REPORT ON THE 2008 DYE TRACER STUDY TO EVALUATE TRANSPORT AND MIXING IN THE HYPOLIMNION OF ONONDAGA LAKE

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LIST OF ACRONYMS

GPS	Global Positioning System
NYSDEC	New York State Department of Environmental Conservation
ROD	Record of Decision
SMU	Sediment Management Unit
UFI	Upstate Freshwater Institute
ug/l	Microgram per liter (one ug/l in water is one part per billion)
USEPA	United States Environmental Protection Agency
USGS	United State Geological Survey
YSI	Yellow Springs Instruments

DEFINITIONS OF TERMS

Epilimnion – During summer stratification, the upper portion of the water column in the profundal (deep water) zone (*i.e.*, SMU 8 in Onondaga Lake) between the water surface and 30-ft (9-meter) water depth in Onondaga Lake. The epilimnion waters are warm and well-mixed by wind and waves.

Hypolimnion - The lower portion of the profundal 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 waters are, unlike the epilimnion waters, not well-mixed by winds or inflows to the lake.

Profundal 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 littoral zone closer to shore.

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 changes significantly with depth is referred to as the thermocline.

EXECUTIVE SUMMARY

Five dye tracer tests were conducted in the deep water portion of Onondaga Lake for Honeywell from late July through early October 2008 following a late June pre-test. This work was performed in accordance with a work plan approved by the New York State Department of Environmental Conservation (NYSDEC) before the work began.

Each of the dye tracer tests involved the release of four or eight liters (one or two gallons) of rhodamine WT dye over a short period of time from a temporary diffuser placed in the hypolimnion of the lake at a water depth of 14 to 17 meters (46 to 56 ft). Following release, measurements of dye concentration, temperature, depth, and position were made using boat-based sensors. Wind conditions were generally low during these tests. The horizontal dispersion coefficients calculated from dye cloud monitoring data varied from 0.030 to 0.15 square meters per second with a mean of 0.073 square meters per second. These dispersion coefficients are consistent and appropriate for use in the design and analysis of a system for releasing a dissolved electron acceptor (*i.e.*, nitrate and/or oxygen) into the hypolimnion of Onondaga Lake. Additional data useful for quantifying horizontal dispersion will be collected by Honeywell during the summer of 2009 as part of the nitrate application field trial.

1.0 INTRODUCTION

Addition of an electron acceptor, nitrate and/or oxygen, to the hypolimnion of Onondaga Lake is being evaluated as part of the remedy being implemented by Honeywell for Onondaga Lake in accordance with the remedy prescribed by the NYSDEC and the United States Environmental Protection Agency (USEPA) in the Record of Decision (ROD) for the lake bottom (NYSDEC and USEPA, 2005) and the 2007 consent decree signed by Honeywell and NYSDEC. The purpose of adding an electron acceptor is to reduce the release of methylmercury from the profundal sediments during summer stratification. Either nitrate or oxygen would be added to the hypolimnion from one or more fixed release locations within the hypolimnion, or from a boat-based release system. For either nitrate addition or oxygenation, and for either a fixed or boat-based release system, a reasonably uniform distribution of the added chemical over the sediment area from which methylmercury release may occur is required for successful operation. The design of a system to attain such a uniform distribution requires knowledge of the horizontal dispersion coefficient in the hypolimnion of the lake during summer thermal stratification.

Studies of horizontal dispersion or diffusion in the hypolimnion of stratified lakes are rare (Murthy 1976, Fischer *et al.*, 1979, Coleman and Armstrong 1983, Maiss *et al.*, 1995, Peeters *et al.* 1996). This may be due, at least in part, to the fact that sources or sinks of pollutants are often relatively uniformly distributed in the horizontal within the hypolimnion, so that significant horizontal gradients in concentrations of interest do not develop. Artificial point sources of pollutants, such as wastewater outfalls, are most often located in the surface waters because these oxygenated layers have greater capacity to assimilate pollutants.

This report describes dye tracer tests conducted to directly measure the horizontal dispersion coefficient in the hypolimnion of Onondaga Lake during thermal stratification. This series of tests was based on the rapid release of a quantity of rhodamine WT fluorescent dye into the hypolimnion, followed by tracking of the movement and spreading of the resulting cloud of dye. These dye tracer tests were conducted under generally low wind and low tributary streamflow conditions during the summer and early fall of 2008. The magnitude of dispersion was determined for each of the five dye release periods. The relationship of the dispersion coefficient to commonly observed environmental conditions (wind, tributary inflow, thermal stratification) and to direct and indirect measures of water motion in the hypolimnion of the lake was evaluated.

Results from the 2008 dye tracer study provide information required for the design of a long-term nitrate and/or oxygen application system for the lake. An analysis of transport and mixing conditions in the hypolimnion that may be used to support the design of an application system would likely involve the application of some type of numerical model of spatial and perhaps temporal variations in nitrate or oxygen concentrations in the hypolimnion. The model used could cover the range from a simple steady-state analytical model that would be based on numerous simplifying assumptions to a complex, dynamic, three-dimensional numerical model such as ELCOM (Hodges *et al*., 2000). Regardless of the model used, the horizontal dispersion coefficient must be specified as a model input.

A nitrate application field trial, scheduled for 2009, will provide additional information on dispersion within the hypolimnion. Design of a pilot test and a full-scale nitrate application system for Sediment Management Unit (SMU) 8 would likely include use of a modeling tool to predict movement of nitrate within the hypolimnion. Dispersion estimated during the 2008 dye tracer tests and the 2009 field trial would be a key model input parameter. The purpose of this modeling tool would be to help project the extent to which nitrate would need to be added to the hypolimnion to minimize methylmercury formation when nitrate concentrations reduce during summer months toward levels that can result in increased methylmercury water concentrations.

A note is made here regarding the use of the word dispersion to describe the observed spreading in the hypolimnion of Onondaga Lake. Diffusion refers to the effect of turbulent eddies, or random fluctuations in motion, in spreading of a solute. Dispersion refers to spreading that is caused by spatial variations in the sustained or time-averaged flow (not eddies or fluctuations). It is known that vertical variations in sustained water motion occur in the stratified hypolimnion of lakes and reservoirs (Fischer *et al*., 1979; Schlatter *et al*,. 1997). These vertical variations may be due to boundary layer-type conditions near the lake bottom, or may result from intrusions propagating from the sloping sides of the basin into the interior of the hypolimnion, with compensating return flow toward the boundary at nearby depths. The thickness of layers propagating in this manner are typically on the order of tens of centimeters, which is smaller than the thickness of the dye cloud that was created in the later tests, as described below. As a result, it is likely that some of the spreading observed in these dye tracer tests was due to dispersion and the remainder of the spreading was associated with turbulence. The term “dispersion coefficient” is used to describe the combined effects of these processes as identified or captured by spreading of the tracer cloud.

2.0 DYE TRACER TEST METHODS AND RESULTS

One pre-test and five dye tracer tests were conducted in Onondaga Lake for Honeywell during the summer and fall of 2008. Regulatory agencies were notified approximately one week prior to beginning each dye tracer test. A pre-test was conducted on June 26 to test the operation of the equipment in the field. This was followed by five dye tracer tests over the time period from July 22 to October 9, 2008. A summary of the tests is given in Table 1. The preliminary schedule for dye tracer tests presented in the work plan for this study (Upstate Freshwater Institute - UFI, 2008) included a pre-test and four tests. A fifth test in the north basin was added in early October, for a total of three tests in the north basin and two in the south basin.

The work plan stated that dye concentrations would be measured on the day prior to each test in order to confirm that background levels were reached before initiation of the next test. However, residual dye from previous tests was not measured and most likely had a negligible effect, because consecutive tests were conducted at least two weeks apart and in different basins.

The equipment used in releasing the dye included two pumps with accompanying hoses and 12-volt batteries; two 55-gallon mixing containers; and a diffuser pipe constructed from 8 ft-lengths of 1.5-inch diameter PVC pipe. The dye tracer chemical used was rhodamine WT, 20% by weight solution, supplied by Keystone Aniline Corp. Following release into the lake, *in situ* monitoring of dye concentration in the lake was conducted using a Yellow Springs Instruments (YSI) Model 6130 rhodamine WT fluorometric sensor. Also included in this YSI sensor package were water temperature and depth sensors, and a global positioning system (GPS) position instrument. This sensor package was connected via a long cable to a YSI data logger to record all measurements (dye concentration, water temperature, depth, latitude and longitude) at a selected time interval, which was generally five seconds. This stream of measurements was displayed on the data logger during monitoring. The sensors were maintained at depth in the water column by manually raising or lowering the cable and by its own weight. As a result, maintaining a sensor depth of roughly 16 meters required the boat to move slowly during the tracking operation.

The initial approach to dye release was to prepare a batch of diluted dye, the density of which matched the density of the ambient waters of the lake at the selected depth of release. This volume of diluted dye was then pumped through the diffuser and into the lake with a minimum of artificial mixing. The 8 ft long diffuser pipe contained a number of very small (1/16-inch diameter) holes, with the diffuser pipe oriented horizontally. Given that the concentrated (20% by weight) solution obtained from the manufacturer was considerably more dense (specific gravity of approximately 1.15 compared to 1.00 for fresh water) than ambient lake waters at any depth, neutral buoyancy was achieved by mixing the raw dye solution with a pre-determined volume of lake surface water. During the pre-test conducted on June 26, 2008, the diluted dye remained at the depth of release (16.9 meters; Table 1), thus confirming the initial dilution of the prepared batch dye solution. In addition, the fluorometer was able to measure detectable concentrations for a number of hours after the release. However, there was some concern during the pre-test that the resulting dye cloud was relatively thin and hard to detect.

Nonetheless, the pre-test was successful in meeting the primary goal of delivering the dye to the target depth.

On July 22, 2008, a batch mixture of 4 liters (1.1 gallons) of the concentrated dye and 340 liters (90 gallons) of ambient lake water was released at a depth of 15 meters (49 ft) in the north basin near the North Deep buoy. The diluted dye was released over a period of about 20 minutes, at a rate of about 17 liters per minute (4.5 gallons per minute). Subsequent tracking of the dye cloud indicated that, despite the fact that eight times more dye was used relative to the pre-test, it was difficult to detect the presence of a cloud; significant dye concentrations following release were very "patchy", and were found only in a very thin vertical layer. While measurable dye concentrations were detected on the following days through July 25, it was determined that a greater amount of dye and a greater level of initial mixing during dye release would increase the initial size and uniformity of the dye cloud and allow dye tracking to proceed more easily.

As a result, for the four subsequent dye tracer tests (Table 1), the following changes were made. First the raw dye volume was increased from 4 to 8 liters (approximately 1 to 2 gallons). Second, changes were made to increase the level of mixing induced by the diffuser so as to initially create a dye cloud thicker in the vertical plane and less patchy in the horizontal plane. These changes were achieved by using larger capacity pumps, larger diameter hoses, and by orienting the diffuser pipe in the vertical direction. Due to limitations on the volume of a pre-mixed, neutral buoyancy batch solution that could be prepared on the boat, operations were changed to a limited-duration, continuous-flow mixing and release operation. Ambient lake water from the selected depth of release was pumped into a mixing container at a rate of about 75 liters per minute (20 gallons per minute). Over a period of approximately 40 minutes, raw dye solution was continuously added to the mixing container. Turbulence in the container was sufficient to cause rapid mixing of the dye. A second identical pump was used to move the resulting solution from the mixing container through the diffuser and into the lake. The dilution of the dye in the mixing container was sufficiently large so that the density of the mixture was not significantly increased by addition of the dye; because the makeup water came from the depth of release, the resulting mixture was neutrally buoyant in the water column. This modified release procedure produced a thicker, more continuous dye cloud.

Monitoring of the dye cloud consisted of making a series of passes through the cloud. Ideally, a pass through the dye cloud would consist of moving the boat in a straight line beginning outside the cloud where no dye was present, proceeding into the cloud and through the opposite side until again no dye was detected. Again ideally, a number of such passes would produce a complete "snapshot" or picture of the horizontal distribution of the dye. The goal of the monitoring was to obtain two such "snapshots" or "sweeps" of the dye cloud per day. However, a full day was commonly needed to make a sufficient number of measurements to acquire a reasonably complete representation of the horizontal distribution of the cloud. The time required to acquire a reasonably complete sweep was largely due to the practical constraint of making measurements from a slow moving boat using a single sensor, and the uncertainty in knowing how the cloud was moving and spreading from one day to the next.

Water motion and resulting turbulent mixing in the hypolimnion of stratified lakes has been linked to internal wave or seiche activity, sometimes referred to as “rocking of the thermocline”. This wave motion is largely driven by wind. In that design of a nitrate addition or oxygenation system would focus on low mixing conditions, an effort was made to conduct the dye tests under low wind conditions, or at least to avoid high wind periods. As shown in Table 1, three of the tests were conducted in the North Basin, and the remaining two were conducted in the South Basin.

The rate of degradation of rhodamine WT in the hypolimnetic water column has potentially important implications for tracking the dye cloud over time and for persistence of the dye within the lake. In surface water applications the primary loss process for rhodamine WT is degradation by ultraviolet light. Significant ultraviolet light does not reach the hypolimnetic layers of Onondaga Lake where these dye tracer tests were conducted. However, other loss processes, including adsorption to suspended particulate matter, could affect the persistence of rhodamine WT in the hypolimnion. A holding-time evaluation was conducted to determine the system-specific loss rate of rhodamine WT in the hypolimnion of Onondaga Lake.

On August 11, 2008, 19 biochemical oxygen demand bottles (each with a volume of approximately 10 ounces) were filled with water from 18 meter water depth of the hypolimnion at the South Deep location. All samples were transported to the UFI laboratory and spiked with rhodamine WT to a nominal concentration of 25 µg/L (micrograms per liter or parts per billion) on August 11. Five of these samples were analyzed immediately, using the same YSI fluorometer employed in the field, to quantify variability associated with sample preparation. The five replicate samples yielded a mean value of 25.5 µg/L and a standard deviation of plus or minus 0.4 µg/L, which indicated a high degree of accuracy and precision (Table 2). In order to simulate conditions in the hypolimnion, the remaining 14 spiked samples were refrigerated (8°C) under dark, anoxic conditions until analysis. These samples were analyzed one at a time over the following 25 days (August 11 through September 5, 2008). Fluorometric concentrations remained nearly constant over 25 days, indicating no measurable degradation of rhodamine WT (Table 2). Based on these results, it was concluded that no significant degradation of the rhodamine WT dye occurred during the dye tracer tests, so the tracer mass does not appear to change physically or chemically over the timeframe of interest.

Three snapshots of the dye cloud were acquired during September 10–11, 2008. Dye concentrations measured on September 11 were less than 10 µg/L and the dye cloud at that time had grown to about 100,000 square meters (25 acres) in size. As a result, it was decided that attempting to track the dye cloud on September 12 was unnecessary and unlikely to be productive.

3.0 DISPERSION CALCULATIONS FROM 2008 DYE TRACER TEST RESULTS

With dye concentration measurements being made rapidly (12 per minute) over many hours, a large number of measurements were made. The position or location of each individual dye measurement was measured by the GPS sensor and recorded as latitude and longitude. These 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:

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

where the rotation angle $\theta = -45$ degrees.

The method of moments (Fischer *et al.,* 1979 and Murthy, 1976) was used to compute the dispersion coefficient. This method is consistent with procedure described in Appendix A of the work plan (UFI, 2008). The position of the center of mass or centroid of the dye cloud was computed from

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

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

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 $\Delta l_i \Delta v_i$ area in the horizontal plane associated with this measurement. The summations in the numerator and denominator of Equation 2 are made for all measurements making up an individual sweep or snapshot of the dye cloud. For the five 2008 dye tracer tests (Table 1), between three and five sweeps of the dye cloud were conducted as part of each dye tracer test, with thousands of individual measurements comprising each sweep and thus considered in the summations. It should be noted that an approximation symbol used in the expressions for l_0 and v_0 in Equation 2, 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 could be fully evaluated. In practice, this ideal cannot be achieved because a single dye sensor cannot fully observe the entire areal extent of a dye cloud.

The "variance", a statistical measure of spread about the mean, of the dye cloud in the longitudinal (σ_L^2) and transverse (σ_V^2) directions were computed by

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

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

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 Equation 3 involve all of the measurements made in an individual sweep of the dye cloud, and l_0 and v_0 are computed from Equation 2 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

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

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

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 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

$$\sigma_R^2 \approx \frac{\sum r_i^2 \, C_i \, 2\pi r_i \, \Delta r_i}{\sum C_i \, 2\pi r_i \, \Delta r_i} \qquad \text{(Equation 5a)}$$

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

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

In equations 2, 3, and 5a, the concentration C_i was determined as follows:

$$C_i = \begin{cases} C_i & \text{if } C_i \geq C_L \\ 0 & \text{if } C_i < C_L \end{cases} \qquad \text{(Equation 6)}$$

where C_L is a lower limit to concentrations to be used in the calculation of dispersion. The detection limit of the YSI Model 6130 fluorometer is 0.5 micrograms per liter (µg/l). A number of analyses were conducted to investigate the sensitivity of the calculations of the selection of C_L. For example, the sensitivity of the calculated spread (Equations 3a, 3b, and 5a) for the data collected on October 9, 2008 is shown in Table 3. The spread is quite insensitive to values of C_L up to 1 µg/l, which is twice the detection limit. A value of C_L = 0.1 µg/l was used here. This allowed virtually all of the measurements to be used in the calculations, even the less reliable measurements below the detection limit of the sensor.

The monitoring periods that comprise each sweep of the dye cloud for the five 2008 dye tracer tests are summarized in Table 4. Generally a sweep was comprised of all the measurements made on a particular day. However, on September 11, October 7, and October 8, 2008, two sweeps of the dye cloud were made each day. Table 4 also lists that average elapsed time after the dye release for the measurements included in a particular sweep, and the number of dye concentration (fluorometer) measurements. For each of the sweeps of the dye cloud, 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 (Table 4).

An example of the one of the sweeps of the dye cloud is shown in Figure 2, which shows the 3213 measurements made on the afternoon of September 10 (Test 3, Tables 1 and 4). The dye concentration measurements are shown as a function of longitudinal position *l*. The spread of the cloud in the longitudinal direction (σ_L), computed from Equation 3a with the summations performed for all 3213 points, is shown. Note that the spread (82 meters or 270 ft) is about three times less than the extent or size of the cloud (225 meters or 740 ft). While the size or extent of the cloud may be visually more representative, it is a descriptive and informal measure; the spread σ_L is the quantity from which the dispersion coefficient is computed (Equations 4 and 5b). The extent or size of the dye cloud, and the position of the centroid, is displayed graphically in Figures 3 through 7 for each of the sweeps conducted during the five dye tracer tests.

All complete observations (dye concentration, depth, and position) made in the depth range of the dye cloud were included in the calculations. At times, the GPS instrument reported an obviously erroneous longitude position for a continuous period of a number of minutes. In some cases, reasonable estimates of the longitude could be interpolated from earlier and later measurements. Rhodamine concentration data is presented graphically as color contours in Appendix A as a means of depicting the variability of the concentrations within the cloud.

As expressed by Equations 4 and 5b, the dispersion coefficients are determined from the rate of increase of the variance (the square of the "spread") over time. The dispersion coefficient for each dye tracer test was determined by performing a linear least-squares regression of the variance versus time, from which the average rate of increase with time (slope of the regression line) was determined. This calculation is illustrated in Figures 8 through 12 for the five respective tests. For example, Figure 8 displays the results for the first dye tracer test conducted from July 22 through July 25, 2008). Figure 8a indicates the values of spread (σ_L, σ_T and σ_R) given in Table 4. The corresponding values of variance (σ_L^2, σ_T^2 and σ_R^2) are shown in Figure 8b, together with the least squares regression lines for the values of each measure of variance (longitudinal, transverse and radial) determined in the four sweeps.

The resulting values of dispersion coefficients for the five tests are given in Table 5. The dye release protocol resulted in more reliable measurements in Tests 2 through 5 relative to Test 1. In the first test, a greater percentage of the measurements were zero. While no attempt was made to quantify this, it can be stated that there is a greater degree of uncertainty in the results from the first test relative to the subsequent tests.

As in all test measurements, there is some uncertainty in these values of dispersion (Table 5). The greatest source of uncertainty is almost certainly associated with the use of a limited, finite number of measurements to characterize the distribution of dye mass in the cloud. Although thousands of individual measurements were made in each sweep of the cloud, a small fraction of the total area or volume of the cloud was sampled by the fluorometric sensor. While there is little guidance in the literature to aid in quantifying the variability or uncertainty in this type of monitoring program, the accuracy of the measurements of variance is estimated to be in the range of plus or minus 20%.

It should also be noted that, even if very accurate measurements of variance could somehow be obtained, it would not be expected that the observed variance would increase over time at a constant rate (Figures 8 through 12), or in other words it is not expected that the dispersion coefficient itself is constant over the course of a particular dye tracer test. At least two factors contribute to this. First, the environmental conditions that drive dispersion, most importantly wind, varied over the course of each dye tracer test, so that the actual dispersion coefficient varied over the course of each test. In addition, in many turbulent flows, the dispersion coefficient is scale-dependent, meaning that the rate at which the variance increases in time (the slope of the line in Figures 8 through 12) itself increases as the size of the dye cloud increases. Given the weak, intermittent, and patchy nature of turbulence in the hypolimnion of a stratified lake under low mixing conditions, there is some question as to whether this scale-dependent behavior exists (Wüest and Lorke, 2003). Some acceleration in the rate of spreading observed during Test 1 (Figure 8) and Test 3 (Figure 10) dye tracer tests, but given the uncertainty in the underlying experimental values of variance, it is difficult to conclude that scale dependent dispersion is at work here. The dispersion coefficients in Table 5 are best described as being average values over the duration of an individual test, based on incomplete measurements of the spreading of the dye cloud.

The relative magnitude of the computed dispersion coefficients in the longitudinal and transverse directions showed the ratio varied from 0.2 to 5.4 (Table 5). The relative magnitude of the longitudinal and transverse dispersion coefficients may be related to the relative magnitude of longitudinal and transverse components of wind speed. The relationship between the ratio of directional components of these quantities was weak (Figure 14). This result is not surprising given the modest length/width ratio of 3.7 for Onondaga Lake. Given that there is not a consistent pattern in the directional components of dispersion, the use of a single radial dispersion coefficient may be warranted to describe dispersion in the horizontal plane. Adopting this approach, an average horizontal dispersion coefficient of 0.073 square meters per second was determined for each of the five 2008 dye tracer tests, with a range of 0.030 to 0.15 square meters per second which corresponds to one-half an order of magnitude.

For the purposes of designing a system for releasing a chemical into the hypolimnion of Onondaga Lake, one might assume that a reasonable range of low-mixing conditions in the hypolimnion were captured in the tests, so that the average dispersion coefficient (0.073 square meters per second) or the range of observed dispersion (0.030 to 0.15) could be used in the analysis of alternative designs. However, the choice of a reasonable dispersion coefficient for design may be supported by relating the observed variability in dispersion to more easily observed meteorological, hydrologic, or lake conditions.

Table 6 summarizes the values of the horizontal dispersion coefficient determined from dye tracer studies in other lakes. The range of values determined in this study for Onondaga Lake are within the range reported by Murthy (1976) for the hypolimnion of Lake Ontario, and for a number of Swiss lakes as described by Peeters *et al.,* (1996). The values observed by Coleman and Armstrong (1983) for Tub Lake are four to five orders of magnitude smaller, while values for Lake Constance (Maiss *et al.*, 1995) are one to two orders of magnitude larger. There are many variables affecting dispersion (such as wind speed, wind direction, shape and position of the lake relative to prevailing winds, and width and depth of the lake) that limit comparisons of dispersion from one lake to another. The method used to quantify dispersion is the same for each of the lake studies cited herein.

Vertical dispersion was observed to be very slow relative to horizontal dispersion. The dye clouds were not observed to spread in the vertical plane over the two to three-day duration of each of the 2008 dye tracer tests. Graphs depicting the depth distribution of rhodamine dye concentrations are presented in the Appendix A.

No systematic differences in horizontal dispersion were indicated between the North Basin and South Basin by the results of the 2008 dye tracer tests. However, it is noted that the average radial dispersion in the South Basin based on two tests (0.044 m^2/sec) was less than the average radial dispersion in the North Basin based on three tests (0.091 m^2/sec).

4.0 EVALUATION OF DISPERSION COEFFICIENT CALCULATIONS

The primary driving force for water motion in the hypolimnion of a thermally-stratified lake is wind. The stress on the water surface caused by wind tends to push water toward the downwind end of the lake. The resulting slope of the water surface directly causes barotropic pressure gradients, and indirectly causes the vertical movement of the thermocline and other isothermal surfaces in the hypolimnion, which creates baroclinic pressure gradients. The effect of pressure gradients is to create an unbalanced horizontal pressure force, which creates motion.

The motion of the thermocline is sometimes known as an internal wave or internal seiche. While this motion is driven by wind, it is also affected by thermal stratification. Internal waves oriented along the longitudinal (northwest-southeast) axis of the lake basin may be expected to cause greater movement of the thermocline and velocity in the hypolimnion because such winds cause greater wind stress, and produce internal waves of greater wavelength and amplitude.

A second potential driving force is tributary inflow. During thermal stratification, the direct effect of inflow from tributary streams and the outfall from the Metropolitan Wastewater Treatment Plant located along the south shore (upstream end) of the lake are largely felt above the thermocline, due to density or buoyancy considerations. However, it is possible that a large input of water to the epilimnion over a short period of time may cause displacement of the thermocline and associated internal waves, in the same general manner as wind. However, this effect would only be significant under very high runoff event or streamflow conditions, and is very likely to be a secondary effect.

Wind speed and direction through the summer and fall of 2008 were observed and recorded for 15-minute intervals at a special monitoring buoy operated by UFI at South Deep. From this raw data, the component of wind speed in any particular direction, such as along the long axis of the lake, may be determined. Flow rates of Onondaga Creek, Ninemile Creek, and Ley Creek are measured throughout the year by the United States Geological Survey (USGS).

A thermistor chain, (model TR-7 manufactured by Aanderaa), was deployed at South Deep throughout the period of the 2008 dye tracer tests. The thermistor chain consisted of 11 temperature sensors located along a cable, each sensor 1.25 meters apart, thus covering a distance of 12.5 meters. The string was suspended vertically in the water column from a surface buoy, with the upper-most temperature sensor at a depth of about 6 meters. A data logger was attached at the bottom of the string to record all measurements and, by its weight keeps the string vertical. The temperature of each sensor was recorded every 5 minutes. Thermistors are typically used to detect the presence of internal waves or seiches, which cause the stratified layers of the lake to move vertically, and thus cause temperature observed at a fixed depth to fluctuate over time.

For this analysis, the thermistor data was used to determine the vertical displacement of the thermocline at South Deep where the instrument was deployed. This evaluation was done as follows. The thermocline was located on each day at the depth of maximum vertical temperature gradient, and the daily average temperature at that depth computed. The temperature record for 24 hours before and 24 hours after was then interrogated to determine how far above and below the thermocline position that the average temperature was observed. This range of depth is designated as the thermocline displacement range.

The variation of wind, tributary streamflow, and thermocline displacement over the period of the dye tracer tests is shown in Figure 15. Specifically, the 3-hour moving average of the component of the wind along the long axis of the lake (northwest-southeast) is shown in Figure 15a, which indicates that the highest winds occurred in Test 2, while relatively low winds occurred in Tests 1, 4, and 5. Inflows to the lake from tributaries were generally low during the five tests; modest runoff events occurred during Tests 1, 2, and 3 (Figure 15b). It is not expected that streamflow has a significant impact on dispersion in the hypolimnion. Thermocline displacement (Figure 15c) was relatively low in Tests 1, 2, and 4; the most noteworthy event in thermocline displacement occurred on September 15, 2008 which was associated with the passage of the remnants of Hurricane Ike through the area. Relatively high wind speeds and shifting wind direction occurred during this period (Figure 15a). Sustained wind speeds averaged 15 miles per hour, and wind gusts exceeded 40 miles per hour.

Correlations of the observed variation in the dispersion coefficient to various measures of the wind speed were computed. The best correlation was obtained using a two-day average of the long-axis wind component, with the averaging period beginning the day before the dye release. However, even the best correlation leads to the incorrect conclusion that dispersion decreases with increasing wind speed, as indicated by the regression line in Figure 16a. It is apparently the case that a single scalar average of the dynamic wind vector cannot represent the effect of wind on dispersion. Better results were obtained when the observed dispersion coefficients were compared to measures of thermal stratification, including the maximum vertical temperature gradient (Figure 16b), and the top-bottom temperature difference in the water column (Figure 16c). These comparisons support the conventional wisdom that increasing thermal stratification tends to dampen or decrease dispersion (Fischer *et al.*, 1979). The dispersion coefficient also tended to increase as the depth of the thermocline increased (Figure 16d), which generally occurs during late summer and fall with the approach to fall turnover. Perhaps the best available measure of large-scale or basin-wide motion in the hypolimnion is the vertical movement of the thermocline (Figure 15c). If the values for dispersion from the 2008 dye tracer tests are compared to the maximum range of thermocline depth which occurred during each dye tracer test, the expected result that dispersion increases with thermocline displacement range is seen (Figure 16e).

5.0 CONCLUSIONS AND RECOMMENDATIONS

The horizontal dispersion coefficient in the hypolimnion of Onondaga Lake during thermal stratification was calculated from dye concentrations measured during five dye tracer tests conducted from late July to early October, 2008. Each of the dye tracer tests involved the release of a quantity of rhodamine WT dye over a short period of time from a diffuser located in the hypolimnion at a water depth of 14 to 17 meters (46 to 56 ft). Following release, measurements of dye concentration, temperature, depth and GPS position were made using boat-based sensors. Wind conditions were generally low during these tests.

Analysis of the observations led to calculations of the horizontal dispersion coefficient in the direction of the longitudinal and transverse axes of the lake basin. The relative magnitude of dispersion in these two directions was variable and not strongly related to the wind speed or direction. As a result of variable longitudinal and transverse dispersion, a single radial dispersion coefficient was also computed for each test. Radial dispersion coefficients for the five dye tracer tests were in the range of 0.030 to 0.15 square meters per second, with a mean of 0.073 square meters per second. The observed variability in the radial dispersion coefficient was not correlated in the expected manner with various simple scalar average values of the time varying wind vector. Positive correlations were found with various measures of thermal stratification, including maximum vertical temperature gradient, surface-bottom temperature difference, thermocline depth, and vertical range of thermocline movement.

The observed horizontal dispersion coefficients are consistent and appropriate for use in the design and analysis of a system for releasing a dissolved electron acceptor (*i.e.*, nitrate and/or oxygen) into the hypolimnion of Onondaga Lake. Some judgment must be used in applying a dispersion coefficient to design an electron acceptor application system. A conservative approach would be to use the minimum observed value of 0.030 square meters per second observed in the second test. In the analysis of a particular design, a sensitivity analysis could be performed where the dispersion coefficient is varied over the range described here (0.03 to 0.15 square meters per second). One of the objectives of the 2009 nitrate application field trial being planned by Honeywell is to provide additional measurements of horizontal dispersion in the hypolimnion using more dye and measuring the dye cloud over longer time periods compared to the 2008 dye tracer tests.

Design of a diffuser for releasing nitrate and/or oxygen into the hypolimnion will consider the variation of thermal stratification conditions that occurs in Onondaga Lake from summer to fall. The correlations of the observed dispersion coefficient with measures of thermal stratification (Figures 16b through 16e) indicate that a dispersion coefficient toward the low end of the observed range may be more appropriate for conditions where thermal stratification is relatively strong and the thermocline relatively shallow. Larger values may be more appropriate during the approach to fall turnover when stratification is weaker and the thermocline is deeper.

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TABLE 1

SUMMARY OF INDIVIDUAL DYE TRACER TESTS, ONONDAGA LAKE HYPOLIMNION, 2008

Test Number	Dye Volume, liters	Basin	Release Date (2008)	Release Time (24-hour clock)	Depth of Release, meters
Pre-Test	0.5	South	26 June	09:35	16.9
1	4.0	North	22 July	10:00	14.9
2	8.0	South	12 Aug	09:20	15.4
3	8.0	North	10 Sept	09:30	14.1
4	8.0	South	23 Sept	09:20	16.1
5	8.0	North	7 Oct	09:00	14.7

TABLE 2

RESULTS OF A HOLDING-TIME EVALUATION FOR RHODAMINE WT CONDUCTED OVER THE AUGUST 11, 2008 TO SEPTEMBER 5, 2008 INTERVAL

Day	Date	Time	Concentration (µg/L)
1	8/11/08	15:00	25.0, 25.5, 25.5, 26.0, 25.5
1	8/11/08	16:45	24.8
2	8/12/08	18:35	26.4
3	8/13/08	15:55	25.3
4	8/14/08	16:45	25.0
6	8/16/08	13:05	25.0
7	8/17/08	13:45	24.7
8	8/18/08	15:48	24.9
9	8/19/08	16:40	25.1
12	8/22/08	17:00	25.0
14	8/24/08	14:40	25.1
17	8/27/08	17:20	25.2
19	8/29/08	16:30	25.4
21	9/1/08	14:00	25.0
25	9/5/08	14:45	25.0

TABLE 3

SENSITIVITY OF CALCULATIONS OF DYE CLOUD SPREAD ON OCTOBER 9, 2008 TO THE ASSUMED LOWER LIMIT OF DYE CONCENTRATIONS

Lower Limit C_L (µg/l)	**Spread (meters)**		
	Longitudinal σ_L	**TRANSVERSE** σ_T	**Radial** σ_R
0	232	145	336
0.1	233	145	338
0.2	234	145	340
0.5	235	144	346
1	229	141	349

TABLE 4

CALCULATION OF DYE DISPERSION CHARACTERISTICS

Date (2008)	Monitoring Interval (24-hr clock)	Time after release, hours	Number of dye measure-ments	Centroid position from release point, meter		Spread, meters		
				L_0	V_0	σ_L	σ_T	σ_R
22 July	10:00	0						
22 July	13:01 – 14:19	3.7	884	12	18	25.6	23.4	34.8
23 July	08:41 – 13:14	24.9	3183	150	-3	37.2	31.8	120
24 July	08:27 – 12:19	48.4	2751	-14	20	62.1	90.2	123
25 July	08:18 – 11:30	71.9	2257	-1	150	142	83.2	199
12 Aug	09:20	0						
12 Aug	13:38 - 16:47	5.7	2061	81	110	65.3	35.4	79.6
13 Aug	09:42 - 12:46	25.9	2207	173	242	63.1	100	151
14 Aug	09:55 – 15:22	50.8	2632	12	542	116	60.0	161
10 Sept	09:30	0						
10 Sept	12:25 - 16:57	5.2	3213	-39	17	82.0	44.4	119
11 Sept	08:41 - 12:21	25.0	2618	-29	117	111	137	178
11 Sept	13:33 - 15:36	29.1	1476	34	32	94	129	220

TABLE 4 (CONT.)

CALCULATION OF DYE DISPERSION CHARACTERISTICS

Date (2008)	Monitoring Interval (24-hr clock)	Time after release, hours	Number of dye measure-ments	Centroid position from release point, meter		Spread, meters		
				L_0	V_0	σ_L	σ_T	σ_R
23 Sept	09:20	0						
23 Sept	12:08 - 16:54	5.2	3417	306	87	70.0	60.1	143
24 Sept	08:03 – 17:36	27.6	5548	257	56	124	95.4	179
25 Sept	08:13 - 14:57	51.9	2825	256	-27	124	122	243
26 Sept	08:11 – 11:15	72.4	2209	387	90	125	144	274
7 Oct	09:00	0						
7 Oct	11:43 – 14:48	4.26	2219	102	57	83.8	86.5	131
7 Oct	14:50 – 16:20	6.58	1078	-12	132	56.4	37.2	95.8
8 Oct	08:48 – 11:29	25.14	1922	142	74	90.5	120	223
8 Oct	12:38 – 15:34	29.11	2111	529	236	157	111	288
9 Oct	10:47 – 13:49	51.31	2155	652	112	233	145	338

TABLE 5

DISPERSION COEFFICIENTS CALCULATED FROM THE 2008 ONONDAGA LAKE DYE TRACER TEST RESULTS

Test	Location	Time Period (2008)	Dispersion coefficient, square meters per second			Ratio E_L / E_V
			E_L	E_V	E_R	
1	North Basin	22-25 July	0.037	0.016	0.035	2.3
2	South Basin	12-14 Aug	0.030	0.0055	0.030	5.4
3	North Basin	10-11 Sept	0.021	0.096	0.088	0.2
4	South Basin	23-26 Sept	0.018	0.034	0.057	0.5
5	North Basin	7-9 Oct	0.14	0.050	0.15	2.9
Average			0.050	0.040	0.073(1)	1.2

(1) Avg E_R (north) = 0.091 sq. meters per second.
Avg E_R (south) = 0.044 sq. meters per second.

TABLE 6

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

Reference	Lake(s)	Dispersion Coefficient (square meters per second)
Murthy (1976)	Lake Ontario	0.016 to 0.38
Coleman and Armstrong (1983)	Tub Lake, Wisconsin	0.000047
Maiss *et al.* (1995)	Lake Constance, Switzerland	7 to 30
Peeters *et al.* (1996)	Lakes Alpnach, Vitznauer, Urner, and Neuchatel, Switzerland	0.02 to 0.3
This study	Onondaga Lake	0.030 to 0.15

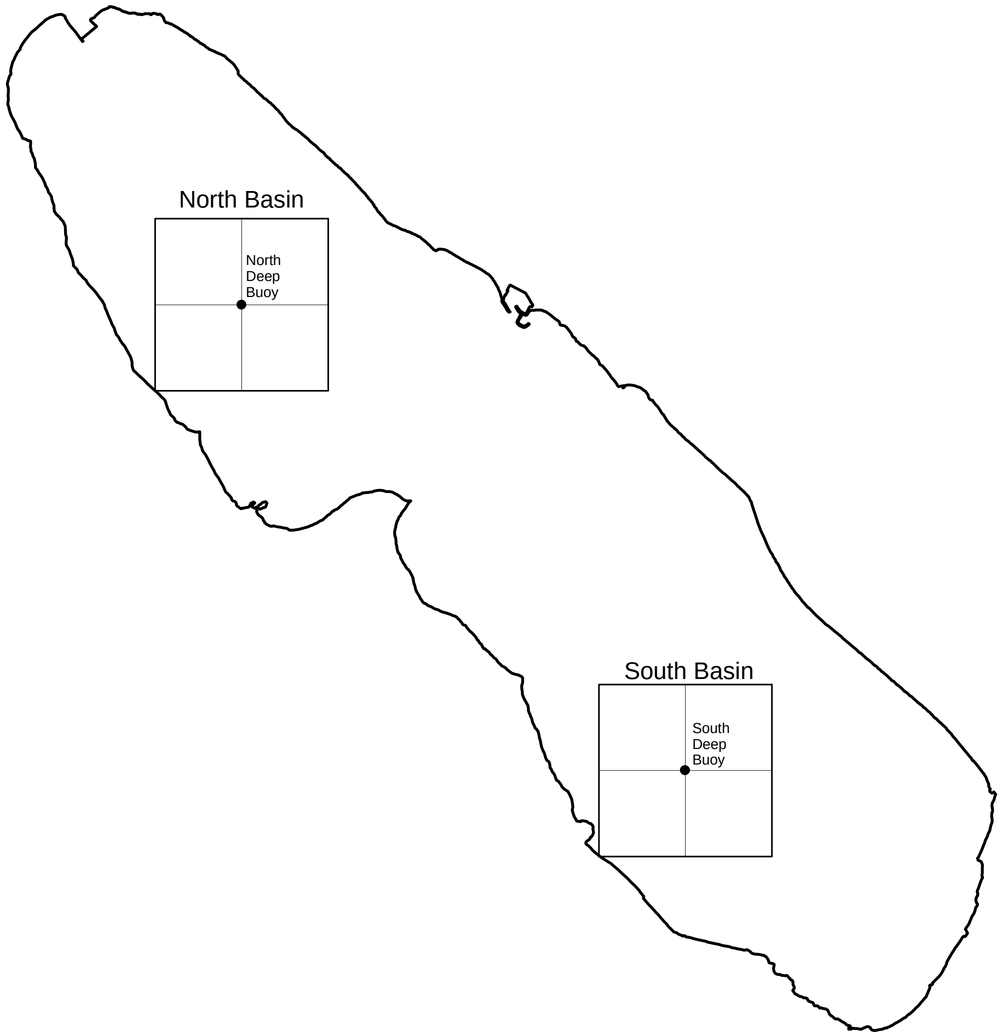


Figure 1. Map of Onondaga Lake, showing the North and South Basins where the hypolimnetic dye tracer studies were conducted. The boxes are 1000 x 1000 meter areas centered on the North and South Deep Buoys. Dye releases were made within a few hundred meters of these buoys.

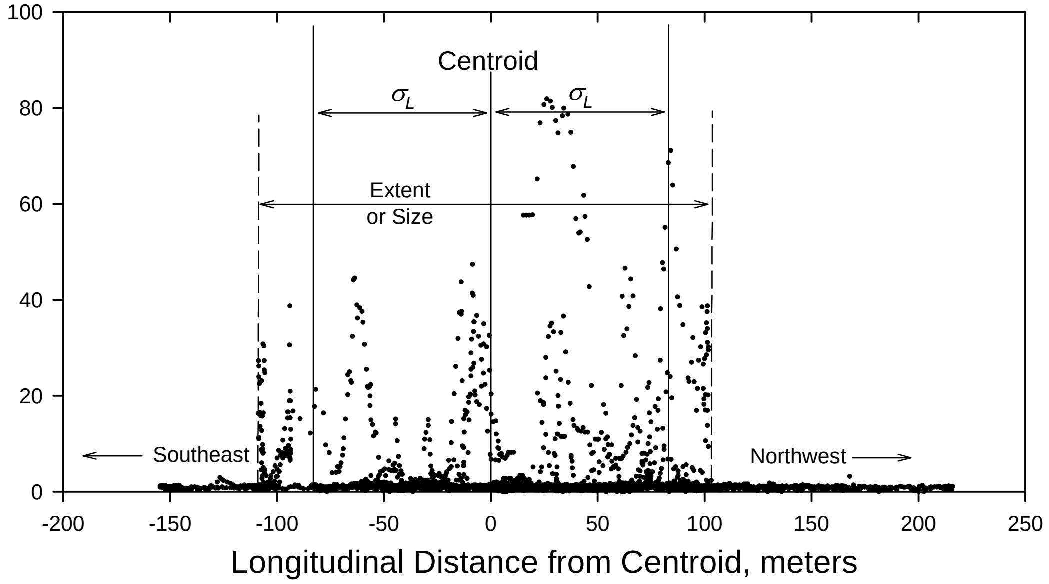


Figure 2. Dye concentration measurements made on the afternoon of Sept. 10, following release at 9:30 AM that morning. The longitudinal position and concentration of the 3213 measurements are shown. The "spread" of the cloud in the longitudinal direction (σ_L) is equal to 82 m, while the extent or size of the cloud is about 225 m. Many of the low concentration measurements near the centroid are at some distance from the center of the cloud in the transverse direction.

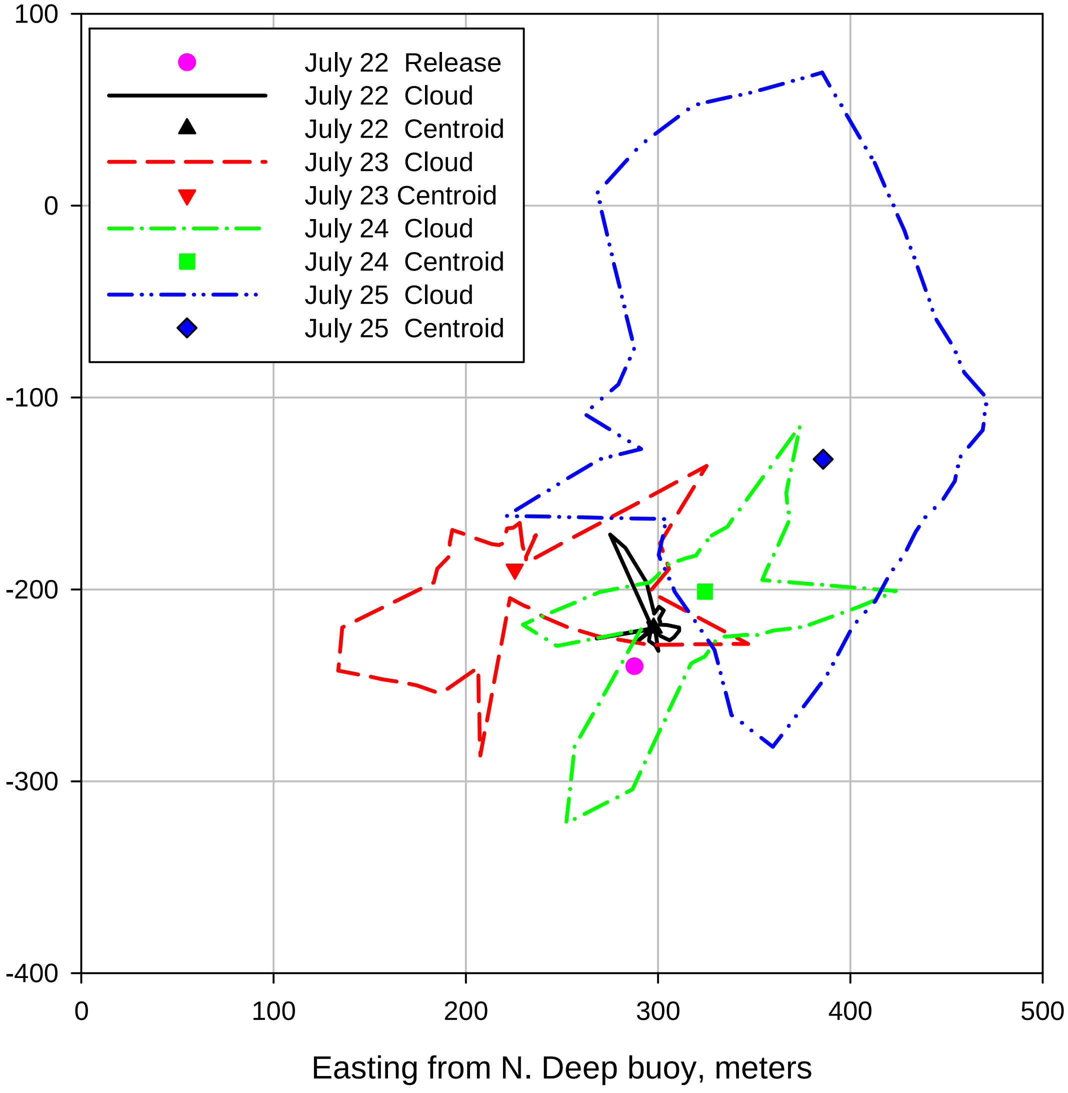


Figure 3. Extent of the dye cloud, and its centroid location, for the 22-25 July 2008 experiment in the North Basin.

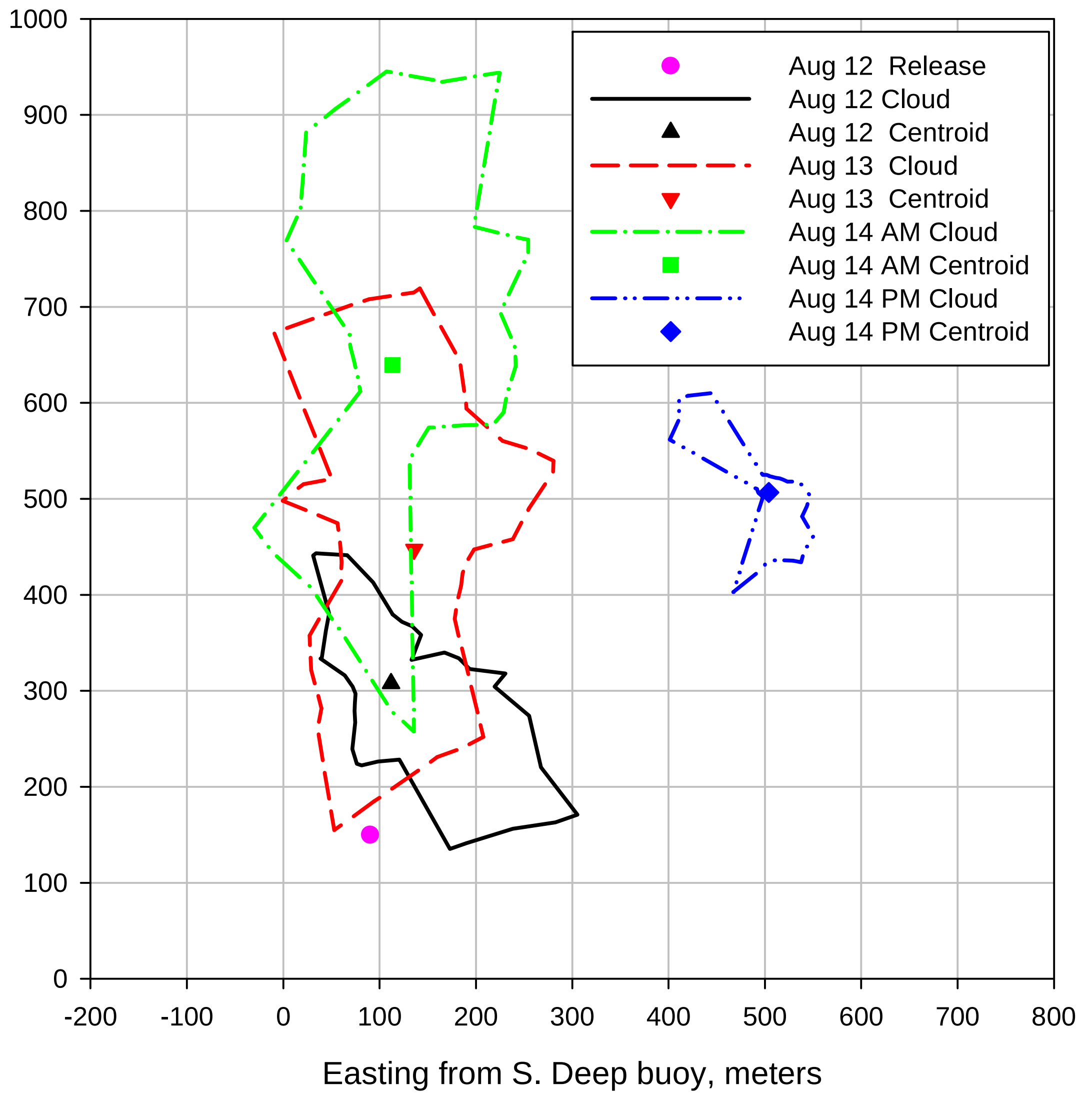


Figure 4. Extent of the dye cloud, and its centroid location, for the 12-14 August 2008 experiment in the South Basin.

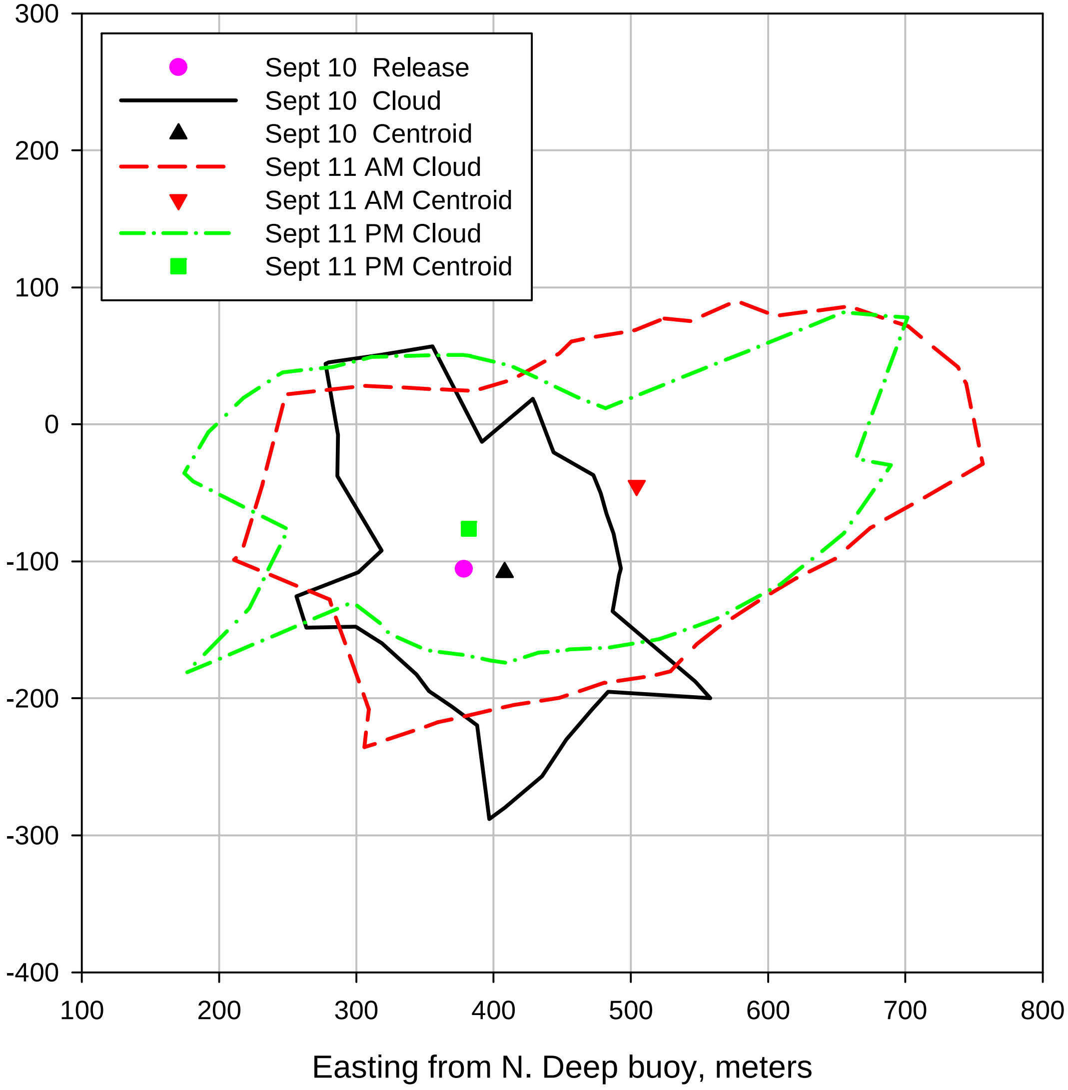


Figure 5. Extent of the dye cloud, and its centroid location, for the 10-11 September 2008 experiment in the North Basin.

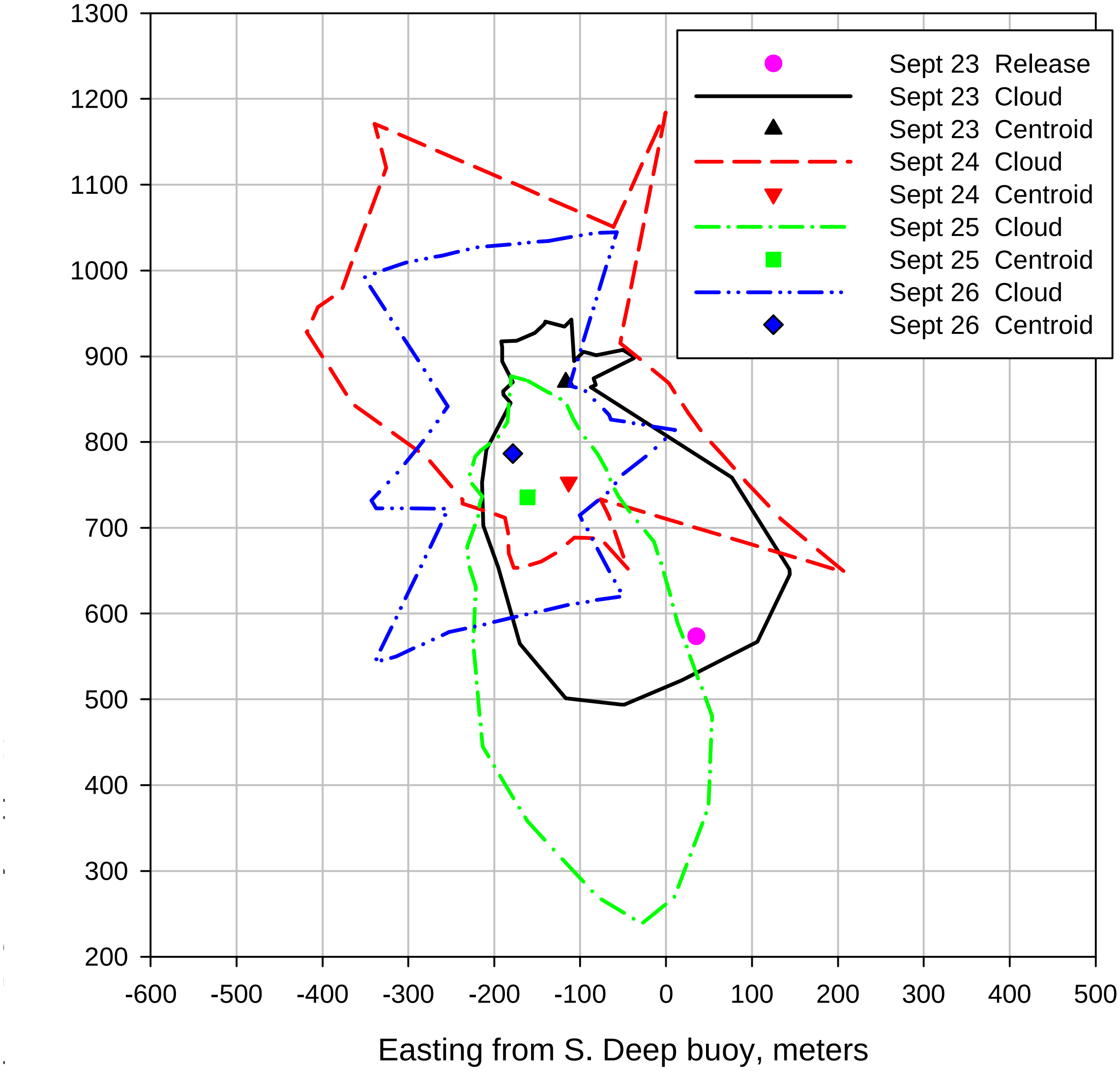


Figure 6. Extent of the dye cloud, and its centroid location, for the 23-26 September 2008 experiment in the South Basin.

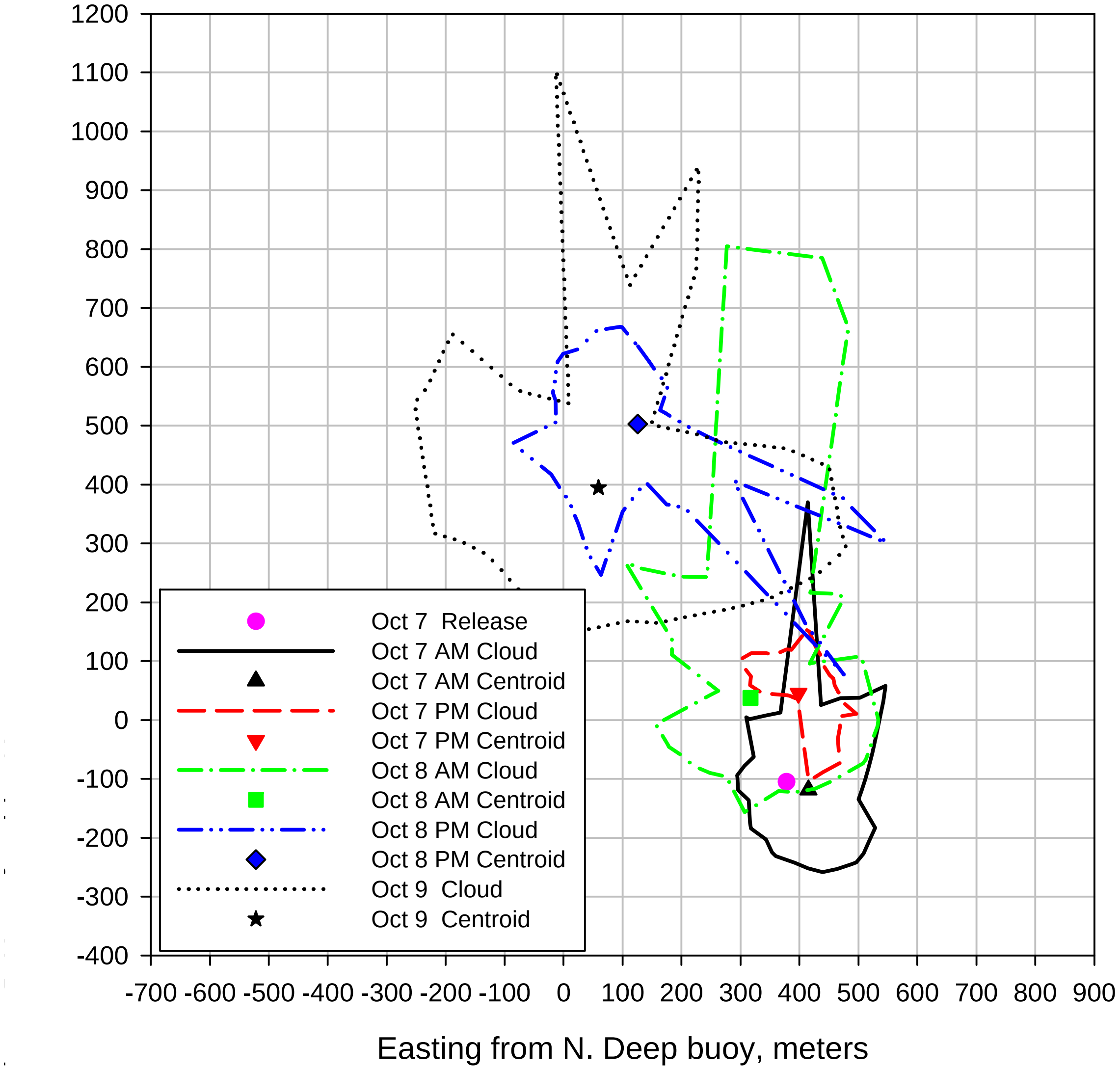


Figure 7. Extent of the dye cloud, and its centroid location, for the 7-9 October 2008 experiment in the North Basin.

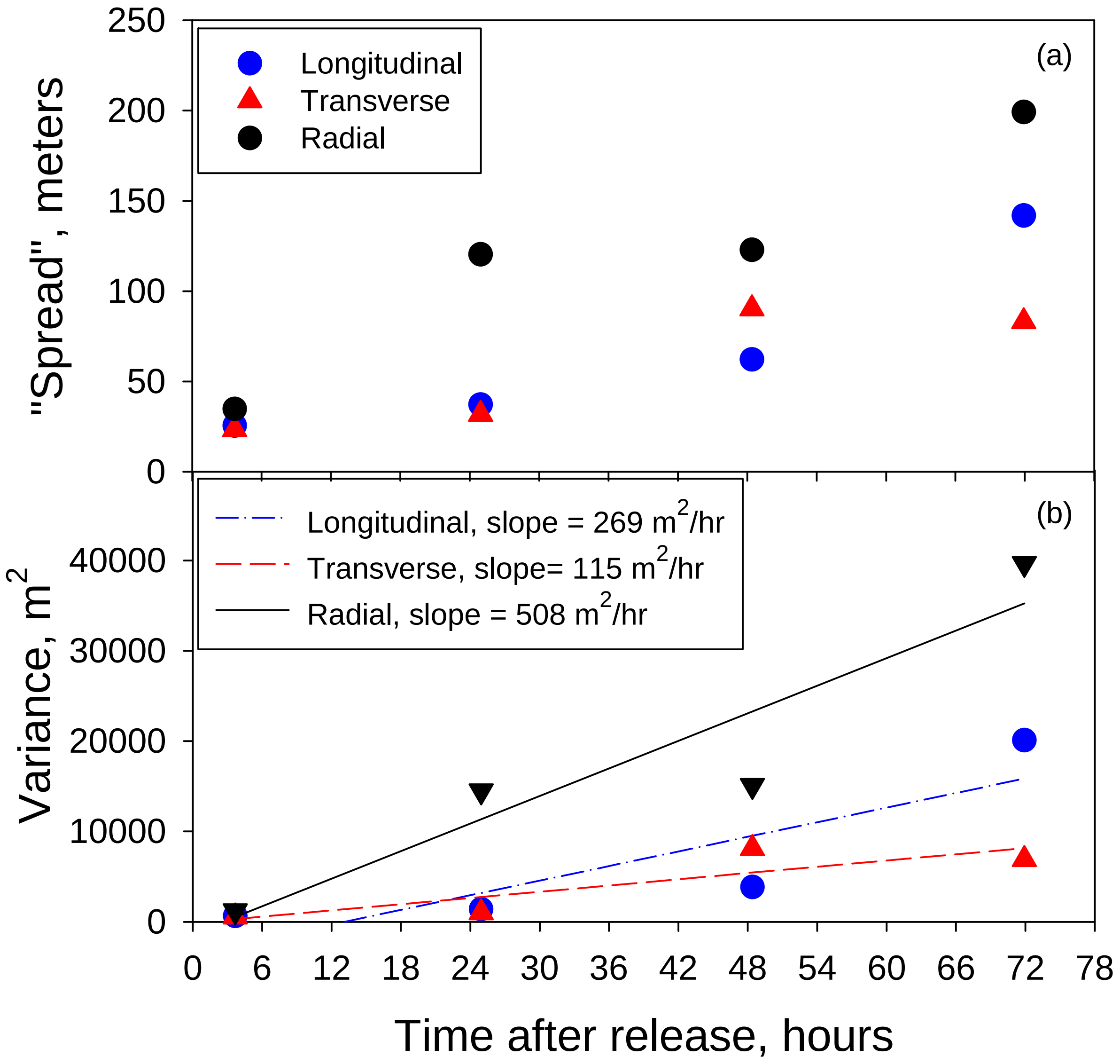


Figure 8. Results of (a) spread and (b) dispersion calculations, 23-26 July 2008.

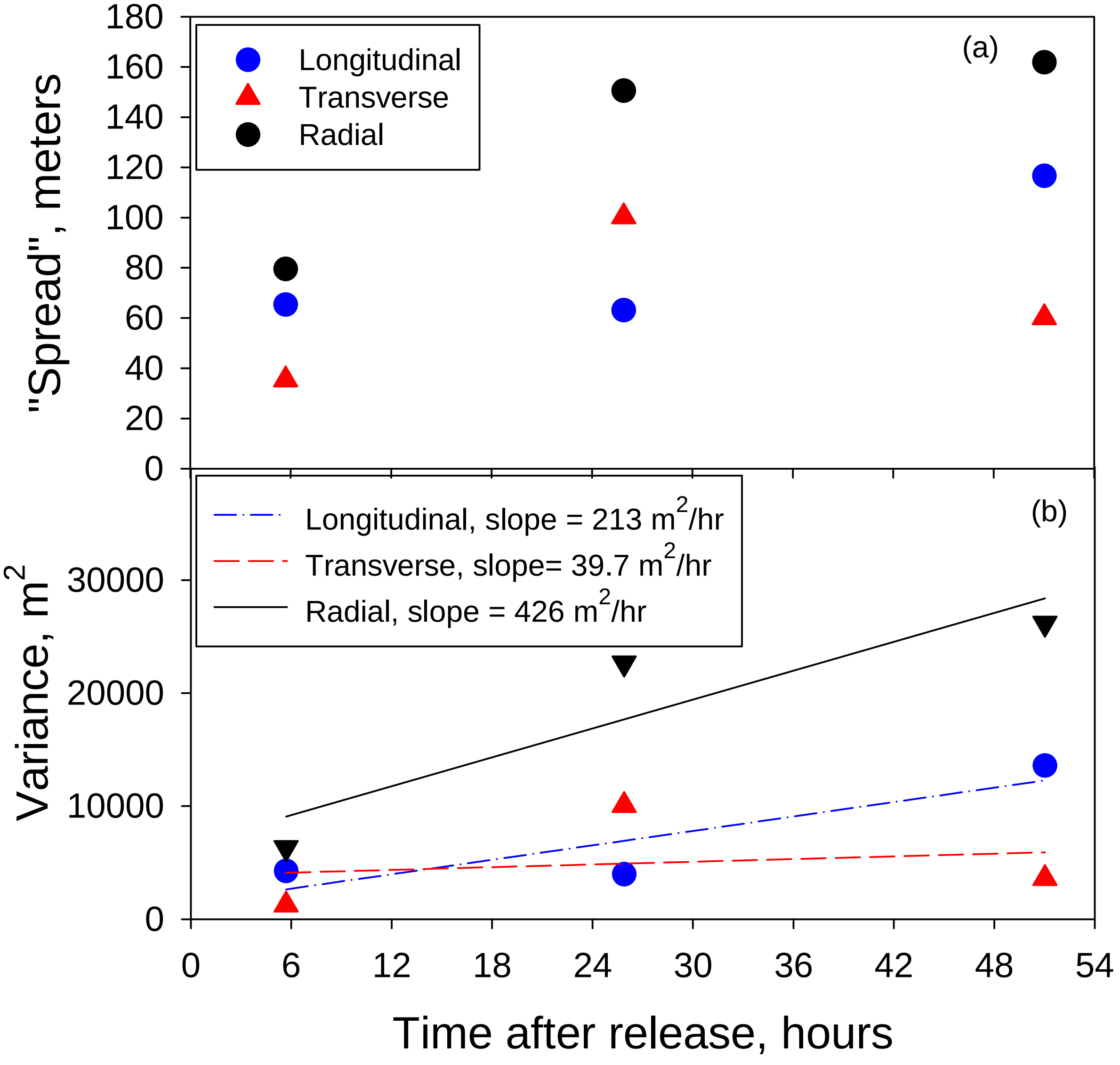


Figure 9. Results of (a) spread and (b) dispersion calculations, 12-14 August 2008.

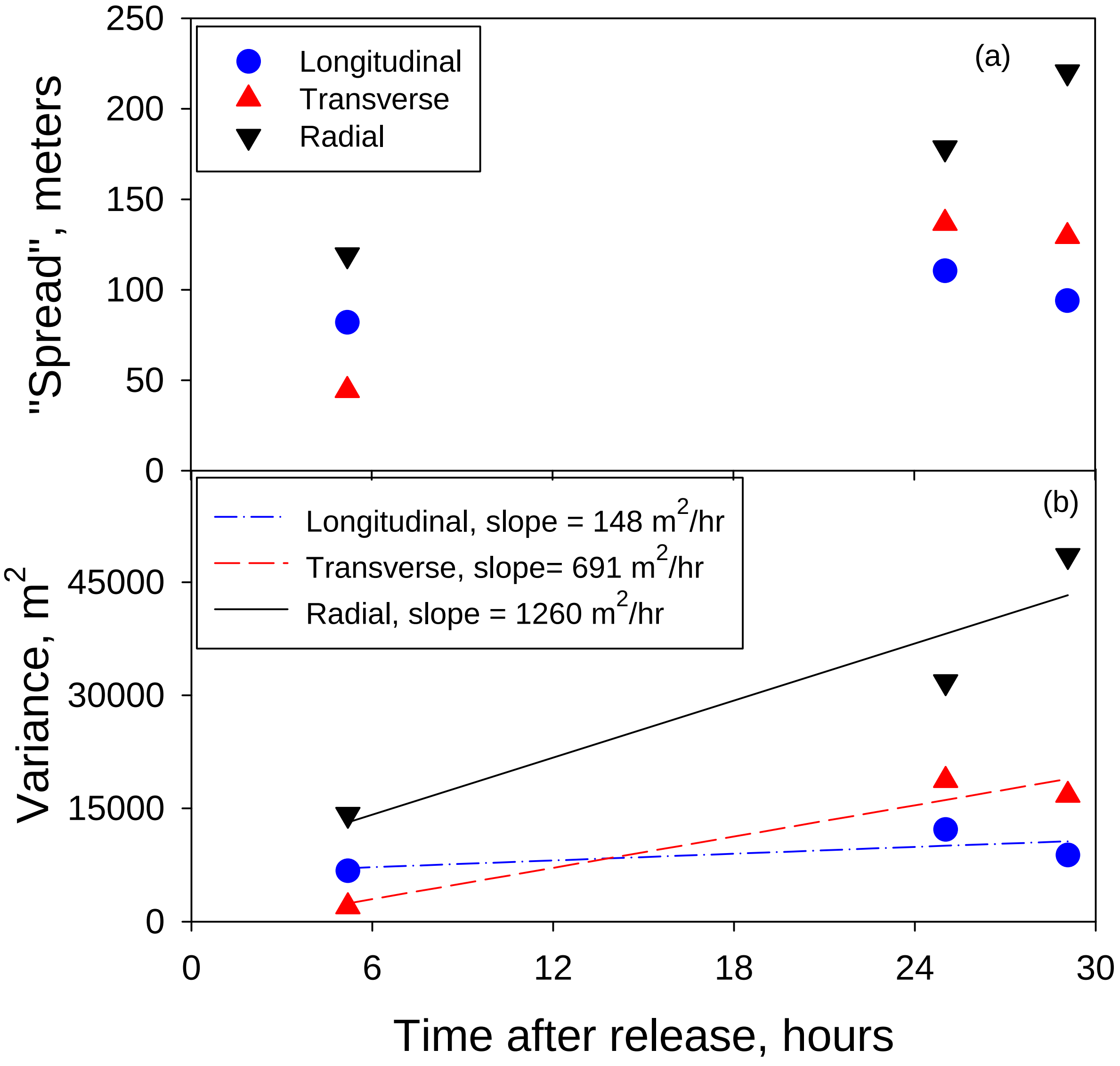


Figure 10. Results of (a) spread and (b) dispersion calculations, 10-12 September 2008.

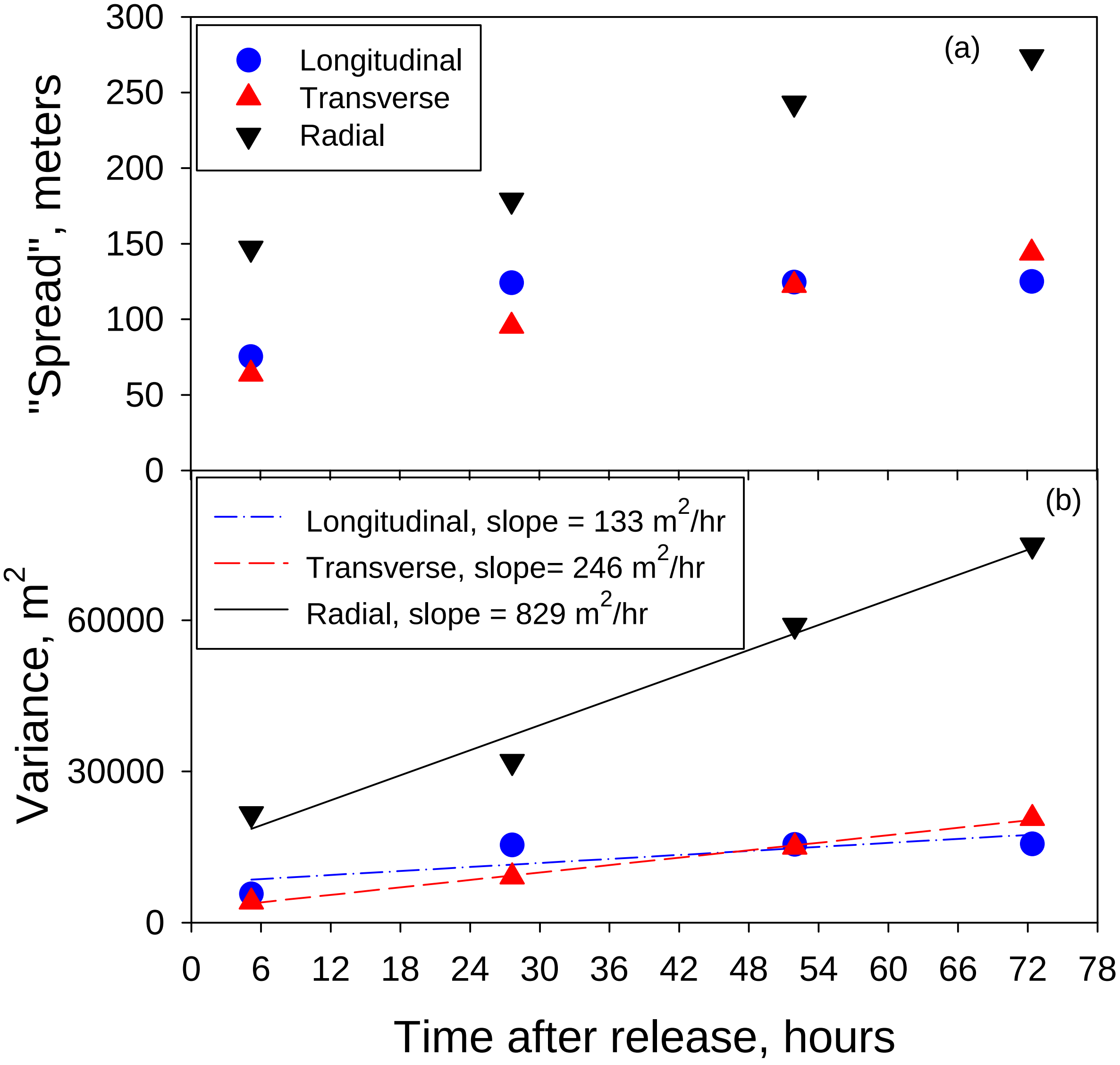


Figure 11. Results of (a) spread and (b) dispersion calculations, 23-26 September 2008.

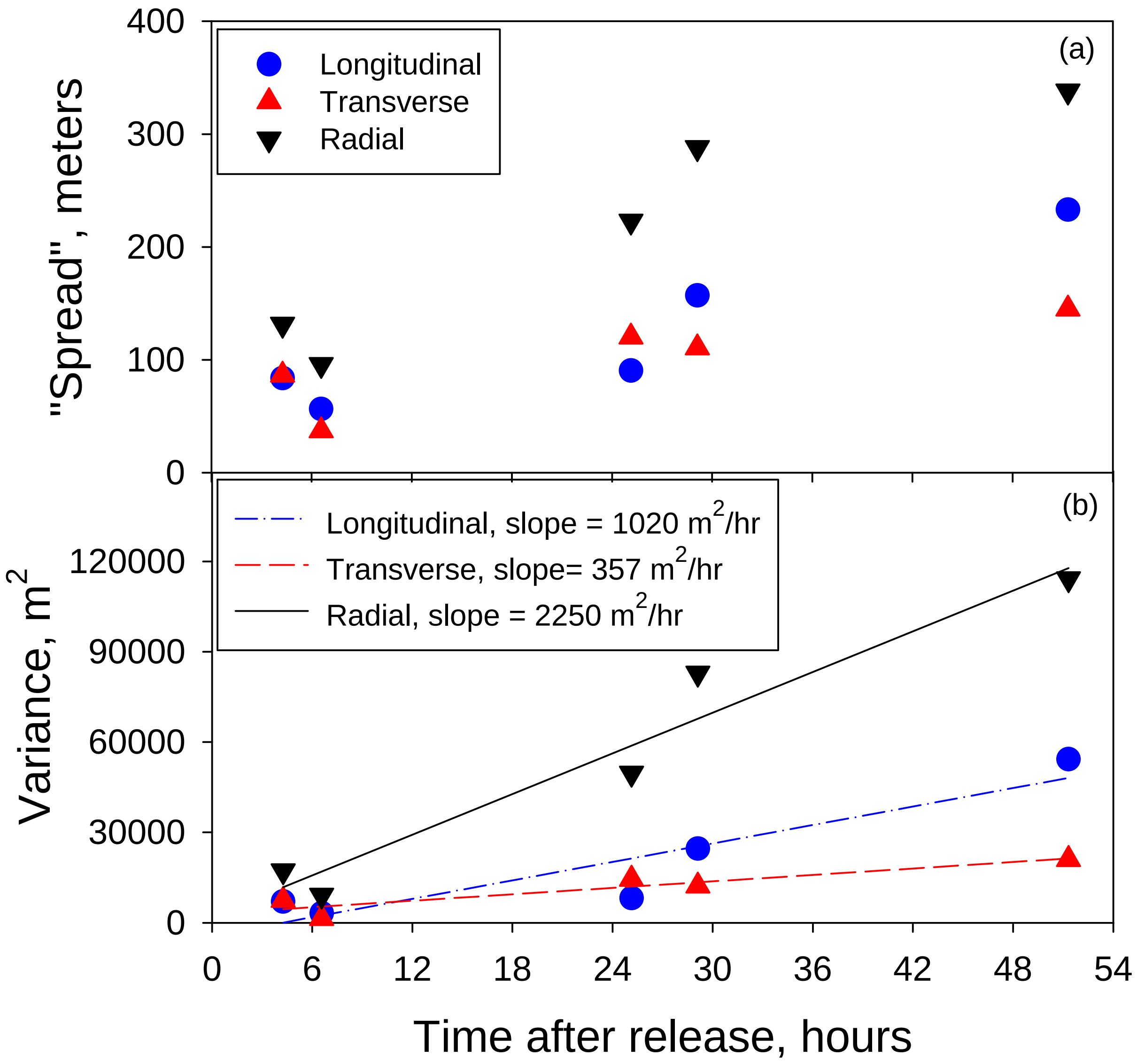


Figure 12. Results of (a) spread and (b) dispersion calculations, 7-9 October 2008.

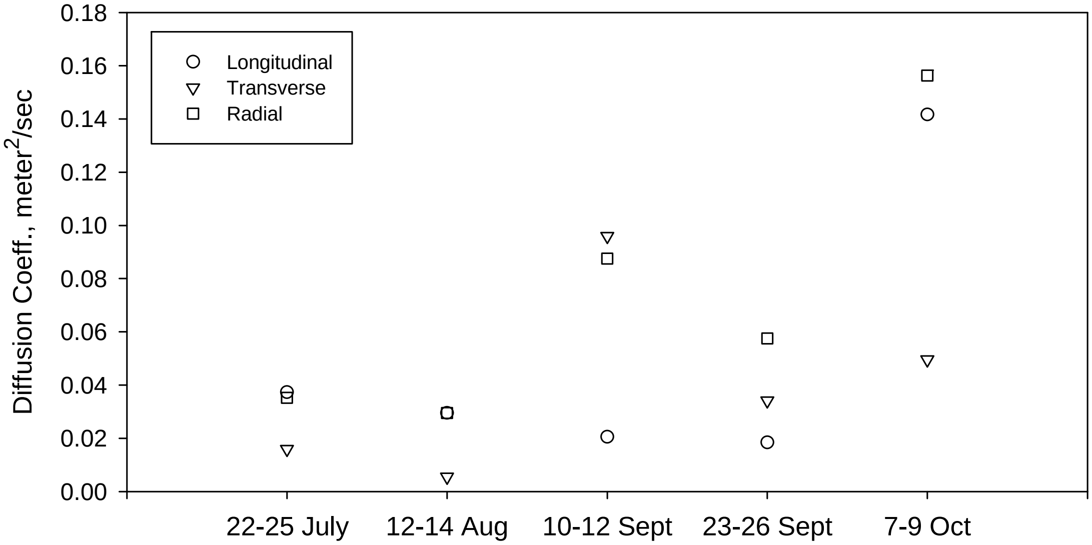


Figure 13. Variation of the horizontal dispersion coefficients (longitudinal, transverse, and radial) for the 5 dye tracer experiments.

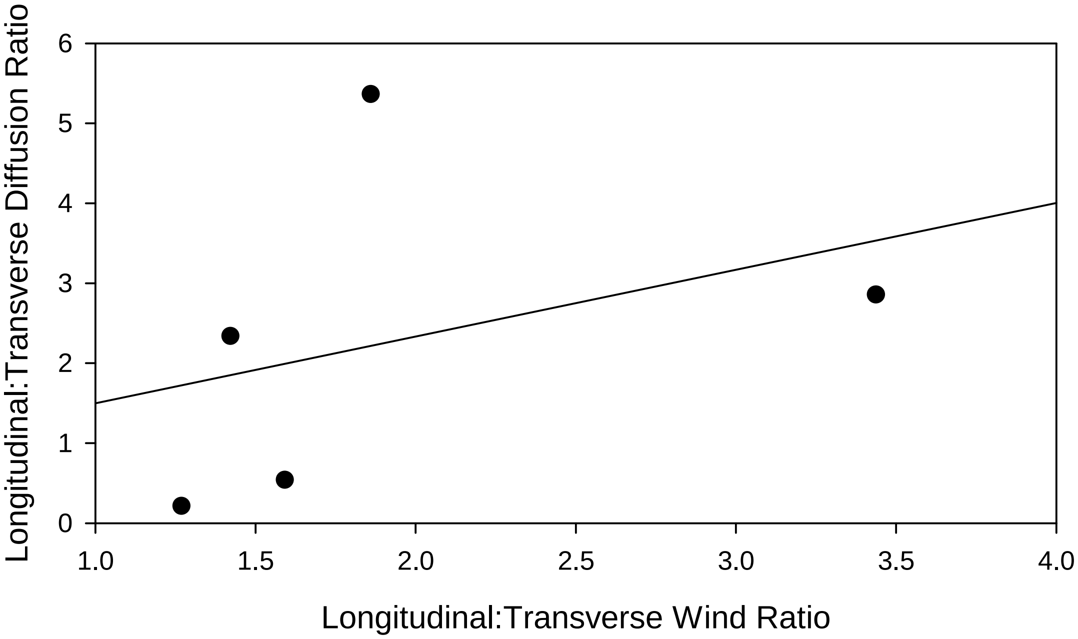


Figure 14. Comparison of the ratio of ratio of longitudinal to transverse dispersion coefficient to similar ratio of wind direction.

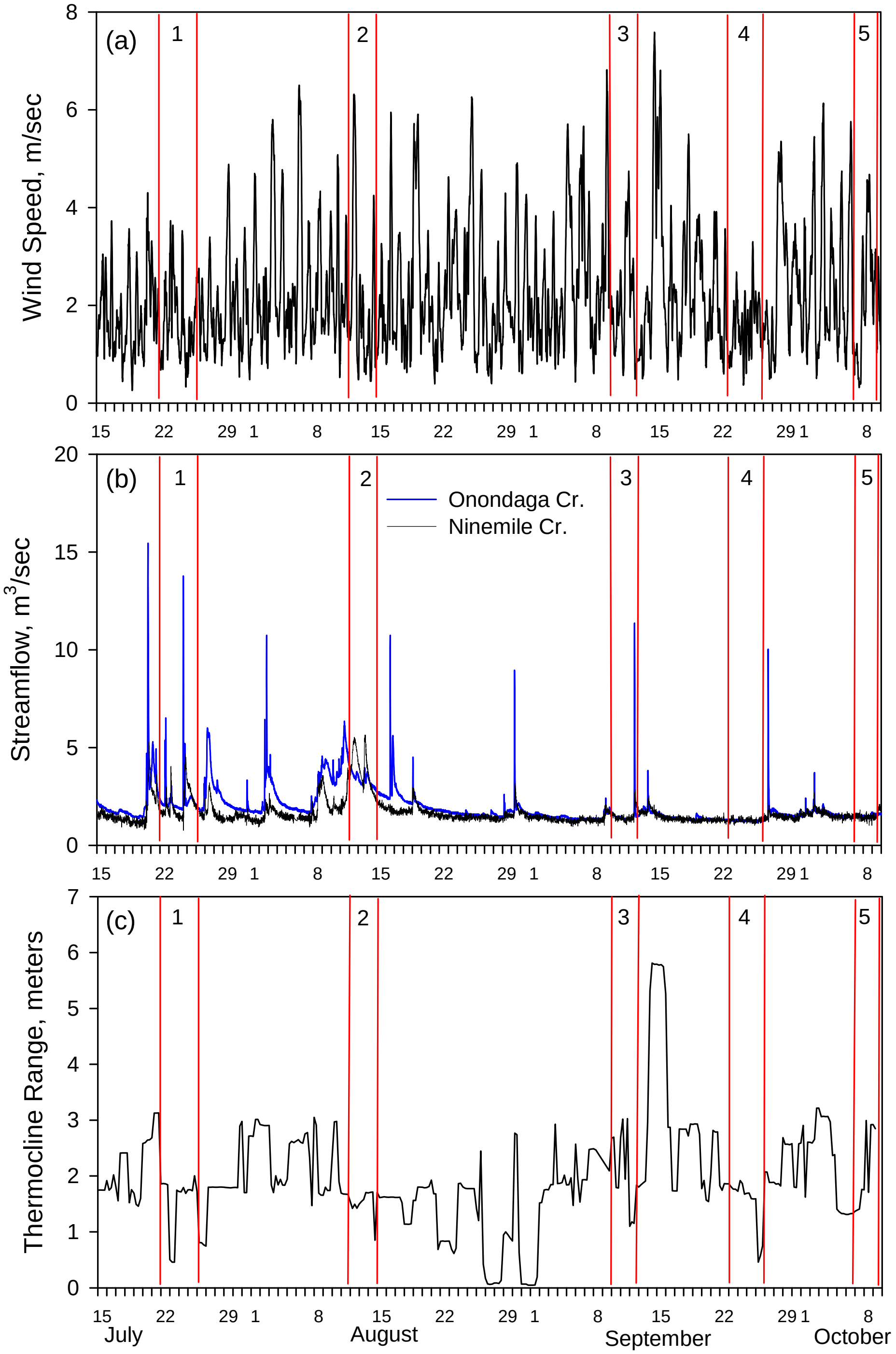


Figure 15. Environmental conditions for Onondaga Lake during the 5 dye tracer experiments: (a) 3-hour average of the longitudinal (northwest-southeast) component wind speed observed at buoy at south deep; (b) streamflow for Onondaga Creek and Ninemile Creek, and (c) range of vertical movement of thermocline determined from thermistor string deployment at south deep.

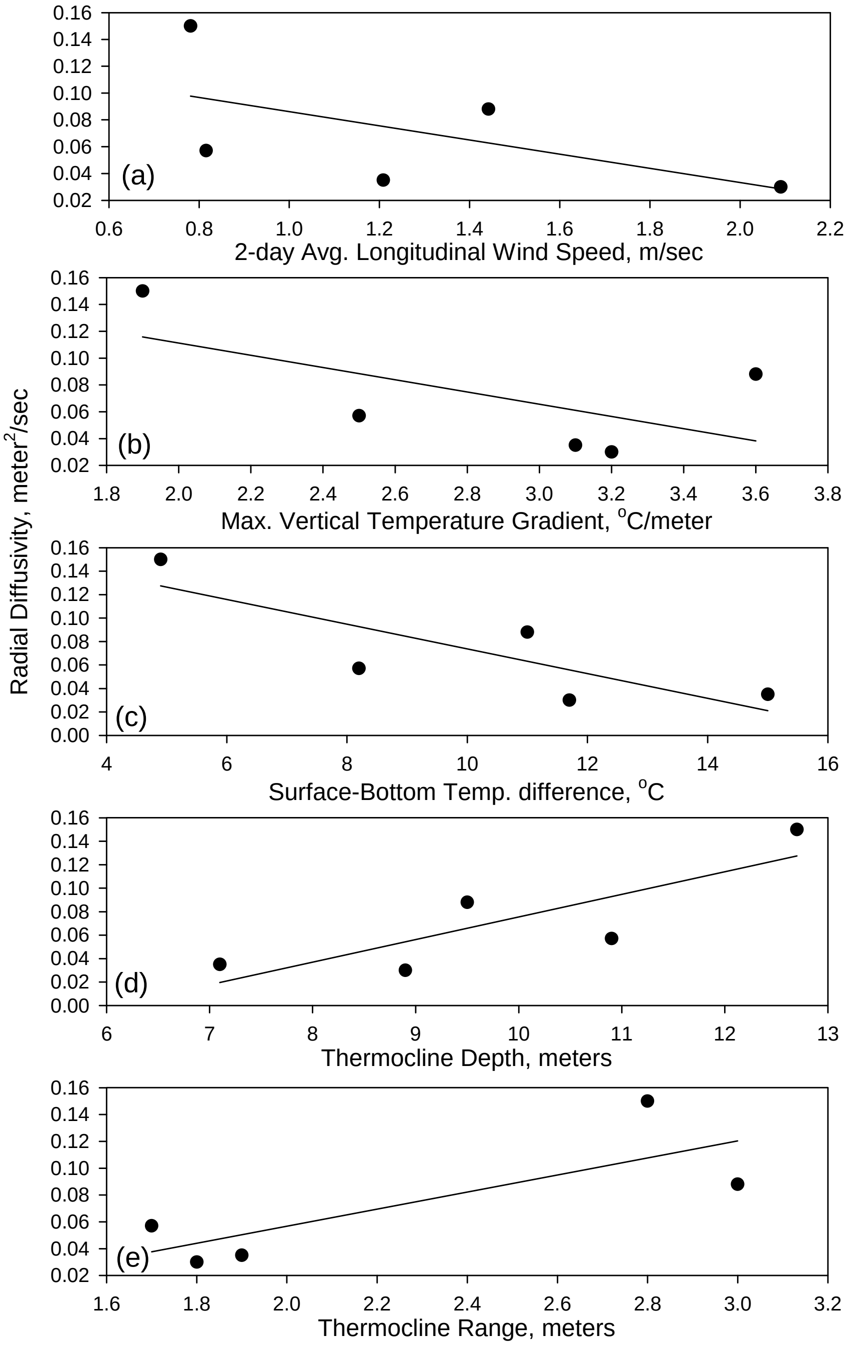
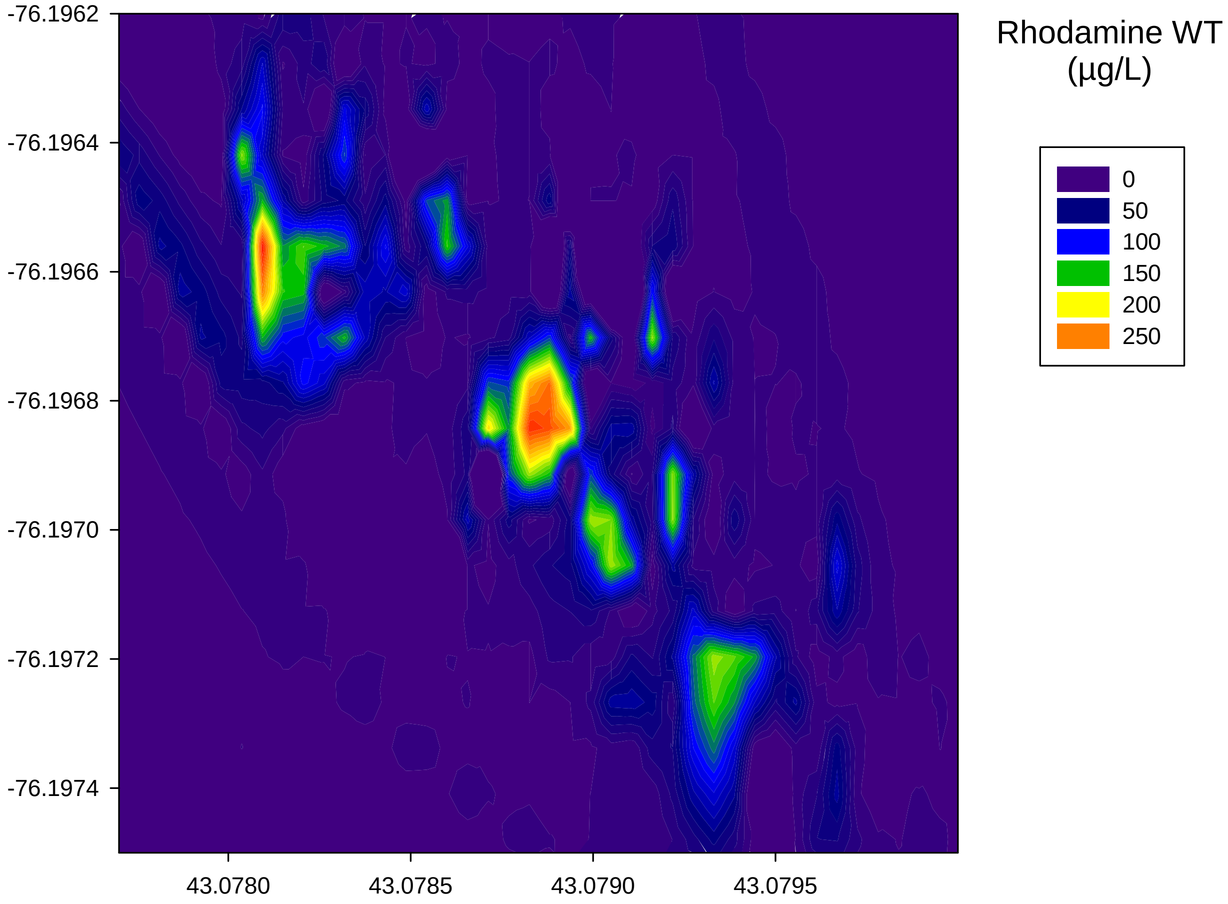


Figure 16. Relationship between radial diffusivity determined from the 5 dye tracer experiments and various environmental conditions: (a) 2-day average longitudinal component of wind speed beginning day before start of experiment; (b) maximum vertical temperature gradient; (c) top-bottom temperature difference; (d) thermocline depth; and (e) range of vertical movement of the thermocline.

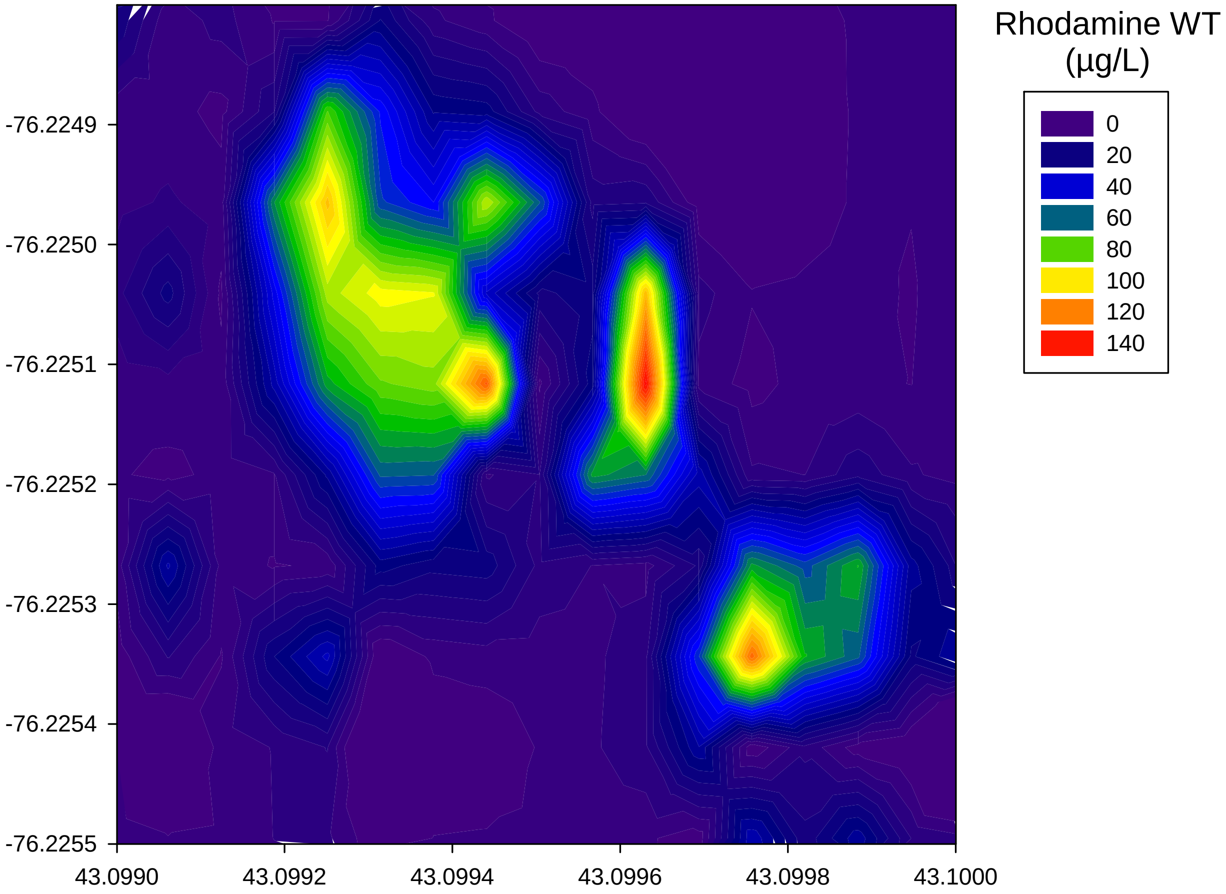
APPENDIX A

EXAMPLE DYE CONCENTRATION DATA PLOTS

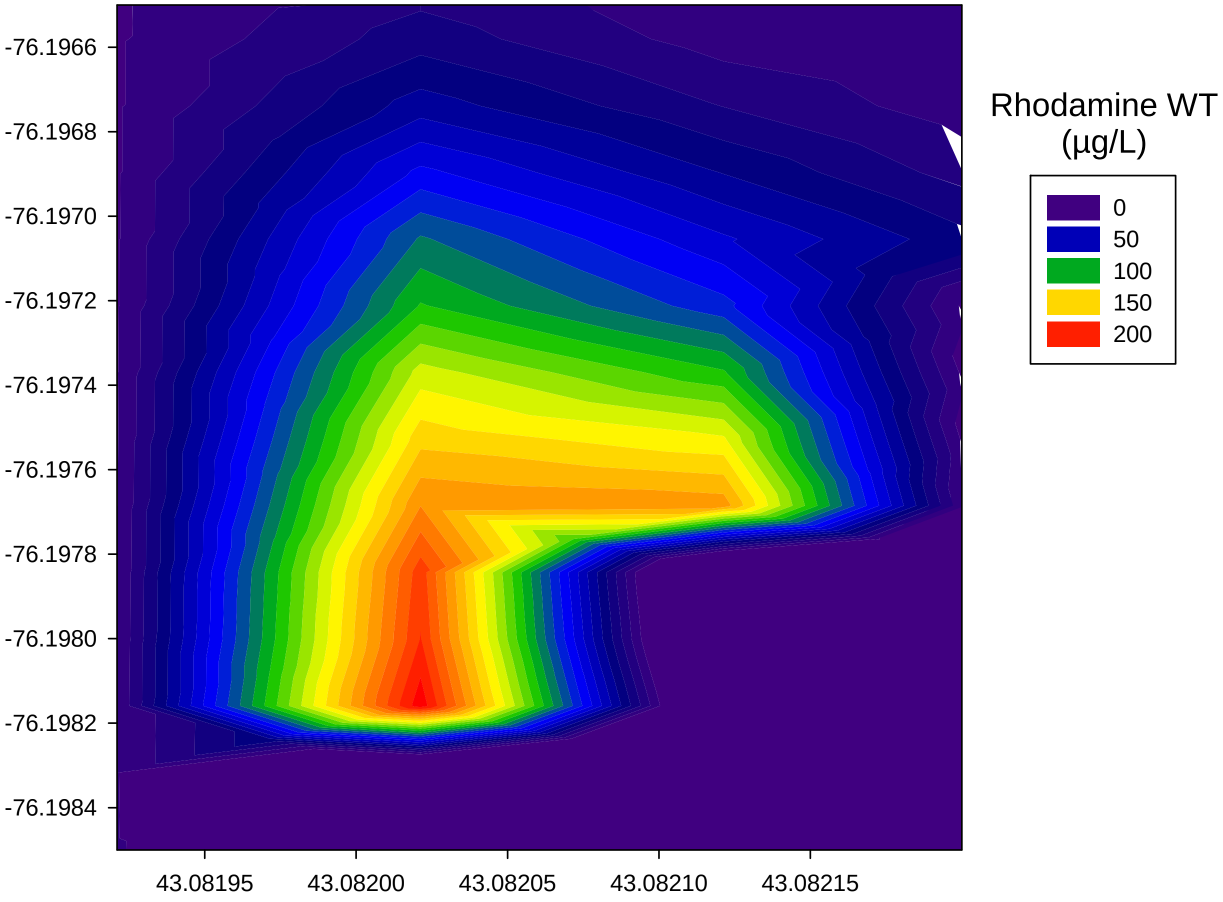
Dye Concentration Data from Day 1 of 2008 Dye Tracer Test No. 2
8/12/2008



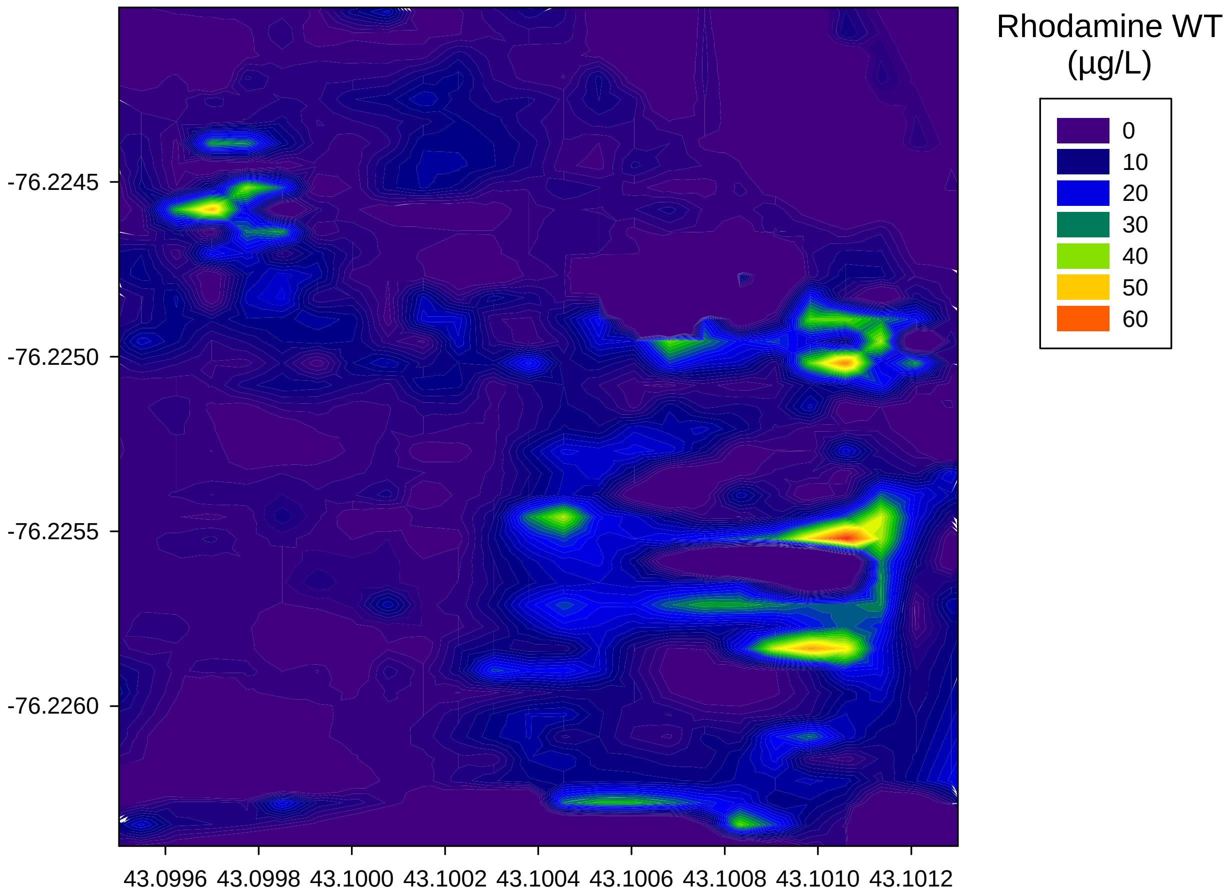
Dye Concentration Data from Day 1 of 2008 Dye Tracer Test No. 3
9/10/2008



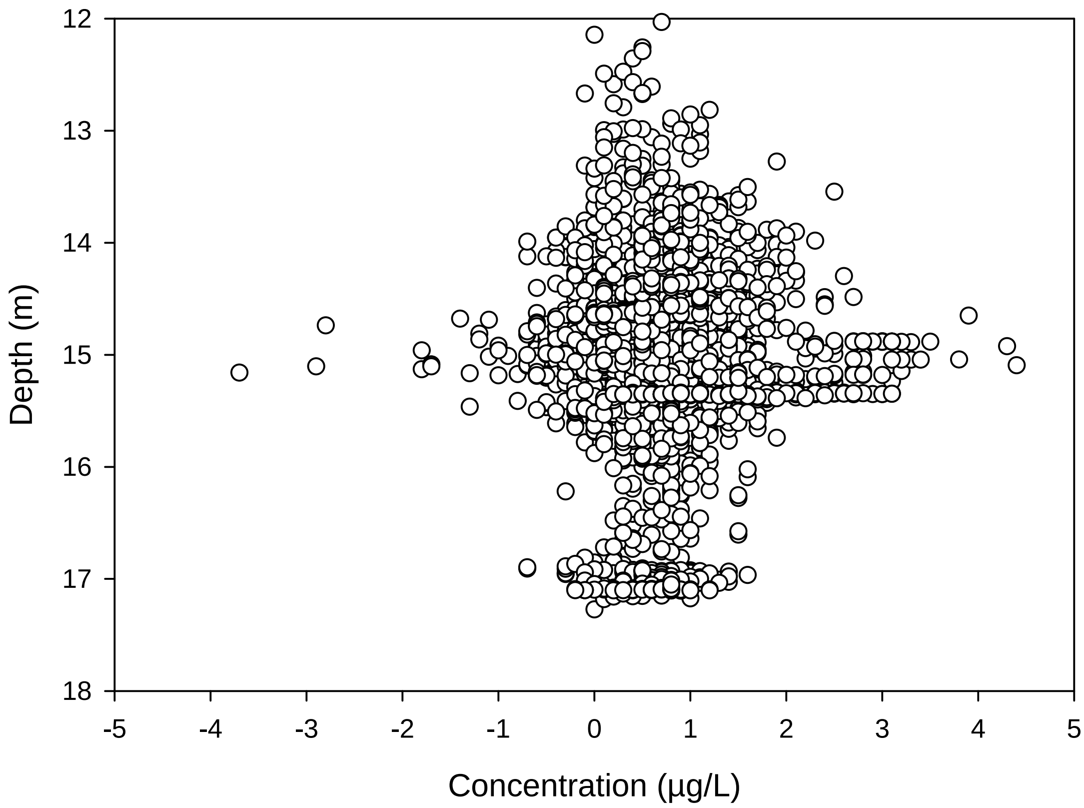
Dye Concentration Data from Day 2 of 2008 Dye Tracer Test No. 4
9/24/2008



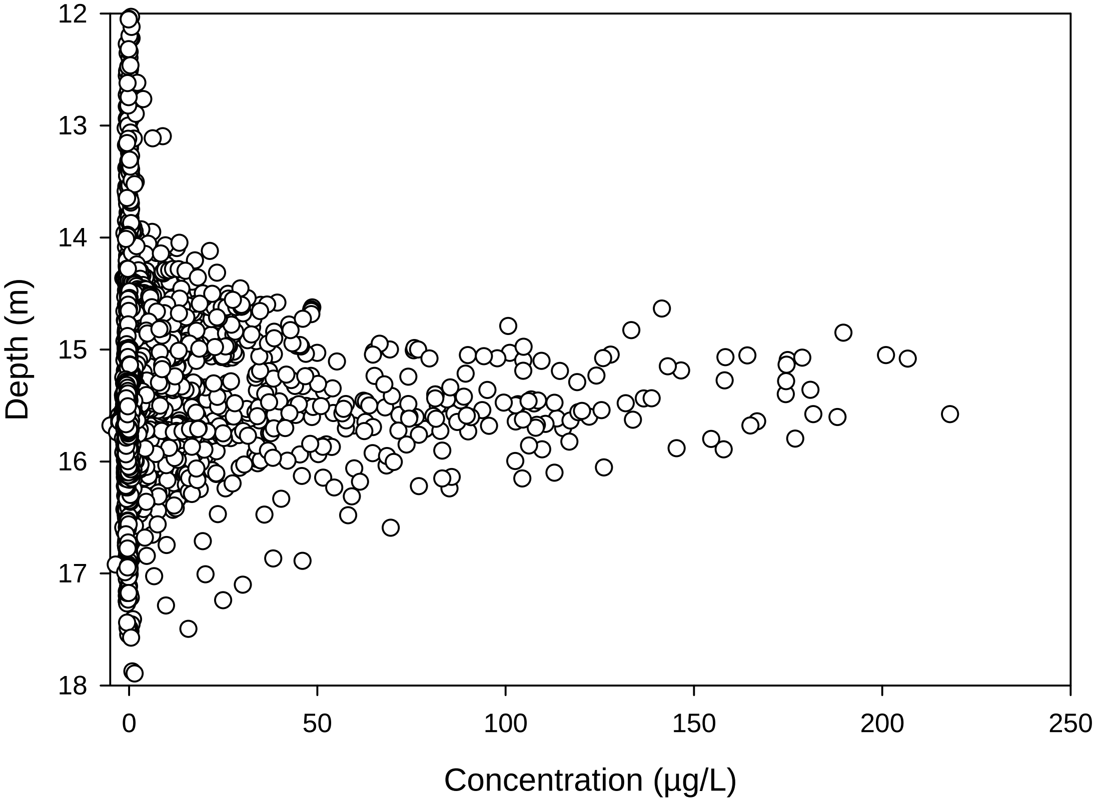
Dye Concentration Data from Day 1 of 2008 Dye Tracer Test No. 5
10/7/2008



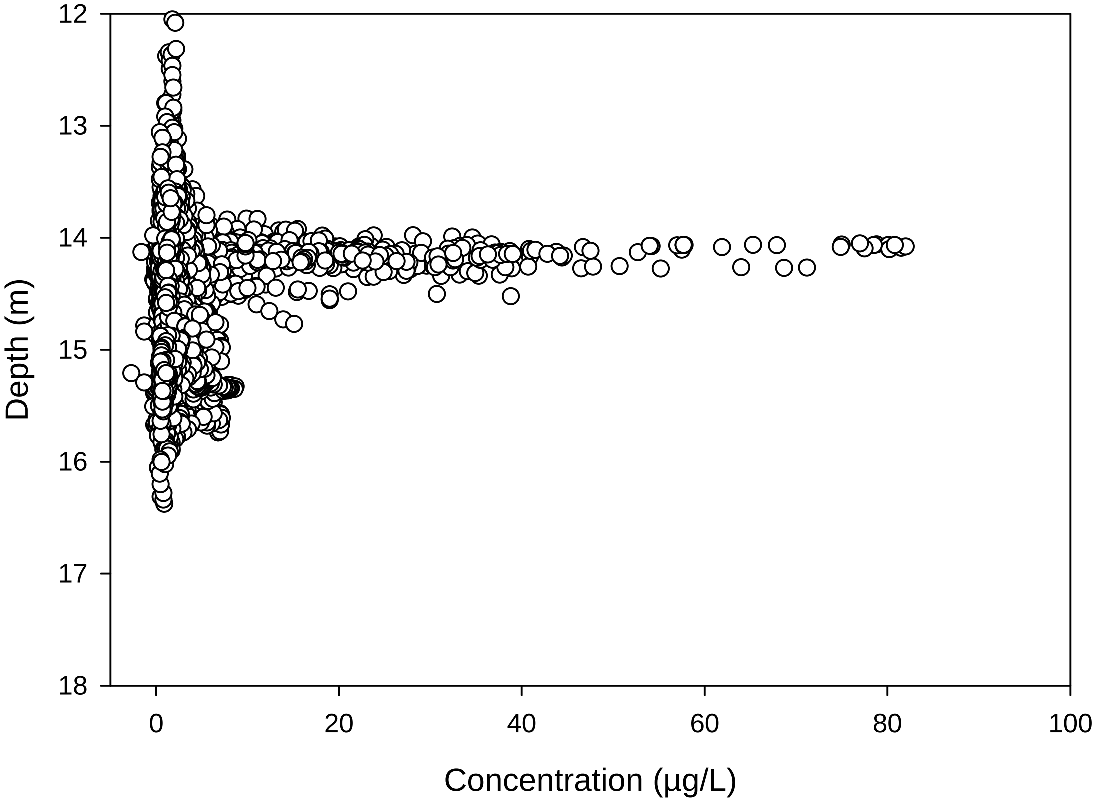
Depth Distribution of Rhodamine Dye Concentrations, Test #1



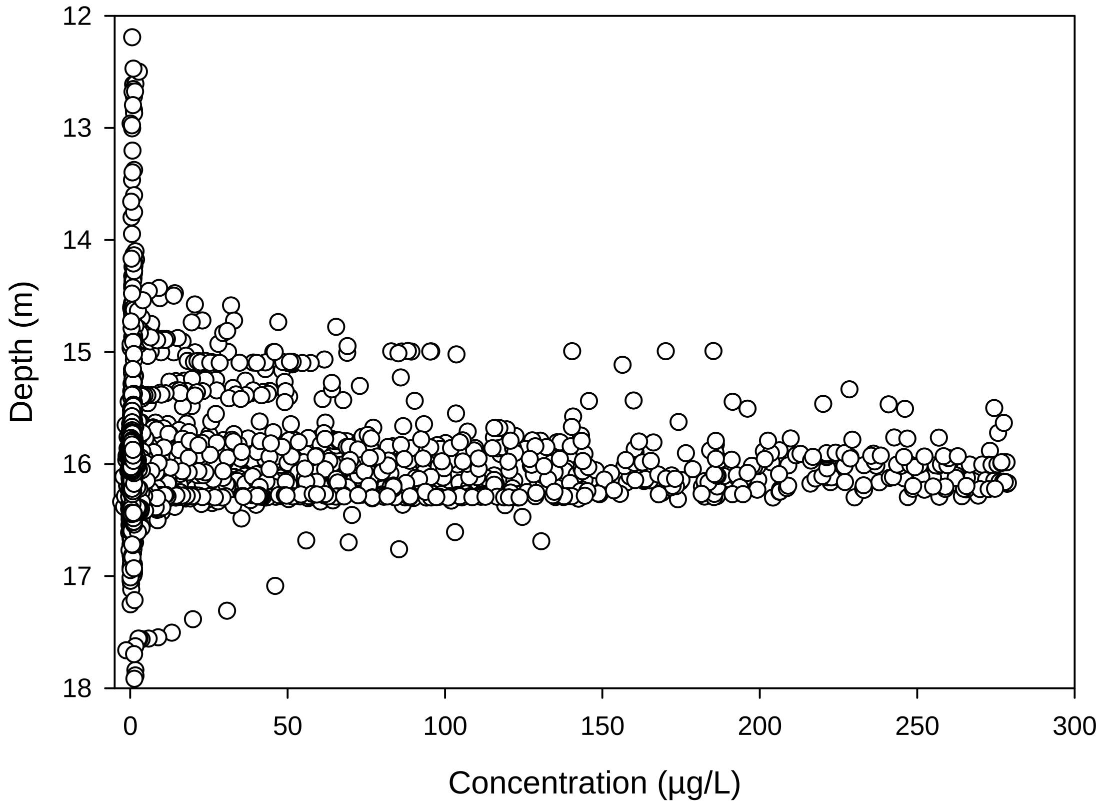
Depth Distribution of Rhodamine Dye Concentrations, Test #2



Depth Distribution of Rhodamine Dye Concentrations, Test #3



Depth Distribution of Rhodamine Dye Concentrations, Test #4



Depth Distribution of Rhodamine Dye Concentrations, Test #5