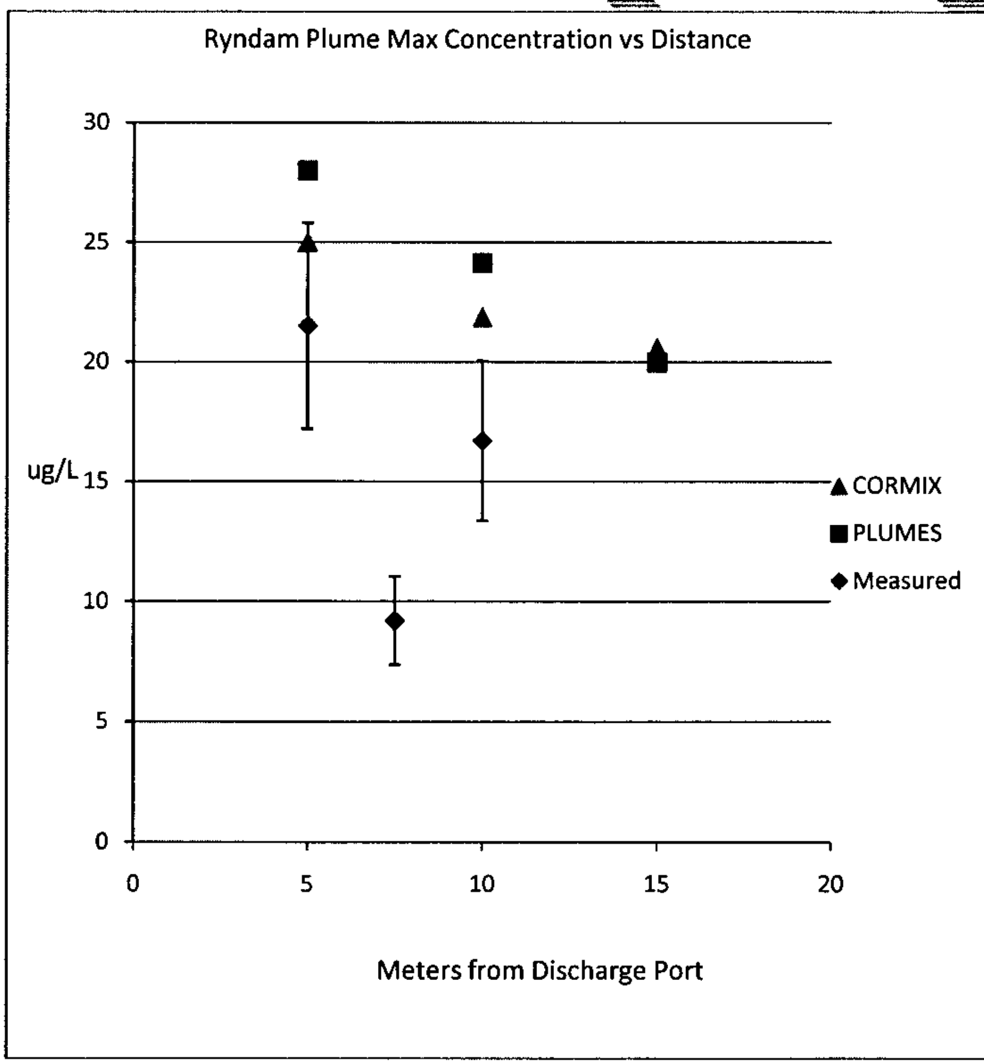

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Figure 6 Plume maximum dye concentration vs distance from the discharge port at 3 meters depth.

Millennium

The vessel Millennium was sampled on July 15, 2008 and the results of the plume distribution survey are plotted in Figure 7. In this case the plume was located primarily at 5 meters depth and although the orientation of the ship and structure of the plumes were similar to those seen in the Ryndam survey, the direction that the plumes were moving was completely reversed, near 270°. In the case of the Millennium sampling, the tide was flowing in toward the harbor and during the Ryndam sampling it was ebbing away. Unfortunately the nearest current meter data that we have from the Millennium survey is at 3 meters depth and the results do not correlate well with the observed plume movements.

The maximum plume concentrations that were observed during the Millennium survey appeared to be higher than the Ryndam values. In addition to the 5 meter depth transects that are plotted in Figure 7, extensive transects were also completed for depths of 1.5, 3, and 7.5 meters, however, no major plumes were detected.

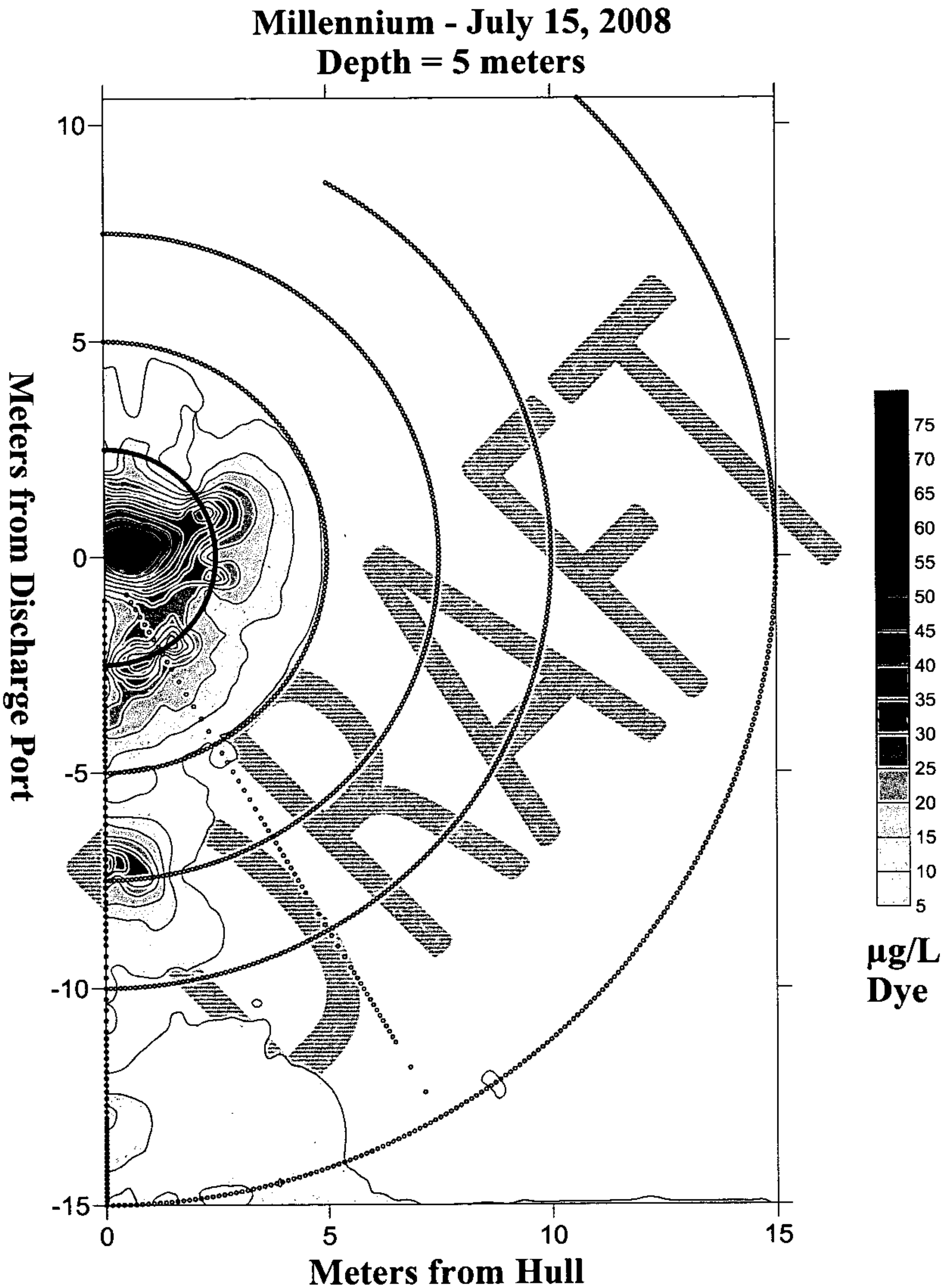

Figure 7 Plume Distribution Near the Millennium at 5 meters Depth

Figure 8 details the maximum concentration that was measured for the Millennium. The average dilution factor for the measured maximum was 1/39 for the 5 to 15 meter range. The PLUMES model generated an average dilution factor of 1/20. The CORMIX model generated an average dilution factor of 1/12. The modeled values again predicted less dilution than was observed, but the agreement between the models show considerable divergence. The large estimated error for the observed values are based on the measured variation in the input dye concentration.

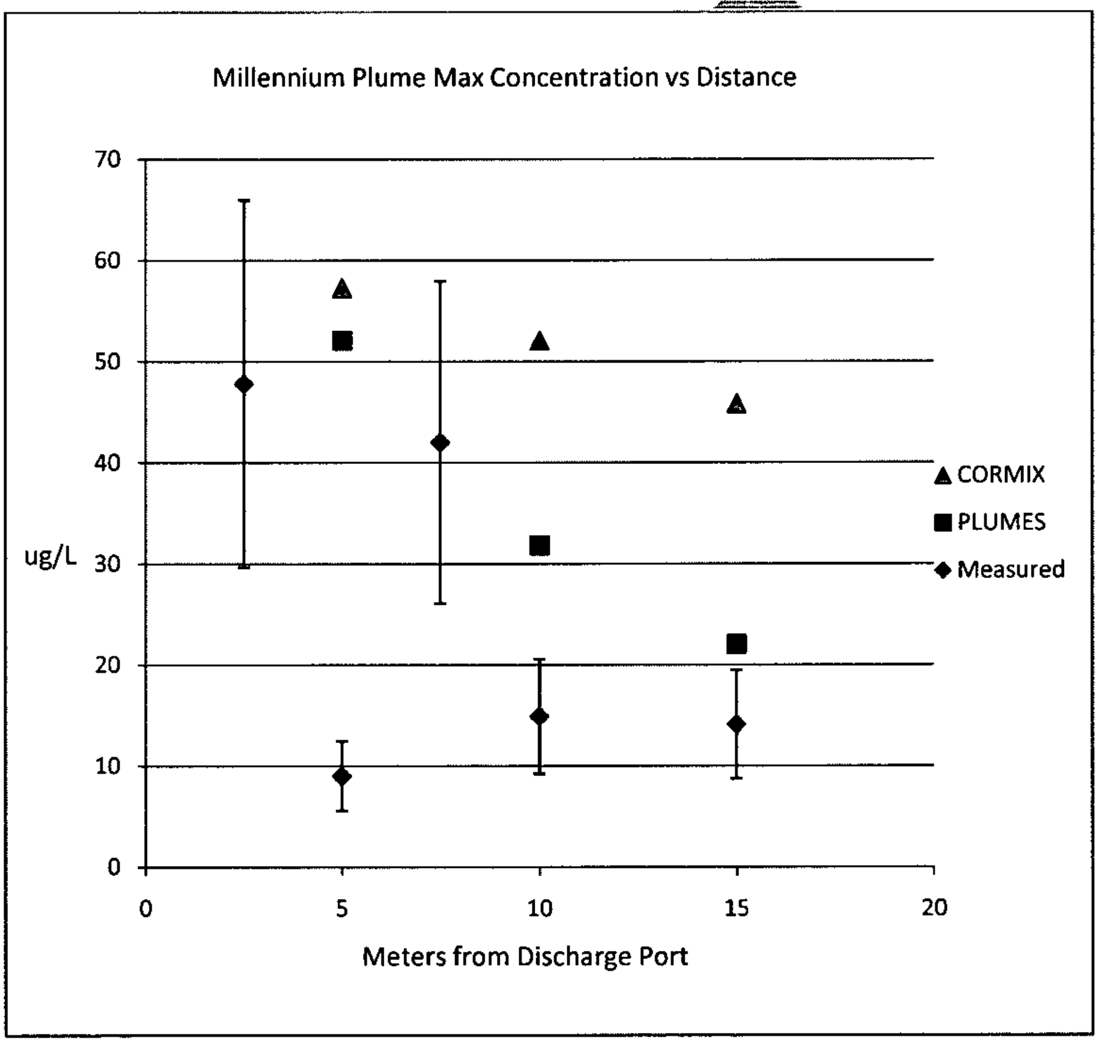

Figure 8 Plume Maximum vs Distance from the Discharge Port for the Millennium

Norwegian Star

Significant plumes were found over a wider range of depths when the Norwegian Star was surveyed on July 16, 2008. Plumes were detected at 3, 4 and 5 meter depths. No plumes were found at 1.5, 2.5 and 7.5 meters. Figure 9 provides a visualization of the plumes at two levels, approximately 3.5 and 5 meters. In this plot the upper left corner would point forward toward the bow and the Northeast. The ship would still be on the left of the plot. The plumes in both the upper and lower zones appear to be advecting along an angle of 135 ° where 90 ° is at the top left corner. One apparent difference between the two plots is an extensive plume that was mapped at the 3.5 meter level but was not seen at the 5 meter depth.

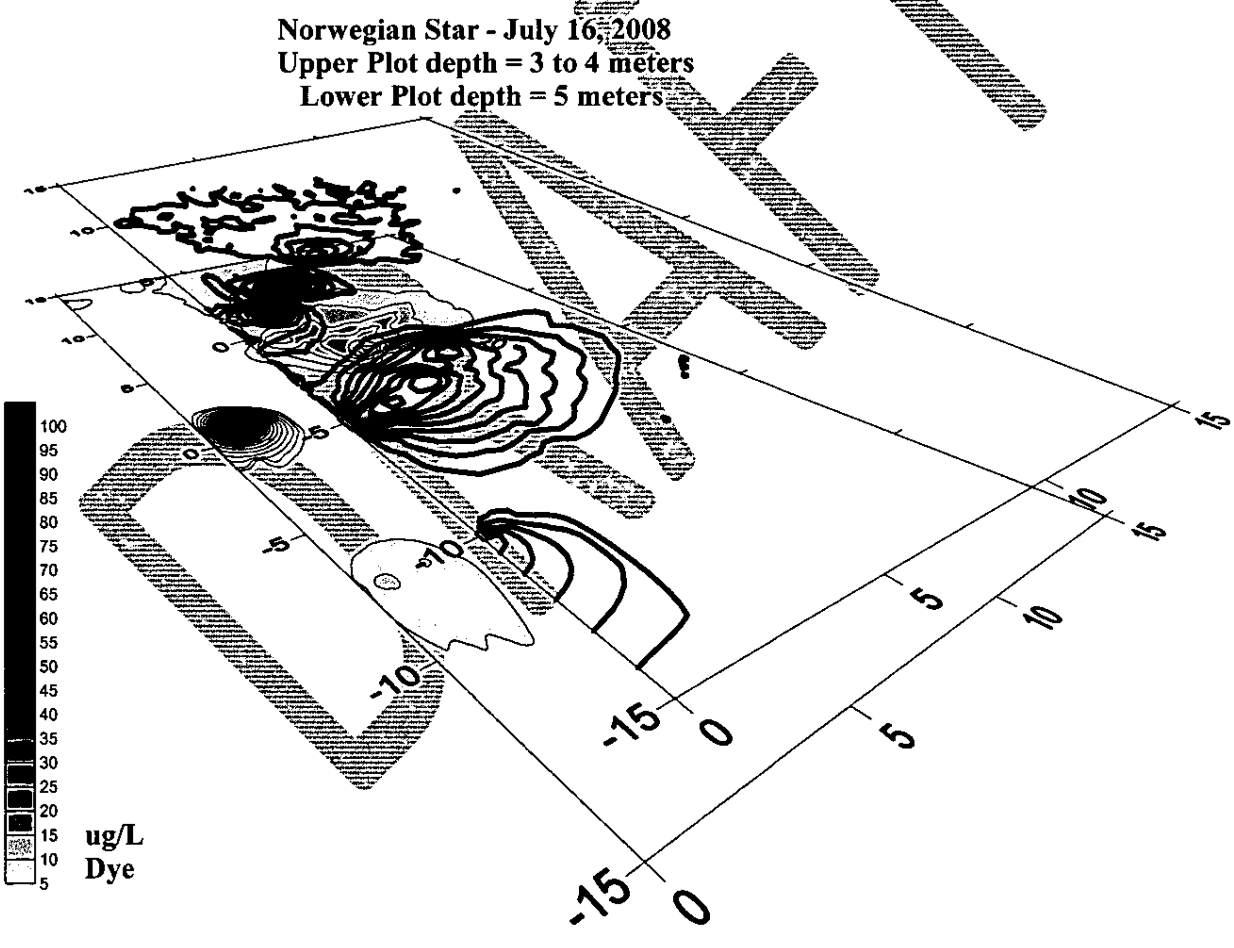

Figure 9 Plumes detected near the Norwegian Star at multiple depths.

Figure 10 details the maximum concentration that was observed for the Norwegian Star. The average dilution factor that was observed in the 5 to 15 meter distance from the discharge port was 1/22. The PLUMES model average was 1/19 and CORMIX predicted 1/12. The PLUMES model, while still conservative, did appear to provide a closer approximation to the observed plume maximums.

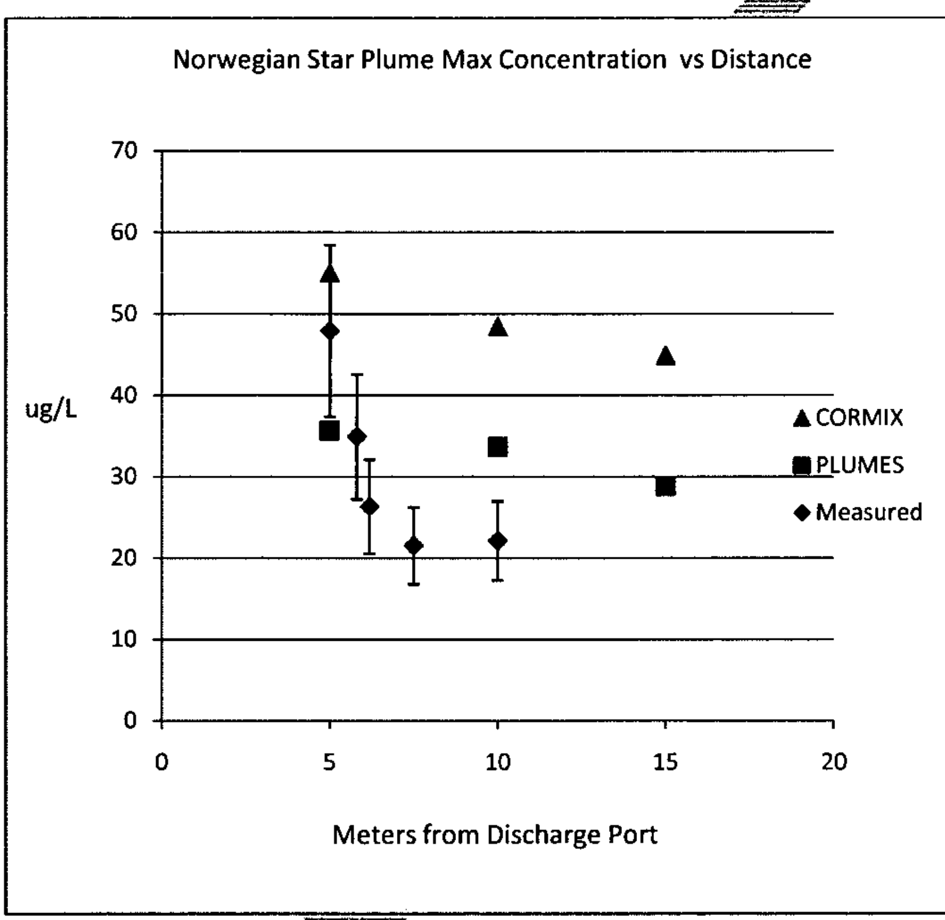

Figure 10 Plume Maximum vs Distance for the Norwegian Star at 3 meters depth.

In Figure 11 the upper level from plot 9 is shown in greater detail. While not in perfect alignment with the plume's directions, currents with a speed of 10 cm/sec were recorded at 3meters depth and they likely contributed to the measured plume distributions.

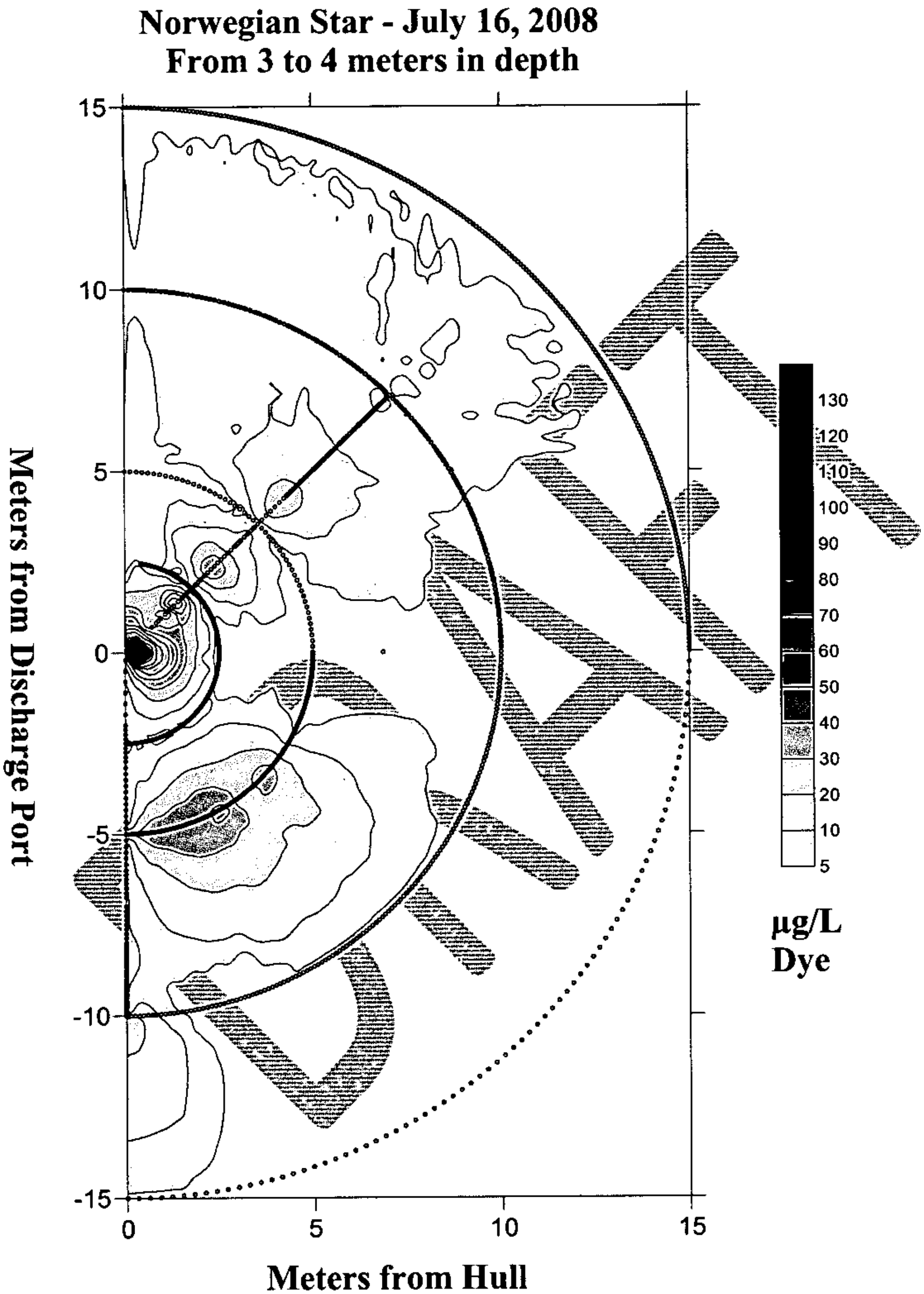

Figure 11 Plume distributions near the Norwegian Star between 3-4 meters depth from the surface.

Volendam

In Figure 12 the stern of the vessel Volendam lies in the direction of the top of the page and bow and Northeast are toward the bottom. The majority of the plumes were detected at 5 meters depth and appear to be advected away at an angle of 225°, which is consistent with the direction of the incoming tide. The dominant 10 cm/sec current that was recorded for this depth is in fairly good agreement with the plume direction, but is about 15° from overlaying it directly. The maximum dye concentrations and the general patterns of plume distributions appear to be consistent with the conditions found in the previous surveys.

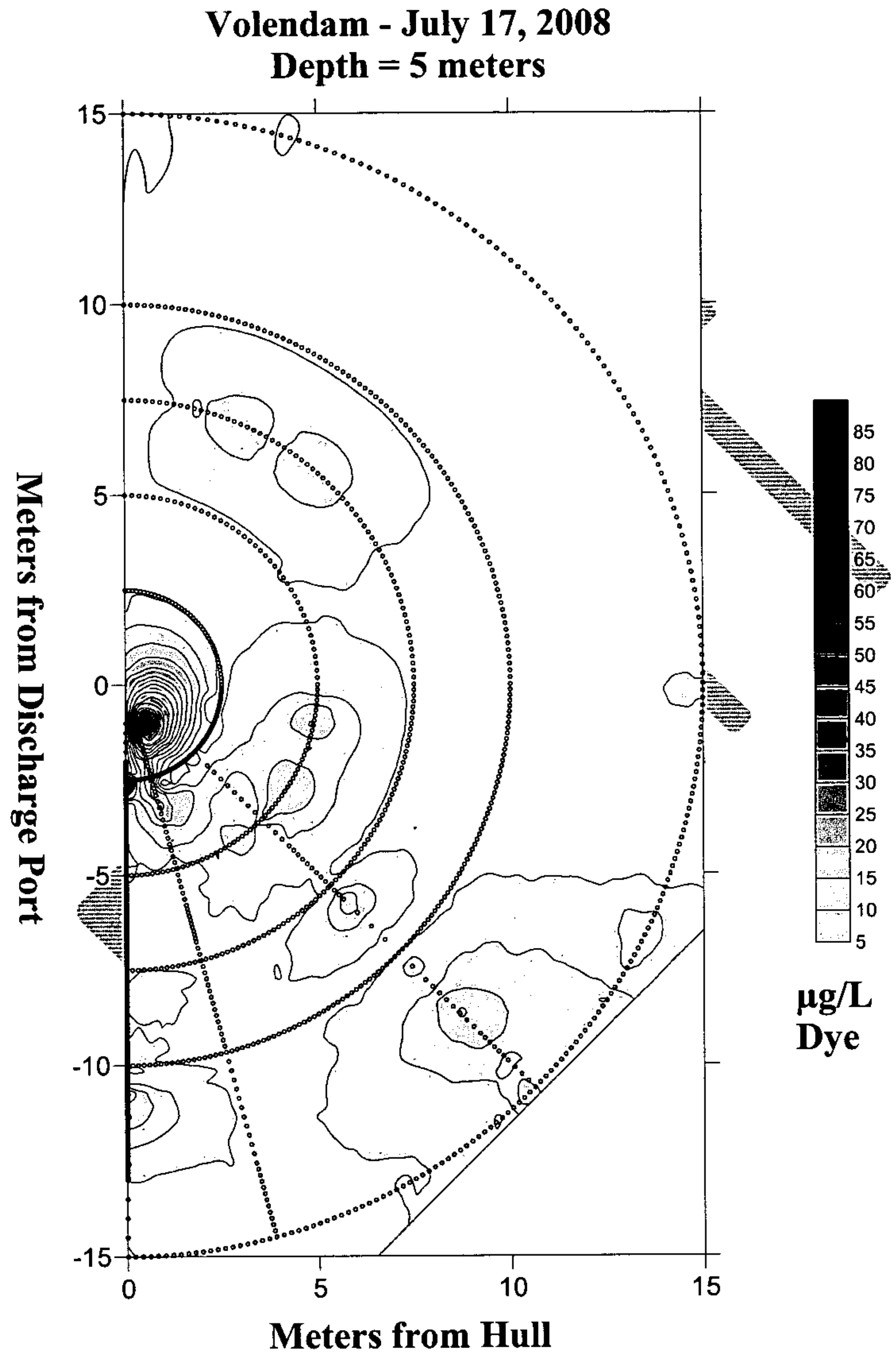

Figure 12 Plume distributions near the Volendam at 5 meters depth.

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The average measured plume dilution factor for the measurements between 5 and 15 meters from the ship was 1/48. In contrast to the other surveys that were done, the PLUMES generally predicted greater dilution factors with associated lower plume maximum values than were measured. The PLUMES average dilution factor was 1/59. This value is nearly identical to value that was calculated in 2004 for the Volendam for a distance of 5 meters. Compared to the measured maximum plume concentrations the PLUMES model overestimates the dilution seen near the Volendam. The CORMIX model did predict a mean dilution factor of 1/44 that was closer to the observed value of 1/48. In Figure 13 the value for the CORMIX calculated plume maximum actually overlays the observed value at 5 meters.

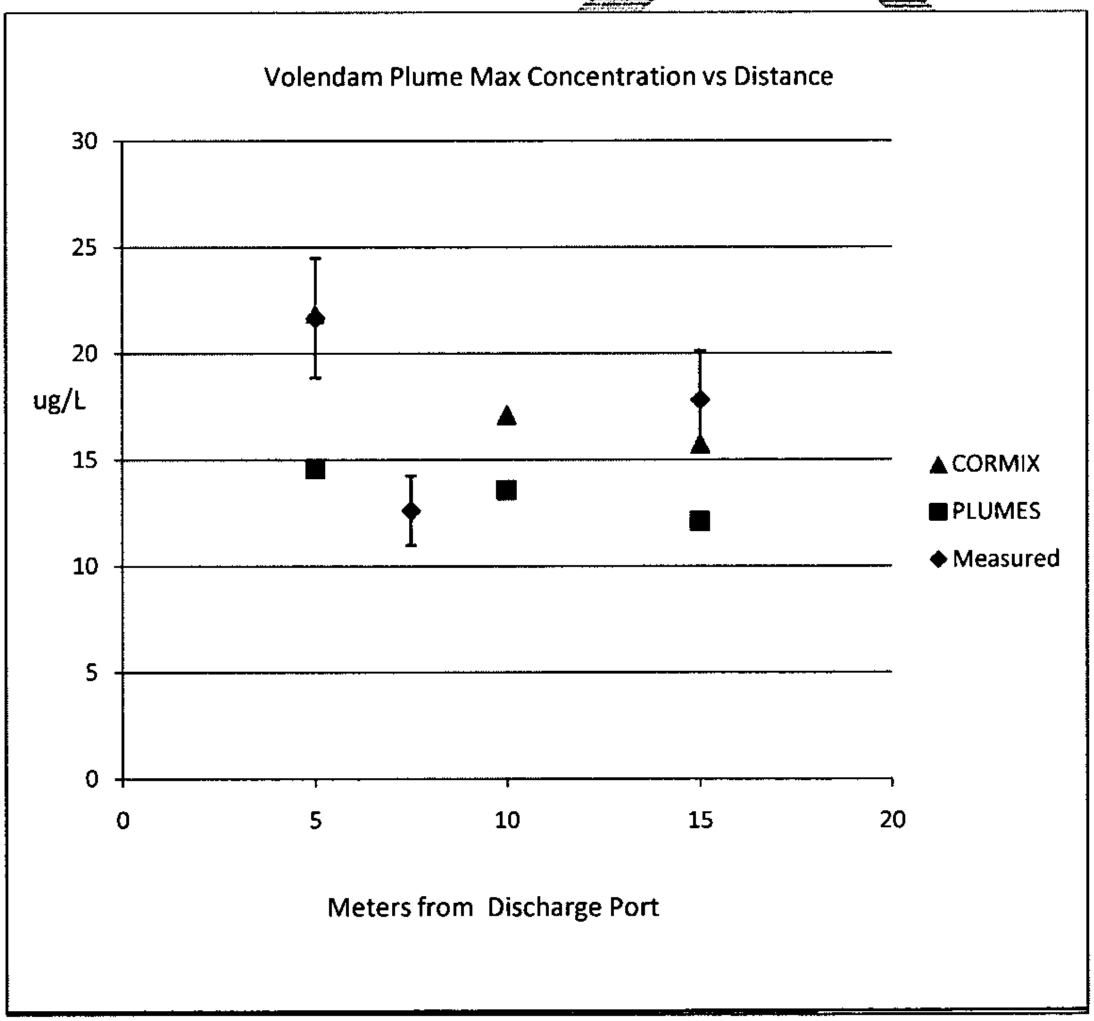

Figure 13 Plume maximum vs distance near the Volendam at 5 meters depth.

Discussion

In order to assess the significance of the dilution factors that were measured for each of the six cruise ships in this study, we will focus attention on the permit requirement that the discharges must meet the Alaska Water Quality Standards for ammonia, copper, nickel and zinc at the point of discharge. The data that have been reported to DEC by these ships for the 2008 cruise season show that the criteria for these four parameters are not consistently being met.

Water Quality Standard	Ammonia	Cu	Ni	Zn
	mg/L	ug/L	ug/L	ug/L
Salt water	2.9	3.1	8.2	81
Vessel				
	mg/L	ug/L	ug/L	ug/L
Millennium	4.3	2.3	[illegible]	65
Ryndam	8.2	26.3	[illegible]	[illegible]
Volendam	[illegible]	[illegible]	14.8	[illegible]
Norwegina Star	[illegible]	[illegible]	[illegible]	160
Star Princess	[illegible]	140	21	[illegible]
Coral Princess	100	88.1	[illegible]	208
Generic worst case	150	140	[illegible]	[illegible]

Table 2 Maximum measured concentrations of ammonia, Cu, Ni, and Zn found in 2008 in the discharge of the cruise ships that were surveyed in this study as well as the overall maximum values from all ships that discharged in 2008 (e.g. Generic worst case) at the point of discharge.

Table 2 lists the maximum value for each of the four parameters of concern that were measured in cruise ship effluent during 2008. The generic worst case entry indicates the maximum value detected by any large cruise ship that discharged into Alaska waters during 2008. Of the six ships that participated in the plume dilution survey only the Millennium would meet the Water Quality criteria for Cu and Zn. During 2008, only one large cruise ship out of the 23 that reported data to DEC for 2008 met the criteria for the water quality standards for all the parameters listed above. That vessel only discharged selected streams of accommodation graywater.

Immediately after the discharge leaves the port, it begins an initial dilution characterized by rapid and turbulent entrainment and a vertical rise usually of a few meters. The dilutions that result in the near field zone which extends out to about 2.5 meters were measured during this study and they ranged from about 1/4 to 1/12. The results of applying these measured near field dilution factors to the concentrations from Table 2 are listed in Table 3. The highlighted values represent calculated concentrations that still exceed the Water Quality Criteria for ammonia and copper even after the initial mixing. When dividing by worst case dilution (1/4), all parameters exceed water quality standards at 2.5 meters.

Water Quality Standard		Ammonia mg/L	Cu ug/L	Ni ug/L	Zn ug/L
Salt water		2.9	3.1	8.2	81
Vessel	Factor				
Millennium	1/12	0.4	0.2	1.3	5.4
Ryndam	1/4	1.4	[illegible]	4.3	25
Volendam	1/6	8.2	[illegible]	2.6	17
Norwegian Star	1/4	[illegible]	1.6	3.7	42
Star Princess	1/9	[illegible]	[illegible]	2.4	47
Coral Princess	1/7	[illegible]	[illegible]	2.5	30
Generic worst case	1/4	[illegible]	[illegible]	[illegible]	[illegible]

Table 3. Calculated Concentrations Expected after Initial Dilution (2.5 meters from discharge port)

Table 4 summarizes the information that was plotted in figures 6, 8, 10 and 13 above. Those figures compared the mean measured dilution to the modeled values for the range 5 to 15 meters from the discharge port. In almost all cases where a comparison can be made, the average dilution predicted by combining both model outputs would predict a maximum concentration that is higher than the measured concentration. Therefore, the models are conservative and more protective of the environment. The one standard deviation error that is reported for the observed values was computed based on the measured plume concentrations. For each ship this value is larger than that calculated based on the changing dye concentration caused by pipe flow variation. The range in plume maximum concentration is most likely the result of highly turbulent mixing that takes place near the ship's hull in addition to the discharge flow variation.

In the case of all four vessels where the plume distributions were mapped in detail between 5 and 15 meters away, using the actual maximum reported ammonia, Cu, Ni, and Zn concentrations from the 2008 season, the discharge from these ships would have met the water quality standards. The measured dilutions in that range were sufficiently adequate to reduce the concentrations below the criteria. For the range 0 to 5 meters away, however, most of the discharges from these ships would have exceeded the water quality standards for ammonia and copper.

	2008 Field Study 5 to 15 meter distance			2008 Model		2008 Model		
	n	dilution		n	PLUMES dilution	n	CORMIX dilution	Average Modeled dilution
Millennuim	4	39	±20	3	18	3	11	14
Ryndam	3	50	±23	3	30	3	31	30
Volendam	3	48	±13	3	58	3	49	54
Norwegian Star	5	22	±7	3	19	3	12	16
Star Princess		*			*		*	
Coral Princess		*		3	27	3	17	22

* not determined

Table 4 Compare Averaged Measured Dilutions to 2008 Models for 5 to 15 meters.

The modeling in this study in 2008 produced dilutions that were considerably smaller than those produced in the 2004 study, probably because more of the input parameters needed for the models were measured and not estimated.

Parameter		Ammonia (mg/L)	Cu (µg/L)	Ni (µg/L)	Zn (µg/L)
Alaska Water Quality Standard		2.9	3.1	8.2	81
2008 Maximum Measured Concentration		150	140	43.2	501
Highest Dilution Factor	63	2.4	2.2	0.7	7.9
Lowest Dilution Factor	28	[redacted]	[redacted]	1.5	17.9

Table 5 The maximum plume concentration based on measured dilutions at 15 meters

If the comparison to water quality standards is based on the measured dilution factors and the maximum concentrations for the four parameters and the lowest the dilution factor (28) is applied, then the concentrations of ammonia and copper still exceed the respective water quality standards. As shown in table 5 even at a dilution of (63) the results for ammonia and copper are higher than the water quality standard.

Based upon the maximum concentrations for ammonia (150 mg/L) and copper (140 µg/L) that were recorded for all ships in the 2008 season, a dilution factor necessary to achieve the water quality criteria would be 1/135 for ammonia and 1/117 for copper. This value includes a 2.6 factor to accommodate 'reasonable potential' and would provide a conservative design criteria in order to meet the requirement of state regulations. "Reasonable Potential" is a term used to increase the maximum observed value to what one may expect over the life of a permit. It is a statistically determined multiplier from EPA's Technical Support Document for Water Quality-based Toxics Control (EPA, 1991).

The distance away from any large stationary cruise ship that is required to achieve that level of dilution varies between vessels and the environmental conditions found at each Alaskan port. Using the PLUMES model as a guide for the ships in this study, the range of distances to reach a dilution factor of 1/135 for ammonia is from 40 to 150 meters from the discharge port. In the case of the CORMIX model, the distances range from 460 to 1040 meters (between 0.29 and 0.64 miles) for ammonia. The distances are smaller for copper.

The differences in results between the two models is probably due to the way the size and location of a plume is calculated. With the PLUMES program a deeper, narrower plume was calculated. For CORMIX, the plume flattened out due to "trapping" in a stratified water column, i.e. one with less dense fresh water above more dense saline water, and became thin and wide.

Vessel	PLUMES		COREMIX	
	Distance (m) to reach 1/135 ammonia	Distance (m) to reach 1/117 copper	Distance (m) to reach 1/135 ammonia	Distance (m) to reach 1/117 copper
Coral Princess	40	26	553	523
Ryndam	57	44	556	510
Millennium	150	132	673	619
Norwegian Star	105	89	1040	958
Volendam	49	42	460	381

Table 6 Modeled Distances to Reach Dilutions that Achieve Water Quality Standards

Both the CORMIX and the PLUMES models correlate well with the measured field data for distances up to 15 meters from the discharge point. However, the results from applying the two computer models to greater distances vary significantly. Therefore, it may not be appropriate to use these two computer models to predict the concentration of the pollutants in the receiving water at distances far from the discharge port.

A one-way analysis of variance (ANOVA) was applied to the 2008 monitoring data for ammonia to determine if the averages from the individual cruise ships could be summarized into an overall average. Table 7 lists the results of that calculation.

	Sum of Squares	df	Mean Square	F
Between ships	140782.28	18	7821.24	22.16
Within each ship	64237.11	182	352.95	
Total	205019.39	200		

Table 7 Results of ANOVA

The calculated F value equals 22.16 which greatly exceeds the expected value of 2. This indicates that it is statistically not valid to combine the individual ammonia averages of the ships into one pooled mean. Data from each ship must be treated separately when evaluating the dilutions of effluent from stationary vessels.

A one-way analysis of variance was also performed for the 2008 monitoring data for copper and the calculated F value of 13.68 is also much greater than the expected value. The copper data cannot be pooled.

It is important to note that when the individual input parameters from each vessel were used, including the pipe diameters, port size and shape and the flow characteristics, that the measured and modeled plume concentrations were reasonably consistent. In order to use the models effectively to predict the attainment of water quality standards, a number of requirements must be met. Each ship should be modeled individually so that the physical characteristics of the discharge systems are included as inputs. The concentration of pollutants in the waste stream needs to be measured and characterized. In addition, realistic hydrographic inputs should be developed for each harbor where the vessel docks.

While the comparison of the actual and modeled plume values that were determined in this study do appear to be in reasonable agreement, it is important to stress the limitation of the models to capture all the parameters that lead to variability in the real world. The disclaimers for the models routinely state that the resulting values have a variability of 50%. It was found during sensitivity testing of both models in this study that the results from CORMIX were much more sensitive to the angle and velocity assigned to the external tidal currents.

This information is often not available to the modeler and it is assumed the discharge is perpendicular to the current.

Conclusions

None of the vessels that were surveyed in this study in Skagway harbor in July 2008 can currently meet the State of Alaska Water Quality Standards for ammonia and selected metals at the point of discharge.

The initial dilution which occurs within the first 2.5 meters from ship is insufficient to bring the discharges into compliance for ammonia and copper in 5 of the 6 ships that were studied.

Between 5 and 15 meters away from the ships after additional dilution has taken place, the maximum measured dye concentrations were in fair agreement with the modeled values predicted by the PLUMES and CORMIX models. The modeled values calculated in this study produced somewhat higher maximum plume concentrations compared to those that were observed. Therefore, the models are more conservative and more protective of the environment.

Using the highest reported concentrations from the 2008 season for ammonia and copper as a worst case guide, modeled distances as great as 1040 meters and 958 meters from a discharge (0.64 and 0.59 mile respectively) may be needed to ensure compliance with the Water Quality Standards criteria.
Both the CORMIX and the PLUMES models correlate well with the measured field data for distances up to 15 meters from the discharge point. However, the results from applying the two computer models to greater distances vary significantly. Therefore, it may not be appropriate to use these two computer models to predict the concentration of the pollutants in the receiving water at distances far from the discharge port.

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United States
Environmental Protection
Agency

Sampling Episode Report
Cruise Ship Plume Dilution Study
Skagway, Alaska

U.S. Environmental Protection Agency

Oceans and Coastal Protection Division
Office of Wetlands, Oceans, and Watersheds

Office of Water
1200 Pennsylvania Avenue, NW
Washington, D.C. 20460

February 25, 2009

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EXECUTIVE SUMMARY

Sampling Episode Report for Cruise Ship Plume Dilution Study

This Sampling Episode Report (SER) describes a plume dilution study conducted under the direction of the U.S. Environmental Protection Agency (EPA) in collaboration with the Alaska Department of Environmental Conservation (ADEC). This study, part of a survey conducted in Alaska by EPA's Ocean Survey Vessel *Bold* in July 2008, was designed to characterize near-field cruise ship discharge plumes from six cruise vessels while they were docked in Skagway Harbor, Alaska. Sampled vessels represented three cruise lines and a variety of advanced wastewater treatment system types, wastewater discharge flow rates, discharge port sizes, and port depths below the waterline. This study was conducted as a continuation of EPA's assessment of standards for sewage and graywater discharges from large cruise ships operating in Alaska.

Using in-situ measurements of Rhodamine WT dye in the effluent plume, the survey team determined the location and concentration of each vessel's treated sewage and graywater discharge plume. A metering pump injected Rhodamine WT dye into the discharge line upstream of the discharge port, with a target dye discharge concentration of 700 μg/L (ppb). Dye concentrations in the resulting discharge plume were measured using a submersible fluorometer. Additional parameters (temperature, conductivity, depth, turbidity, and salinity) were measured simultaneously with plume discharge dye concentration, while manual notations of distance and location from the discharge port were made. Performing transects for plume characterization required approximately two hours per ship, with one ship tested per day. Measurements of the harbor current in the vicinity of the discharge plumes were collected using magnetic current meters. Dye concentrations in discharge plumes typically decreased by a factor of 65 or more within 15 meters of the discharge port.

1. INTRODUCTION

This Sampling Episode Report describes sampling and analysis activities to characterize graywater and sewage discharge plumes from six cruise vessels (Star Princess, Coral Princess, Holland America Ryndam, Celebrity Millennium, Norwegian Star, and Holland America Volendam) discharging at port in Skagway Harbor, Alaska. This study, which was conducted from July 7 through July 17, 2008, is a collaboration of EPA's Oceans and Coastal Protection Division and the Alaska Department of Environmental Conservation (ADEC). This sampling study was partially funded via an interagency agreement between EPA and ADEC.

This study was part of a survey conducted in Alaska by EPA's Ocean Survey Vessel *Bold* and is a continuation of EPA's assessment of the need for additional standards for sewage and graywater discharges from large cruise ships operating in Alaska under the "Certain Alaskan Cruise Ship Operations" law (also known as "Title XIV"; 33 USC 1901 Note). The data and information gathered through this sampling episode were collected using EPA's authority under Section 308 of the Clean Water Act, as also provided by Title XIV. The cruise lines voluntarily provided information and data gathered for and represented in this report, notwithstanding the above authority, in the interest of research for the improvement of wastewater treatment standards.

This plume dilution study was designed to provide information on near-field cruise ship treated sewage and graywater effluent discharge plume characteristics in harbor waters. The study will also provide preliminary information on whether these plumes behave as predicted by modeling performed by ADEC (Assessment of Cruise Ship and Ferry Wastewater Impacts in Alaska, 2004). ADEC used EPA's *Visual Plumes* model system[1] to simulate the dilution of discharges from both large and small vessels. ADEC's estimated dilution factor for initial dilution of discharges from stationary cruise ships in Skagway during a neap tide ranged from 5 to 60. The objectives of this study were to (1) determine the effluent dilution characteristics of discharges from stationary cruise ships; (2) track the near-field mixing dynamics of the effluent plume; and (3) provide information that can be used to validate the modeling studies (see Survey Plan, Appendix I).

Other sampling programs supporting EPA's assessment of cruise ship wastewater discharge standards in Alaska include two onboard sampling programs conducted during the 2004 and 2005 Alaska cruise seasons that focused on characterizing pollutants found in wastewater (graywater and sewage) onboard cruise vessels and evaluating the performance of the advanced wastewater treatment systems. The results of these sampling programs can be found on EPA's website at www.epa.gov/owow/oceans/cruise_ships/results.html.

Section 2 of this report describes the cruise vessels selected to participate in this study. Section 3 describes the data collection methodology. Section 4 presents the results. Section 5 provides a quality assurance assessment of the study.

[1] EPA's Visual Plumes model system is a Windows-based software application for simulating surface water jets and plumes. http://www.epa.gov/ceampubl/swater/vplume/

3. DATA COLLECTION METHODOLOGY

3.1 Pre-Sampling Activities

Visits to each of the six ships were conducted during the week prior to the start of the sampling episode. Visits were made to establish ship contacts, communications, and safety and emergency procedures, and to inspect sampling ports and associated fittings.

3.2 Sampling Schedule

Discharge plumes from six different cruise ships were monitored per the schedule in Table 3-1. Only one plume dilution study was conducted per day.

Table 3-1. Sampling Schedule

Cruise Vessel	Date of Study	Times of Study	Skagway Pier
Star Princess	July 10, 2008	1025 to 1230	Railway
Coral Princess	July 11, 2008	1040 to 1245	Railway
Holland America Ryndam	July 12, 2008	1025 to 1205	Railway
Celebrity Millennium*	July 15, 2008	0950 to 1135	Railway
Norwegian Star*	July 16, 2008	1000 to 1145	Ore
Holland America Volendam	July 17, 2008	1005 to 1140	Broadway

* Trial testing was also conducted on the Celebrity Millennium on July 7, 2008, and the Norwegian Star on July 9, 2008, to refine sample collection methodology.

3.3 Dye Injection Methodology

Metering pumps (Series 2001HEC-30 Variable Speed Peristaltic Pump, Flomotion Systems) were used to inject Rhodamine WT dye (Rhodamine WT Liquid, ORCO Organic Dyestuffs Corporation) into the cruise ships' treated sewage and graywater discharge. The pumps were installed downstream of the advanced wastewater treatment system, but as far upstream of the discharge port as possible so that multiple pipe bends and fittings provided thorough mixing of the dye.

Strap-on ultrasonic flow meters (BE 6000 Ultrasonic Flow Meter, Flomotion Systems) were installed on the discharge piping to record discharge rates (presented in Appendix G). Measured discharge rates were multiplied by the known Rhodamine WT dye feed stock concentration to calculate and adjust discharge dye concentration to attain the target concentration (discussed below). Discharge dye concentration also was measured directly on three cruise vessels (Celebrity Millennium, Norwegian Star, and Holland American Volendam) using a fluorescence sensor with a flow-through cell (SCUFA®, Turner Designs) installed on the discharge piping as close as possible to the discharge port. While the shipboard survey team was able to monitor discharge dye concentration via laptop computer connected to the SCUFA® sensor, it was not possible to electronically log these data. Therefore, the survey team kept manual logs of discharge dye concentrations. Tables F-1 through F-4 of Appendix F contain the raw data obtained from the fluorometer (see Section 5.1).

Trial dilution studies conducted on the Celebrity Millennium and the Norwegian Star revealed that the originally planned target discharge dye concentration of 100 ppb (see Survey Plan, Appendix I) was too low to be detected outside the cruise vessel (see Section 5.1, Accuracy and Calibration). Therefore, the target discharge Rhodamine WT dye concentration was increased to 700 ppb for most transects (Table 3-2). Target dye concentration was decreased during the Star Princess study because the plume was visible on the surface of the water (most likely because of the relatively shallow discharge port; see Table 2-1); this was the only vessel where the plume was visible on the surface of the water. Target dye concentration was increased during the Coral Princess study because the highly intermittent nature of the discharge; in addition strong water currents made plume detection difficult (see Section 4.1).

Table 3-2. Target Discharge Rhodamine WT Dye Concentrations by Cruise Vessel

Cruise Vessel	Discharge Rhodamine WT Dye Concentration (ppb)
Star Princess	700 (cast 4), then 420 (casts 5 through 11)
Coral Princess	700 (casts 2 through start of 5), 875 (portion of cast 5), 1,050 (end of cast 5 through cast 7)
Holland America Ryndam	700
Celebrity Millennium	700
Norwegian Star	700
Holland America Volendam	700

Discharge dye concentrations are the product of the known initial dye concentration, dye injection rate, and discharge flow rate. While the initial dye injection concentration and dye injection rate were constant (with the exception of the Coral Princess; see Section 4.1), discharge flow rates varied, resulting in variability of the discharge dye concentration. Any analysis of the data collected in this study should consider this variability when calculating near-field discharge plume dilution.

On four cruise vessels, temperature, turbidity, and pH of the treated effluent also were recorded from the ship's wastewater treatment control panel. These data are provided in Appendix F. Similar data were not available for the remaining two ships.

3.4 Plume Monitoring Methodology

Dye was injected into the treated sewage and graywater discharge for approximately two hours on each cruise vessel. During that time, dye concentrations in the water outside the cruise vessel were measured to determine near-field plume dilution after discharge. (The cruise vessels all were positioned so that the discharge ports faced the harbor and not the piers.) Prior to dye injection, measurements were taken of background fluorescence concentrations in the water. These measurements verified that no background seawater fluorescence was detected above the detection limit of fluorometer, which was approximately 1.6 ppb. For most ships, a salinity depth profile also was performed prior to dye injection to locate the halocline.

Dye concentrations were measured using an in-situ fluorometer (SCUFA®, Turner Designs) integrated into a Sea-Bird SBE-19 conductivity, temperature, and depth (CTD) sensor package (Sea-Bird SBE-19, Sea-Bird Electronics, Inc.) (Figure 3-1). This sampling array was deployed from a rigid inflatable boat (RIB) conducting transects at low speed (Figure 3-2).

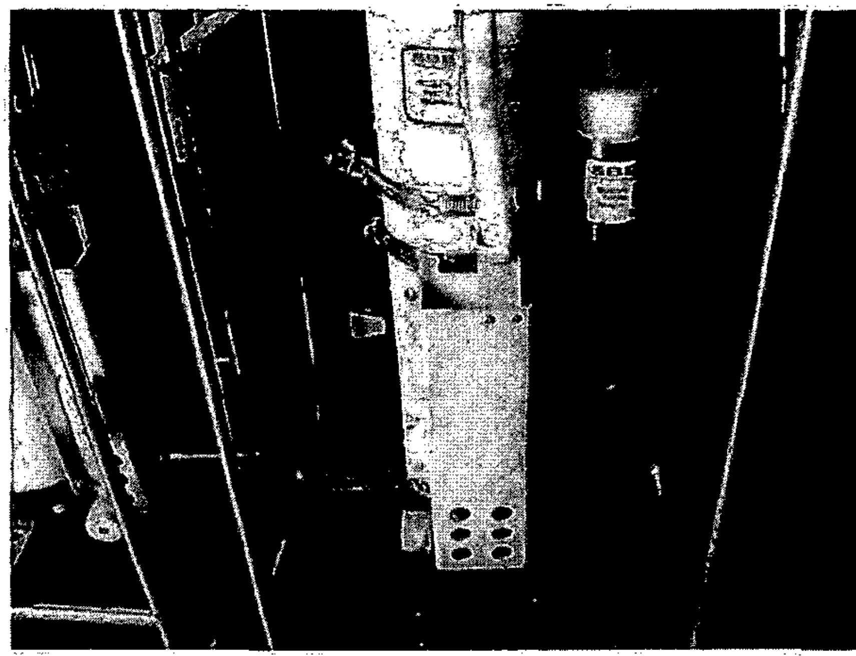

Figure 3-1. Sea-Bird SBE-19 CTD Sensor with Integrated SCUFA® Fluorometer

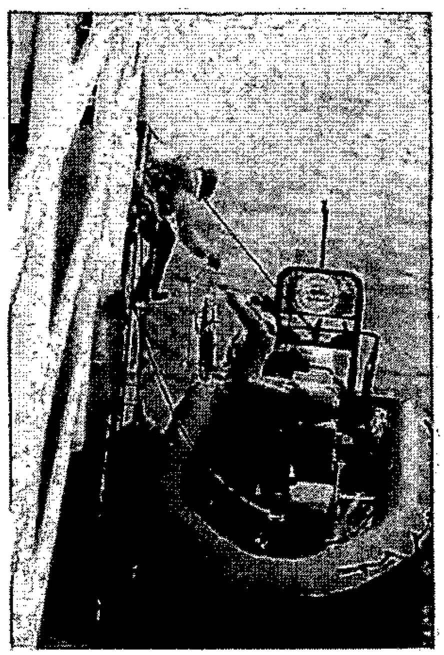

Figure 3-2. Rigid Inflatable Boat

One rope was used to control the depth of the towed array, while a second rope was used to control the distance of the towed array from the discharge port. This second rope was tied to the bow of the RIB and attached to the cruise vessel via a hull magnet affixed just above the waterline at the location of discharge port. Sensor depth was recorded electronically by the sampling array, while RIB location relative to the hull magnet was recorded manually by the sampling team onboard the RIB. The RIB sampling team also monitored sensor measurements, including Rhodamine WT dye concentrations, in real time using a laptop computer. The following measurements were collected by CTD + SCUFA® sampling array at 0.5 second intervals during the plume transects: dye concentration (uncorrected; see Section 5.1); temperature; conductivity; depth (of the sensor array); turbidity; and salinity.

For most ships, a variety of transect types were conducted to provide detailed characterization of the discharge plumes (see Appendix A). Transects can be described by visualizing polar axes on the water surface, with the location of the hull magnet corresponding to the origin, and the array location and movement indicated by a radius (distance from cruise vessel) and polar angle (estimated in degrees by the RIB sampling crew) (see Figure 3-3). For example, 90° indicates the array is located to the right of the discharge port at the ship's hull, while 270° indicates the array is located to the left of the discharge port at the ship's hull. Four different types of transects were performed to characterize the discharge plumes:

- Arc. Array was moved in an arc (e.g., 90° to 270°) at a fixed distance from the hull magnet. Arc transects at varying water depths and distances from the hull magnet were the most common type of transect performed, and were the primary means to locate and characterize discharge plumes.

- Inward or Outward Profile. Array was moved toward or from a fixed position on the hull (i.e., the hull magnet) at a constant angle (e.g., 225°). Inward and/or outward profiles were performed after the location of the discharge plume was determined using arc transects. These profiles produced continuous dye dilution profiles determined by distance from the hull magnet.

- Stationary. Array was maintained at a fixed location (depth, distance, and angle from the ship) over a period of time. This profile produced a continuous dye dilution profile at a fixed array location as the plume moved past the array over time. This was the primary type of transect used for the Star Princess because the plume was visible on the surface of the water (most likely because of the relatively shallow discharge port on the vessel; see Table 2-1), therefore an arc transect was unnecessary to find the plume. This type of profile also was used frequently for the Coral Princess, where ship discharge flow rates were highly variable and/or intermittent.

- Depth Profile. Array was maintained at a fixed distance and angle from the ship while the array was raised or lowered through the water column. These profiles produced continuous dye dilution profiles by depth.

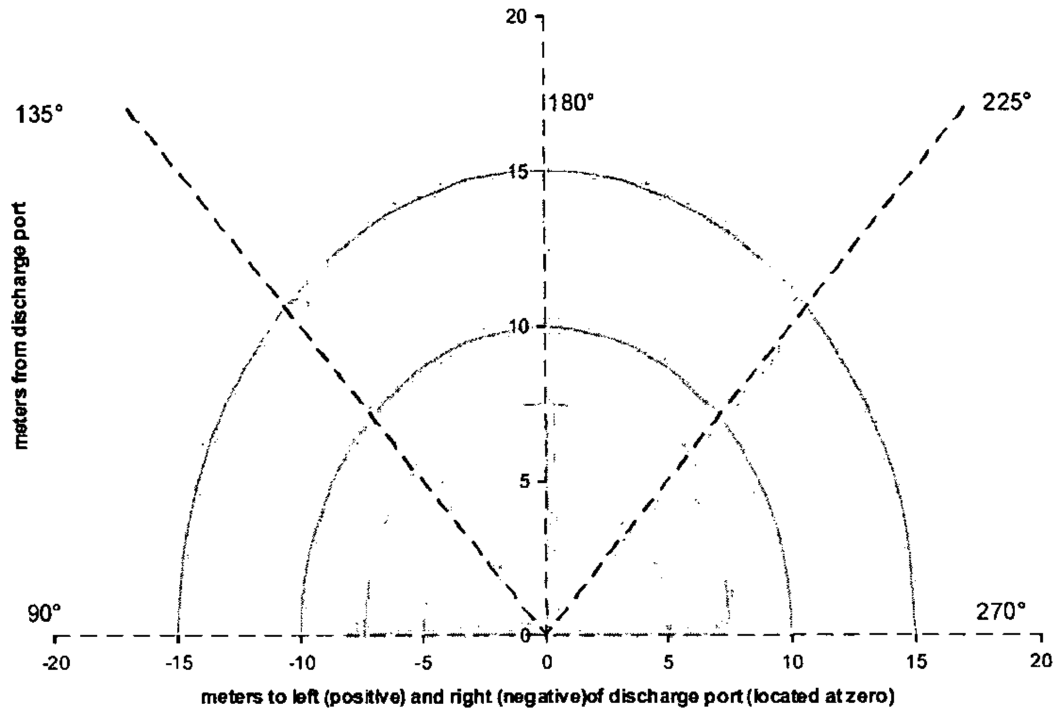

Figure 3-3. Orientation of Arc Transects for Dye Measurements

3.5 Current and Weather Measurements

At least two current meters (S4 current meters, InterOcean Systems, Inc.) were deployed to collect current measurements during the dilution studies for each cruise vessel (in some cases, three meters were used). The meters were deployed from the cruise vessels (to negate current meter motion relative to the vessels), approximately 15 meters away from the discharge port and approximately three meters out from the hull (to avoid interference from the vessel's metallic hull with the magnetic sensor of the current meter). The current meters were deployed at depths of one and three meters (or at depths of one, three, and five meters if a third current meter was used). Current measurements documented the ambient currents that affected the trajectory and dilution of the plume.

Weather conditions (e.g., air temperature, wind speed, and wind direction) were recorded by OSV *Bold* personnel during the dilution studies.

4. RESULTS

4.1 Discharge Plumes

Uncorrected dye concentration data for all transects are provided in Appendix B (see Section 5.1). In general, it appears that most near-field dilution occurs within the first 2.5 meters from the discharge port, with an average minimum dilution factor of approximately 50. After the first 2.5 meters, the plumes remained relatively intact to distances of 15 meters. At a distance of 15 meters, the average of the minimum dilution factors was approximately 65. These data will be further analyzed by the Alaska Department of Environmental Conservation to validate previous modeling studies on nearfield dilution of these treated sewage and graywater discharges.

Star Princess. This ship's discharge port was the shallowest of all the sampled cruise vessels (see Table 2-1). The discharge plume was the only one visible from the water surface; it moved along the hull at an angle between 255 and 270° from the discharge port location. Detected dye concentrations ranged up to approximately 57 ppb. It is unknown whether higher concentrations may have been detected if the CTD + SCUFA® array was able to measure dye concentrations near the surface of the water column (see section 5.1). Detected dye concentrations observed along the 270° transect were approximately similar at distances of 5 meters and 7.5 meters from the discharge port, and somewhat lower at a distance of 10 meters; however, the highest concentration was observed along the 255° transect at a distance of 10 meters. EPA did not prepare a profile of arc transect results for the Star Princess because arc transects were not performed.

Coral Princess. Discharge from the Coral Princess was highly intermittent. During periods of no flow, the shipboard survey team suspended dye injection to minimize dye accumulation in the discharge piping which would cause spikes and variability in discharge Rhodamine WT dye concentration. As a result, dye concentration data in Appendix B for the Coral Princess represent intermittent wastewater discharge with discharge dye concentration variability that is not well characterized. Because of this variability and strong water currents, the discharge plume was difficult to detect. Toward the end of the sampling period, detected plume dye concentrations ranged up to 270 ppb and were highly variable in concentration and in location as measured both by depth and degrees from the discharge port. EPA did not prepare a profile of arc transect results for the Coral Princess due to the highly intermittent nature of the discharge.

Holland America Ryndam. The discharge plume was most clearly characterized moving at an angle of 135° from the discharge port. Plumes were also detected at angles of 180° and 90°, particularly toward the end of the sampling period. Detected plume dye concentrations ranged from 5 ppb to approximately 20 ppb. During the arc transects, the minimum dilution factor, approximately 34, was observed at a distance of 5 meters from the discharge port. Maximum dye concentrations observed during arc transects, at various distances and depths are presented in Figure 4-1.

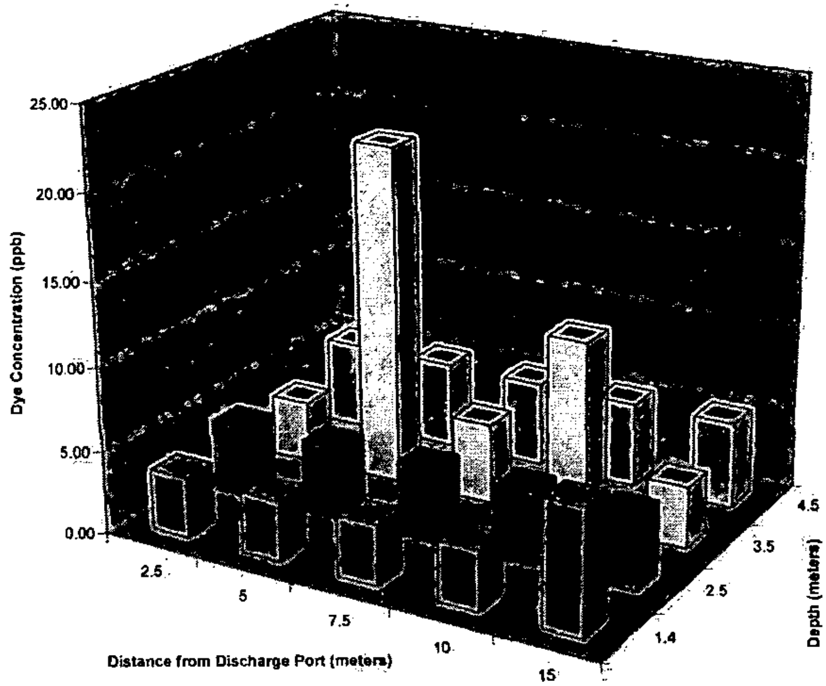

Figure 4-1. Profile of Arc Transect Results for Holland America Ryndam

Celebrity Millennium. The discharge plume was most clearly characterized moving at angles ranging from 240° to 270° from the discharge port. The discharge plume was observed at depths ranging from 5 to 7 meters. Detected plume dye concentrations ranged up to 47 ppb. During the arc transects, the minimum dilution factor, approximately 11, was observed at a distance of 2.5 meters from the discharge port. Maximum dye concentrations observed during arc transects, at various distances and depths are presented in Figure 4-2.

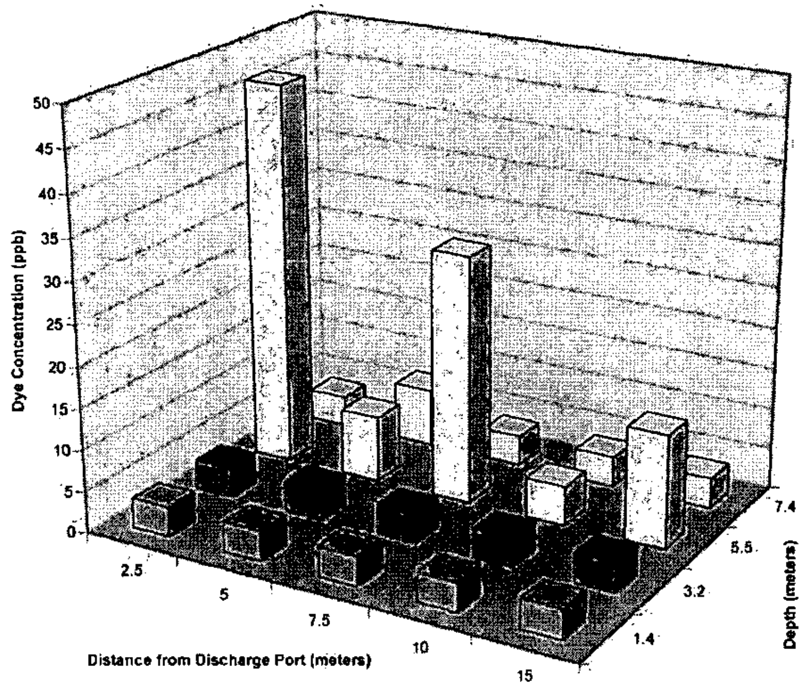

Figure 4-2. Profile of Arc Transect Results for Celebrity Millennium

Norwegian Star. The discharge plume was most clearly characterized moving at angles ranging from 250° to 270° from the discharge port. The discharge plume was observed at depths ranging from 3 to 5.5 meters. Detected plume dye concentrations ranged up to approximately 88 ppb. During the arc transects, the minimum dilution factor, approximately 13, was observed at a distance of 5 meters from the discharge port. Maximum dye concentrations observed during arc transects, at various distances and depths are presented in Figure 4-3.

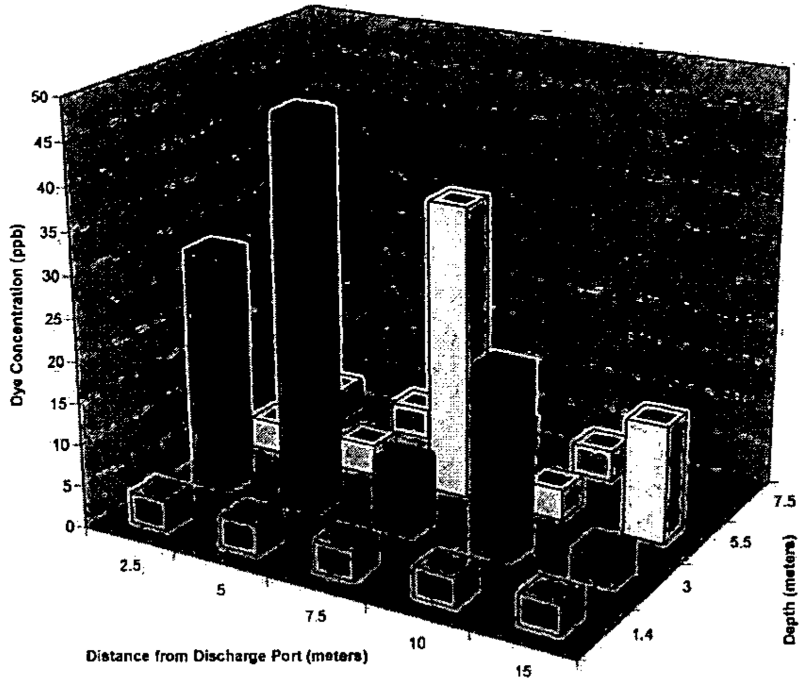

Figure 4-3. Profile of Arc Transect Results for Norwegian Star

Holland America Volendam. The discharge plume was most clearly characterized moving at angles within the range of 125° to 225°. The discharge plume was generally observed at a depth of 5.3 meters with detected dye concentrations ranging up to approximately 21 ppb. During the arc transects, the minimum dilution factor, approximately 37, was observed at a distance of 5 meters from the discharge port. Maximum dye concentrations observed during arc transects, at various distances and depths are presented in Figure 4-4.

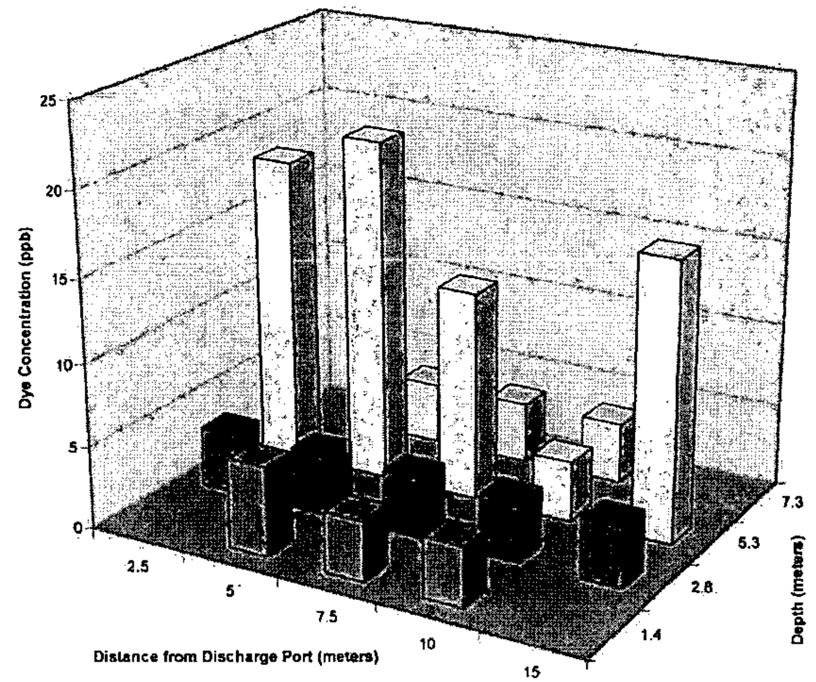

Figure 4-4. Profile of Arc Transect Results for Holland America Volendam

4.2 Transect Water Quality Data

Data on water temperature, conductivity, depth (of the sensor array), turbidity, and salinity from each transect are provided in Appendix B. Skagway Harbor salinity depth profiles (from the pre-dye transects for most ships) are provided in Appendix C. For all vessels, the halocline appeared to be below the discharge port depth (see Figures C-1 through C-4 in Appendix C).

4.3 Current Measurements and Weather Data

Current measurements collected during the cruise ship plume dilution studies are provided in Appendix D (see Figures D-1 through D-13 in Appendix D). For the polar plots, magnetic north corresponds to 0°. In Skagway, true north is 22.6° east from magnetic north. The heading of all the cruise vessels in this study was 40° east from true north. Therefore, when analyzing the current data, the ships' heading was 62.6° east from magnetic north.

The current meters were pre-programmed to begin data collection well before actual deployment from the cruise ships, and that the meters continued to collect data until the data were downloaded after their retrieval. Current data presented in this report include only the subset of data collected during the cruise ship plume dilution studies (see Table 3-1).

National Oceanic and Atmospheric Administration Tide Tables for Skagway for July are provided in Appendix E. These tide tables are provided to supplement and inform the current measurements.

Weather data (air temperature, wind speed, and wind direction) recorded during the cruise ship plume dilution studies are provided in Appendix H.

5. DATA QUALITY

Quality assurance/quality control (QA/QC) procedures applicable for this program are outlined in the *Quality Assurance Project Plan for Support for OSV Bold Survey of Large Cruise Ship Wastewater Impacts in Alaskan Waters (QAPP)*, which is reproduced in Appendix J. This section provides an assessment of the QAPP project data quality objectives specific to the cruise ship plume dilution study, which were established for the key measurements of the concentration of Rhodamine WT dye in the near-field plume and in the cruise ship discharge. In addition, this section provides a brief quality assurance assessment of non-key measurements.

Trial dilution studies were conducted on the Celebrity Millennium on July 7 and on the Norwegian Star on July 9 to refine the sample collection and analysis methodologies. Data from these trial studies are not presented in this report. Sampling on the Celebrity Millennium and the Norwegian Star was repeated on July 15 and July 16, respectively.

5.1 Quality Assurance Assessment of Key Plume Dilution Study Measurements

For the cruise ship plume dilution study, the key measurements identified in the QAPP are the concentration of Rhodamine WT dye in the near-field plume and in the cruise vessel discharge (end-of-pipe). The data quality objectives for these measurements are defined in terms of completeness, accuracy, precision, representativeness, and comparability.

Completeness (Near Field Plume Dye Concentrations)

Dye concentration data in the near-field plume are complete for all vessels surveyed except the Star Princess. The discharge plume for the Star Princess was visible at the surface of Skagway Harbor. The CTD + SCUFA® array is designed to take measurements at approximately 1.5 meters of depth and deeper. As a result, data for the Star Princess do not characterize the entire plume, but only the portion of the plume at depths of approximately 1.5 meters or greater.

Completeness (Cruise Ship Discharge Dye Concentrations)

Discharge dye concentration was calculated by multiplying the measured discharge rates by the known feedstock dye concentration. On three cruise vessels (Celebrity Millennium, Norwegian Star, and Holland American Volendam), a SCUFA® fluorescence sensor was installed on the discharge piping to verify dye concentration. For the other three vessels, the SCUFA® sensor could not be used to verify dye concentration due to damage sustained during an unannounced emergency generator power drill on one of the ships. On these three ships, the survey team verified dye discharge by visual observation. Dye concentration was assumed to be the nominal calculated concentration..

Accuracy and Calibration

Dilution series performed for the three SCUFA® fluorometers prior to field testing showed excellent accuracy, with a highly linear response from approximately 5 ppb through 300 ppb. The dilution series and initial trial testing on Celebrity Millennium on July 7 revealed that the practical detection limit for the fluorometers was the seawater background signal of approximately 1.6 ppb (contrary to the detection limit of 0.04 ppb reported by the manufacturer[2]). A calibration curve for the range of 5 to 50 ppb was found to be linear ($R^2 > 0.99$). Actual dye concentrations are obtained using the following expression:

$$C = 0.768*C' + 4$$

where C equals dye concentration and C' is the uncorrected fluorometer response.

In consideration of the loss of two orders of magnitude of SCUFA® sensitivity, the survey team increased the target shipboard dye concentration from the planned 100 ppb to 700 ppb. Consequently, a second calibration curve was prepared for high dye concentrations. For the calibration range of 84 to 660 ppb, the calibration curve was linear ($R^2>0.99$) and fit the following expression:

$$C = 1.02*C' + 9$$

where C equals dye concentration and C' is the uncorrected fluorometer response.

Precision and Representativeness

The QAPP specified collection of duplicate CTD+SCUFA® data using a pair of arrays towed side-by-side from the rigid inflatable boat. Field duplicate sampling using two adjacent CTD+SCUFA® arrays was not performed. The secondary CTD+SCUFA® array was dismantled to provide a SCUFA® to replace the shipboard unit that was damaged during an emergency generator power drill onboard one of the cruise vessels.

Comparability (Among Ship Discharge Tests)

The sample collection and analysis methodology was consistent for all cruise ship plume dilution studies. Dilution study transects were generally consistent among ships, with some deviations to account for ship-specific conditions and weather conditions during each test.

Overall Data Quality Assessment

This data quality assessment indicates that the key measurements collected during the cruise ship plume dilution study are of sufficient quality for use in analyzing near-field mixing dynamics of the effluent plumes from stationary cruise ships in Skagway Harbor.

5.2 Quality Assurance Assessment of Non-Key Plume Dilution Study Measurements

Discharge Flow Measurements

Ship discharge flows were measured on all cruise vessels except the Norwegian Star. For the Norwegian Star, discharge flows were measured only during the set-up period because the meter malfunctioned at the start of the sampling period. Repeated attempts to reinstall the flow

[2] Telephone contact with the manufacturer revealed that the reported detection limit can be achieved only under ideal, laboratory conditions.

meter were unsuccessful. For this Norwegian Star, discharge dye concentration was measured using a SCUFA® sensor (as it could not be calculated using flow rates).

While discharge flow data were monitored by the shipboard survey team, they were not reliably logged electronically because of a smaller than expected data-logging buffer capacity. For the Star Princess, Coral Princess, Holland America Ryndam, and Celebrity Millennium sampling events, electronic data logs are available for only the last 7 to 15 minutes of testing. For the Norwegian Star, electronic data logs are available for the last 2 hours of testing. For the Holland America Volendam, electronic data logs are complete for the entire period of testing. Electronically logged discharge flow data are supplemented by field logs taken by the shipboard survey team (see Appendix F).

Two ships, Holland America Ryndam and Holland America Volendam, operated flow meters on their discharge. On both of these ships, ultrasonic flow meter measurements closely matched measurements made by these ships' installed meters.

Current Measurements

Harbor current was measured during all sampling events for all 6 ships. For two of the six ships tested, current meters were deployed at 1m, 3m, and 5m depths. For the other four ships current meters were deployed only at 1m and 3m depths due to the difficulty of deploying the meters. For one ship (Norwegian Star), current was not measured at the 1m depth due to water seepage into the connector cover. Current measurements are reasonable, based on their correlation to the location and direction of the detected plume.

Weather Data

Weather conditions (e.g., air temperature, wind speed, and wind direction) were recorded by the OSV *Bold* personnel during the dilution studies, with the exception of the Coral Princess plume dilution study on July 11.