Modeling Aeration Performance for Energy Reduction

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ABSTRACT

The Boulder Water Resource Recovery Facility (WRRF) is making a concerted effort to save energy. The plant is located at high altitude where the oxygen saturation concentration and hence oxygen transfer are relatively low. This results in high airflow rates and increased blower power demand. The aeration system accounts for 35 to 50% of the plant's electricity demand. Reducing aeration is therefore a key way to save energy.

A BioWin model of the Boulder WRRF was calibrated to performance data collected over six months. The model accurately predicted plant performance. A linear correlation between total blower power draw and airflow rate was input to BioWin, along with the electricity rate schedule imposed by Xcel Energy. The model calculated the power and electricity cost associated with aeration over the calibration period. The model was then used to investigate the treatment performance implications and energy savings of various aeration reduction strategies.

KEYWORDS

Energy savings, blower power, BioWin modeling, aeration cost, post-anaerobic digester performance

INTRODUCTION & BACKGROUND

The Boulder WRRF in the city of Boulder, Colorado, treats an average flow of 56.8 ML/d (15 mgd) in a 4-Stage Bardenpho biological nitrogen removal system. The plant was modelled in BioWin version 6.0 (EnviroSim, Canada). The layout of the overall plant is shown in Figure 1.

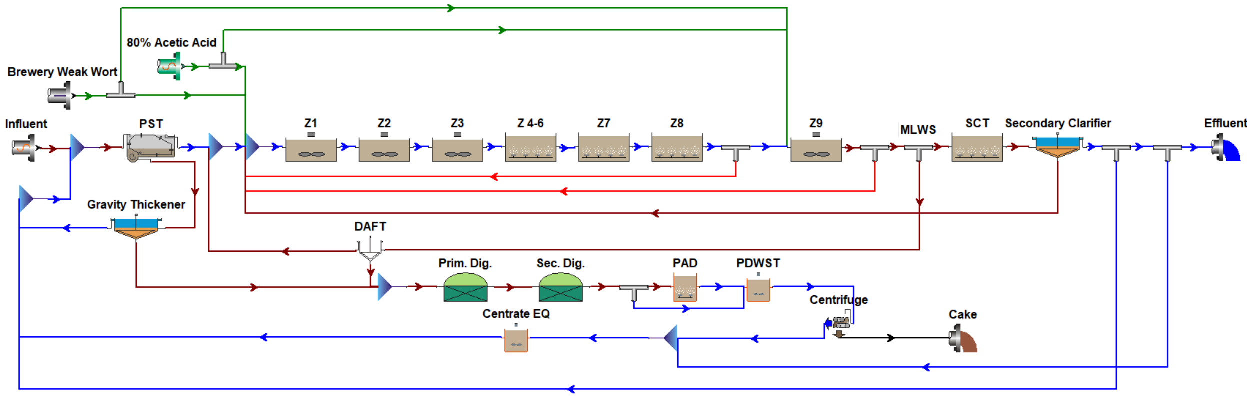

Figure 1 Overall BioWin Model Layout for the Boulder WRRF.

The liquid train includes a secondary anoxic reactor (Z9) followed by a re-aeration reactor (solids contact tank, SCT). The purpose of the aerated SCT is to prevent sludge gassing in the downstream secondary clarifiers. The solids retention time (SRT) in the liquid train is volumetrically controlled by adjusting the waste flow rate from the Mixed Liquor Waste Splitter (MLWS) to achieve a target aerobic SRT. The primary sludge and waste activated sludge (WAS) are concentrated in respective gravity thickeners and dissolved air flotation thickeners (DAFT) and then combined in two mesophilic anaerobic digesters in series. A portion of the digested sludge is treated in a post-anaerobic digester (PAD) where the ammonia released during digestion is simultaneously nitrified and denitrified (SND). This reduces the mass of TN in the centrate that is returned to the liquid train upstream of the primary settlers.

The raw influent has a low TKN/COD ratio (*i.e.* 0.07 mg N / mg COD) which is favourable for biological nitrogen removal. However, the returned centrate increases the TN load on the liquid train by approximately 10%. The Boulder WRRF receives an intermittent stream of brewery weak wort which provides some additional carbon for improved denitrification. The plant can also dose acetic acid into the anoxic zones. This dosing is paced to the measured nitrate concentration in the secondary anoxic reactor (Z9).

Over the past five years, the Boulder WRRF has been making a concerted effort to monitor energy consumption and reduce energy costs. The facility has an on-site solar photovoltaic system and a cogeneration system that can use digester biogas; these systems can respectively supplement 20-25% and 15-20% of the plant's annual power needs. The remaining energy requirement is purchased from Xcel Energy. The Boulder WRRF is currently conducting an energy audit to investigate ways to save energy. The aeration system accounts for 35 to 50% of the total electricity requirement of the facility. The Boulder WRRF is located at high altitude (5328 ft above sea level) where the blower inlet pressure, oxygen saturation concentration and hence oxygen transfer are relatively low compared to plants situated near sea level. This results in high discharge airflow rates and hence elevated blower power demand. Therefore, reducing process aeration is a key way to save energy at the plant.

In this study, a BioWin model of the Boulder WRRF was calibrated to performance data collected over six months of operation from August 1st, 2017 to January 31st, 2018. The aeration system was accurately simulated by inputting site-specific diffuser parameters, blower parameters and operating conditions (relative humidity, surface pressure, ambient air and liquid temperatures, *etc*). A measured linear correlation between blower power draw and airflow rate was input to the model, along with the electricity fee structure imposed by Xcel Energy. The model was used to (1) calculate the power consumption and electricity cost associated with aeration over the selected operating period and (2) investigate the process performance implications and quantify the energy savings of four different aeration reduction strategies. The aeration power and cost associated with the calibrated model served as the baseline for comparing the four different aeration-saving scenarios. The objective of this paper is to demonstrate the power of modeling as a plant management tool for investigating energy reduction strategies.

METHODOLOGY

The BioWin model of the Boulder WRRF was calibrated according to the procedure described by Wilson and Dold (1998) and WERF (2003). The selected period of operating data was August 1st, 2017 to January 31st, 2018.

The first step of the model calibration was to analyse the plant influent data. Certain ratios were calculated and compared to typical ranges for raw wastewater, as shown in Table 1. The average influent TKN/COD ratio is 0.07 mg N / mg COD, which is lower than the typical ratio of 0.10 mg N / mg COD for raw municipal wastewater. This low influent TKN/COD ratio is favourable for biological nitrogen removal.

Table 1 Measured Raw Influent Parameters and Selected Ratios for the Period August 1st, 2017 to January 31st, 2018.

Parameter	Average	Typical Range
Flow (mgd)	12.1	-
BOD (mg/L)	279	-
COD (mg/L)	576	-
TSS (mg/L)	222	-
VSS (mg/L)	216	-
TKN (mg/L)	40.2	-
NH3 (mgN/L)	25.3	-
TP (mgP/L)	5.2	-
TSS/COD	0.41	0.35 – 0.60
COD/BOD	2.0	1.90 – 2.20
TKN/COD	0.07	0.07 – 0.12
TP/COD	0.01	0.01 – 0.03

Wastewater characteristics have a very significant impact on system performance, particularly for nutrient removal systems. A set of wastewater fractions was derived from the measured influent data to be applied in the simulation analysis. Table 2 summarizes the key wastewater fractions. The ratio of influent particulate unbiodegradable COD to total COD (F_{UP}) and the ratios of particulate substrate and inert COD:VSS ($F_{CV,XS}$ and $F_{CV,XI}$) were initially estimated based on the measured influent data and then later refined through model calibration. Most of the fractions fall within ranges typically observed at North American wastewater treatment plants with the exception of the $F_{CV,XS}$ and $F_{CV,XI}$ ratios which are higher than typical. In general, the data review did not reveal any significant anomalies that would preclude modeling the Boulder WRRF.

Table 2 Key Wastewater Ratios for the Period August 1st, 2017 to January 31st, 2018.

Parameter	**Average**	**Typical Range**
$\mathbf{f_{BS}}$ Fraction of total influent COD that is soluble readily biodegradable	0.24	0.05 – 0.25
$\mathbf{f_{US}}$ Fraction of total influent COD that is soluble unbiodegradable	0.05	0.04 – 0.10
$\mathbf{f_{UP}}$ Fraction of total influent COD that is particulate unbiodegradable	0.13	0.07 – 0.22
$\mathbf{f_{NA}}$ Fraction of influent TKN that is ammonia	0.64	0.50 – 0.75
$\mathbf{f_{PO4}}$ Fraction of influent TP that is soluble phosphate	0.48	0.4 – 0.6
$\mathbf{f_{CV,XS}}$ Particulate biodegradable COD/VSS ratio (mg COD / mg VSS)	1.86	1.4 – 1.6
$\mathbf{f_{CV,XI}}$ Particulate inert COD/VSS ratio (mg COD / mg VSS)	1.84	1.4 – 1.6

Figure 2 highlights the requirements for setting up a simulation of a wastewater treatment process. Key information was gathered on the inputs to the process, the process configuration, and the process operating conditions. The recorded average daily flow rates were input to the various splitters and solids separation tanks in the model. The Boulder WRRF model was simulated over the calibration period and the predicted data was compared to the observed plant performance. A number of simulation runs were performed, iteratively adjusting one parameter at a time (*e.g.* the estimated influent F_{UP}, $F_{CV,XS}$ and $F_{CV,XI}$ fractions, the solids capture across the primary and secondary settling tanks, gravity thickener and DAFT, *etc.*) to achieve good correlation between the overall trend of predicted and observed values over the calibration period. Particular attention was given to matching the aerated SRT and solids concentrations in the liquid train and recycle streams to respective measured values.

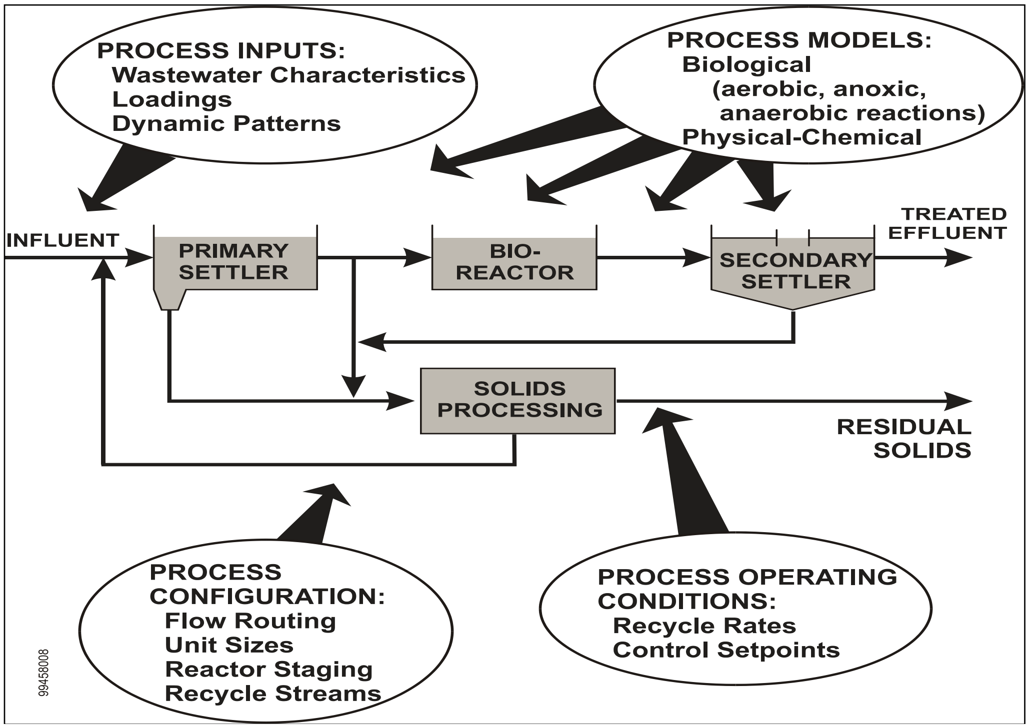

Figure 2 Requirements for Wastewater Treatment Process Simulation (after Wilson and Dold, 1998).

The plant uses fine bubble aeration in the liquid train and coarse bubble aeration in the PAD. The total airflow requirement of the liquid train and PAD is provided by two blowers; a single blower that operates continuously, and a second blower that provides additional airflow when the demand exceeds approximately 11,000 SCFM (18,690 m^3/h). A third standby blower is available for redundancy. Different types of disc diffusers are installed in each aerated zone. In the BioWin model, appropriate diffuser parameters were selected by comparing model-predicted plots of standard oxygen transfer efficiency (SOTE) per unit tank depth versus airflow rate per diffuser to manufacturer data. Additional required aeration model information such as the diffuser density and measured alpha factor was input to each aerated reactor in the model. The hourly measured dissolved oxygen (DO) concentration was input to each aerated zone in the liquid train and the model-predicted airflow rates in each zone were compared to recorded data over the calibration period. Note that in the airflow calculation, transfer of DO in recycle streams and carryover of DO from aerobic to anoxic zones was considered.

The PAD reactor is operated at a low DO concentration (*i.e.* less than 0.2 mgO_2/L) to achieve simultaneous nitrification-denitrification (SND). Although the DO concentration is very low, the airflow rates delivered to the PAD are relatively high because the oxygen transfer efficiency is very poor. This low oxygen transfer is due to (a) the coarse bubble aeration system which is less efficient than the fine bubble aeration applied in the liquid train (b) the high solids concentration of approximately 2.2%, which results in a low alpha factor, and (c) the lower DO saturation concentration associated with the high liquid temperature. The PAD receives heated sludge from the mesophilic digester; the average liquid temperature over the calibration period was 34.0°C. The measured average daily liquid temperature in the PAD was input to the model. The recorded hourly airflow rate was input to the PAD reactor and the model-predicted DO concentrations were compared to recorded data over the calibration period. The alpha factor was iteratively adjusted (to 0.14) to bring the predicted DO concentrations in line with the measured levels.

Airflow data and the associated blower power draw were obtained from the Boulder WRRF. The increase in power demand with airflow is essentially linear over the range of airflows observed for the operation of one and two blowers. This enabled a linear regression to be performed to obtain a relationship between power demand and airflow. The data and regression equation are shown in Figure 3. The linear regression parameters shown in Figure 3 were input to BioWin to translate the simulated airflows to an associated power demand. This conversion calculation takes into consideration site-specific conditions such as surface pressure, blower intake filter pressure drop, and the recorded ambient air temperature and humidity. The average daily air temperature and humidity measured on site over the selected operation period were input to BioWin.

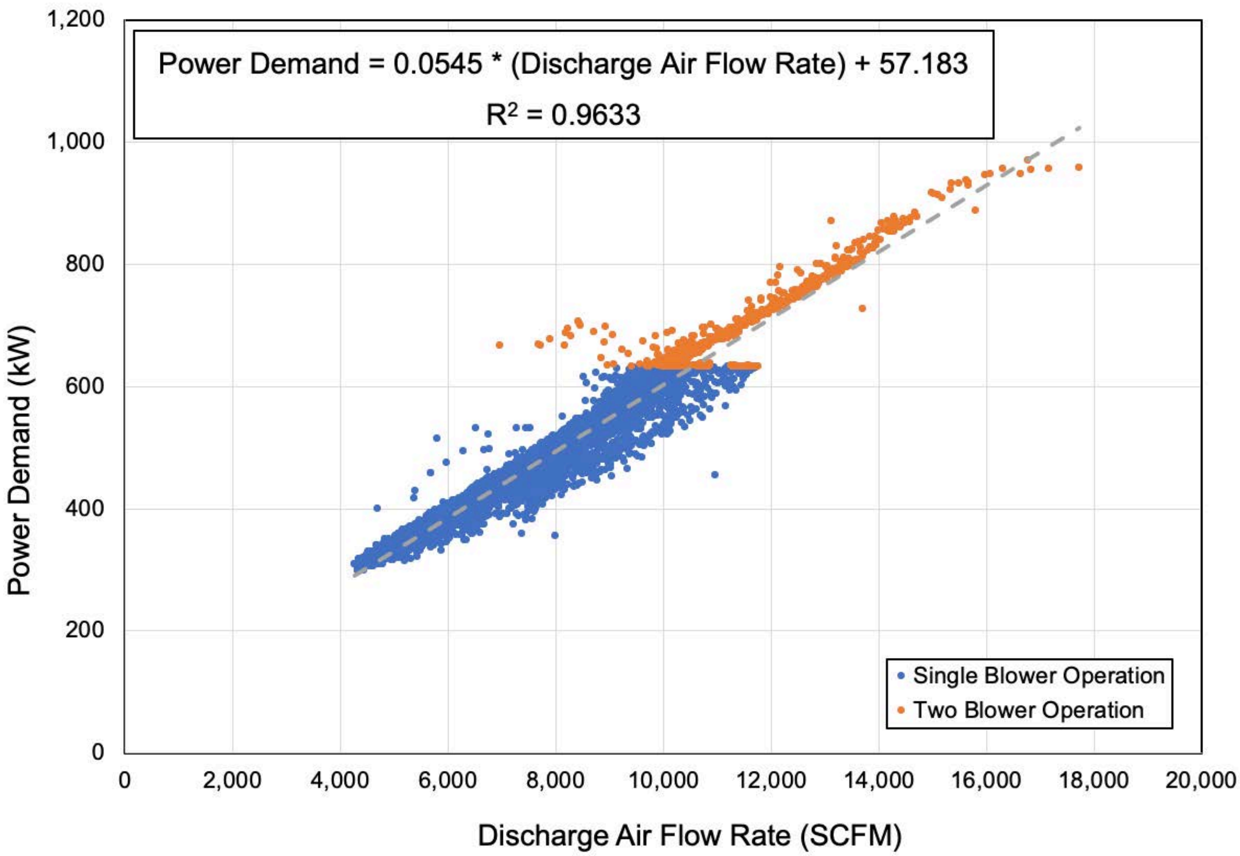

Figure 3 Linear Relationship between Power Demand and Discharge Airflow Rate for the Boulder WRRF.

The Boulder WRRF is subject to electricity rates that vary according to time-of-day and season, as shown in Figure 4. The on-peak period runs from 9:00 am until 9:00pm and the off-peak period runs from 9:00pm until 9:00am (there is no mid-peak period). The on-peak and off-peak periods and rates are the same every day of the year (*i.e.* weekdays, weekends, summer and winter). However, the peak demand charge is USD $21.50 / kW in summer whereas it is USD $16.79 / kW in winter. Summer begins June 1st and winter begins October 1st. The service charge is USD $322 per month. The electricity monthly subtotal is also subject to a 2.12% adjustment fee. The electricity fee structure was directly input to BioWin for the period from August 1st, 2017 to January 31st, 2018. The Boulder WRRF model was used to track the electricity costs associated with aeration over the 6-month operation period.

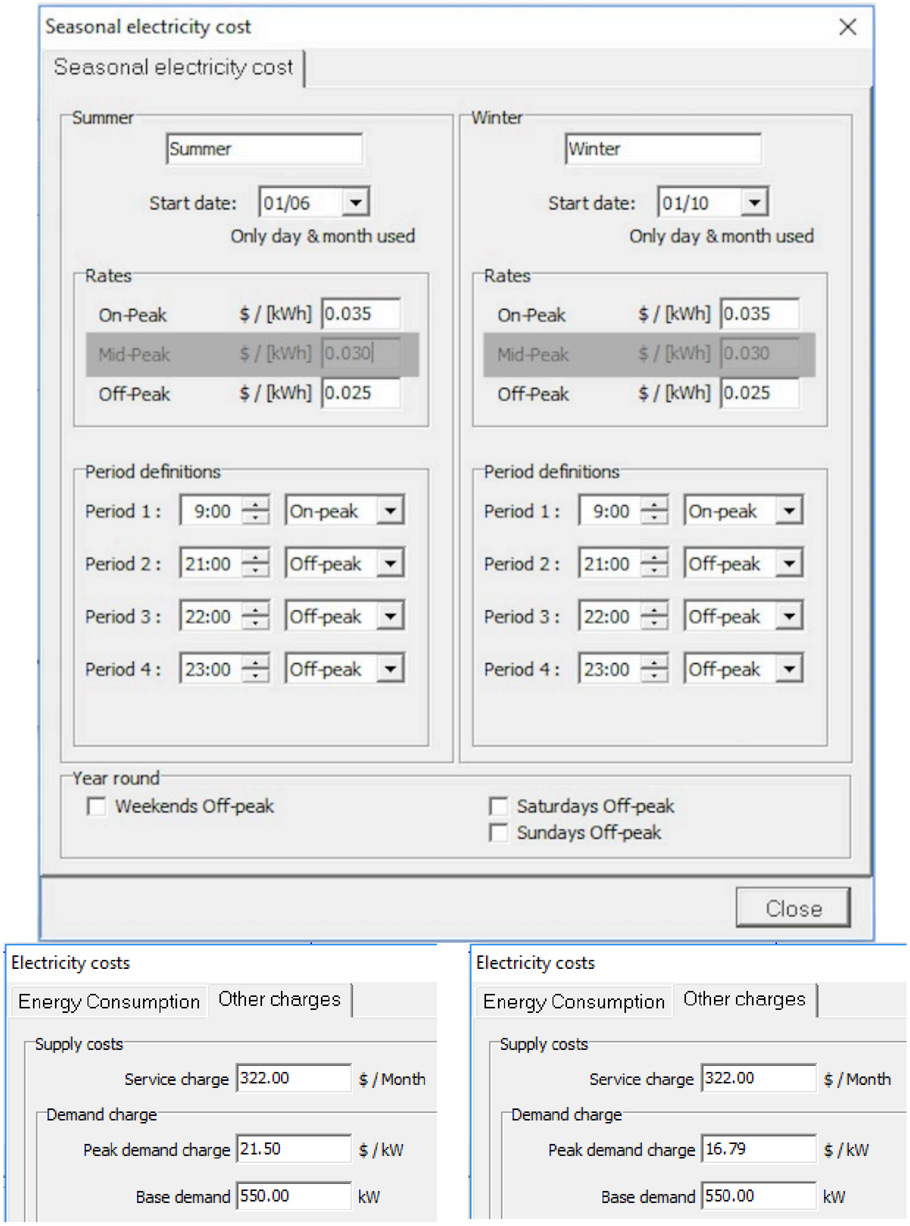

Figure 4 Electricity Cost (USD) for the Boulder WRRF Input to BioWin: Seasonal (top), Summer Peak Demand Charge (bottom left) and Winter Peak Demand Charge (bottom right).

RESULTS

Calibrated Model: Airflow Rates and Blower Power

The calibrated model accurately predicted the aeration performance over the period of operation from August 1st, 2017 to January 31st, 2018. As previously mentioned, the hourly measured dissolved oxygen (DO) concentration was input to each aerated zone in the liquid train in the plant model. Figure 5 shows that the predicted average daily discharge airflow rates (at field inlet conditions) in zones 4-6, 7 and 8 and the SCT of the liquid train closely matched the respective recorded values. The measured airflow rate in the PAD (also shown in Figure 5) was directly input to the model, as discussed in the Methodology section. The predicted DO concentration in the PAD over the calibration period was in line with the measured level of less than 0.2 mgO_2/L.

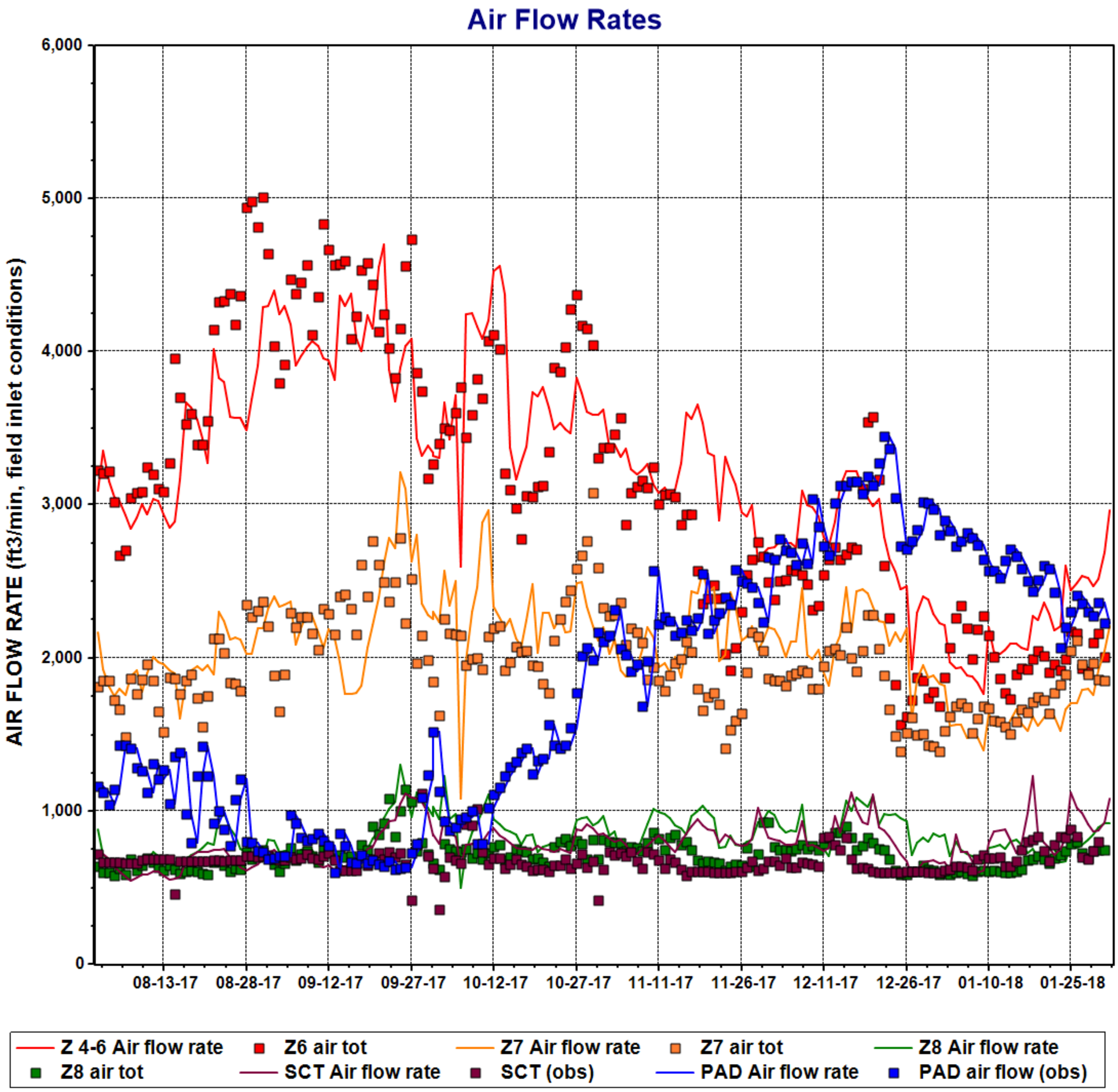

Figure 5 Predicted versus Observed Average Daily Airflow Rates in Zones 4-6, 7 and 8 and the SCT (August 1, 2017 to January 31, 2018).

The simulated airflows for the individual aerated zones and PAD shown in Figure 5 were added together, resulting in the total airflow pattern shown in Figure 6 (solid line) over the selected 6-month period of operation. Actual blower data is also plotted on Figure 6. Figure 7 shows the predicted and observed hourly total blower power demand over one week, from November 28th to December 5th, 2017. During each diurnal cycle, the blower demand peaked when the aeration basin was treating the maximum influent load. The simulator tracks the total aeration power demand very well.

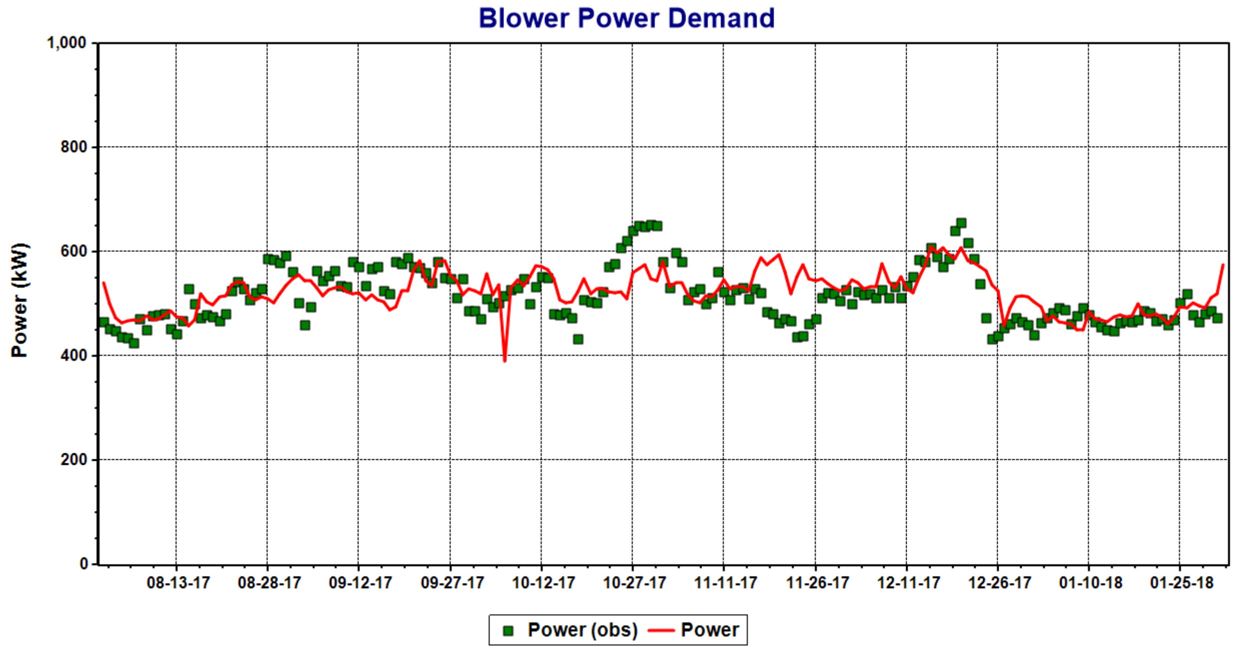

Figure 6 Predicted versus Observed Average Daily Total Blower Power Demand for the Liquid Train and PAD (August 1, 2017 to January 31, 2018).

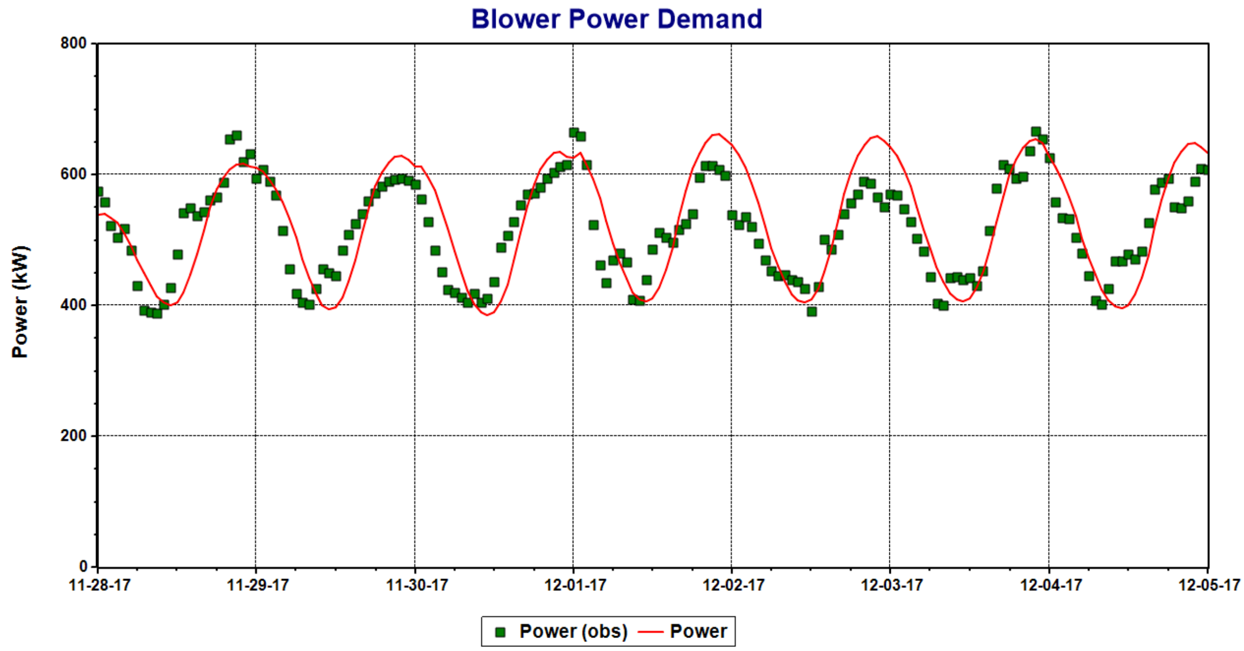

Figure 7 Predicted versus Observed Average Hourly Total Blower Power Demand for the Liquid Train and PAD (November 28 to Dec 5, 2017).

Calibrated Model: Aeration Energy and Cost

The calibrated BioWin model was used to calculate the monthly blower energy consumption for the liquid train and PAD at the Boulder WRRF over the period from August 1st, 2017 to January 31st, 2018, as shown in Figure 8.

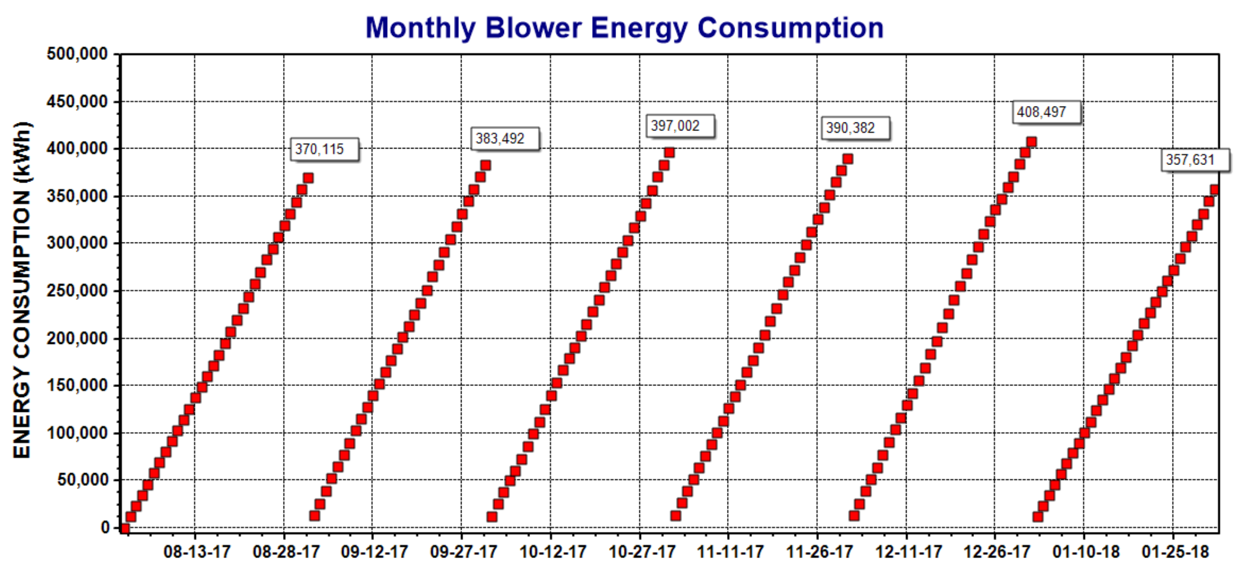

Figure 8 Predicted Monthly Blower Energy Consumption for the Boulder WRRF (August 1, 2017 to January 31, 2018).

The model-calculated monthly energy consumption for the aeration system was compared to the recorded total energy consumption of the Boulder WRRF, as shown in Figure 9. The monthly aeration energy consumption was between 44 and 49% of the total plant energy consumption over the selected operating period.

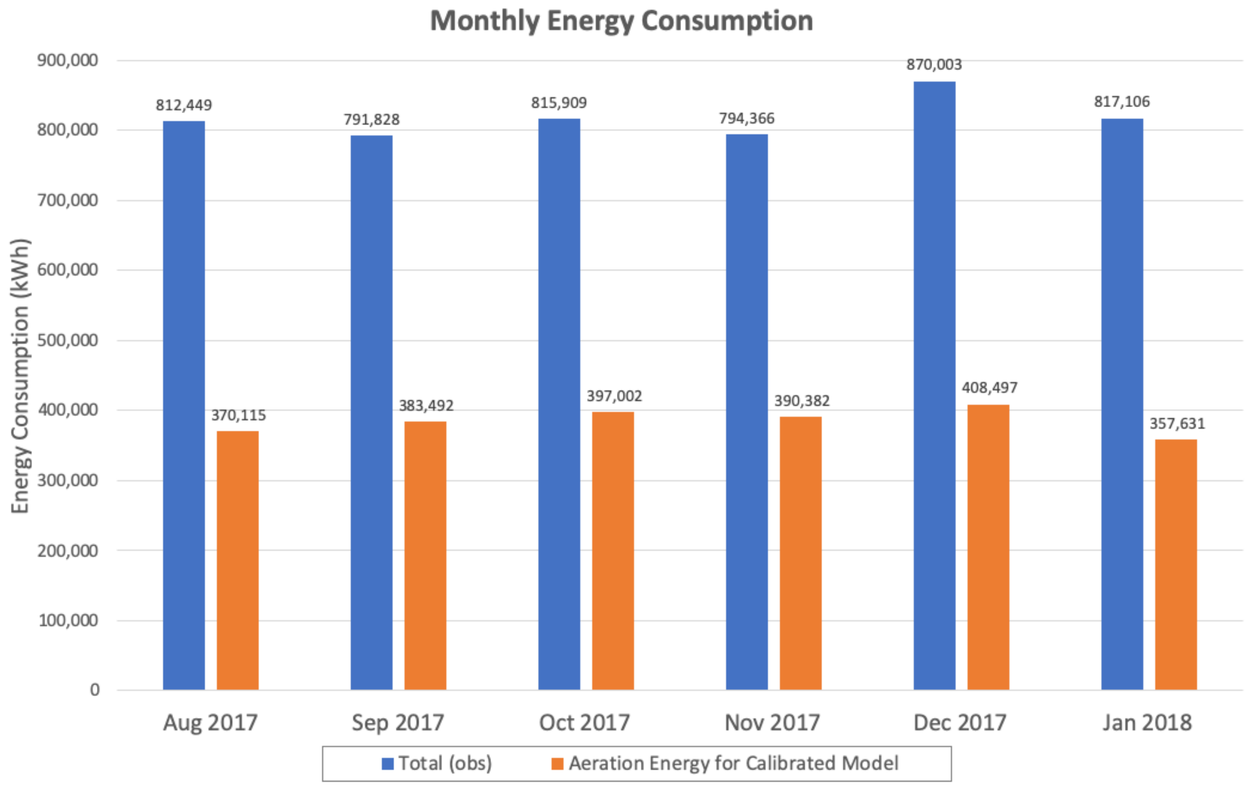

Figure 9 Monthly Energy Consumption of the Total Plant and the Aeration System at the Boulder WRRF (August 1, 2017 to January 31, 2018).

From August 1st, 2017 to January 31st, 2018, the Boulder WRRF purchased 72 to 88% of its total monthly electricity requirement from Xcel Energy and the remainder was supplied by on-site solar and cogeneration. The electricity fee structure imposed by Xcel Energy was directly input to BioWin and the calibrated Boulder WRRF model was used to track the electricity costs associated with aeration. During the selected operating period, the Boulder WRRF paid between USD $44,500 and $53,500 per month for electricity; the portion associated with aeration ranged from USD $20,500 to $25,500 per month.

The total aeration cost is comprised of the peak demand, consumption and service charge, as shown in Figure 10. The monthly peak demand charge was calculated by multiplying the seasonal peak demand rate ($/kW) by the blower power demand (kW) concurrent with the plant peak demand observed over a 15-minute period in the previous month. As shown in Figure 10, more than half of the total aeration cost is comprised of the peak demand charge. Therefore, a key way to reduce aeration energy at the Boulder WRRF is to reduce the blower peak demand.

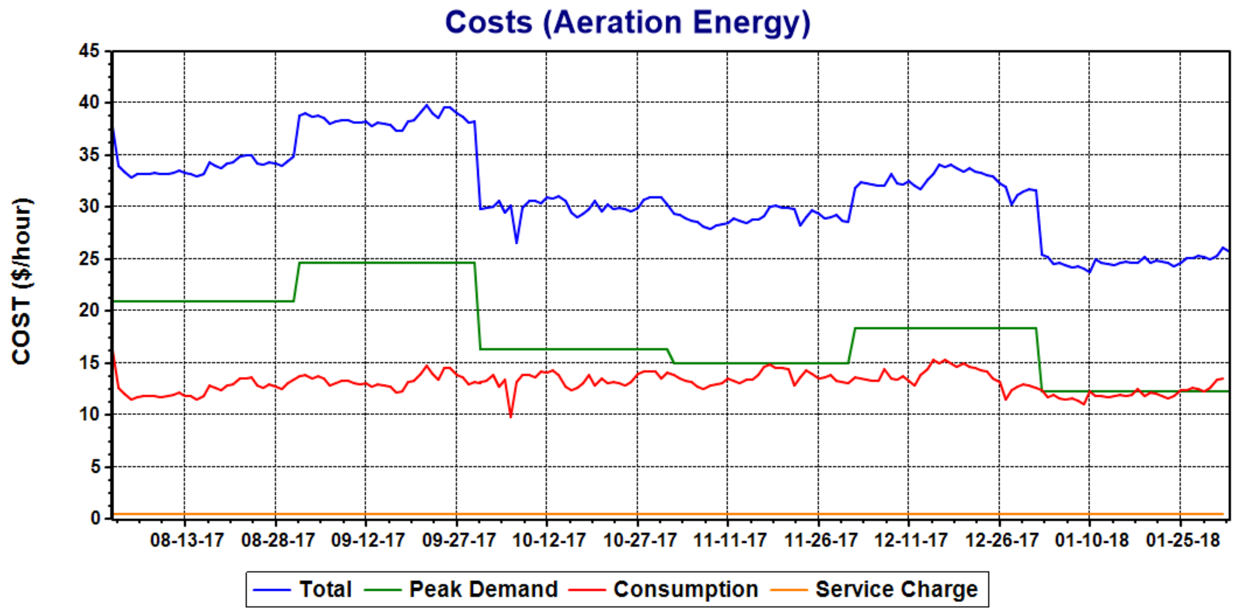

Figure 10 Predicted Aeration Energy Cost (USD $/hour) at the Boulder WRRF (August 1, 2017 to January 31, 2018).

Aeration Reduction Strategies

The calibrated BioWin model of the Boulder WRRF achieved a good correlation between the overall trend of predicted and observed values. This indicates that the model may be used with confidence to investigate the process performance implications and quantify the energy savings of various aeration reduction strategies. The aeration power and cost associated with the calibrated model served as the baseline for comparing the potential savings associated with the various strategies.

The following aeration reduction strategies were investigated:

1. On/off aeration in Zone 8.
2. Lowering the DO setpoint in the SCT.
3. Ammonia based aeration control in the liquid train.
4. Switching from coarse-bubble to fine-bubble aeration in the PAD to reduce the required airflow rates.

1. On/Off Aeration in Zone 8

The calibrated dynamic model of the Boulder WRRF was used to demonstrate that Zone 8 in the liquid train was over-aerated from August 1st, 2017 to January 31st, 2018. As discussed in the Methodology section, the hourly measured DO concentration was input to each aerated zone in the liquid train and the model-predicted airflow rates in each zone were compared to recorded data over the calibration period. The airflow calculation considered the transfer of DO in recycle streams and carryover of DO from aerobic to anoxic zones. As shown in Figure 11, the average daily measured DO concentrations in Zone 8 were relatively high, *i.e.* between 1.2 and 4

mgO_2/L. The plant's SCADA system is programmed to control the airflow rate in Zone 8 to achieve a target DO concentration of 2 mgO_2/L in this zone. However, the measured DO concentration often exceeded this setpoint. The predicted (and measured) average daily airflow rate in Zone 8 ranged from 600 to 1000 SCFM (1020 to 1700 m^3/h), as previously presented in Figure 5. The airflow rates in Zone 8 could be substantially lowered while maintaining aerobic conditions, *i.e.* DO concentrations of at least 1 mgO_2/L.

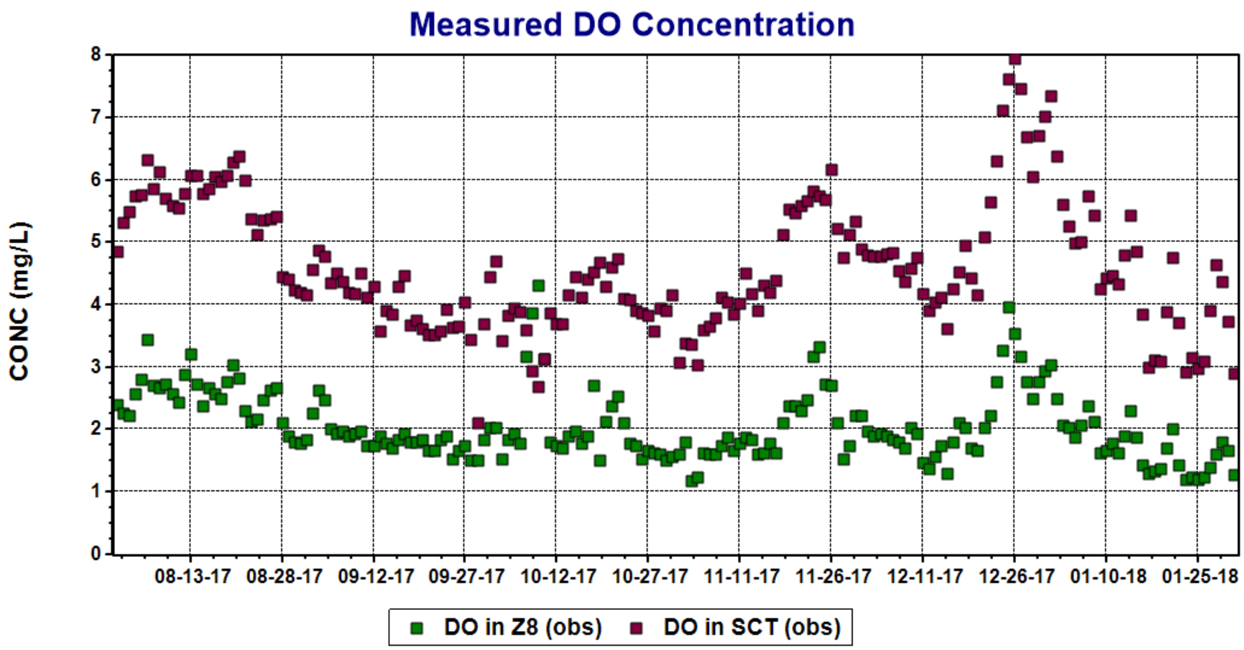

Figure 11 Measured Average Daily DO Concentration in Zone 8 and SCT (August 1, 2017 to January 31, 2018).

Further evidence of over-aeration across the liquid train as a whole is the predicted ammonia concentration across the plant. The calibrated model was simulated at steady-state to calculate the average ammonia concentration in each zone, as shown in Figure 12. The average ammonia concentration in Zone 8 over the selected 6-month operating period was only 0.2 mgN/L; hence the average nitrification oxygen demand in Zone 8 was also very low. This indicates there is opportunity for aeration reduction through ammonia-based aeration control, which will be discussed later.

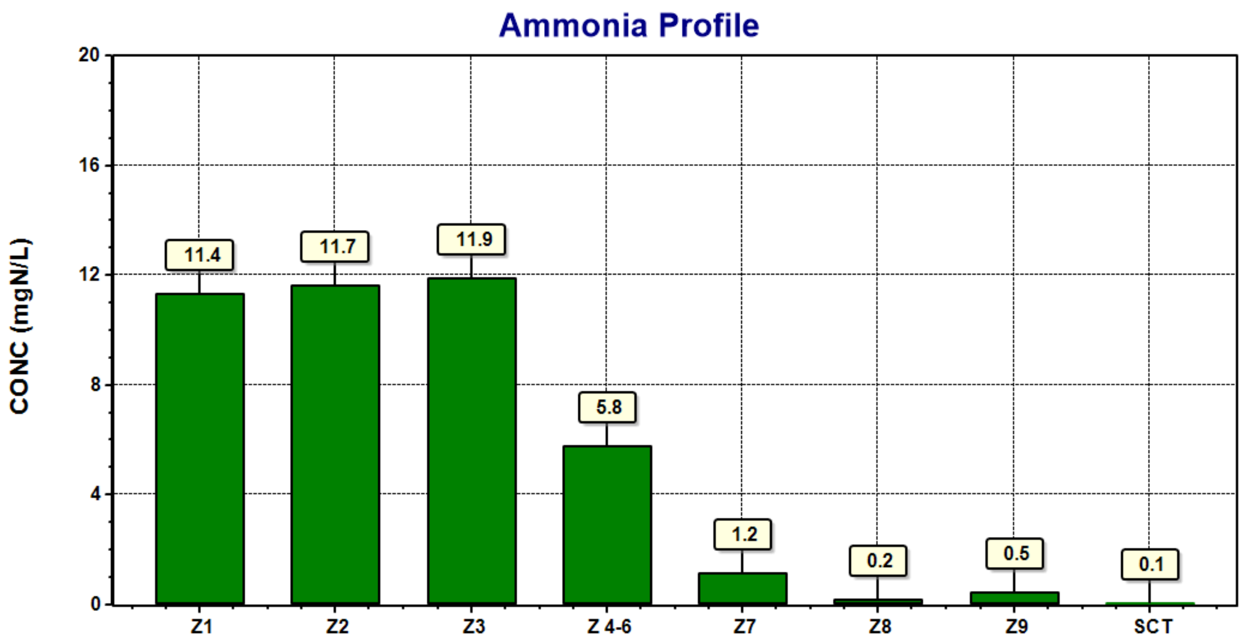

Figure 12 Average Ammonia Concentration in the Liquid Train Predicted by the Calibrated Model at Steady-State (August 1, 2017 to January 31, 2018).

Furthermore, the measured (and predicted) dynamic effluent ammonia concentrations over the selected 6-month operating period were very low, as shown in Figure 13. The predicted daily composites (green line) closely match the measured daily composites (green points); both series are well below the daily maximum limit of the discharge permit (blue line). The measured monthly average (red points) is also far less than the limit of the discharge permit (pink line). (The discharge permit limits shown in Figure 13 were effective beginning December 1st, 2017).

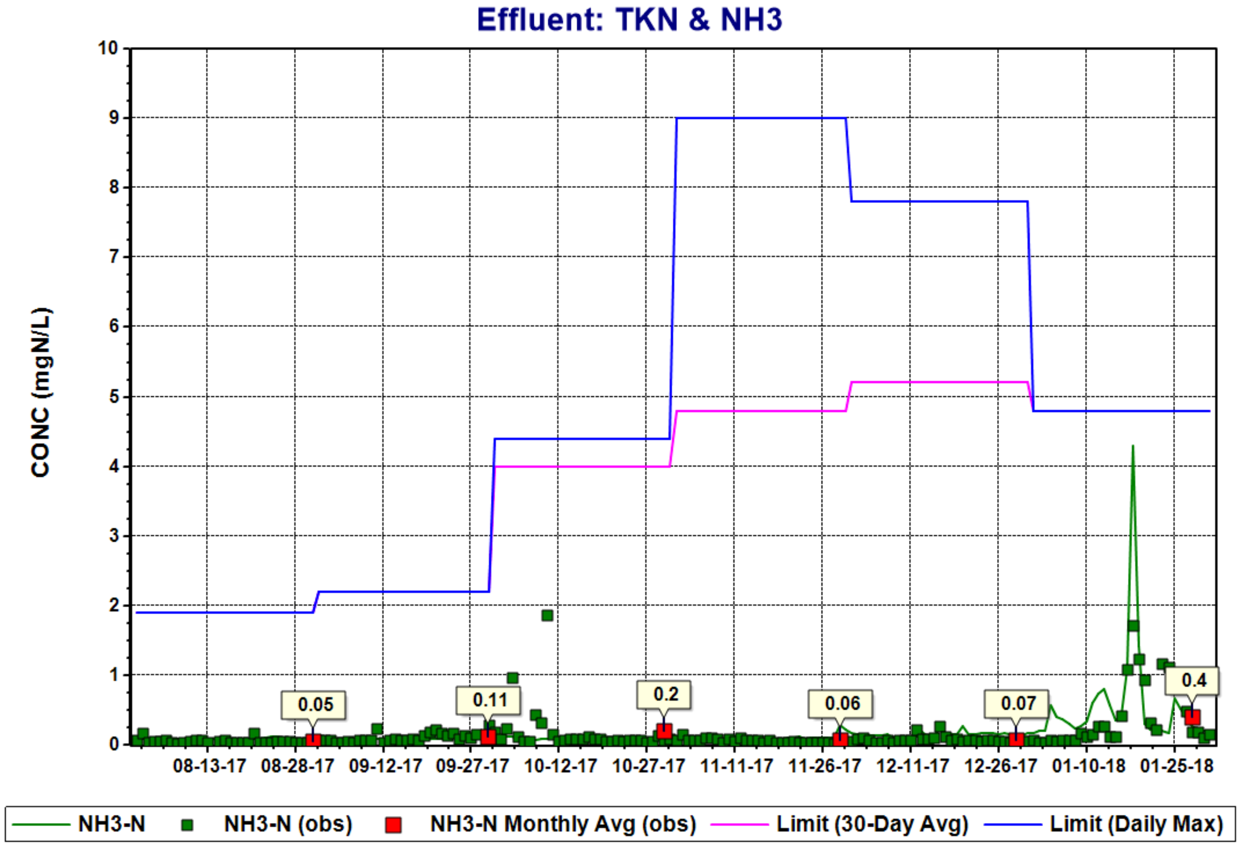

Figure 13 Predicted and Measured Effluent Ammonia Concentration and Effluent Ammonia Limits (August 1, 2017 to January 31, 2018).

The limits of the discharge permit are summarized in Table 3. During the months of August to November, 2017, the plant was achieving the lower ammonia limits that only came into effect on December 1st, 2017. As shown in Figure 13, the effluent ammonia increased in January 2018 however the daily and monthly average remained below the effluent limits. The effluent ammonia concentration increased in January 2018 because the aerobic SRT required for complete nitrification increased above the operating aerobic SRT at the plant. As shown in Figure 14, the measured (and predicted) aerobic SRT of the Boulder WRRF was held fairly constant at 8 days from August 1st, 2017 to January 18th, 2018. As the liquid temperature in the aeration basin declined over winter, the nitrifier growth rates decreased and hence the required aerobic SRT for complete nitrification increased. The aerobic SRT was increased to 11.5 days from January 18th onwards in attempts to reduce the effluent ammonia concentration. In retrospect, the effluent ammonia spikes may not have occurred had the aerobic SRT been increased several weeks earlier.

Table 3 Boulder WRRF Effluent Limitations Maximum Concentrations (Flow < 20 mgd) for the Period August 1st, 2017 to January 31st, 2018 (Colorado DPHE, 2015).

Effluent Parameter	Month	30-Day Average	Daily Max.	Monitoring Frequency	Sample Type
Nitrate (mgN/L)	All	**N/A**	**17.9**	Daily	Composite
Ammonia (mgN/L)	Aug.	**11.1**, **1.9**	**30**, **1.9**	Daily	Composite

until Nov 30/17 beginning Dec 1/17	Sept.	**11.1**, **2.2**	**11.1**, **2.2**		
	Oct.	**11.1**, **4.0**	**28.3**, **4.4**		
	Nov.	**13.9**, **4.8**	**29.5**, **9.0**		
	Dec.	**5.2**	**7.8**		
	Jan.	**4.8**	**4.8**		
Effluent Parameter	**Month**	**30-Day Average**	**7-Day Average**	**Monitoring Frequency**	**Sample Type**
CBOD5	All	25	40	2 d/wk	Composite
TSS	All	30	45	2 d/wk	Composite

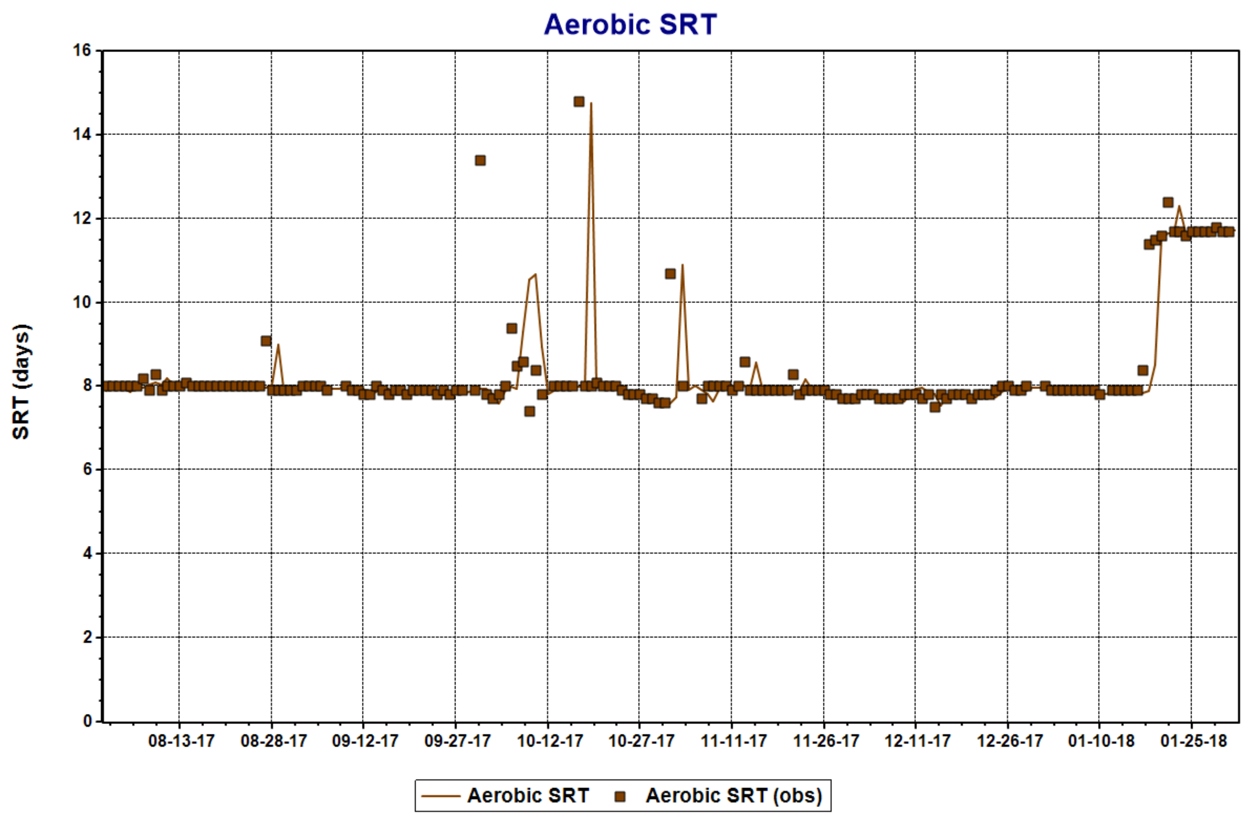

Figure 14 Predicted versus Observed Aerobic SRT (August 1, 2017 to January 31, 2018).

The relatively high measured DO concentrations in Zone 8 along with the lower-than-required effluent ammonia concentrations indicate that the airflow rates in Zone 8 could be reduced without negatively affecting plant performance. An aeration pattern was implemented in Zone 8 in the plant model whereby the air was cycled on and off every 2 hours at DO setpoints of 1 and zero mgO_2/L. The maximum airflow rate delivered to Zone 8 was set at 400 SCFM (680 m^3/h). The measured airflow rates over the selected 6-month operating period were input to the other aerated zones and the PAD.

The model was then dynamically simulated from August 1st, 2017 to January 31st, 2018. The predicted effluent ammonia concentrations remained below the applicable effluent limits. In addition, the predicted effluent CBOD5 and nitrate concentrations remained below the effluent limits shown in Table 3.

Using this energy saving strategy, the monthly blower energy consumption for the whole plant was calculated and compared to that estimated by the calibrated model, as shown in Figure 15. Also shown in Figure 15 is the predicted monthly blower energy consumption for the other three aeration reduction strategies that will be discussed in the next sections. By capping the airflow rate and applying on/off aeration in Zone 8, the total blower energy demand for the whole plant was reduced by 7 to 10% each month. This translates to an estimated savings of USD $1,820 per month on the Xcel Energy invoice (assuming the same contributions from renewable energy sources as the calibrated model).

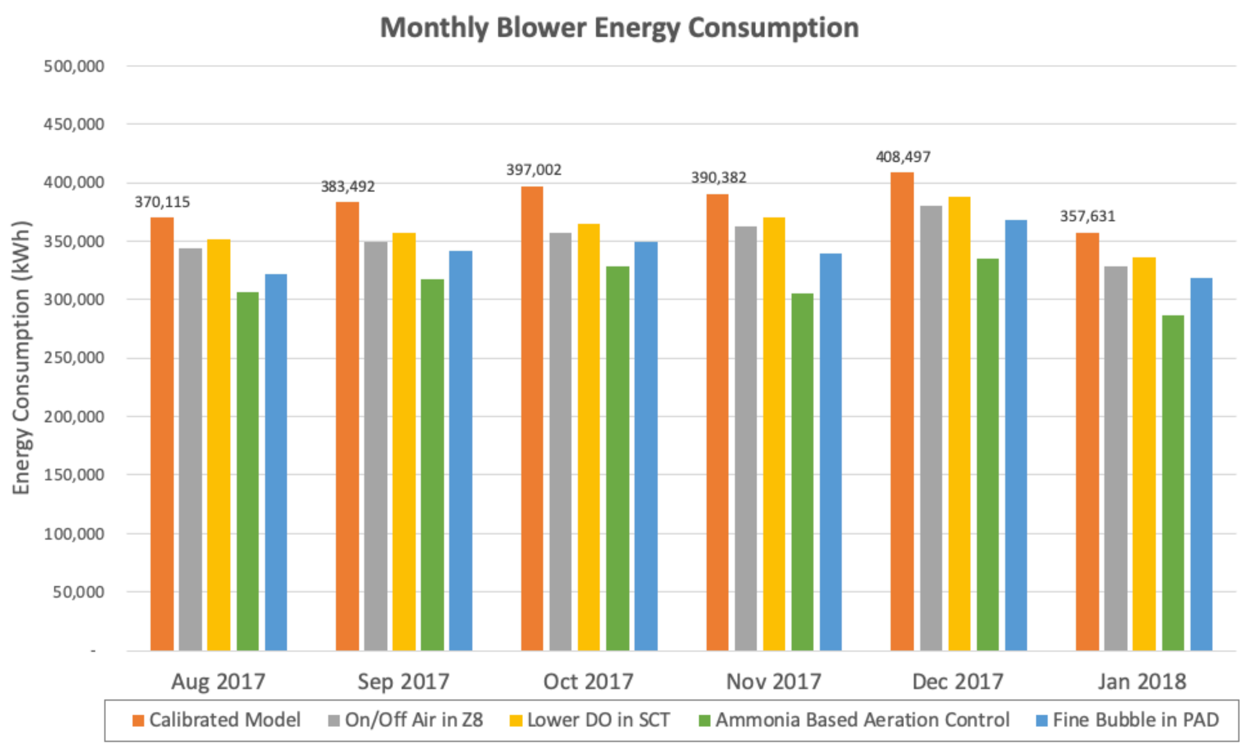

Figure 15 Monthly Blower Energy Consumption at the Boulder WRRF for the Calibrated Model versus Various Aeration-Reduction Strategies (August 1, 2017 to January 31, 2018).

2. Lowering the DO Setpoint in the SCT

Similar to Zone 8, the SCT in the liquid train was over-aerated from August 1st, 2017 to January 31st, 2018. As shown in Figure 11 in the previous section, the average daily measured DO concentrations in the SCT were very high, ranging from 2 to 8 mgO_2/L. The airflow rate to the SCT is controlled at a DO setpoint of 2 mgO_2/L. However, the airflow rate is also maintained at a minimum required level for adequate mixing. Because the oxygen demand was relatively low in the SCT, the minimum required airflow rate for mixing exceeded the calculated airflow rate to achieve the DO setpoint. The predicted (and measured) average daily airflow rate in the SCT ranged from 500 to 1200 SCFM (850 to 2039 m^3/h), as previously presented in Figure 5. The airflow rates in the SCT could be appreciably lowered while maintaining a minimum DO concentration of 1 mgO_2/L in this tank. This could be achieved in practice by retrofitting the

SCT with a mixer, allowing operation at a much lower DO concentration (*i.e.* around 1 mgO_2/L). As discussed previously, the measured effluent ammonia concentration over the selected operating period was well below the limits, indicating the total aeration in the liquid train could be lowered without negative consequences to the effluent quality.

In the plant model, a DO set point of 0.4 mgO_2/L was applied in the SCT and the maximum airflow rate was set at 400 SCFM (680 m^3/h). The measured airflow rates over the selected 6-month operating period were input to the other aerated zones and the PAD. The model was then dynamically simulated from August 1st, 2017 to January 31st, 2018. The predicted effluent concentrations of ammonia, CBOD5 and nitrate remained below the applicable effluent limits previously shown in Table 3.

The monthly blower energy consumption for the whole plant using reduced airflow rates in the SCT was compared to the baseline estimated with the calibrated model. This comparison was shown in Figure 15 in the previous section. By lowering the DO setpoint and capping the airflow rate in the SCT, the total blower energy demand for the whole plant was reduced by 5 to 8% each month. This translates to an estimated savings of USD $1,360 per month on the Xcel Energy bill (assuming the same contributions from renewable energy sources as the calibrated model).

3. Ammonia Based Aeration Control in the Liquid Train

As demonstrated in the preceding sections, the liquid train was over-aerated during the selected period from August 1st, 2017 to January 31st, 2018. The DO concentrations in the aerated zones often exceeded the DO setpoint of 2 mgO_2/L and the plant effluent ammonia concentration was well below the discharge limits.

Figure 16 shows the predicted ammonia concentration in the aerated zones of the liquid train (*i.e.* zones 4-6, 7, 8 and the SCT) for the calibrated model. The predicted ammonia concentration in the SCT (at the end of the liquid train) remained below 0.5 mgN/L for most of the 6-month period except for a few small spikes that occurred in January 2018. As previously discussed, these ammonia spikes occurred because the aerobic SRT required for complete nitrification increased above the operating aerobic SRT at the plant. The aerobic SRT was increased from 8 to 11.5 days on January 18th, 2018 by lowering the mixed liquor waste flow rate. A dynamic simulation was performed where the aerobic SRT was increased much earlier (*i.e.* on December 1st, 2017). The predicted ammonia concentration in the SCT remained below 0.5 mgN/L until the end of the simulation on January 31st, 2018.

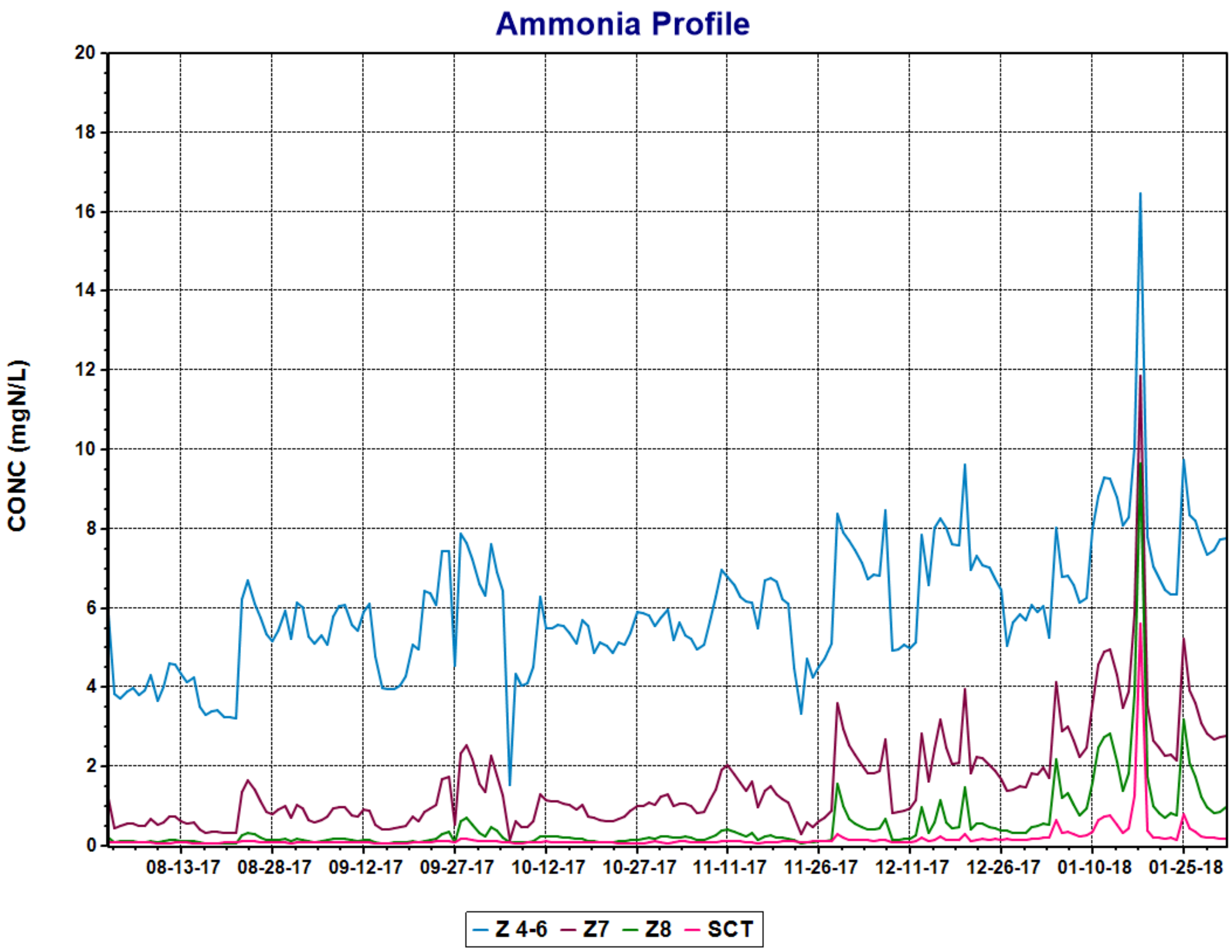

Figure 16 Predicted Ammonia Concentration in the Aerated Zones of the Liquid Train at the Boulder WRRF (Calibrated Model – August 1, 2017 to January 31, 2018).

Ammonia-based aeration control was then applied to this dynamic simulation (where the aerobic SRT was increased to 11.5 days on December 1st, 2017) using BioWin Controller. The objective was to reduce the total airflow rates in the liquid train while maintaining the ammonia concentration in the SCT at 0.5 mgN/L. The DO concentration in Zones 4-6 was controlled between zero and 2 mg O_2/L. A PI controller was used to calculate the required total airflow to the liquid train. A second controller was used to distribute the total airflow to the different aerated zones in the liquid train.

The PAD airflow rates were not affected by the ammonia-based aeration control in the liquid train; the PAD airflow rate itinerary was unchanged from the calibrated model. The model was then dynamically simulated from August 1st, 2017 to January 31st, 2018. The predicted effluent concentrations of ammonia, CBOD5 and nitrate remained below the applicable effluent limits previously shown in Table 3.

Although the Boulder WRRF is not regulated on effluent TKN, TN or total inorganic nitrogen (TIN), the plant is participating in a voluntary incentive program to delay the implementation of low effluent TP and TN limits. The facility's current plan is to achieve an annual effluent TIN concentration of 9.0 mgN/L beginning in 2018. In the voluntary incentive program, credit is earned toward a maximum compliance period of 10 years by achieving annual median effluent concentrations below an effluent TIN limit of 15 mgN/L as outlined in Colorado Regulation 85 (Colorado DPHE, 2012). Figure 17 shows the measured effluent TIN concentration over the period from August 1st, 2017 to January 31st, 2018, along with the TIN concentration predicted by the calibrated model. The predicted concentrations closely match the measured values. The average measured TIN concentration over this 6-month period was 8.8 mgN/L, which satisfies both the plant target and voluntary compliance limits (although these are based on the annual mean). Using the dynamic model with the ammonia-based aeration control strategy outlined above, the predicted effluent TIN concentration was calculated. The average predicted effluent TIN over the 6-month operation period was 8.6 mgN/L, which is below the plant target of 9 mgN/L and the limit of 15 mgN/L for the voluntary compliance program. The external carbon dosing pattern over the operating period was unchanged from the calibrated model; this could be optimized for improved denitrification and potentially lower effluent TIN concentrations.

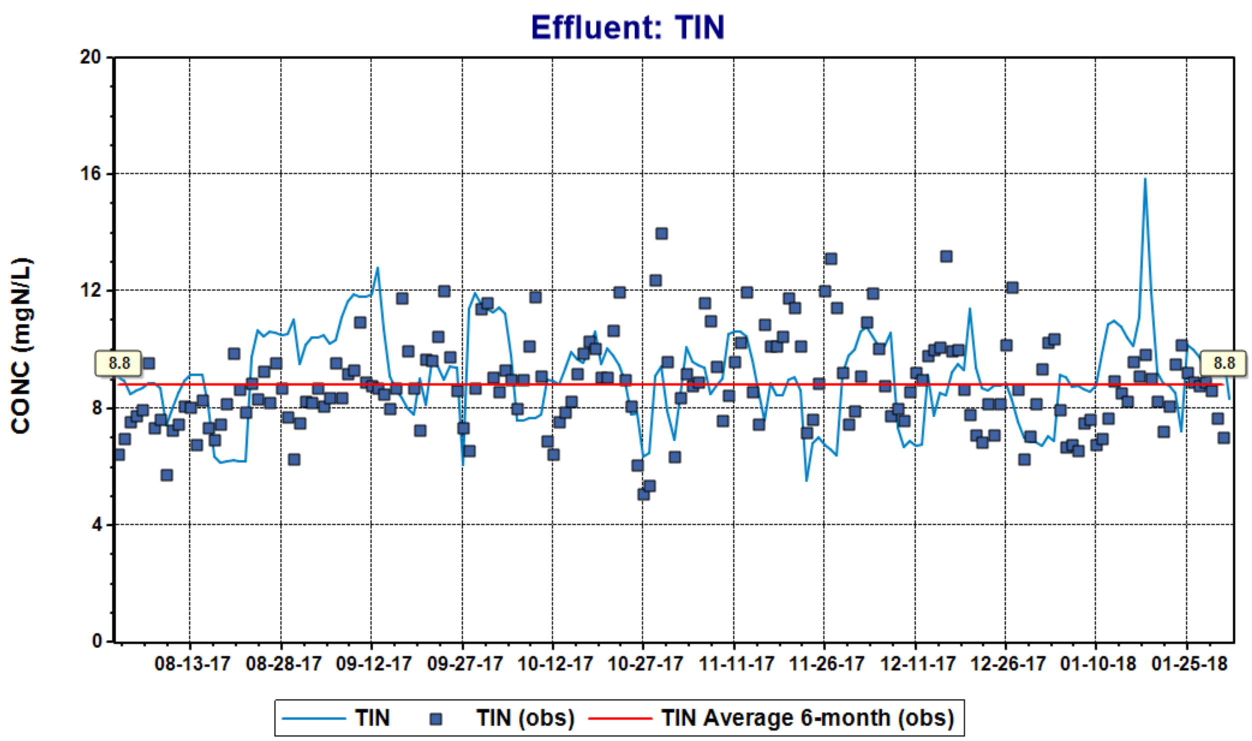

Figure 17 Predicted and Measured Effluent TIN Concentration at the Boulder WRRF (Calibrated Model – August 1, 2017 to January 31, 2018).

The monthly blower energy consumption for the whole plant using ammonia-based aeration control in the liquid train was compared to the baseline estimated with the calibrated model. This comparison was shown in Figure 15 in the previous section. By applying ammonia-based aeration control in the liquid train, the total blower energy demand for the whole plant was reduced by 17 to 22% each month. This translates to an estimated savings of USD $4,200 per month off the Xcel Energy bill (assuming the same contributions from renewable energy sources as the calibrated model).

4. Switching from Coarse-Bubble to Fine-Bubble Aeration in the PAD

The calibrated BioWin model of the Boulder WRRF accurately predicted the performance of the PAD as well as the sludge mass across the solids train. This indicates the calibrated model may be used with confidence to investigate the process performance implications and energy savings associated with switching from coarse-bubble to fine-bubble aeration in the PAD. The model calibration to the existing PAD system is briefly summarized below before discussing the scenario with fine-bubble aeration in the PAD.

Over the selected period of operation, an average of 52% of the secondary digester effluent flow was treated in the PAD. Figure 18 shows the measured ammonia concentration in the secondary digester over the period from August 1st, 2017 to January 31st, 2018. The reported values ranged from approximately 900 to 2000 mgN/L, although the data is limited. The predicted ammonia concentration was approximately 1200 mgN/L over the calibration period, which is in line with the measured data.

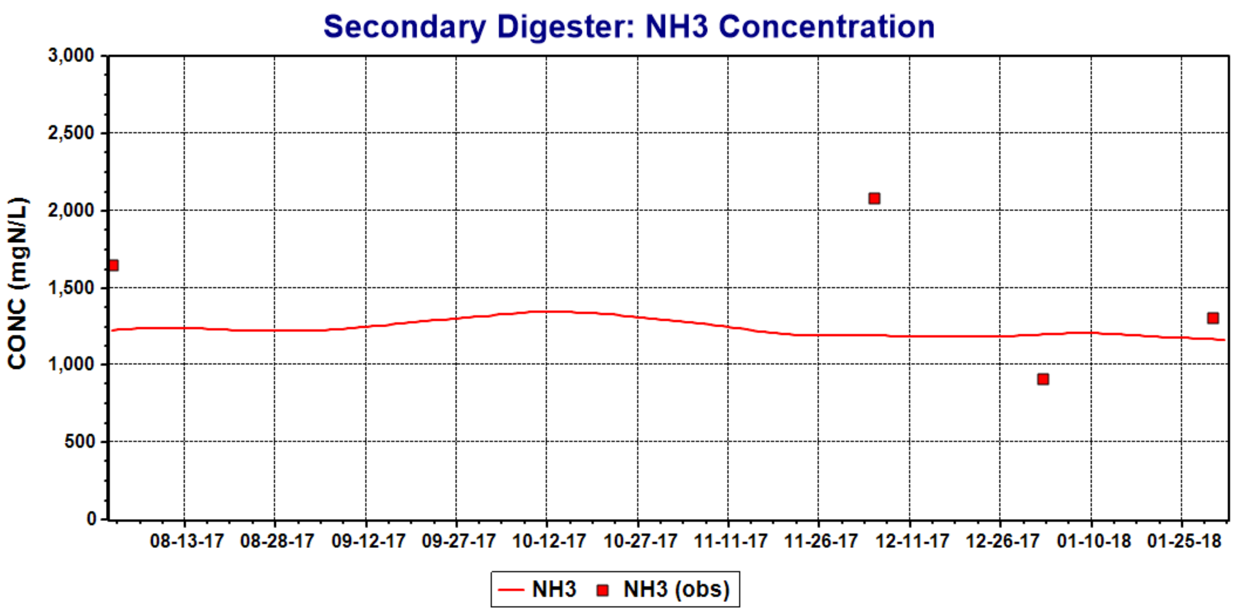

Figure 18 Predicted and Observed Ammonia Concentrations in Secondary Digester (Calibrated Model – August 1, 2017 to January 31, 2018).

Figure 19 shows the predicted and observed ammonia, nitrate and nitrite concentrations in the PAD from August 1st, 2017 to January 31st, 2018. The predicted concentrations are in line with the measured data, indicating that the model accurately tracked the performance of the PAD. The ammonia concentration entering the PAD was 1200 mgN/L and it was reduced to between 100 and 400 mgN/L in the PAD through nitrification. As shown in Figure 19, essentially all of the NO_X generated through nitrification was denitrified. Therefore, the concentration of ammonia removed by SND in the PAD was between 800 and 1100 mgN/L.

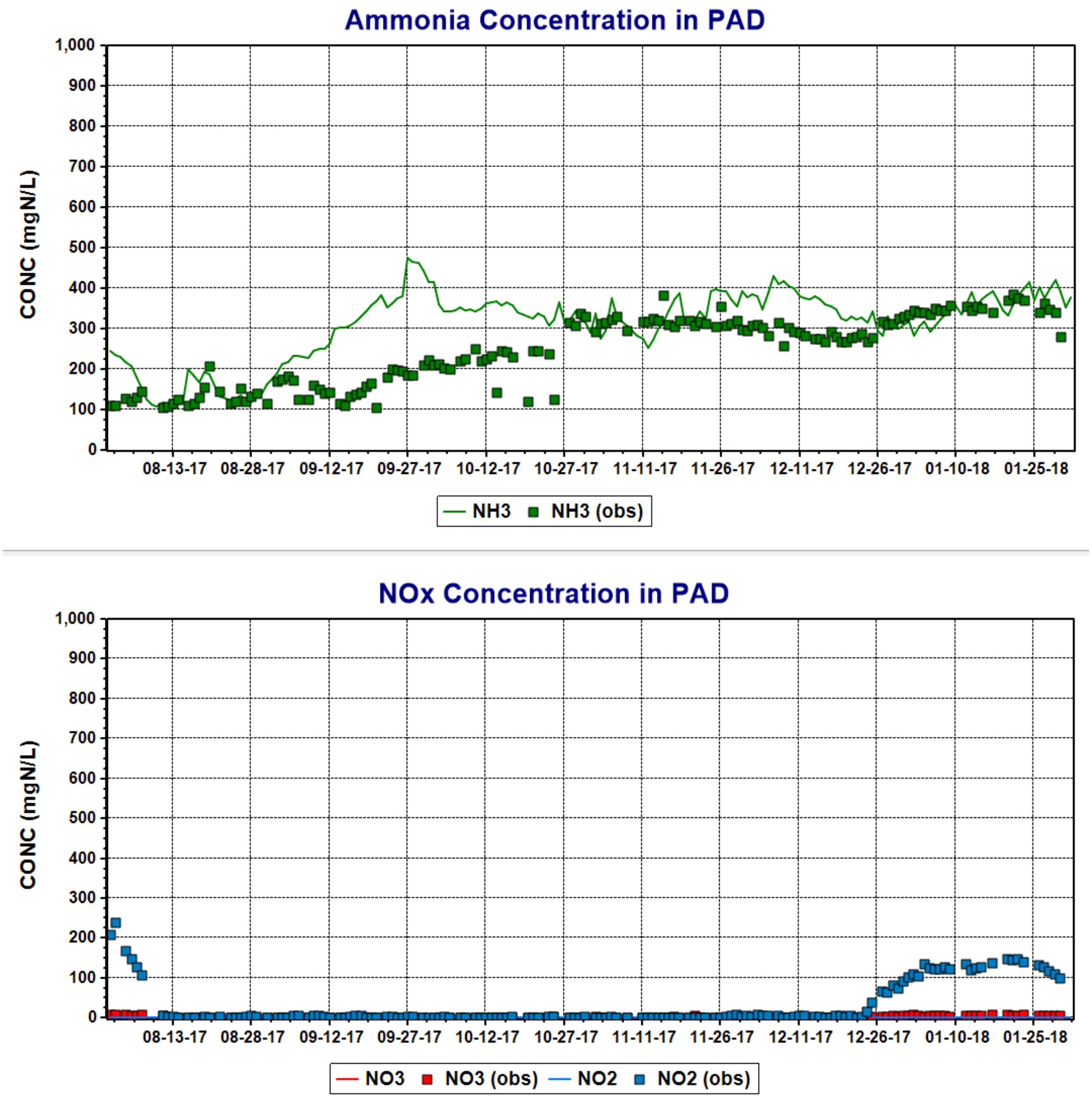

Figure 19 Predicted and Observed Concentrations of Ammonia (top) and Nitrate and Nitrite (bottom) in PAD (Calibrated Model – August 1, 2017 to January 31, 2018).

Figures 20 and 21 show the predicted and measured TSS and VSS concentrations in the secondary digester and PAD for the calibrated plant model over the period from August 1st, 2017 to January 31st, 2018. The average VSS destruction across the primary and secondary digester was 59.6% over the calibration period. An additional 4.0% average VSS destruction was achieved in the PAD.

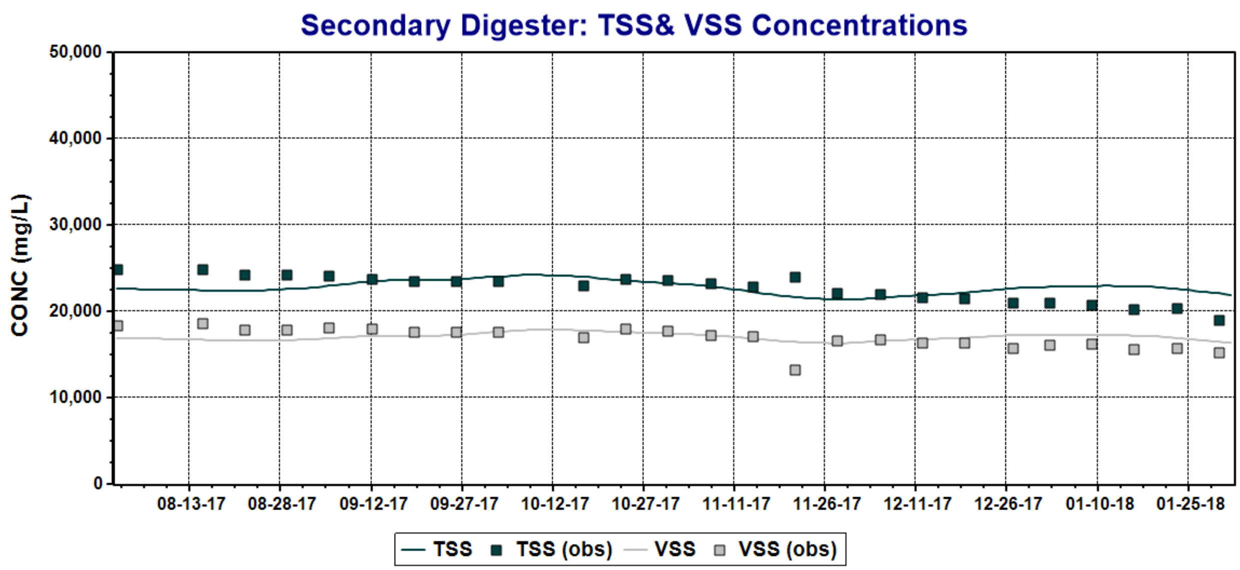

Figure 20 Predicted versus Observed TSS and VSS Concentrations in Secondary Digester (Calibrated Model – August 1, 2017 to January 31, 2018).

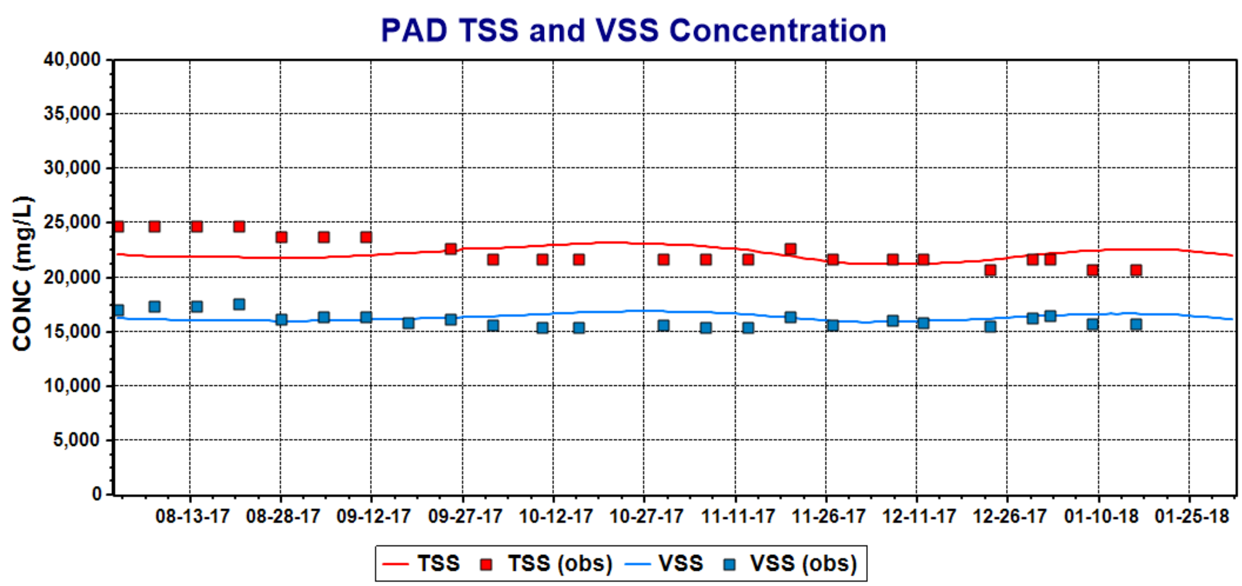

Figure 21 Predicted versus Observed TSS and VSS Concentrations in PAD (Calibrated Model – August 1, 2017 to January 31, 2018).

The accurate prediction of the PAD performance indicates that the calibrated model may be used with confidence to investigate the overall plant treatment implications and energy savings associated with optimizing the PAD aeration. The PAD uses coarse bubble aeration which is less efficient than fine bubble. The diffuser parameters in the model were modified to represent a typical fine bubble aeration system. The DO set point was set at 0.2 mgO_2/L, *i.e.* the average value measured over the selected 6-month operation period. The measured airflow rates in the PAD ranged from 600 to 3200 SCFM (1019 to 5437 m^3/h) over the calibration period. When the Boulder WRRF model was simulated using fine-bubble aeration in the PAD, the predicted airflow rates in the PAD dropped substantially to between 400 and 600 SCFM (680 to 1020 m^3/h).

The monthly blower energy consumption for the whole plant using fine-bubble aeration in the PAD was compared to the baseline estimated with the calibrated model (using coarse-bubble aeration in the PAD). This comparison was shown in Figure 15 in the previous section. By switching to fine-bubble aeration in the PAD, the total blower energy demand for the whole plant was reduced by 10 to 13% each month. This translates to an estimated savings of USD $2,700 per month off the Xcel Energy bill (assuming the same contributions from renewable energy sources as the calibrated model).

DISCUSSION & CONCLUSIONS

In this study, a BioWin model of the Boulder WRRF was calibrated to performance data collected over 6 months from August 1st, 2017 to January 31st, 2018. The calibrated model accurately predicted the plant performance in terms of MLVSS concentrations, effluent parameter concentrations, SRT, SND in the PAD, *etc*. A linear correlation between total blower power demand and airflow rate was directly input to BioWin. The model accurately tracked the power and electricity cost associated with aeration over the calibration period.

The Boulder WRRF is making a concerted effort to save energy. The calibrated Boulder WRRF model was used to investigate the process performance implications and quantify the energy savings of four aeration reduction strategies:

1. On/off aeration in Zone 8.
2. Lowering the DO setpoint in the solids contact tank (SCT).
3. Ammonia based aeration control in the liquid train.
4. Switching from coarse-bubble to fine-bubble aeration in the PAD.

The average monthly reduction in aeration energy using strategies 1 through 4 above was 8%, 6%, 19% and 12%, respectively. This translates to an estimated savings of between USD $1,360 and $4,200 per month off the Xcel Energy bill (assuming the same contributions from renewable energy sources as the calibrated model). Applying ammonia-based aeration control and switching to fine-bubble aeration in the PAD are associated with the greatest energy savings. The Boulder WRRF is currently investigating the capital and operational expenditures associated with these two improvements. The plant is presently using the calibrated BioWin model to investigate the energy and cost benefits of applying various combinations of the four energy-savings strategies listed above, as well as optimizing the external carbon dosing. Modeling is a strong tool for evaluating the process performance implications associated with strategies to reduce the total aeration demand and overall operating costs at the plant.

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APPENDIX

Figure 22 shows the measured MLSS and MLVSS concentrations in the liquid train (Zone 9) over the selected 6-month operating period along with the respective concentrations predicted by the calibrated BioWin model.

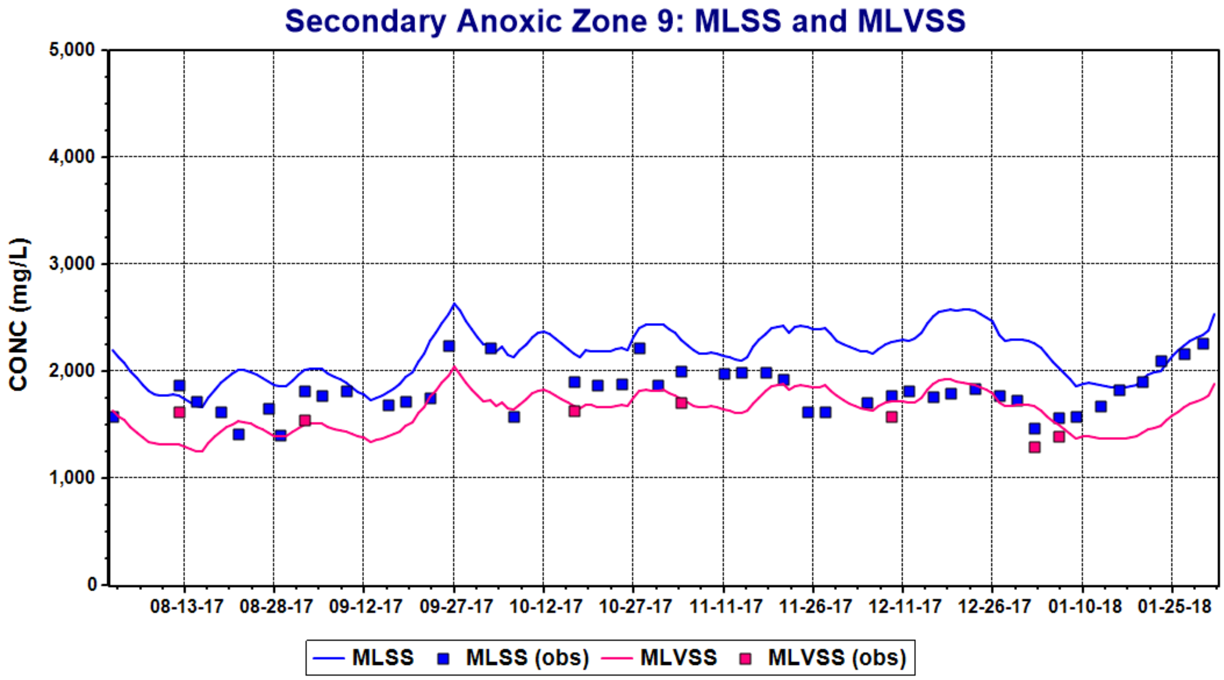

Figure 22 Predicted versus Observed MLSS and MLVSS Concentrations in Secondary Anoxic Zone 9 (Calibrated Model – August 1, 2017 to January 31, 2018).

Figure 23 shows the measured effluent TSS concentrations over the selected 6-month operating period along with the concentration predicted by the calibrated BioWin model.

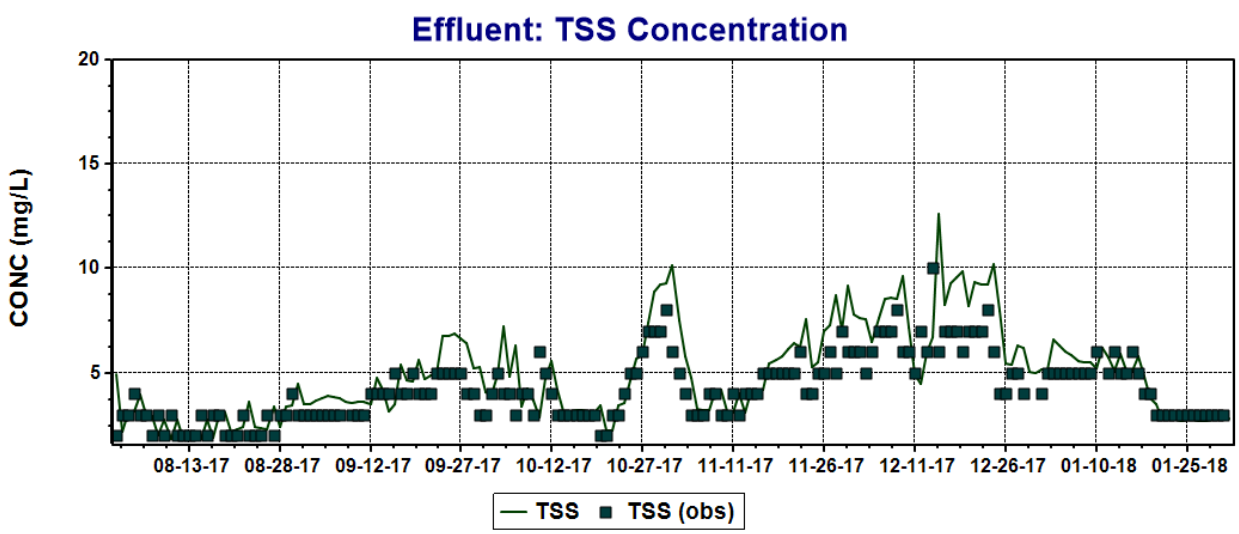

Figure 23 Predicted versus Observed Effluent TSS Concentrations (Calibrated Model – August 1, 2017 to January 31, 2018).