Changes in Dissolved Oxygen, Ammonia, and Nitrate Levels in an Extended Aeration Wastewater Treatment Facility When Converting From Counter Current to Disc Diffuser Aeration

A Research Paper

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Abstract

In 2012, the Miller Avenue Wastewater Treatment Plant in Jackson, Tennessee converted their two basin aeration system from a counter current aeration system to a disc diffuser aeration system for operations and maintenance cost reduction. An earlier analysis predicted plant performance improvements would be realized after the conversion. An observational study from October of 2011 to January of 2013 analyzed dissolved oxygen, ammonia, and nitrate levels before, during, and after the conversion. Statistical analyses consisted of t-tests for the dissolved oxygen study. Analysis of variance was used for the ammonia and nitrate studies, and Tukey's honest significant difference test was used for mean separation. Both aeration system types as well as the number of basins in operation were taken into consideration. The study showed that dissolved oxygen levels at this location were significantly ($p < 0.001$) higher after conversion to the disc diffuser system. There was no significant difference in ammonia or nitrate levels between the two systems; however, differences existed between single and dual basin operation. Ammonia levels were significantly higher ($p < 0.05$) when operating only one basin compared to two basins of either system. Nitrate levels were significantly lower ($p < 0.05$) when operating one basin compared to two basins with the disc diffuser system. The results of this study could impact the standard operating procedure of the basins. A future study of total nitrogen removal is planned to compare single disc diffuser aeration and dual disc diffuser aeration.

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Chapter 1. Introduction

Wastewater treatment is the process of removing pollutants from wastewater using a combination of biological, physical, and chemical methods. The pollutants can be microorganisms, nutrients such as nitrogen and phosphorus, industrial and pharmaceutical chemicals, and inorganic substances such as sand. The wastewater treatment process disposes of three end products. Grit and trash are removed for disposal during pretreatment. Biosolids are the biological component of the wastewater solution and are separated at various steps in the treatment process. Lastly, treated effluent wastewater is discharged into a receiving stream.

The Miller Avenue Wastewater Treatment Plant in Jackson, Tennessee utilizes an extended aeration process to treat an average flow of 30.28 megaliters (8 million gallons) of wastewater per day. Pretreatment consists of three mechanical bar screens and two aerated channels for grease and grit removal. Following pretreatment, the wastewater is equally divided into two extended aeration basins. The basins discharge into four final clarifiers with a portion of the flow returning to each basin as activated sludge.

The pretreated wastewater and return activated sludge enter each basin via an anoxic zone. The anoxic zone consists of a non-aerated ring in the center of the inlet side of each basin. The mixture flows from the anoxic zone into the aerated portion of the basin before discharging into the final clarifiers. After clarification, waste activated sludge is sent to a gravity thickener for further treatment while the effluent wastewater is routed to an aerated chlorine contact chamber before discharging into the South Fork of the Forked Deer River.

The area of interest for this study is the aerated portion of each basin which has a 26.12 megaliter (6.9 million gallon) capacity. The original aeration design was the Schreiber Counter

Current Aeration System (Schreiber LLC, Trussville, AL), consisting of two rotating aeration bridges per basin (Figure 1). The inlet side of each basin consisted of a bridge equal in length to the diameter of the inlet side. The outlet side of each basin consisted of a half-bridge equal in length to the radius of the outlet side. Both bridges move across the entire surface of their respective sides to complete one circuit. The inlet bridges contained fine pore perforated membrane tube diffusers that extended from the end of the anoxic zone to the outer end of each bridge. In contrast, the outlet bridges were equipped with fine pore perforated membrane tube diffusers over their entire length. Each basin contained 2,452 tube diffusers equally divided between the inlet and outlet bridges.

Figure 1: The Schreiber Counter Current Aeration System featuring anoxic center rings, tandem bridges (left), and single bridges (right). (Cassandra Fuller, Jackson Energy Authority)

During the study period, the counter current system of rotating bridges, mixers, and tube diffusers was replaced with a disc diffuser system consisting of 228.6 mm (9- inch), perforated membrane discs (Sanitaire, Little Rock, AR). These discs are arranged along a grid of PVC air ducts covering the floor of each aeration basin (Figure 2). Each basin contains 17,952 fine pore perforated membrane discs.

Research Objectives

The Schreiber Counter Current Aeration System formerly in operation at the Miller Avenue Wastewater Treatment Plant was replaced with the fixed disc diffuser system after a thorough analysis predicted a substantial savings in operations and maintenance costs while providing significant engineering improvements. The purpose of this study was to determine if any changes in dissolved oxygen, ammonia, or nitrate levels occurred in the treatment plant as a result of this conversion. The study compared these operational metrics before, during, and after construction.

The two basin design offered the redundancy needed to complete the construction project. The ability to operate in single basin mode is also necessary when maintenance is required on one of the basins. Data collected during the construction phase was analyzed to understand how each system would operate in single basin mode. Data collected before and after the conversion was used to determine if differences existed between the two systems in dual basin mode.

The goal of this project was to answer the following questions.

1. Was there a difference in dissolved oxygen levels between the counter current aeration system and the disc diffuser aeration system operating in both single and dual basin modes?

2. When comparing counter current aeration and disc diffuser aeration in single and dual basin mode, was there a difference in ammonia levels?
3. Was there a difference in nitrate levels among dual counter current, single fixed disc diffuser, and dual fixed disc diffuser operation?

Figure 2: Construction of the fixed disc diffuser array. (Tony Fitts, Jackson Energy Authority)

Chapter 2. Literature Review

Overview of Wastewater Aeration

Wastewater treatment plants that utilize aeration seek to provide the aerobic bacteria inherent in wastewater with the oxygen necessary to oxidize carbonaceous and nitrogenous compounds (Kerri et al., 2006). Aeration basins that are continuously supplied with air are called extended aeration basins. Extended aeration basins require less operational control than intermittently aerated basins (Dedman, 1983). Extended aeration is used in conjunction with activated sludge in most instances. Activated sludge refers to a process that returns a portion of the previously aerated wastewater solution to the aeration basin with the influent wastewater. Counter current and disc diffuser aeration are two types of aeration systems used in extended aeration-activated sludge treatment.

Counter Current Aeration

The precursor to counter current aeration was the result of Dutch research conducted in the 1960s in an attempt to find affordable solutions to the extended aeration process (Dedman, 1983). The first counter current aeration system was developed by Dr. August Schreiber of Germany. The Schreiber Counter Current Aeration System added fine bubble diffusers to the original Dutch design (Dedman, 1984). By the 1980s, counter current aeration systems had become a common design for low-cost extended aeration (USEPA, 1983).

Counter current aeration basins are circular or oval in shape. This design allows for conservation of momentum. The ability to maintain velocity with little expenditure of force translates to reduced energy cost (Dedman, 1984). Air is supplied to the counter current aeration basin through fine bubble diffusers made of porous stone. The diffusers are encapsulated in tubes constructed of ceramic or plastic (USEPA, 1983). The diffusers are typically positioned 6 inches from the basin floor and attached to a rotating bridge. The bridge is allowed to pivot around an anchor in the center of the basin. An electric motor supplies power to rubber wheels for motion. The solids in the wastewater are re-suspended at each revolution (Dedman, 1983).

The predecessors to counter current aeration required more air to mix and suspend the activated sludge than was required for oxygen demand (Dedman, 1984). The rotating bridges of the counter current aeration system contribute to the mixing function of the aeration system. This reduces the number of diffusers necessary to achieve aeration. Lastly, the rotation of the bridge creates an inclined trajectory from the diffuser to the surface. The bubbles trail behind the bridge (Figure 3). The longer bubble path increases contact time with the wastewater solution. The term counter current refers to the opposite trajectory of the bubble path in relation to wastewater flow. (USEPA, 1983)

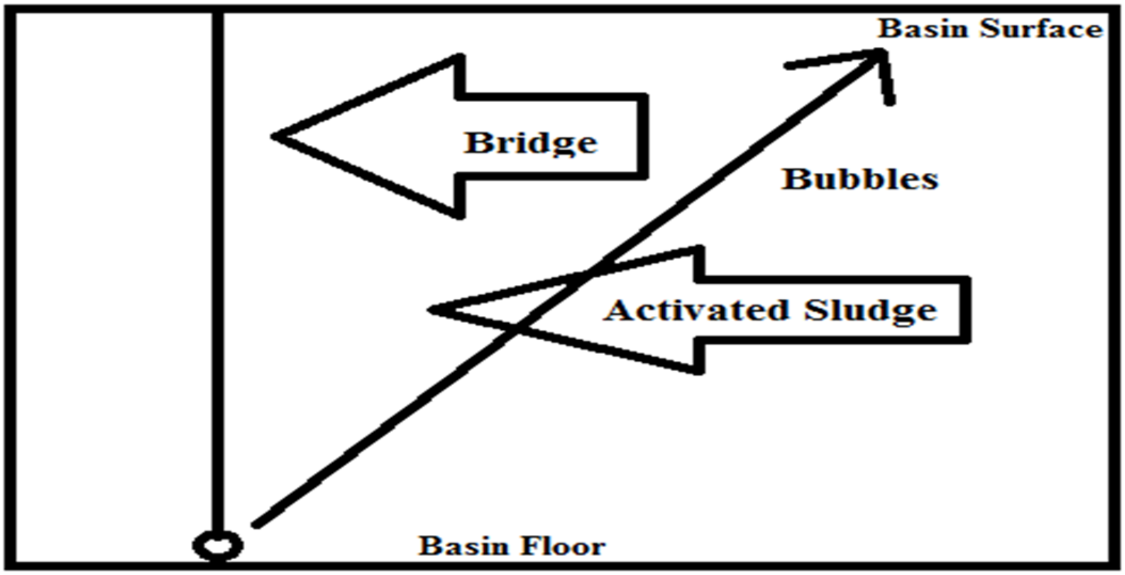

Figure 3: The bubble path from diffuser to aeration basin surface, in relation to the direction of the rotating bridge and activated sludge flow.

Disc Diffuser Aeration

Disc diffuser aeration is a type of fixed aeration. Fixed aeration differs from the counter current rotating bridge system in that the diffusers are mounted to the basin floor and remain stationary. Before the development of disc diffusers, fixed diffusers were much larger. As a result, voids between diffusers were greater. The counter current system was considered an improvement over the fixed diffuser system.

In contrast to the counter current system, the wastewater solution moves with the air bubbles of the fixed diffuser system (USEPA, 1983). The vertical flow created by the fixed diffuser forces the bubbles to rise to the surface much faster than in a counter current system (Dedman, 1983). The trajectory from the diffuser to the surface of the basin is also more direct. The result is a shorter distance traveled from the diffuser to the basin surface. The fixed diffuser lacks the force created by the rotating bridge (Dedman, 1984). As a result, the air bubbles are carried along with the wastewater flow instead of against it (Figure 4). These factors decrease the contact time between each bubble and the wastewater solution.

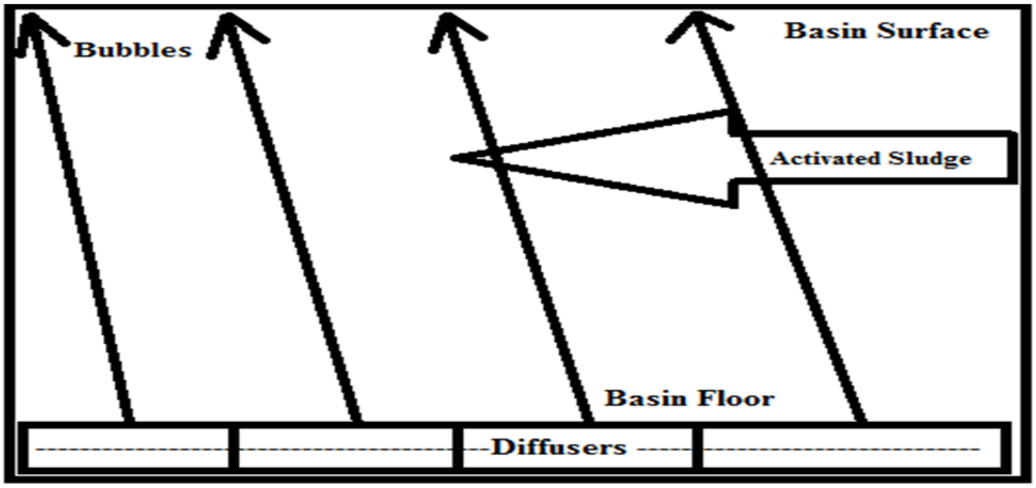

Figure 4: The bubble path from fixed diffusers to aeration basin surface in relation to activated sludge flow.

Disc diffuser aeration systems consist of small, flat disc attached to a network of grids on the aeration basin floor. Diffusion is achieved using a flexible membrane as opposed to porous stone (USEPA, 1999). The small discs allow for a closer spacing of discs within the grid on the basin floor. Void spaces are virtually eliminated. The grid arrangement is an improvement over older fixed aeration systems (Groves et al., 1992).

Dissolved Oxygen

Dissolved Oxygen (D.O.) is the level of molecular oxygen in the wastewater solution expressed as milligrams per liter (mg/l) (Kerri et al., 2006). The dissolved oxygen level is controlled by the amount of air added to the basin. The optimum dissolved oxygen level for an aeration basin is referred to as the dissolved oxygen set point. The dissolved oxygen set point for the aeration basins in this study is 2.0 mg/l. A previous study found a range of 1.5 to 1.7 mg/l to be the best set point for complete nitrification and denitrification to occur (Habermayer and Sanchez, 2005). Dissolved oxygen is an operational metric that is related to a design metric called oxygen transfer efficiency.

Comparisons of different aeration equipment are often performed on bench or pilot scale plants. The equipment is rated based on the oxygen transfer efficiency in clean water (ASCE, 2007). This measures dissolved oxygen in an off-gas analyzer from 0 mg/l to the point of near saturation and is used to gauge power consumption through nonlinear regression. Variability in oxygen transfer efficiency values in a full scale treatment facility have been demonstrated when off-gas analysis was performed at multiple sample points (Bellandi et al., 2011). Another study shows that the use of real-time analysis of off-gases can be used to improve plant operations (Leu et al. 2009). The horizontal flow created by the rotating bridge in a counter current system increases the oxygen transfer efficiency per diffuser by 40% over a fixed, vertical flow (Dedman, 1983). This assumes a similar array of diffusers. Disc diffuser arrays have a higher population density and produce more bubbles than previous designs (USEPA, 1999). Dissolved oxygen is the metric used by most treatment operations rather than oxygen transfer efficiency (Leu et al. 2009).

Ammonia

Ammonia (NH_3) is a nitrogenous compound that is oxidized in a process called nitrification. The nitrification of wastewater is necessary to remove or reduce the amount of nitrogen compounds in wastewater; these compounds act as environmental pollutants in the receiving stream. Nitrification occurs when nitrifying bacteria, *Nitrosomonas* spp. convert ammonia and other nitrogen compounds into nitrite (NO_2^-) and *Nitrobacter* spp. convert nitrite into nitrate (NO_3^-). The nitrification process uses about 2.04 kilograms (4.5 pounds) of molecular oxygen (O_2) for every kilogram of ammonia that is nitrified (Kerri et al. 2006). The nitrification process can occur at D.O. levels as low as 1 mg/l (Habermayer and Sanchez, 2005).

Aeration also reduces ammonia levels through physical means. Ammonia levels in wastewater can decrease through the process of desorption (Patoczka and Wilson, 1984). Desorption of ammonia is often referred to as stripping. Surface turbulence caused by mixing and aeration releases or strips the ammonia molecules from the wastewater solution into the atmosphere (Kerri et al. 2006). Disc diffuser arrays have been found to release more ammonia to the atmosphere as a result of increased turbulence on the surface of the wastewater solution (Monteith et al., 2005). The increased turbulence is a product of the volume of small bubbles produced in the densely arranged array.

Wastewater treatment plants discharge their treated effluent into a receiving stream. If ammonia is allowed to enter a stream it can be oxidized. Molecular oxygen in the receiving stream may drop to levels harmful to aquatic environments. Therefore, aeration of the wastewater is necessary to remove ammonia before the effluent is discharged.

Nitrate

The nitrification process converts ammonia into nitrate. After nitrification, denitrification must occur to remove nitrate from wastewater. Denitrification is an anaerobic process that reduces nitrate into molecular nitrogen (N_2) gas. Many types of anaerobic and facultative bacteria metabolize nitrate to obtain oxygen. However, this process does not occur under aerobic conditions (Kerri et al., 2006).

In wastewater treatment, denitrification occurs in an un-aerated section of the aeration basin called the anoxic zone. The anoxic zones for the basins in this study are located in the center of the inlet side of the basin. The anoxic zone receives the raw wastewater as well as the portion of activated sludge that was previously nitrified. After denitrification in the anoxic zone, the denitrified activated sludge and raw wastewater exits the anoxic zone into the aerated section of the basin. Aeration releases the denitrified nitrogen gas to the atmosphere. Denitrification is the rate-limiting step in total nitrogen removal from wastewater (Habermayer and Sanchez, 2005).

A relationship exists between dissolved oxygen, ammonia, and nitrate levels in wastewater. It is important to monitor each of these levels in the wastewater and make adjustments to the wastewater treatment process when necessary. Failure to do so can result in the excessive discharge of pollutants into the wastewater receiving stream.

Chapter 3. Materials and Methods

Dissolved Oxygen

Dissolved oxygen levels were measured using a Hach Sc200 dissolved oxygen probe (Hach Company, Loveland, CO) mounted in each basin. A certified treatment operator recorded dissolved oxygen levels daily in mg/l. Three sampling intervals and statistical analyses were conducted for dissolved oxygen due to the variations in sample size and seasonal bias (Table 1).

The dual basin analysis compared each aeration system under normal operating conditions. The data for this analysis were paired by selecting matching dates from different years representing the period before and after construction (Table 1). Matching dates were selected to remove seasonal bias. A paired t-test was used to compare dissolved oxygen means of the two systems.

The single basin analysis compared each aeration system under stress. It is common to operate under these conditions when maintenance is performed on one of the basins. The data for this analysis were collected during the construction phase. The data could not be paired for this test because no matching dates were available (Table 1). An F-test was used to determine if the variances could be assumed equal. Then an independent two sample t-test was used to compare dissolved oxygen means.

The side-by-side analysis offered the best comparison of the two systems as one basin was operating under each aeration strategy. The influent wastewater flow was equally divided between the two basins allowing the data to be paired and a paired t-test was used (Table 1).

Table 1: Dissolved oxygen sampling dates and statistical analysis methods

	Sampling Dates		
Aeration Type	**Start**	**End**	**Statistical Analyses**
Dual Counter Current	10/2/2010	1/25/2011	Paired t-test
Dual Disc Diffuser	10/2/2012	1/25/2013	
Single Counter Current	2/19/2011	8/9/2011	2-sample t-test
Single Disc Diffuser	8/29/2011	2/16/2012	
Side by Side Comparison	8/10/2011	8/28/2011	Paired t-test

Effluent Samples

Effluent samples for ammonia and nitrate were collected using a Hach Sigma 900 Max sampler (Hach Company, Loveland, CO) located at the discharge of the chlorine contact chamber. Each sample was a composite, based on effluent flow over a 24-hour period. The minimum number of grab samples per composite was twenty. The samples were tested by qualified lab personnel and results were reported in mg/l.

Ammonia

Ammonia was sampled approximately three times per week for 60 days during each study period (Table 2). Each treatment yielded 25 composite samples. The ammonia samples were tested in accordance with Standard Methods 4500-NH_3-D (AWWA, 2012). A completely randomized design was used for analysis. Four treatments were tested: dual counter current, single counter current, single disc diffuser, and dual disc diffuser.

Nitrate

The nitrate analysis consisted of four composite samples taken during the study period (Table 3). The nitrate samples were tested according to United States Environmental Protection Agency (USEPA) method 353.2 (USEPA, 1993). A completely randomized design with three treatments was used. The treatments included dual counter current, single disc diffuser and dual disc diffuser. No data were collected for single counter current operation.

Statistical Analyses

All statistical analyses were conducted in Microsoft Excel 2010 (Microsoft, Redmond, WA). T-tests were conducted using the data analysis toolpak in Excel. Analysis of variance (ANOVA) and Tukey's honest significant difference test (Tukey's HSD) were chosen for the ammonia and nitrate datasets using a completely randomized design. Mean separation in Excel was achieved using DSAASTAT (University of Perugia, Perugia, Italy), a statistical analysis macro.

Table 2: Ammonia study period for each aeration treatment

	Study Period	
Aeration Type	**Start**	**End**
Dual Counter Current	5/25/2010	7/23/2010
Single Counter Current	5/25/2011	7/23/2011
Single Disc Diffuser	8/29/2011	10/27/2011
Dual Disc Diffuser	5/25/2012	7/23/2012

Table 3: Nitrate study period for each aeration treatment

	Study Period	
Aeration Type	**Start**	**End**
Dual Counter Current	2/4/2010	10/7/2010
Single Disc Diffuser	8/29/2011	2/16/2012
Dual Disc Diffuser	10/16/2010	1/2/2013

Chapter 4. Results

Effects of Aeration System on Dissolved Oxygen

The dual basin study was conducted to compare the dissolved oxygen levels between each aeration system under normal operating conditions. Data was collected on matching dates of different years to remove seasonal bias. It was impossible to remove the effect of differing years from the analysis. During the study period, the dual disc diffuser aeration system had a mean dissolved oxygen of 3.98 mg/l which was significantly ($p < 0.0001$) higher than the dual counter current aeration system mean dissolved oxygen of 1.52 mg/l. The recorded values were greater than or equal to the 2 mg/l dissolved oxygen set point 85.78% of the time for the dual disc diffuser aeration system compared to 33.62% for the dual counter current aeration system (Figure 5).

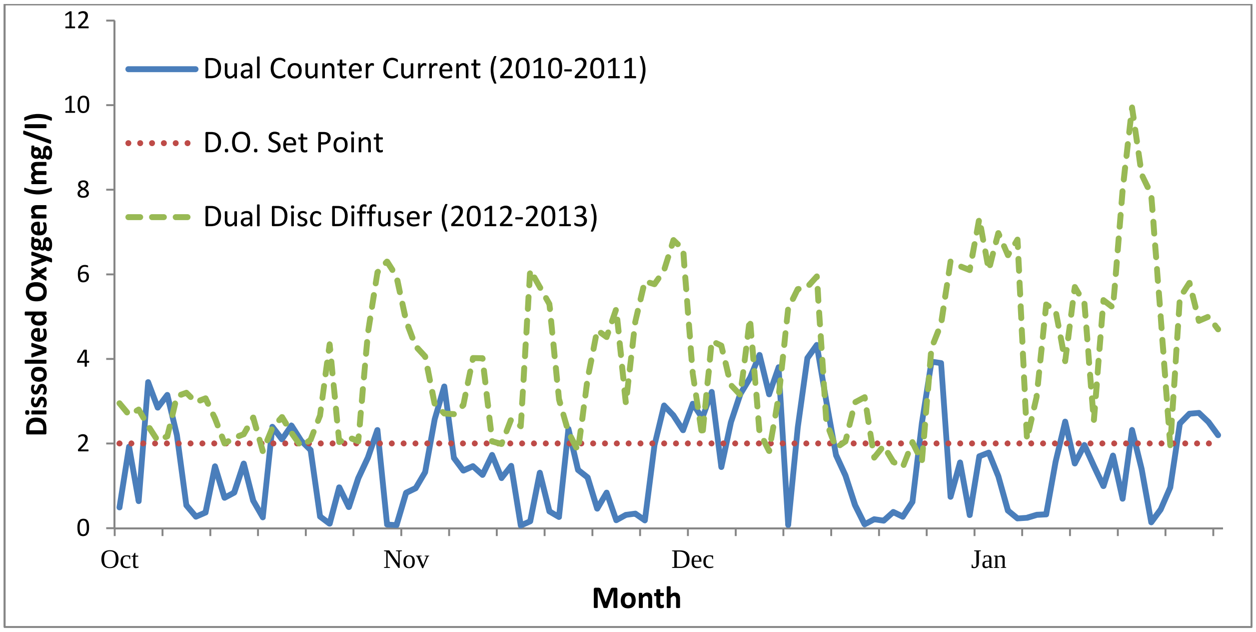

Figure 5: Dissolved oxygen levels for each dual aeration system in relation to the dissolved oxygen set point.

The construction process required that each basin operate singly while the other basin was converted to the new aeration system. This condition will continue to occur when one of the basins goes offline for maintenance or repair. There was no way to meaningfully pair the data, so an independent t-test was used. The F-test for variances indicated that variances were significantly ($P< 0.0001$) different, so the t-test assuming unequal variances was used. During the study period, the single disc diffuser aeration system had a mean dissolved oxygen level of 2.13 mg/l which was significantly ($p < 0.0001$) higher than the mean dissolved oxygen level of 0.52 mg/l for the single counter current aeration system. The recorded values were greater than or equal to the 2 mg/l dissolved oxygen set point 50.0% of the time for the single disc diffuser aeration system (Figure 6a) compared to 4.07% for the single counter current aeration system (Figure 6b).

During the side-by-side comparison, basin one was operated using the counter current aeration system. Basin two was operated using the disc diffuser aeration system. The flow was equally divided between the two systems. For the study period the disc diffuser aeration system in basin two had a mean dissolved oxygen level of 3.55 mg/l which was significantly ($p < 0.01$) higher than the mean dissolved oxygen level of 1.25 mg/l for the counter current aeration system in basin one. The recorded values were greater than or equal to the 2 mg/l dissolved oxygen set point 52.63% of the time for the disc diffuser aeration system compared to 26.32% for the counter current aeration system (Figure 7). There is a considerable drop in dissolved oxygen levels for the disc diffuser system during the study period. It is possible that the system contractor modified the operational settings in response to the dissolved oxygen levels being much higher than the set point of 2 mg/l.

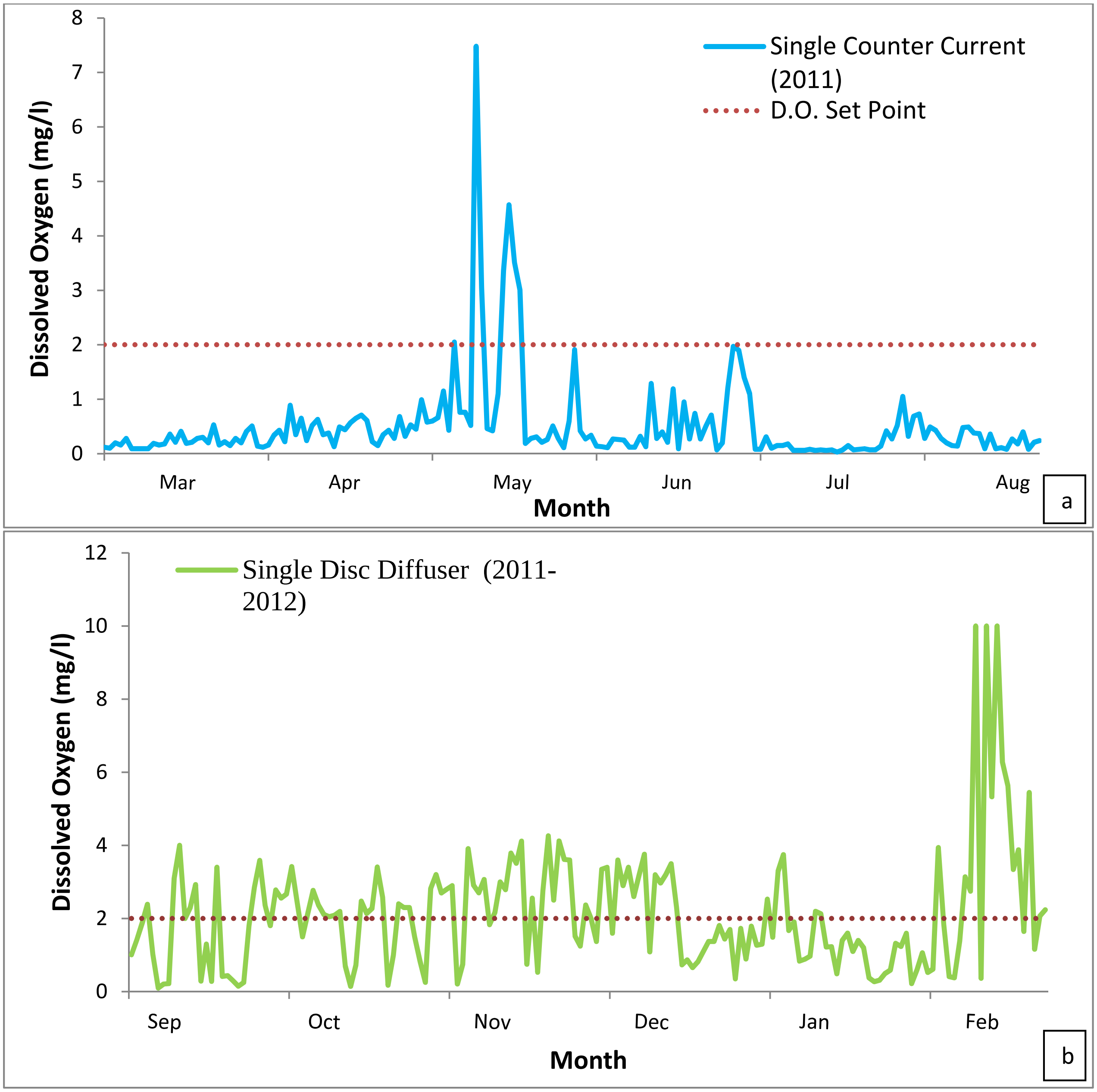

Figure 6: Dissolved oxygen levels (a) the disc diffuser single aeration system and (b) the counter current single aeration system, in relation to the dissolved oxygen set point.

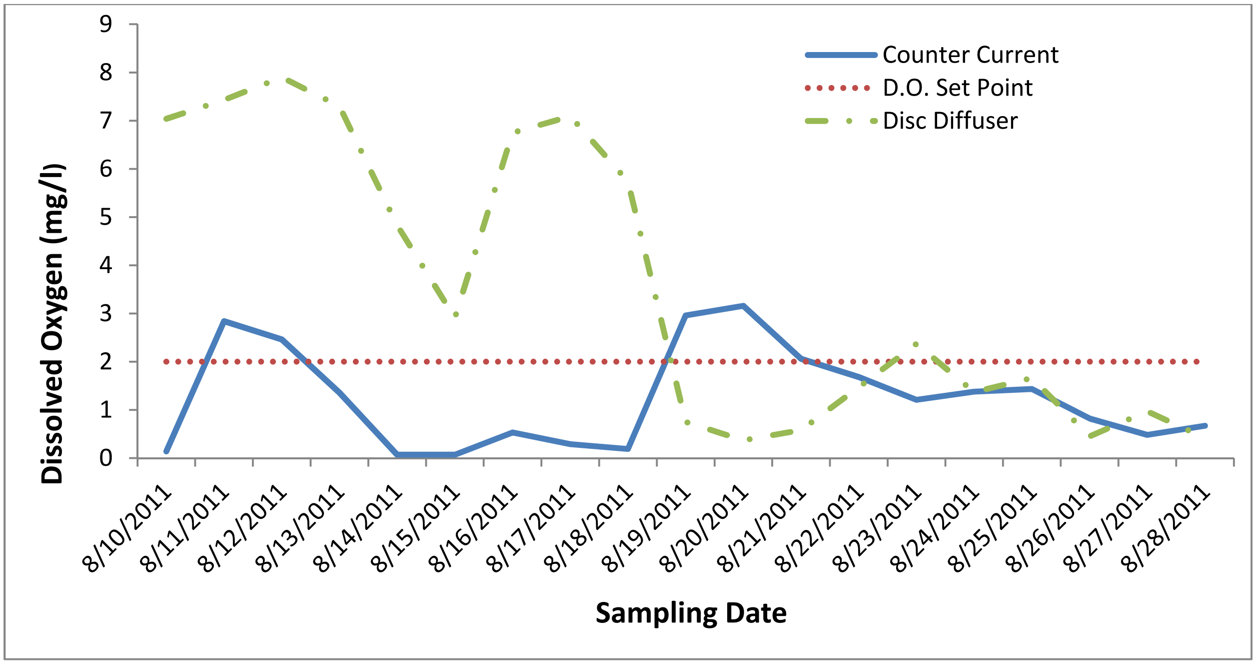

Figure 7: Dissolved oxygen levels for each aeration system operated side by side, in relation to the dissolved oxygen set point.

Effects of Aeration System on Ammonia

There was a significant difference ($p<0.0001$) in ammonia levels among the treatments in this study (Table A.5). However, there was no significant difference between counter current aeration and disc diffuser aeration. The differences in ammonia levels existed between single and dual aeration for both systems. The mean ammonia levels for both dual aeration systems were significantly lower than the means of both single aeration systems (Table 4).

Effects of Aeration System on Nitrate

There was a significant difference (P=0.0332) in nitrate levels among the treatments in this study (Table A.6). However, there was no significant difference between the dual counter current system and either the single or dual disc diffuser system. The single disc diffuser had significantly lower nitrate levels than the dual disc diffuser system (Table 5.)

Table 4: Mean ammonia levels for counter current aeration and disc diffuser aeration operated in single and dual mode.

Treatment	Mean
Single Disc Diffuser	1.16a
Single Counter Current	0.83a
Dual Disc Diffuser	0.16b
Dual Counter Current	0.16b

[t] Means followed by the same letter are not significantly different ($P<0.05$) according to Tukey's honest significant difference test. (n=25)

Table 5: Mean nitrate levels for dual counter current aeration, single disc diffuser aeration, and dual disc diffuser aeration.

Treatment	Mean
Dual Disc Diffuser	9.00a
Dual Counter Current	4.33ab
Single Disc Diffuser	1.68b

[t] Means followed by the same letter are not significantly different ($P<0.05$) according to Tukey's honest significant difference test. (n=4)

Chapter 5. Discussion

The disc diffuser aeration system produced significantly higher dissolved oxygen levels than the counter current aeration system in all three tests. This confirms the predictions made about engineering improvements in the pre-construction analysis. However, this increase in dissolved oxygen did not translate into enhanced ammonia removal. The evidence suggested that the counter current aeration system was able to remove ammonia as designed and as well as the disc diffuser system. This study could not differentiate between volatilization or nitrification in regards to ammonia removal.

The results of the nitrate study were inconclusive. Nitrate levels were significantly higher in the dual disc diffuser system than in the single disc diffuser system. Since ammonia levels were not significantly different, a likely culprit was the increased nitrification of ammonium (NH_4^+) and organic nitrogen due to the increased availability of dissolved oxygen. It is also possible that the higher dissolved oxygen level was carried over into the anoxic zone with the activated sludge. This could reduce denitrification of nitrate regardless of whether the nitrification rate increased. The lack of significance in nitrate levels between the dual counter current system and the other treatments was unexpected.

Chapter 6. Conclusion

The disc diffuser system increased dissolved oxygen levels over the counter current system in all tests performed at the Miller Avenue Wastewater Treatment Plant. Additional study sites are needed to confirm these results for other treatment plants with differing wastewaters. A more in-depth side by side analysis of the two systems would be the most beneficial scenario.

The aeration systems in this study were equally effective at ammonia removal. However, the wastewater in the disc diffuser system contained higher nitrate levels in dual operation than in single operation. A future study has been planned to compare total nitrogen removal between single disc diffuser operation and dual disc diffuser operation. The outcome of the study might dictate whether the plant is operated with a single or dual basin. Increased anoxic zones are also a possibility.

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Appendix

Table A.1: Results of paired t-test comparing means of dual counter current aeration and dual disc diffuser aeration.

t-Test: Paired Two Sample for Means

	Treatment 1	*Treatment 2*
Mean	1.524	3.979
Variance	1.675	3.497
Observations	232	232
Pearson Correlation	-0.020	
Hypothesized Mean Difference	0	
df	231	
t Stat	-16.282	
P(T<=t) one-tail	1.63E-40	
t Critical one-tail	2.343	
P(T<=t) two-tail	3.25E-40	
t Critical two-tail	2.597	

Table A. 2: Results of F-test comparing variances of single counter current aeration and single disc diffuser aeration.

F-Test Two-Sample for Variances

	Treatment 1	*Treatment 2*
Mean	0.516	2.125
Variance	0.704	2.648
Observations	172	172
df	171	171
F	0.266	
P(F<=f) one-tail	0	
F Critical one-tail	0.777	

Table A.3: Results of t-test comparing means of single counter current aeration and single disc diffuser aeration.

t-Test: Two-Sample Assuming Unequal Variances

	Treatment 1	*Treatment 2*
Mean	0.516	2.125
Variance	0.704	2.648
Observations	172	172
Hypothesized Mean Difference	0	
df	256	
t Stat	-11.533	
P(T<=t) one-tail	2.33E-25	
t Critical one-tail	2.341	
P(T<=t) two-tail	4.65E-25	
t Critical two-tail	2.595	

Table A.4: Results of paired t-test comparing means of counter current aeration and disc diffuser aeration operated side by side.

t-Test: Paired Two Sample for Means

	Treatment 1	*Treatment 2*
Mean	1.2526	3.5474
Variance	1.0646	8.7064
Observations	19	19
Pearson Correlation	-0.190	
Hypothesized Mean Difference	0	
df	18	
t Stat	-3.0258	
P(T<=t) one-tail	0.0036	
t Critical one-tail	2.5524	
P(T<=t) two-tail	0.0073	
t Critical two-tail	2.8784	

Table A.5: Results of ANOVA comparing ammonia levels for counter current aeration and disc diffuser aeration operated in single and dual basin mode.

ANOVA

Source of Variation	*df*	*SS*	*MS*	*F*	*Pr>F*	*F crit*
Treatment	3	18.93	6.31	9.607	1.32E-05	2.699
Error	96	63.07	0.66			
Total	99	82.01				

Table A.6: Results of ANOVA comparing nitrate levels for dual counter current aeration, single disc diffuser aeration and dual disc diffuser aeration.

ANOVA

					Pr>F	
Source of Variation	*df*	*SS*	*MS*	*F*	*P-value*	*F crit*
Treatment	2	109.70	54.85	5.090	0.0332	4.256
Error	9	96.98	10.78			
Total	11	206.69				