Is ammonia-based aeration control worth the effort?

SUSAN GUSWA, PE, Woodard & Curran, Northampton, Massachusetts
JULIA BENI, Woodard & Curran, Northampton, Massachusetts
JEFFREY GAMELLI, City of Westfield, Westfield, Massachusetts
KEN GAGNON, City of Westfield, Westfield, Massachusetts

ABSTRACT | Ammonia-based aeration control (ABAC) can be successfully implemented at smaller water resource recovery facilities (WRRFs). The authors conducted a pilot test at the 6.1 mgd (23 ML/d) water recovery facility (WRF) in the city of Westfield, Massachusetts, to demonstrate the benefits and impacts of ABAC. The objectives were to quantify the energy savings, understand impacts on biological nutrient removal, identify other process and maintenance impacts, and calculate a return on investment (ROI) of implementing ABAC. The Westfield WRF realized a positive ROI, but this will not necessarily be true for all smaller WRRFs. Importantly, the pilot test reinforced that successful implementation of newer technologies like ABAC needs ownership by the operators and must build on fundamentally sound process operations and control to fully realize the ROI.

KEYWORDS | Ammonia-based aeration control (ABAC), ammonia sensors, energy savings, process optimization, activated sludge, nutrient removal, return on investment (ROI)

INTRODUCTION

Ammonia-based aeration control (ABAC) is advanced process control beyond dissolved oxygen (DO) control for activated sludge systems. ABAC uses real-time ammonia concentration data to control the airflow delivered to aeration tanks. Doody et al. (2017) describe the two types of instruments that measure ammonia in an aeration tank:

- Analyzers using wet chemistry use a pump to withdraw a sample of the mixed liquor from the aeration basin; it is then filtered and analyzed with reagents using a gas sensitive electrode
- Probes using ion selective electrode (ISE) technology are submerged directly in the aeration basin

Various ABAC control schemes are used at WRRFs, including both feed forward and feedback control (Rieger et al., 2014; Doody et al., 2017; Anderson et al., 2018). The specifics of the control scheme can vary. For instance, either the absolute value or the rate of change of the ammonia concentration can be used for control. The ammonia value can control the speed of the blowers directly or can be part of cascaded loop control with DO and/or air flow values.

ABAC's main advantage over traditional DO control is the potential for energy savings. DO is needed to facilitate biochemical oxygen demand (BOD) removal and nitrification. Standard design and operating guidelines suggest a DO concentration of 2 mg/L should be maintained within aeration basins (NEIWPCC, 2016). However, in plug flow reactors, complete nitrification is often achieved for all or part of the day prior to the end of an aeration tank. The same level of BOD removal and nitrification often can be achieved at lower DO concentrations. Further, reducing the DO concentration low enough can slow the nitrification reaction, allowing the full aeration tank volume to be used while sending less air to the system. Monitoring real-time ammonia concentrations in aeration tanks provides more precise process control and reduced risk of effluent permit violations caused by incomplete nitrification (Rieger et al., 2014).

Additionally, lower DO concentrations in aeration tanks can improve biological nitrogen and phosphorus removal by reducing the amount of DO returned to anaerobic and anoxic zones via the return activated sludge (RAS) or internal mixed liquor recycle (IMLR). Lower DO concentrations in aeration tanks can also facilitate some simultaneous nitrification and denitrification. Enhanced denitrification leads to alkalinity recovery and reduced reliance on supplemental alkalinity, lowering the overall carbon footprint of the process.

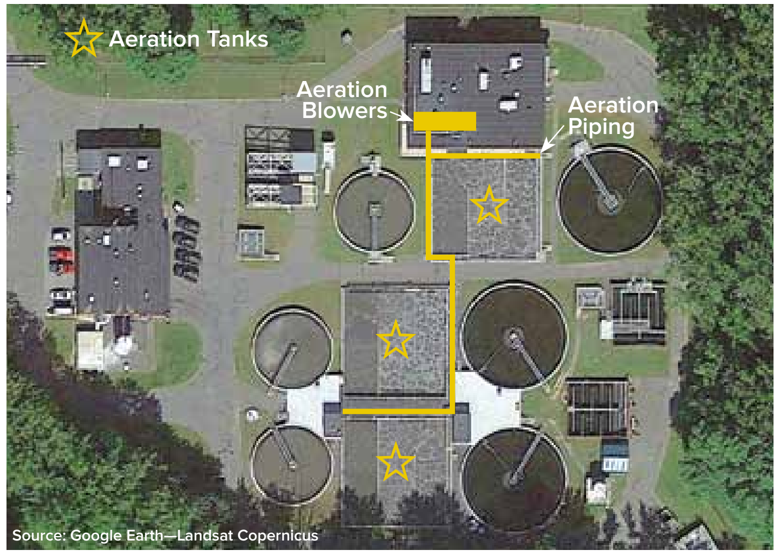
Maintaining lower DO concentrations in aeration tanks, even for part of the day, can result in net energy savings. Aeration for activated sludge systems typically accounts for 50 percent of energy use at WRRFs (EPA, 2013). Thus, any reduction of air requirements for biological treatment reduces energy use. Real-world applications of ABAC have quantified typical aeration energy savings between 10 percent and 20 percent compared to DO control applications (Rieger et al., 2014; Doody et al., 2017; Anderson et al., 2018). Despite the benefits of implementing ABAC, few WRRFs smaller than 10 mgd (38 ML/d) use ABAC for control within the United States.

A pilot test at the 6.1 mgd (23 ML/d) water recovery facility (WRF) in Westfield, Massachusetts, evaluated potential benefits and impacts of ABAC. The primary pilot test goals were to understand the obstacles of implementing ABAC at a smaller municipal WRRF and to determine whether energy and chemical savings realized at larger facilities would apply to the smaller facility. Specifically, pilot test objectives were to quantify energy savings, understand impacts on biological nutrient removal, identify other process and maintenance-related impacts, and quantify a return on investment (ROI) of implementing ABAC. A grant from Massachusetts Clean Energy Center supported the project.

BACKGROUND

The Westfield WRF serves around 50,000 customers and treats wastewater from residential, commercial, industrial, and institutional sources within the city and neighboring municipality. Average daily flow is approximately 3.4 mgd (13 ML/d), and the design capacity is 6.1 mgd (23 ML/d). The Westfield WRF has 10 operations and maintenance professionals.

Liquid treatment consists of screening, grit removal, primary clarification, activated sludge, secondary clarification, disinfection, and dechlorination. The activated sludge system is configured in three plug-flow aeration tanks. These tanks contain three passes each and were originally designed to be fully aerobic with air supplied via fine bubble diffusers. Solids are thickened, dewatered, and hauled off site for incineration. Figure 1 shows the Westfield WRF.



Source: Google Earth—Landsat Copernicus

Figure 1. Westfield WRF

Table 1. Summary of NPDES permit limits and 2019 performance

Constituent	NPDES Permit Limits Winter	NPDES Permit Limits Summer	2019 Average Effluent Summer
Biochemical oxygen demand (BOD)	30 mg/L	20 mg/L	5 mg/L
Total suspended solids (TSS)	30 mg/L	20 mg/L	< 5 mg/L
Ammonia (NH_3)	Report	3 mg/L	1 mg/L
Total nitrogen (TN)	Report	Report	8 mg/L
Total phosphorus (TP)	1.0 mg/L	0.46 mg/L	0.36 mg/L

The National Pollutant Discharge Elimination System (NPDES) permit limits at the Westfield WRF are more stringent in the summer. Table 1 presents Westfield WRF's NPDES permit limits along with 2019 performance.

The WRF was designed for seasonal nitrification and phosphorus removal via chemical precipitation with sodium aluminate to achieve permit limits. To mitigate the alkalinity loss due to nitrification, the Westfield WRF adds sodium hydroxide (NaOH) to the aeration tanks. To reduce operating costs associated with chemical phosphorus removal, operators converted the first aerobic pass in each tank to an anaerobic zone to promote enhanced biological phosphorus removal (EBPR). Denitrification of the nitrate recycled with the RAS is also achieved.

Blower and Aeration Control Upgrades

In 2016, the Westfield WRF completed a project to right-size its aeration blowers, which were too large, and to improve energy efficiency. Three, 125 hp (93.2 kW), high-efficiency, positive-displacement blowers supply air to the aerobic portions of the aeration basins. The blowers discharge into a common air header that branches into air supply headers dedicated to each basin.

At the same time, the DO-based aeration control system was updated. Each basin's air header has an automated control valve, air flow meter, and a manual control valve. Each train has an *in situ* optical DO probe at the end of the second pass that measures DO concentration, which is used to control blower speed. The automatic control valves are modulated to distribute the air between the basins based on the DO concentration. The control logic is written with most open valve control, which aims to minimize the system air pressure to save energy. Control setpoints, deadbands, and step adjustments can be changed, and operators monitor performance through the Westfield WRF's SCADA system.

Initial Ammonia-Based Aeration Control Trial

In the late summer of 2017, the Westfield WRF operators added an ion selective electrode (ISE) ammonium probe to the aerobic zone in Train 1. An ISE-style probe was preferred over reagent analyzers because the ISE probes are immersed within the mixed liquor without the need for liquid reagents, which can freeze in winter temperatures. A specific brand of ISE ammonium probe was selected to ensure compatibility with the brand of existing instruments and controllers at the Westfield WRF.

The SCADA programming was updated to include another control loop to raise or lower the DO setpoint based on the probe's measured ammonia concentration. Once nitrification was established in the spring of 2018, the Westfield WRF began to run the system with its updated aeration control scheme based on the ammonia probe measurements. While this period was not part of the official pilot test, it led to several insights, including the following:

- The ISE ammonia probe was initially at the end of the aeration basin (at the end of Pass 3). When the Westfield WRF is fully nitrifying, ammonia concentrations at this location are typically less than 1 mg/L and outside the probe's accuracy range. In the summer of 2018, the probe was relocated upstream to the center of the aerobic portion of the aeration train (at the end of Pass 2) to measure higher *in situ* ammonia concentrations (within the optimum range of the probe) and obtain better ABAC control.
- The Westfield WRF maintains the probes with routine calibrations and has an annual service contract with the probe supplier. Despite these efforts, there have been instances where the accuracy of the probe has drifted. Since the Westfield WRF has only one probe, it was decided to maintain DO as the primary control parameter and investigate permutations of ABAC coupled with DO control to maintain maximum process stability and avoid potential permit violations and deleterious environmental impacts.

Diffuser Upgrades

In March 2019, the Westfield WRF operators replaced the membrane diffusers along the bottom of Aeration Basin 1 to improve overall oxygen transfer efficiency within the system. Because of this upgrade, data from prior years could not be used as a direct comparison for the ABAC pilot testing period.

METHODOLOGY

The ABAC pilot test occurred between June 2019 and October 2019. Testing was divided into two phases: 1) a DO control mode to establish baseline conditions, and 2) the ABAC mode. Operational impacts of ABAC mode at the Westfield WRF were quantified, including DO concentrations, energy use, and chemical use. Additionally, overall nutrient removal performance and other operating and maintenance impacts were tracked during the pilot test.

Baseline—DO Control Mode

The pilot test plan included one month of operation in DO mode to establish a new baseline to compare to the ABAC mode results. Between June 17, 2019, and July 15, 2019, the system was operated in DO control mode with a fixed DO setpoint of 2 mg/L. These concentrations were measured in real time by *in situ* optical DO probes at the end of the second pass in each of the three aeration basin trains and reported to both the SCADA system and the programmable logic controller (PLC)-based DO control system. The SCADA system logged the data continuously while the PLC-based DO control system used the DO concentration in the control loop.

Demonstration—ABAC Mode

Because the Westfield WRF has only one ISE-ammonium probe, it was decided to continue with an ammonia feedback control loop to the DO system rather than use direct control. In ABAC mode, the operator sets an ammonia concentration setpoint via the SCADA system. The ammonia probe measures the ammonia concentration and compares it to the setpoint to determine whether changes in DO setpoints are required. If the ammonia concentration exceeds the setpoint, the system will increase the DO setpoint, and if it is lower than the setpoint, the system will decrease the DO setpoint. Upper- and lower-bound DO setpoints are also programmed into the system.

Throughout the ABAC mode period, tuning parameters for the control system were re-evaluated based on performance. Overall, adjustments were minor and included modifications to the ammonia trim settings and valve adjustment timing tuning.

Data Collection

Throughout the pilot test period, water quality data, probe maintenance efforts, operational parameters, and chemical and energy use were monitored to assess piloted control strategy performance. The data collection plan included the following:

- SCADA system data was exported and analyzed, including real-time ammonia and DO concentrations from the probes, blower speeds, header pressures, valve positions, and airflows
- Influent, primary effluent, and final effluent 24-hour composite samples were monitored for BOD, total suspended solids, total nitrogen, ammonia, and total phosphorus. The samples were analyzed both by a third-party contract laboratory and the Westfield WRF in-house laboratory. Twenty-four-hour composite effluent samples confirmed system performance. Sampling frequency aligned with the Westfield WRF's permit requirements and included daily and weekly collection frequencies.
- Chemical addition quantities of caustic soda and sodium aluminate
- Weekly ISE-ammonium probe cleaning and calibration results
- Operational data such as solids retention time (SRT) and sludge settleability

Energy Use

Energy use during each pilot mode was calculated based on Adiabatic principles (see Equation 1).

Operations

Throughout the pilot test period operations were kept consistent by maintaining a stable SRT and keeping a constant number of trains in service. Primary effluent BOD and influent Total Kjeldahl Nitrogen (TKN) sample results remained relatively uniform as shown in Figure 2.

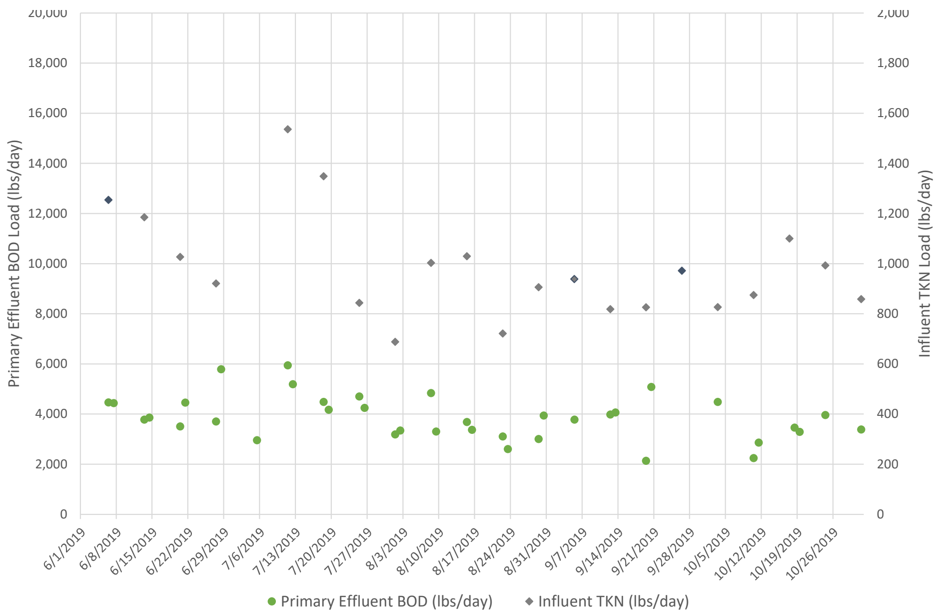


Figure 2. Primary effluent BOD and influent TKN loads during pilot test period

Aeration Tank Profiles

DO concentrations were measured, and grab samples were collected at eight points along the aeration basin and analyzed for ammonia, nitrate, and ortho-phosphate using a spectrophotometer during the pilot test. Figure 3 illustrates the grab sample collection locations along the length of the tanks. The DO and ammonia probes are located approximately in Area 5.

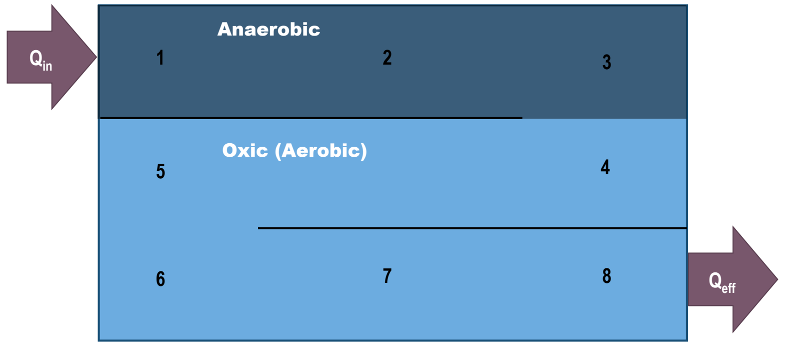


Figure 3. Aeration basin profile grab sample collection locations

Equation 1

$$kWh = brake\ horsepower\ of\ the\ blower * \frac{0.746\,\frac{kWh}{hp}}{motor\ efficiency * VFD\ efficiency}$$

Where: motor efficiency = 95% and VFD efficiency = 97% and

$$brake\ horsepower = \left(\frac{CFM*0.01542*inlet\ pressurePSIA*\left(\left(\frac{(14.7+header\ pressure\ PSIG)}{inlet\ pressure\ PSIA}\right)^{(0.283)}-1\right)}{blower\ efficiency}\right)$$

Where: blower efficiency varies between 65% - 70%, and inlet pressure = 14.7 PSIA

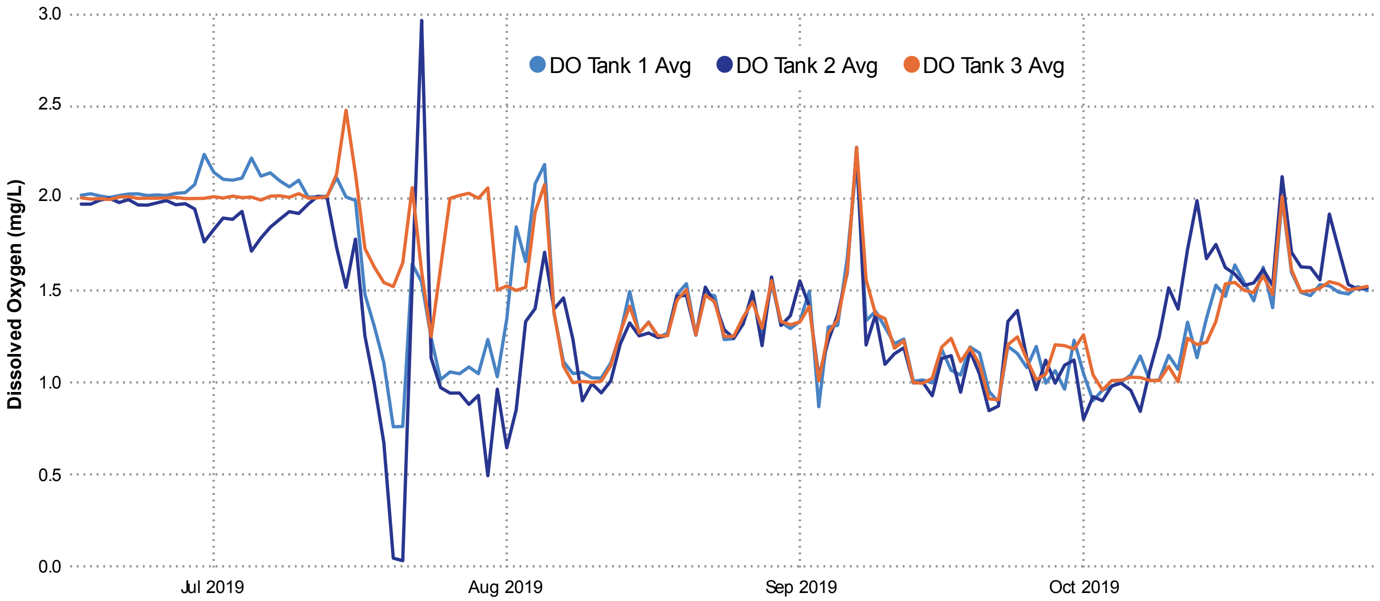


Figure 4. Dissolved oxygen concentrations pilot test period (June 17– October 31, 2019)

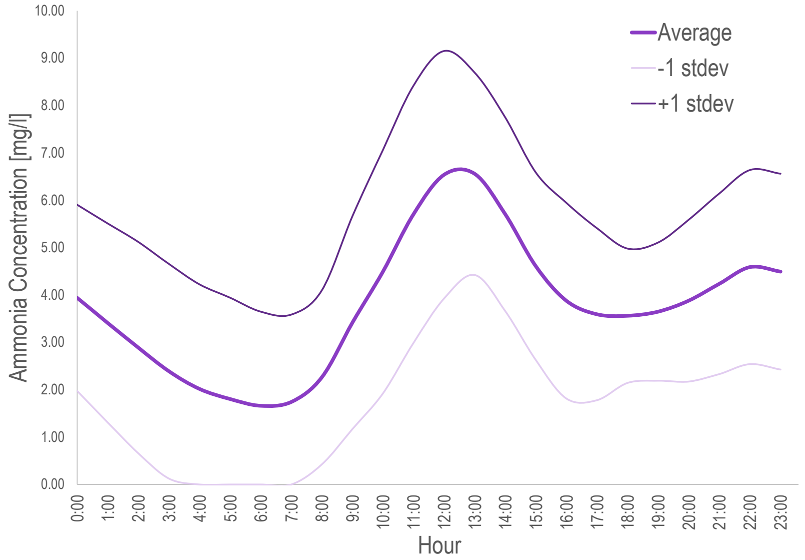


Figure 5. Ammonia concentration trend from probe for September 2019

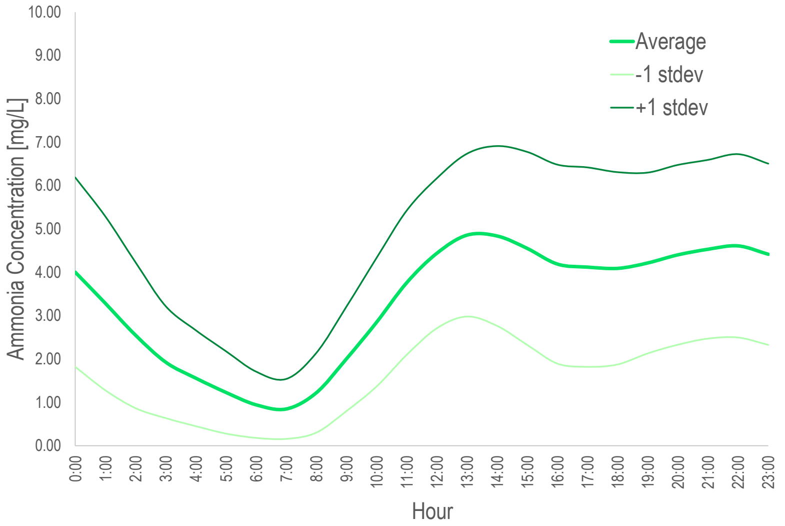


Figure 6. Ammonia concentration trend from probe for October 2019

RESULTS

Unstable Aeration Control Period

Before the start (in mid-July) of the ABAC pilot test period, the quantity of air supplied by the blower was controlled based on average DO concentrations from DO probes in the three trains. As shown in Figure 4, this resulted in variability in the DO concentrations among the trains.

In mid-July, when the DO setpoint was lowered by the ABAC control loop, the differences became more pronounced and resulted in unstable control that negatively affected performance. The Westfield WRF worked with its SCADA contractor to update the control scheme, and the system re-stabilized in mid-August. The ABAC pilot test was restarted on August 12, 2019, and ran through October 31, 2019. DO concentrations averaged closer to 1.4 mg/L in ABAC mode versus 2 mg/L during the DO control mode baseline.

Changing Influent Load Dynamics

A major industrial discharger to the Westfield WRF ceased operations on September 30, 2019. While changes to influent loads based on the Westfield WRF's 24-hour composite samples (Figure 2) were not readily apparent, it did change the dynamics within the aeration basins. Figures 5 and 6 show the average daily ammonia trend measured by the ammonia probe for September 2019 and October 2019, respectively. Because of the lower peak nutrient loading, the ammonia control loop was rarely triggered in October, and the system remained operating primarily in DO control mode.

Therefore, the comparison between DO control mode and ABAC mode was based on the following periods when operational conditions were stable and representative:

- DO control baseline data was collected between June 17, 2019, and July 15, 2019
- ABAC control data was collected between August 12, 2019, and September 30, 2019

Energy Savings

Figures 7 and 8 show the average daily blower energy use during the pilot test baseline period from June 17, 2019, to July 15, 2019 (Figure 7) and ABAC period from August 12, 2019, to September 30, 2019 (Figure 8).

The average daily blower energy use was calculated using Equation 1. The average daily blower energy use was 1,780 kWh for the DO baseline period and 1,510 kWh for the ABAC period.

The DO baseline period comprised 29 days (29 samples), and the ABAC period comprised 50 days (50 samples). Each day is considered an individual sample within the pilot study period. The average daily blower energy use values were compared to determine if they were statistically significantly different using the student's two-sample t-test with correction for unequal sample size, at a significance level (alpha) of 0.05. The actual aeration energy reduction of 15 percent was calculated to be highly statistically significant at the given alpha (the p-value of the test was 4.00 E -8). This indicates that the energy reductions are unlikely to be caused by random variations in Westfield WRF operation and lends credence to the effectiveness of the ABAC operating mode.

Figure 9 shows the average diurnal energy use comparison between the DO control baseline period and the ABAC mode period. Throughout most of the day, energy consumption was lower in ABAC mode. Energy consumption during ABAC exceeded the average of DO control mode for only a short duration in the afternoon when the diurnal peak load was received by the aeration basins. This condition usually persisted for less than three hours.

Chemical Savings

Operating in ABAC mode reduced the amount of sodium hydroxide needed for the secondary process by 20 percent, as shown in Figure 10. Approximately 250 gal (946 L) per day of sodium hydroxide was added during the DO baseline period, and only 200 gal (757 L) per day was added during the ABAC period. However, no savings accrued from sodium aluminate usage as that need was not reduced during the pilot test when the system was operating in ABAC.

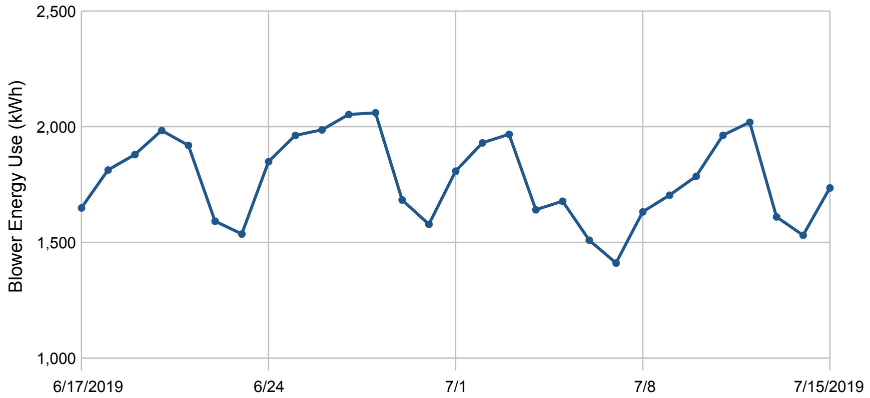


Figure 7. Pilot test baseline, DO control mode—blower energy use

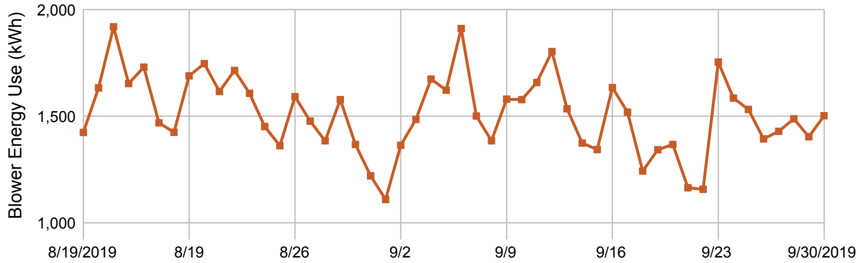


Figure 8. Pilot test ABAC mode—blower energy use

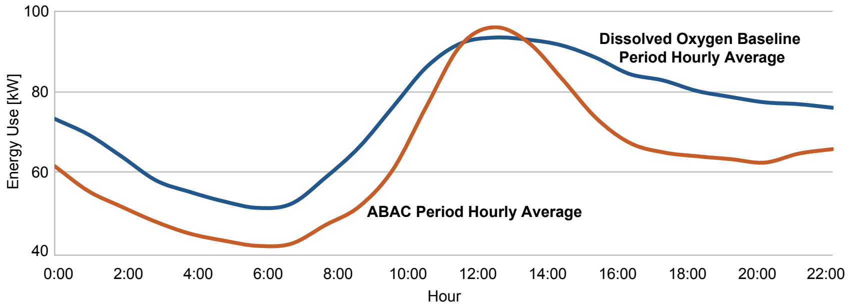


Figure 9. Average blower energy consumption by hour during pilot test periods

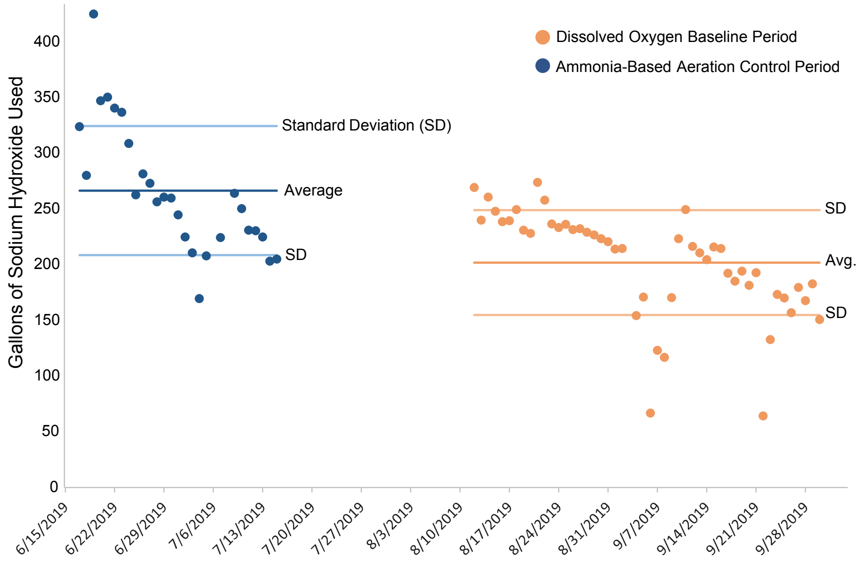


Figure 10. Sodium hydroxide use during pilot periods

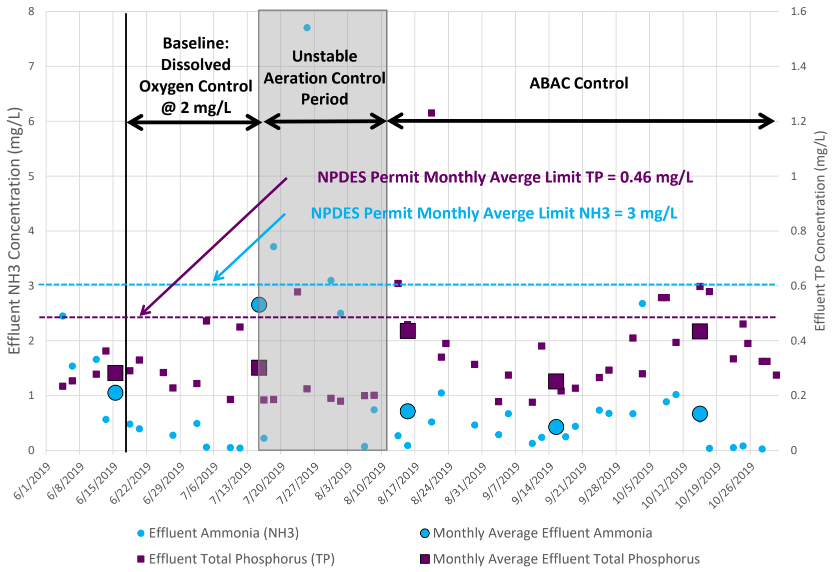


Figure 11. Effluent ammonia and total phosphorus

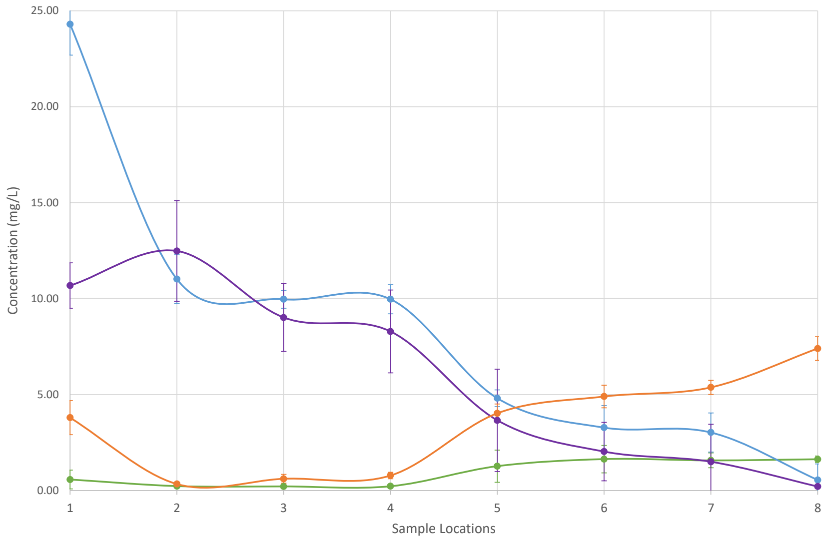


Figure 12. Average pilot test sample location constituent concentrations

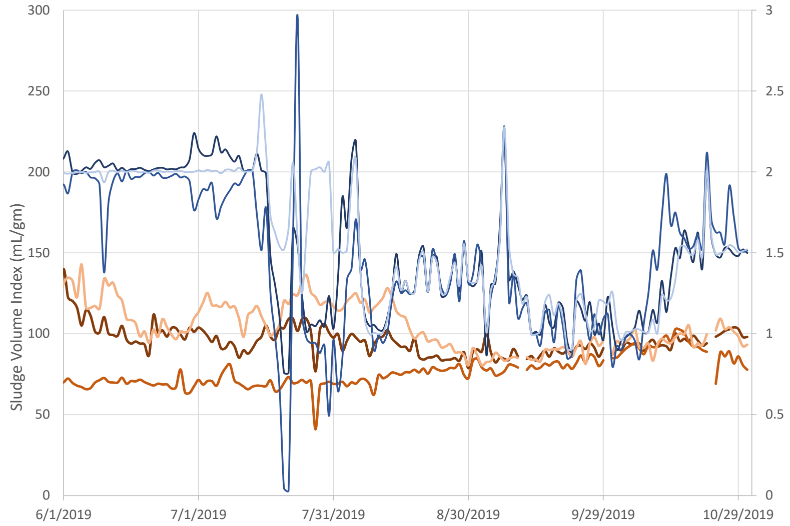


Figure 13. SVI versus dissolved oxygen concentrations in aeration trains

Impact on Nutrient Removal

Twenty-four-hour composite effluent samples confirmed system performance. The Westfield WRF continued to meet its NPDES permit requirements, including phosphorus and ammonia limits, throughout the pilot study, as shown in Figure 11.

Aeration Tank Profiles

Constituent concentration profiles along the lengths of the aeration basins were developed from samples taken on three Monday afternoons: July 1, July 8, and July 15. Figure 12 summarizes the chemical profile results measured within Aeration Basin 1.

Figure 12 illustrates what is expected in this type of nutrient removal system, including a reduction of nitrate (which is returned to the head of the aeration tank in RAS) in Area 1 of the anaerobic zone, phosphorus increase in the anaerobic zone, and low DO throughout the anoxic/anaerobic zone. In the aerobic zone, the concentration of ammonia decreases as nitrate increases, and the concentration of phosphorus decreases.

DISCUSSION

An aeration system energy reduction goal of 10 percent to 15 percent was targeted at the start of the pilot. The pilot achieved this energy savings goal while also meeting the NPDES phosphorus and ammonia permit limits. The actual aeration energy reduction averaged 15 percent. The average DO concentrations while operating in ABAC mode were 1.4 mg/L, while average DO concentrations operating in DO control mode were 2.0 mg/L.

When operating in ABAC mode, the Westfield WRF experienced no major negative impacts on solids handling and the operational mode did not increase odor production. Sludge settleability also remained relatively consistent throughout the pilot. In fact, the sludge volume index (SVI) in the three trains converged following the updates to the aeration control system in mid-August, as shown in Figure 13.

Despite minimal impacts on process performance, the Westfield WRF operators and their pilot test partners collected and analyzed data to confirm how the ABAC process was performing. The Westfield WRF also engaged its SCADA programmers to collect the required data from SCADA and then implement changes to the control scheme based on the data analysis. This learning curve and initial investment during startup and tuning would be expected for any WRRF implementing ABAC (or any new control scheme).

Return on Investment

Table 2 summarizes the ROI for implementing the ABAC pilot test at the Westfield WRF.

The ROI is about seven years and was calculated based on the following:

- Cost of the ammonia probe and replacement parts, calibration, monitoring, and maintenance (The probe was plugged into an existing controller and no additional wiring was needed.)
- Cost of SCADA controls upgrade to incorporate an ammonia loop into the aeration control system, monitoring, and tuning
- Data analysis and pilot test support
- Blower energy use savings
- Chemical addition savings with pH/alkalinity control

When the Massachusetts Clean Energy Center grant amount of $50,000 is credited to the capital cost, the payback period drops to three years.

The ABAC system cost will vary based on the size and complexity of the aeration system (number of tanks, automatic valves and associated flow meters, existing SCADA control logic, and instrumentation). ABAC implementation requires a facility to automatically modulate airflows to the aeration tanks via automatic control valves and blower airflow controls. Facilities without this level of automation already will require an additional investment to put these components into place in addition to the ammonia probes and control logic.

CONCLUSIONS

Based on the results of this pilot test and the calculated ROI, ABAC was successfully implemented at the Westfield WRF. The Westfield WRF plans to continue using the piloted ISE ammonium probe for process monitoring and ABAC.

Staff at the Westfield WRF are passionate about communicating the value of clean water, and they sought to become a local innovation showcase from which other operators can learn and to speed adoption of the ABAC technology more broadly. During the pilot test, the Westfield WRF hosted a successful Poo & Brew on October 16, 2019, which was co-sponsored by NEWEA and the Northeast Residuals & Biosolids Conference. Over 100 young professionals, operators, engineers, equipment suppliers, regulators, students, and public officials, including the mayor of Westfield, attended the event.

These results show that ABAC can be implemented at smaller WRRFs. However, the ROI for every facility will differ. While the ammonia probe is the cornerstone of ABAC, the overall control scheme hinges critically on a foundation of right-sized blowers, a stable aeration control system, and an air delivery system composed of modulating valves, DO probes, and diffusers that can deliver air where and when needed. Westfield WRF already had this foundation in place when it implemented ABAC, but other WRRFs may require greater capital investments. By implementing ABAC, the Westfield WRF also reduced the quantity of sodium hydroxide needed for supplemental alkalinity, a significant factor regarding ROI. A thorough ROI analysis that considers more than just the initial ammonia probe costs and the savings from energy reductions is important.

Table 2. Return on investment for WRF pilot project

Category	ROI
Baseline blower energy use[1]	1,780 kwh/day
Projected energy savings[2]	15%
Fraction of year nitrifying[3]	0.58
Unit electricity cost[4]	$0.125
Energy savings[2]	$7,000
Chemical savings[2]	$10,000
Annual cartridge and maintenance costs[5]	$3,500
Total annual costs and savings[5]	$13,500
Capital equipment/ SCADA cost[6]	$90,000
Simple payback	6.7 years

1. Based on Westfield SCADA Data
2. Calculated based on pilot test
3. Westfield WRF was not designed for year-round ammonia removal and cannot maintain nitrification during cold temperatures in winter. Based on past data, the WRF nitrifies approximately seven months out of the year.
4. City of Westfield
5. Based on current supplier service contract for probe, replacement cartridges, and cost for in-house probe calibration analytical supplies. Labor costs were not included for this project because no additional Westfield WRF staff were required.
6. Equipment and initial installation costs for a new ISE probe and accessories estimated to be $10,000 based on a quote provided by the probe supplier to the City of Westfield on April 20, 2018. One ISE ammonium probe is approximately $7,500. Related mounting equipment, cables, cleaning units, and one-year service warranty are approximately $7,600. Westfield added the probe to an existing controller, and no new conduit/wires were needed. SCADA modifications, data analysis and support during the grant period were based on the ABAC project cost of $75,000.

Toth et al. (2018) developed a methodology to assess control systems for fixed-bed activated sludge systems and found that while an ROI was possible using ABAC, operator skill also affects the ROI. This pilot study reinforces the importance of the operators in implementing ABAC successfully.

Advanced control strategies such as ABAC need ownership by the operators to fully realize the ROI. Westfield WRF operators needed time to become comfortable with maintaining the instruments, interpreting the data, and subsequently fine-tuning and optimizing the control schemes. The ammonia probe requires frequent calibration; Westfield WRF calibrates its probe every week. With buy-in from the operators to closely monitor and optimize their process, and a clear understanding of the fundamentals, similar-sized utilities can take steps that will achieve savings.

This article was originally published with WEFTEC 2020 Proceedings and is reprinted with permission from the Water Environment Federation.

ACKNOWLEDGMENTS

Special thank you to the City of Westfield for its support and assistance throughout this project, specifically Department of Public Works Director David Billips and the Westfield WRF staff. Thank you also to the Massachusetts Clean Energy Center for its grant support and to the Hach Company for its partnership on this project.

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ABOUT THE AUTHORS

- Susan Guswa has more than 25 years of experience and is Woodard & Curran's municipal wastewater practice leader. She focuses on wastewater treatment and nutrient removal with broad experience in collection systems and pump stations, stormwater, and reuse water. Ms. Guswa received a Bachelor of Science from Duke University and a Master of Science from Stanford University in civil and environmental engineering. She is currently a WEF delegate for NEWEA.
- Julia Beni is an engineer at Woodard & Curran. Her work focuses on wastewater projects. She is interested in the targeted integration of real-time data and statistical analyses to drive performance outcomes and insights for clients. Ms. Beni received her Master of Science in environmental engineering at the University of Minnesota.
- Jeffrey Gamelli has eight years of experience working for the City of Westfield water recovery facility (two years as an operator, six years as deputy superintendent). He focuses on management of the city's wastewater treatment, process control, and nutrient removal and also has experience in collection systems and pump stations. He received a Bachelor of Science in civil and environmental Engineering from UMass Amherst and is a MA Licensed Grade 7-C Operator.
- Ken Gagnon is the chief operator of the Westfield Water Recovery Facility with 15 years of experience in that position. He created and maintains the "heartbeat of the plant" work order system, which has been a crucial asset to the proper operation and maintenance of the facility. He is valued as a "jack of all trades" who can come up with a solution to almost any problem that may arise. Mr. Gagnon holds a MA Grade 7-C Full wastewater operator license.