Effects of a Surface Circulator on Temperature, Dissolved Oxygen, Water Velocity, and Photosynthetic Yield in Falling Creek Reservoir

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ABSTRACT

Cyanobacteria are a naturally occurring component of reservoir aquatic ecosystems. Given that some species possess the ability to control their depth within the water column, they have a competitive advantage over other species of photosynthetic organisms. This leads to the potential for cyanobacteria blooms, and because of taste and odor problems, as well as possible toxin production associated with certain species of cyanobacteria, these organisms can cause major problems in drinking water production. The Western Virginia Water Authority installed a solar-powered circulator in Falling Creek Reservoir, located in Bedford County, Virginia, in an attempt to limit the growth of these organisms through limiting light exposure by circulating them deeper within the reservoir. Experiments were performed during the summer of 2008 to quantify the effect of the circulator on the reservoir. Temperature, dissolved oxygen, water velocity, and photosynthetic yield were monitored before and during operation of the unit. The overall effect of the mixer was limited to the first 10 m immediately adjacent to the unit during the afternoon. The effect was stronger during the morning when the difference in density between the intake water and the surface of the reservoir was smaller, allowing the water to travel up to 80 m away from the unit. Although the circulator was only intended to mix and possibly deepen the epilimnion, the entire reservoir became mixed about two weeks after the circulator was put into operation. The reservoir is quite shallow, leading to a weak stratification that is easily disrupted by the operation of the circulator.

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1.0 INTRODUCTION

High chemical costs associated with water treatment may encourage treatment facilities to place more of an emphasis on source water quality management in order to reduce overall treatment costs. The primary problems encountered at reservoirs used for drinking water are hypolimnetic oxygen depletion during stratification and algae and cyanobacteria blooms, as well as pathogens and dissolved organic carbon. Taste and odor problems, as well as some toxins, are often associated with certain cyanobacteria blooms. The toxins are generally well controlled with conventional treatment processes. Coagulation removes intact cells with intracellular contaminants, and disinfection typically oxidizes and degrades most toxins (Drikas et al. 2001). Since the taste and odor compounds are quite difficult to remove, it may be more cost effective to treat these problems in the reservoir instead of at the treatment plant.

Many techniques have been employed over the years to address problems associated with cyanobacteria and algae blooms. These include the broad categories of algaecides, algistats, and circulators, and each employs differing mechanisms to control the growth of algae and cyanobacteria. Copper sulfate is the most common algaecide currently in use. Other algaecides that are presently used include hydrogen peroxide-based applications (Samuilov et al. 1999) as well as several copper chelates. These chemicals can be effective control agents, however, at high cell concentrations, the use of these chemicals can cause the release of undesirable levels of toxins and taste and odor compounds into the reservoir (Jones and Orr 1994). Two other forms of algaecides include ultrasound and hybrid ultrasound/ozone systems. Both aluminum sulfate and modified clays can be used as algistats, limiting growth by reducing available phosphorus. Barley straw is also used as an algistat. A final group of algistats includes bioaugmentation agents, which involves the addition of aerobic bacteria to the aquatic ecosystem, which theoretically deplete bio-available nitrogen and phosphorus.

Two other methods for limiting algae growth are controlling nutrient concentrations and artificial mixing, which can be induced using a surface circulator or a bubble plume aerator. The role of bubble plume aerators is to weaken stratification and to allow wind to mix the reservoir and to oxygenate the hypolimnion. If the influence of a bubble plume aerator or a surface circulator is not strong enough to mix the stratified surface layers outside of the immediate vicinity of the plume or mixer, then there is still a habitat for buoyant cyanobacteria to exploit (Visser et al. 1996). Artificial destratification of a reservoir has been shown to prevent cyanobacteria blooms (Heo and Kim 2004).

During May of 2006, the Western Virginia Water Authority installed a surface mixer in Falling Creek Reservoir in an attempt to control the growth of cyanobacteria, of which *Anacystis* was the principle problematic organism. The effects of the circulator on aquatic temperature, dissolved oxygen concentration, water velocities, and photosynthetic yield were studied during the summer of 2008.

2.0 RESEARCH OBJECTIVE

The primary research objective for this project was to investigate the ability of a surface circulator to control growth of cyanobacteria. In order to accomplish this, the circulator must mix the epilimnion. If it can also increase the depth of the surface mixed layer, effectively pushing some cyanobacteria below the photic zone in the reservoir, then growth inhibition would be even more effective.

In order to accomplish this, the following parameters were monitored:

- Temperature profiles – These profiles were monitored to give an indication of how far the cooler water from the intake of the mixer travels across the warmer surface of the reservoir.
- Dissolved oxygen profiles – These profiles, similarly to the temperature profiles, show how far the entrained water (with a different dissolved oxygen concentration) will travel across the surface of the reservoir. Both temperature and dissolved oxygen profiles indicate the degree of mixing induced by the circulator.
- Photosynthetic yield – This measurement helps quantify the effect of circulation on algae present in the reservoir, in addition to revealing how far-reaching this effect is.
- Water velocity profiles – These measurements give a direct measurement of the velocity and direction of water near the surface mixer.
- Bathymetry – No complete bathymetry data were available for Falling Creek Reservoir, so an investigation into the elevation contours of the reservoir is critical to understanding how it will respond to mixing.

- Summary – By comparing the results of the various measurements, a clearer picture of the overall effects of the surface mixer on Falling Creek Reservoir will be obtained.

3.0 BACKGROUND

Cyanobacteria are naturally-occurring components of aquatic ecosystems, and when environmental conditions are optimal, blooms can occur. Several characteristics allow these organisms to dominate other types of algal growth in lakes and reservoirs given appropriate environmental conditions. Some species are able to control their buoyancy. The ability to adjust the content of gas vacuoles, which are aggregates of gas vesicles, present within a given cell allows them to position themselves at a location of optimum light intensity within the water column. A number of other reasons contribute to the success of these organisms in such a broad assortment of environmental conditions. These include, but are not limited to, the ability to capture lowered photosynthetic photon flux densities, the ability to exploit warmer aquatic temperatures, and the ability to use low total nitrogen to total phosphorus ratios as well as to access low dissolved carbon dioxide concentrations (Steinberg and Hartmann 1988).

Cyanobacteria are photosynthetic prokaryotes found in both aquatic and terrestrial environments. Because of their photosynthetic nature, exposure to optimal levels of sunlight is essential. The way that cyanobacteria adjust to excess sunlight is critical given that photoinhibition will occur upon excess excitation of the photosynthetic reaction centers (Andersson and Styring 1991; Aro et al. 1993; Samuelsson et al. 1987), which may perhaps occur because of damage to the reaction centers of photosystem II. Excess irradiation appears to cause the most damage to the D1 polypeptide, which is part of photosystem II. When light intensity is low, these damaged polypeptides can be replaced by new ones (Guenther and Melis 1990). However, at increased intensities of irradiance, the rate of damage sustained to photosystem II is greater than the rate of repair (De Las Rivas et al. 1992; Öquist et al. 1992; Reuter and Mueller 1993), thus leading to a decline in photosynthetic yield.

Most plants intake nitrogen in the form of nitrate or ammonium, but some cyanobacteria can convert dissolved nitrogen to ammonium. This process, called nitrogen fixation, allows them to use a source of nitrogen that is not available to other algae. Studies have shown that cyanobacteria are responsible for a majority of planktonic nitrogen fixation, and these rates are high only when cyanobacteria are present in large numbers (Howarth et al. 1988). Phosphorus is often found to control the growth of phytoplankton, even if nitrogen supplies are limited, because nitrogen deficits are compensated by nitrogen fixation (Schindler 1977). Cyanobacteria, unlike eukaryotic micro-algae, are able to store considerable amounts of nitrogen in the form of cyanophycin and phycobiliprotein (Oliver and Ganf 2000). Many cyanobacteria can also store excess phosphorus for use in times of phosphorus deficiency within the water column (Carr and Whitton 1982).

The capacity of some species of cyanobacteria to control buoyancy can be attributed to gas vesicles within individual cells, which not only provide buoyancy and reduce losses by sedimentation (Reynolds and Walsby 1975), but also assist in maintaining cells in a favorable light environment during times of low turbulence (Humphries and Lyne 1988). Gas-vacuolate cyanobacteria have the ability to regulate their buoyancy by one of several methods. Buoyancy regulation can take place by the control of gas vesicle production within a cell (Oliver 1994; Walsby 1994). This form of regulation involves controlling the degree of gas vacuolation due to either a reduction in gas vesicle production or by the collapse of gas vesicles due to increased turgor pressure. Cell density, however, can also be adjusted quite rapidly by the modification in the composition of cellular components. This occurs by the accumulation or loss of dense polysaccharides, which takes place during the processes of photosynthesis and respiration (Kromkamp and Mur 1984; Kromkamp and Walsby 1990). These carbohydrates can also be converted to less-dense proteins. Environmental conditions cause differences in the rates of both accumulation and processing, thus inducing changes to cell density (Oliver 1994; Walsby 1994).

Reservoir conditions, especially nutrient content and previous light history, strongly affect the buoyancy of cyanobacteria cells. In general, when nutrients, primarily nitrogen and phosphorus, are abundant, then buoyancy is promoted, but it decreases when these nutrient levels become depleted (Oliver 1994). Combined with less efficient carbohydrate metabolism, nitrogen limitation induces a reduction in buoyancy because the volume of gas vesicles is reduced by limited amounts of nitrogen (Klemer et al. 1982). This is, however, a reversible process (Konopka et al. 1993).

Carbon also plays a role in buoyancy regulation. Carbon dioxide limitation of photosynthesis, which can not only prevent the collapse of gas vesicles, but also prevents polysaccharide accumulation, can promote short-term buoyancy. However, persistent carbon limitation lessens buoyancy regulation by restricting both gas vesicle and polysaccharide formation (Klemer et al. 1996).

Buoyancy regulation is also affected by changes in temperature. Kromkamp showed that a sufficient decrease in temperature causes a reduction in buoyancy, due to both an increase in ballast and a decrease in gas vesicle volume (Kromkamp et al. 1988).

Vertical migration and buoyancy loss have been observed in several species of cyanobacteria (Brookes et al. 1999; Ganf 1974; Konopka 1982). Even when this loss of buoyancy is observed, a large proportion of cells still retain buoyancy because of the presence of sufficient gas vesicles, whose buoyant properties overcome the addition of dense polysaccharides. Nutrient enrichment often induces this persistent buoyancy (Brookes et al. 1999).

If cyanobacteria cells are circulated to a sufficient depth, then the hydrostatic pressure could be enough to cause the collapse of a large portion of the gas vesicles (Oliver and Ganf 2000). A continuously circulated reservoir would entrain cells that lack gas vesicles, thereby reducing their effective sinking rate since in a mixed water column, it takes 4.6 times longer to eliminate particles than it does for still water (Reynolds et al. 1984). It has also been suggested that intermittent circulation could be more appropriate than continuous circulation (Steinberg and Gruhl 1992; Visser et al. 1996), which would allow non-buoyant cells to sediment more quickly. Permanent destratification has not always resulted in satisfactory cyanobacteria control. (Steinberg and Gruhl 1992) showed that changing from permanent to intermittent destratification led to decreased numbers of cyanobacteria in a small reservoir. It was hypothesized that this improvement occurred because of elevated biomass losses via sedimentation during times without mixing. Another strategy has been to circulate reservoir water through a deep pipe where the hydrostatic pressure was great enough to cause the collapse of all gas vesicles (Clarke and Walsby 1988).

(Steinberg and Hartmann 1988) analyzed several water bodies and concluded that above a total phosphorus concentration of 10 mg/m^3, the presence of cyanobacteria was dependent primarily on physical factors, especially water column stability. They supported the view that manipulation of the mixing regime would be a quicker and more effective means of managing cyanobacteria populations than nutrient reduction or biomanipulation. It has also been suggested that eutrophication, especially by phosphorus, frequently induces shifts in phytoplankton species composition towards bloom-forming cyanobacteria (Reynolds 1987; Steinberg and Gruhl 1992; Steinberg and Hartmann 1988).

Cyanobacteria blooms cause several problems when it comes to drinking water reservoirs. The most common concerns are associated with the taste and odor problems that these organisms can cause; however, some are also capable of producing toxins, which can cause acute and possibly chronic health problems in humans, as well as lethal poisonings in other animals (Carmichael 1992; 1994; Hunter and Roberts 1991). Skin irritation and an increase in the probability of gastrointestinal issues can be caused by exposure to cyanobacteria in recreational waters used for swimming (Hashimoto et al. 1976; Moikeha and Chu 1971).

Algaecides have long been utilized for the control of both algae and cyanobacteria in drinking water reservoirs. Copper sulfate has been the most widely used algaecide, having been used for decades (Hrudey et al. 1999). The use of copper sulfate as an algaecide causes cell lysis to occur, which kills the cells, but it can also release toxins (Falconer 1999), which is a concern. Another concern originates from the fact that copper will not biodegrade leading to accumulation within the reservoir (Burch et al. 2001). Copper can persist indefinitely in reservoir sediments. An additional problem that can occur from the use of this algaecide stems from the fact that different species of algae require different dosages of copper sulfate to effectively control growth, and copper-resistant algae or cyanobacteria may develop. Hanson and Stefan found that usage of copper sulfate allowed the *Aphanizomenon* species, which is a type of cyanobacteria requiring a higher dosage for growth control, to become the dominant species present in the Fairmont Lakes, Minnesota (Hanson and Stefan 1984). Previous data from Falling Creek Reservoir show a similar trend, with cyanobacteria being the primary organisms present during years when copper sulfate algaecide was utilized (Figure 1).

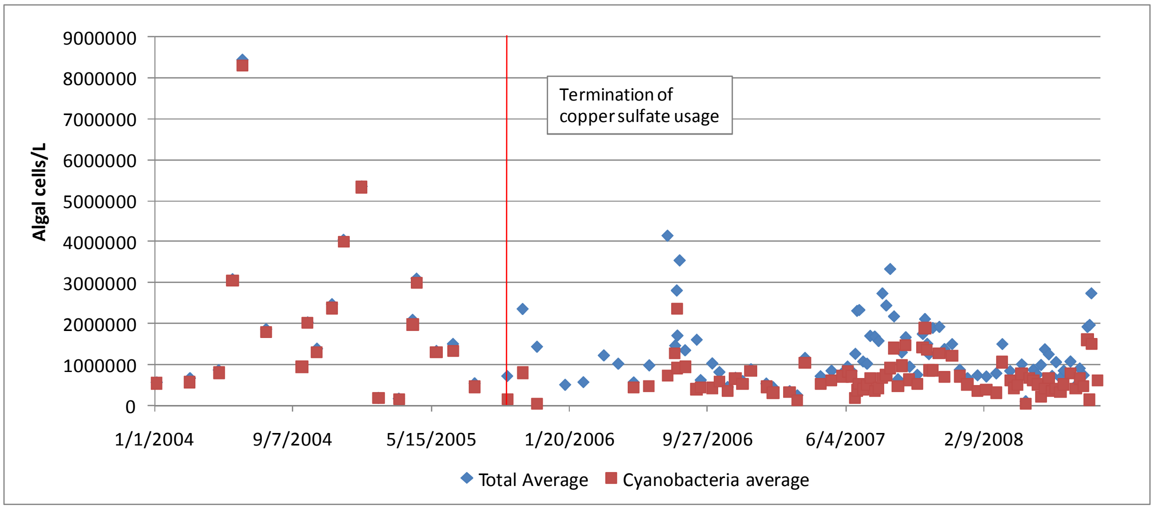

Figure 1 Algae and cyanobacteria concentrations at Falling Creek Reservoir

Alternate methods of controlling cyanobacteria growth are available, however, many of the methods presented previously include the introduction of chemicals into the aquatic ecosystem. An alternate method uses a surface circulator to mix water in the reservoir. The principle cause of reduced algal growth comes from light limitation induced by an increased depth of mixing (Cooke et al. 1993). SolarBee, Inc., produces solar-powered circulators, and their units have been installed in several reservoirs specifically to control the growth of cyanobacteria, replacing the use of copper sulfate (Sullivan 2004), which may reduce treatment costs (Weismantel 2003).

4.0 STUDY SITE

Falling Creek Reservoir, located just northeast of Roanoke, VA, is located in Bedford County. This reservoir covers 8.5 hectares and holds around 322 ML of water when completely full. Beaver Reservoir, which covers around 27.9 hectares and holds about 1,647 ML of water, can feed water into Falling Creek reservoir if needed, but did not contribute water to Falling Creek Reservoir during the time period of this study. The

Falling Creek water treatment facility treats nearly 3.8 ML of water per day, which is used to supply drinking water to a portion of Roanoke, VA (WVWA 2008).

Water from this reservoir has a history of taste and odor problems, which are often associated with cyanobacteria blooms. Copper Sulfate ($CuSO_4$) was used through 2005 as an algaecide, but during 2006, no algae treatment was utilized. A SolarBee surface mixer was installed in May of 2007, but has been operated only sporadically since then. The circulator is at a location that is normally around 3.5-4 m deep, with the deepest location in the reservoir normally at 8-9.5 m deep.

Figure 2 Falling Creek Reservoir

In the past, depth samples have been taken at the following elevations: 507 m, 505 m, 503 m, and 501 m. The reservoir is full at an elevation of 508.5 m, but it is not always at this level. The 501 m elevation is within two meters of the bottom of the reservoir at its deepest point. These depth samples are taken near the intakes for the water treatment facility in the deepest portion of the reservoir. Analysis for temperature, pH, alkalinity, hardness, dissolved oxygen, turbidity, color, odor, algae (organisms/liter), total iron, and total manganese takes place for each sample. This process historically was completed on a monthly basis year-round, with a higher frequency of samples taken during the spring and summer, however lingering odor problems have caused an increase in the number of samples taken within the past year.

5.0 THE SURFACE CIRCULATOR

SolarBee, Inc. produces a “solar-powered, up-flow long-distance circulator,” which was installed at Falling Creek Reservoir. According to SolarBee, Inc., this particular unit (specifically a SB10000v12) is rated at 10,000 gallons per minutes (3,000 gallons per minute of direct flow through its intake and 7,000 gallons per minute of induced flow outside of the intake hose when running at full power), and it runs 24 hours a day (SolarBee 2008 (1)). A schematic of this unit is shown (Figure 3).

The circulator brings in water at the depth of the intake hose. The intake on this unit was originally set at approximately 1.8 m deep, however the Western Virginia Water Authority requested that it be raised after the first week of experiments to approximately 1.1 m deep (this took place on July 29). This was requested because of the presence of low-quality, high-odor water found near the reservoir sediments, and the Authority wanted to keep the intake as far away from this water as possible. The intake hose is 0.9 m in diameter, and a horizontal plate (of slightly larger diameter) is attached 0.3 m below the bottom of the intake. SolarBee, Inc. states that this should draw a 0.3 m horizontal slice of water toward the intake hose. Figure 1 shows a SolarBee unit with the attached intake hose. According to SolarBee, Inc., the intake water is brought to the surface and pumped out in a radial fashion in “near laminar flow” in all directions. There are two basic designs. One design withdraws water from below the thermocline. This is used primarily for hypolimnetic oxygenation. The other design withdraws water at or from just above the thermocline. This is used largely for cyanobacteria control. The location of the intake on this unit is within or above the thermocline (depending on its exact location) during summer stratification.

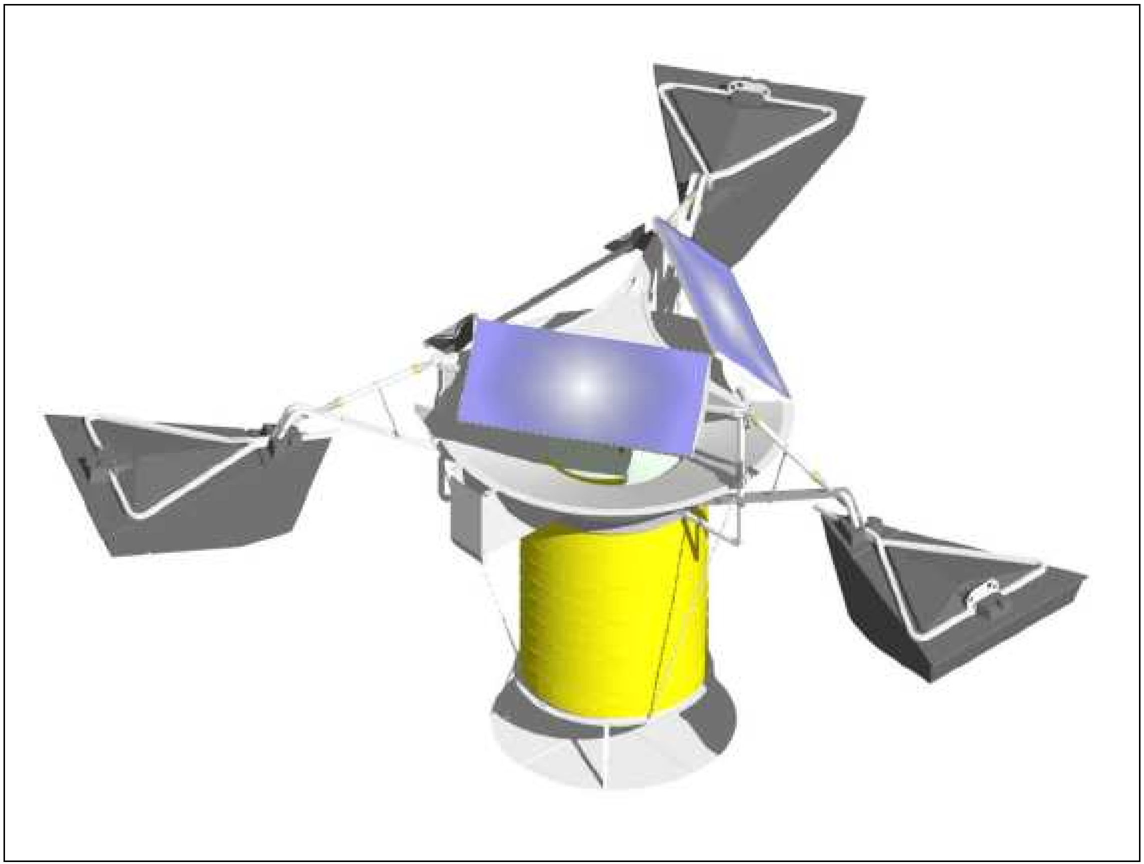

Figure 3 SolarBee unit with intake hose (SolarBee 2008 (2))

The purpose of this algae-control method is to disturb the preferential habitat of the cyanobacteria. According to the manufacturer, as the water is pumped out across the water surface, it moves out to the edge of the lake and then falls back down to the depth from which it was originally withdrawn. It sinks back to its original depth because of its temperature/density properties, which are a function of lake elevation. This assumes that the difference in density between the reservoir surface and water flowing from the circulator is small enough as to not inhibit movement of water from the circulator across the surface. This circulation, which induces light limitation, is theoretically the mechanism of growth control of the cyanobacteria. Since some species of cyanobacteria can control their depth in the water column, this gives them a competitive advantage over other types of algae. If this ability is disrupted, then excessive blooms should not occur, although the cyanobacteria will still be present, just in less significant numbers. According to SolarBee the unit installed at Falling Creek Reservoir can impact a reservoir of up to 14.2 hectares in size.

6.0 DATA COLLECTION

During the course of this project, temperature, dissolved oxygen, water velocity, and photosynthetic yield were all measured. Comparison of these readings both before and after circulator operation gives an indication of the effectiveness of this unit at mixing the epilimnion. Temperature and dissolved oxygen profiles indicate the extent of the effect of circulation on these parameters. They also indicate if circulation is able to deepen the surface mixed layer, which could increase the effectiveness of the unit. Use of the ADCP shows numerically the effects of circulation on velocities within the reservoir. Finally the use of the PAM fluorometer shows the effect of circulation on the photosynthetic yield of algae within the reservoir.

6.1 Temperature and Dissolved Oxygen

Temperature and dissolved oxygen profiles were collected using a Sea-Bird Electronics SBE-19*plus* SEACAT Profiler CTD. This unit, when turned on, runs continuously, sampling at four Hz (four scans per second).

Temperature and dissolved oxygen profiles were obtained both before and after the circulator unit was turned on. The circulator unit was rarely used during the summer of 2008 prior to the time period of this research. It was on briefly during June, but was off for three weeks prior to the field work for this project, allowing sufficient time for the return of natural stratification.

Profiles were collected at 1, 2, 3, 5, 10, 20, 50, 100, 150, 200, and 340 m from the circulator unit, as shown in Figure 4. These locations were marked in the reservoir using buoys so that data could be collected at the same location each time. Profiles were collected during the two days prior to turning on the circulator, and also during the morning prior to activation of the unit. This data will give a baseline of what the temperature and dissolved oxygen levels look like naturally within the reservoir. After the circulator was turned on, profiles were again collected later that day, as well as the following two days, and then weekly for the following two weeks. This will show the effect that the circulator has immediately in the first 3 days as well as over the long term.

The reservoir is expected to be stratified, having both higher temperature and dissolved oxygen readings closer to the surface. Because of this stratification, there should be a difference in both the temperature and dissolved oxygen readings at the level of the intake and at the surface, where the water is pumped out of the circulator. The profile spacing was chosen with several closely spaced locations closer to the circulator to be able to locate where the cooler, denser water from the circulator falls back within the reservoir. This will show how far the water travels from the circulator, as well as any large-scale effects that circulation has on temperature and dissolved oxygen.

Figure 4 CTD sampling locations

6.2 Velocity Profiles

Velocity profiles were collected using a Workhorse Rio Grande1200 kHz ADCP, which is manufactured by Teledyne RD Instruments, Inc. The accuracy of this unit is +/- 0.25% of the water + boat velocity. For the velocity profiles, the boat remained stationary so that the boat velocity was effectively zero.

The ADCP functions by producing an acoustic signal and sending it out into the water column. Once this is reflected off of "scattering particles" (basically anything large enough to reflect the acoustic energy), it returns to the ADCP, and the velocity of these scattering particles can be determined. The majority of scattering particles are moving with the movement of the water within the reservoir, so if the velocity of these objects is known, then the velocity of the water within the reservoir can be determined.

One limitation in the use of the ADCP for velocity measurements is in its range of data collection, since it cannot be used to collect data over the entire water column. A zone exists, both at the surface as well as along the reservoir bottom, where the ADCP is unable to obtain velocity measurements. Along the surface, a small section is missed because the ADCP actually sits several centimeters below the surface of the water. A blanking distance is also present just below the ADCP unit. This occurs because the ADCP is used to both produce sound and then record its backscatter. After the sound is produced and sent out into the water column, the ADCP cannot detect the backscattered acoustic energy until the vibration that is produced lessens to a level that won't contaminate the acoustic energy that is returning to the unit. Therefore, the blanking distance is the distance that the sound moves during this interval. The ADCP also can not measure velocity near the sediments. This occurs because most of the energy produced by the transducer is transmitted within the main beam. There are, however, side lobes produced, which have lower energy. These do not cause a problem for most of the water column since they are fairly low in energy, but they do cause problems near the sediments. Because of the angle at which the beams are set, some of the side lobe beams strike the sediments and reflect back to the ADCP at the same time that the main beam is reflecting off of scattering particles near the sediment. This signal is weaker than the reflection of the side lobes off the sediment, therefore, the acoustic energy from the main beam near the sediment is contaminated. The distance that cannot be measured is approximately six percent of the total depth from the surface to the sediments.

Because of these limitations, the velocity of water along the surface cannot be measured; however, the velocity of water within most of the water column can be measured. This includes water at the depth of the intake. The ADCP should be able to show how strong the influence of the circulator is at the depth of the intake for this unit. Therefore, the ADCP profiles were set up at one-meter intervals. These began 1 meter away from the unit, and continued through eight meters away from the unit. This will give water velocity and direction for specified depths at each of these eight distances away from the circulator. The sampling locations are shown in Figure 5.

Figure 5 ADCP profiling locations

6.3 Photosynthetic Yield

Harris identified a fluorescence ratio (the DCMU-sensitive chlorophyll a fluorescence divided by the *in vivo* chlorophyll fluorescence), which, during stratification, showed a vertical gradient (Harris 1980). Later Harris concluded that this ratio could be used as an indication of mixing within the surface waters (Harris 1986) since the timescales of both mixing and the photochemical process associated with phytoplankton are similar (Denman and Gargett 1983). Harris' observations are now better understood because of the availability of improved fluorometers (Oliver and Whittington 1998) .

Photons are absorbed by pigments within an algal cell and then enter an excited state. One method of returning to the ground state is by the emission of a fluorescence photon (Campbell et al. 1998).

The maximum fluorescence yield (F_m) occurs when all of the reaction centers are closed momentarily by a saturating light pulse. The difference between this and the minimum fluorescence yield (F_o) when the reaction centers are open gives information on the photochemical state of photosystem II. Variable fluorescence ($F_v = F_m - F_o$) is the difference between the maximum and minimum fluorescence yield, and is usually normalized to F_m, and the ratio F_v/F_m is very closely related to the maximum yield of photosynthesis (Genty et al. 1989), therefore, for convenience, all following references to this ratio will be referred to as photosynthetic yield. This ratio can also be used as an indicator of photo-inhibition (Demmig-Adams and Adams 1992; Ibelings 1996; Whittington et al. 2000). Brookes has also showed that it can be used to determine the light history of phytoplankton within a stratified lake (Brookes et al. 2003).

The premise for circulation as a method of algae growth control is that the mixer will deepen the epilimnion, and as cyanobacteria are mixed within this layer, they are forced periodically through deeper portions of the reservoir, where light limitations will limit their growth. During afternoon hours when sunlight is at its brightest, the photosynthetic yield will be depressed at the reservoir surface because of photoinhibition, as well as deeper in the reservoir because of light limitation. Therefore, when adequate mixing is present, the surface layers will have an increased photosynthetic yield compared to non-mixed conditions.

7.0 RESULTS AND DISCUSSION

Data were collected from June through August of 2008. The circulator was turned on July 28, 2008 at 13:00, and it was turned off on August 13, 2008 at 09:41. The majority of the data collection took place during and immediately before this period.

7.1.0 Temperature

7.1.1 Near-field Temperature Profiles

The near-field data, which is considered to be all data collected within the first 10 m away from the circulator, will be considered first. This range was chosen to show more detail in the temperature profiles in the immediate vicinity of the unit. Typically the top two meters of the water column were isothermal in the morning (Figure 6), although with solar heating, stratification develops until there is a temperature gradient of 1.2 °C between the surface and the top two meters by about 15:00 hours (Figure 7). Table 1 shows sampling times for the temperature (and dissolved oxygen) profiles.

	Day								
	1	2	3	4	5	13	19	20	27
Time	11:50	09:10	09:04	11:00	09:45	09:15	09:00	02:00	01:00
		10:45	10:55	13:05			Mixer Off		
		12:37	Mixer On				09:50		
		14:41	14:50				11:30		

Table 1 CTD (temperature and dissolved oxygen) profiling dates and times

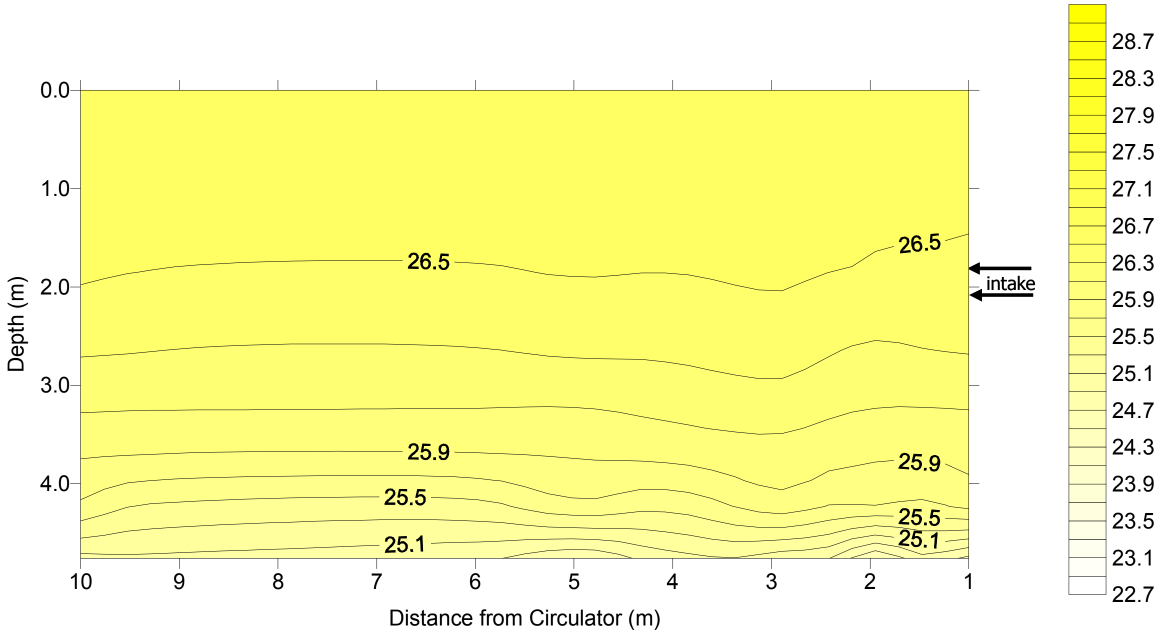

Figure 6 Early morning temperature profile with circulator off (7/27/08 09:10)

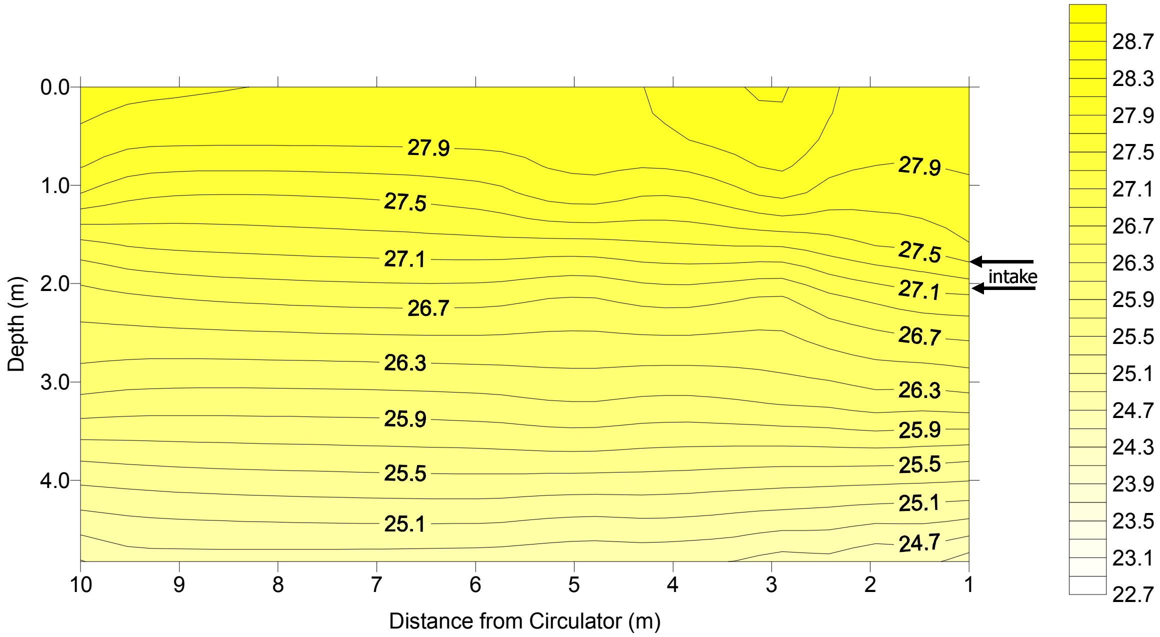

Figure 7 Afternoon temperature profile with circulator off (7/27/08 14:41)

Once the circulator was activated, it had an effect on the temperature profiles, especially on profiles directly adjacent to the unit. The water from the circulator can be seen to be dropping back down within the reservoir near the surface during morning circulator operation (Figure 8). A trend can be seen with the coldest surface water found near the circulator and the warmest surface water found farthest from the unit. An investigation into the complete set of temperature profiles for the reservoir will give a better indication as to how far past the 10 m mark the water travels along the surface before falling back within the reservoir. Typically water did not travel more than a few meters from the circulator during afternoon hours (Figure 9). Here the coolest water appears to drop back within the reservoir more quickly than in the morning, which occurs because of the increased temperature, and thus density, gradient found in the water near the surface in the afternoon. This increased density variation makes it more difficult to force the water across the surface away from the circulator, and it therefore will not travel as far along the surface.

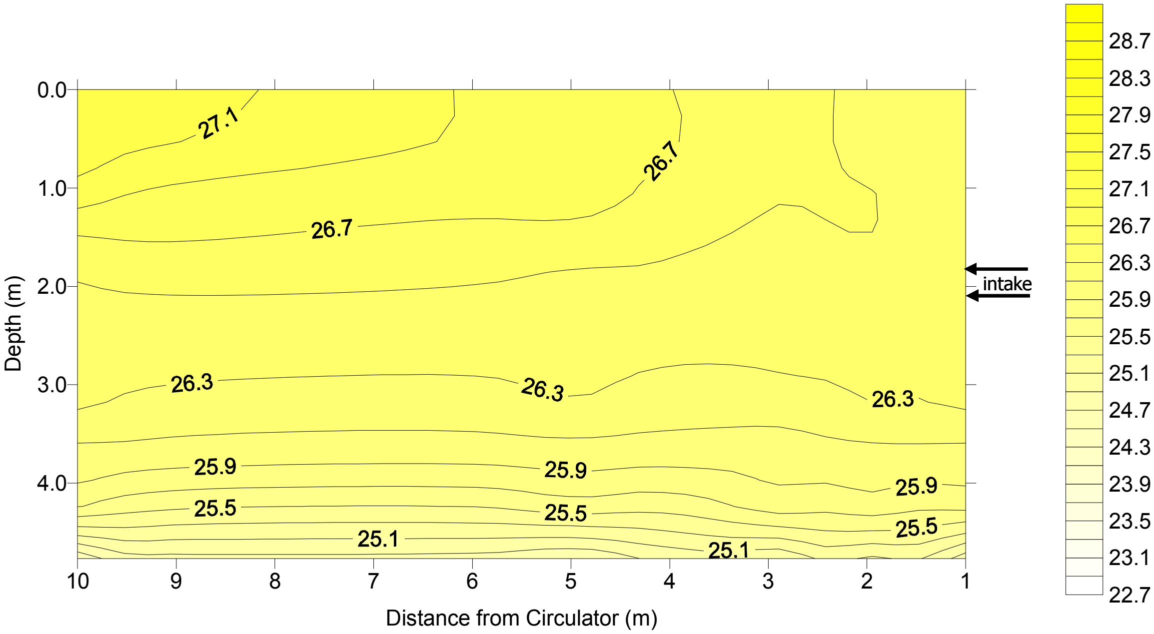

Figure 8 Morning near temperature profile within the first week of circulator operation (7/29/08 11:00)

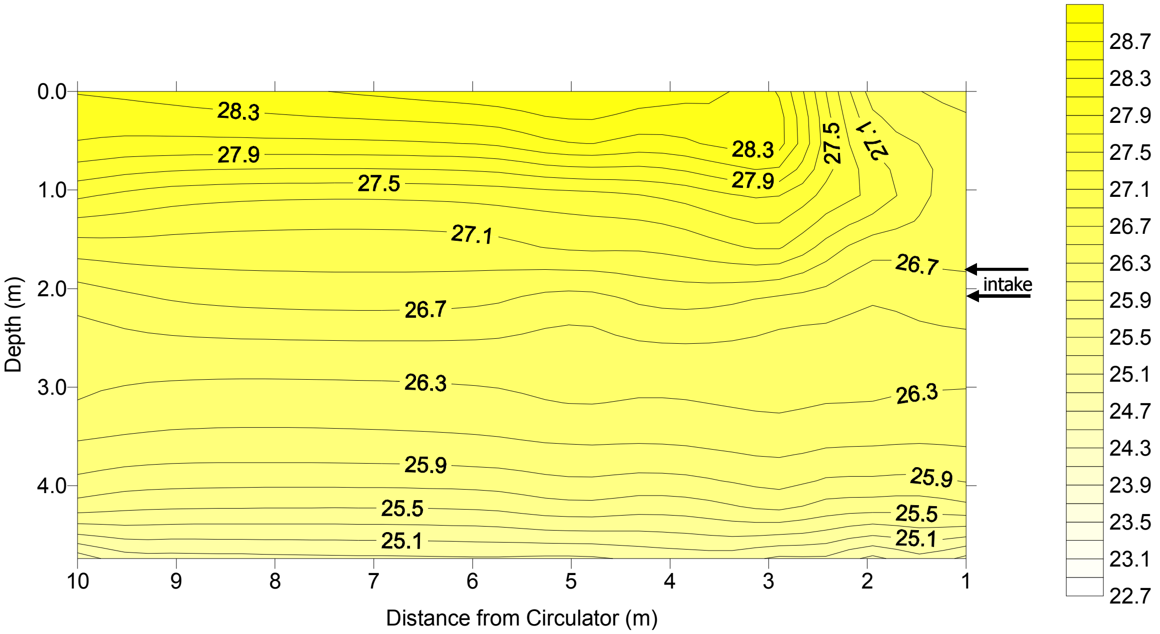

Figure 9 Afternoon near temperature profile within first week of circulator operation (7/29/08 13:05)

Near-field temperature profiles look different after one week of operation. The profile, which has an increased resolution of 0.1°C to show more detail, is isothermal within the top two meters, except immediately adjacent to the circulator (Figure 10). Observation of the complete set of temperature profiles should give an indication as to how deep this mixing occurs through the deeper portions of the reservoir. Similarly this entire portion of the reservoir appears to be mixed after two weeks of circulator operation (Figure 11). This circulator is supposed to only mix the epilimnion, but appears to mix the entire reservoir, although this portion of the reservoir is fairly shallow. Investigation of the far-field temperature profiles will confirm or refute this observation. The unit was turned off after two weeks of operation. After one week without circulation, the reservoir began to return to stratified conditions (Figure 12).

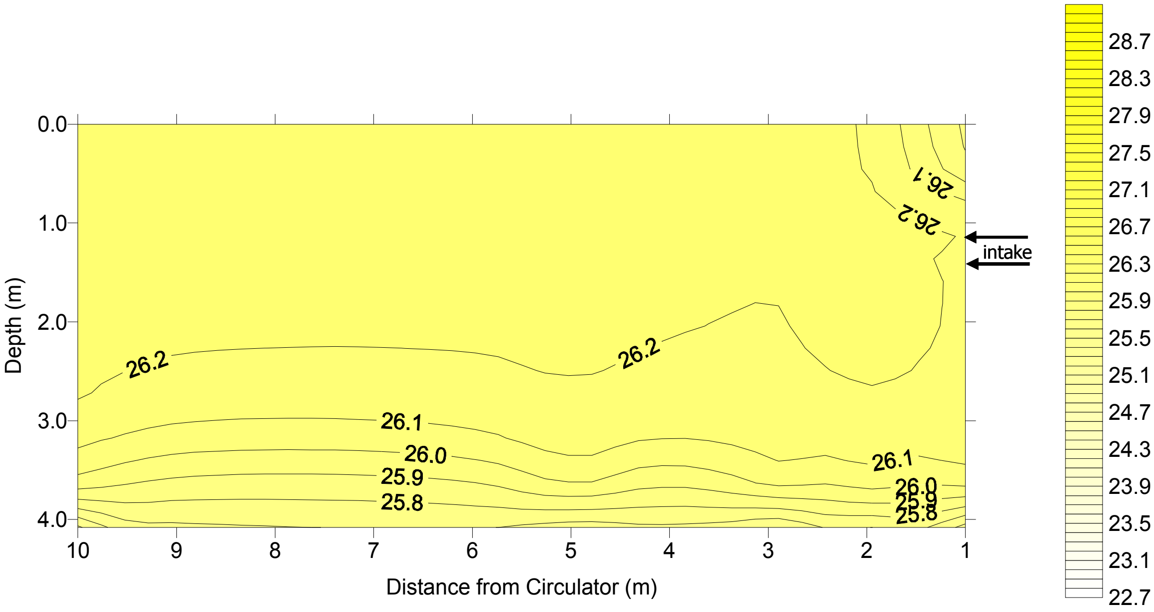

Figure 10 Near-field temperature profiles after one week of circulator operation with increased resolution (8/7/08 09:15)

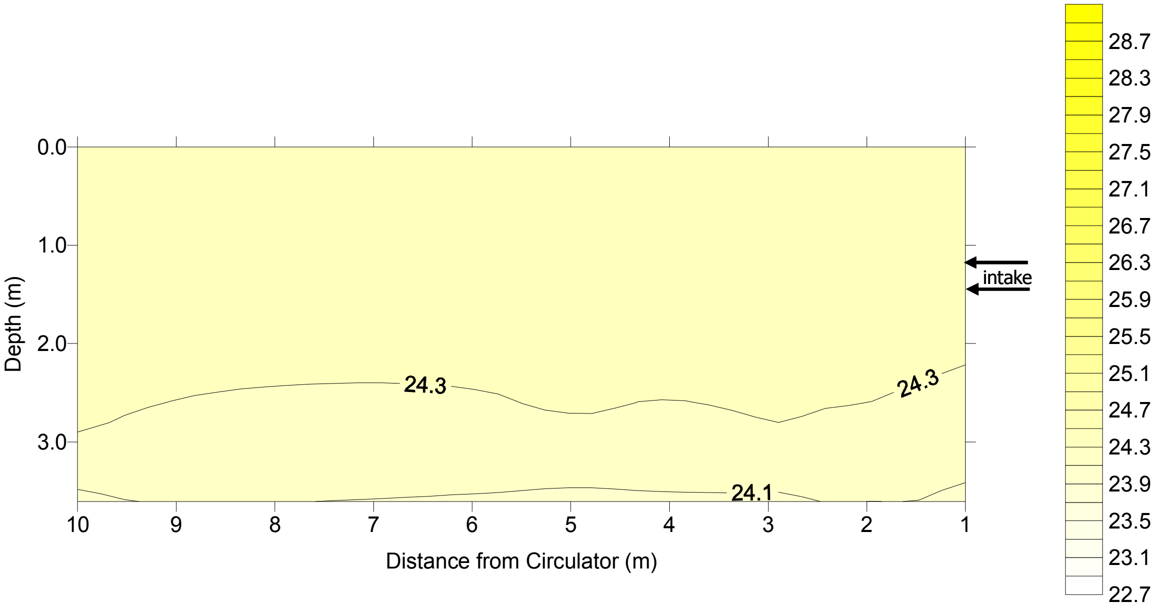

Figure 11 Near-field temperature profiles after two weeks of circulator operation (8/13/08 09:00)

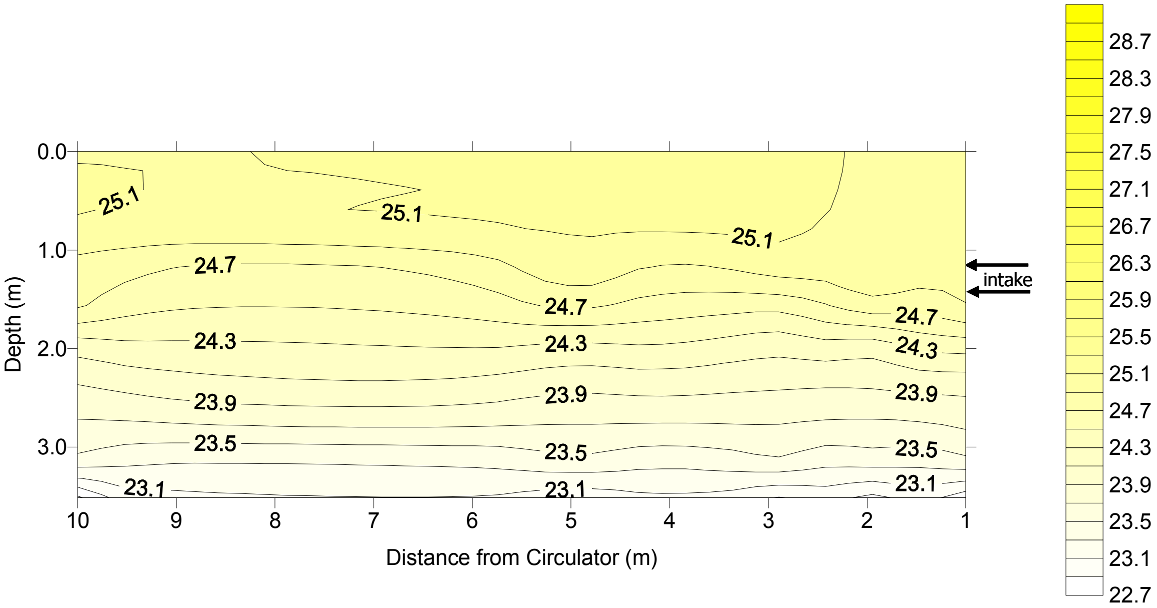

Figure 12 Near-field temperature profile after circulation was terminated for two weeks (8/21/08 13:00)

7.1.2 Complete Temperature Profiles

The complete set of temperature profiles are now considered; and it is these profiles that show the degree to which the circulator has an effect on temperature within the entire reservoir. These profiles provide a representation of the reservoir sediments, which was not necessary for the near-field profiles. There is little change in temperature in the top two meters during morning hours (Figure 13), however as temperatures increase during the afternoon, surface waters begin to warm (Figure 14). One observation to note is that in both sets of profiles the surface temperature is warmest at the farthest location from the circulator. This is because of the position of the reservoir in relation to the sun. The farthest locations experience full sunlight for most of the day, while the locations in closer proximity to the circulator are shaded by trees for a portion of the day.

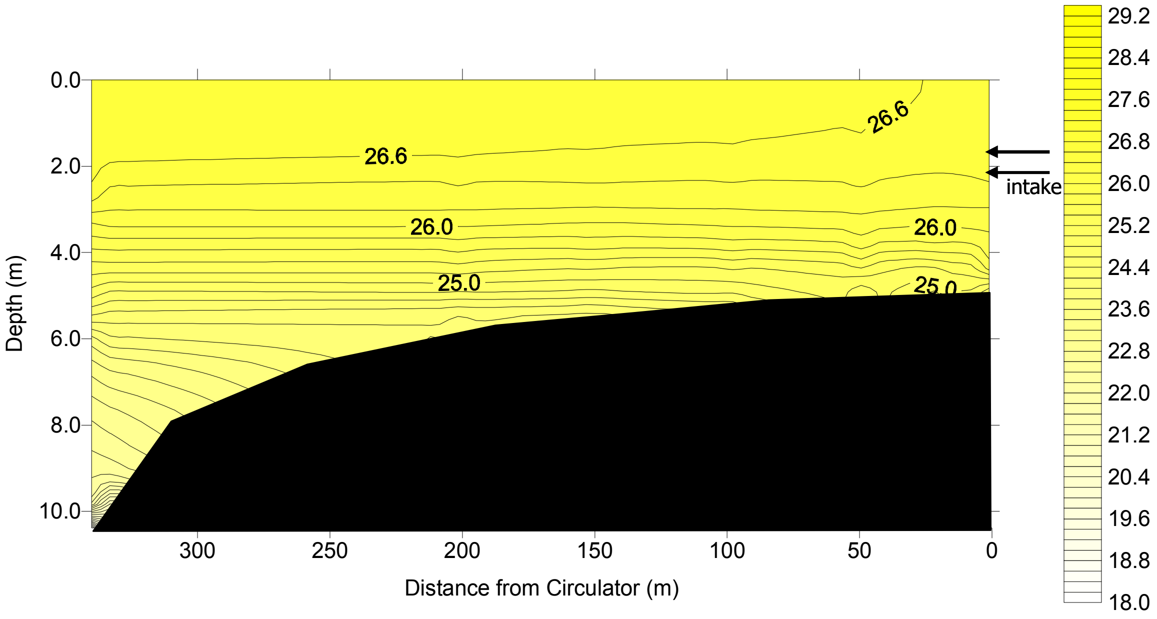

Figure 13 Typical morning complete temperature profile without circulation (7/27/08 09:10)

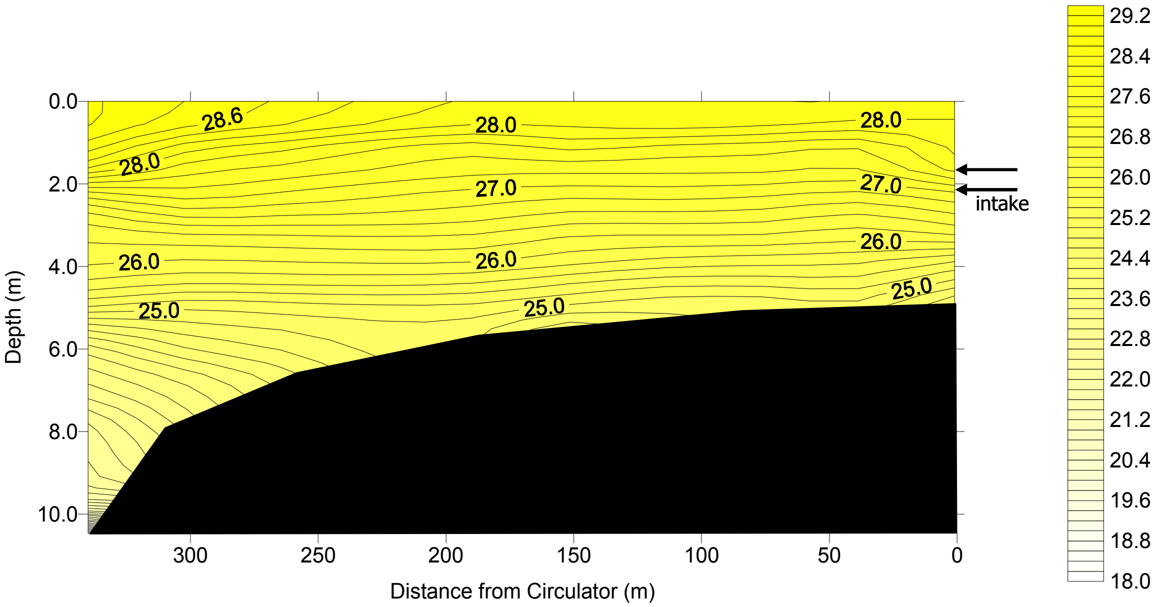

Figure 14 Typical afternoon complete temperature profile without circulation (7/27/08 14:41)

Once the circulator has been activated, it has an effect on the temperature profiles. In the morning (Figure 15), a weaker temperature gradient of waters near the surface allows the water leaving the circulator to travel farther (about 80 meters) than in the afternoon (less than 10 meters) (Figure 16).

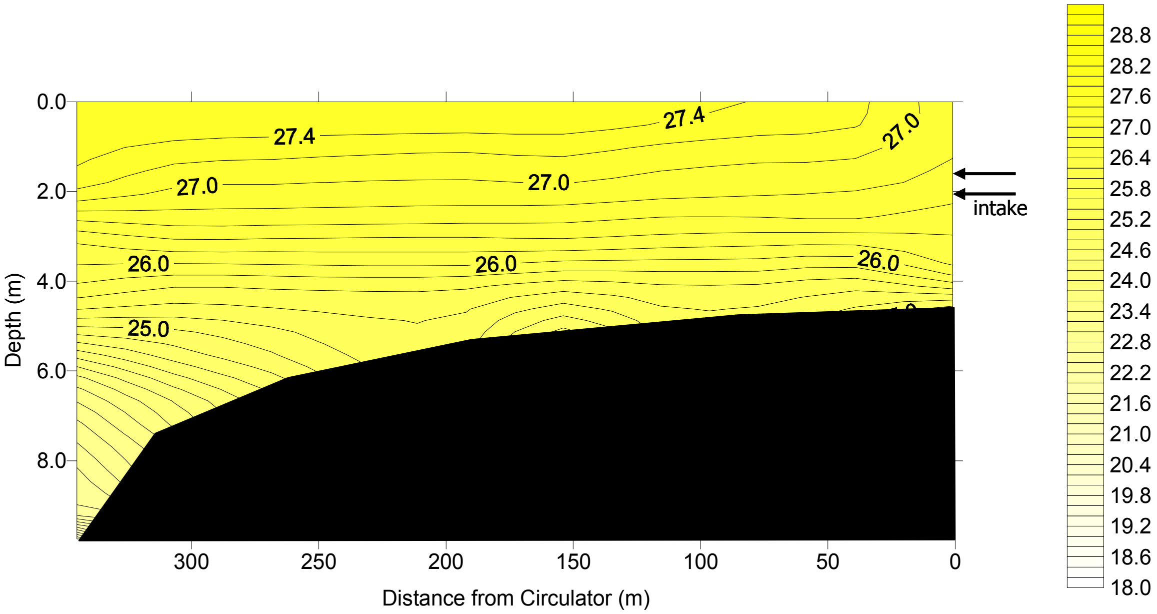

Figure 15 Complete morning temperature profile after circulator on for two days (7/30/08 09:45)

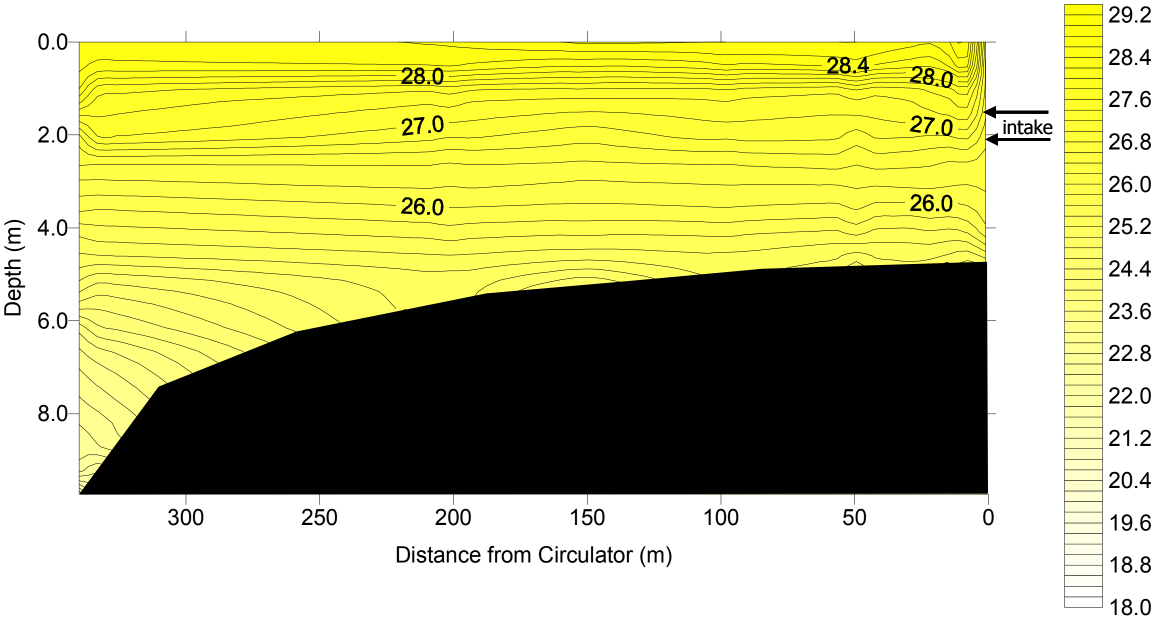

Figure 16 Complete temperature profile in afternoon with circulation (7/28/08 14:50)

These results were basically as expected. After one week of operation, however, the effect of the circulator became more pronounced. The uppermost three meters became nearly isothermal at this point (Figure 17), yet the deepest portion of the reservoir is still strongly stratified below this point. This shows that the reservoir is not completely mixed, although from near temperature profiles from this same date (Figure 10), it appears as though the upper portion of the reservoir, which is much shallower, was basically mixed. After two weeks, it can be seen that there is little more than 1.2°C temperature difference between the surface and eight meters deep (Figure 18). The temperature does, however, drop off steeply within the last meter, which indicates that the reservoir is basically mixed through the entire water body except for the very deepest portion.

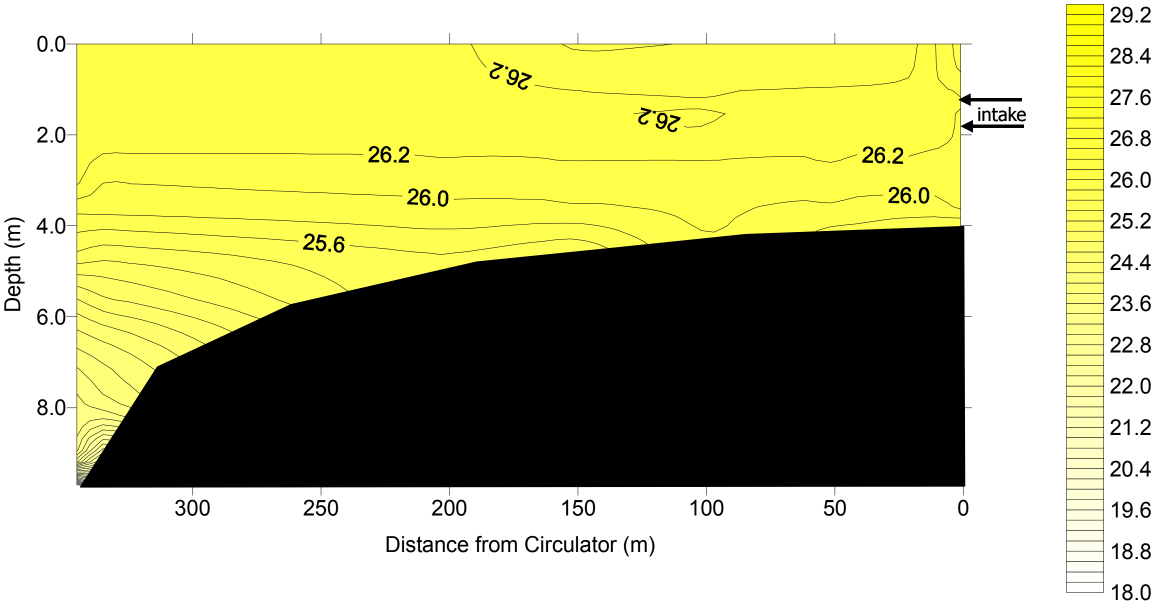

Figure 17 Complete temperature profile after one week of circulation (8/7/08 09:15)

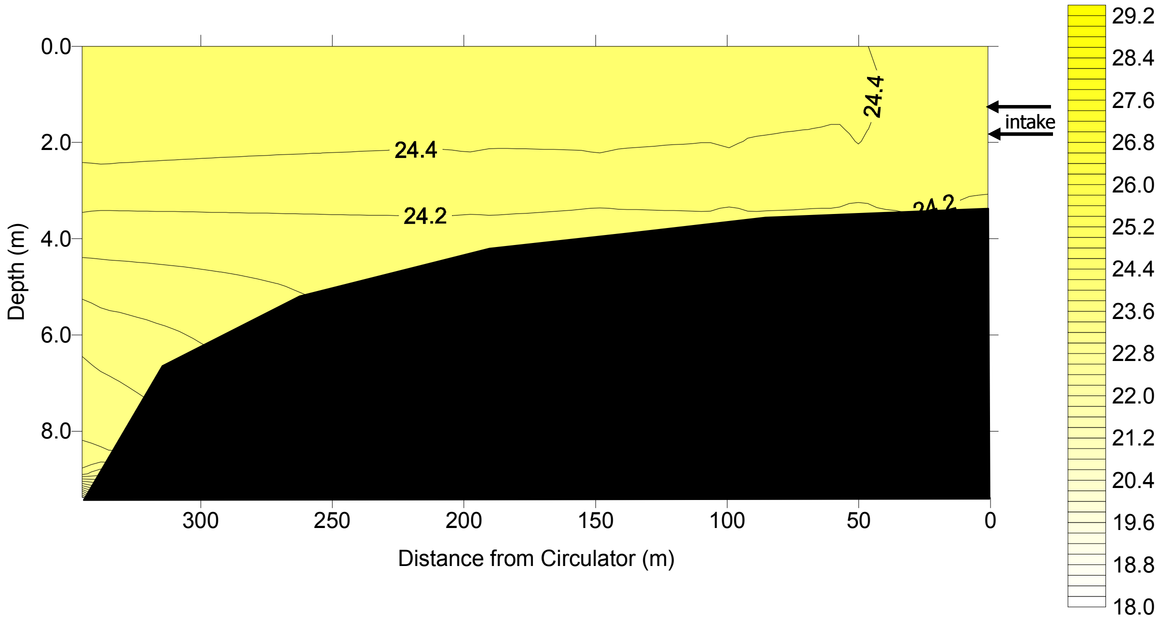

Figure 18 Complete temperature profile after two weeks of circulation (8/13/08 09:00)

7.2.0 Dissolved Oxygen

7.2.1 Near-field Dissolved Oxygen Profiles

Near-field (all profiles within the first 10 m) dissolved oxygen profiles are considered next. Profiles collected during both the morning and afternoon were very similar in appearance. Typically, without circulation, a strong dissolved oxygen concentration gradient can be seen below 2.5 m (Figure 19), with nearly constant readings found above this level.

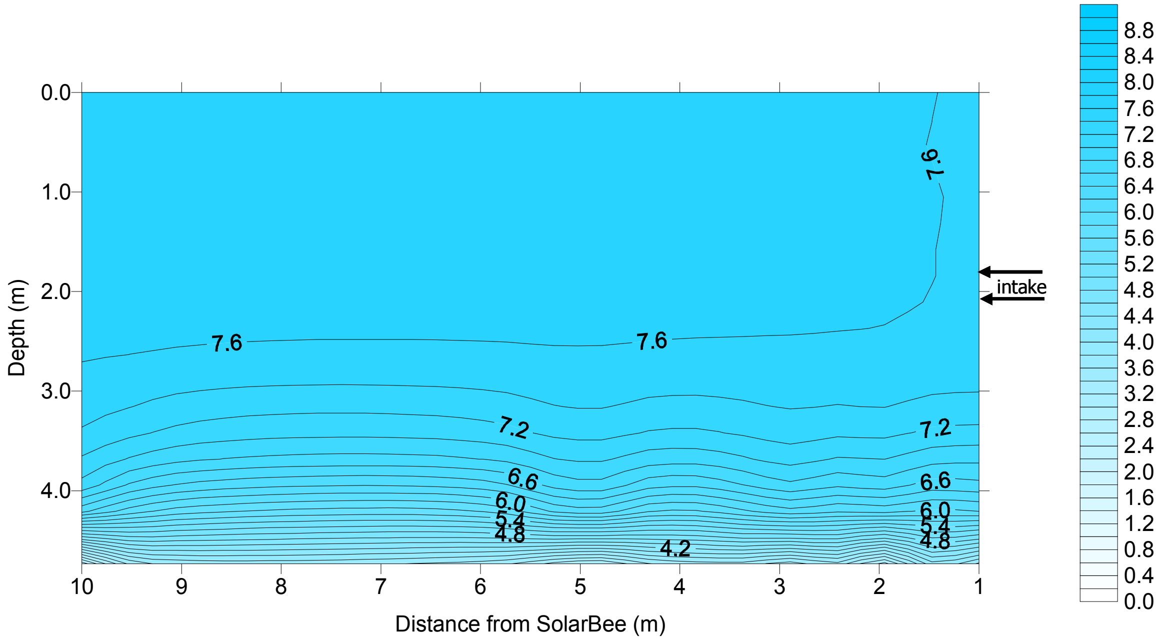

Figure 19 Near-field dissolved oxygen profiles without circulation (7/27/08 10:45)

The near-field dissolved oxygen profiles after activation of the circulator (Figure 20) show the profile appears to be slightly disturbed compared to the profiles in Figure 19, however these changes are slight and not as straightforward as the circulation-induced changes seen in the temperature profiles. Additional dissolved oxygen profiles while the circulator was active (Figure 21) also show that the profile was disturbed within the top 2.5 m, but not strongly affected with only slight shifts in dissolved oxygen concentrations. The primary reason for this phenomenon is that the dissolve oxygen profiles before circulation show a thick (the upper 2.5 m) zone with almost constant dissolved oxygen concentrations. Unless the circulator can deepen the epilimnion enough to reach deeper water with lower dissolved oxygen concentrations, then there won't be a strong influence of circulation on overall dissolved oxygen profiles since the water at the intake to the circulator has a very similar dissolved oxygen concentration compared to water at the surface of the reservoir.

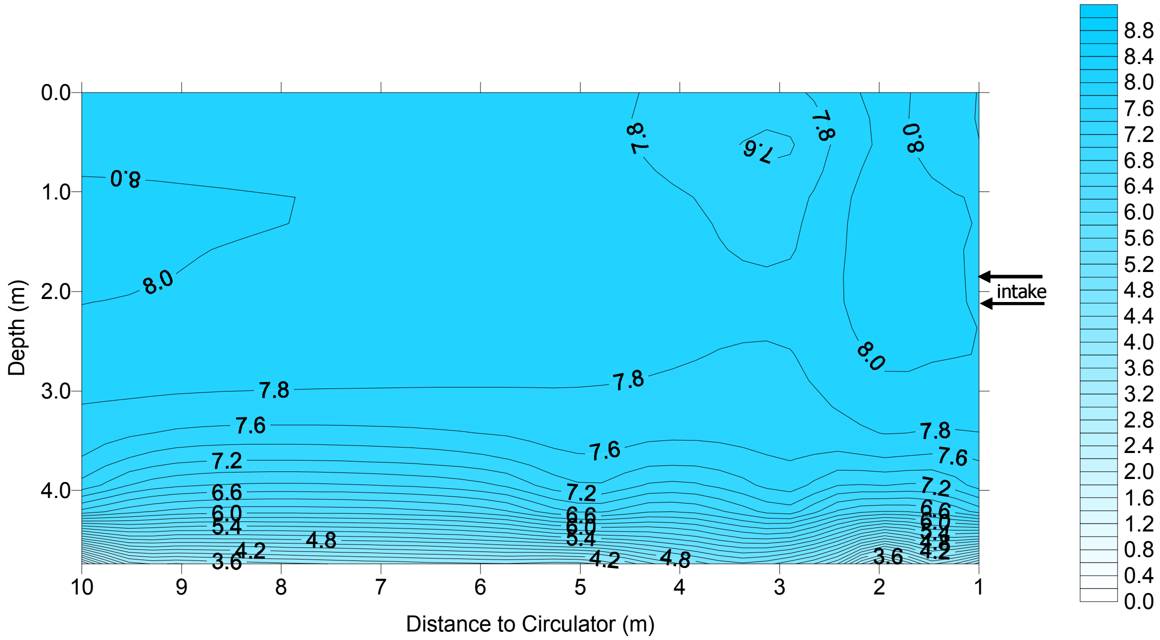

Figure 20 Near-field dissolved oxygen profiles with circulation (7/29/08 13:05)

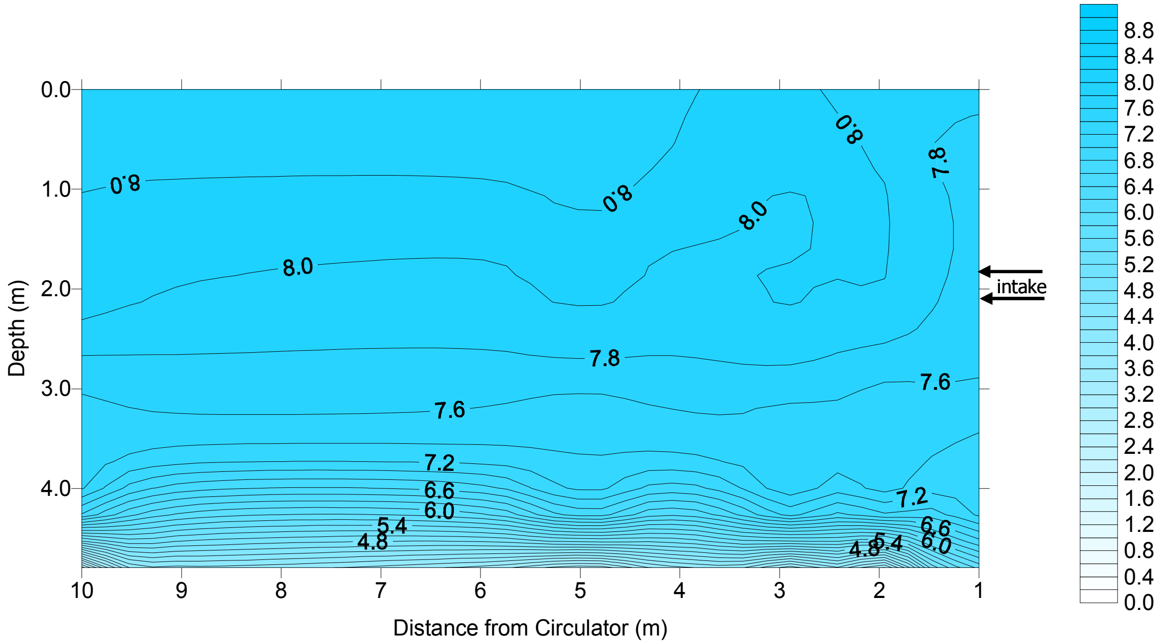

Figure 21 Near-field dissolved oxygen profiles with circulation (7/28/08 14:50)

After two weeks of circulation, the reservoir appears to be completely mixed, with almost constant oxygen concentrations in the first 10 m (Figure 22). The overall dissolved oxygen concentration is lower than that observed previously. For this set of profiles, the measurements at a distance of two meters were discarded because of a temporary problem with the oxygen sensor.

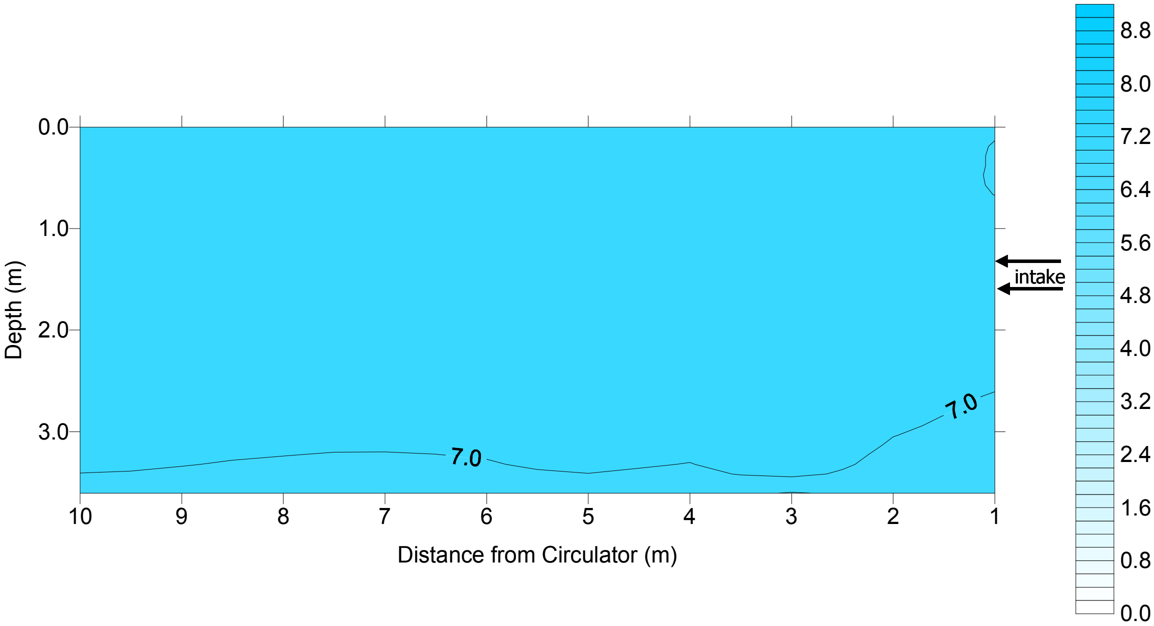

Figure 22 Dissolved oxygen profiles after two weeks of circulation (8/13/08 09:00)

7.2.2 Complete Dissolved Oxygen Profiles

Typically, complete dissolved oxygen profiles without circulation show the upper 2.5 m with nearly constant oxygen concentrations (Figure 23). After circulation is induced (Figure 24) the overall profile looks very similar. Again this is because the water at the intake level in the reservoir has a very similar dissolved oxygen concentration compared to the surface water.

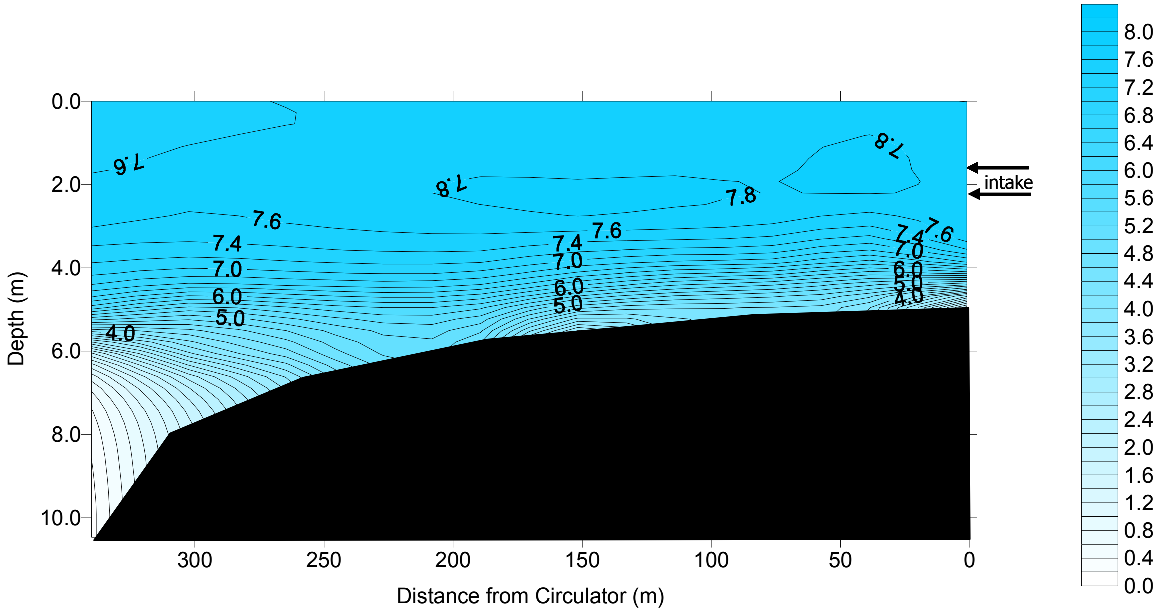

Figure 23 Typical complete dissolved oxygen profile without circulation (7/27/08 14:41)

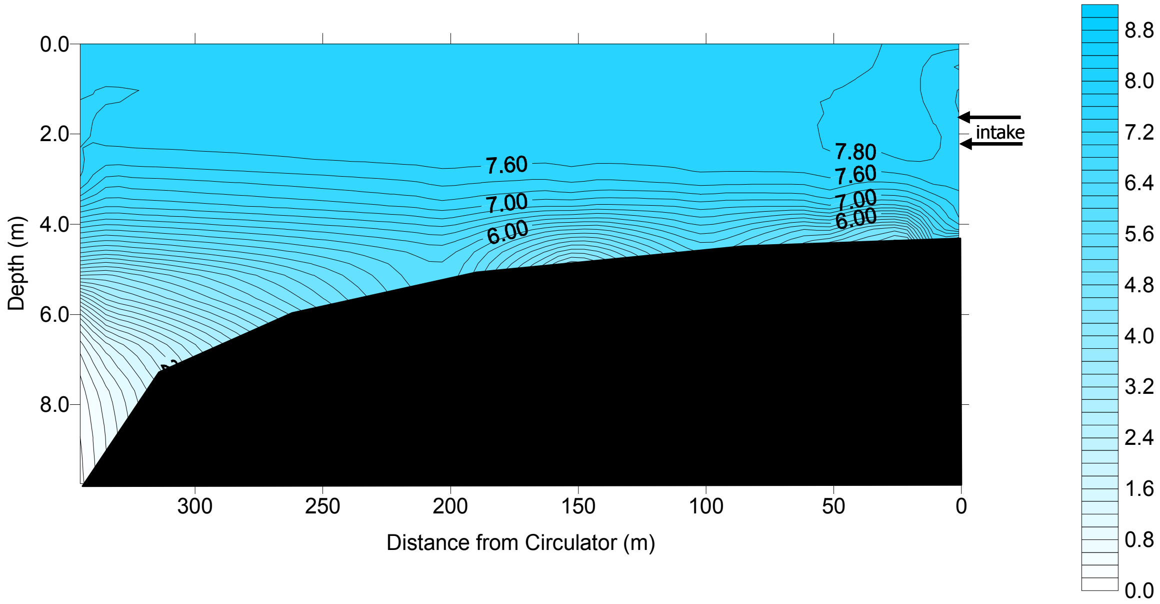

Figure 24 Dissolved Oxygen profile with circulation (7/30/08 09:45)

Complete dissolved oxygen profiles after two weeks of circulation show nearly complete mixing of the reservoir (Figure 25), as indicated in the temperature profiles for this same time period. The oxygen concentration drops rapidly in the final meter at the deepest location within the reservoir, but in the remainder of the reservoir, concentrations vary little from the surface down to about 8.5 m.

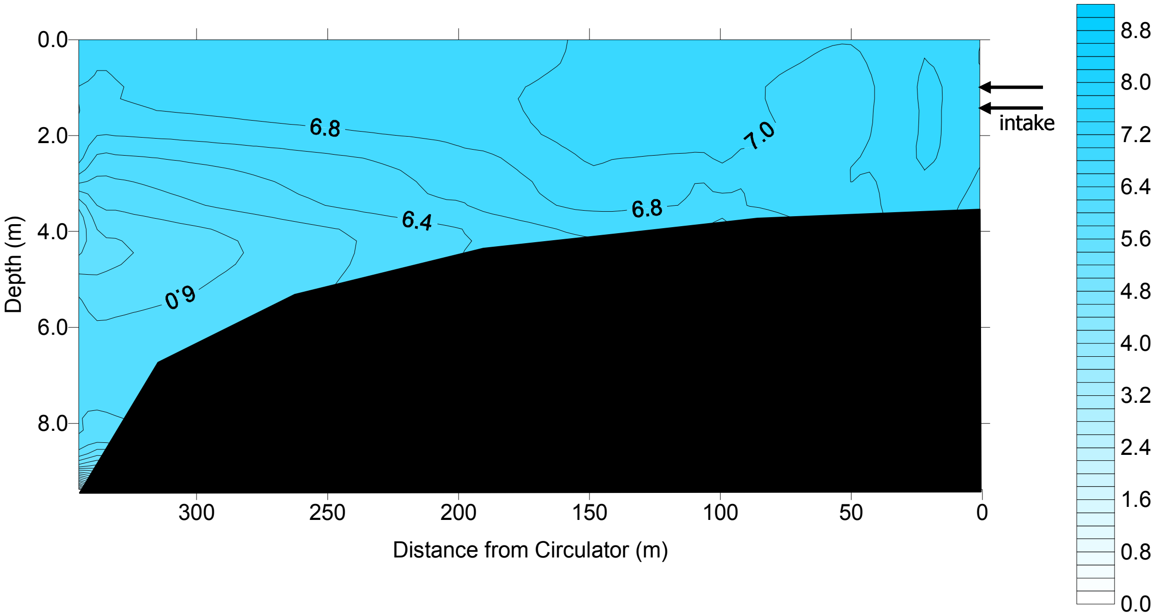

Figure 25 Dissolved oxygen profile after two weeks of circulation (8/13/08 09:00)

Observation of both temperature and dissolved oxygen profiles at individual locations in the reservoir show similar trends. At a distance of five meters from the circulator, there is little difference in either parameter after one week of circulation, but both temperature and dissolved oxygen levels decrease after two weeks of mixing (Figure 26). At a distance of 340 m from the circulator (Figure 27), a similar trend is observed in the upper portion of the reservoir. The temperature profiles become nearly isothermal except in the final one meter of depth near the sediments, where the temperature drops rapidly. Observation of the dissolved oxygen profiles show a strong stratification in dissolved oxygen within the reservoir, which disappears after two weeks of circulation. At this point, the dissolved oxygen concentration is nearly constant throughout the reservoir, but drops rapidly in the final meter near the sediments. These measurements were all taken at about 9:00 in the morning.

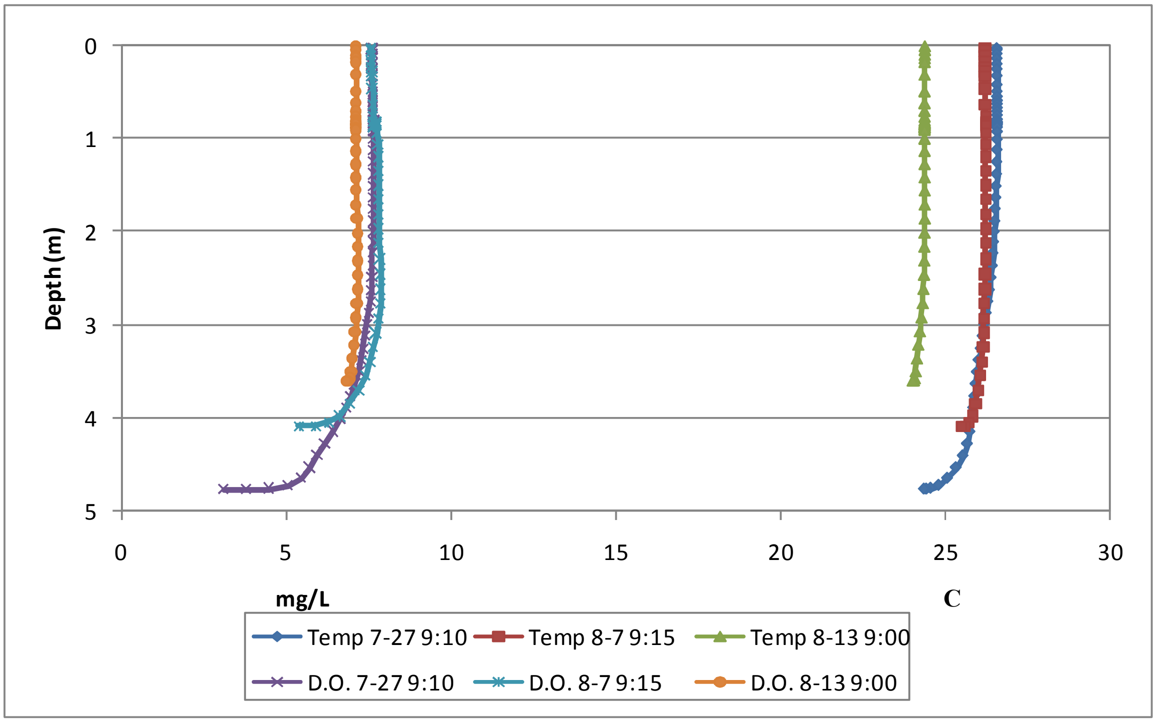

Figure 26 Temperature and dissolved oxygen profiles before and during circulation at a distance of five meters from the circulator

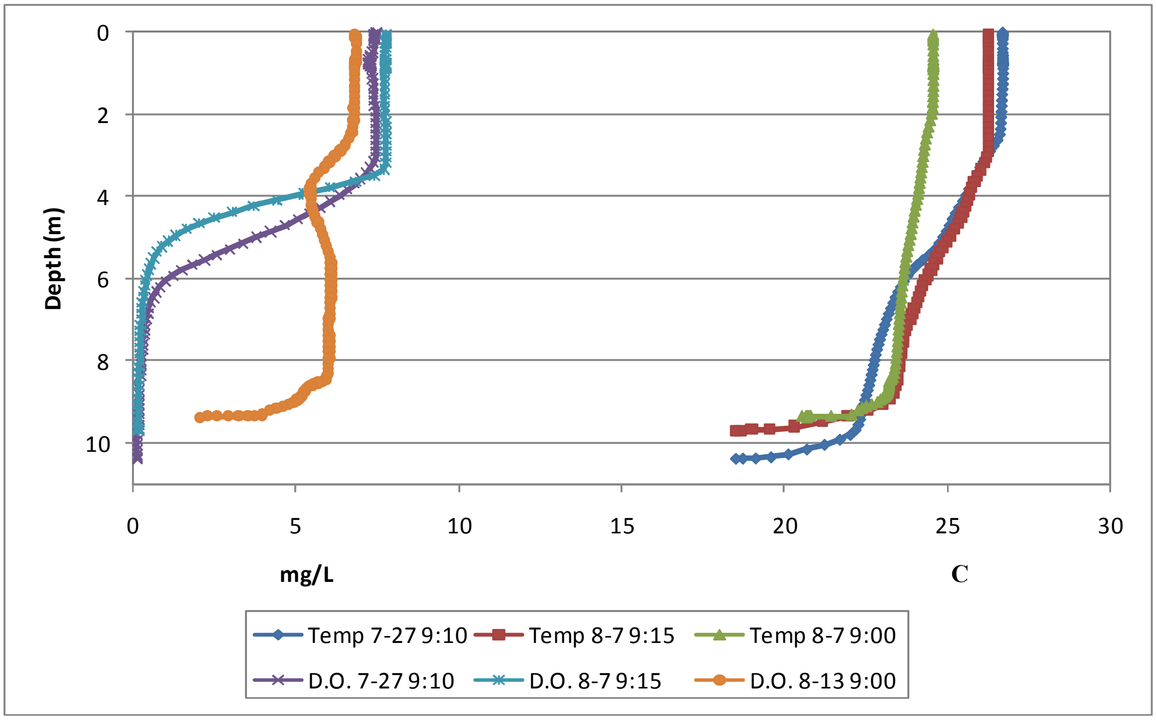

Figure 27 Temperature and dissolved oxygen profiles before and during circulation at a distance of 340 m from the circulator

7.3 Bathymetry

The bathymetry of the reservoir has a strong effect on how easily stratification can be disrupted. Shallower regions will not be as strongly stratified, and therefore, can be more easily manipulated. No complete bathymetry data were available for Falling Creek Reservoir, however, the depth measuring and gps abilities of the ADCP allowed the bathymetry of the reservoir to be investigated.

The ADCP unit was used to measure depth, and an attached gps unit allowed collection of geographic location data. Transects were made across the reservoir at approximately 30 m intervals. This data was then used to extract the bathymetry data for Falling Creek Reservoir. The water surface elevation for the sampling date was 507 m above sea level. The resulting contour plot for the reservoir (Figure 28) and a three-dimensional representation of the same depth data (Figure 29) are shown below. It can be seen in these figures that a majority of the reservoir is less than five m deep, which indicates the potential for a fairly weak stratification structure. It should also be noted that the amount of water in the reservoir fluctuated daily, and when the data was collected for these figures, the water level was up to 1.5 m lower than some of the days that the circulator experiments took place.

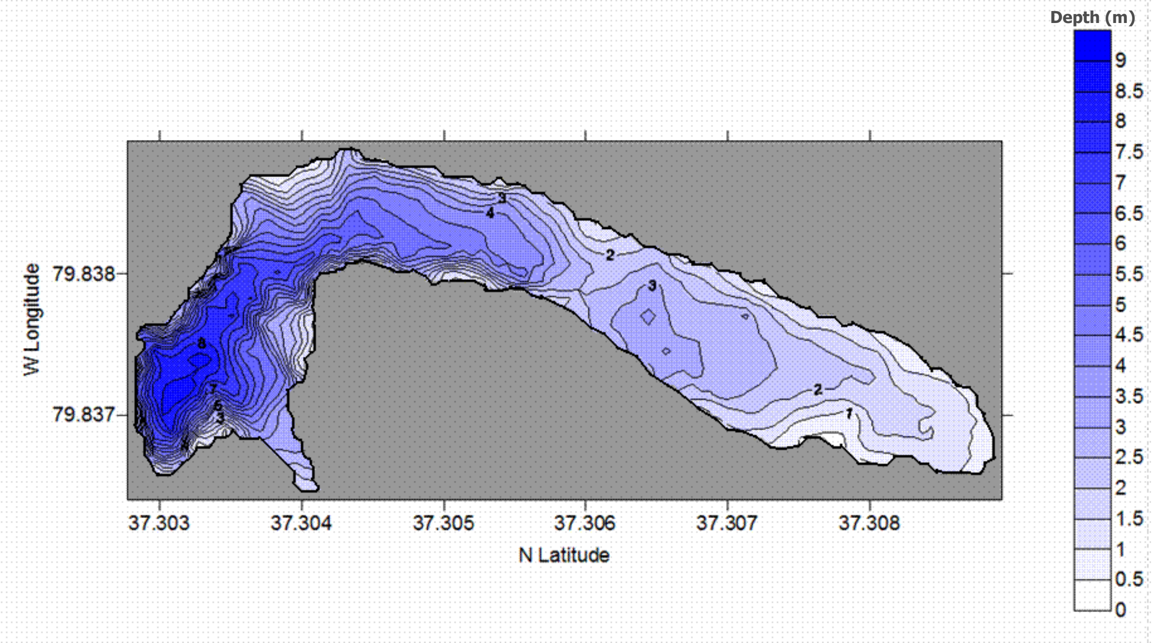

Figure 28 Falling Creek Reservoir elevation contours

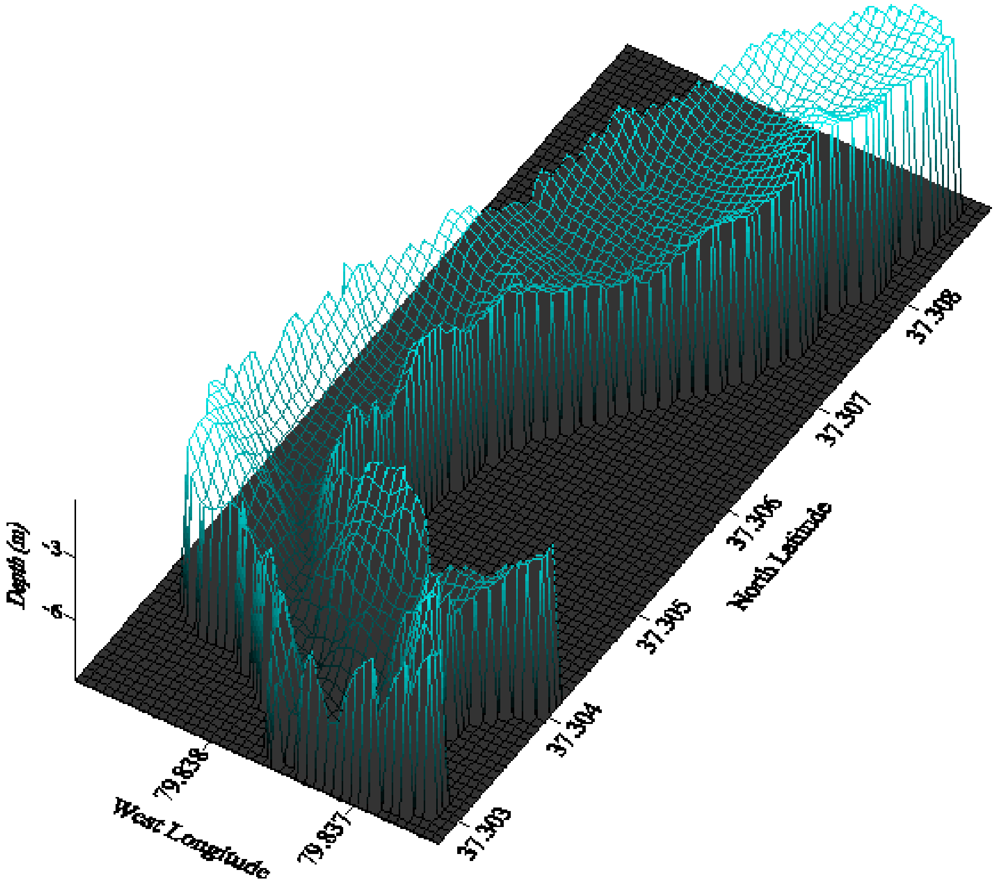

Figure 29 Three-dimensional representation of Falling Creek Reservoir bathymetry

7.4 Velocity Profiles

The velocity profiles were taken both before and during operation of the circulator. The velocity profiles with the circulator turned off show that there is no pattern to the orientation of the velocity vectors (Figure 30). However, after initiating circulation, the intake appears to affect velocity out to a distance of five m from the circulator, and this affected area is about one meter thick (Figure 31). Outside of this zone, velocities appear as before, with no apparent pattern in direction or magnitude. The vectors shown in these two figures are in an east/west up/down orientation. The "east/west" direction is not geographical east/west. East is automatically assigned as flow in the direction that the

ADCP is facing, and the ADCP was oriented facing the circulator for these observations. This east/west orientation also lines up with the longitudinal axis of the reservoir. North/south would have given the transverse movement of water in the reservoir, however, it is the longitudinal portion of the velocity vector that these profiles are focused on. Therefore, the vectors in these profiles indicate if the water was moving either toward or away from the circulator (in the longitudinal direction) and they also indicate if the water was moving either up or down, as well as the magnitude of velocity.

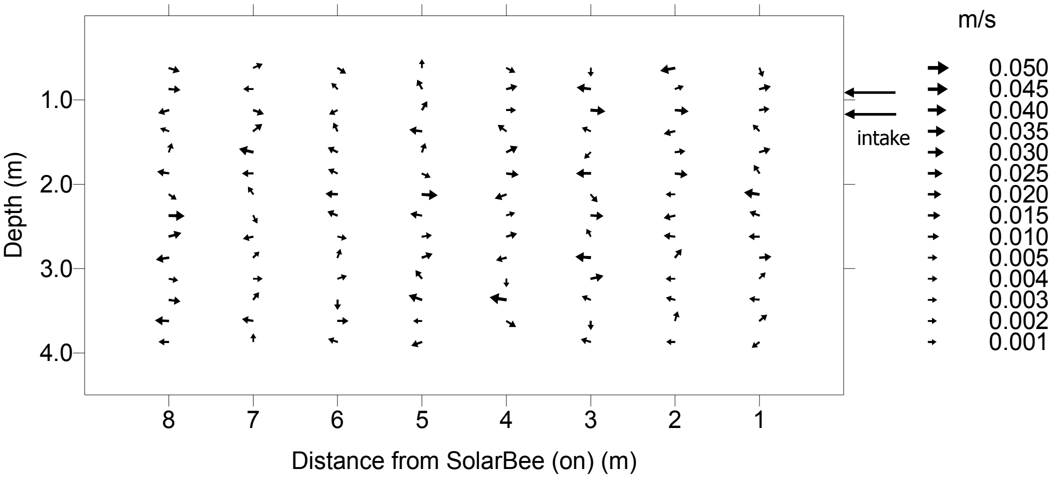

Figure 30 Velocity profiles with no circulation

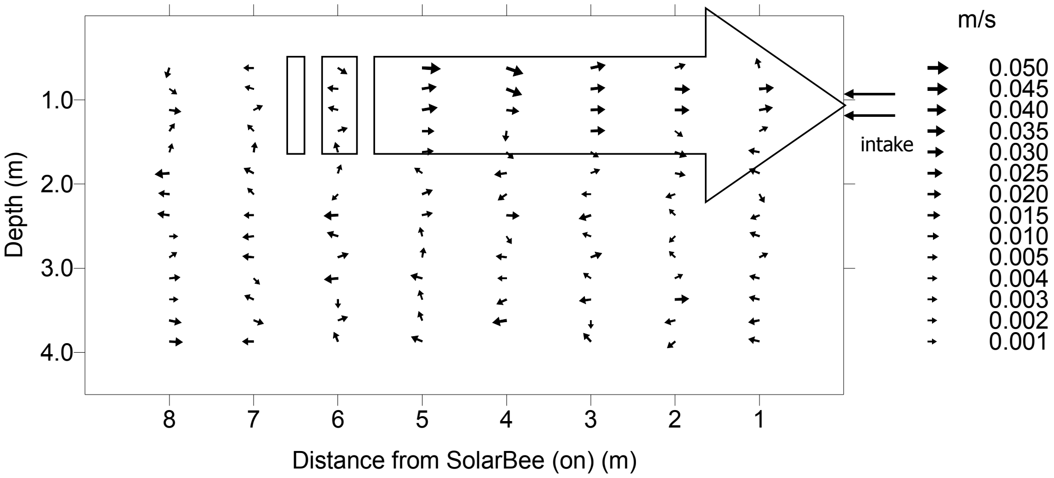

Figure 31 Velocity profiles with circulation (primary area effected by circulation enclosed within arrow)

7.5 Photosynthetic Yield

Cell physiology of phytoplankton was probed with samples taken radially away from the mixer to establish the extent of the zone where photosynthetic activity was altered. Sampling was conducted over three days, 27-29 July 2008.

Sampling occurred three times on July 27 at 11:00, 13:00, and 15:00. The sampling scheme was designed to assess photoinhibition radially away from the mixer before it was turned on. Photoinhibition was evident at each sampling time. At 15:00, it can be seen that the yield is lowest for the surface layer and highest for two to four meters deep, and the yield values are very similar between the two sampling locations (at the mixer and 150 m from the mixer), although the surface and 0.3 m deep measurements are slightly more depressed at a distance of 150 m from the circulator (Figure 32). Yield was also measured at a depth of 0.3 m at seven locations away from the circulator, which was similar at all sites and (Figure 33). The data for these figures is also included (Table 2).

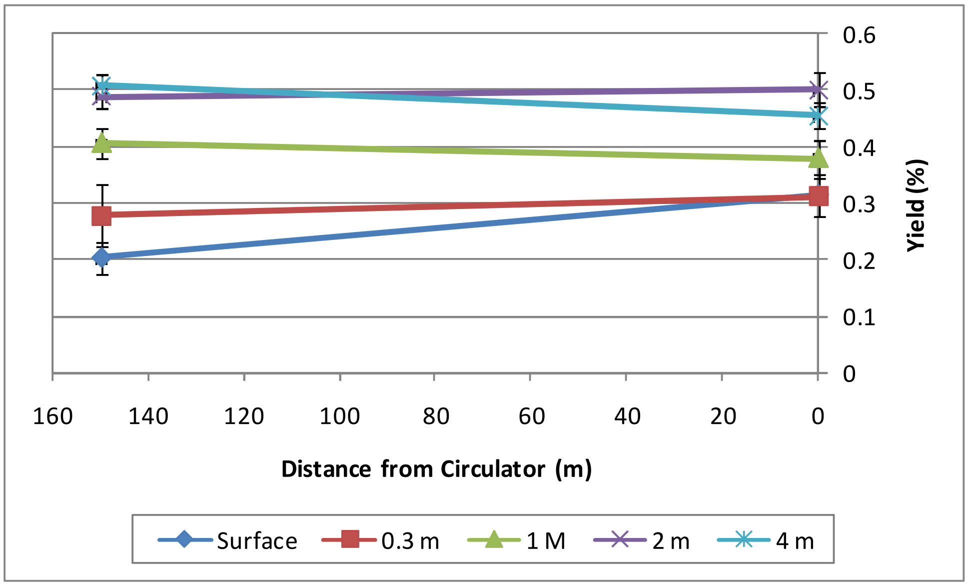

Figure 32 Photosynthetic yield profiles with no circulation – error bars indicate standard deviation (7/27/08 15:00)

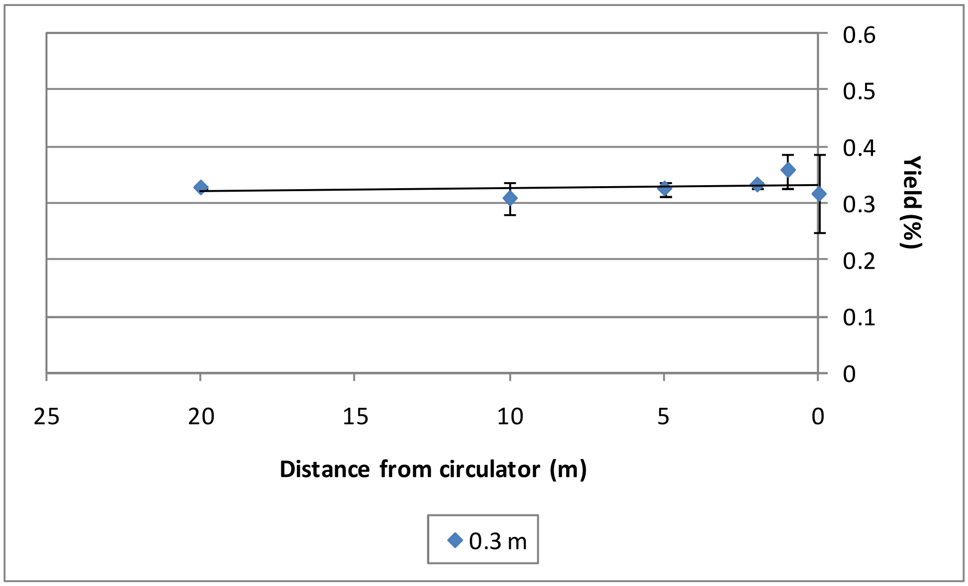

Figure 33 Photosynthetic yield at a depth of 0.3 m without circulation – error bars indicate standard deviation (7/27/08 11:00)

Time									
11:00	**Distance from mixer**								
Depth	0m	1m	2m	5m	10m	20m	50m	100m	150m
0	0.295								
0.3	0.317	0.358	0.333	0.326	0.309	0.328	0.284	0.329	
1	0.468								
2	0.498								
4	0.471								
Time									
13:00									
Depth	0m	1m	2m	5m	10m	20m	50m	100m	150m
0	0.283								
0.3	0.262	0.253	0.256	0.263	0.328	0.289	0.288	0.246	
1	0.416								
2	0.511								
4	0.431								
Time									
15:00									
Depth	0m	1m	2m	5m	10m	20m	50m	100m	150m
0	0.315								0.204
0.3	0.313								0.278
1	0.379								0.406
2	0.501								0.489
4	0.456								0.508

Table 2 Photosynthetic yield prior to operation of the circulator (7/27/08)

Sampling on July 28 was designed to investigate the zone of influence of the circulator on phytoplankton within the reservoir. Sampling at 9:30 showed limited depression in yield values because of low light exposure, however, a stronger vertical yield gradient was established by 11:15 because of increased light exposure. After the circulator was activated, the yield gradient was eroded at the mixer, but remained intact at distances of 20 m and greater. Sampling continued on July 29, and results are shown in the following two figures. After circulation is induced, the effect of mixing is clearly seen to be strongest directly adjacent to the unit (Figure 34 and Figure 35). Mixing appears to have no affect on sites further than 20 m from the circulator, and its primary effect is on the top two depths (surface and 0.3 m). Photosynthetic yield values after 24 hours of circulation are given (Table 3).

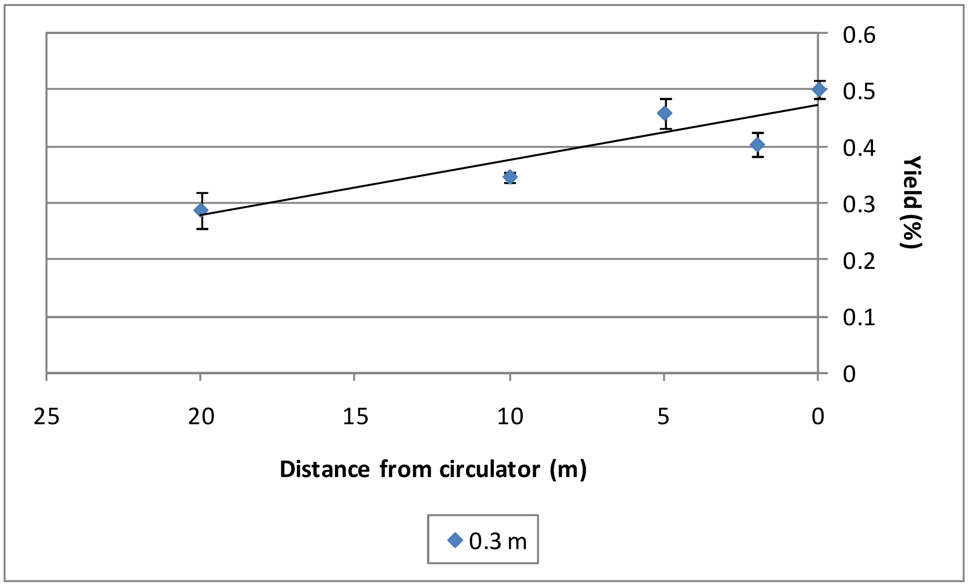

Figure 34 Photosynthetic yield at a depth of 0.3 m after 24 hours of circulation – error bars indicate standard deviation (7/29/08 13:00)

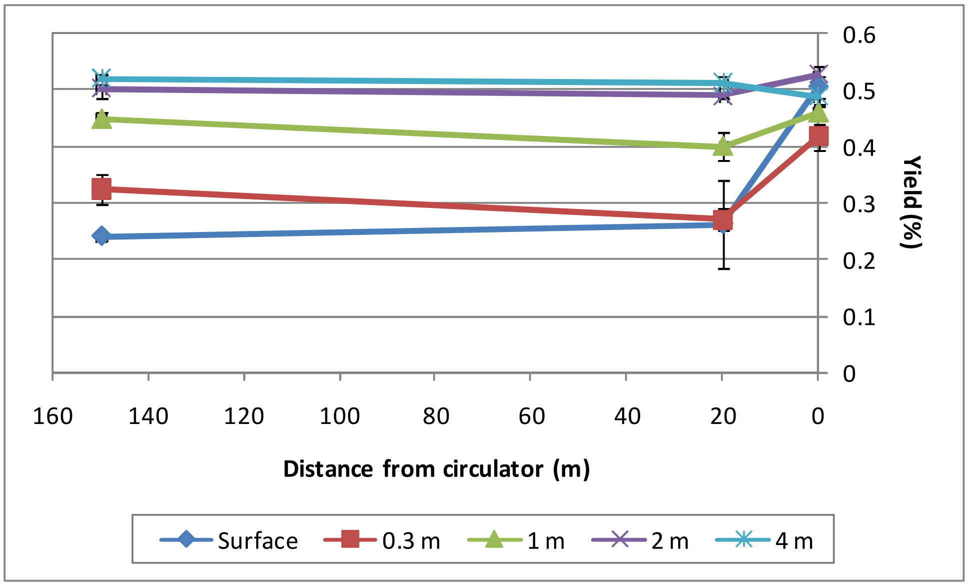

Figure 35 Photosynthetic yield at several depth with circulation – error bars indicate standard deviation (7/28/08 15:00)

Time 9:30

	Distance from mixer		
Depth	0m	20m	150m
0	0.458	0.477	0.378
0.3	0.458	0.454	0.410
1	0.480	0.498	0.493
2	0.487	0.522	0.487
4	0.497	0.466	0.477

Time 11:15

Depth	0m	20m	150m
0	0.456	0.333	0.331
0.3	0.471	0.367	0.340
1	0.515	0.488	0.444
2	0.530	0.511	0.507
4	0.493	0.488	0.519

Time 13:00 pre-mixer

Depth	0m	20m	150m
0	0.377		
0.3	0.402		
1	0.503		
2	0.519		
4	0.491		

Time 13:00 mixer on

Depth	0m	20m	150m
0	0.446	0.290	
0.3	0.438	0.323	
1	0.452	0.433	
2	0.483	0.486	
4	0.396	0.465	

Time 15:00

Depth	0m	20m	150m
0	0.507	0.263	0.242
0.3	0.417	0.271	0.325
1	0.461	0.401	0.449
2	0.527	0.490	0.503
4	0.489	0.512	0.520

Table 3 Photosynthetic yield before and after activation of the circulator

Time 13:00

	Distance from mixer					
Depth	0m	2m	5m	10m	20m	150m
0	0.543				0.278	0.308
0.3	0.503	0.405	0.461	0.348	0.288	0.393
1	0.487				0.418	0.422
2	0.538				0.508	0.470
4	0.503				0.406	0.444

Table 4 Photosynthetic yield values after 24 hours of circulation

8.0 DISCUSSION

A synthesis of the effects of the surface mixing unit on temperature, velocities near the intake, and photosynthetic yield during the afternoon is given in Figure 36, which shows that the overall effect of the mixer is limited to the first 10 m immediately adjacent to the unit. The largest effects of the unit, however, are seen during the morning hours when the difference in density between the intake water and the surface of the reservoir is much smaller, allowing the water to travel up to 10 times further than during afternoon hours. Although the water from the mixer does not remain at the surface, it was observed to travel upwards of 80 m from the unit during cooler times of the day.

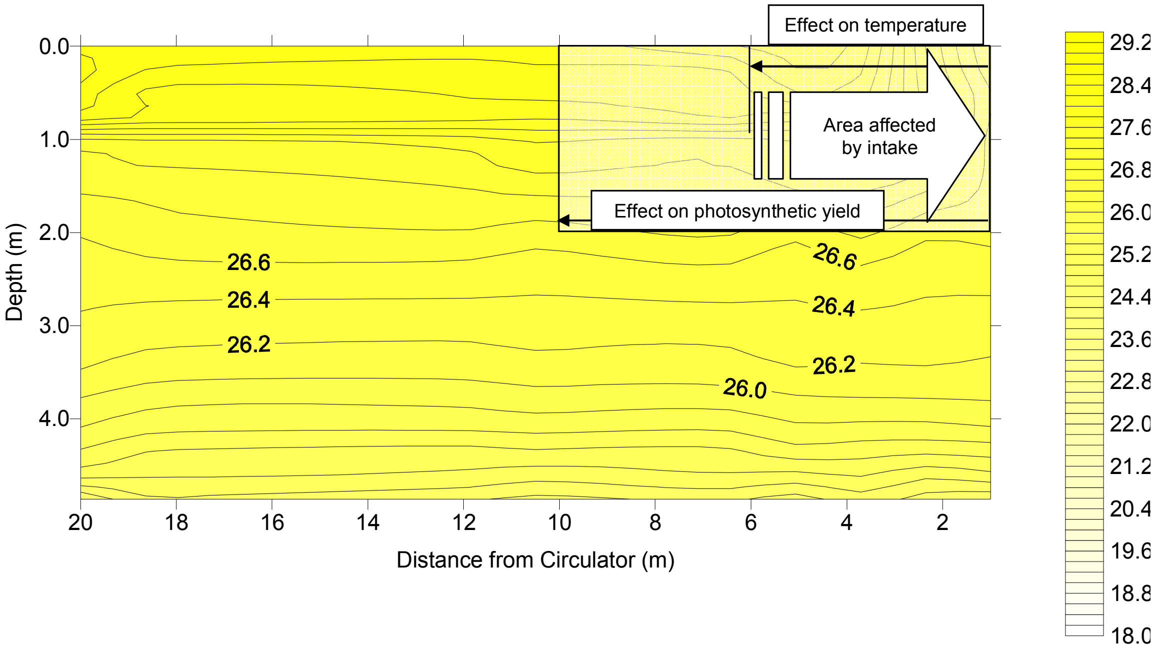

Figure 36 Overall effect of circulator during warmer afternoon hours (7/29/08 13:05)

The temperature and dissolved oxygen profiles show that circulation induced nearly complete mixing of Falling Creek Reservoir within two weeks of operation. Historical reservoir temperature and wind data show that the mixing event is not a normal occurrence, and therefore, must have been caused by the circulator. Temperature profiles at four elevations within the reservoir during the summer of 2007 are given (Figure 37), and the range of six meters covers a large portion of the reservoir. At no time during this period did the reservoir become naturally mixed.

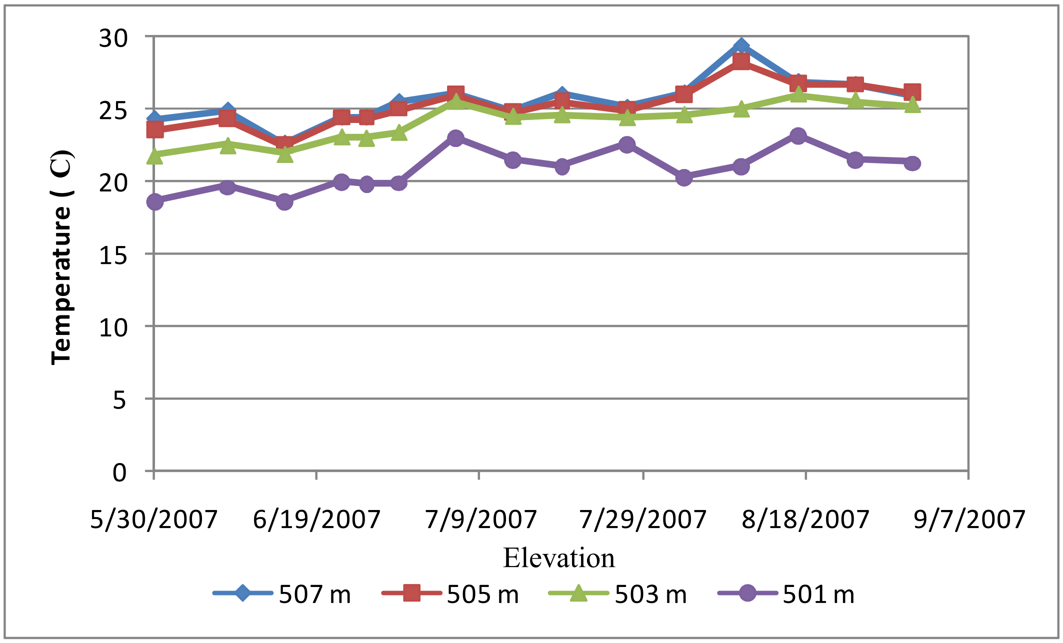

Figure 37 Temperature profiles during summer months of 2007

Temperature profiles for the summer of 2008 show the effects of circulation (Figure 38). For this experiment, the circulator was activated from July 28 – August 13. It was also activated from June 14 – July 9 by the Western Virginia Water Authority. This figure shows that within one to two weeks of continuous circulator activity, the reservoir becomes mixed in each case.

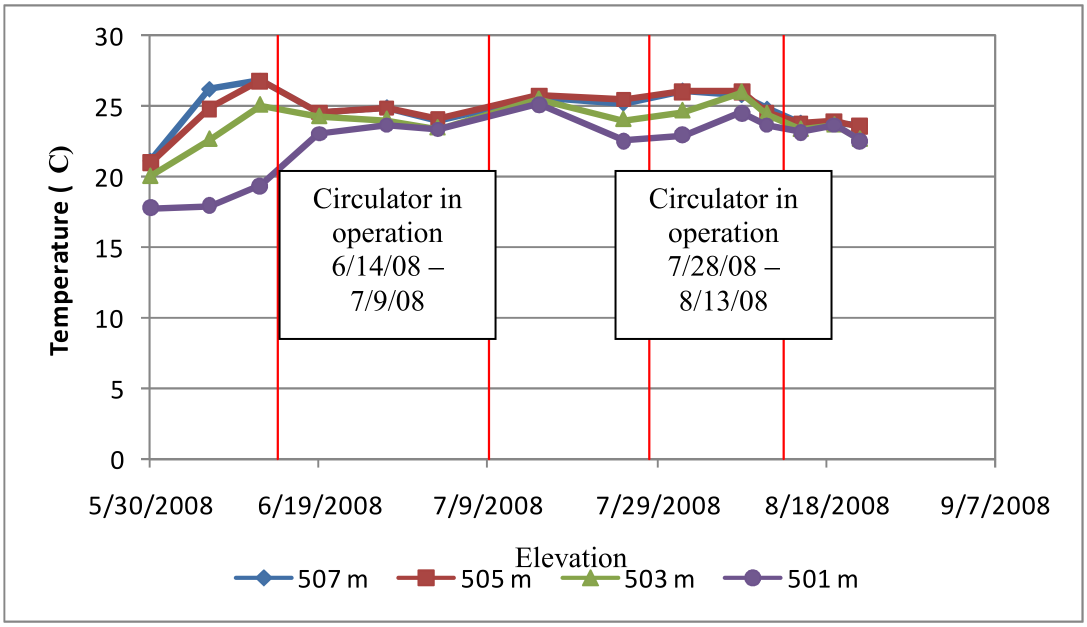

Figure 38 Temperature profiles during summer months of 2008 with circulation

Continuous temperature data available from deployed thermistors at a distance of 150 m from the circulator show a cooling trend after the circulator had been active for 11 days (Figure 39). These temperature readings are for elevations of 504.4 m and 506.8 m, and they show a leveling off of the cooling trend after the circulator was deactivated, with the warmer higher-elevation waters warming more quickly.

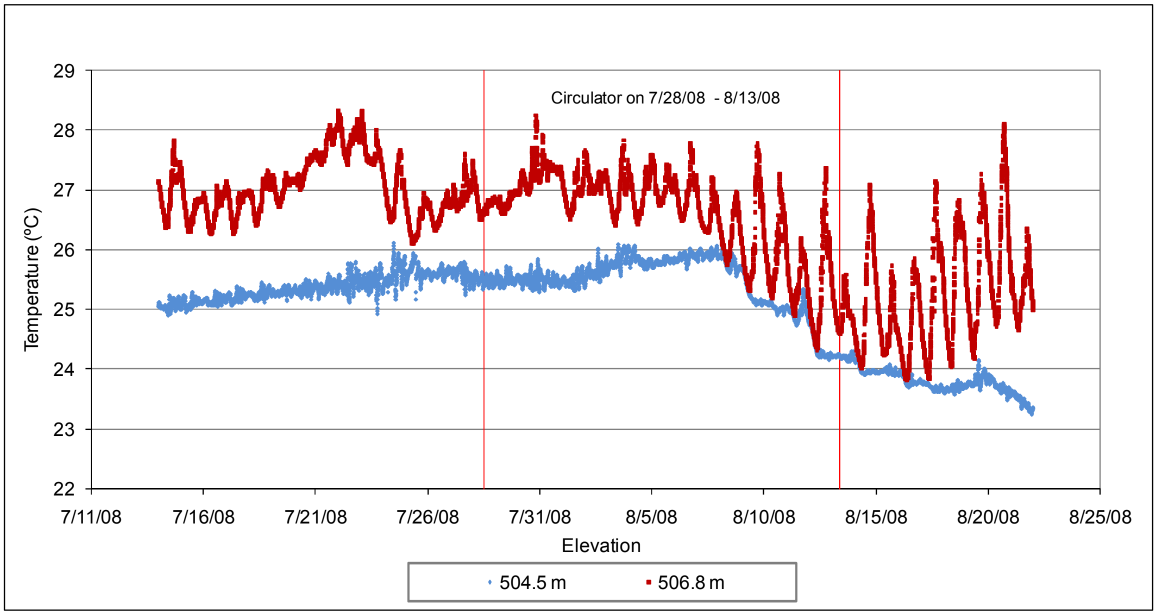

Figure 39 Continuous temperature data for two elevations 150 m from the circulator

Another indication that reservoir mixing was induced by the circulator is wind data that was collected and averaged over 10 minute intervals during the time of this experiment. All wind measurements both during the experiment and in the days before and after the experiment are given (Figure 40). The date with the highest wind speeds occurred on July 22, and stratification is still present within the reservoir in the days following this date (Figure 38). The wind data remained fairly constant through the time period of this experiment.

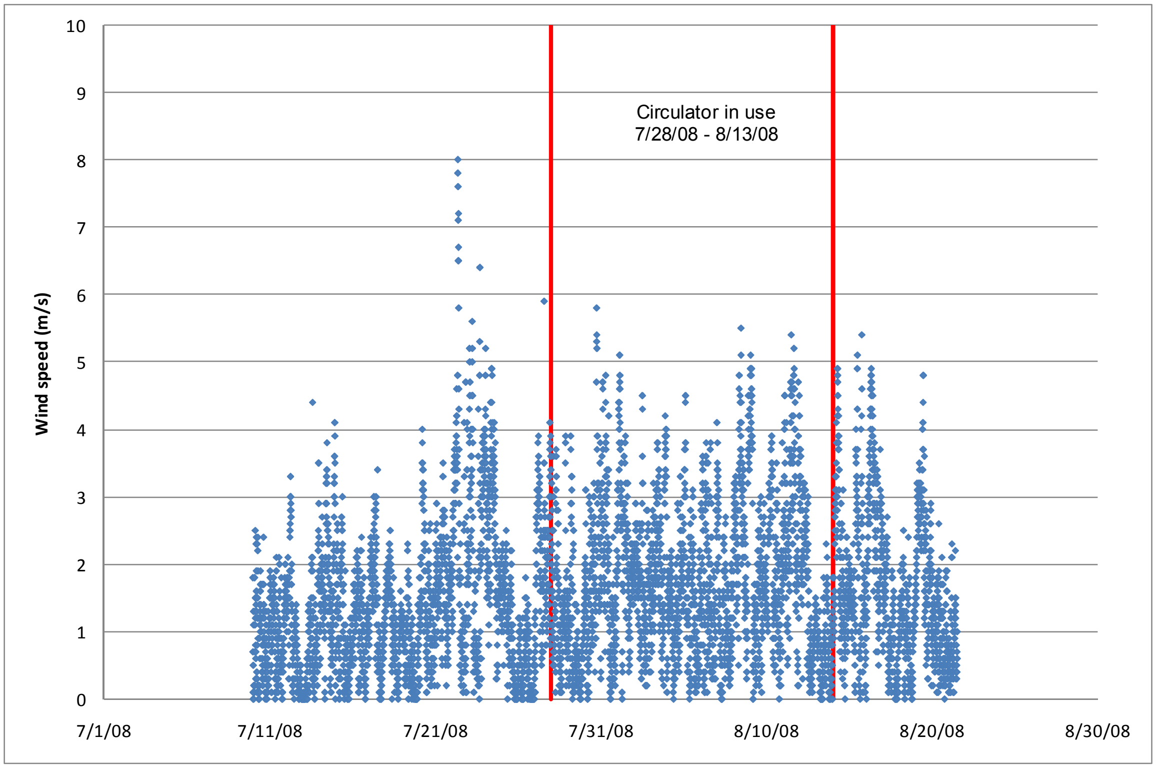

Figure 40 Wind speed in days surrounding circulator experiment

Temperature profiles for August 21, which was one week after the termination of circulation show that stratification is beginning to return to Falling Creek Reservoir (Figure 41), and the wind measurements for this and immediately previous dates is similar to the average wind speed on days during the experiment when stratification was disrupted. The overall conclusion from this data is that the wind at this reservoir is not enough to disrupt stratification, but combined with the mixing effects of the circulator, the stratification structure of this reservoir can be disrupted.

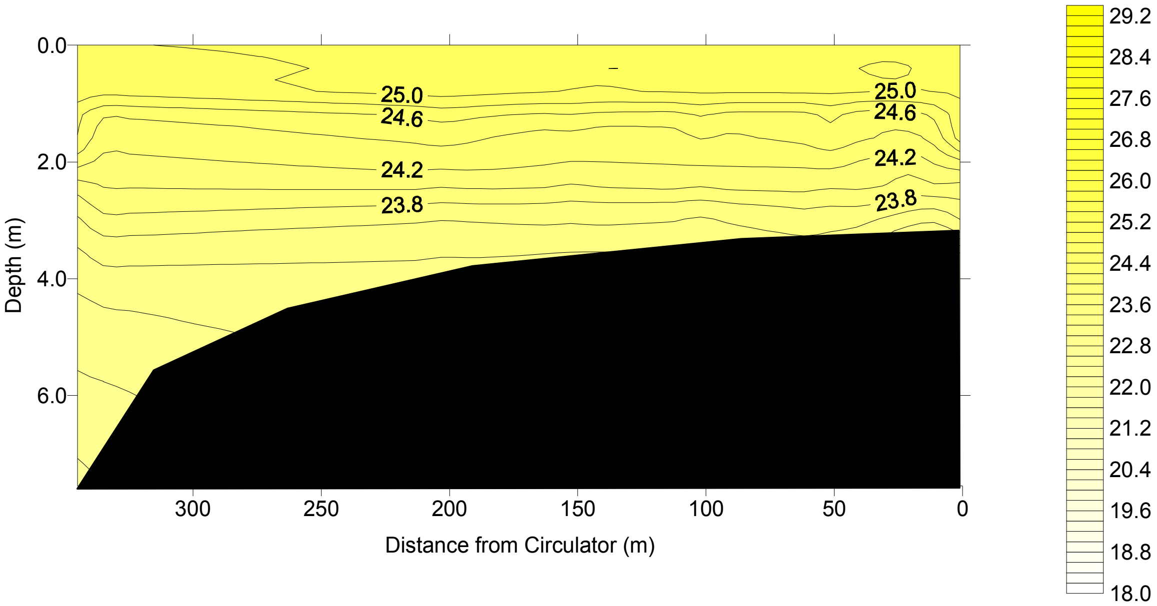

Figure 41 Complete temperature profile after circulator turned off for one week

9.0 CONCLUSIONS

The purpose of the mixing unit is to mix and deepen the epilimnion, which should help to control cyanobacteria growth by intermittently mixing the cells to depths of suboptimal light energy. This in turn should result in lowered rates of photosynthesis, and therefore, depressed growth rates. Observation of the temperature and dissolved oxygen profiles indicate that operation of the surface mixer, along with wind energy present at the reservoir, were enough to completely mix Falling Creek Reservoir. The circulator induced more mixing than intended. Falling Creek Reservoir is fairly shallow, with a large portion of the reservoir being less than six meters deep. This results in a more weakly stratified water body, which is more easily mixed. Mixing the entire reservoir has the potential to mix nutrients and organics, as well as iron and manganese, which are released during hypolimnetic anoxia, into the rest of the reservoir. This, however, is only a problem when the circulator has been activated after the onset of stratification during the summer months. Historically, the highest odor levels at Falling Creek Reservoir are recorded in water withdrawn from the deepest portions of the reservoir, and complete mixing would bring these high-odor waters to higher elevations, leading to an increased odor level in water sent to the treatment facility, thus defeating the original intent of the mixer. Therefore, reservoir stratification characteristics should be considered before activating a circulator.

Prior to destratification, the effects of the mixer reach further from the unit during the cooler hours of late evening through early morning. Temperature profiles show cooler water from the mixer reaching as far as about 80 m away from the unit before dropping back down within the reservoir. However, during afternoon hours, where increased solar intensity causes an increase in the temperature near the surface, and thus a decrease in the surface water density, water from the mixer travels much shorter distances before the higher density of the cooler water causes the water to drop back down to a zone of equal density. The unit was less effective at moving water away from the circulator during the afternoon compared to the cooler period of the day.

Overall, this specific surface mixing unit is strong enough to induce near complete mixing in Falling Creek Reservoir in about 2 weeks of operation. If the intent is to only mix and slightly deepen the epilimnion, precautions must be made in choosing a properly sized mixer so as not to induce complete reservoir mixing. Although the circulators is designed by the manufacturer to only mix the epilimnion, the stronger mixing that was induced during operation could expose cyanobacteria to increased light limitation because of complete reservoir mixing. Further investigation into the effect of complete mixing on photosynthetic yield could give a direct measurement of the effect of destratification on algal growth. Further study of a smaller unit at Falling Creek Reservoir or an equivalent unit on a deeper reservoir would give a clearer indication of the effectiveness of these circulators at controlling cyanobacteria growth.

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