REPORT FOR THE NITRATE APPLICATION FIELD TRIAL IN THE HYPOLIMNION OF ONONDAGA LAKE (SEDIMENT MANAGEMENT UNIT 8)

Prepared For:

Honeywell

301 Plainfield Road, Suite 330
Syracuse, NY 13212

Prepared By:

PARSONS

301 Plainfield Road, Suite 350
Syracuse, New York 13212

and

UPSTATE
FRESHWATER
INSTITUTE
P.O. Box 506
Syracuse, New York 13214

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LIST OF ACRONYMS

ADV	Acoustic Doppler Velocimeter
CN-8	Calcium nitrate solution applied during the field trial
gpm	Gallons per minute
GPS	Global Positioning System
ISUS	*in situ* ultraviolet spectrophotometry
Metro	Metropolitan Wastewater Treatment Plan
NYSDEC	New York State Department of Environmental Conservation
RDWP	Remedial Design Work Plan
ROD	Record of Decision
SMU	Sediment Management Unit
SOP	Standard Operating Procedure
SOW	Statement of Work
SU	Syracuse University
UFI	Upstate Freshwater Institute (based in Syracuse, NY)
USEPA	United States Environmental Protection Agency
YSI	Yellow Springs Instruments

GLOSSARY OF TERMS

Deep Water Zone – The portion of a water body where water depths are greater than the depth to which sunlight penetration can support aquatic plants, in contrast with the zone of the lake closer to shore. Sediment Management Unit (SMU) 8 is the deep water zone of Onondaga Lake. The minimum lake water depth in SMU 8 is 30 feet.

Epilimnion – During summer stratification, the upper portion of the water column located between the 0 and 30-ft (0 and 9-meter) water depth in Onondaga Lake. The epilimnion is warm and well-mixed by wind and waves.

Hypolimnion - The lower portion of the deep zone water column during summer stratification where water temperatures are cooler than upper waters (typically below the 30-ft water depth in Onondaga Lake). The hypolimnion is not well-mixed by winds or inflows to the lake.

Methylmercury - An organic form of mercury, which can be created from metallic or elemental mercury by bacteria in sediments and water.

Thermocline - During summer stratification, a layer of water at approximately mid depth shows temperature changes with depth from the epilimnion temperature at the top to the hypolimnion temperature at the bottom. This mid-depth layer where water temperatures change significantly with depth is referred to as the thermocline.

NITRATE APPLICATION FIELD TRIAL IN THE HYPOLIMNION OF ONONDAGA LAKE (SEDIMENT MANAGEMENT UNIT 8)

EXECUTIVE SUMMARY AND CONCLUSIONS

Honeywell has successfully completed a nitrate application field trial in Onondaga Lake. The results of this field trial will be used to further advance the evaluation of nitrate addition, and contribute to an increased understanding of lake-bottom dynamics in the deep water. This work was conducted consistent with the work plan (Parsons, 2009b) approved in advance by the New York State Department of Environmental Conservation (NYSDEC) and was a follow up to dye tracer tests performed in 2008.

The field trial was designed to meet two objectives: (1) demonstrate a widely-available nitrate solution can be added effectively to the hypolimnion of Onondaga Lake, and (2) provide additional measurements of horizontal dispersion in the hypolimnion. Nitrate has been shown to inhibit formation of methylmercury in water (Upstate Freshwater Institute and Syracuse University (UFI and SU), 2008).

The field trial consisted of continuous, six-hour applications of a diluted calcium nitrate solution (called CN-8) and Rhodamine-WT dye on July 22 and July 29, 2009. The liquid calcium nitrate solution added during the field trial was a commercially-available product that is heavier than water (specific gravity is 1.48). The first application on July 22 was conducted in the North Basin, and the second application on July 29 was conducted in the South Basin. A self-propelled barge approximately 16 ft by 32 ft in size was used to conduct both applications. Monitoring of the nitrate and dye was conducted by Upstate Freshwater Institute (UFI) prior to and for two to three days following each of the two applications. The calcium nitrate solution was successfully added at water depths of 52 to 55 ft (16 to 17 meters) or 3 to 6 ft (1 to 2 meters) above the lake bottom, thus demonstrating the ability to effectively deliver to the hypolimnion significant quantities of nitrate-nitrogen.

Field trial results were consistent with output from the method of calculation used to quantify dilution of the calcium nitrate solution needed to match lake water density at the application water depth. Results from the field trial also highlighted the point that the rate of CN-8 application (or any similarly dense solution) from a discharge location is affected by the temperature difference between the dilution water (i.e., the warmer shallow water) and the target water (the cooler hypolimnion water). For example, if the temperature difference is very low, an excessive amount of water from the shallow water (epilimnion) may be required to dilute the CN-8 solution sufficiently to match the lake water density at the target depth. Nitrate could need to be added during late summer to early fall if natural oxygen and nitrate levels become depleted; during this time period, temperature differences between epilimnion and hypolimnion waters generally remain significant until lake waters turn over and oxygen and nitrate from upper waters replenish the hypolimnion.

The 2009 field trial also significantly increased understanding of the range of dispersion that is encountered in the hypolimnion waters of Onondaga Lake. Levels of dispersion observed during the second application and during the early portion of the first application were generally consistent with dispersion observed during the 2008 dye tracer tests. Dispersion observed during the first application was an order of magnitude higher than during the second application due primarily to results from the second portion of the first application. Moderate increases in wind speed were observed during the second portion of the first application, and wind direction was from the southeast.

This type of nitrate addition will not significantly impact water quality. Nitrate could be added as needed from a barge at a rate commensurate with target levels in the hypolimnion, and that rate can easily be controlled and modified. Nitrite-nitrogen levels in hypolimnion waters were also measured as requested by NYSDEC and found to be low enough that it was impossible to distinguish from background nitrite levels, even directly within the released solution.

1.0 INTRODUCTION

This report describes a nitrate application field trial performed during July 2009 as two nitrate applications, one application in the North Basin of Onondaga Lake in Sediment Management Unit 8 (SMU 8) and one application in the South Basin of SMU 8.

The remedy for the Onondaga Lake bottom is described in a 2005 Record of Decision (ROD) prepared by the NYSDEC and the United States Environmental Protection Agency (USEPA). The Statement of Work (SOW) appended to the Consent Decree for the Onondaga Lake remedy (U.S. District Court, Northern District of New York, 2007) specifies that Honeywell conduct a study to determine if nitrate addition would effectively reduce formation of methylmercury in the water column while preserving the normal lake stratification cycle. Performance of a nitrate application field trial is included in the Remedial Design Work Plan (RDWP) for the lake bottom (Parsons, 2009a). The nitrate application field trial was conducted during July 2009 in accordance with the SOW, and the results from that field trial are presented herein.

As indicated in the work plan for the nitrate application field trial approved by NYSDEC (Parsons, 2009b), the purpose of the field trial was to demonstrate that an electron acceptor (in this case, a widely-available calcium nitrate solution) can be effectively added and mixed with lake bottom waters in a manner that retains the electron acceptor within the lake bottom waters to counteract nitrate depletion below critical levels which can occur in late summer when the lake is stratified. Results from this field trial also provide additional information about horizontal dispersion of the electron acceptor as a follow-up to the 2008 dye tracer tests (UFI, 2008). This field trial did not include an evaluation of effects of nitrate addition on methylmercury formation, so sampling and analysis for mercury were not included. An evaluation of effects of nitrate addition on methylmercury formation will be included as part of future nitrate application work by Honeywell.

When Onondaga Lake is thermally stratified (typically each year between late May and mid-to-late October), oxygen and nitrate concentrations decline gradually over time in hypolimnion waters and when concentrations of oxygen and nitrate are low enough, sediments can release methylmercury to the water column, and inorganic mercury already in the water column can become methylated. During 2007 and 2008, releases of methylmercury to the hypolimnion were found to be substantially lower than in previous years due primarily to wastewater treatment processes implemented at the Onondaga County Metropolitan Wastewater Treatment Plant (hereafter called Metro) located along the southern (i.e., upstream) side of Onondaga Lake. Wastewater treated at Metro is discharged into the nearshore waters of the lake between the south shore and SMU 8. In 2004, Onondaga County began operating a biologically active filter system at Metro which converts ammonia to nitrate. As a result, the available nitrate pool in the hypolimnion at the start of summer stratification roughly doubled. In 2005, Onondaga County activated a phosphorous-removal system resulting in decreased algal growth in the upper waters and reduced demand for electron acceptors in the hypolimnion. As a consequence of these additional wastewater treatment processes added at Metro, nitrate levels persisted in the Onondaga Lake hypolimnion for a significantly greater duration during the summers of 2007 and 2008, which inhibited the release of methylmercury from SMU 8 sediments (UFI and SU, 2007a, Todorova et al., 2009).

In light of these recent water quality improvements, the benefit of adding an electron acceptor such as nitrate or oxygen to hypolimnion waters of Onondaga Lake has declined substantially since 2005 when the ROD for the lake bottom was issued. Nonetheless, future addition of an electron acceptor in the lower waters of the lake’s hypolimnion through the use of an engineered system may be warranted under certain future conditions in the lake to maintain sufficient quantity of one or more electron acceptors to further reduce water column methylmercury levels. In case future addition of an electron acceptor such as nitrate is warranted, mechanical equipment and field procedures for adding nitrate to the lake hypolimnion need to be tested in a manner that mimics maximum anticipated rates for applying nitrate. In order to mimic maximum anticipated nitrate application rates, the field trial was designed to place a maximum nitrate application rate at a single location within the SMU 8 hypolimnion.

Five different dye tracer tests were conducted by UFI for Honeywell between July 22 and October 7, 2008. The work plan and report documenting results from these 2008 dye tracer tests have been provided separately (UFI, 2008 and UFI, 2009). Each of these tests involved placing Rhodamine-WT dye into the SMU 8 hypolimnion at water depths of 14.7 to 16.1 meters (48 to 53 ft) within the North Basin and the South Basin. These tests consisted of placing dye for 20 to 40 minutes at a flow of approximately 20 gallons per minute (gpm). In contrast, the 2009 field trial included continuous applications of nitrate and dye over six-hour time periods.

2.0 FIELD TRIAL DESIGN SUMMARY

2.1 Characteristics of Calcium Nitrate and Rhodamine-WT Dye

Calcium nitrate ($Ca(NO_3)_2$) was the source of the electron acceptor applied to the lower waters of the Onondaga Lake hypolimnion during the field trial. The solution of calcium nitrate, commercially known as CN-8, was obtained from Yara North America (www.yara.us). Rhodamine-WT dye was used as a tracer to monitor horizontal dispersion in the hypolimnion.

During June 2009, UFI analyzed a sample of CN-8 solution for nitrite-nitrogen, nitrate-nitrogen, ammonia-nitrogen and phosphorus prior to applying the solution to the lake. The results indicated the solution contained 121 grams-nitrogen per liter (g-N/L) of nitrate (NO_3^-), 110 micrograms-nitrogen per liter (μg-N/L) of nitrite (NO_2^-), 295 milligrams-nitrogen per liter (mg-N/L) of total ammonia ($T\text{-}NH_3$) and 200 micrograms-phosphorus per liter (μg-P/L) of total phosphorus.

The field trial design originally specified mixing 30 parts of water to one part of CN-8 and 0.015 parts of Rhodamine-WT dye prior to applying the entire solution into the hypolimnion. To evaluate the behavior of a representative CN-8 and Rhodamine-WT mixture, UFI performed two laboratory experiments during June 2009 one month prior to the field trial. During the first experiment, UFI prepared a solution by mixing 10 parts of CN-8 and one part of Rhodamine-WT dye by volume. This resulted in the progressive formation of a precipitate over a few minutes and accumulation of solid phase material at the bottom of the experiment apparatus. As such, the ratios were modified during the second experiment to prepare a solution more representative of actual field conditions. The solution was prepared by mixing eight parts of water, one part of CN-8, and one part of Rhodamine-WT dye. Precipitate formed initially, but gradually dissolved. Ultimately, the decision was made to apply the dye separate from the CN-8 because of uncertainties regarding the reactions between the dye and CN-8, the added control of dye addition provided by separate application, and ability to more easily observe the position of the rotameter float if the CN-8 and dye were applied separately.

2.2 Dilution and Density

To ensure the solution of heavier-than-water CN-8 and the Rhodamine-WT dye would remain at the target depth upon release (i.e., would not rise or plunge excessively), it is necessary to ensure the solution density matches that of the surrounding lake water. By diluting the CN-8 solution with epilimnetic water, a solution's density can be adjusted to match that of the hypolimnion.

The model used to calculate densities of lake water, as well as density of the solution to be added, was developed by Chen and Millero (1978) and has been applied to the study of Onondaga Lake (Effler et al., 1996). Solution density is a function of water temperature and salinity. Salinity values were derived from measured specific conductance values via the 1978 Practical Salinity Scale (Lewis 1980, UNESCO 1981). Temperature and specific conductance data were obtained from daily monitoring at the South Deep station posted on the website www.ourlake.org . The density of a mixture would be based on the characteristics of the component streams. The weighted averages of temperature and salinity can be put into the Chen and Millero model to enable calculation of the density of the resulting mixture.

The general approach to identifying the required dilution of the CN-8 solution with epilimnion water from Onondaga Lake involved two dilution steps: first, the CN-8 solution was diluted on board 1:1 with epilimnion water from the 2-meter (7-ft) water depth (to aid in material handling and metering); second, this mixture was then blended with a higher flow of water, also from the 2-meter water depth, for pumping and discharge through diffusers set at the target depths (16 meters in the North Basin and 17 meters in the South Basin). The degree of dilution required in the second step was targeted to achieve the same density as the target depth of application.

During step 1 of the dilution process, the CN-8 solution was diluted with an equal volume of epilimnion water from the 2-meter water depth. The specific conductance and temperature of the epilimnetic water were known. The salinity of the CN-8 is 486 parts per thousand, and temperature was assumed to be equal to that of epilimnion lake water from the 2-meter depth. The weighted salinity and temperature of the CN-8-epilimnetic water solution were then calculated (and these used to determine the density).

During step 2, this solution was mixed with an additional flow of epilimnion water. The salinities and temperatures of the initial mixture and the epilimnion water were combined to determine the weighted characteristics (salinity and temperature) of the solution to be discharged through the diffusers. These final values for salinity and temperature determine the density of the discharged solution. The flow rate of epilimnion water during this second step was determined by the dilution required to produce a match with the density of lake water at the discharge depth.

Initially, there was a proposed third step, an additional 10:1 dilution to be accomplished in the near-field of the discharge by mixing with hypolimnion water from the 16-meter (52-ft) water depth. However, a re-assessment of the methodology presented in the work plan to quantify the necessary dilution indicated a more appropriate and conservative approach would be to discount this third-step dilution and focus on achieving the target density with just the two step process. Subsequent monitoring of the plumes following discharge did indicate that a better predictor of plume behavior would be the two-step calculation process.

Preliminary calculations prior to the initial application in the North Basin were based on mixing 0.46 gpm of CN-8 solution (materially different from the work plan proposed rate of 1.1 gpm since third step dilution was discounted and lake temperatures during the week of application were different from those anticipated when the work plan was completed) with an equal flow of epilimnion water from the 2-meter water depth, followed by a second dilution with an additional 97 gpm of epilimnion water, and then discharge through the two diffuser(s). Total dilution with epilimnion water was 210:1. However, monitoring indicated the resulting plume was plunging, so the flow of CN-8 solution was modified so the water-calcium nitrate-dye mixture would match the density of water at the 16-meter water depth. This was accomplished by cutting back slightly on the CN-8 flow (to 0.38 gpm) and maintaining the flow rate from the epilimnion water at 97 gpm. The total dilution under this scenario was 256:1, and the resulting plume did stay within the hypolimnion near the target water depth of 16 meters, although the plume appeared to rise a bit by the second day of monitoring.

For the second application, in the South Basin (to a slightly greater water depth of 17 meters), lake conditions indicated a lower level of dilution was required. A CN-8 flow of 0.60 gpm was mixed on board 1:1 with epilimnion water and subsequently mixed in the discharge pipes with 114 gpm of epilimnion water, for a total dilution of approximately 190:1. This dilution was effective, with the plume staying within the target depth zone.

2.3 Application Quantities and Application Rates

2.3.1 Calcium Nitrate

CN-8 is an available liquid form of nitrate commonly used as agricultural fertilizer. The quantity of nitrate to apply during the field trial was calculated in the work plan based on the highest estimated nitrate application rate that may need to be implemented in the future. The quantity needed was based on peak four-week rolling average nitrate uptake rates in the hypolimnion water as measured at the South Deep station by UFI during 2007 and was estimated to be approximately 0.8 metric tons of nitrate per day. This equated to an application rate of 1.1 gpm of the calcium nitrate solution over six hours. This flow rate was reduced to between 0.38 and 0.60 gpm based on changes described in Section 2.2 related to density and diffuser dilution requirements.

2.3.2 Rhodamine-WT Dye

Rhodamine-WT dye does not degrade significantly in hypolimnion lake water where sunlight is absent. A holding time evaluation of Rhodamine-WT dye conducted by UFI in the absence of sunlight showed that no significant degradation of the dye occurred. The amount of Rhodamine-WT applied during the field trial was quantified based on the experience of the UFI team from the 2008 dye tracer tests. UFI recommended an approximate concentration of 100 mg/L (active dye) in a stream flow of 30 gpm. On this basis, 4.6 gallons of Rhodamine-WT was applied during each six-hour application. The dye application pumps were therefore set to flow at a rate that would release approximately 4.6 gallons of Rhodamine-WT over the course of one six-hour field trial. This resulted in a concentration of active dye of 26 mg/L, prior to applying the dye to the lake.

2.4 Diffuser Design

A diffuser was designed and fabricated to enhance mixing upon application of the CN-8, dye, and epilimnion lake water. The diffuser design for the field trial specified a diffuser consisting of four ¾-inch nozzles, separated by 90 degree angles (in the horizontal plane), each oriented upward, 10 degrees from the lake bottom. A photo of the diffuser is included in

Appendix A. The upward orientation of the diffuser nozzles had an additional benefit of avoiding disturbance of SMU 8 sediment that is recovering naturally.

Based on UFI's 2008 dye tracer results (UFI, 2009), vertical dispersion is orders of magnitude smaller than horizontal dispersion in the hypolimnion of Onondaga Lake. To ensure the discharge of CN-8 and Rhodamine dye would be sufficient enough to develop a plume thick enough for reliable monitoring, two diffusers were set at two separate depths, one meter apart, with more accurate control of flow rate to each diffuser.

3.0 FIELD TRIAL PROCEDURES AND QUALITY ASSURANCE

3.1 Nitrate and Rhodamine-WT Dye Application

Agencies were notified one week prior to each application. The decision about when to conduct each application was made in conjunction with NYSDEC based primarily on weather and lake conditions and on the weather forecast.

Work activities not specifically described in this report, such as waste management activities, were conducted in accordance with procedures documented in the Phase I Pre-Design Investigation Work Plan (Parsons, 2005). Laboratory procedures were conducted in accordance with the Standard Operating Procedures (SOP) included in Book 1 Work Plan for Baseline Monitoring (UFI and SU, 2008). An onshore support zone was not needed for the nitrate application field trial work described herein.

The amount of CN-8, dye, and epilimnion lake water applied during each application were quantified based on results from the 2008 dye tracer tests with the intent of providing concentrations of the Rhodamine-WT dye that remain detectable in the hypolimnion for a few days following an application, as described in Section 2.

Both field trial applications were conducted by applying CN-8 and dye continuously for approximately six hours during morning and early afternoon timeframes to allow as much time as possible for tracking the applied solutions within the lake over the course of the first day. The first application was conducted in the North Basin, and the second application was conducted in the South Basin (see Figure 1 for application locations).

To begin each application, the 16-ft by 32-ft barge was moved to the application location. Inflow and outflow piping with an end-of-pipe diffuser was positioned in the lake water column. CN-8 and dye were mixed on the barge with epilimnetic lake water and applied to the hypolimnion. The procedure used to implement the field trial, including photographs of the barge, equipment, pumps, and diffusers is presented in Appendix A. The barge set-up included an anchoring system that consisted of one large concrete block (weighing approximately 2,000 lbs) that held the bow of the barge on location at the application location, and another smaller anchor was positioned off the stern to prevent the barge from rotating due to wind action.

3.2 In-Lake Monitoring

After allowing time for some initial spreading, the nitrate and dye were monitored by UFI during and following both applications using two monitoring boats. While monitoring, the position of the monitoring boat and output from the monitoring sensors were recorded at regular intervals by an on-board computer.

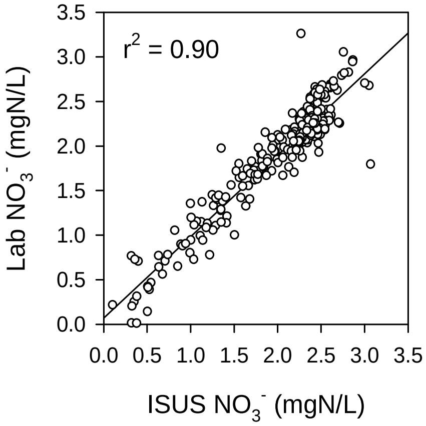
Monitoring of rhodamine dye and nitrate concentrations in the lake was conducted using two boats. The first boat used the identical sensors that were used during the 2008 dye tracer studies conducted by UFI in Onondaga Lake. This sensor package was manufactured by Yellow Springs Instruments (YSI) and measured rhodamine dye concentration, temperature, specific conductivity, and depth. A handheld GPS (global positioning system) sensor (Garmin eTrex H) was integrated into the package to simultaneously measure latitude/longitude. The second boat contained a sensor package that included all of the measurements on the first boat, but also included an *in situ* ultraviolet spectrophotometry (ISUS) optical nitrate sensor. Each sensor package was connected to an on-boat computer that recorded all observations at a fixed time interval over the period of observation. The YSI measurements were made at a 5-second interval, while those from the instrument package that included the ISUS were made at a 1-second interval; the latter interval was shorter than necessary, but increasing the time interval could not be achieved due to software constraints.

After the beginning of rhodamine dye and CN-8 release on the first day of each application, monitoring proceeded by attempting to observe and define the extent of the dye and nitrate plume in the vertical direction, and to measure the spreading of the plume in the horizontal plane. Vertical profiles were used to identify the range of depth of the plume, and to ensure that the fixed depth monitoring was conducted at the depth where significant dye was present. Horizontal spreading was assessed by observing concentration variations in the horizontal directions at a fixed depth for periods of time.

The water monitoring sensors may have induced some small-scale mixing of the dye and nitrate as the sensors were towed through the dye cloud. However, this mixing was: (a) weak because towing of the monitoring sensors was conducted as slowly as reasonably possible (boat speed of approximately 2 knots or 2 to 3 miles per hour); (b) small scale because the fluorometer probe is approximately 12 inches (30 centimeters) in size; and (c) sustained for a short period of time at any position as the monitoring sensors were towed. The field objective was consistent with the objective of the 2008 dye tracer tests conducted for Honeywell which was to measure sustained, large-scale mixing over tens to hundreds of meters, which is not affected in any significant manner by the towing of instruments. The sampling approach also provides flexibility to measure various dye shapes in an implementable manner.

New York State has established water quality standards to protect aquatic biota from the potential toxic effects of nitrite. The New York State nitrite water quality standard applicable to Onondaga Lake is 100 µg-N/L for protection of warm-water fish. The CN-8 solution was found to contain a nitrite concentration of 110 µg-N/L, and nitrite is a potential byproduct of incomplete denitrification (conversion of nitrate to dinitrogen gas). Therefore, it was considered prudent to track nitrite concentrations during the field trial (Table 1). Concentrations of nitrite in the anoxic hypolimnion exceeded New York State water quality standards before, during, and after the nitrate application field trial. Elevated nitrate concentrations can occur in anoxic waters as a result of incomplete nitrification (conversion of ammonia to nitrate) or denitrification (conversion of nitrate to nitrogen gas). Nitrite concentrations in the oxygenated epilimnion before and after the field trial were below the water quality standard as shown on Table 1. There is no evidence that the CN-8 application exacerbated the existing nitrite toxicity concern in Onondaga Lake. See UFI and SU (2007a) and references therein for a more complete discussion of nitrite toxicity and its history in Onondaga Lake.

The performance of the ISUS optical nitrate probe was assessed in 2006, 2007, and 2008 through comparisons with laboratory measurements. The ISUS and laboratory results have compared closely in each year, as shown here for 2008.



Tracking of the dye (and nitrate as practicable) was conducted during daylight hours for three days.

Unanticipated or unforeseen circumstances or conditions did not arise during either application. No significant modifications of the planned field trial procedures were needed.

4.0 RESULTS

4.1 Nitrate and Rhodamine Dye Application

Table 2 provides a summary of the quantities of the calcium nitrate, dye, and water applied during each application.

4.2 In- Lake Monitoring

A summary of the observations for the two applications is given in Table 3. The rhodamine dye observations enumerated in Table 3 were made from both boats, while the nitrate observations were made from the single boat deploying the ISUS sensor.

The extent of the rhodamine dye cloud in the horizontal plane over the three days of monitoring of the North Basin release is shown in Figure 2. The "extent" of the cloud identifies the region in which non-zero dye concentrations were observed. As in the case of the 2008 tests, roughly 4 to 5 hours of monitoring was required to identify the extent of the dye cloud and to obtain a reasonable picture of horizontal variations in concentration within the cloud. On this basis, generally two "sweeps", or reasonably complete characterizations of the dye cloud, were made on each monitoring day; the exception was July 24, when monitoring was ended early due to a thunderstorm in the area. The spreading of the dye cloud accelerated significantly along the longitudinal axis (northwest – southeast) of the lake basin on the afternoon of July 23 (Figure 2). For the second application in the South Basin (Figure 3), the rate of spreading was lower.

The CN-8 solution, as delivered by the manufacturer, is considerably denser than the bottom waters of the lake. If this undiluted solution were to be released into the lake, it would sink to the lake bottom and flow down any slope at the bottom to a low point, without mixing with the lake waters. A primary objective of the nitrate application field trial was to demonstrate that the hyper-concentrated calcium nitrate solution could be diluted and released in such a manner that the resulting mixture entered and mixed with the ambient waters of the hypolimnion without plunging to the lake bottom.

Unlike the rhodamine dye, non-zero nitrate concentrations exist in the hypolimnion of Onondaga Lake. In mid-summer when these applications were conducted, nitrate concentrations generally decrease with depth in the hypolimnion and are decreasing over time at a fixed depth. The concentration of nitrate present in the lake prior to release of nitrate from the diffuser is referred to as "background". The vertical variation of the background concentration was identified by monitoring immediately before and during the early portion of the dye/nitrate release operation. It was determined that the background concentration of nitrate C_B could be accurately estimated from depth D. Based on this monitoring data, the following empirical relationships were used to estimate the background concentration of nitrate for the first nitrate field trial (22-24 July):

$$D < 17\text{ m}, \quad C_B = 2.802 - 0.0841\, D$$

$$D > 17\text{ m}, \quad C_B = 5.342 - 0.234\, D$$

These equations predict background concentrations in the range of 1.1 to 1.5 mg-N/L (Figure 4). For the second field trial (29-31 July), background concentration was estimated from:

$$\begin{aligned} D < 17.5\text{ m}, &\quad C_B = -0.0064\, D^2 + 0.156\, D + 0.503 \\ D < 17.8\text{ m}, &\quad C_B = 6.304\, D^2 - 224.5\, D + 1999 \\ D > 17.8\text{ m}, &\quad C_B = 0.7 \end{aligned}$$

These equations predict background concentrations in the range of 0.7 to 1.4 mg-N/L (Figure 5).

During the early hours of the nitrate/dye release on 22 July, nitrate concentrations in excess of the background were observed over a narrow range of water depths between 16 and 17 meters (Figure 4a). For the entire day of 22 July, nitrate in excess of background occurred over the water depth range from 12.2 to 16.8 meters (Figure 4b). Nitrate concentrations at background concentration levels were observed at water depths less than 12.2 meters, and at water depths between 16.8 meters and the bottom (approximately 18.2 meters). These results indicate that the nitrate released through the diffuser system was limited to water depths of 12.2 to 16.8 meters. The distinct vertical bands of dye depicted in Figure 4b may have been caused by variations in the density of the solution released through the diffuser or wind-induced seiche motion of the thermal structure. The first explanation is more likely to be the cause than the second, particularly given the modest winds encountered during the field trial. The occurrence of these bands highlights the importance of matching the density of the nitrate solution with the water density at the target water depth. Seiche activity would likely promote mixing of the injected solution throughout the hypolimnion through increased turbulence rather than the creation of distinct bands.

For the second application the results were similar, but nitrate in excess of background occurred at greater depths (Figure 5). Elevated nitrate concentrations were measured at water depths of 16.2 to 18.2 meters. While some nitrate concentrations in excess of background were observed immediately above the bottom, these concentrations were low relative to those observed 0.5 to 1 m higher in the water column. The observed vertical distribution of rhodamine dye was similar to that of nitrate.

Based on these results, it is concluded that both of the CN-8/rhodamine releases were successful in terms of demonstrating the ability to release a large quantity of nitrate through a diffuser and to isolate or trap the resulting nitrate plume within a range of depth in the hypolimnion above or immediately adjacent to the lake bottom. This was generally achieved by diluting the high-density, concentrated calcium nitrate solution with low-density (warm) ambient epilimnetic water to produce a mixture with a density equal to the ambient waters of the hypolimnion.

5.0 DISPERSION CALCULATIONS

With dye and nitrate concentration measurements being made rapidly, and observation periods lasting hours, a large number of measurements were made (Table 3). The position of each individual concentration measurement was measured by the GPS sensor and recorded as latitude and longitude, and by depth. These latitude/longitude data were converted to Universal Transverse Mercator easting (x) and northing (y) coordinates using standard transformation equations. Given the somewhat long, narrow shape of the Onondaga Lake basin, there is reason to choose an alternate coordinate system oriented along the length and width of the basin for dispersion calculations. As a result, the longitudinal coordinate l (positive to the northwest) and transverse coordinate v (positive to the northeast) were used in place of (x,y). Transformation to the longitudinal/transverse system was computed using the simple rotation:

$$(l_i, v_i) = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} (x_i, y_i) \qquad (1)$$

where the rotation angle θ= -45 degrees.

Spreading of rhodamine dye over time was the primary means of estimating dispersion coefficients for these two applications. Dye concentrations were measured from both boats, and thus the greatest characterization of spreading was available with dye. However, given that nitrate was successfully diluted to neutral buoyancy, the same ambient transport characteristics determine the spreading of dye and nitrate. As a result, the spreading of nitrate was also used to estimate dispersion. This analysis assumed that no significant depletion of released nitrate occurred over the duration of the applications. Given that this duration was less than three days, this is a reasonable assumption. Some difference in dispersion coefficients determined from nitrate and dye may be expected because dye was measured with two boats, while nitrate from one. Release rates for nitrate and dye were generally constant and occurred over the same time interval. As a result, consistency in the dispersion coefficients determined for the two constituents is a measure of the veracity of the results upon which the calculated dispersion coefficients are based.

The method of moments (Fischer et al 1979; Murthy 1976) was used to compute the dispersion coefficient for dye and nitrate. The position of the center of mass or centroid of the dye cloud was computed from:

$$l_0 \approx \frac{\sum l_i \, C_i \, \Delta l_i \, \Delta v_i}{\sum C_i \, \Delta l_i \, \Delta v_i} \qquad (2a)$$

$$v_0 \approx \frac{\sum v_i \, C_i \, \Delta l_i \, \Delta v_i}{\sum C_i \, \Delta l_i \, \Delta v_i} \qquad (2b)$$

where l_0 and v_0 are the longitudinal and transverse position of the centroid, l_i, v_i, and C_i are the position and dye concentration of an individual measurement, and $\Delta l_i \, \Delta v_i$ is the area in the horizontal plane associated with this measurement. For the case of rhodamine dye, C_i is the observed concentration, while for nitrate it is the observed concentration in excess of background, with the restriction that $C_i \geq 0$. The summations in the numerator and denominator of Equations 2a and 2b are made for all measurements making up an individual sweep or snapshot of the dye cloud. For the two applications (Table 1), between five and six sweeps of the dye cloud were conducted, with thousands of individual measurements comprising each sweep and thus considered in the summations. Note that an approximation symbol was used in the expressions for l_0 and v_0 in Equations 2a and 2b, and in others below. If a “complete” sampling of the entire area of the dye cloud in the horizontal plane could be made, then this approximation would become an equality. In practice, this ideal cannot be achieved because one or two sensors deployed from slow-moving boats cannot fully observe and define the entire areal extent of the cloud.

The "variance" of the dye cloud in the longitudinal (σ_L^2) and transverse (σ_V^2) directions were computed by

$$\sigma_L^2 \approx \frac{\sum (l_i - l_0)^2 C_i \, \Delta l_i \, \Delta v_i}{\sum C_i \, \Delta l_i \, \Delta v_i} \tag{3a}$$

$$\sigma_V^2 \approx \frac{\sum (v_i - v_0)^2 C_i \, \Delta l_i \, \Delta v_i}{\sum C_i \, \Delta l_i \, \Delta v_i} \tag{3b}$$

The square root of the variance has dimensions of length and is a measure of the "width" or "spread" of the distribution in the longitudinal and transverse directions. Again the summations in Equations 3a and 3b involve all of the measurements made in an individual sweep of the dye cloud, and l_0 and v_0 are computed from Equations 2a and 2b for the same corresponding sweep. Repeated sweeps of the dye cloud yield a series of values of variance and spread that increase over time. The rate of increase determines the dispersion coefficient, as given by

$$E_L = \frac{1}{2}\frac{d}{dt}(\sigma_L^2) \tag{4a}$$

$$E_V = \frac{1}{2}\frac{d}{dt}(\sigma_V^2) \tag{4b}$$

where E_L and E_V are the dispersion coefficients in the longitudinal and transverse directions. In rivers, longitudinal mixing is substantially larger than in the transverse direction (Fischer *et al*. 1979). In very long, narrow lake or reservoir basins, this relative magnitude may also be observed, at least in surface waters. The longitudinal and transverse calculations are performed to determine if a consistent degree of anisotropy in dispersion exists in the hypolimnion waters of Onondaga Lake. In some cases, the ratio of longitudinal to transverse dispersion may be variable with no consistent pattern. In such cases, it may be more reasonable to define a single dispersion coefficient in the horizontal plane, this being a coefficient that defines dispersion in the radial direction outward from a source. In this case, a radial variance may be computed as

$$\sigma_R^2 \approx \frac{\sum r_i^2 C_i \, 2\pi r_i \, \Delta r_i}{\sum C_i \, 2\pi r_i \, \Delta r_i} \tag{5a}$$

where $r_i^2 = (l_i - l_0)^2 + (v_i - v_0)^2$, so r_i is the distance of an individual measurement from the centroid. The radial dispersion coefficient E_R is determined from

$$E_R = \frac{1}{4}\frac{d}{dt}(\sigma_R^2) \qquad \text{(5b)}$$

For each of sweep of the dye and nitrate clouds, the location of the center of mass or centroid (relative to the position of dye release) and the spread of the dye cloud in the longitudinal, transverse, and radial directions were computed. The results for dye and nitrate are shown in Tables 4 and 5, respectively.

The process of dispersion is evident in the rate of increase of the various measures of spread over time (Figures 6 through 9). Using linear regression analysis, estimates of the rate of change of the square of the 3 measures of spread (longitudinal, transverse, and radial) spread with time (the right sides of Eqs. 4a, 4b, and 5b) were determined. These lead to the estimates of the dispersion coefficients shown in Tables 6 and 7. The results for the first application (22 to 24 July) indicate that, through roughly mid-day on July 23, or the first three sweeps, the dye and nitrate clouds were spreading at rates generally consistent with the observations from 2008 (approximately 0.1 m^2/sec). However, on the afternoon of July 23, the rate of spreading of both dye (Figure 6a) and nitrate (Figure 7a) increased substantially.

6.0 DISCUSSION OF RESULTS

Estimates of the dispersion coefficient in the hypolimnion of Onondaga Lake were made using data from tracking the rhodamine dye and CN-8. For the second application (29 to 31 July), the dispersion coefficients determined from the two constituents were quite consistent (Table 7). Larger differences were observed for the first (22 to 24 July) application (Table 7). Given the variability of dispersion in surface water bodies (Fischer et al., 1979), the consistency of the dye and nitrate results is judged to be good. This consistency generally supports the procedure that was used to estimate dispersion.

6.1 Supporting Measurements

During the period of the nitrate field applications, observations of other quantities that may be expected to affect dispersion in the lake were made. These are described in this section.

6.1.1 Wind Measurements

UFI deployed a recording anemometer on a buoy at the South Deep Station in Onondaga Lake during the period of these applications. In addition, Parsons operated a similar instrument on the southwest shore of the lake, as does the National Weather Service at Hancock airport. Comparison of the observations from these three instruments indicated that UFI wind speed measurements on the lake correlate well with National Weather Service airport data, while the Parsons lake shore data recorded consistently lower speeds. There were significant differences between the UFI wind direction data and the other two sensors. While applying a constant rotational correction to these observations improved consistency with the Parsons and NWS sensors, the correlation was judged to be inadequate. As a result, the UFI wind speed observations, and the Parsons' direction measurements were combined and used for analysis. The resulting data for late July 2009 are shown in Figure 10a. During the first application (22 to 24 July), a wind event occurred on the afternoon of 23 July (not shown in Figure 10a), with the wind direction oriented along the long axis of the lake (scalar wind speed and longitudinal component of wind are equal). For the second application (29 to 31 July) winds were more moderate.

6.1.2 Thermistor Chain Measurements

UFI deployed a single thermistor chain at the South Deep Station for the period of the two applications. The chain consisted of an array of 11 sensors measuring water temperature along a chain 12.5 meters in length, with each thermistor separated by 1.25 meters. The array was suspended vertically from a surface buoy, with the upper-most sensor at a depth of 4.5 meters, and the lower-most at 17 meters. Water temperature was recorded every five minutes. These instruments were deployed to observe the water temperature fluctuations associated with internal wave (seiche) activity in the lake. Water motion in the portion of the hypolimnion where the dye and nitrate releases occurred is expected to occur largely as a result of this process.

The thermistor observations were processed and evaluated in order to determine the "thermocline range", defined as the range of vertical movement of the thermocline from a position above its mean (rest) position to a point below that position. The results are shown in Figure 10c. The greatest vertical movement of the thermocline occurred late on July 23 and early July 24, likely in response to the increased wind along the long axis of the lake (Figure 10a).

6.1.3 In-Lake Velocity Measurements

Parsons deployed a single Acoustic Doppler Velocimeter (ADV) instrument in the vicinity of the release points for each of the two nitrate field applications. The Vector uses the Doppler effect by transmitting a short pulse of sound, listening to its echo and measuring the change in pitch or frequency of the echo.

To deploy the vectors, a stationary frame made of steel was fabricated. This frame ensured the vector's sensors would remain in a fixed position throughout the sampling event. The frame was designed to allow for two vectors to be positioned 1 meter apart vertically and deployed at the same location.

Approximately one day prior to the CN-8 application in the North Basin (i.e., the first application), two vectors were deployed approximately 100 ft from the application location. The bottom vector was positioned 1 meter from the sediment water interface, or mudline, and the second vector positioned at 2 meters above the mudline. Data was collected and stored in the vector's memory card from the time of deployment until approximately one day after the application. Upon retrieval of the vectors in the North Basin, a cable connecting the top vector sensor to the housing unit became damage beyond field repair.

Due to the damaged vector cable, only one vector was deployed during the second application within the South Basin. This vector was positioned 2 meters above the mudline and data was collected approximately one day prior to the application until approximately one day after the application. The location of this vector was approximately 100 ft from the application location.

During both deployments, all vectors were programmed for continuous sampling. A short pulse of sound or 'burst' was released once every minute. This burst lasted 16 seconds during which time 120 velocities were recorded.

Observed velocities over the period of the field applications are shown in Figure 11. The time series show the cyclical variation associated with internal waves, with positive and negative fluctuations occurring over time and mean values of roughly zero. Peak values of 0.04 meters per second (1.6 inches per second) were observed on 23 July one day following the first application, and on 29 July during the second application.

6.2 Correlation of Supporting Measurements and Observed Dispersion

Levels of dispersion observed during the second application (29 to 31 July) and during the early portion of the first application (22 to 23 July) were generally consistent with values observed during the 2008 dye tracer tests in Onondaga Lake (Table 8). Levels of radial dispersion E_R for these observations are in the range of 0.030 to 0.175 square meters per second for the rhodamine dye analyses. The most dramatic variation in dispersion occurred on the afternoon of 23 July; consideration of all data from the first application lead to a value of E_R = 0.419 meter^2/second for that application. Moderate increases in wind speed (Figure 10a) occurred on the afternoon of 23 July, with wind direction from the southeast. These wind conditions are consistent with the increase in internal wave motion in the hypolimnion waters of the lake, as observed in both the vertical motion of the thermocline (Figure 10c) and the directly observed water motion near the lake bottom (Figure 11a). Aside from wind, the only environmental condition that could plausibly affect hypolimnion transport is tributary streamflow; Onondaga Creek experienced two minor runoff events during the late July, while Ninemile Creek had none (Figure 10b). There is no evidence that variations in streamflow had a discernable effect on hypolimnion dispersion. It is important to note that the increase in dispersion on the afternoon of 23 July was evident both in the rhodamine dye and nitrate observations.

Considering the variability in the dispersion observed during both the 2008 dye tracer test and the 2009 applications in Onondaga Lake, a range of about an order of magnitude was found. The range of variation observed in Onondaga Lake is about the same as that found by Murthy (1976) in Lake Ontario, and by Peeters et al. (1996) in several Swiss lakes (Table 9).

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TABLES

TABLE 1

NITRITE CONCENTRATIONS MEASURED IN THE EPILIMNION (2-METER WATER DEPTH) AND IN THE HYPOLIMNION BEFORE, DURING, AND AFTER THE NITRATE APPLICATION FIELD TRIAL (IN MICROGRAMS PER LITER (µG/L) OR PARTS PER BILLION AS NITROGEN)

Water Depth (meters)	Before Field Trial	North Basin Application			South Basin Application		After Field Trial
	7/20/09	7/22/09	7/23/09	7/23/09	7/29/09	7/30/09	8/4/09
2	**36**	**-**	**-**	**-**	**-**	**-**	**37**
12	93	-	-	-	-	-	65
14	-	182	158	159	-	-	
16	205	-	-	-	-	-	160
17	-	-	-	-	152	-	
18	201	-	-	-	-	14	67

TABLE 2

CHARACTERIZATION OF RELEASES DURING BOTH APPLICATIONS

	Application No. 1: July 22, 2009	**Application No. 2: July 29, 2009**
Location	North Basin	South Basin
Time Frame	8:58am – 3:15pm	7:48am – 1:50pm
Gallons of CN-8 Applied	143 gallons	211 gallons
Gallons of Rhodamine WT Dye Applied	5.8 gallons	4.4 gallons
Gallons of Epilimnion Water mixed with CN-8	36,000 gallons	41,000 gallons
Diffuser depths or distance above bottom, meters	1 and 2 meters above bottom	1 and 2 meters above bottom
Diffuser Characteristics Number of ports Port diameter in inches Angle of Orientation	4 ports ¾-inch ports 10 degrees upward from horizontal	4 ports ¾-inch ports 10 degrees upward from horizontal
Release variation(s) during application	Static mixer used in line downstream from CN-8 and dye application points. Plume was sinking according to UFI approx. 1.5 hours into application, changed dilution ratio from 200:1 to 250:1 Rhodamine dye application rate was incorrectly set at approx. 100 ml/min for the first 2-3 hours, then reset to correct rate of 47 ml/min.	Static mixer not used due to head loses it created in the system. Design dilution ratio of 200:1 maintained throughout.

TABLE 3

SUMMARY OF LAKE MONITORING ACTIVITIES BY UFI DURING 2009, NITRATE APPLICATIONS, ONONDAGA LAKE, 2009

Application Number	Basin	Monitoring Period (24-hour clock)	Number of Rhodamine Observations	Number of Nitrate Observations
1	North	22 July, 08:00-18:12	35,734	24,570
		23 July, 07:03–18:50	34,743	20,506
		24 July, 07:36-15:56	19,931	9,738
2	South	29 July, 08:20-19:22	35,197	18,614
		30 July, 07:02-19:48	43,159	28,271
		31 July, 07:02-20:26	46,670	27,316

TABLE 4

SPREADING CHARACTERISTICS DURING FIELD TRIAL USED TO COMPUTE RHODAMINE DYE DISPERSION CHARACTERISTICS

Date	Monitoring Interval (24-hr clock)	Time after release, hours	No. of Dye Meas.	Centroid Position from release point, meter		Spread, meters		
				l_0	v_0	σ_L	σ_T	σ_R
22 July	Release	0		0	0	0	0	0
22 July	09:32 – 12:29	2.2	17,389	-3	60	24	17	37
22 July	13:55 – 19:08	8.4	18,345	-84	54	54	35	81
23 July	07:03 – 12:54	25.6	17,785	-229	11	165	95	264
23 July	13:57 – 18:50	32.6	16,958	-207	213	363	95	526
24 July	07:36 – 16:00	50.9	19,931	-87	204	417	219	552
29 July	Release	0		0	0	0	0	0
29 July	08:20 – 12:29	0.9	15,549	-11	-60	27	37	54
29 July	13:49 – 19:33	8.9	19,648	15	-16	31	35	63
30 July	07:02 – 12:57	26.0	20,023	159	23	123	96	192
30 July	14:01 – 19:30	32.8	23,136	-159	-123	101	79	155
31 July	07:02 – 12:20	49.7	20,518	-200	5	128	103	189
31 July	13:35 – 20:14	56.9	26,152	-389	-34	101	95	166

TABLE 5

SPREADING CHARACTERISTICS DURING FIELD TRIAL USED TO COMPUTE NITRATE DISPERSION CHARACTERISTICS

2009 Date	Monitoring Interval (24-hr clock)	Time after release, hours	No. of Nitrate Meas.	Centroid Position from release point, meter		Spread, meters		
				l_0	v_0	σ_L	σ_T	σ_R
22 July	Release	0	0	0	0	0	0	0
22 July	09:32 – 12:29	2.2	11,430	118	274	25	16	40
22 July	13:55 – 19:08	8.4	13,140	-85	58	49	35	77
23 July	07:03 – 12:54	25.6	11,160	-259	-29	126	91	245
23 July	13:57 – 18:50	32.6	9,346	-183	274	283	70	495
24 July	07:36 – 16:00	50.9	9,738	118	274	393	164	618
29 July	Release	0	0	0	0	0	0	0
29 July	08:20 – 12:29	0.9	7,431	-17	-61	30	46	70
29 July	13:49 – 19:33	8.9	11,183	17	-13	30	35	67
30 July	07:02 – 12:57	26.0	13,325	149	28	121	101	190
30 July	14:01 – 19:30	32.8	14,946	-164	-113	97	76	153
31 July	07:02 – 12:20	49.7	11,747	-183	-28	151	95	193
31 July	13:35 – 20:14	56.9	15,569	-367	-57	101	86	153

TABLE 6

DISPERSION COEFFICIENTS DETERMINED FROM RHODAMINE DYE OBSERVATIONS DURING FIELD TRIAL. THE RESULTS FOR APPLICATION 1, 22 TO 23 JULY 2009 INCLUDE THE FIRST THREE OF FIVE SWEEPS

Application	Dates (No. of Sweeps)	Dispersion coefficient, meter^2/sec			Ratio
		E_L	E_V	E_R	E_L / E_V
1	22-24 July (5)	0.440	0.094	0.419	4.7
	22-23 July (3)	0.138	0.046	0.175	3.0
2	29-31 July (6)	0.033	0.023	0.037	1.4

TABLE 7

DISPERSION COEFFICIENTS DETERMINED FROM ISUS BOAT OBSERVATIONS. THE RESULTS FOR APPLICATION 1, 22 TO 23 JULY 2009 INCLUDE THE FIRST THREE OF FIVE SWEEPS

Application	**Dates (No. of Sweeps)**	**Dispersion coefficient, meter^2/sec**			**Ratio**
		E_L	E_V	E_R	E_L / E_V
1 – Dye	22-24 July (5)	0.417	0.084	0.387	4.9
1 – Nitrate		0.342	0.055	0.456	6.2
1 – Dye	22-23 July (3)	0.144	0.048	0.192	3.0
1 – Nitrate		0.081	0.042	0.150	6.2
2 – Dye	29-31 July (6)	0.039	0.026	0.045	1.5
2 – Nitrate		0.043	0.024	0.044	5.4

TABLE 8

DISPERSION COEFFICIENTS DETERMINED FROM 2008 AND 2009 RHODAMINE DYE APPLICATIONS

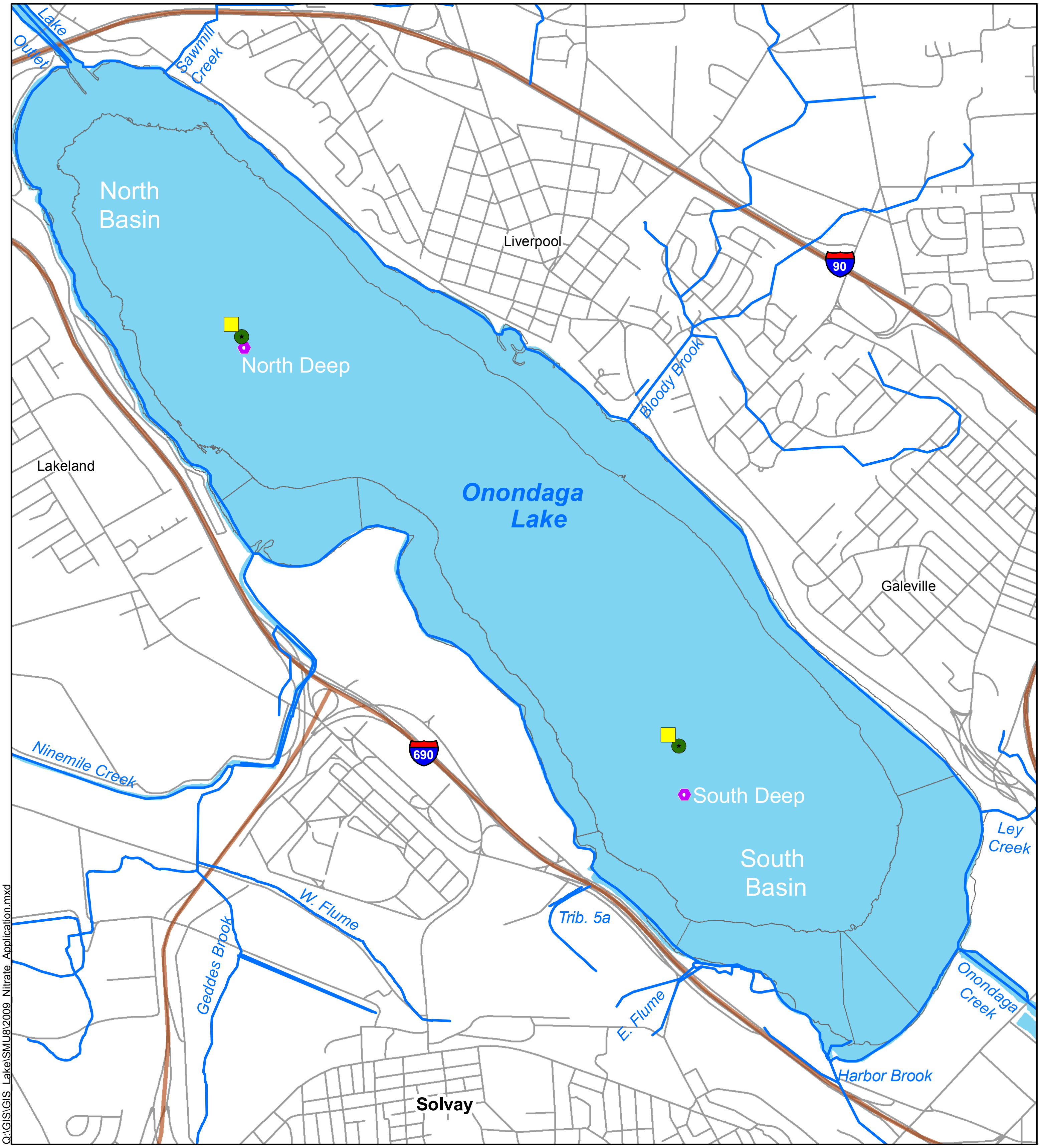
Dye Test (2008) or Application (2009)	**Location**	**Dates**	**Dispersion coefficient, square meters per second**			**Ratio**
			E_L	E_V	E_R	E_L / E_V
1 (2008)	North Basin	22-25 July	0.037	0.016	0.035	2.3
2 (2008)	South Basin	12-14 Aug	0.030	0.0055	0.030	5.4
3 (2008)	North Basin	10-11 Sept	0.021	0.096	0.088	0.2
4 (2008)	South Basin	23-26 Sept	0.018	0.034	0.057	0.5
5 (2008)	North Basin	7-9 Oct	0.14	0.050	0.15	2.9
1 (2009)	North Basin	22-24 July	0.440	0.094	0.419	4.7
	North Basin	22-23 July	0.138	0.046	0.175	3.0
2 (2009)	South Basin	29-31 July	0.033	0.023	0.037	1.4

TABLE 9

HORIZONTAL DISPERSION COEFFICIENTS DETERMINED BY DYE TRACER STUDIES IN HYPOLIMNION WATERS OF OTHER LAKES

Reference	Lake(s)	Dispersion Coefficient (square meters per second)
Murthy (1976)	Lake Ontario	0.016 to 0.38
Imboden and Emerson (1978)	Greifensee	0.01 to 0.10
Coleman and Armstrong (1983)	Tub Lake, Wisconsin	0.000047
Imboden and Joller (1983)	Baldegersee	0.012 to 0.058
Maiss et al. (1994)	Lake Constance, Switzerland	7 to 30
Peeters et al. (1996)	Lakes Alpnach, Vitznauer, Urner, and Neuchatel, Switzerland	0.02 to 0.3
2008 dye applications (5)	Onondaga Lake	0.030 to 0.15 (E_R)
This study: dye applications (2)	Onondaga Lake	0.037 to 0.42 (E_R)

FIGURES



Q:\GIS\GIS Lake\SMU8\2009 Nitrate Application.mxd

- ● 2009 Nitrate Application Location
- 🟨 2009 Vector Velocity Location
- — River or Brook
- — Major Road
- — Minor Road
- — SMU Boundaries

Note:
Nitrate Application in North Basin Occurred on 7-22-2009.
Nitrate Application in South Basin Occurred on 7-29-2009.

0 1,250 2,500 5,000 7,500
Feet

Revised: 08/19/2009

Figure 1

Honeywell

Onondaga Lake
Syracuse, New York

Nitrate Application Locations

PARSONS

301 Plainfield Road, Suite 350; Syracuse, NY 13212 Phone:(315)451-9560

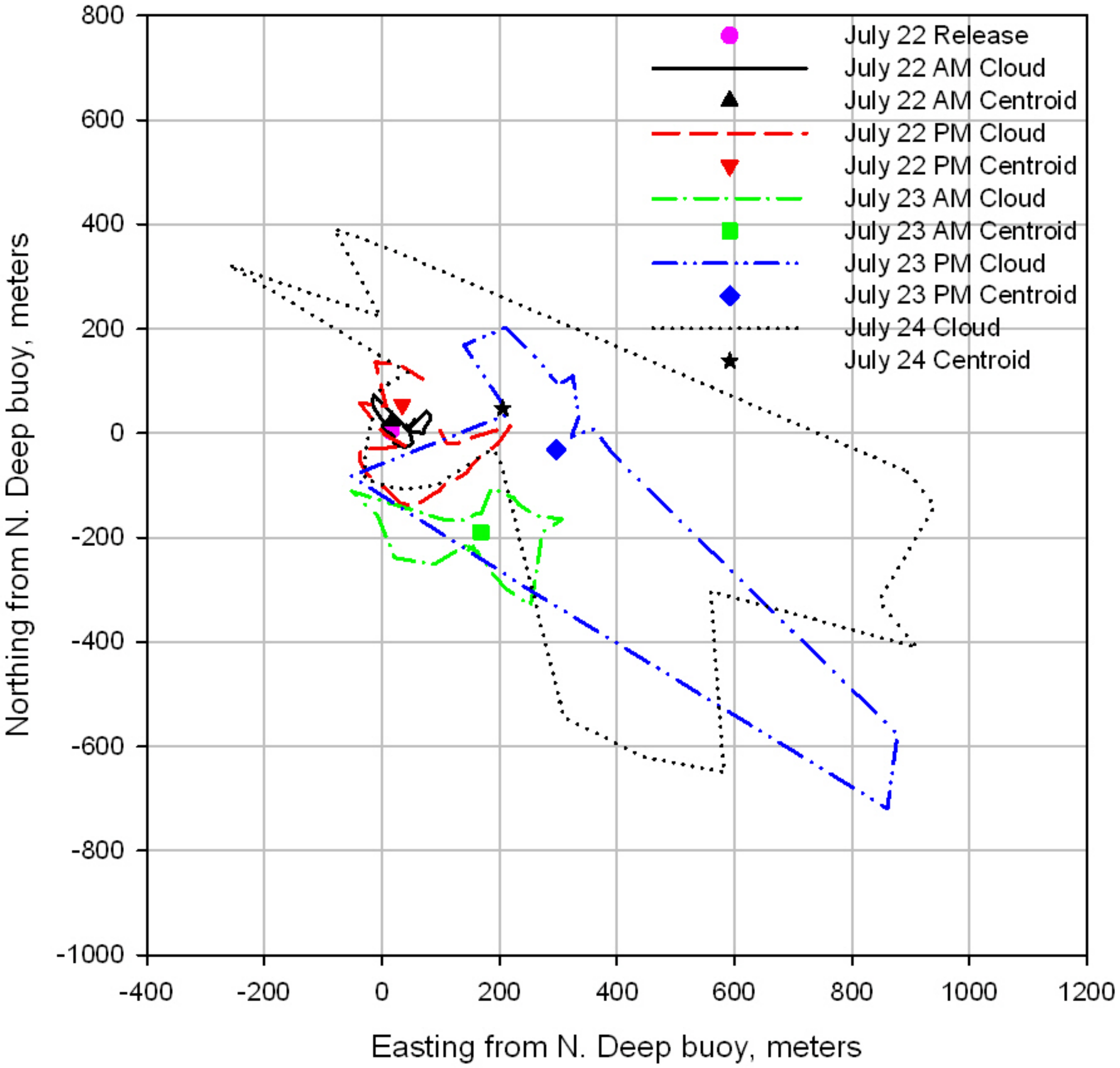


Figure 2. Extent of the rhodamine dye cloud, and its centroid location, for the 22-24 July 2009 application in the North Basin.

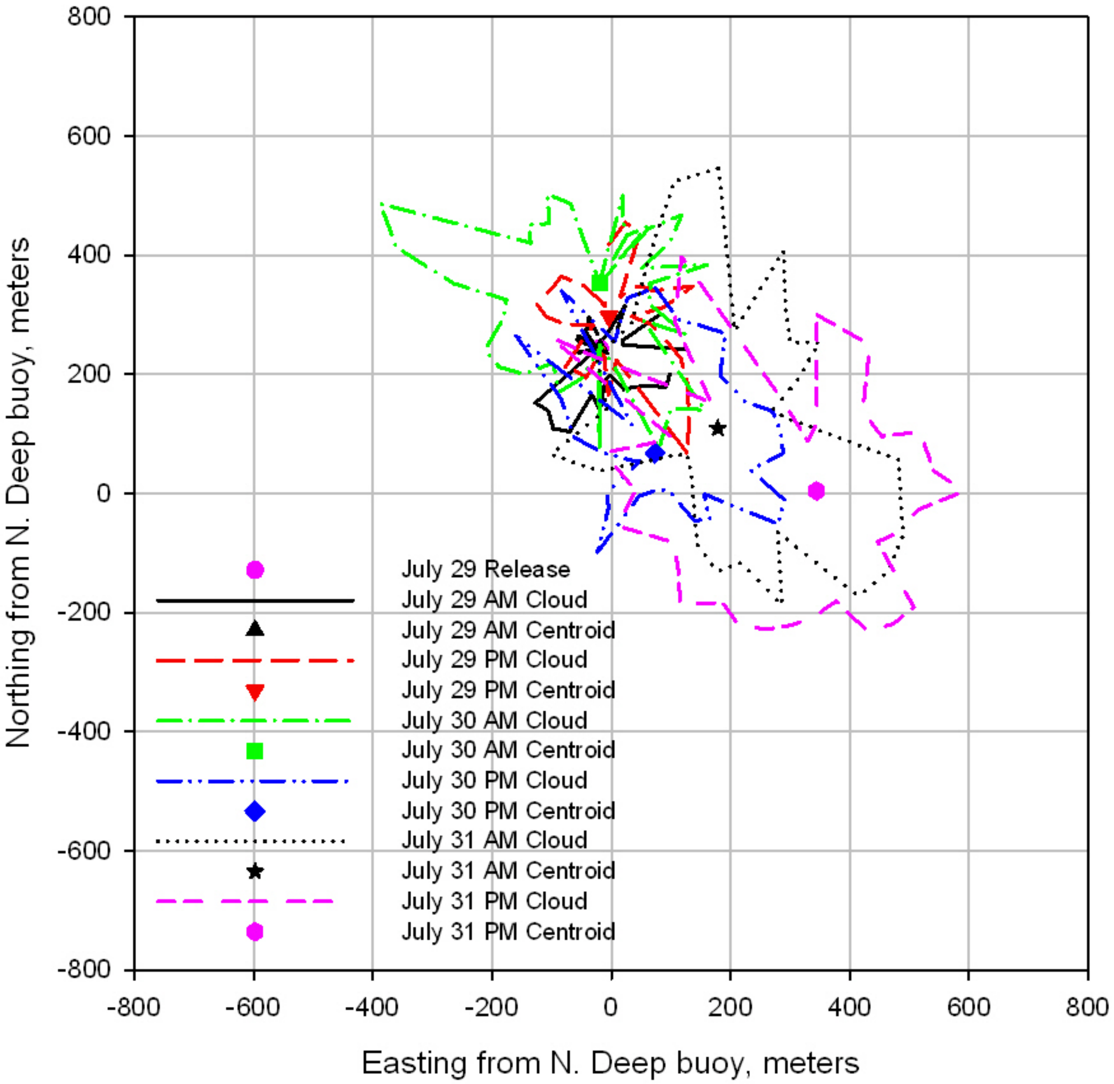


Figure 3. Extent of the rhodamine dye cloud, and its centroid location, for the 29-31 July 2009 application in the South Basin.

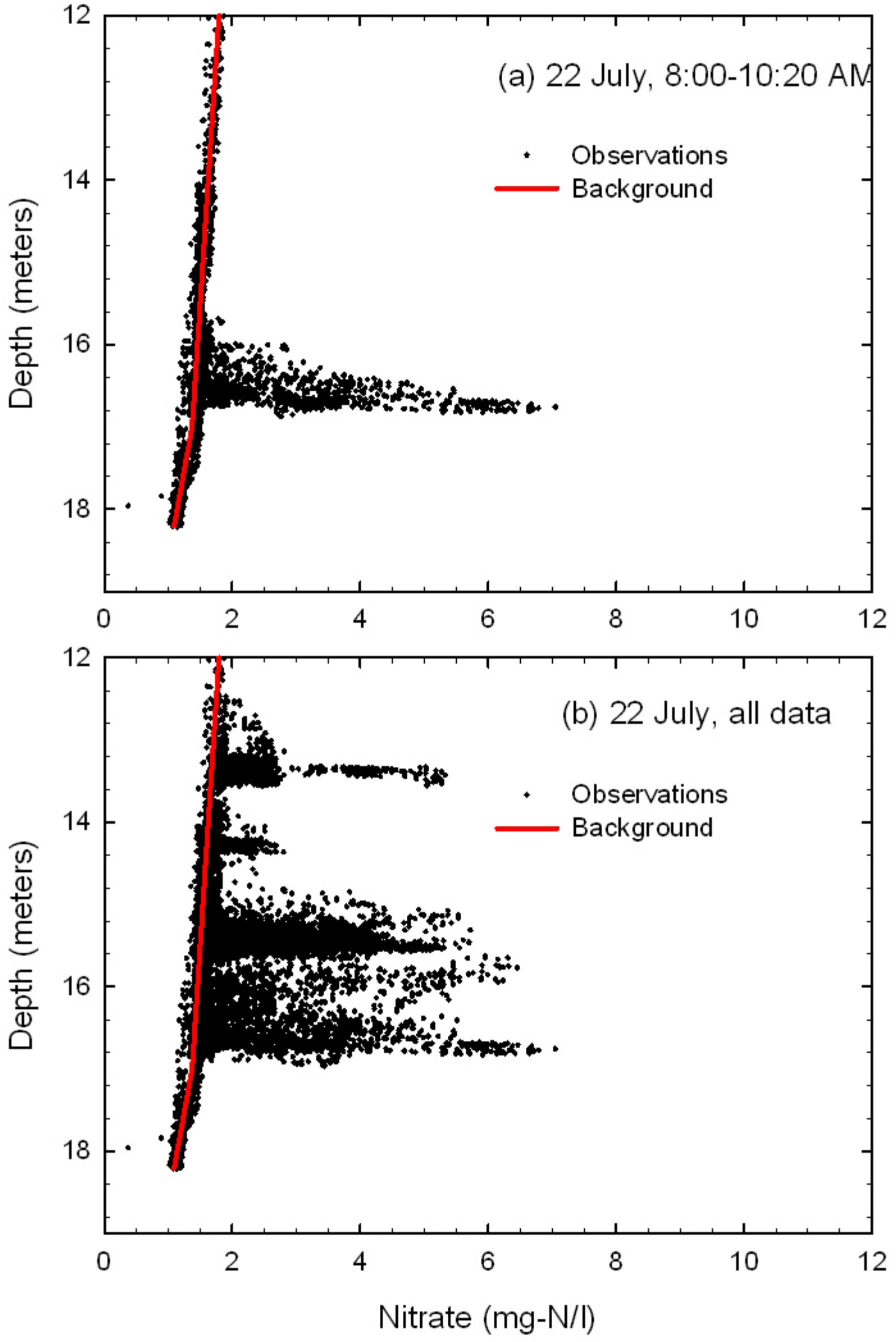


Figure 4. Nitrate concentrations (mg-N/liter) observed near the north deep release point on 22 July 2009: (a) observations and estimated background concentrations from 8:00 to 10:20 AM, (b) all observations on 22 July.

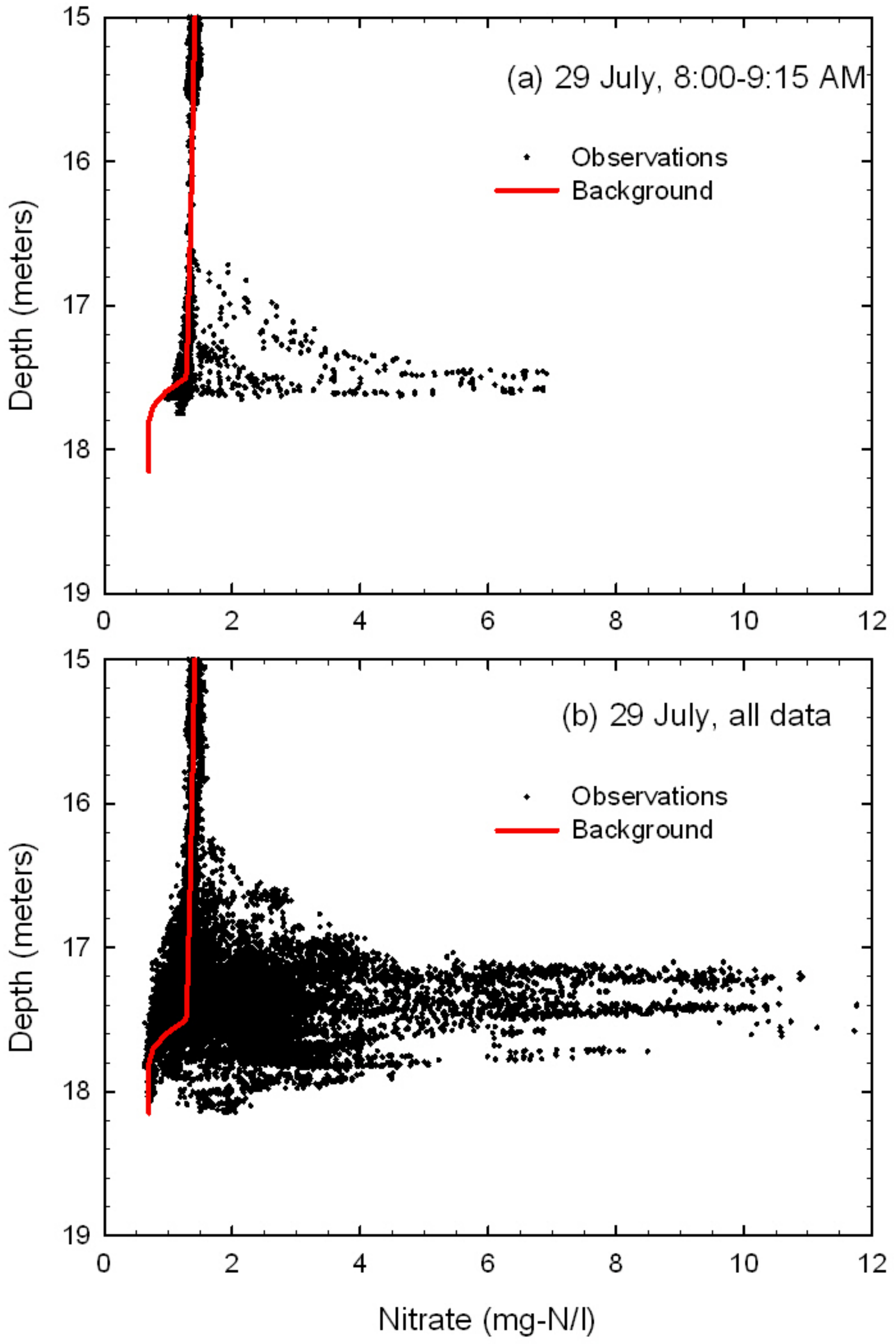


Figure 5. Nitrate concentrations (mg-N/liter) observed near the south deep release point on 29 July 2009: (a) observations and estimated background concentrations from 8:00 to 9:15 AM, (b) all observations on 29 July.

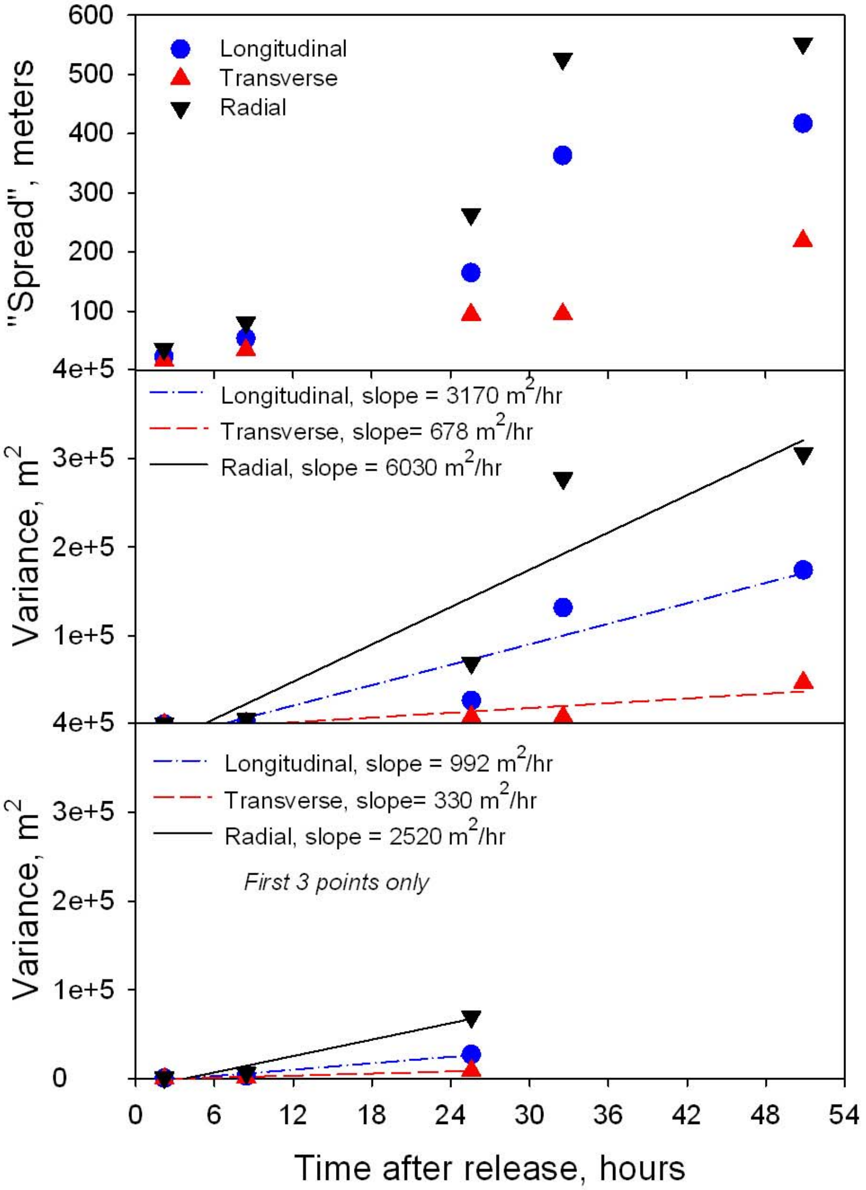


Figure 6. Dispersion results for rhodamine dye for the 22-24 July 2009 application.

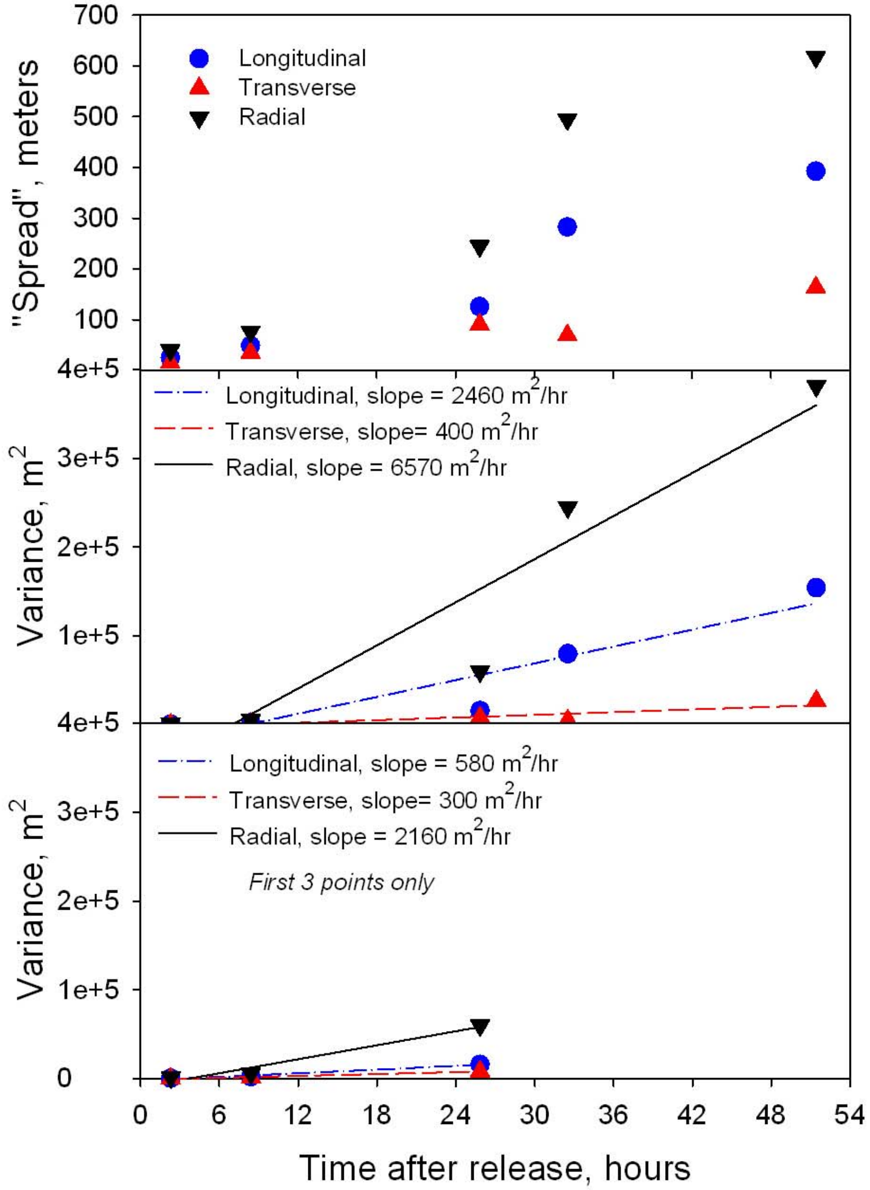


Figure 7. Dispersion results for nitrate for the 22-24 July 2009 application.

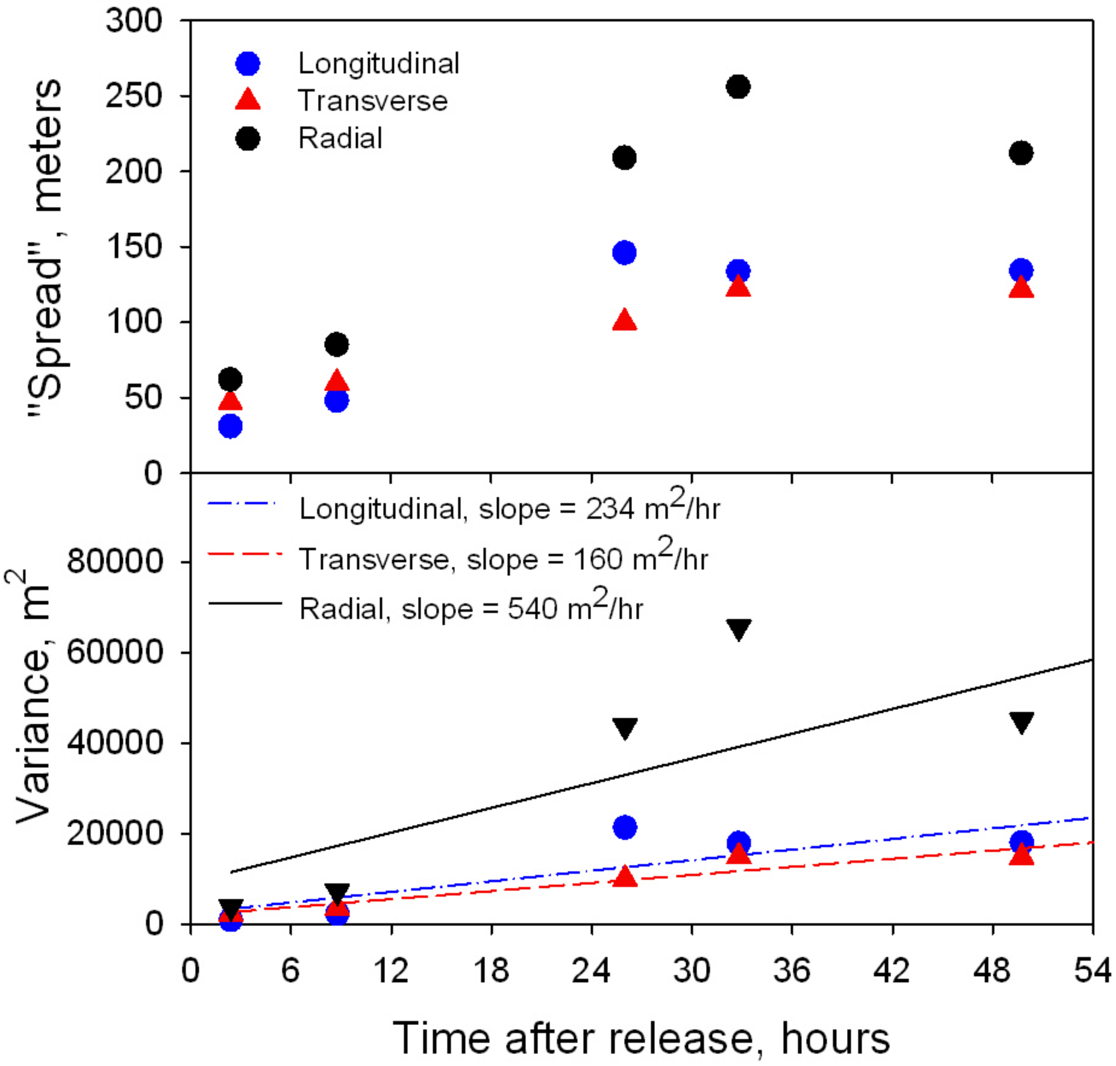


Figure 8. Dispersion results for rhodamine dye for the 29-31 July 2009 application.

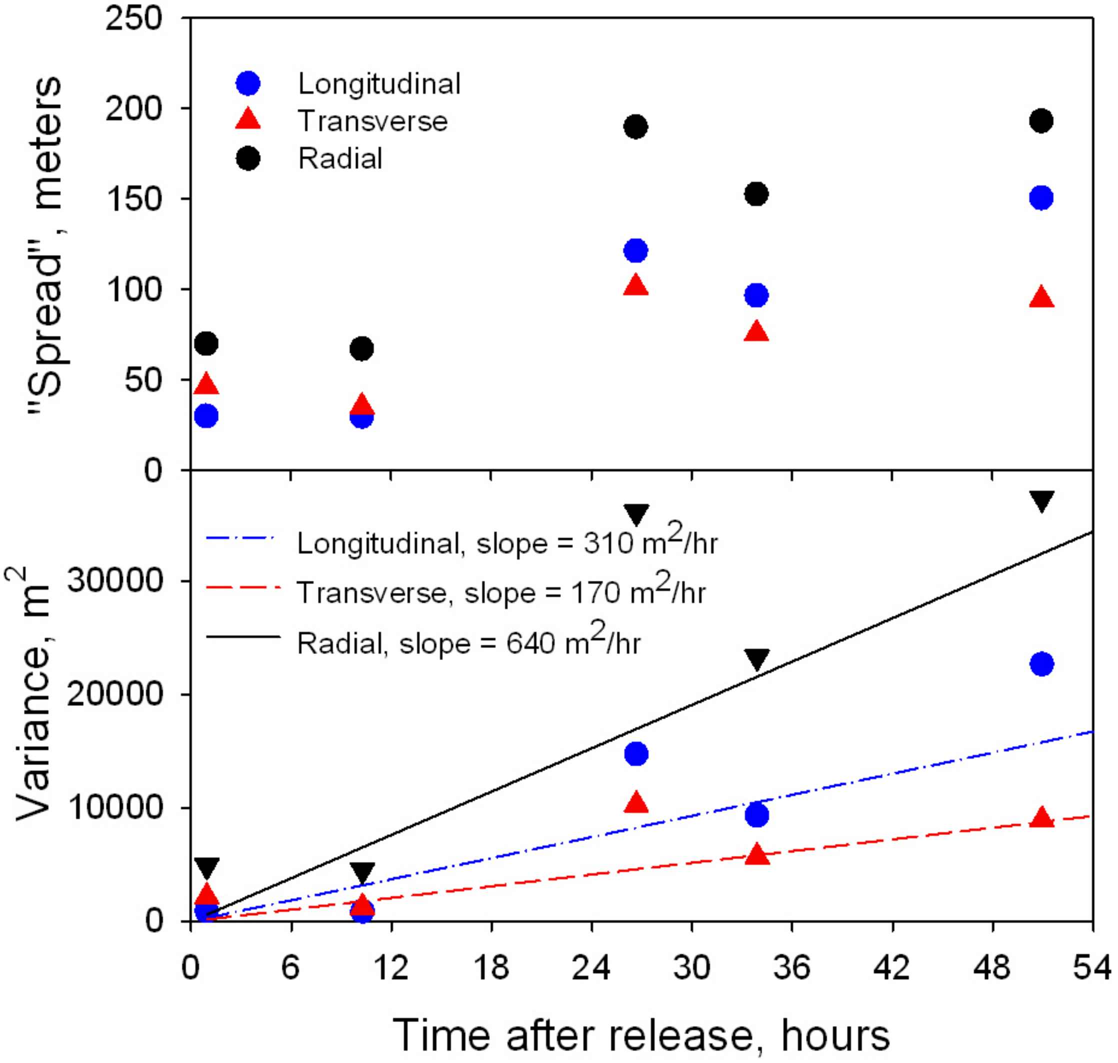


Figure 9. Dispersion results for nitrate for the 29-31 July 2009 application.

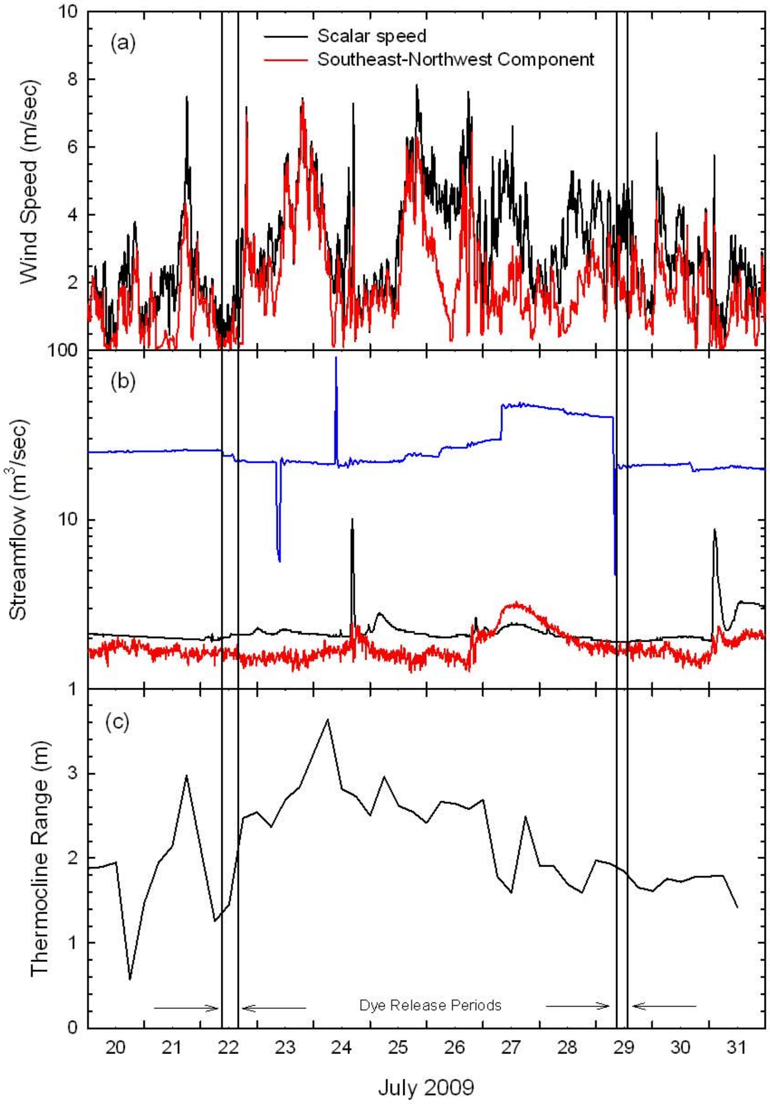


Figure 10. Environmental conditions during the two applications, July 2009: (a) scalar wind speed measured from the UFI South Deep buoy and the wind component along the long axis of the lake basin (southeast-northwest) measured from the Honeywell lakeshore station located at the former Willis Avenue plant site, (b) streamflow for Onondaga Creek at Spencer St. (black line), Ninemile Creek at State Fair Boulevard (red line), and Seneca River at Baldwinsville (blue line), and (c) thermocline range (thickness) determined from thermistor chain deployed at South Deep.

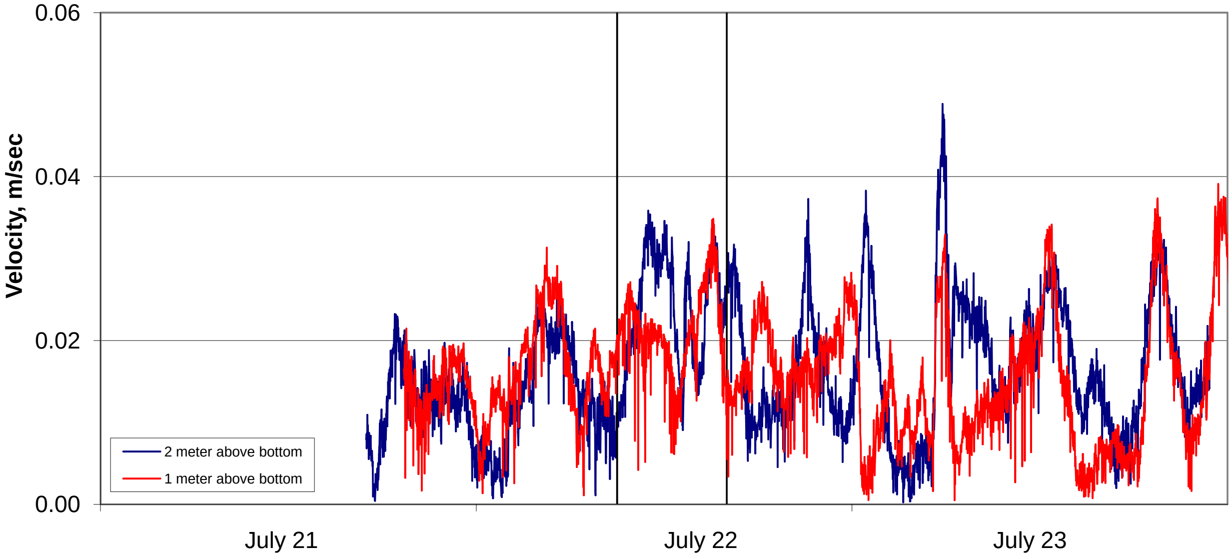


Figure 11a. Acoustic Doppler Velocimeter (ADV) data for the 22 to 24 July 2009 application, measured one and two meters above the lake bottom at north deep

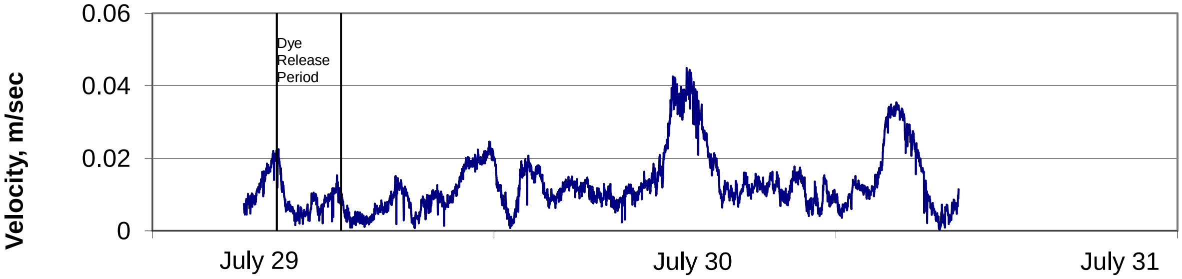


Figure 11b. Acoustic Doppler Velocimeter (ADV) data for the 29 to 31 July 2009 application, measured two meters above the lake bottom at south deep.

APPENDIX A

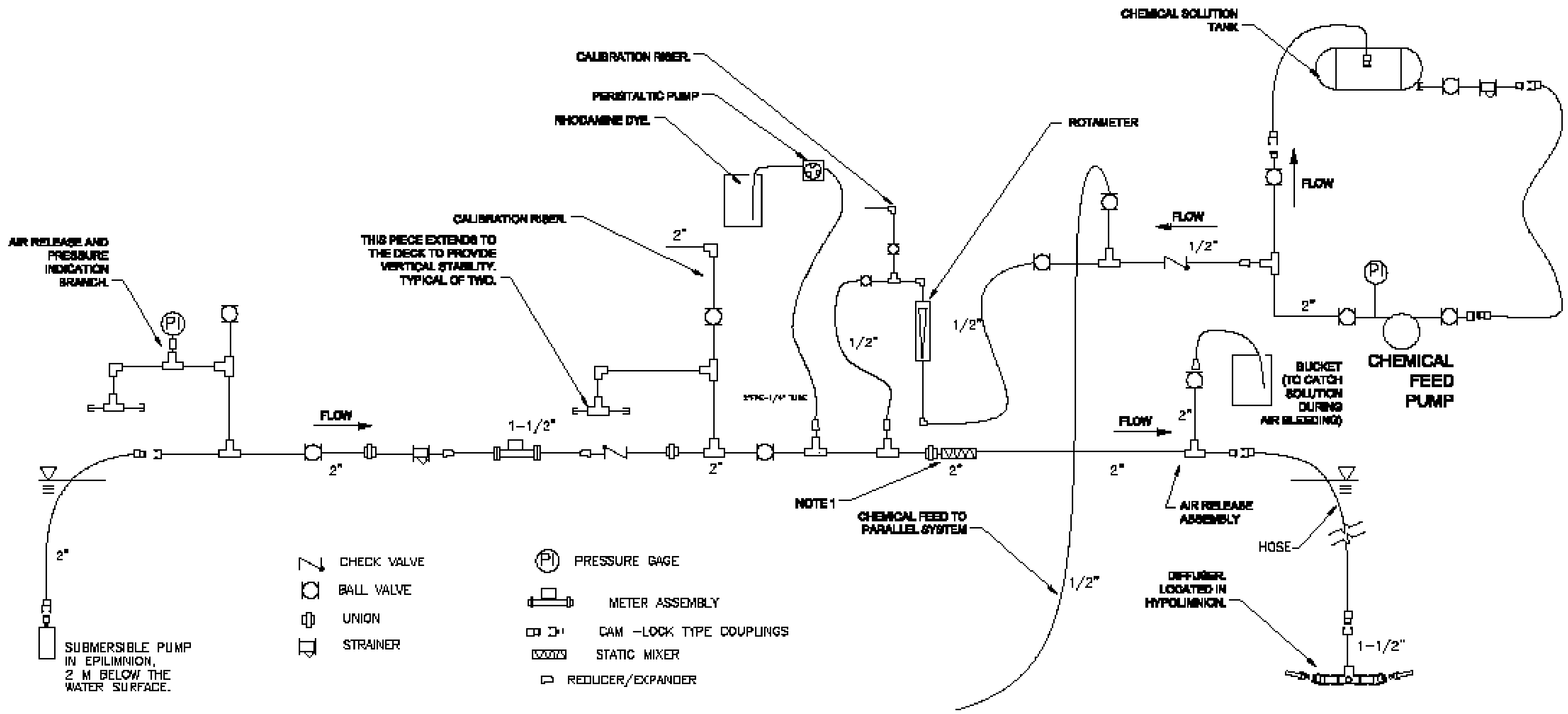
PHOTOGRAPH LOG OF NITRATE APPLICATION PROCEDURE

APPENDIX A

PHOTOGRAPH LOG OF NITRATE APPLICATION FIELD TRIAL PROCEDURE

This appendix describes the procedure used to apply the epilimnion water, Rhodamine-WT dye, and calcium nitrate (CN-8) to the hypolimnion of Onondaga Lake during July 2009 at a depth of approximately 1 and 2 meters above the lake bottom. Figure 1 is a schematic diagram of the piping, instrumentation, and pumps. Figure 2 shows a cross-section view of the apparatus indicating the relative depths for lake water extraction and application of the nitrate, dye, and lake water relative to the barge and the lake bottom.

During the day prior to each application, the location on the lake surface at which the application was to be conducted was marked by a buoy. On the day of each application, the barge (16 ft by 32 ft) was moved into the position indicated by the buoy. A global positioning system (GPS) was used to ensure the barge was at the correct location. The barge was held in placed by two anchors. One large concrete block (weighing approximately 2,000 lbs) held the bow of the barge on location at the application location, and another smaller anchor was positioned off the stern to prevent the barge from rotating due to wind action. A small buoy anchored by a cinder block was placed near one corner of the barge to serve as a visual representation of the barge movement throughout both nitrate applications. During the first application on 22 July, multiple GPS readings were taken throughout the day. During the second application on 29 July, the GPS was unavailable and the small buoy was used as a positional reference. Based on observations of the GPS, the small buoy, and plumbness of the large anchor line, the field crew estimated that the barge did not move more than 2 feet laterally during either application.



NOTES:

1. STATIC MIXER WAS NOT USED IN SECOND TRIAL.
2. TWO SEPARATE PIPING SYSTEMS WERE USED. EACH DESIGNED FOR 60 GPM (NOMINAL)
3. DIFFUSERS WERE SET AT DIFFERENT DEPTHS, ONE DIFFUSER WAS 1 METER DEEPER THAN THE OTHER.

NOT TO SCALE.

LAYOUT2.DWG

DRAFT

Figure 1

Piping and Pumps for 2009
Onondaga Lake Nitrate Application Field Trial
Syracuse, NY

PARSONS

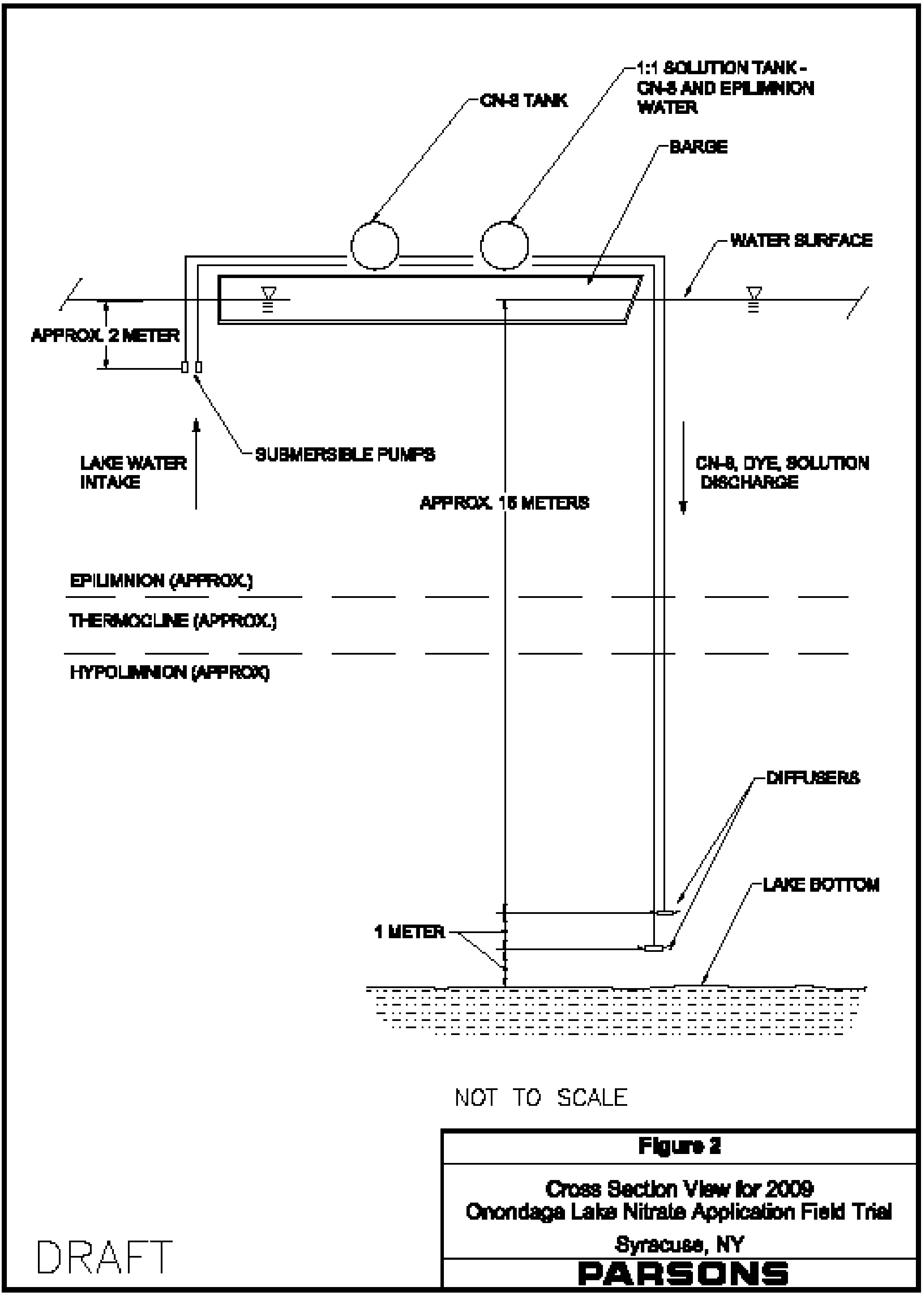


Figure 2

Cross Section View for 2009
Onondaga Lake Nitrate Application Field Trial
Syracuse, NY

PARSONS

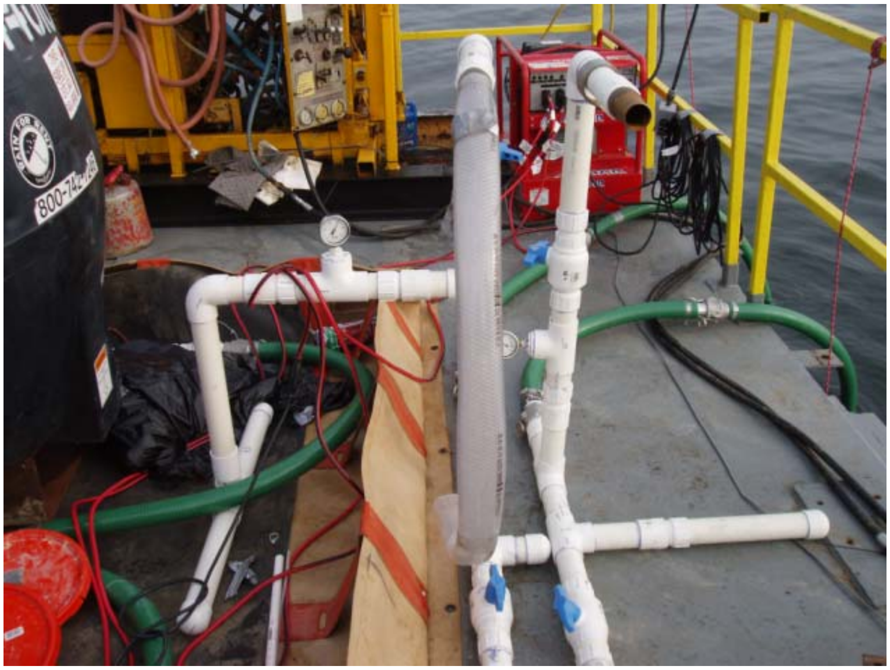
Step 1:

Water was pumped from the epilimnion of the lake approximately 2 meters below the water surface, as seen in the photograph below. Submersible pumps (each rated at 60 gpm) delivered water to the system through the two green hoses shown extended into the water. The pumps were powered by a 9,000-watt, gasoline-powered generator (located at the corner of the barge).

Raw water intake hoses and generator.

Step 2:

The green flex hosing carrying epilimnion water connected into the PVC piping on the barge where water first passed a branch with an air release and pressure gage. The pressure gauge was used to ensure that the pump worked within its design operating range. The air release was used to release air that may have been trapped in the line near the upstream end. The flexible hose shown on the left air release was used to direct the air-water mixture off the deck. The flexible hose was removable and could be used in other applications where it was desired to direct water from the system back to the lake.



Raw water pressure gages and air bleed risers.

Step 3:

Next the water flowed through strainers to trap debris that may have been present in the raw lake water. The strainers were placed upstream of the flow meters to preclude debris interfering with the meter operation.

The flow meters were positive-displacement and were installed to provide accurate measurements of the amount of epilimnion water flowing through the system. The meters were calibrated before the first application. Valves was arranged to force water through the vertical 2-inch pipe shown at the right of the photo. The flexible 2-inch hose, previously mentioned, was attached to the barbed adaptor and positioned to discharge into a barrel. Both flow meters were calibrated and accurate to within one gallon.

Check values were positioned downstream of the flow meters. The check values ensured that nothing added to the system downstream of the valves could reverse flow and release into the epilimnion.

Raw water strainers, flow meters, and calibration riser.

Step 4:

Next, Rhodamine-WT dye was injected into the main line. Peristaltic pumps were used to transfer the dye from the dye bucket directly into the main line. The peristaltic pumps had been calibrated previously to relate the dial setting on the pumps to the rate of flow. Based on dye tracer test work conducted by UFI during 2008, the field trial team decided on a dye application rate of approximately five gallons throughout one six-hour period.

Rhodamine dye pumps.

Rhodamine dye application points.

Step 5:

There were two 600-gallon tanks on board, each of which was provided secondary containment equal to greatest volume of the tanks. One tank contained only calcium nitrate (CN-8), while the other tank was used to dilute the CN-8 with epilimnion water at a 1:1 mix. The solution of CN-8 and water was added within the pipeline immediately downstream of the dye.

600-gallon tanks with secondary containment.

Pumping the 1:1 solution was preferred over pumping CN-8 alone, because pumping the 1:1 solution reduced the density and the viscosity of the injected fluid. The reduced density and viscosity increased the accuracy of the rotameters that were used to measure the flow rate of the injected mix. The rotameters were calibrated for each application. During each application, the rotameter reading was within 25% of midscale.

Rotameters for 1:1 split of CN-8 and epilimnion water

The two photos on the next page show the chemical solution piping. The 1:1 solution was pumped in a loop from the bottom of the tank to the top of the tank. The circulation pump is shown in the center of the first photo. The lines were tapped from this loop. A valve in the loop was adjusted to provide the back pressure needed to force the 1:1 solution into the main water line. The lines were fitted with check valves, ball valves for setting flow (based on the readings of the rotameters, air release/calibration points, and flow meters (the rotameters) to control the addition of CN-8.

CN-8 solution (1:1 solution) system.

1:1 solution lines upstream of static mixers and the static mixers.

Step 6:

Next, a static mixer was used downstream of 1:1 solution points to ensure complete mixing of the water, CN-8, and dye. After the first application, the static mixer was removed due to the head loss it was creating which resulted in decreased outflow rates. During the second application, flow rates increased without the mixer in place, and it was determined that the water, CN-8 and dye were still becoming well-mixed, due to turbulence in the downstream piping and diffusers, prior to release.

Step 7:

The final step on the barge was another air release apparatus, the purpose of which was to release any air that may have been trapped at the top of the discharge pipe. An entrapped air bubble at this point would have increased back pressure and reduced flow rate. Note that the air release apparatus is at the high point of the discharge line. The 5-gallon pails shown in the photo below were placed to collect any solution mixture that may have escaped during manual operation of the air release ball valves.

Air release apparatus at discharge.

Step 8:

The epilimnion water, dye, and CN-8 flowed downward through two diffusers positioned near the bottom of the hypolimnion approximately 1 meter and 2 meters above the lake bottom. Piping on the barge between the chemical feed and each diffuser was the same for both diffusers. Each diffuser was used throughout both applications. Both diffusers were four-port diffusers; each port had a 0.75-inch diameter nozzle that pointed up approximately 10 degrees above horizontal (see the last photo on the next page). Each diffuser was weighted down by a 25-pound weight to ensure that both diffusers remained stationary throughout the six hours of release. The field crews observed the hoses extending into the water remained vertical and straight down throughout both applications indicating the diffusers remained stationary.

Discharge lines off forward starboard side barge.

Diffuser before being submerged.