Examination of Effluent Plume Behavior
Delray Beach, Florida
Ocean Outfall

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September 2006
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1.0 INTRODUCTION

The cities of Boynton Beach and Delray Beach, Florida, jointly administer a wastewater treatment plant (WWTP) which discharges an average of 14 million gallons a day of partially treated sewage effluent into the coastal waters of Palm Beach County. Operated by the South Central Regional Wastewater Treatment and Disposal Board (SCRWWTDB), this outfall is one of six found along the southeast Florida coast. The outfalls all discharge into the ocean along the western boundary of the northward flowing Florida Current (aka Gulf Stream Current). The SCRWWTDB outfall discharges one mile offshore, directly east of Atlantic Avenue, downtown Delray Beach and is the northernmost of the south Florida ocean outfalls. The Delray discharge is 90 feet below the ocean surface and terminates directly within a coral reef tract that parallels the Palm Beach County coastline, also approximately one mile offshore.

1.1 PBCRR Investigations

The volunteer organization Palm Beach County Reef Rescue (PBCRR) has monitored Lyngbya algal blooms in the coral reef environment down current of the Delray effluent outfall pipe since the blooms first became evident in early 2002. PBCRR has issued five reports beginning September 2003, detailing their investigations of the distribution of Harmful Algae Blooms (HAB) on the south Palm Beach County coral reef tracts. The south county Lyngbya bloom has been documented to occur only on the coral reef tract immediately down current of the SCRWWTDB outfall pipe (Figure 1). PBCRR reports document a connection between the quantity of nutrients discharged from the outfall and the spatial and temporal distribution of HABs in the down current receiving environment.

PBCRR performed water quality nutrient analyses in the south Palm Beach County coastal environment during the second half of 2005. The water quality monitoring project established background conditions and detected elevated nutrient concentrations down current of the Delray Beach ocean outfall. Results of that investigation provide an added link between the occurrence of HABs and nutrient loading from SCWWTDB.

1.2 NOAA Tracer Study

During June 2004 the Ocean Chemistry Division of the National Oceanic and Atmospheric Administration (NOAA) Miami, performed a farfield tracer study of the Hollywood, Florida outfall, located 35 miles south of the Delray Beach outfall. Data developed by the NOAA farfield tracer study provides a means to examine outfall effluent behavior in the coastal environment and determine if plume configuration and dilution predicted by the NOAA model verify levels of nutrient enhancement found by the PBCRR water quality investigation.

1) See: http://www.reef-rescue.org/research.htm for copies of reports.
2.0 NOAA FARFIELD EFFLUENT PLUME TRACER STUDY

The 2004 NOAA Hollywood, Florida outfall study “Farfield Tracing of a Point Source Discharge Plume in the Coastal Ocean Using Sulfur Hexafluoride” published 2005, in Environmental Science & Technology, Vol. 39, No. 22 (provided as Appendix A), employed sulfur hexafluoride (SF$_6$) as an effluent tracer and was able to track the Hollywood outfall effluent plume down current 40 miles as it traveled northward paralleling the coastline (Figure 1 and 5 of Appendix A). Data developed from this experiment, while specific to the study, has potential bearing on other outfalls along the south Florida coast where similar conditions exist.

Several aspects of the NOAA tracer study were examined to determine relevance to the Delray outfall. The study showed that the effluent plume was controlled by current and flowed northward parallel to the coast with a broadening of the plume to about 3 km wide at a point 66 km from the outfall. Current velocities were variable in magnitude and direction during the six day NOAA study but showed a net northward flow. Since the outfall effluent is freshwater and positively buoyant in the marine environment it rises to the surface at the outfall terminus and forms a seawater effluent surface layer. The effluent is transported as a near surface plume with the current until the density contrast is eroded by dilution with surrounding water. The tracer study suggests the effluent advects from the outfall in filaments and/or as boluses until down current equilibrium is achieved (Figure 2).

One objective of the study was to determine at what point the discharge was mixed vertically in the water column and reached the bottom to assess its possible effect on the benthos. Three depth profiles of SF$_6$ were measured at 13, 17, and 66 km from the outfall terminus along the projected centerline of the plume to determine the vertical distribution of the plume tracer. High levels of SF$_6$ were observed to the bottom at each location sampled, indicating that vertical mixing of the discharged effluent with surrounding waters occurred within 13 km of the outfall. However, in the first 20 km from the outfall, SF$_6$ surface concentrations were highly variable. Maximum SF$_6$ concentrations decreased by about 200-fold per kilometer as the plume traveled northward from the outfall source.

The NOAA study determined that effluent dilution occurs in a systematic fashion and can be represented by a linear decrease with distance (Figure 8 of Appendix A). A dilution equation developed from the study (Equation 1, presented below) while only applicable to the conditions encountered, illustrates dilution with distance from the source and is in accord with earlier SEFLOE II (1) data that suggest at a distance of 800 meters from the outfall a dilution on the order of 100:1 is attained. While the 2004, tracer study Equation 1 suggests a dilution of 160:1. More importantly, the study indicated that dilution mechanisms, while complex, resulted in a linear decrease in SF$_6$ concentrations over the entire reach of the study area.

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1) SEFLOE II: Southeast Florida Outfall Experiment: http://www.aoml.noaa.gov/general/project/oadal1.html
   Also see: http://www.epa.gov/region4/water/uic/downloads/ra/06-ocean.pdf
3.0 PBCRR COASTAL WATER QUALITY MONITORING PROJECT

PBCRR performed a coastal water quality monitoring project during the second half of 2005. Samples were collected at two depth intervals from multiple locations both up and down current of the SCRWWTDB Delray ocean outfall pipe (Figure 3). The purpose of the program was to establish background conditions and determine if nutrient enhancement from the Delray outfall could be detected in the coastal waters. Eight separate sample collection episodes were completed from August 16, 2005 through November 8, 2005, representing a total of over 100 water samples collected from between Seagate Reef, Delray Beach, northward to the Boynton Beach Inlet. Nutrient analysis was performed by Chesapeake Biological Laboratory (CBL), University of Maryland, Center for Environmental Science. Field measurements were conducted for specific conductance and temperature by PBCRR. Current direction, velocity, weather and sea conditions were recorded at the time of collection.

The water quality program was performed in cooperation with Palm Beach County Department of Environmental Resources Management (PBCDERM) and Harbor Branch Oceanographic Institute (HBOI). Matching funding for the project was provided by PBCDERM against contributions, discounts and volunteer efforts by PBCRR, HBOI, CBL, Starfish Dive Charters, Lantana and Underwater Explorer Dive Charters, Boynton Beach, Florida. Results of this investigation established background nutrient levels and demonstrated a nutrient contribution to the coral reef ecosystem north and down current of the Delray outfall during north current sampling episodes. Samples collected during south current events show nutrient concentrations north of the outfall pipe to be at background levels with no nutrient enhancement detected (Appendix B).
4.0 EXAMINATION OF DELRAY OUTFALL EFFLUENT PLUME

The environmental setting of the Delray outfall is analogous in many respects with that of the Hollywood outfall, located approximately 35 miles to its south. While the discharge volume of Delray is less than Hollywood the outfall terminus is at an equivalent depth and subject to similar current dynamics.

Effluent dilution and plume configuration data from the NOAA Hollywood outfall tracer study were employed to examine the Delray outfall coastal water quality monitoring results obtained by PBCRR. Calculations derived from the NOAA study were used to evaluate if down current nutrient concentrations found by PBCRR were present at the levels predicted by the tracer study. For the evaluation SCRWWTDB Discharge Monitoring Report (DMR) effluent testing results and PBCRR water quality monitoring data obtained on the same day were compared. Nutrient values reported in the SCRWWTDB DMR were used to calculate anticipated down current effluent concentrations by employing NOAA dilution Equation 1. These resulting values were compared to the actual nutrient levels found in the environmental samples collected both up and down current of the Delray outfall. A percent recovery of predicted value was then calculated.

From the eight completed PBCRR sampling episodes only data obtained during north current sampling events were examined. Four sets of water quality results were selected for evaluation. A fifth north current data set (October 18, 2005) was not considered since a negligible current velocity of 0.1 kts was measured. Video taped on-site observations found a stationary effluent pool, surrounding the vicinity of the outfall pipe occupying the upper 1/2 to 1/3 of the water column, suggesting minimal down-field effluent migration from the discharge point. South current event data were not examined in this way since no nutrient enhancement above background concentrations was detected in the investigation area north of the outfall.

4.1 Parameter Comparison

As a NPDES (1) permit condition SCRWWTDB conducts effluent nutrient analysis on a weekly basis. The analysis is performed for informational purposes only, since the permit sets no nutrient discharge limits. The analysis is performed on a flow-proportional composite sample collected on Tuesdays. The PBCRR water (grab) samples were also collected on Tuesdays to coincide with the WWTP analysis and allow for a comparison of seawater nutrient data with sewer plant effluent results. SCRWWTDB effluent is analyzed for the parameters of Total Kjeldahl Nitrogen, Ammonia, Nitrite/Nitrate and Total Phosphate. The PBCRR environmental samples were analyzed for Ammonia, Nitrite/Nitrate and Ortho-Phosphate. For purposes of down current effluent dilution comparison Dissolved Inorganic Nitrogen (DIN) concentrations were examined. Ammonia and Nitrite/Nitrate concentrations were combined to derive the DIN value.

1) National Pollution Discharge Elimination System. See: http://cfpub.epa.gov/npdes
Gulf Stream Reef water quality monitoring Station 5 was chosen as the down current (north of outfall) location for data comparison, (Figure 3). Station 5 is the location of persistent Lyngbya algal blooms at a point where the theoretical Delray outfall effluent plume contacts the reef and is 6.8 km north of the outfall terminus. Based on the width versus distance plume model generated by the NOAA study (Figure 4) the effluent plume is believed to be approximately 250 meters wide at Station 5. Due to the narrow width of the effluent plume at this close proximity to the outfall and variability of analytical data generated from sampling stations closer to the source, it was felt evaluation of predicted DIN recovery at points closer to the outfall would be impractical due to the inconsistent nature of the effluent plume as demonstrated by SF$_6$ concentrations found in the near-field water column reported in the NOAA study. In fact, variability of PBCRR DIN concentrations between the 20 and 45 foot (6.1 and 13.7 meter) depth intervals as observed at Station 5, suggest that 6.8 km may be as close to the source as practical for effluent mixing in the water column to occur with any reasonable degree of homogeneity. NOAA measurements within the first 20 km of the Hollywood outfall showed large variability in concentrations on a sub-kilometer scale and a poorly defined tracer field. NOAA explains the lack of near-field effluent uniformity as a filament or bolus effect and did not find complete mixing in the water column until measured 13 km down current.

To compare nutrient levels predicted by the NOAA tracer study with the actual nutrient concentrations found in the environment down current of the Delray outfall the following set of equations were employed:

To calculate the predicted down current nutrient enhancement for Station 5, the DMR DIN is first divided by the dilution factor derived from NOAA Equation 1.

**Equation 1 (NOAA):**

\[
\text{Dilution} = 212 \times \text{distance (km)}
\]

Station 5 is 6.839 km north of the outfall; 212 times 6.839 equals a dilution factor of 1450.

To obtain the predicted DIN concentration (as µg/l) at Station 5, Equation 2 is employed,

**Equation 2:**

\[
\frac{\text{mg/l (as N)} \times 1000}{1450} = \frac{\text{predicted enhancement (as µg/l N)} + \text{background (as µg/l N)}}{1450} = \text{predicted DIN concentration}
\]

where the DRM DIN is divided by the dilution factor (1450) to obtain the predicted enhancement value and this product is then added to the DIN concentration from background Station 1, up current (south) of the outfall to obtain the predicted DIN concentration.
Finally, the predicted DIN concentration is compared to the actual analytical DIN result from Station 5 and a percent recovery is calculated as represented by Equation 3.

**Equation 3:**
\[
\frac{\text{DIN concentration found}}{\text{predicted DIN concentration}} \times 100 = \% \text{ recovery}
\]

In this way a comparison can be made between the effluent dilution predicted by the NOAA study and the actual nutrient levels found in the down current environment. The comparison of predicted versus actual results adds to the understanding of nutrient enrichment from the outfall effluent in the down current coral reef environment impacted by Lyngbya blooms and serves to validate PBCRR field observations and water quality data interpretation.

4.2 **Examination of Data**

Two depth intervals, 20 and 45 feet below surface were analyzed during the course of the PBCRR water quality monitoring project. For the purpose of evaluating predicted nutrient enhancement the combined average DIN of both intervals was examined. In addition, due to the lack of homogeneity of nutrient distribution in the water column the higher DIN concentration of the two depth intervals was also considered.

Data from PBCRR Seagate Reef Station 1, two kilometers up current (south) of the outfall, were employed to establish background nutrient concentrations. The background concentration was determined by averaging the combined DIN total of the 20 and 45 foot depth intervals. When evaluating data sets, only background, DMR and down current water sample results generated on the same day were compared.

The DIN variability found in the effluent plume at Station 5 was not observed in concentrations at PBCRR background locations, either between depth intervals or from one day’s data to another. For the episodes selected for data review the background DIN concentration (Station 1) averaged 3.48 µg/l (as N) and ranged from 1.8 to 4.6 µg/l. While DIN values at down current Station 5, ranged from 2.0 to 24.2 µg/l (as N).

In addition to reviewing the four individual episodes the overall average of predicted versus actual down current enhancement is presented.
5.0 FINDINGS

A summary of the calculated recoveries for the individual sampling episodes are presented below. Appendix C provides the calculations, site maps and results of individual analyses. The overall average of predicted versus actual DIN enhancement recovery for the four sampling episodes examined equals 56%. When only the highest DIN depth interval concentration from each episode is considered the average predicted versus actual DIN enhancement recovery equals 85%.

When the relationship of current velocity with predicted DIN recovery is examined, it was found the two episodes with velocities of approximately 0.8 kts exhibited a higher percentage of calculated recovery than the two episodes where lower current velocities of approximately 0.3 kts were measured. While no explanation is offered, a raison d'être is considered. Variation in current velocity may effect effluent dilution and/or plume configuration. Also, PBCRR sampling trips were conducted from south to north in an effort to increase the likelihood of obtaining samples from within the same northward traveling water mass. Elapsed time between sample collections at Station 1 and Station 5 was generally one hour. At increased current velocities the Station 5 sample is more likely to be representative of the water mass encountered at Station 1, as when compared to sampling episodes conducted during decreased current velocity.

The predicted down current DIN concentrations were calculated from the results of analyses performed on 24 hour flow-proportional composite samples collected at the WWTP. These values were compared to PBCRR grab samples for the purpose of calculating percent recovery. It is unrealistic to anticipate a perfect 1:1 relationship between these values. Nutrient concentrations released at the outfall discharge point into the coastal environment cannot be expected to identically match the concentration of nutrients present in the WWTP 24 hour composite sample. Additional variables capable of impacting absolute agreement can include; effluent plume configuration, loss of low-level ammonia from the environmental samples, weather and sea conditions, current amplitude, velocity and duration, and flux in effluent quality and quantity.

5.1 Summary of Calculations

August 16, 2005 Sampling Episode
Measured current = North 0.795 kts.

DMR DIN = 17.16 mg/l = 11.83 µg/l (as N) predicted enhancement
1.45
Predicted concentration = 11.83 µg/l + Bg (3.45 µg/l) = 15.25 µg/l
Found = 14.8 µg/l

Recovery (average of both depth intervals) = 97.0%
20 ft. depth interval = 24.2 µg/l = 159% recovery
**August 30, 2005 Sampling Episode**  
Measured current = North 0.829 kts.

DMR DIN = 19.55 mg/l = 13.48 µg/l (as N) predicted enhancement
1.45

Predicted concentration = 13.48 µg/l + Bg\(^{(1)}\) (3.05 µg/l) = 16.53 µg/l  
Found = 7.08 µg/l

Recovery (average of both depth intervals) = 42.8%  
45 ft. depth interval = 13.6 µg/l = 82.3% recovery

**September 13, 2005 Sampling Episode**  
Measured current = North 0.321 kts.

DMR DIN = 13.81 mg/l = 9.52 µg/l (as N) predicted enhancement
1.45

Predicted concentration = 9.52 /µg/l + Bg (3.20 µg/l) = 12.72 µg/l  
Found = 4.05 µg/l µg

Recovery (average of both depth intervals) = 31.8%  
45 ft. depth interval = 4.6 µg/l = 36.2% recovery

**October 11, 2005 Sampling Episode**  
Measured current = North 0.343 kts.

DMR DIN = 15.0 mg/l = 10.34 µg/l (as N) predicted enhancement
1.45

Predicted concentration = 10.34 µg/l + Bg M1\(^{(1)}\) A/B (3.85 µg/l) = 14.19 µg/l  
Predicted concentration = 10.34 µg/l + Bg 1 A/B (4.20 µg/l) = 14.54 µg/l

Found = 7.50 µg/l

Recovery (average of both depth intervals) = 52.9% (with M 1 A/B as background)  
Recovery (average of both depth intervals) = 51.6% (with 1 A/B as background)

(45 ft. depth interval = 9.10 µg/l = 64.1% recovery with M 1A/B as background)  
(45 ft. depth interval = 9.10 µg/l = 62.6% recovery with 1A/B as background)

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\(^{(1)}\) Bg = Background location. Following the first several rounds of current measurements additional background  
Station M1 was placed to be more inline with the northerly current axis flowing parallel to the coastline, than the  
more inshore Station 1 on Seagate Reef. As such, M1 was positioned to most accurately reflect background water  
quality entering the investigation area. See Figure 3 for sample collection station location and designation.
6.0 CONCLUSIONS

PBCRR water quality monitoring data demonstrate nutrient enrichment of the environment down current of the Delray outfall (Station 5) as evidenced by the increase in DIN values above those found at upcurrent background locations (Stations 1 and M1). The down current DIN enhancement was found only during north current sampling episodes. When current flow reversed to the south, DIN values at Station 5 returned to background levels, supporting the conclusion elevated DIN values found at Station 5 originate from current transport of effluent from the Delray outfall.

Effluent plume dynamics established by the NOAA farfield tracer study further serve to validate PBCRR findings by providing plume model calculations which can be used to estimate dilution and characteristics of an effluent plume in the coastal environment. The down current dimensional plume modeled from NOAA measurements suggest a Delray outfall plume width and configuration (Figure 3), nearly identical to the PBCRR theoretical plume representation, presented February 2004, which was developed based on Lyngbya delineation (Figure 5). Down current PBCRR DIN values are in agreement with DIN values predicted by SF$_6$ dilution at comparable distances from the source. PBCRR down current DIN concentrations, while present at the anticipated concentrations, did exhibit the variability within the water column as exemplified by NOAA measurements obtained in near proximity to the source.

The NOAA study found that effluent contact with the benthos and complete mixing across the entire water column does not occur in the immediate vicinity of the outfall terminus. The nearest vertical profile to the source measured by NOAA was obtained 13 km down current of the outfall where SF$_6$ concentrations confirmed mixing. However, it is reasonable to assume effluent enrichment of the benthos does occur at a point closer to the outfall than 13 km down current. The location of concentrated Lyngbya proliferation present 5 to 7 km down current of the Delray outfall has been used to argue that another nutrient source supporting the bloom must exist in closer proximity to the impacted zone than the outfall terminus. On the contrary, Lyngbya proliferation as observed in the down current zone is found where NOAA data suggest effluent mixing in the water column would likely begin to occur. This particularly holds true in the Boynton/Delray circumstance where along the axis of the theoretical effluent plume significant change in bathometric relief is found between the outfall (90 - 95 ft. below surface) and the down current Lyngbya proliferation zone, present at a depth of 45 - 55 feet below surface. This abrupt change in topography, not reported as a component in the Hollywood study, very likely contributes to vertical mixing of the effluent plume at a location coincident with the persistent Lyngbya growth.

Considering the number of potential variables, the ability to recover an average 85% of the anticipated DIN value in down current PBCRR environmental samples must be viewed as confirmation of the NOAA SF$_6$ effluent plume dilution model. The presence of elevated
nutrient concentrations down current of the Delray outfall, at levels predicted by NOAA
dilutions, leaves little doubt that nutrient enrichment found in the Lyngbya bloom zone on
Gulf Stream Reef originates from the SCRWWTDB effluent discharge.
APPENDIX A

Farfield Tracing of a Point Source Discharge Plume in the Coastal Ocean Using Sulfur Hexafluoride

(Reprinted from: ENVIRONMENTAL SCIENCE & TECHNOLOGY /VOL. 39, NO. 22, 2005)
Farfield Tracing of a Point Source Discharge Plume in the Coastal Ocean Using Sulfur Hexafluoride

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Pathways and dilution of a point source ocean discharge in the farfield (=10–66 km) were measured using the deliberate tracer sulfur hexafluoride (SF6). The injection of SF6 was performed by bubbling the gas over a period of 6 days into an ocean outfall pipe discharging into the southeast Florida coastal ocean. The surface SF6 concentrations show that the discharged water flowed northward parallel to the coast with a broadening of the width of the plume to about 3 km at the farthest point sampled, 66 km from the outfall. The discharge was fully mixed throughout the water column within 13 km of the outfall terminus. In the first 20 km from the outfall, SF6 surface concentrations were highly variable, while beyond this the SF6 concentrations decreased monotonically going northward. The currents were measured during the study with a bottom-mounted acoustic Doppler current profiler (ADCP) located 5.5 km from the outfall. Velocities were variable in magnitude and direction but showed a net northward flow during the 6-day study. Maximum concentrations decreased by about 200-fold per kilometer from the outfall to the northern end of the study area. The study shows that SF6 is an effective method to trace point source releases far from their origin.

Introduction

The Florida Area Coastal Environment (FACE) program is an effort of state and federal agencies and water utilities to study the sources of nutrients and pollutants appearing in the coastal ocean of southeast Florida. To achieve FACE goals, it is necessary to determine the relative contributions of potential terrestrial and oceanic sources to the nutrients and pollutants at given coastal ocean locations. Among the several natural and anthropogenic sources of nutrients are ocean outfalls. In southeast Florida coastal waters, outfall discharges occur using piping systems that extend 3–6 km into the coastal ocean. The discharges are believed to be rapidly diluted with surrounding water. However, no direct observations of flow paths and dilution in the farfield, defined as the region beyond 400 m of the outfall, have been obtained to date.

The coastal regime in which the outfall terminus is located is strongly influenced by the Florida Current. Several studies have shown that numerous current features present at the outfall site are unique to this environment (1, 2). The ambient current conditions during the present study appeared to be a combination of Florida Current-related flows, such as eddies, and wind-dominated flows. Variations in the location of the Florida Current are common and were observed during the southeast Florida ocean outfall experiments conducted from 1986 to 1993 (3). Periodically, the outfalls discharge shoreward of the Florida Current. This study was performed under these conditions.

Initial dilutions, defined as dilutions that occur during the vertical rise of the positively buoyant discharge, from the terminus of the outfall pipe to the surface equal to 20:1 or greater were determined during the Southeast Florida ocean outfalls experiment (SEFLOE II) (4). Dilutions of approximately 100:1 were measured at a distance of 800 m from the outfalls (5). Little is known about the farfield dilutions and pathways of discharges into the ocean. Direct tracing of the farfield discharge has not been possible to date. As stated in the SEFLOE II report, "measurements of farfield dilutions are the most difficult field measurements to obtain" (3).

The present effort pioneers the application of sulfur hexafluoride (SF6) for the determination of pathways and dilution at great distances from the source of discharge. By injection of SF6 into the source water, it can be a clear marker of this discharge in the coastal ocean and provide reliable and attributable dilution estimates in the farfield. These farfield dilution estimates are of interest because of uncertainties in regard to the potential effects of low levels of pollutants. SF6 is a good tracer to study point source releases as it has low background levels in the environment. It is nontoxic, stable, and measurable at low concentrations.

Fluorescent dyes, with their ease of injection, the ability to measure their concentrations in situ, high sampling frequency, reasonable short-term stability in natural water, and low toxicity at dilute concentrations, have been used extensively for this purpose and are approved by EPA protocols to quantify nearfield dilutions (6). For farfield studies, however, the limitations of dyes with respect to longterm stability and relatively high detection limits, which requires large dosages, become apparent (7). SF6 can augment fluorescent dyes for farfield studies. However, there are some limitations in its use. It is poorly soluble in water (8) which makes injection of quantifiable amounts of SF6 into the water difficult. The gas escapes from the water column at the air–water interface, ultimately limiting the extent and duration of surface water studies. Detection cannot be done in situ but, rather, the water must be brought onboard, and the gas must be extracted from the water sample onboard or at a shore-based laboratory prior to analysis.

The low detection limit of SF6 of less than 40 fm (1 fm = 10−15 mol L−1) using static headspace analysis or continuous gas strippers, and 2 orders of magnitude lower than this with trap and purge techniques (9), has made SF6 tracer studies possible over large space scales and long time scales. In the outfall study described here, the outfall water was traced 66
km north of the release site (Figure 1) by performing a continuous injection of SF6 over 6 days into the main discharge pipe. The continuous release was performed to create a quasi-stationary tracer field in the ocean. This type of release, along with successful detection of the tracer at 3 orders of magnitude above background concentrations 66 km from the source, makes this proof-of-concept study unique and clearly shows the potential utility of SF6 for following point-source releases in the aquatic environment.

This application adds to the utility of SF6 previously used as a tracer of gas exchange processes in the ocean (10–12) and lakes (13–15); as a surface water dispersion tracer (16–19); as a tag for surface water in Lagrangian studies (17–18); and to determine mixing in the deep ocean (20, 21).

The present study provides pathways and dilution estimates of the predominant northward motion of the discharge. The movement of a discharge plume in the coastal ocean of southeast Florida is complex. The Gulf Stream in this region is called the Florida Current and flows northward along the coast. The western (shoreward) edge of the Florida Current meanders such that on some occasions the outfall site is directly beneath it and at other times the outfall site is affected by western boundary eddies and secondary current systems (1, 5). Particularly during the latter situations there is significant variability in magnitude and direction of current flow. Although not conclusive, the sampling suggests that during the time of the field measurements the major discharge pathway was generally along the coast. This work provides unique new information on the farfield dilution of a discharge plume in proximity to the coast of southeast Florida.

Experimental Section

Injection. SF6 was injected into a 150-cm i.d. outfall pipe at a capped-off shunt. A 1/8-in. o.d. stainless steel tube with a small stainless steel diffuser at its end was snaked through the 10-cm i.d. shunt into the main outfall pipe, and SF6 was injected in gaseous form into the discharge stream at a rate of 0.5–1 L min\(^{-1}\) (STP). The dissolution process is inefficient because SF6 is an insoluble gas with a solubility coefficient of 2.5 \(	ext{mol SF6 L}^{-1} \text{water (at 25 °C)}\). We expect that a portion of the SF6 was dissolved during the injection process while the remainder of the gas was swept along above the flow and concentrated in various air pockets in the pipe. Some of the excess SF6 gas was possibly released through static air release valves beyond the location where the SF6 was injected.

The length of the pipe from the SF6 injection point to outfall is about 3.5 km. The outfall is located about 3.2 km offshore at a water depth of about 27 m (4). The outfall terminus is located about 1 m from the bottom and has a single release point without dispersers. The injection of SF6 began on June 4, 2004 (10 a.m. EDT) and ended on June 9, 2004 (3 p.m. EDT). The daily freshwater flow in the outfall ranged from 95 \(\times 10^6\) to 190 \(\times 10^6\) L day\(^{-1}\) with low flows in the early morning and maxima in the early evening. Under these conditions, the transit time of effluent in the pipe was 50–100 minutes before reaching the outfall terminus.

The SF6 gas injection into the discharge was monitored with a ball flow meter. Quantitative SF6 injection estimates were obtained from the change in weight of the liquefied SF6 in the gas tanks over time. Two 17-L tanks that each contained about 18 kg of SF6 were used. The first tank was used from June 4–6, 2004 with an average flow of 0.9 L min\(^{-1}\). The flow was higher than planned due to a bias in the ball flow meter probably caused by backpressure in the injection line and diffuser. The first tank was replaced by a second tank 18 h before the survey, resulting in a 3-minute interruption in flow. The SF6 flow from the second tank was decreased to 0.5 L min\(^{-1}\). During the June 7–9, 2004 survey period, the SF6 flow was steady at the lower rate. SF6 concentrations were not monitored in the pipe or right at the outfall, as the concentrations were too high to measure with the available analytical equipment without jeopardizing the lower concentration measurements in the farfield.

Sampling. The sampling survey of the coastal ocean waters began on June 7, 2004 at 11 a.m. EDT and ended on June 9, 2004 at 11 a.m. EDT. Sampling was performed in a continuous mode using a towed “fish” containing a Seabird MicroCat.
CT (conductivity—temperature) sensor and a submersible water pump. The submersible pump pushed water into a second pump on the deck of the 24-m-long research ship R/V Coral Reef II to provide sufficient inlet pressure for the permeable membrane extractor (PME) used to extract the SF<sub>6</sub><sup>aq</sup> from the water. About half of the water was diverted and drained before reaching the PME to decrease the residence time of water in the tubing. The internal volume of the 40-m-long 1.25-cm o.d. nylon tubing was about 5 L, and the flow through the PME averaged 2.1 L min<sup>-1</sup>. During survey operations, the “fish” was towed at approximately 2-m depth over the starboard side of the ship. Ship speed during surveying was about 3 knots. The survey track shown in Figure 1 started near the outfall. After an irregular course within 17 km of the outfall terminus, the track proceeded in a systematic zigzag pattern northward, crossing the eastern (seaward) boundary of the tracer patch before returning shoreward. The distance between sample points was about 250 m based on a sample throughput of 20 samples per hour at the survey speed of 3 knots.

On three occasions the ship dropped anchor and the tow fish was lowered to the bottom to obtain vertical profiles of SF<sub>6</sub><sup>aq</sup> in the water column. The water depths at the stations were 12, 20, and 20 m at a range of 13 km, 17 km, and 66 km, respectively. The vertical sampling was performed by lowering the “fish” to mid-depth and then to the bottom. After remaining at the bottom for 0.5 h or more, it was raised to mid-depth and back to the surface. The mid-depth location was sampled for at least 15 min at the 13- and 17-km sites to ensure full flushing of the lines.

**Analysis.** SF<sub>6</sub><sup>aq</sup> was analyzed by extracting it from seawater with a stream of nitrogen using a PME cartridge (Celgard LiquiCel). The SF<sub>6</sub><sup>aq</sup> in the nitrogen stream was then analyzed with a gas chromatograph equipped with an electron capture detector (ECD). The analytical instrumentation and procedures are described in Wanninkhof et al. (9), and the application of a LiquiCel for SF<sub>6</sub><sup>aq</sup> analyses is detailed in Ho et al. (19) and Caplow et al. (16). In short, water pumped from the towed “fish” was first passed through a 40-μm filter and then through the PME. The PME consisted of a bundle of gas permeable microtubes (lumen). SF<sub>6</sub><sup>aq</sup> in the water stream diffused through the walls of these tubes into a nitrogen stream that was diverted to a 1.5-mL sample loop. The loop was injected into a gas chromatograph at 3-minute intervals, after which the gases were swept onto a 1.5-m, 1/8-in. o.d. molecular sieve 5A column. The SF<sub>6</sub><sup>aq</sup> was separated on the column from oxygen and other gases and measured with the ECD.

A linear calibration of the detector response was performed with two SF<sub>6</sub> standards with concentrations of 55.1 parts per trillion by volume (pptv) and 1109 pptv using the gas sample loop. Thirty of each standard were analyzed during the survey with standard deviation of the SF<sub>6</sub> standards being less than 1%, indicating that the ECD response was stable during the study. The gas transfer efficiency of the PME was quantified on the first day of the survey by sampling aliquots of water before and after the LiquiCel and analyzing their SF<sub>6</sub> content. The efficiency of extraction was calculated to be 50%, and results were corrected by this factor. Pump failure prevented a redetermination of the efficiency at the end of the study, but previous work has shown minimal changes (<5%) in extraction efficiency over several days (22).

The range of SF<sub>6</sub><sup>aq</sup> encountered during the June 7–9 survey was 13 fm to about 90 fm (1 pm = 10<sup>-12</sup> mol L<sup>-1</sup>). The aqueous SF<sub>6</sub><sup>aq</sup> concentrations, SF<sub>6</sub><sup>aq</sup> below 8 pm were precise to within 5%. The precision of the SF<sub>6</sub><sup>aq</sup> measurements between 8 and 24 pm determined with the automated system was believed to be within 30%. The greater uncertainty was caused by a lack of calibration gases in this range. The response of the detector was off-scale for SF<sub>6</sub><sup>aq</sup> greater than 25 pm using the PME, and none of the SF<sub>6</sub><sup>aq</sup> measurements made with the PME greater than 25 pm were used in the calculations. All of the observations beyond 27 km from the outfall were below 8 pm. Concentrations up to 550 pm were measured in spot samples near the outfall terminus on June 6, the day before the survey began (Figure 2). These samples were diluted with SF<sub>6</sub>-free water to bring the concentration into range of the standards. They were measured by headspace analysis in a glass syringe. The precision of these samples, accounting for uncertainty in dilutions, was within 10%.

**Currents.** Two sources of current information were available for this study. An acoustic Doppler current profiler (ADCP) mounted in 11-m water depth at the South Florida Ocean Measurement Center (SFOMC) at Dania Beach, FL (26.075°N, 80.094°W), 1.6 km offshore and 5.5 km from the outfall terminus, provided a continuous record of near-shore currents near the bottom, at mid-depth, and near the surface shoreward of the release site. Current and temperature measurements were also obtained from dropsondes at 27°N, 79.93°W, about 12 km from the coast and 30 km beyond the northernmost point of the survey area, on June 7 and June 9, 2004.

**Results**

The continuous injection of SF<sub>6</sub> into the outfall pipe was performed to facilitate tracking of the farfield SF<sub>6</sub> levels by creating an environment of elevated SF<sub>6</sub><sup>aq</sup> concentrations along the flow path of the plume. A few spot samples were taken near the outfall on June 6, the day before the survey began, with the locations of the sampling shown in Figure 2. The maximum observed concentration near the outfall was 550 pm a day after the injection commenced. The survey tracks close to the outfall are shown in Figure 3 with concentration levels coded by different symbols. The measurements within the first 20 km of the outfall showed large variability in concentrations on a sub-kilometer scale and a poorly defined tracer field. The variable concentrations near the outfall terminus shown in Figures 2 and 3 suggest predominantly advective transport after the initial dilutions and variability in discharge concentration. The tracer appears to advect from the outfall in filaments and/or as boluses but full determination of pathways of the discharge immediately after nearfield dilution requires further study.

The tracer field between 27 and 66 km from the outfall terminus is more coherent. The concentrations increased systematically going shoreward, and the highest concentra-
Concentrations were measured near shore (Figure 1), sometimes increasing to the point that the ship turned seaward to avoid shallow depths and other navigation hazards. Concentrations decreased northward. SF$_6$ concentrations along the entire cruise track are provided in Figure 1 using a color-coding scheme for different concentration ranges.

One objective of the study was to determine at what point the discharge was mixed vertically in the water column and reached the bottom to assess its possible effect on the benthos. Since the outfall discharge is positively buoyant, it will rise to the surface at the terminus and form a seawater–effluent surface layer about one-third of the water depth ($\frac{1}{3}$). It is transported as a near surface plume until the density contrast is eroded by dilution with surrounding water. Three depth profiles of SF$_6$ measured nominally at 13, 17, and 66 km from the terminus in the projected centerline of the plume were taken to determine the vertical distribution of the tracer plume. High levels of SF$_6$ were observed to the bottom at each location sampled, indicating that vertical mixing of the discharged waters with surrounding waters occurred within 13 km of the outfall (Figure 4).

During sampling at the 17-km location, a 4-fold concentration increase was observed while the intake was at mid-depth. The surface samples showed an 8-fold increase when the “fish” was raised back to the surface as compared to the start of the depth sampling. This is another indication of significant meandering of the tagged water with time. Alternatively, this could be caused by the pulsating nature of the discharge and transport in boluses. The study of the actual causes of variability and characterization of the buoyant spreading and vertical diffusion of the plume close to the outfall were beyond the scope of the study.

A contour plot of surface water SF$_6$ concentrations is shown in Figure 5. A kriging interpolation scheme with a 5:1 aspect ratio in search radius oriented to the north was used. These plots clearly show the narrow swath where SF$_6$ was detected. The slight oscillating pattern at the offshore boundary was caused by a memory effect of the sampling equipment. When the ship left the patch, SF$_6$ concentrations decreased more slowly than when the ship re-entered the patch. This condition was likely caused by a combination of incomplete flushing of the tubing and SF$_6$ adsorption/desorption processes in the tubing and instrumentation.

Cross-sectional surface concentration profiles plotted versus longitude are shown in Figure 6 for the shore-bound legs. The outbound transects (not shown) show higher concentrations and more gradual decreases offshore due to memory effects of the sampling equipment. The inbound transects were used to estimate the total mass of SF$_6$ transported along the coast.

The near-shore ADCP current record, obtained from the bottom-mounted ADCP, is shown in Figure 7. In general, there is alongshore northward flow during the injection punctuated by an occasional southward reversal. The record provides a qualitative explanation of the observed variability in tracer concentration near the outfall. At the start of the injection, flow was predominantly northward but with variability of a factor of 4 in flow over the first day. Such variability was observed throughout the study with reversals from northward to southward flow occurring on a frequency of 1–2 days. The east–west component of the record showed an average westward (= shoreward) flow but with rapid changes in magnitude and direction. The pattern is caused by a complex interplay of tidal motions, wind drift, and interactions of the near-shore boundary currents with the Florida Current (1). In particular, some of the translations can be attributed to eddies passing through the study area. The combination of the variable discharge and the near-shore current variability are the likely causes of the observed

---

**FIGURE 3.** Concentrations of SF$_6$ in the region near the outfall measured at the start of the survey. Concentration ranges (in pM and fM) are marked with different symbols as indicated in the legend. The grid boxes are approximately 2 km $\times$ 2.2 km.

**FIGURE 4.** SF$_6$ concentrations (in pM) at the surface, mid-depth, and bottom measured at 13, 17, and 66 km from the outfall. Every point is an average of at least three samples with error bars indicated. When no error bar is apparent, the standard deviation is less than the size of the symbol. At the 17-km sampling site, a large concentration increase was observed at mid-depth and the surface while sampling during the upcast.
concentration variability within the first 20-km from the outfall. On longer time and space scales the current fluctuations facilitate mixing of the plume.

The currents were also variable during the survey with a strong flow reversal to southward flow during the first day of the survey and smaller reversals thereafter. The average flow from the ADCP record at 1.5 km from shore was about 20 cm s\(^{-1}\). The flow offshore was higher with dropsonde profiles 12-km from shore showing currents of 80 cm s\(^{-1}\) for the mean water column and 200 cm s\(^{-1}\) at the surface. While there was significant variability in vertical flow as determined from the 16 vertical bins of the ADCP, there was no systematic shear in the water column over time. The standard deviation of the flow in the 16 depth bins is on the same order of magnitude as the mean flow in the water column. Despite considerable variation in horizontal and vertical flow, the \(\text{SF}_6\) concentrations observed beyond 27 km from the terminus vary systematically. This suggests that far away from the outfall the current variability can be considered a stochastic mixing mechanism that homogenizes the tracer field.

For the water column \(\text{SF}_6\) integrals, the cross sectional areas perpendicular to the coast were determined along with the \(\text{SF}_6\) concentrations along the transect. The surveys stopped about 0.5–0.8 km from the beach, and the concentration data were extrapolated to the shoreline assuming the same concentration as the last measured point. This assumption is based on the flattening of the cross sectional profiles for most of the transects (Figure 6). It was assumed that \(\text{SF}_6\) concentrations were homogeneous to the bottom, or to the bottom of the mixed layer at 25 m, whichever was shallower. Gridded bottom topography and shoreline data were obtained from NOAA’s National Geophysical Data Center. The estimated mass flow of \(\text{SF}_6\) for each transect is given in Table 1. The cross sectional \(\text{SF}_6\) mass integrals at four positions gave similar values ranging from 4.4 to 5.1 mol day\(^{-1}\). The cause of the smaller integral of 2.8 mol day\(^{-1}\) for section D is unclear. The similarity of mass flow for the other transects suggest that no significant \(\text{SF}_6\) losses occurred by advective features such as eddies or jets along the flow path.

Since \(\text{SF}_6\) is a gas, it escapes into the atmosphere through the air-sea gas transfer. A rough estimate of the loss of \(\text{SF}_6\) was obtained using an average current speed of 50 cm s\(^{-1}\), a mixed layer depth of 25 m, and a wind speed of 6 m s\(^{-1}\) based on wind speed records from NOAA’s National Data
Buoy Center weather station LKWF1 located on an ocean pier in the town of Lake Worth, FL, just north of our study area. A quadratic relationship between the gas transfer and wind speed, \( k = 0.31 U^2 (Sc/660)^{-1/2} \), was used to estimate the gas loss, where \( U \) is the wind speed and \( Sc \) is the Schmidt number of \( SF_6 \) of 650 at 28 °C.(23). The \( SF_6 \) concentrations would be expected to decrease by about 2.5% per 10 km due to gas exchange based on this parametrization or about 16% from the outfall terminus to the end of the observation area 66 km to the north. Using lower/higher current speeds or shallower/deeper mixed layer depths would make the \( SF_6 \) loss over distance due to air–sea gas exchange proportionally greater/less.

**Discussion**

Due to the exploratory nature of this study, not all relevant physical parameters were measured to fully characterize the discharge plume. The results are, therefore, semiquantitative at best. Nonetheless, the work provides important information of the flow path and farfield dilution of a point source discharge. While the discussion is cast in a framework of a quasi-steady-state tracer field, based on the systematic decrease of the \( SF_6 \) concentrations north of 27 km from the release point, the flow reversals in Figure 7 are indicative of near-shore eddies and other modes of flow variability. A possible scenario for the observed uniformity of concentrations is that the survey proceeded in the same direction as the flow at about one-third the speed as the inferred flow. Therefore it is possible that, for instance, a northward-translating eddy containing \( SF_6 \) was sampled over and over again, rather than that the tracer field was homogeneous. While this alternative would cast our results in a different light, the pathway of transport and dilution estimates are valid under either scenario.

The discharge plume rises to the ocean surface upon exiting the outfall pipe terminus at 26-m depth and occupies the upper few meters of the oceanic water column (3). Data shown in Figures 2 and 3 suggest that the discharge plume material was transported in a meandering but generally northerly direction from the outfall site. Samples were not gathered south of the outfall, nor were transects made in a direction perpendicular to the northerly plume sampling track for the first 6 km. No vertical casts were made near the outfall because of the high and variable concentrations encountered making sampling problematic.

Tracks with east–west lengths of approximately 7 km were carried out at the general latitude of Port Everglades Inlet (26.092°N). Peak \( SF_6 \) concentrations were observed approxi-

### Figure 6

**Figure 6.** Surface \( SF_6 \) concentrations (in pM) for the shorebound legs of the survey. The locations of these transects are shown in Figure 1.

### Figure 7

**Figure 7.** ADCP velocity records at about 4.5-m depth from the South Florida Ocean Measurement Center (SFOMC) located at the 11-m isobath 5.5 km north of the outfall (26.07°N, 80.09°W): (a) v-component (north–south); (b) u-component (east–west). The first part of the record (JD 156–158) shows 6-minute averages taken each hour; the second part shows hourly averages. Velocities are in \( \text{mm s}^{-1} \). The start of the injection and survey period are marked.
studies have heretofore not been conducted in southeast Florida coastal ocean waters, mixing effects for discharge plumes, not previously recognized, may have been observed. On the basis of previous studies, the environmental conditions encountered during this study with northward coastal flow and southeasterly winds prevail about 40% of the time (3).

North of Port Everglades Inlet, the tracer field followed the coast. Peak concentrations were observed near the coast with a gradual decrease northward. The width of the tracer field generally increased with distance from the release point. Using the distance between peak concentration and a concentration of $e^{-1}$ (= 37%) of peak levels as the characteristic width of the tracer streak, the width increases from 1.0 to 2.3 km between 29 and 61 km from the outfall. As shown in Table 1, the widths at intermediate points vary from 0.9 to 1.5 km in a nonsystematic fashion, suggesting undulations in the currents and/or variability in the tracer field. The shapes of the surface concentration curves for the five shoreward transects in Figure 6 show the general broadening and corresponding decrease in peak concentration with increasing distance.

**Injection Efficiency and Dilutions.** The injection efficiency of SF$_6$ into the outfall pipe was estimated by using the SF$_6$ mass flow along the coast (Table 1) and SF$_6$ injection rate into the pipe. The SF$_6$ injection rate into the outfall pipe in the latter part of the study of 0.5 L min$^{-1}$ yields 29 mol of gaseous SF$_6$ bubbled into the discharge per day. For cross section B (Figure 1), the SF$_6$ area integral and flow of 50 cm s$^{-1}$ translated into a mass flow of SF$_6$ through the section of about 4.4 mol SF$_6$ per day. This translates into an injection efficiency of 15%. There is a large and unquantifiable uncertainty associated with this estimate because of variations in coastal water flow. The injection efficiency is within the range of efficiencies for gaseous SF$_6$ injections in lake studies (14, 24).

Figure 8 gives the estimated minimum dilutions at increasing distance from the outfall. The estimates are based on the maximum concentrations encountered during the surveys. The estimates also assume SF$_6$ injection of 0.5 L min$^{-1}$ with an efficiency of 15% into an average discharge flow of $140 \times 10^6$ L day$^{-1}$. This yields a calculated SF$_6$ concentration at the outfall terminus of $3.1 \times 10^{-4}$ mol L$^{-1}$. The highest concentration measured in the ocean corresponds to a 60-fold dilution compared to the calculated value at the terminus, and concentrations decreased in a systematic pattern to a dilution of 14 000 at 66 km from the outfall. The absolute dilution values depend on the assumptions about the SF$_6$ concentrations at the outfall terminus, but the relative dilutions in the coastal waters are observation-based. The dilution can be well approximated as a linear trend with distance (Figure 8). Excluding the low dilutions at 13–14 km that coincidentally were encountered twice on surveys almost a day apart, the relation forced through zero at the outfall terminus yields:

$$\text{Dilution} = 212 \times \text{distance} \quad r^2 = 0.98 \quad (1)$$

where distance is in kilometers. The uncertainty in the slope of the linear regression is ±6 (≈3%). Including all points and not forcing the relationship through zero at the outfall increases the slope to 230 and the uncertainty in the slope to ±11 (≈5%). The good fit to this relationship (Figure 8) suggests that the dilution occurs in a systematic fashion and can be well represented by a strong linear decrease with distance. Equation 1 will, of course, only be applicable for the conditions encountered but illustrates the rapid dilution with distance from the source.

The dilution equation determined in this study is in accord with SEFLOE II data (3) near the terminus that suggest that at a distance of 0.8 km from the outfall a dilution on the order of 100:1 is attained while eq 1 would suggest a dilution of 160:1. More importantly, this study indicates that dilution mechanisms, while complex, result in a linear decrease in SF$_6$ concentrations over the entire reach of the study, suggesting continued rapid dispersion of the discharge.

While the feasibility study fulfilled its objectives of tracing the discharge plume in the farfield, it lacked supporting measurements for full quantification of the observations. Future studies would benefit from better quantification of the amount of tracer injected into the effluent and denser spatial and temporal sampling. Continuous monitoring of SF$_6$ concentrations at the terminus would be desirable to determine the variability of the input levels. Ideally, an injection procedure could be devised that assured constant levels of tracer into the discharge. Continuous observations throughout the study region starting before and ending after the injection would help to estimate the flushing rate. This would be particularly useful for estimating the effect of catastrophic releases of undesirable compounds.

### TABLE 1. Cross Sectional Area Integral for SF$_6$ Cross-Sections and Width of Tracer Streak

<table>
<thead>
<tr>
<th>transect$^a$</th>
<th>distance from outfall$^b$ (km)</th>
<th>farthest sample from shore$^c$ (km)</th>
<th>nearest sample to shore$^d$ (km)</th>
<th>SF$_6$ integral$^e$ (mol day$^{-1}$)</th>
<th>width streak$^f$ (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>29</td>
<td>4.1</td>
<td>0.7</td>
<td>4.9</td>
<td>1.0</td>
</tr>
<tr>
<td>B</td>
<td>35</td>
<td>4.2</td>
<td>0.8</td>
<td>4.4</td>
<td>1.5</td>
</tr>
<tr>
<td>C</td>
<td>43</td>
<td>4.9</td>
<td>0.6</td>
<td>5.0</td>
<td>0.9</td>
</tr>
<tr>
<td>D</td>
<td>51</td>
<td>3.3</td>
<td>0.5</td>
<td>2.8</td>
<td>1.3</td>
</tr>
<tr>
<td>E</td>
<td>61</td>
<td>4.9</td>
<td>1.3</td>
<td>5.1</td>
<td>2.3</td>
</tr>
</tbody>
</table>

$^a$ Inbound legs of the survey from south to north with letters referring to the transects shown in Figure 1. $^b$ Distance of transect from the outfall. $^c$ Distance from the coast to where the outer edge of the tracer patch was encountered. $^d$ Nearest sample taken to the coast is assumed that the concentration is constant from this point to the beach for calculation of the SF$_6$ inventory. $^e$ Cross sectional integration for the transect using the SF$_6$ concentrations measured (Figure 6) along the transect and using a bathymetry from www.ngdc.noaa.gov/mgg/bathymetry.relief.html. An average current velocity of 50 cm s$^{-1}$ is used for these calculations. $^f$ Distance from peak concentrations to $e^{-1}$ (37%) peak concentration.

![FIGURE8. Dilution estimates based on maximum SF$_6$ concentrations measured at different distances downstream from the outfall. The line is a best-fit linear relationship forced through the origin excluding the points at 13 km.](image-url)
current information would be desirable as well from a combination of fixed observations in the study region and from deployment of drifters. This study has provided important groundwork and background information to successfully execute a more quantitative study of the fate of a multitude of continuous point source discharge releases in the coastal environment of southeast Florida.

Acknowledgments

This study was performed under the auspices of the Florida Area Coastal Environment (FACE) program. The support of the captain and crew of the R/V Coral Reef II was indispensable in the execution of the program. Dr. Molly Baringer of NOAA/AOML provided offshore current and temperature data. The ADCP data set is the legacy of the NSU/USF SFOMC project. Dan Metzger of the NOAA Geophysical Data Center assisted in retrieving the coastal bathymetry. Gail Derr of NOAA/AOML provided offshore current and temperature data. The ADCP data set is the legacy of the NSU/USF SFOMC project. Dan Metzger of the NOAA Geophysical Data Center assisted in retrieving the coastal bathymetry. Gail Derr of NOAA/AOML provided editorial assistance. The help of the thorough and helpful reviews of two anonymous reviewers are gratefully acknowledged. This research was assisted in retrieving the coastal bathymetry. Gail Derr of NOAA/AOML provided editorial assistance. The help of the thorough and helpful reviews of two anonymous reviewers are gratefully acknowledged. This research was carried out in part under the auspices of the Cooperative Institute for Marine and Atmospheric Studies (CIMAS), a Joint Institute of the University of Miami and the National Oceanic and Atmospheric Administration, cooperative agreement NA17RR1226.

Literature Cited


Received for review November 29, 2004. Revised manuscript received August 24, 2005. Accepted August 25, 2005.

ES048126+
APPENDIX B

Comparison of Current Direction with Dissolved Inorganic Nitrogen Enhancement Station 1 versus Station 5.
Comparison of Current Direction with DIN Enhancement
Station 1 versus Station 5

<table>
<thead>
<tr>
<th>North Current</th>
<th>South Current</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>August 16, 2005</strong></td>
<td><strong>August 23, 2005</strong></td>
</tr>
<tr>
<td>Current = North 0.795 kts.</td>
<td>Current = South 0.483 kts.</td>
</tr>
<tr>
<td>5 A/B DIN average = 14.8 µg/l (1)</td>
<td>5 A/B DIN average = 2.65 µg/l</td>
</tr>
<tr>
<td>1 A/B DIN average = 3.45 µg/l</td>
<td>1 A/B DIN average = 2.60 µg/l</td>
</tr>
<tr>
<td>5 A/B : 1 A/B ratio = 4.29 : 1.00</td>
<td>5 A/B : 1 A/B ratio = 1.02 : 1.00</td>
</tr>
</tbody>
</table>

| **August 30, 2005** | **September 27, 2005** |
| Current = North 0.829 kts. | Current = South 0.355 kts. |
| 5 A/B DIN average = 7.80 µg/l | 5 A/B DIN average = 4.45 µg/l |
| 1 A/B DIN average = 3.05 µg/l | 1 A/B DIN average = 4.42 µg/l |
| 5 A/B : 1 A/B ratio = 2.23 : 1.00 | 5 A/B : 1 A/B ratio = 1.01 : 1.00 |

| **September 13, 2005** | **November 8, 2005 (2)** |
| Current = North 0.321 kts. | Current = South 0.511 kts. |
| 5 A/B DIN average = 4.05 µg/l | 5 A/B DIN average = 9.95 µg/l |
| 1 A/B DIN average = 3.20 µg/l | 1 A/B DIN average = 14.9 µg/l |
| 5 A/B : 1 A/B ratio = 1.27 : 1.00 | 5 A/B : 1 A/B ratio = 0.67 : 1.00 |

| **October 11, 2005** |  |
| Current = North 0.343 kts. |  |
| 5 A/B DIN average = 7.50 µg/l |  |
| 1 A/B DIN average = 4.20 µg/l |  |
| 5 A/B : 1 A/B ratio = 1.79 : 1.00 |  |

| **North Sampling Episode Average** | **South Sampling Episode Average** |
| 5 A/B DIN average = 8.54 µg/l | 5 A/B DIN average = 3.55 µg/l |
| 1 A/B DIN average = 3.48 µg/l | 1 A/B DIN average = 3.51 µg/l |
| 5 A/B : 1 A/B ratio = 2.45 : 1.00 | 5 A/B : 1 A/B ratio = 1.01 : 1.00 |

Average background @ 1 A/B = 3.48 µg/l Average background @ 5 A/B = 3.55 µg/l

---

1) All DIN concentration values expressed as µg/l N.
2) Anomalous post-hurricane conditions. Samples collected shortly after the passage of Hurricane Wilma are presented, but not considered as representative of reef stasis and not included in final averages.
3) See Figure 3 for sample collection station locations.
Comparison of Averaged DIN Concentrations
Stations 1 and 5
North versus South Current Events
(August 16 through October 11, 2005)

<table>
<thead>
<tr>
<th></th>
<th>North Sampling Episode Average</th>
<th>South Sampling Episode Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 A/B DIN average = 8.54 µg/l</td>
<td>5 A/B DIN average = 3.55 µg/l</td>
</tr>
<tr>
<td></td>
<td>1 A/B DIN average = 3.48 µg/l</td>
<td>1 A/B DIN average = 3.51 µg/l</td>
</tr>
<tr>
<td></td>
<td>5 A/B : 1 A/B ratio = 2.45 : 1.00</td>
<td>5 A/B : 1 A/B ratio = 1.01 : 1.00</td>
</tr>
</tbody>
</table>

Average background @ 1 A/B = 3.48 µg/l  
Average background @ 5 A/B = 3.55 µg/l

Notes:
Background location defined as station farthest up current from outfall terminus.
Depth interval designation, A = 20 ft., B = 45 ft. below surface.
See Figure 3 for station designation and location.
APPENDIX C

Examination of Delray Outfall Down Current
Dissolved Inorganic Nitrogen Enhancement
Examination of Delray Outfall Down Current DIN Enhancement

**Distance from outfall to Station 5 = 6.839 kilometers**

**Equation 1 (NOAA):**
\[
\text{Dilution} = 212 \times \text{distance (km)}
\]
\[
212 \times 6.839 \text{ (km)} = 1450
\]

**Equation 2:**
\[
\frac{\text{mg/l (as N)}}{1000} = \text{predicted enhancement (as µg/l N)} + \text{background (as µg/l N)} = \text{predicted DIN concentration}
\]
\[
1450
\]

**Equation 3:**
\[
\frac{\text{DIN concentration found}}{100} = \% \text{ recovery}
\]

Dissolved Inorganic Nitrogen (DIN) = the sum total of Ammonia and Nitrite/Nitrate.
Background (Bg) obtained at Station 1 = the arithmetic average of the 20 & 45 depth intervals, unless otherwise noted.

---

**August 16, 2005 Sampling Episode**

DMR DIN = 17.16 mg/l = 11.83 µg/l (as N) predicted enhancement
\[
\frac{11.83}{1.45}
\]
Predicted concentration = 11.83 µg/l + Bg (3.45 µg/l) = 15.25 µg/l
Found = 14.8 µg/l
Recovery = 97.0%

(20 ft. depth interval = 24.2 µg/l = 159% recovery)

Current = North 0.795 kts. @ 345°

---

**August 16, 2005 - WWTP DMR, Part B Results**

<table>
<thead>
<tr>
<th>Flow</th>
<th>TKN</th>
<th>Ammonia</th>
<th>Nitrite/Nitrate</th>
<th>DIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.84 MGD</td>
<td>1,452 lbs./day</td>
<td>1,187 lbs./day</td>
<td>78.1 lbs./day</td>
<td>1,265 lbs./day</td>
</tr>
<tr>
<td>(all values expressed as N, except for flow)</td>
<td>16.1 mg/l</td>
<td>1.06 mg/l</td>
<td>17.16 mg/l</td>
<td></td>
</tr>
</tbody>
</table>
Examination of Delray Outfall
Down Current DIN Enhancement

**August 30, 2005 Sampling Episode**

DMR DIN = 19.55 mg/l = 13.48 µg/l (as N) predicted enhancement

1.45

Predicted concentration = 13.48 µg/l + Bg (3.05 µg/l) = 16.53 µg/l

Found = 7.08 µg/l

Recovery = 42.8%

(45 ft. depth interval = 13.6 µg/l = 82.3% recovery)

**August 30, 2005 - WWTP DMR, Part B Results**

<table>
<thead>
<tr>
<th>Flow</th>
<th>TKN</th>
<th>Ammonia</th>
<th>Nitrite/Nitrate</th>
<th>DIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.67 MGD</td>
<td>1,771 lbs./day</td>
<td>1,620 lbs./day</td>
<td>120 lbs./day</td>
<td>1,740 lbs./day</td>
</tr>
<tr>
<td>(all values expressed as N, except for flow)</td>
<td>18.2 mg/l</td>
<td>1.35 mg/l</td>
<td>19.55 mg/l</td>
<td></td>
</tr>
</tbody>
</table>

Current = North 0.829 kts. @ 002°
Examination of Delray Outfall
Down Current DIN Enhancement

September 13, 2005 Sampling Episode

DMR DIN = \(13.81 \text{ mg/l} \div 1.45\) = 9.52 \(\mu\text{g/l}\) (as N) predicted enhancement

Predicted concentration = 9.52 \(\mu\text{g/l}\) + Bg (3.20 \(\mu\text{g/l}\)) = 12.72 \(\mu\text{g/l}\)

Found = 4.05 \(\mu\text{g/l}\)

Recovery = 31.8%

(45 ft. depth interval = 4.6 \(\mu\text{g/l} = 36.2\%\) recovery)

Current = North 0.321 kts. @ 027°

<table>
<thead>
<tr>
<th>September 13, 2005 - WWTP DMR, Part B Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
</tr>
<tr>
<td>10.43 MGD</td>
</tr>
<tr>
<td>(all values expressed as N, except for flow)</td>
</tr>
</tbody>
</table>

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Examination of Delray Outfall
Down Current DIN Enhancement

October 11, 2005 Sampling Episode

DMR DIN = 15.0 mg/l = 10.34 µg/l (as N) predicted enhancement

\[ \text{Predicted concentration} = 10.34 \mu g/l + \text{Bg M1 A/B (3.85 µg/l)} = 14.19 \mu g/l \]

\[ \text{Predicted concentration} = 10.34 \mu g/l + \text{Bg 1 A/B (4.20 µg/l)} = 14.54 \mu g/l \]

Found = 7.50 µg/l

Recovery = 52.9% (with M 1 A/B as background)
Recovery = 51.6% (with 1 A/B as background)

(45 ft. depth interval = 9.10 µg/l = 64.1% recovery with M 1A/B as background)
(45 ft. depth interval = 9.10 µg/l = 62.6% recovery with 1A/B as background)

Current = North 0.343 kts. @ 348°

October 11, 2005 WWTP DMR, Part B Results

<table>
<thead>
<tr>
<th>Flow</th>
<th>TKN</th>
<th>Ammonia</th>
<th>Nitrite/Nitrate</th>
<th>DIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.62 MGD</td>
<td>1,915 lbs./day</td>
<td>1,550 lbs./day</td>
<td>404 lbs./day</td>
<td>1,954 lbs./day</td>
</tr>
</tbody>
</table>

(all values expressed as N, except for flow)

<table>
<thead>
<tr>
<th>ND</th>
<th>1.9</th>
<th>5.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia (as N), Ortho-phosphate (as P), Nitrite/Nitrate (as N)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ND = not detected, below method detection limit of 3.0 µg/l as N for Ammonia.
Analytical results expressed as µg/l, unless otherwise stated.
The NOAA SF₆ tracer study suggests the effluent advects from the outfall in filaments and/or as boluses until down current equilibrium is achieved.
Effluent plume model based on 2004 NOAA Farfield Tracer Study, width versus distance measurements. Plume width at Station 5 predicted to be 250 meters wide.

Note: Station 2 is the location of the outfall surface boil.

Figure 3
Source: PBCRR
Graph derived from Appendix A, Table I data presentation.

Figure 4
Data source: NOAA