Diffuser Operations at Spring Hollow Reservoir

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ABSTRACT

Stratification is a natural occurrence in deep lakes and reservoirs. This phenomenon results in two distinct layers, the warmer, less dense epilimnion on top and the colder, denser, hypolimnion on the bottom. The epilimnion remains saturated with dissolved oxygen (DO) from mass transfer with the atmosphere, while the hypolimnion continues to undergo oxygen-depleting processes. During seasons of high oxygen demand the hypolimnion often becomes anoxic and results in the release of compounds, such as Iron, Manganese, Hydrogen Sulfide, and Phosphorous from the sediment. Iron, Manganese, and Hydrogen Sulfide can require addition Chlorine for water treatment plants, thus increasing cost and the potential production of DBP's, while the release of phosphorous results in algal blooms the following year. Spring Hollow Reservoir, located in Roanoke County, Virginia is a deep reservoir that undergoes stratification during the summer months. During 1997 Roanoke County purchased a bubble-plume diffuser from Tennessee Valley Authority (TVA) to oxygenate the hypolimnion to maintain long-term water quality. Spring Hollow currently operates the diffuser, with compressed air, during late summer months when DO levels in the hypolimnion reach approximately 4 mg/L. Observations during oxygenation have identified changing DO addition rates during diffuser operation and changing DO depletion rates following termination of oxygenation. Future research should focus on developing a quantitative understanding of the changing rates as they are related to diffuser induced oxygen demand

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INTRODUCTION

This report presents the results of research that has been performed at Spring Hollow Reservoir, located in Roanoke County Virginia. The primary goal of the research was to develop a better understanding of diffuser induced oxygen demand through improved data collection and analysis.

This report includes new data collected in 1999 and 2000 at Spring Hollow Reservoir. Previous data collected by Wendy Royston in 1996 (Royston, 1996) and Dan McGinnis in both 1997 and 1998 (McGinnis, 1999) are also incorporated.

Hypolimnetic oxygenation is a popular method used to improve water quality in stratified water bodies. It has been applied in many lakes and reservoirs for over 40 years. However, some negative impacts of the oxygenation systems, in particular, diffuser induced oxygen demand during operation have been observed.

2.0 RESEARCH OBJECTIVES

The objectives of this research are to develop an improved sampling strategy while implementing a uniform method of data analysis to quantify diffuser induced oxygen demand.

<u>OBJECTIVE 1: Develop an improved sampling strategy</u>

The improved sampling strategy will enable increased data collection before, during, and after diffuser operation. Analyzing these specific periods will enable identification of the impact hypolimnetic oxygenation has on the hypolimnion. The sampling strategy will entail identifying a representative sampling point based on a comprehensive sampling campaign at Spring Hollow Reservoir in 1999. Once a representative sampling point has been located, it will be used as a location for deployment of an automated sampling device for the 2000 sampling strategy.

<u>OBJECTIVE 2: Implement a uniform method of data analysis</u>

Data has been collected at Spring Hollow Reservoir since 1996; however, a range of data analysis techniques has been employed. To establish continuity, it is important to implement a uniform method of data analysis. This will include standardized techniques to identify the boundary of the thermocline (establishing the extent of the hypolimnion), calculate the oxygen content of the hypolimnion, and quantify hypolimnetic oxygen accumulation and depletion rates. The uniform data analysis will also allow comparison of future data collected at Spring Hollow Reservoir with data analyzed during this study period.

OBJECTIVE 3: Quantify the impact of diffuser induced oxygen demand

Increased oxygen consumption will be evaluated by monitoring oxygen depletion rates before and after diffuser operation in addition to analyzing oxygen accumulation rates during diffuser operation. Observing changes in oxygen accumulation and depletion rates should allow an estimate to be made of diffuser induced oxygen demand.

The research objectives are discussed in sections 5.0, 6.0, and 7.0 respectively.

3.0 BACKGROUND

Many lakes and reservoirs undergo a natural phenomenon during the summer known as stratification. Stratification is a result of energy exchange between the water body and the atmosphere by processes such as evaporation, wind, heat transfer, and absorption of solar energy. As stratification occurs, two distinct layers form: the warmer, less dense epilimnion on top, and the colder, denser hypolimnion on the bottom. The epilimnion maintains a high concentration of dissolved oxygen as a result of gas exchange with the atmosphere. The epilimnion also receives energy provided by sunlight, which results in an environment conducive to algal growth. After algae die they begin to decompose and settle to the bottom, where they become part of the sediment and continue to decay. The required oxygen for algal decomposition coupled with the existing organic material in the sediment leads to an increase in oxygen uptake potentially resulting in an anoxic environment.

The basic reaction occurring in the sediment to break down organic material is an oxidation-reduction (redox) reaction. A redox reaction involves the transfer of electrons from one compound to another. In order for this process to occur both oxidizing and reducing agents must be present. Organic matter is the electron donor (the reducing agent), while oxygen is the terminal electron acceptor (the oxidizing agent) for decomposition under aerobic conditions.

Once the environment becomes anoxic, other compounds become terminal electron acceptors. Redox reactions are controlled by environmental conditions, such as pH, salinity, and available compounds (e.g. oxygen, iron, sulfates, and nitrates). The environment in the hypolimnion under anoxic conditions generally favors iron as the terminal electron acceptor, if sufficiently abundant. In order for iron to be a terminal electron acceptor, it must exist in a reduced state.

In the *Encyclopedia of Hydrology and Water Resources*, the iron cycle is described as the conversion back and forth of iron from an insoluble oxidized state, as ferric iron, to a soluble reduced state, as ferrous ion ($Fe^{+2} \rightleftarrows Fe^{+3}$). Common oxidized iron compounds in the sediment are ferric phosphate and ferric hydroxide. The onset of anoxic conditions results in a reduced environment, thus promoting the conversion of ferric compounds to ferrous iron, which is soluble and diffuses into the hypolimnion (Herschy and Fairbridge, 1999). Highly reduced conditions in the hypolimnion result in the release of hydrogen sulfide (H_2S) (McQueen and Lean, 1983) in addition to the release of manganese (Mn(II)) (Davidson et al., 1985) from the sediment. When iron, manganese, hydrogen sulfide, and phosphorous are released to the water column they each result in a negative impact on water quality. Manganese leads to color problems in drinking water treatment systems and hydrogen sulfide leads to taste and odor problems in water supply reservoirs (Cook and Carlson, 1989). The presence of these species raises costs and may require additional oxidation, which can result in additional formation of disinfectant-by-products such as trihalomethanes.

Phosphates released from the sediment may contribute to algal growth during the subsequent growing season (Jung et al., 1999). Aside from external sources of phosphorous, including runoff and wastewater treatment discharge, the second highest source of phosphate is often internal loading (Auer et al., 1993). One method to control internal loading of phosphorous is to maintain sufficient levels of dissolved oxygen in the hypolimnion provided there is sufficient iron in the sediment (McQueen et al., 1986).

Over the years, several studies have been conducted worldwide regarding hypolimnetic oxygen depletion and its effect on lake and reservoir water quality. In an effort to minimize the negative impacts resulting from an anoxic hypolimnion, oxygenation systems have been installed. Oxygen can be added using compressed air or pure oxygen gas. Design criteria are developed to match the hypolimnetic volume and the estimated dissolved oxygen (DO) depletion rates identified during years preceding installation of the oxygenation system (Ashley, 1985). Observations noted during periods of oxygenation, include increased DO levels, increased oxygen demand during and immediately following operation, and hypolimnetic warming. Increased oxygen demand has been observed in several applications. Oxygen demand was observed to be approximately double pre-aeration demand in Medical lake, Washington (Soltero et al., 1994), was observed to be clearly higher in an aerated lake compared to a control enclosure without aeration (McQueen et al., 1984), was found to be ten times higher in an aerated hypolimnion compared to a non-aerated control hypolimnion (Ashley, 1981), and has been observed to increase three or four times with aeration (Smith et al., 1975; Lorenzen and Fast, 1977; Ashley et al., 1987; Moore et al., 1996). This "induced oxygen demand" is one of the causes of under sizing of aeration systems (Soltero et al., 1994). For example, the maximum oxygen depletion rate for Medical lake was calculated to be 390 kg O_2/day, oxygen demand in 1987 was measured to be 600 kg O_2/day during aeration, which resulted in the Limno aeration system, rated at 475 kg O_2/day, being undersized (Soltero et al., 1994).

The increased DO demand has been observed as net changes in addition rate during periods of oxygenation. The actual addition rate is expected to be constant because the bulk DO concentration (C_{bulk}) is much lower than the saturated DO concentration (C_{sat}) in the deep water of the hypolimnion. In other words, an increase in the bulk dissolved oxygen concentration of a few g/m^3 is usually small relative to the overall concentration driving force ($C_{sat} - C_{bulk}$) The resulting increase in oxygen demand is also influenced by sediment oxygen demand (SOD) and by the effective depth of the hypolimnion.

Mass transfer theory suggests that the driving force for sediment oxygen uptake is regulated by the oxygen concentration between the bulk water and the sediment ($C_{bulk} - C_{sed}$) coupled with movement of water over the sediment (Jorgensen and Revsbech, 1985). Laboratory experiments were performed showing the SOD is dependent on the water velocity immediately above the sediments. Reduction of the boundary layer between the sediment and the bulk water as a result of increased velocity increased SOD (Mackenthun and Stefan, 1998). It appears that the stirring effect induced by the diffuser may decrease the boundary layer thickness or increase the concentration driving force, or both, thereby stimulating sediment oxygen uptake. In addition to thinner sediment-water boundary layers, Ashley (1983) noted an increase in oxygen demand in Black Lake as a result of hypolimnetic aeration increasing the "effective depth" of the hypolimnion by slowing the settling rate, thus creating an actively circulating decomposition zone, which in turn results in greater oxidation of settling organic material.

In addition to increased oxygen demand, hypolimnetic warming has also been observed. The average hypolimnion temperatures of Medical Lake in Washington were found to be significantly higher during all aeration periods compared to pre-aeration years (Soltero et al., 1994). Spruce Knob Lake in West Virginia experienced an increase of 3°C within 5 days of aerator operation (Hess, 1975). Lake Waccabuc in New York observed slight hypolimnion temperature increases during aeration (Fast et al., 1975) and the temperature isopleths of Larson Lake show a steady increase in hypolimnion temperatures from 6°C to 12°C during aeration (Wirth et al., 1975). The hypolimnion temperatures during aeration of Wahnbach Reservoir in the Federal Republic of Germany were observed to increase from 6°C to 10°C (Bernhardt, 1967). This effect can increase SOD (respiration rates potentially double with a 10°C increase in temperature (Soltero et al., 1994)) and accelerate turnover in the fall. Wahnbach Reservoir showed a rapid decrease in stratification stability compared to pre-aeration years (Bernhardt, 1967).

Despite the increased oxygen demand and hypolimnetic warming, oxygenation systems have proven to be effective in preventing anoxic conditions in deep lakes and reservoirs, minimizing the negative impact on water quality. In 1997, Roanoke County Utility Department (RCUD) installed a bubble-plume diffuser in Spring Hollow Reservoir to improve water quality. The diffuser has been operated several times since installation and continues to supply adequate oxygen to prevent the onset of anoxia. Some data has been collected during oxygenation, but in order to investigate -potential diffuser-induced oxygen demand, a more comprehensive analysis is necessary.

4.0 DESCRIPTION OF SPRING HOLLOW RESERVOIR

Spring Hollow Reservoir was built in 1995 to supply Roanoke County with drinking water. Due to its small size, significant depth, and privacy, Spring Hollow Reservoir provides an exceptional opportunity for studying the oxygenation system. The reservoir and operation of the diffuser system are described in this section.

4.1 Spring Hollow Reservoir

Spring Hollow Reservoir is located on a 2.19 sq km (540-acre) drainage basin and has a surface area of 0.64 sq km (158 acres). It has maximum a depth of 67.1 meters (220 feet) at full pool and has a maximum volume of 13.0 hm^3 (3.4 billion gallons). The volume is maintained by pumping from the Roanoke River, when flow permits, with a pumping capacity of up to 0.030 hm^3/day (80 MGD). The water treatment plant has a 0.011hm^3/day (30 MGD) capacity and is currently operating at 0.003 hm^3/day (7 MGD).

Reservoir stratification usually begins in mid-spring and lasts until mid-December. The upper boundary of the hypolimnion is located between 30.5 to 36.6 meters (100 to 120 feet) below the surface with a hypolimnion volume range of 0.757 hm^3 to 1.70 hm^3 (200 million gallons to 450 million gallons) respectively. The hypolimnion comprises approximately 10%-15% of total volume, but has been observed to be as high as 30%. Spring Hollow Reservoir also has a large metalimnion comprising 30-60 % of total volume during early summer and reducing to approximately 10% in early fall.

4.2 Diffuser System

The diffuser is constructed from high-density polyethylene (HDPE) and is rated for compressed air or pure oxygen. It is 1070 meters (3500 feet) long and is installed along the deepest channel of the reservoir. The diffuser was first operated in late fall of 1997 using the entire length of 1070 meters (3500 feet). However, since the back 765 meters (2500 feet) of the diffuser were located in a relatively shallow region of the reservoir, operation resulted in considerable mixing and had to be discontinued. As of 1998, all operations utilized only the first 305 meters (1000 feet) located in the deeper portion of the reservoir. Air is supplied by two 20 horsepower compressors and is delivered to the diffuser at an average flow rate of $0.71 m^3/min$ (25 SCFM). An image of the components that make up the diffuser is shown in Figure 1.

In Spring Hollow Reservoir, the prolonged use of compressed air for oxygenation creates a problem in the water treatment plant. As the diffuser is operated, dissolved nitrogen builds up in the hypolimnion eventually becoming super-saturated with respect to the atmosphere. RCUD employs coagulation for removal of suspended particles, but has combined the flocculation and sedimentation process into a single basin called a clarifier. The design of the clarifier is similar to a sedimentation basin, but it is reverse fed (water enters from the bottom). Water moves up through the clarifier then passes through a media bed before flowing over weirs to filtration. Raw water is drawn into the plant from a depth of approximately 30 meters (100 feet) and remains at that pressure as it moves through the initial treatment process (addition of chlorine dioxide as pre-treatment and ferric hydroxide as coagulant) until it enters the clarifier. Because the clarifier is exposed to the atmosphere, nitrogen is released from solution when concentrations exceed atmospheric saturation levels, similar to what happens when opening a soda bottle. This results in a negative impact on the clarifier, destroying flocs, overloading the media bed, and potentially overloading filtration. As a result of this disadvantage, operation of the diffuser is monitored closely and immediately shut down when effervescence is observed in the clarifier.

5.0 OBJECTIVE 1: Develop an improved sampling strategy

The first objective of this project is to develop an improved sampling strategy. Increased DO depletion rates during periods of oxygenation have been observed at Spring Hollow Reservoir and at other facilities operating hypolimnetic oxygenation systems. The causes of diffuser induced oxygen demand are not fully understood. Therefore tracking changes in oxygen demand during diffuser operation requires a comprehensive sampling strategy.

Prior to developing an improved sampling strategy, historical data obtained from sampling programs both worldwide and at Spring Hollow Reservoir were evaluated. Following the review of historical methods, a representative sampling point was identified during 1999. In 2000, the representative sampling point was used for the location of an automated sampling device. Additionally, in 2000, a novel idea of tracking dissolved nitrogen was implemented, but unfortunately, had to be discontinued on account of probe limitations.

The review of historical data collection procedures, and the sampling processes implemented in 1999 and 2000 are discussed in the following section.

5.1 Historical Data Collection

Sampling procedures for water bodies in USA, Canada, Switzerland, and Germany undergoing hypolimnetic oxygenation were investigated. The primary constituents being monitored were temperature and DO. Data collection occurred weekly to monthly at one to four meter increments. Sampling strategies followed seasonal changes by increasing data collection in spring during the onset of stratification, and decreasing in winter when the water column profiles were relatively uniform. The number of sample stations varied among studies, but was not influenced by the total surface area. Garrell et al. (1977) monitored Lakes Waccabuc and Oscelata in New York. Garrell et al. originally sampled at three different positions in each lake, but discontinued sampling between stations after observing similar readings. They continued to collect data at a single location in each lake. Fast (1975) in his study of Ottoville quarry in Ohio, which has a surface area of 0.73 ha, monitored six locations. Kortmann et al. (1994) studied Lake Shenipsit in Connecticut. Although Lake Shenipsit has a surface area of 212 ha that is, more than 250 times the size of Ottoville, Kortman et al. only sampled at three locations utilizing one for the entire water column.

Included in the historical data collection review is the data obtained at Spring Hollow Reservoir prior to 1999. Data was collected at four stations (#10, #20, #30 and #40) spaced evenly along the centerline. Figure 2 shows a topographical map of the reservoir with the locations of the sample stations and placement of the diffuser. Traditionally, data collection was performed at 1.5 – 3.0 meters (5-10 feet) depth increments with a YSI data collection probe. Table 1 summarizes the data collection procedures from 1996 to 1998. Because of large variations in data collection procedures there was a need to develop a uniform method of data collection in 1999.

5.2 1999 Sampling Strategy

The goal of the improved sampling strategy is to increase the volume of data collected before, during and after diffuser operation. Sampling prior to 1999 occurred primarily at stations (#10, #20, and #30). To evaluate the overall characteristics of the hypolimnion, four new sample locations were added in 1999 (#5, #15, #25, and #35). Figure 2 shows the position of the additional sample locations chosen to provide extensive coverage of the hypolimnion. Sampling at all seven locations with the YSI probe would generate a more comprehensive understanding of the hypolimnion. In contrast to the sampling strategy prior to 1999, data collection was performed uniformly at 3.0-meter (10-foot) depth increments at least two times per week.

For greater economy in future data collection, a single representative sampling point was desired. This representative sampling location would be used to meet the requirements of increased data collection before, during and after diffuser operation.

A single representative sampling point should reflect the behavior of the hypolimnion as a whole. Dissolved oxygen measurements were taken at all seven sampling locations. The averaging technique used to determine the representative sampling point was applied each time data was collected at all seven locations. For simplicity the data was not weighted nor was center of mass determined. The technique as applied to one day of sampling is presented in Figure 3 in a sample spreadsheet. Data were collected at 3-meter (10-foot) depth increments throughout the hypolimnion, linearly interpolated to 0.6-meter (2-foot) depth increments and aligned in a spreadsheet according to depth (Columns H through N). The data at each depth interval was averaged (Column O). The DO for each station at every depth interval was compared to the overall average at that depth. This difference was represented as an absolute value and referred to as the "station difference" (Columns P through V). The average value of station differences over the entire sampling depth was determined as well as the standard deviation (Rows 49 and 50). The station with the lowest average difference and standard deviation would be chosen as the representative sampling point.

There were several locations that produced similar results and a singular representative location was difficult to determine. Combining stations #20 and #25 provided a better result than any individual location. A box plot of all seven individual sample locations as well as the "combined" sample station (#20 and #25) is presented in Figure 4. It is clear from the plot that the "combined" sample station has the least variance and is closest to zero (smallest difference from the overall average). The use of stations #20 and #25 as a "super-station" would best represent the overall conditions in the hypolimnion.

As previously mentioned, the goal of the improved sampling strategy was to increase the volume of data collected before, during and after diffuser operation. The 2000 sampling strategy would be used to ensure data collection before, during, and after oxygenation to develop the data required to investigate diffuser induced oxygen demand.

5.3 2000 Sampling Strategy

The 2000 sampling strategy provided continuous data collection while following the same guidelines as 1999, focusing on the periods before, during, and after oxygenation. Initially, the sampling strategy implemented for 2000 was similar to that of 1999 for re-evaluation of the representative sampling points, collecting data weekly at uniform 3.0-meter (10-foot) depth increments at all seven stations. The YSI probe was used to sample all seven locations during the first months of stratification; thereafter, the sampling strategy focused on the representative sampling points (#20 and #25) until deployment of the automated sampling apparatus in September.

Additionally, in 2000, the idea of tracking actual oxygen addition by monitoring dissolved nitrogen was considered. Dissolved nitrogen was monitored by measuring total dissolved gas and then subtracting out the contributions from dissolved oxygen and water vapor. Using nitrogen as a tracer during oxygenation would provide a method of calculating the actual oxygen addition rate. Comparing the actual oxygen addition rate with the observed oxygen accumulation rate would permit the actual oxygen consumption rate during diffuser operation to be calculated.

5.3.1 Automated Sampling Strategy

Automated sampling was made possible by the programmable features of the DataSonde 4A purchased from the Hydrolab Corporation. The Hydrolab has the ability to record temperature, DO, total dissolved gas (TDG), pH, ORP, and conductivity. The automated sampling strategy was designed to collect data during the intervals surrounding diffuser operation that had been missed in the past.

The idea of automated sampling originated from similar work performed by Scientific Instruments located in West Palm Beach, Florida. Charles Gantzer worked with SI for several years and provided the contact that resulted in the conversion of the automated concept into a working apparatus. SI provided the assistance to replicate a similar probe movement system by donating equipment and programming services. SI developed the control box, which consists of a basic stepping motor and controller to raise and lower the probe according to pre-determined specifications. The system is designed to be self-contained in a weatherproof housing that floats on the water surface. The control box, weatherproof housing, floatation, and deployment of the apparatus are shown in Figures 5 and 6.

Location of the automated sampling device was originally positioned midway between the two sample locations that constitute the representative sampling points (#20 and #25). After the first week of operation the unit was moved closer to the dam to probe the maximum depth of the hypolimnion. This location also provided connection to a back-up power supply located on top of the intake tower. Even though the representative sampling point was no longer being used, the general trends observed remained informative.

Automated sampling improved data collection substantially. The automated sampler cycled through the water column two times per day and collected data at 0.6-meter (2.0–foot) depth increments, thus providing continuous data collection during diffuser operation. The improved data quality became evident when determining the lower boundary of the thermocline in addition to reducing errors encountered performing linear interpolation. The comparison of the improvement of the Hydrolab over the YSI is apparent in Figure 7, showing temperature and DO profiles from each probe. In addition to improved data quality, the automated sampler provided an alternative method of monitoring the amount of oxygen addition using the TDG probe to track dissolved nitrogen.

5.3.2 Tracking Nitrogen

The air input during diffuser operation was estimated at 25 SCFM (standard cubic foot per minute) based on the reading from a flow meter in line to the diffuser. Accurate readings were difficult to obtain because of constant fluctuations of discharge pressure resulting from compressor loading and unloading. Even if the air flow rate was accurately known, the actual oxygen input rate remains hard to estimate because it is difficult to sample the gas bubbles leaving the hypolimnion. The TDG probe, with the ability to monitor dissolved nitrogen, would enable monitoring of actual input to the water column based on the proportions of nitrogen and oxygen in the influent air. Nitrogen in the diatomic state (N_2) does not react in the water column. Therefore as air is added, nitrogen levels would increase proportional to the amount of oxygen actually being added. Comparison of actual oxygen to observed oxygen would indicate the net oxygen consumption rate. Closely monitoring depletion rates while tracking nitrogen as a tracer during oxygenation would provide the information to quantify diffuser induced oxygen demand.

The total dissolved gas probe had a promising potential to monitor dissolved nitrogen. However, when the data was examined, it was determined that the TDG probe did not function properly at high hydrostatic pressures in the deeper water and did not resume normal operation until it reached lower pressure in shallower water. Figure 8 shows DO, temperature, and dissolved nitrogen profiles for a two-day period in October 2000. The ascending and descending profiles for nitrogen should overlap similar to the profiles for oxygen. The difference observed for nitrogen indicates probe malfunction. Hydrolab Corporation was unsuccessful in determining the cause of the problem, and the problem was directed to Alpha designs, the manufacturer of the probe. Alpha designs confirmed that the probe capabilities were restricted, and that the depth range being monitored exceeded the limitations of the design specifications. Malfunction of the total dissolved gas probe also became evident when several days of data were analyzed simultaneously. Figure 9 shows a graph of temperature, DO, and DN that have been normalized. The jump in the data for dissolved nitrogen corresponding to data retrieval supports the probe malfunction theory. Because of these limitations, the idea of tracking nitrogen had to be abandoned.

6.0 OBJECTIVE 2: Implement a uniform method of data analysis

Uniformity in data analysis between each year of data collection is essential to establish continuity. Factors such as hypolimnion position and volume are taken into consideration for development of a standard analytical method that is applied to each data set. In addition to accounting for the impact varying hypolimnion volume has on calculations of oxygen content, a method to normalize the accumulation and depletion rates will also be used.

6.1 Thermocline Definition

The thermocline is observed at different depths each year, but more importantly at different depths throughout each year. To ensure continuity when determining the extent of the hypolimnion, an accurate method of determining the position of the thermocline is required.

Hutchinson (1957) defines the thermocline as "the plane of maximum rate of decrease in temperature," which is defined mathematically as

$$\theta'' = \frac{d^2\theta}{dz^2} = 0$$

on a depth (z) versus temperature (θ) curve (Hutchinson, 1957).

The regions above and below the thermocline are defined as the epilimnion and hypolimnion, respectively. Herschy and Fairbridge (1998) define the thermocline mathematically in the same way as Hutchinson, but also specify it as the "stratum where temperature drops at least 1 °C with each increase in depth of 1 meter." While both definitions are clear, the mathematical definition fluctuates around zero and the boundaries of the thermocline are difficult to identify. Wetzel (1975) defined the thermocline, also known as the metalimnion, as "the stratum of steep thermal gradient, that can be demarcated by the intersections of a plane along the gradient to the points of maximum curvature from the approximately homoiothermal conditions of the epilimnion and the hypolimnion," graphically depicted in Figure 10.

Using Wetzel's graphical definition in conjunction with the second derivative provides a reliable method to identify the thermocline boundary and the extent of the hypolimnion. Figure 11 shows two points where the second derivative fluctuates close to zero. By comparing the graphical method in this case with the mathematical definition, a consistent method of thermocline boundary identification is obtained. In comparison to "eyeballing", the consistency observed using mathematical and graphical definitions minimizes errors. Figure 12 shows a clear difference between estimation and calculation methods for determination of the hypolimnion. Developing a consistent method to identify the hypolimnion reduces errors in oxygen mass calculations due to inaccurate volume estimation.

6.2 Hypolimnion Volume Calculations: Referencing Elevation Versus Depth

The water level in Spring Hollow Reservoir fluctuates daily. Pumping from the Roanoke River when flow permits increases the water volume in the reservoir. Water is withdrawn daily at a rate of 0.003 hm^3/day (7 MGD) for treatment. The reservoir volume fluctuations are easily observable, but the hypolimnion volume fluctuations are not as clear.

To ensure accuracy in hypolimnion volume calculations, there is an advantage in referencing all data to elevation as opposed to depth. Small fluctuations in the hypolimnion volume can have a significant impact on overall calculations. Data were collected on September 8, 1998 when the reservoir level was 420.9 meters (1381 feet). Data were collected again on October 9, 1998, but the reservoir level had lowered to 419.7 meters (1377 feet). The change in reservoir level appears to be minor, but the difference results in a large discrepancy in calculated volume. McGinnis (1998) collected data and analyzed it based on a depth reference. McGinnis determined that the volume of the hypolimnion was 1.10 hm^3 (290 MG) for both the September and October sampling days. However, the same data analyzed based on an elevation reference indicates that on September 8 the volume was 1.08 hm^3 (285 MG), and on October 9 the volume was 1.22 hm^3 (322 MG). The difference in the volume between these two sampling days is 0.14 hm^3 (37 MG), which constitutes greater than 10% of the hypolimnion volume. Actual oxygen content, based on the recorded DO concentrations on October 9 of 6.0 mg/L, would be approximately 800 kg less when based on depth rather than elevation. Since estimating oxygen content requires integration over volume proper volumetric reference is vital for accurate calculations.

6.3 Oxygen Content

The last step in the hypolimnion analysis is the determination of oxygen content. Dissolved oxygen concentrations are recorded at intervals through the water column. The sampling intervals represent two-foot depth increments and are converted into volumetric slices in proportion to the reservoir volume. The oxygen mass is determined for each interval by multiplying the recorded concentration values with the corresponding slice volume. The mass calculations are summed to obtain the total mass for the defined volume.

The hypolimnion volume fluctuations influence the oxygen mass calculation. Therefore, mass addition and depletion rates are affected more by volume changes than by actual DO variations.

Larger volumetric slices have a greater influence on the overall mass calculation than smaller ones. When the total oxygen mass is calculated the overall value is a weighted representation based on each contributing slice. Dividing the total mass in solution by the total volume results in a weighted average concentration. Monitoring changes in weighted average concentration provides the flexibility to compare each year's accumulation and depletion rates.

7.0 OBJECTIVE 3: Quantify diffuser induced oxygen demand

Diffuser induced oxygen demand is an increase in oxygen consumption as a result of diffuser operation. After oxygenation begins, the oxygen addition rate increases but the rate of increase slows over time. In order to understand this phenomenon, accumulation and depletion rates are monitored very closely before, during, and after diffuser operation.

Because the actual addition rate cannot be explicitly determined from oxygen accumulation rates during diffuser operation, depletion rate analysis prior to diffuser operation is necessary. As previously discussed, the actual oxygen addition rate is expected to be constant provided the air flow rate to the diffuser is essentially constant. Estimating the enhanced depletion of oxygen during diffuser operation is needed to quantify diffuser induced oxygen demand.

Since the diffuser is expected to increase oxygen demand during operation, turning it off should have the opposite effect. Once diffuser operation is terminated, the depletion rates should return to levels observed prior to operation. Monitoring oxygen content following diffuser operation will identify depletion rates immediately after oxygenation as well as depletion rates several days later. The theory of diffuser induced oxygen demand will be supported if later depletion rates are significantly lower than those observed immediately following oxygenation.

Combining the information supporting changing accumulation rates during diffuser operation with changing depletion rates following oxygenation will enable quantification of diffuser induced oxygen demand.

7.1 Hypolimnion Oxygen Depletion Rates

Oxygen depletion rates are measured for three different periods each year:

- depletion rates prior to diffuser operation (initial depletion rates);
- depletion rates for the week immediately following diffuser termination;
- final depletion rates.

Table 2 shows the above-categorized depletion rates observed during 1996 through 2000 in addition to a forth category; diffuser induced oxygen demand. Diffuser induced oxygen demand was calculated from the difference between the depletion rate for the week immediately following diffuser termination and the final depletion rate for that year. An approximate timeline, generated from the 1996 data set, is shown in Figure 13 representing the initial and final depletion rates with corresponding hypolimnion DO levels.

7.2 Hypolimnion Oxygen Accumulation Rates

The diffuser was operated several times over the 5-year study period. The conditions surrounding each period of oxygenation varied significantly. There was no consistency regarding number of times the diffuser was operated, the time of year operated, observed DO levels at the onset of oxygenation, pumping conditions, reservoir level, thermocline position, and duration of operation. Despite these differences, similar accumulation rates are evident. During diffuser operation, three different periods and their corresponding accumulation rates were observed: the initial, final, and net overall. Initial accumulation rates were measured during the 3 days immediately following the start of oxygenation, while final accumulation rates corresponds to the remaining period of oxygenation. The overall addition rate was calculated to compare periods of oxygenation when initial rates could not be determined. Table 3 shows initial, final, and overall addition rates for diffuser operations that occurred in 1997-2000, in addition to diffuser induced oxygen demand estimated from the changing accumulation rates.

On two occasions, sufficient data were collected to support the initial accumulation rate analysis. These occurrences in 1998 and 1999 show a predominant decrease in the accumulation rate.

Based on the expected constant addition rate, the observed change is attributed to increased oxygen consumption, which is directly related to the operation of the diffuser.

Overall accumulation rates vary each year and are potentially influenced by stopping and restarting the diffuser several times during the oxygenation period. This influence was evident for the diffuser operation in 2000 in that the overall accumulation rate is similar to the final accumulation rate observed in 1998 and 1999. Without sufficient data to accurately support this influence, further investigation is recommended during future diffuser operations.

7.3 Diffuser Induced Oxygen Demand

Diffuser induced oxygen demand is an increase in oxygen consumption by the water column and the sediment as a result of increased turbulence created during oxygenation. It is observed during oxygenation as a decrease in the rate at which oxygen accumulates and as a decrease in depletion rates once oxygenation has been terminated. Monitoring depletion and accumulation rates surrounding diffuser operation has identified the following diffuser induced oxygen demand:

- The average decrease in oxygen accumulation rate is 0.27 g/m^3day (0.40 g/m^3day to 0.13 g/m^3day), which is an increase in oxygen consumption greater than a factor of five.
- The average decrease in oxygen depletion rate is 0.09 g/m^3day (0.14 g/m^3day to 0.05 g/m^3day) observed during the week immediately following oxygenation and the remainder of stratification, respectively. The observed change is 2.5 times higher immediately after diffuser operation than the observed end of year depletion rate.

Figure 14 provides a graphical representation of the average depletion and accumulation rates discussed in sections 7.1 and 7.2, in addition to periods identifying diffuser induced oxygen demand. The regions representing diffuser induced oxygen demand correspond to accumulation rates during the first three days of oxygenation and depletion rates following the week immediately after diffuser termination.

Factors influencing diffuser induced oxygen demand cannot be explicitly determined because the water column oxygen demand and sediment oxygen demand are inseparable without further detailed measurements. In order to isolate the large difference observed in diffuser induced oxygen demand (0.27 g/m^{3}day and 0.09 g/m^{3}day) several factors need to be considered. Sediment oxygen demand is influenced by a decrease in the boundary layer above the sediments, resulting in a more rapid uptake of oxygen. Increased turbulence in the water column as discussed by Ashley (1983) may increase the "effective depth" of the hypolimnion. The settling velocity of decaying organic matter is therefore decreased during increased turbulence. Additionally, higher depletion rates were observed during elevated DO concentrations; a comparison of depletion rates and corresponding DO levels is presented in Figure 13. Depletion rates during the end of 1996-1998 were lower than those during initial stratification. When the DO concentration is above 5 mg/L, higher depletion rates were observed; when the DO concentration is below 5 mg/L, lower depletion rates were observed. As the diffuser is operated, it is hypothesized that the increased DO levels may influence the driving force for oxygen uptake. Future investigation of boundary layers between sediment and water interface, settling velocities, and the influence of elevated DO levels on oxygen depletion rates are necessary to further improve our understanding of diffuser induced oxygen demand.

8.0 ADDITIONAL OBSERVATIONS

In addition to diffuser induced oxygen demand, hypolimnetic warming and movement have also been observed during diffuser operation. Additionally the effects of pumping on hypolimnion mixing and oxygen content were observed. These observations, as well as several problems encountered during this research, are discussed in this section.

8.1 Hypolimnetic Warming

Natural warming has been observed in the hypolimnion throughout each year. For the entire period of stratification in 1996, the hypolimnion temperature increased from 6.8°C to 7.5°C (0.03°C per week) and successive years showed similar pre-oxygenation temperature increase rates ranging from 0.03°C to 0.06°C per week. During periods of oxygenation, elevated hypolimnion temperatures are apparent, as shown in Figure 15. The 1997 period of oxygenation had the largest observed increase from 6.3°C to 8.8°C (1.5°C per week), whereas the average rates of warming during oxygenation for 1998 to 2000 were 0.26°C, 0.44°C, and 0.40°C per week respectively. Although respiration rates potentially double with a 10°C increase in temperature (Soltero et al., 1994), this increase would require twenty-five (25) weeks of diffuser operation. Current oxygen demand would be satisfied with seven weeks of oxygenation, but the restrictions from nitrogen effervescence, limits diffuser operation to about three weeks. Although more research on the effect of temperature on kinetics of oxygen uptake (in the range of 6-8°C) needs to be conducted, hypolimnetic warming, even at ten times the natural rate, remains a modest concern.

8.2 Hypolimnion Movement

The hypolimnion is observed to progressively move deeper each year as December approaches leading to subsequent turnover, which is evident in the temperature profiles for 1997, shown in Figure 16. Lind (1985) also documents this downward movement of the hypolimnion. In contrast to the downward trend, the hypolimnion was observed to move upward during oxygenation. Figure 17 shows the initial and final location of the lower boundary of the thermocline throughout stratification, as well as the positioning during oxygenation. The hypolimnion is lower each year in the fall than in early summer. Upward movement is also clear during oxygenation. Figure 18 shows a close-up of the upward movement of the thermocline during diffuser operation. The upward movement may be attributed to thermocline sharpening, but requires further investigation.

8.3 Effects of Pumping

Although a conclusive result of the impact of pumping cannot be determined, it is believed that the pumping that occurred in 1999 influenced oxygen accumulation and depletion rates. Throughout 1999, Roanoke County pumped a total of 12.9 hm^3 (3.4 billion gallons) into the reservoir, which is greater than the entire working volume. It is almost impossible for this volume to not influence the hypolimnion. During periods of pumping greater than 0.057 hm^3/day (15 MGD), the observed depletion rates were elevated, similar to increased depletion rates following oxygenation. The increased depletion rates indicate possible mixing induced by the addition of large quantities of water. The stirring phenomenon was compared to other years when large volumes of water were pumped, but a clear relationship could not be established. Further analysis of the impact of pumping is required.

8.4 Problems

Problems encountered during the study period of 1999 to 2000 to evaluate diffuser induced oxygen demand include the following:

- missed data collection at key points in 1999,
- TDG probe problems in 2000,
- compressor malfunctions, and
- limited allowable operation of diffuser.

Even though the 1999 sampling strategy improved on past data collection at Spring Hollow Reservoir, key times surrounding diffuser operation were missed. Several factors controlled the ability to collect data on a daily basis and information was gathered as best as possible. The restrictions to sample at key periods in 1999 were the driving force for implementing automated sampling in 2000.

The compressors being used for the purpose of oxygenation are operated for only a few weeks each year. This type of operation has proven to be unreliable as time progressed. Each year the compressors were operated, more malfunctions occurred. The apex of this difficulty occurred in 2000 when the governor controlling discharge pressure repeatedly shut down, preventing the compressors from overcoming the hydrostatic pressure at the bottom of the reservoir.

9.0 RECOMMENDATIONS

Based on the work performed during this project, three recommendations are offered.

1.) It is recommended that data collection during future monitoring of the hypolimnion be performed as follows:

- During stratification: Weekly at 1-meter (3-foot) not to exceed 3-meter (10-foot) depth increments.
- During winter (when temperature profiles are uniform throughout the water column): Monthly at 3-meter (10-foot) depth increments.

2.) It is recommended that a standardized method of data analysis be implemented for each of the following calculations:

- Thermocline boundary: Use of mathematical and graphical method to accurately identify location of the thermocline. This is performed to accurately determine the hypolimnion volume.
- Oxygen content: Use of standard integration method to determine total mass of oxygen content normalized by total volume of the hypolimnion for corresponding sample day.
- Depletion rate: Examine depletion rates by plotting normalized oxygen content over time, where the depletion rate is determined from the slope of the line. Projecting this line to the date corresponding to 5 mg/L average hypolimnion oxygen concentration will establish the required start date for diffuser operation. It has been suggested that below 5 mg/L, phosphorous begins to be released from the sediment (Favre, 1991).
- Oxygen addition: Calculation of total mass of oxygen needed to satisfy oxygen demand through December 15 based on observed depletion rates and estimated time to reach 5 mg/L in the hypolimnion. (Depletion rate $\times$ time in days $\times$ hypolimnion volume $\times$ safety factor). Hypolimnion volume can be corrected as

needed. A safety factor of between 3 and 6, as observed in the diffuser induced oxygen demand analysis, may be needed.

3.) It is recommended that the diffuser be operated according to the following guidelines:

- One continuous operation: Minimizing periods of shutdown once oxygenation begins will reduce the overall effect of diffuser induced oxygen demand.
- Compressed Air: Monitoring of the clarifier is essential for rapid shutdown of the diffuser when effervescence is observed.

Pure Oxygen: Use of pure oxygen will eliminate effervescence in the clarifier in addition to improving efficiency of oxygenation. Upgrading to the use of pure oxygen will also minimize the impact of diffuser induced oxygen demand because of reduced mixing.

Following the above recommendations for continued data collection, data analysis, and diffuser operation will help maintain high water quality while minimizing the adverse effects of anoxic conditions in the hypolimnion during periods of stratification.

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10.0 TABLES

Sampling Information				
Year	Location	Increment	Interval	Total Days
1996	10,20,30,40	1.5-3.0 meters (5-10 feet)	1 - 2 Weeks June - Dec.	19
1997	10,20,30,40	1.5-3.0 meters (5-10 feet)	1 - 2 Weeks Feb. - Apr. Bi-monthly Apr.- Nov.*	13
1998	10	3.0-5.0 meters (10-15 feet)	Monthly Feb.- Nov.*	17

* Indicates Increased Sampling During Diffuser Operation

Table 1: Data collection summary for Spring Hollow Reservoir.

Depletion Rates ($g/m^3 day$)				
Year	Initial	Final	1 Week Following Oxygenation	Diffuser Induced O_2 Demand
1996	0.04	0.02		
1997	0.05	0.03	ND	ND
1998	0.04	0.03	0.11	0.07[τ]
			0.18	0.15
1999	0.07	0.11	ND	ND
			0.17	0.06
			ND	ND
2000	0.04	0.05	0.12	0.07
Average	0.05	0.05	0.14	0.09

τ Depletion rate observed prior to second diffuser operation equalled the initial depletion rate of 0.04.

Table 2: Depletion rates observed during 1996-2000 data collection.

Accumulation Rates (g/m^{3}day)				
Year	Initial (< 3 Days)	Final (> 3 Days)	Overall	Diffuser Induced O_2 Demand
1996				
1997	ND	ND	0.42	ND
1998	0.44	0.12	0.16	0.32
1999	0.35	0.13	0.23	0.22
2000	ND	ND	0.14	ND
Average	0.40	0.13	0.24	0.27

Table 3: Accumulation rates observed during diffuser operations for 1997-2000.

11.0 FIGURES

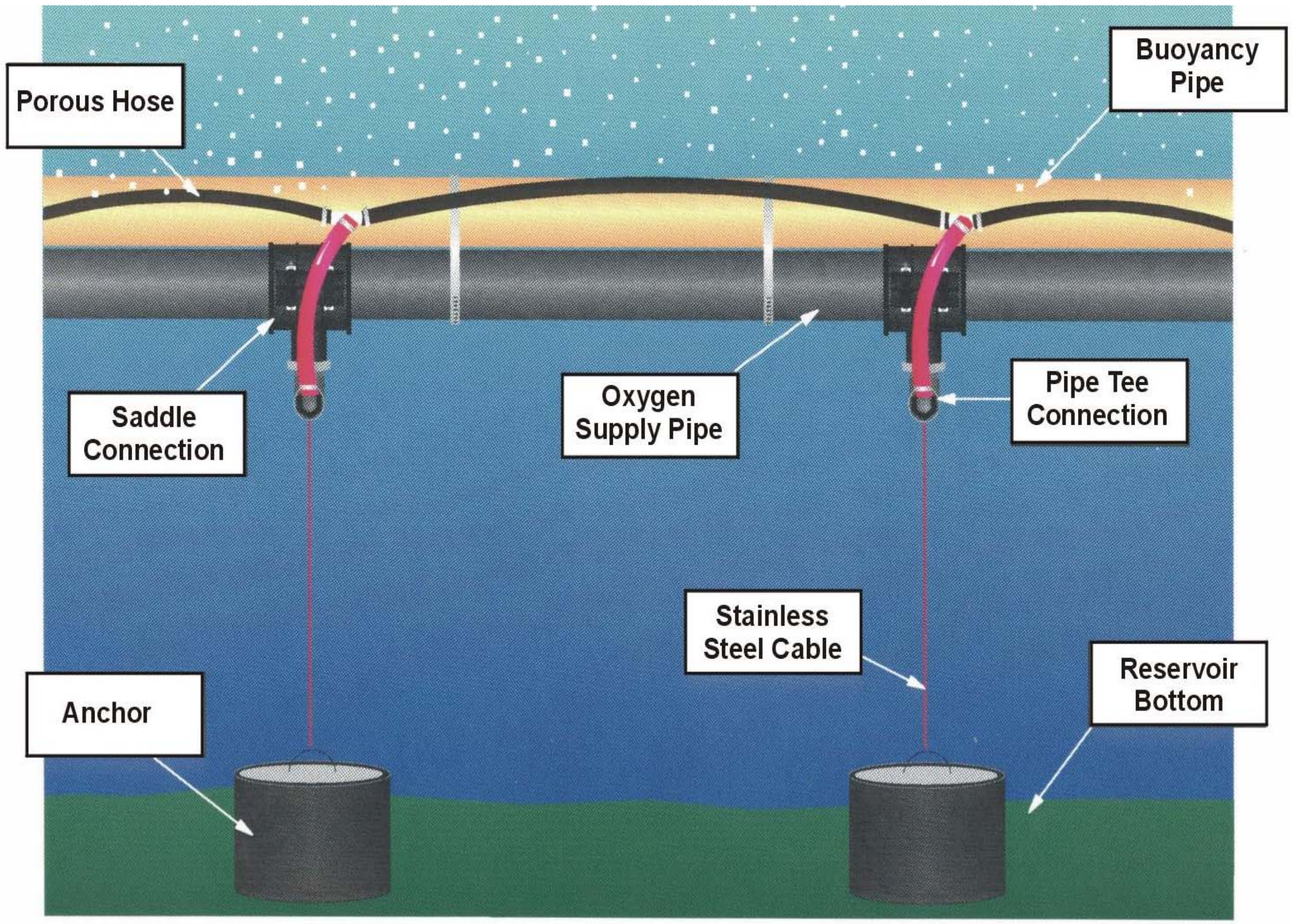

Figure 1: Linear plume diffuser schematic.

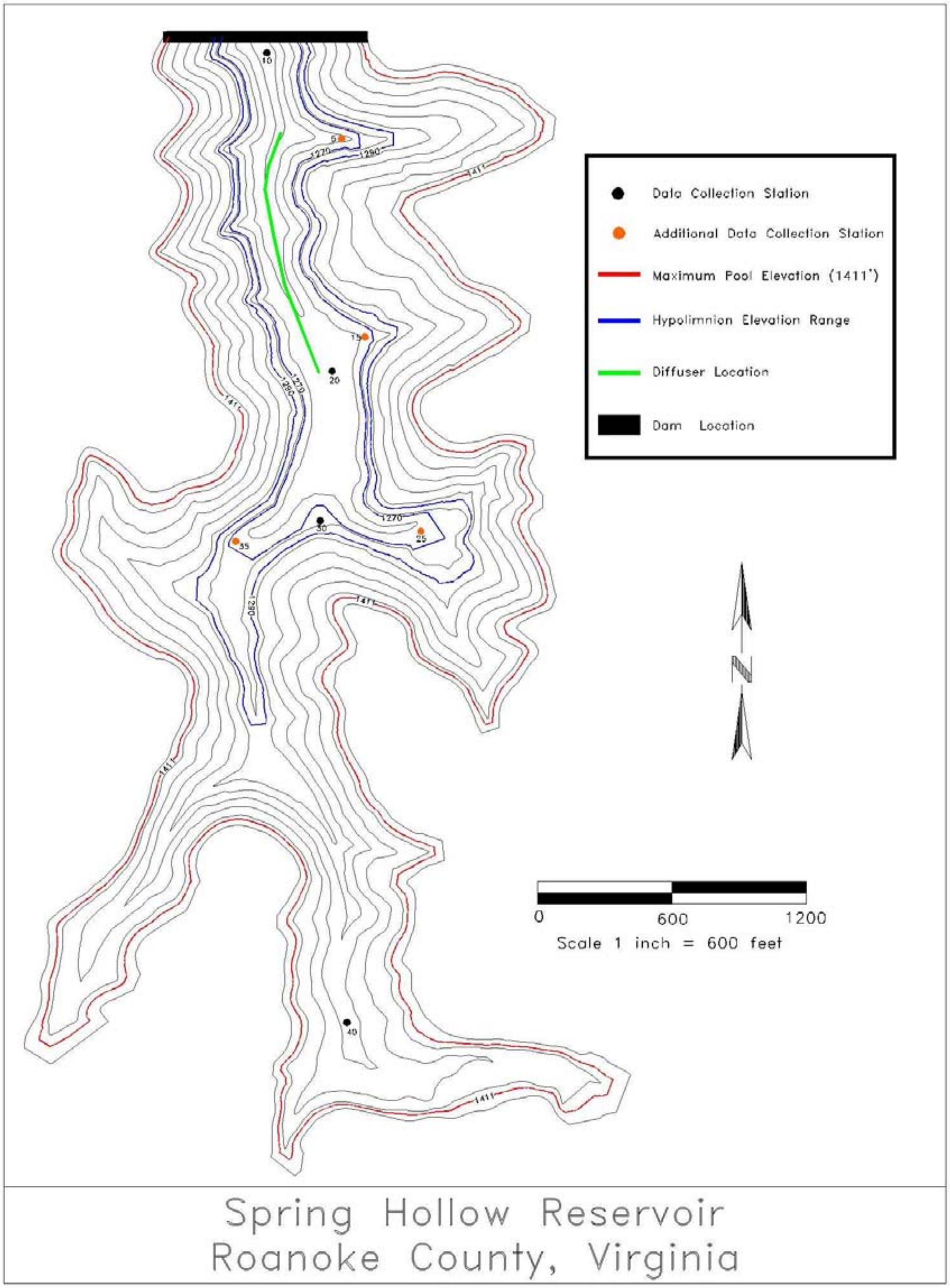

Figure 2: Hypsographic map of Spring Hollow Reservoir, showing diffuser and sampling locations.

	A	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
1	4-Aug-99	Reservoir level 1390.0														
2		Station							DO-avg	Station Difference						
3	Depth	10	20	30	35	25	15	5		10	20	30	35	25	15	5
4	100	8.01	7.41	6.32	6.94	7.38	7.85	7.85	7.39	0.62	0.02	1.07	0.46	0.02	0.46	0.46
5	102	7.99	7.32	6.29	6.93	7.31	7.71	7.71	7.32	0.67	0.00	1.03	0.39	0.01	0.39	0.39
6	104	7.97	7.22	6.25	6.93	7.25	7.57	7.57	7.25	0.72	0.03	1.00	0.32	0.00	0.32	0.32
7	106	7.96	7.13	6.22	6.93	7.18	7.42	7.42	7.18	0.78	0.05	0.96	0.25	0.00	0.24	0.24
8	108	7.93	7.04	6.18	6.93	7.12	7.28	7.28	7.11	0.82	0.07	0.93	0.18	0.01	0.17	0.17
9	110	7.92	6.93	6.14	6.97	7.06	7.14	6.79	6.99	0.93	0.06	0.85	0.02	0.06	0.15	0.20
10	112	7.83	6.96	6.11	6.79	6.99	7.00	6.77	6.92	0.91	0.04	0.81	0.14	0.07	0.07	0.15
11	114	7.74	6.98	6.07	6.60	6.93	6.85	6.76	6.85	0.89	0.13	0.78	0.25	0.08	0.01	0.09
12	116	7.65	7.02	6.04	6.41	6.86	6.75	6.75	6.78	0.87	0.24	0.74	0.37	0.08	0.04	0.04
13	118	7.56	7.05	6.00	6.22	6.80	6.73	6.73	6.73	0.83	0.32	0.73	0.51	0.07	0.00	0.00
14	120	7.47	7.08	5.96	6.03	6.72	6.72	6.72	6.67	0.80	0.41	0.71	0.64	0.05	0.05	0.05
15	122	7.37	7.12	5.94	5.84	6.69	6.70	6.70	6.62	0.75	0.50	0.68	0.78	0.07	0.08	0.08
16	124	7.28	7.15	5.90	5.66	6.66	6.69	6.69	6.57	0.71	0.58	0.67	0.92	0.08	0.11	0.11
17	126	7.18	7.18	5.86	5.47	6.62	6.67	6.67	6.52	0.66	0.66	0.66	1.05	0.10	0.15	0.15
18	128	7.10	7.21	5.83	5.28	6.59			6.40	0.70	0.81	0.57	1.12	0.19		
19	130	6.99	7.25	5.80	5.43	6.55			6.40	0.59	0.85	0.60	0.98	0.15		
20	132	6.96	6.95		4.36	6.52			6.20	0.76	0.75		1.84	0.32		
21	134	6.92	6.60		3.29	6.49			5.82	1.10	0.78		2.54	0.66		
22	136	6.87	6.29			6.45			6.54	0.33	0.25			0.08		
23	138	6.84	5.95						6.40	0.45	0.44					
24	140	6.80	5.60						6.20	0.60	0.60					
49							Average Difference			0.62	**0.27**	0.98	0.49	**0.16**	0.35	0.35
50							Standard Deviation			0.16	**0.18**	0.18	0.25	**0.17**	0.20	0.19

Figure 3: Sample spreadsheet showing representative sampling point identification.

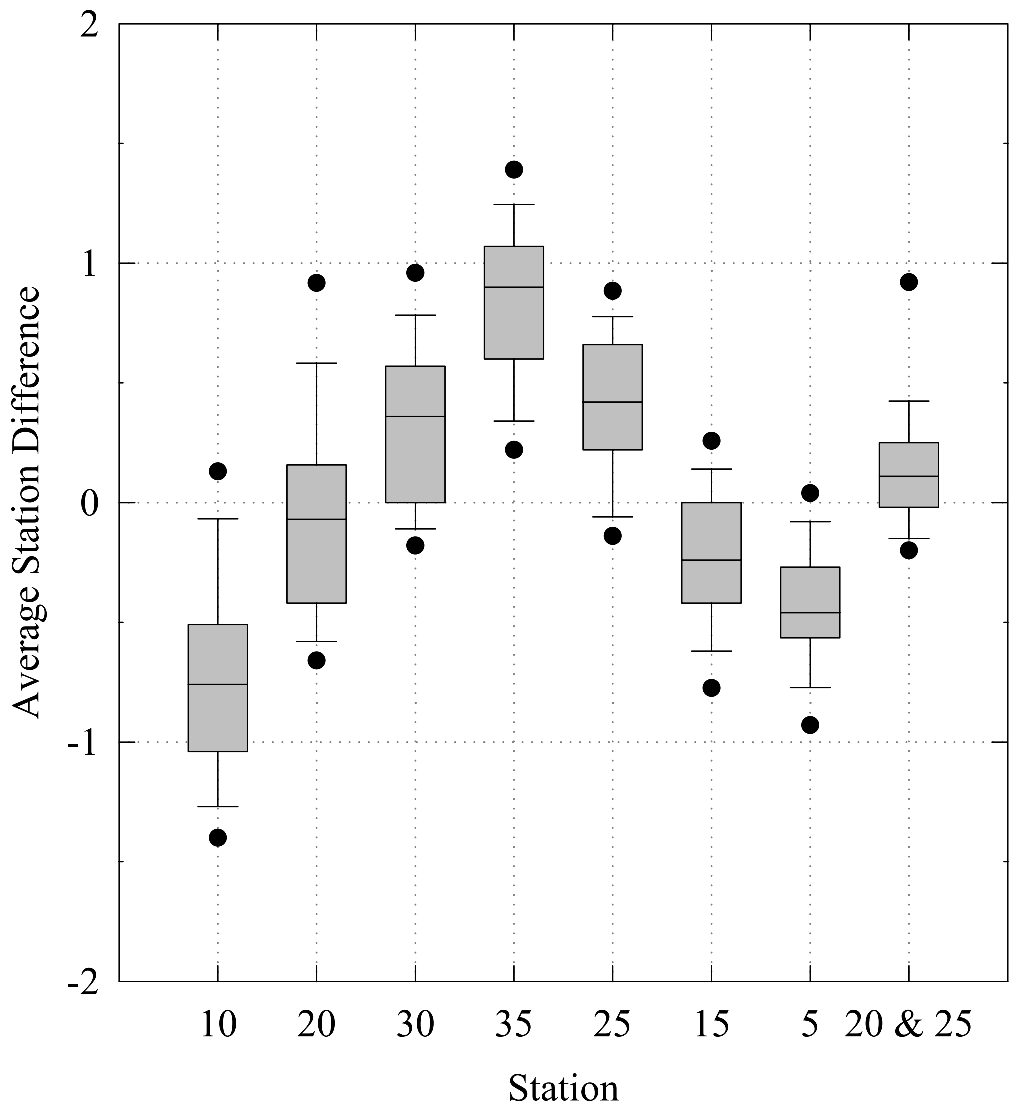

Figure 4: Representative sampling point determination.

Figure 5: Control box showing stepping motor and controller

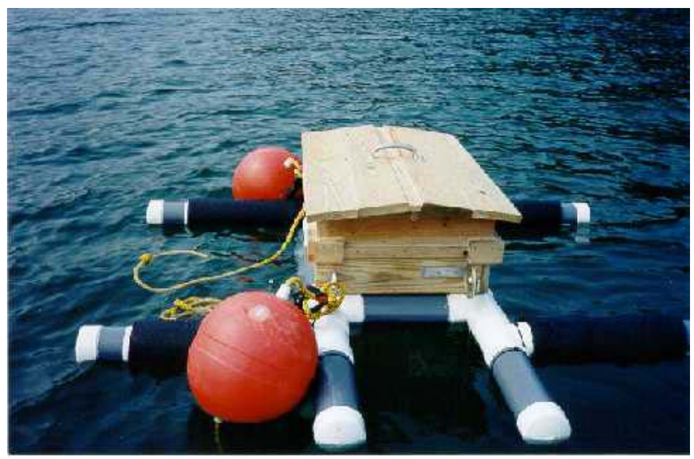

Figure 6: Weatherproof housing and floatation for the automated sampling device.

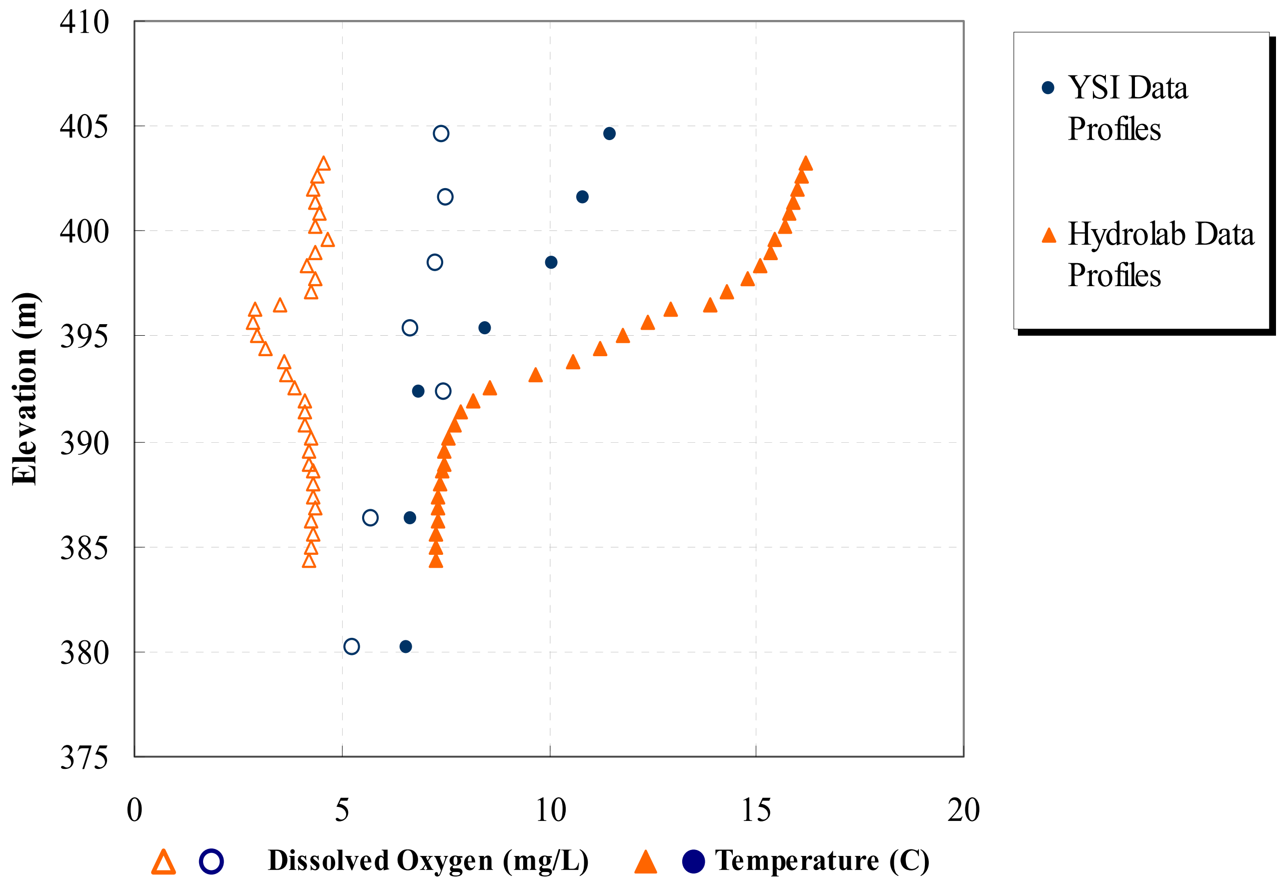

Figure 7: Data profiles showing improved resolution of Hydrolab over YSI.

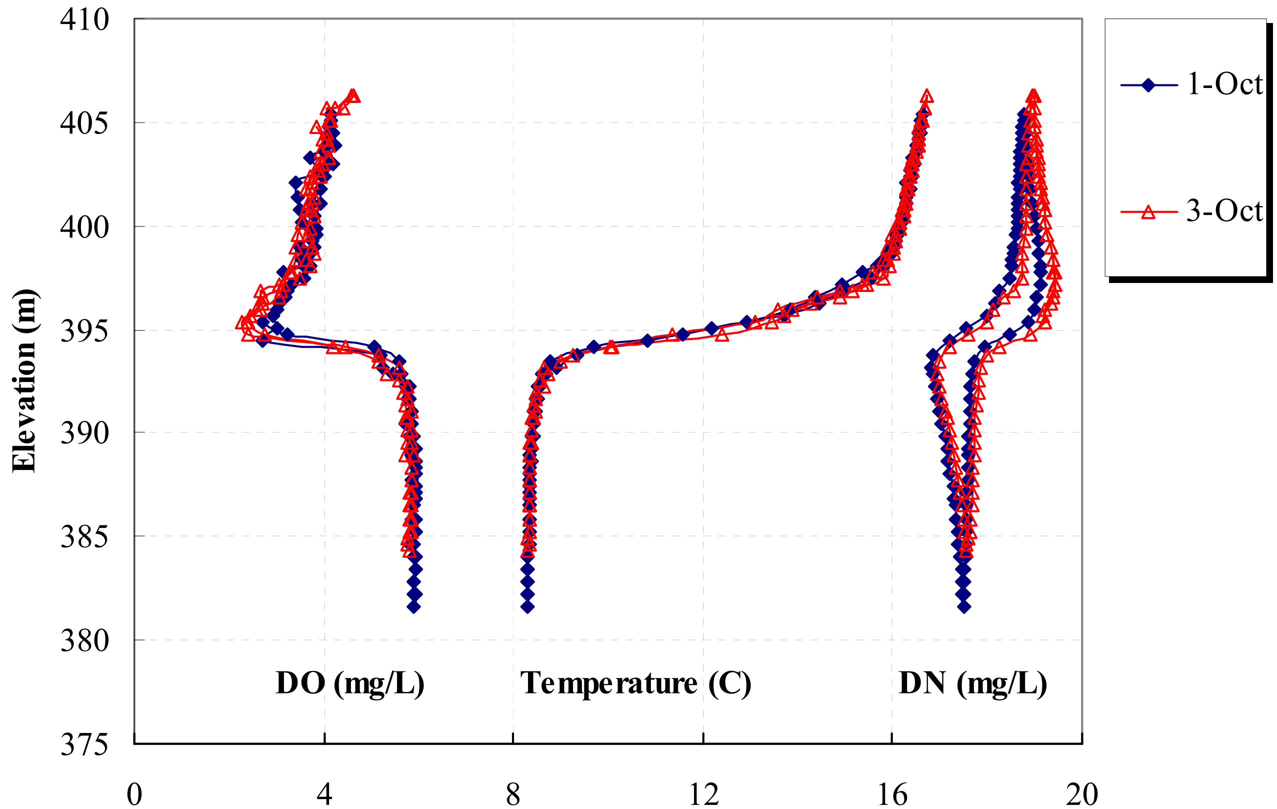

Figure 8: Ascending and descending temperature, dissolved oxygen, and dissolved nitrogen profiles showing hysteresis of nitrogen profiles.

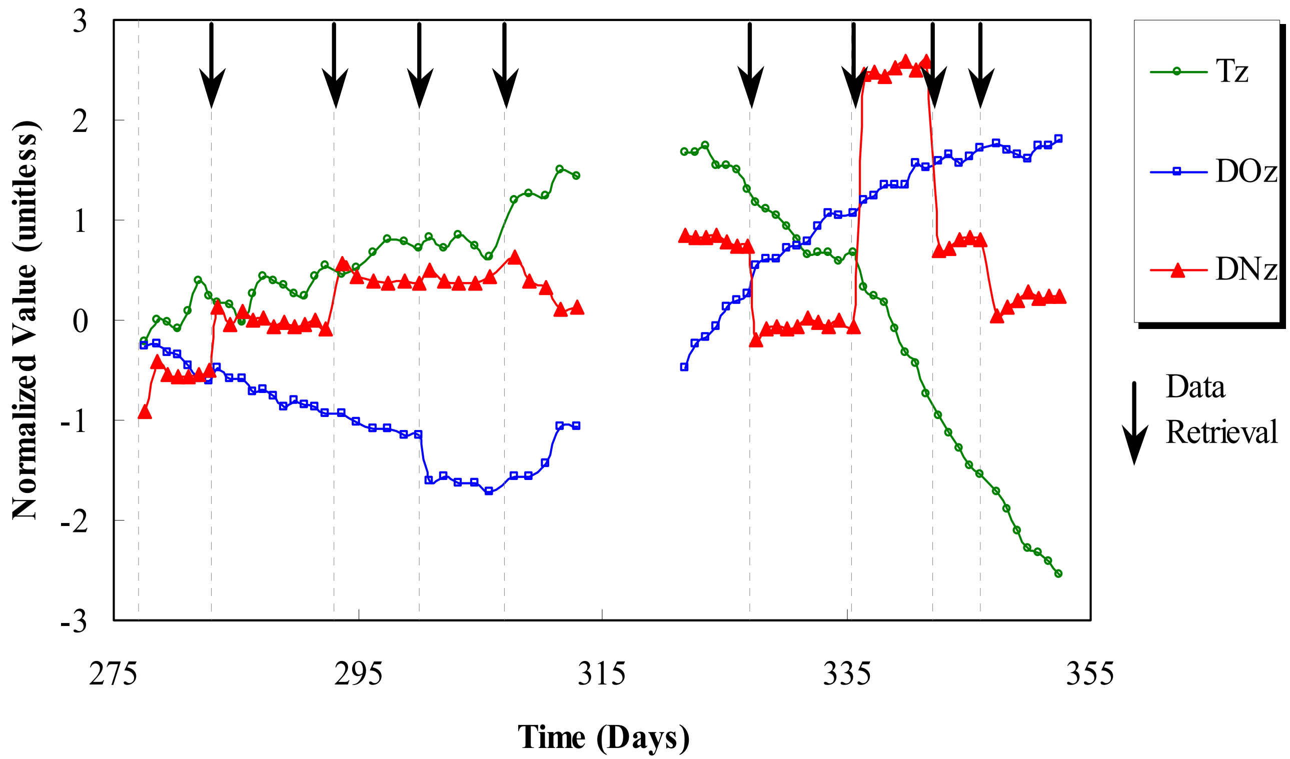

Figure 9: Normalized data sets for temperature, dissolved oxygen, and dissolved nitrogen showing probe discrepancies between periods of deployment.

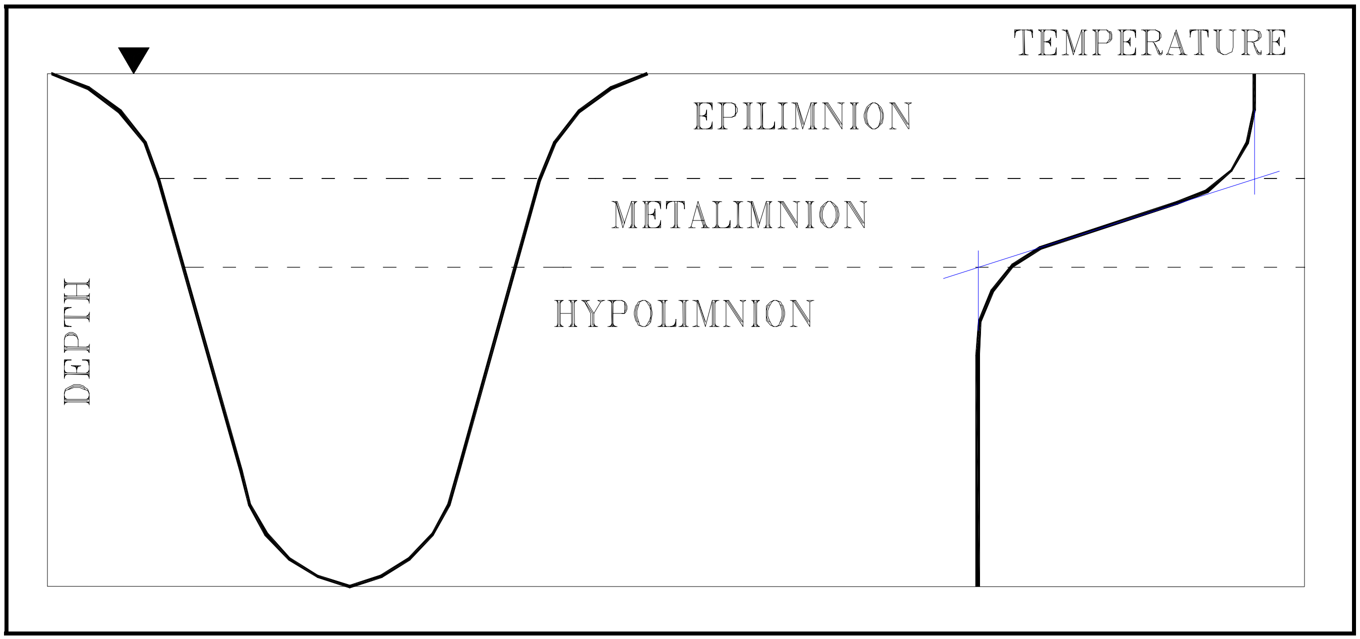

Figure 10:Thermocline (metalimnion) boundary identification using temperature profile.

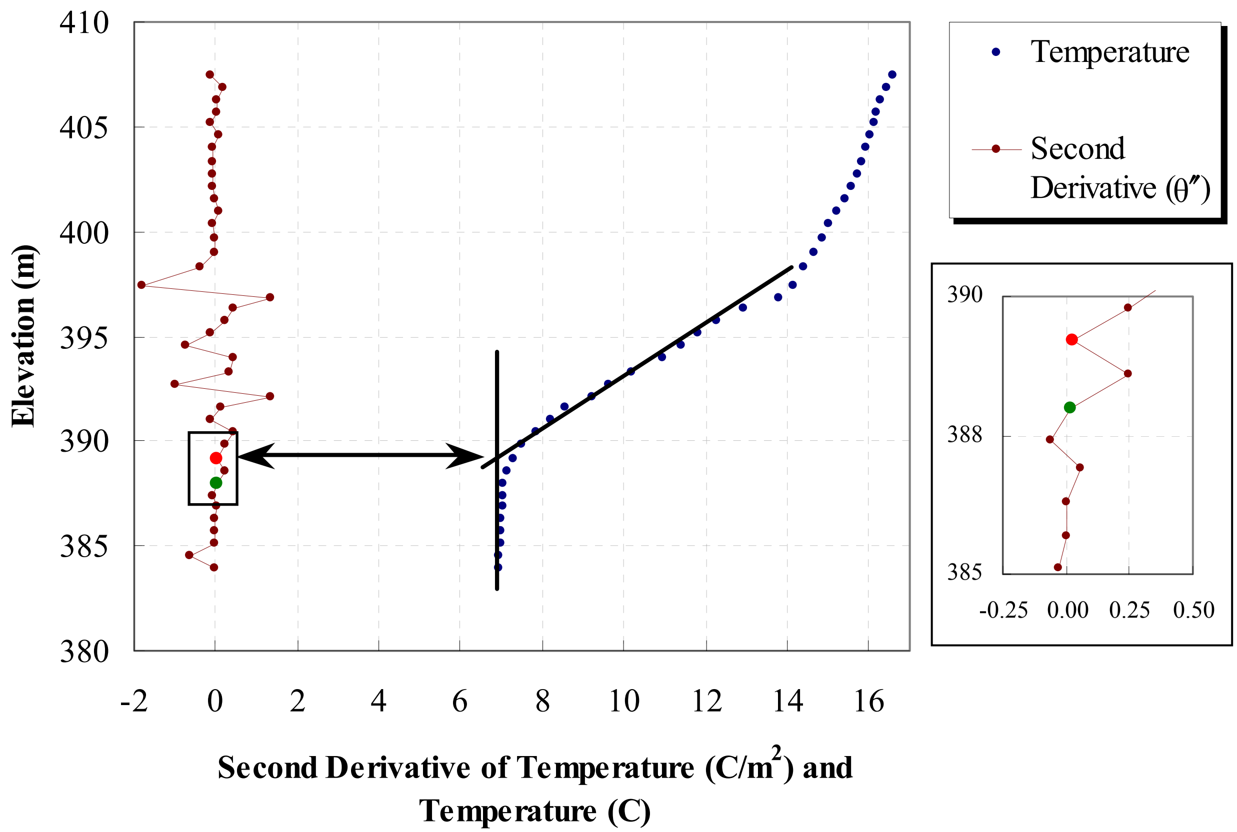

Figure 11: Comparison of mathematical definition with graphical analysis to identify the boundary of the thermocline.

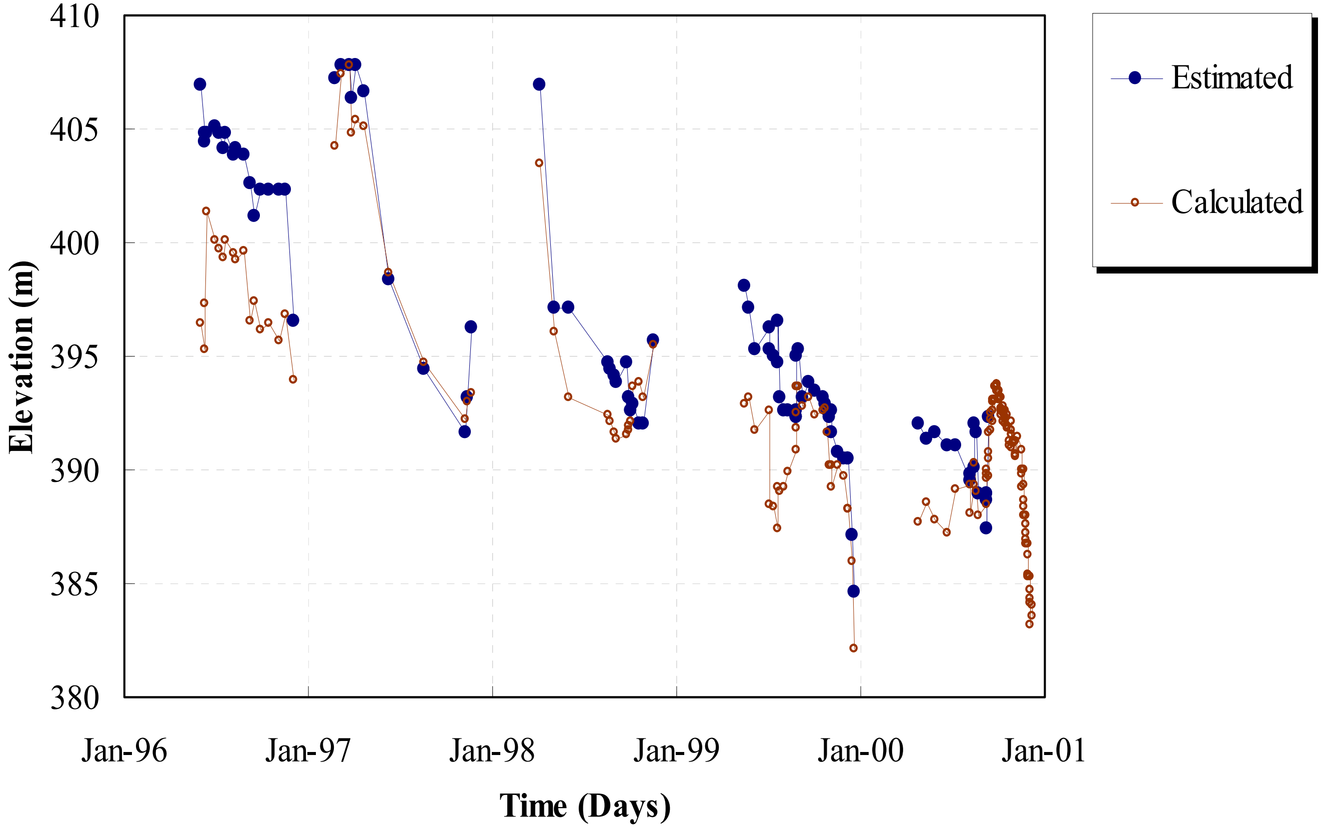

Figure 12: Comparison of estimation and analytical methods of hypolimnion position.

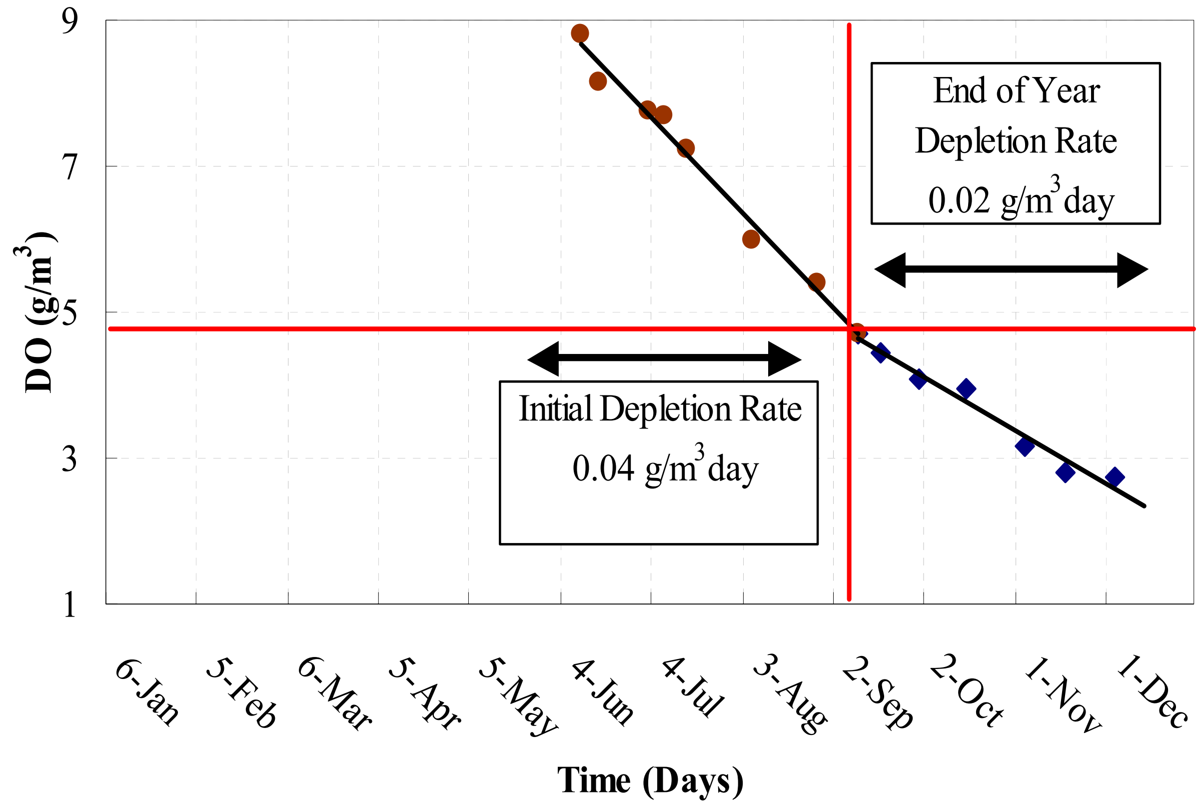

Figure 13: Observed changes in depletion rates over time relative to average hypolimnion DO concentration.

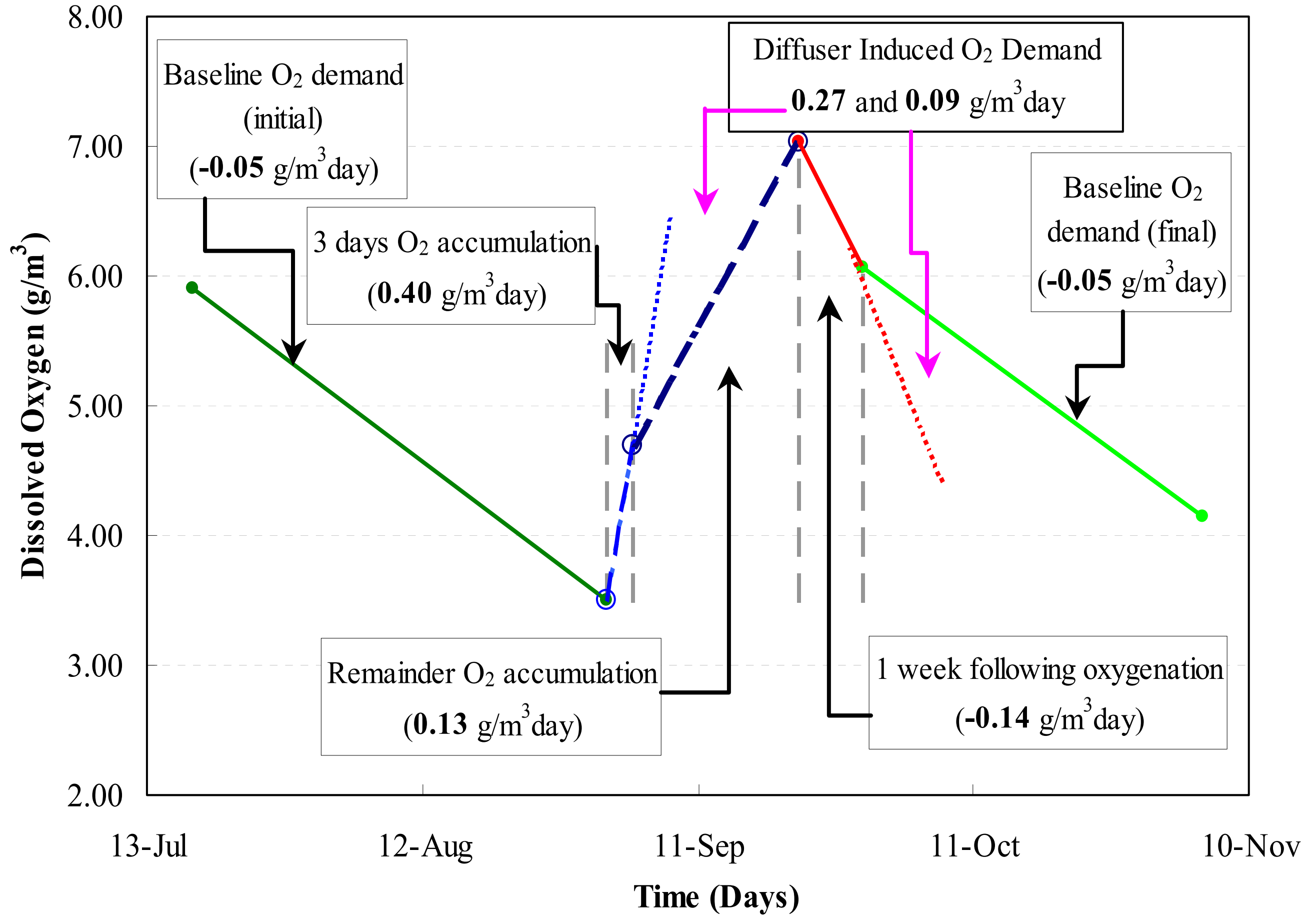

Figure 14: Diffuser induced oxygen demand observed during oxygenation.

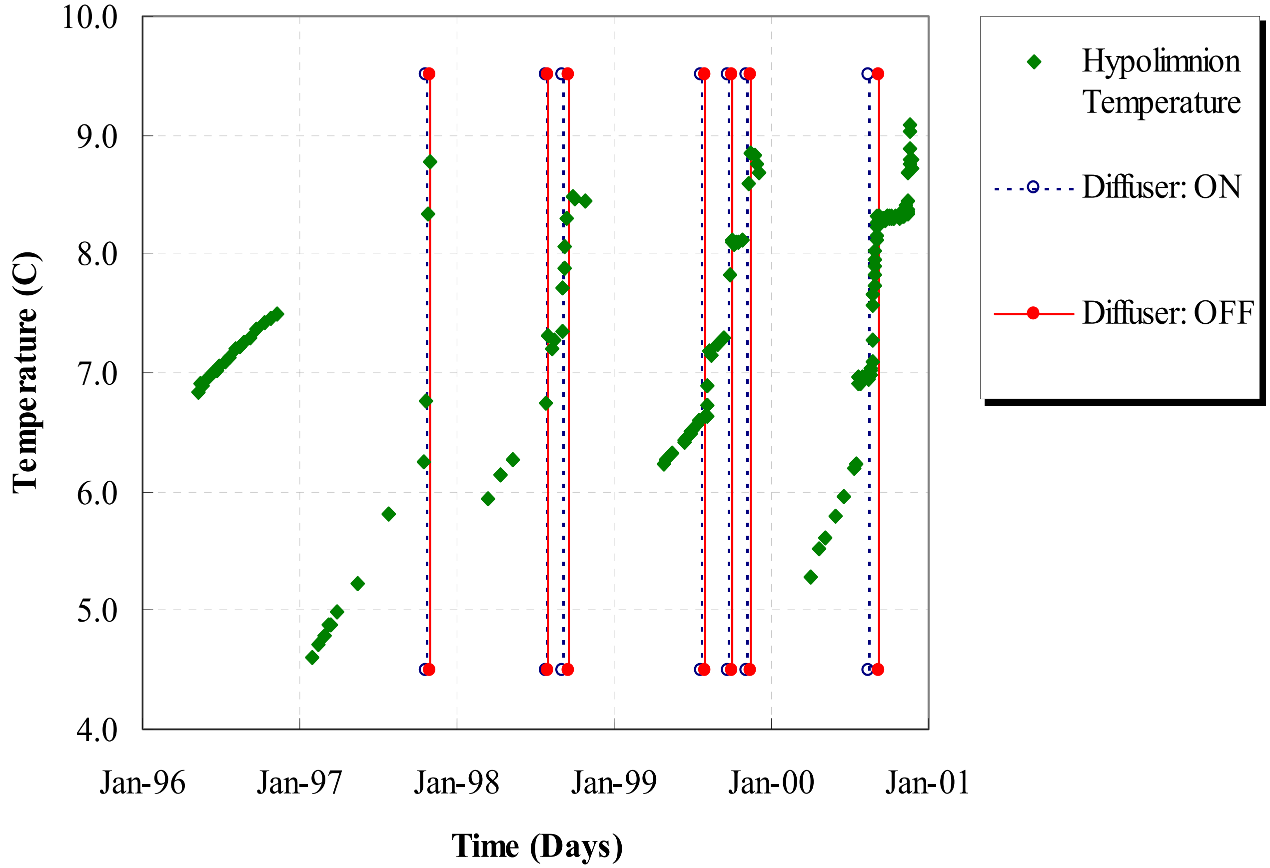

Figure 15: Average hypolimnion temperatures 1996-2000.

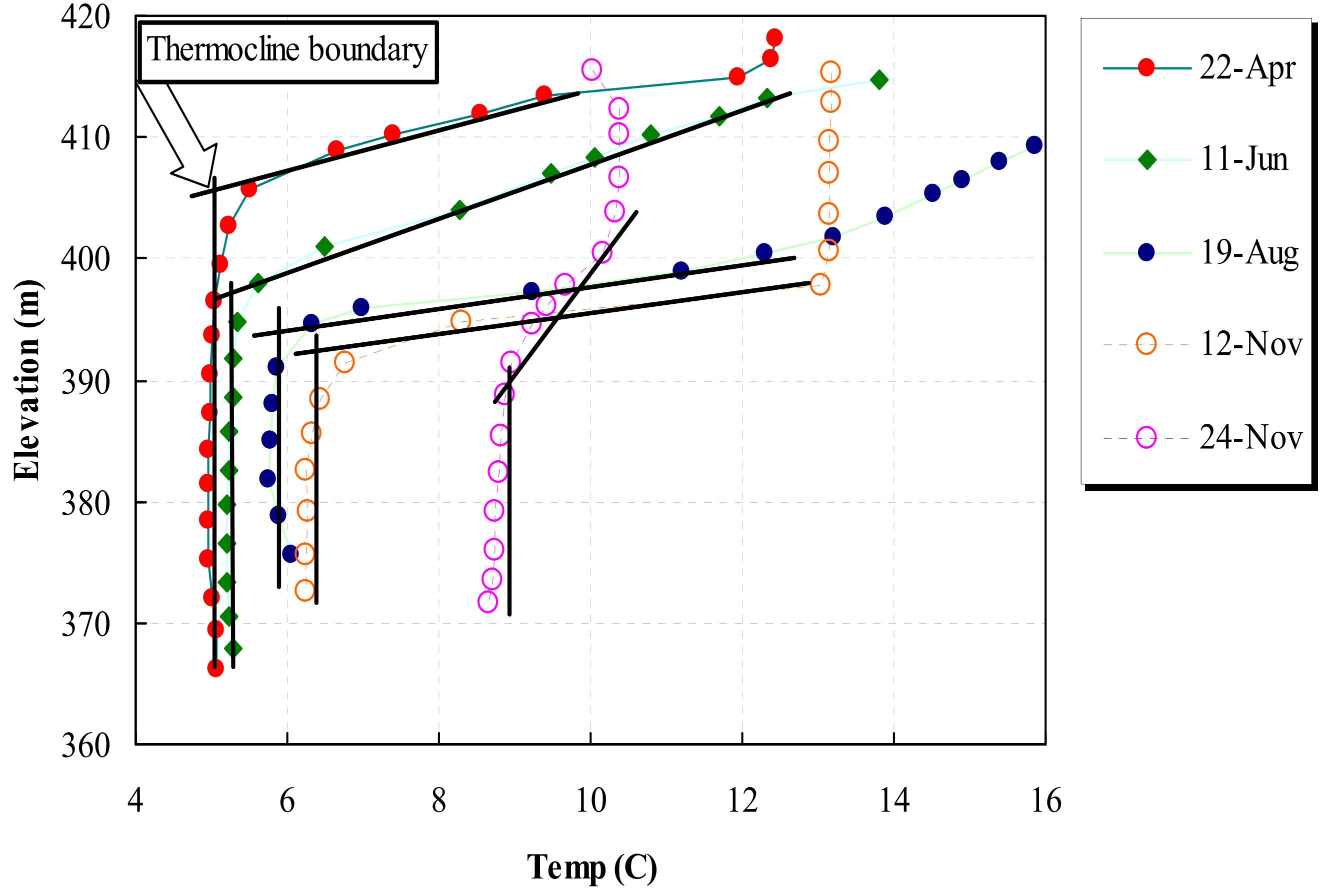

Figure 16: 1997 Temperature profiles showing downward progression of the lower thermocline boundary (hypolimnion).

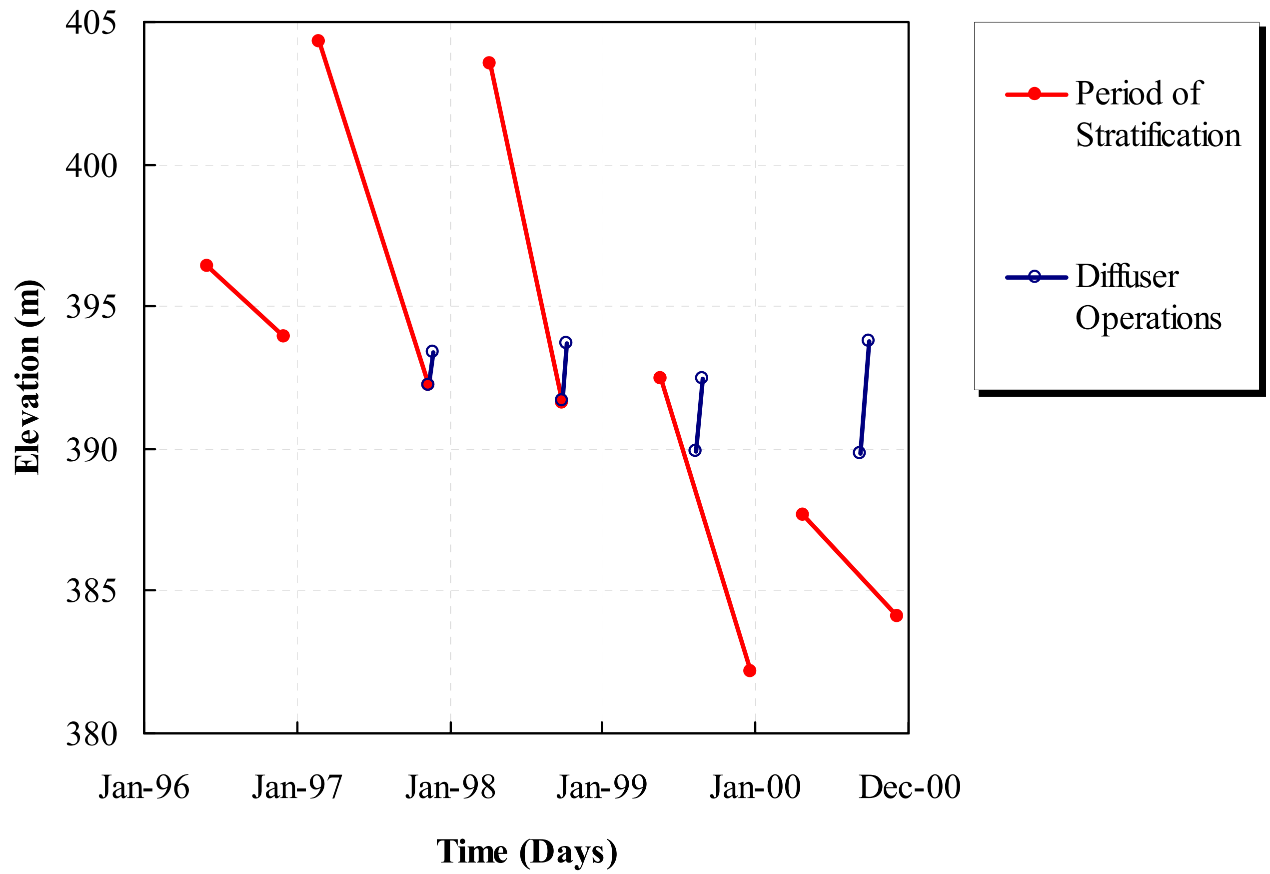

Figure 17: Hypolimnion position observations during periods of both stratification and oxygenation for 1996-2000.

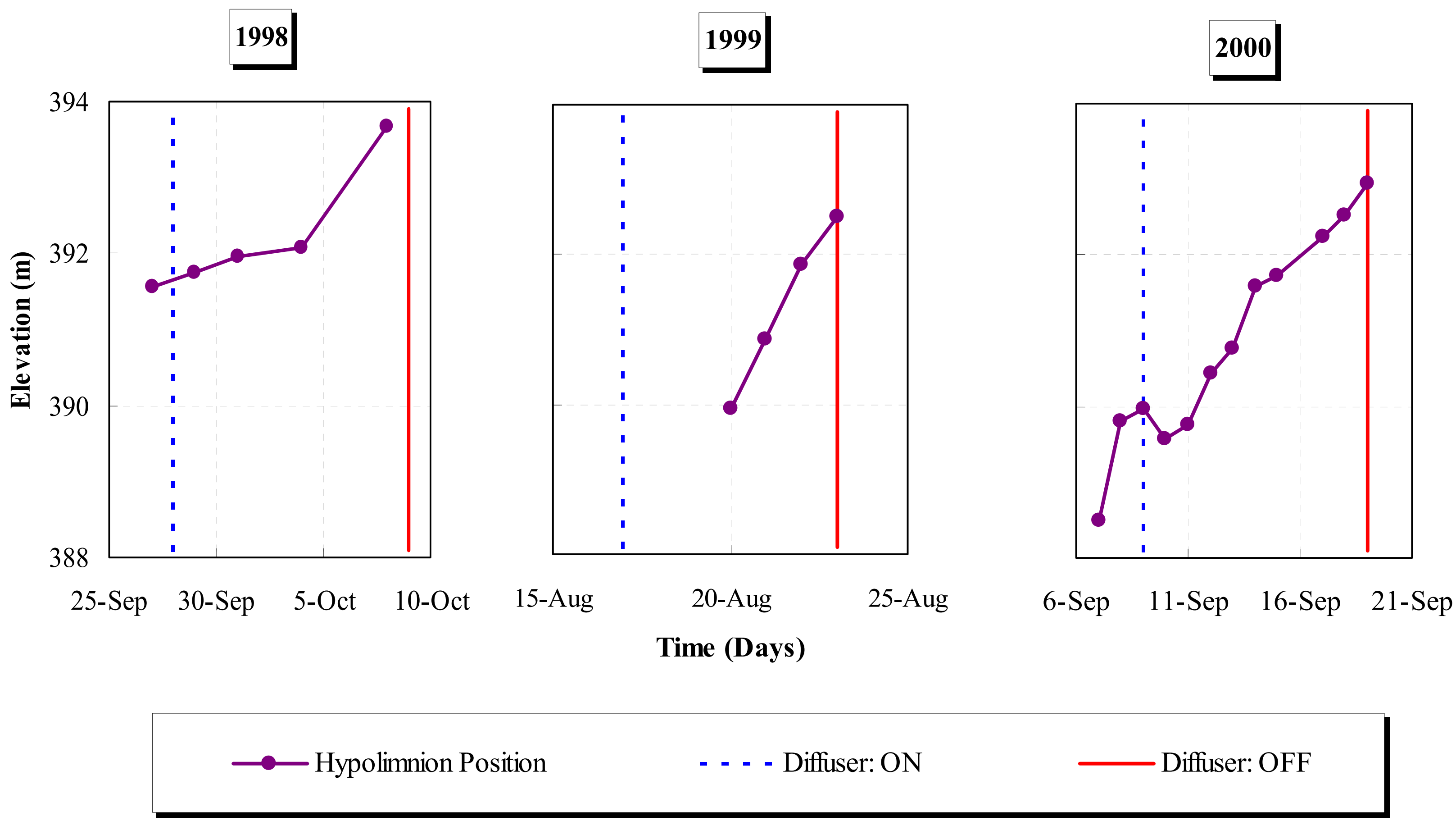

Figure 18: Upward hypolimnion movement observed during diffuser operations for 1998-20

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VITA

Paul A. Gantzer was born on April 4, 1967 to Charles and Martha Gantzer in Kenmore, New York. He successfully completed Navy Nuclear Power Training in 1987 and served on board the aircraft carrier USS Carl Vinson (CVN 70) as an Engineering Laboratory Technician. He attended Valencia Community College in Orlando, Florida where he earned an Associate of Science degree in pre-engineering and graduated with high honors in May 1994. He owned an operated a small business, "Turn-Key Cleaning", in Kissimmee, Florida until his acceptance to Virginia Polytechnic Institute and State University in 1997. He attended Virginia Polytechnic Institute and State University in Blacksburg, Virginia where he earned a Bachelor of Science degree in Civil Engineering and graduated *Summa Cum Laude* in May 2000. Prior to his May 2000 graduation, he was accepted to the Accelerated Masters Program at Virginia Polytechnic Institute and State University. While at Virginia Tech he received a Sussman Fellowship, two Cohen Scholarships for academic achievement, and a teaching assistantship. He studied Environmental Science and Engineering and will graduate with a Master of Science degree in May 2002. Future plans involve continued research at Spring Hollow Reservoir under the guidance of Dr. John Little working towards a PhD beginning in August 2002.

Paul A. Gantzer

May 9, 2002
Blacksburg, Virginia