Real-Time Process Controls to Meet Increasingly Stringent Effluent Limits and Improve Operational Sustainability: A Case Study of Three North Carolina Facilities

Victoria Boschmans[1], Katya Bilyk[2], Erika Bailey[3], Nathan Howell[4], John Dodson[5], Charles Cocker[6]

[1]Hazen and Sawyer, Raleigh, North Carolina
[2]Hazen and Sawyer, Raleigh, North Carolina
[3]City of Raleigh, Raleigh, North Carolina
[4]City of Raleigh, Raleigh, North Carolina
[5]City of Durham, Durham, North Carolina
[6]City of Durham, Durham, North Carolina
[1]Email: vboschmans@hazenandsawyer.com
[2]Email: kbilyk@hazenandsawyer.com
[3]Email: Erika.Bailey@raleighnc.gov
[4]Email: Nathan.Howell@raleighnc.gov
[5]Email: John.Dodson@durhamnc.gov
[6]Email: Charles.Cocker@durhamnc.gov

KEYWORDS
Real-Time Process Control, Automation, Instrumentation, Process Modeling, Nutrient Removal

INTRODUCTION

The purpose of this paper is to present real-time process control (RTPC) programs and illustrate historical plant performance from three North Carolina facilities to demonstrate benefits and challenges associated with using RTPC programs.

RTPC strategies rely on on-line analyzers for process control parameter measurement including ammonia, nitrate, dissolved oxygen (DO), mixed liquor solids concentrations, and plant flows. These controls utilize chemistry and process equations to calculate real-time set points based on system flows, loads, and demands. The purpose of these programs is to assist in reliably maintaining nutrient removal and improving operational efficiency by matching control set points to system demands. Operating data post-program implementation were analyzed to evaluate changes in operational efficiency and cost savings resulting from RTPCs.

MEET THE FACILITIES

The following facilities are presented in this paper: Neuse River Resource Recovery Facility (NRRRF), North Durham Water Reclamation Facility (NDWRF), and South Durham Water Reclamation Facility (SDWRF). Each of these facilities has preliminary treatment, primary clarifiers, a 4 or 5-stage biological nutrient removal (BNR) process, filters, and must meet stringent effluent total nitrogen limits.

Table 1 provides an overview of facility configuration for nutrient removal along with current performance indicators.

Table 1: Facility Summary

Facility	2018 Effluent TN (mg/L)	2018 Effluent TP (mg/L)	Carbon	Metal Salt	Primary Clarifiers
NRRRF	2.1	1.4	Yes	Yes	Yes
NDWRF	2.4	0.1	Yes	Yes	Yes
SDWRF	6.6	0.3	No carbon feed required, but ability to feed carbon	Yes	Yes

Neuse River Resource Recovery Facility

The City of Raleigh's NRRRF is an advanced nutrient removal facility with a permitted flow of 75 mgd. As a significant discharger to the Lower Neuse River Basin, the Neuse River RRF is subject to a stringent annual total nitrogen (TN) load allocation (687,373 lb TN/year) established under the Neuse River Basin Nutrient Management Strategy. As permitted flow increases, the City will be required to achieve lower effluent TN concentrations to continue to meet the same TN load allocation.

NRRRF achieves low level nitrogen through use of a 4-stage biological nitrogen removal activated sludge process followed by denitrification filters for TN removal polishing. The 4-stage process includes a first stage anoxic zone and second stage anoxic zone for nitrogen removal. Supplemental carbon is routinely fed to the second stage anoxic zone to provide additional organic carbon needed for denitrification at the end of the aerobic zone. Supplemental carbon can also be added to the first stage anoxic zone, although this option has not yet been needed. Additional supplemental carbon is added to the filters to drive dentification for any additional nitrate removal needed downstream of the biological treatment system.

The Neuse River RRF must also meet a quarterly average effluent total phosphorus (TP) concentration of less than 2 mg/L. Phosphorus removal has been primarily achieved via chemical phosphorus removal with alum addition to the activated sludge process for precipitation of orthophosphate.

North Durham Water Reclamation Facility

The City of Durham's NDWRF is a 20 mgd plant subject to the Falls Lake Rules, which impose an annual mass limit equivalent to an effluent TN limit of 1.6 mg/L and effluent TP limit of 0.11 mg/L at 20 mgd. NDWRF utilizes preliminary, primary, secondary and tertiary treatment to treat the wastewater.

South Durham Water Reclamation Facility

The City of Durham's SDWRF is a 20 mgd plant treating 10 mgd with a mass equivalent TN limit of 5.5 mg/L and 0.23 mg/L TP at 20 mgd. The TN limit will soon be reduced to 3.0 mg/L as part of the Jordan Lake Rules. SDWRF has a 5-stage BNR process with capability to feed carbon. However, the SDWRF process does not currently require carbon dosing.

REAL-TIME PROCESS CONTROLS

NRRRF, NDWRF, and SDWRF have RTPC strategies for nitrification, denitrification, and solids separation. **Table 2** Illustrates programs and their installation year. **Figure 1** presents a partial site plan and instrumentation diagram at NRRRF as an example of instrumentation utilized for these RTPC programs. **Figure 2** highlights the key automation programs and anticipated benefits of each. In addition to minimizing operational costs, these RTPCs can automate certain routine decisions that operators make, freeing up their time for other tasks.

Table 2: Year in Which RTPC Programs Were Initiated

<table>
<tr><td colspan="2">Nutrient Removal Process</td><td colspan="3">Nitrification</td><td>Denitrification</td><td>Solids Separation</td><td rowspan="2">TN Goal at Design Flow (mg/L)</td></tr>
<tr><td colspan="2">Real-Time Process Control Program</td><td>Ammonia Based Aeration Control</td><td>Aerobic SRT Control</td><td>Ammonia-Load-Based Flow Equalization</td><td>Nutrient-Analyzer-Paced Supplemental Carbon Feed</td><td>Secondary Clarifier Guidance</td></tr>
<tr><td rowspan="3">Facility Name</td><td>NRRRF 75 mgd</td><td>2018</td><td>-</td><td>2018</td><td>2018</td><td>2018</td><td>3.0</td></tr>
<tr><td>NDWRF 20 mgd</td><td>2015</td><td>2016</td><td>2016</td><td>2016</td><td>-</td><td>1.6</td></tr>
<tr><td>SDWRF 20 mgd</td><td>2015</td><td>2016</td><td>-</td><td>2016</td><td>-</td><td>3.0</td></tr>
</table>

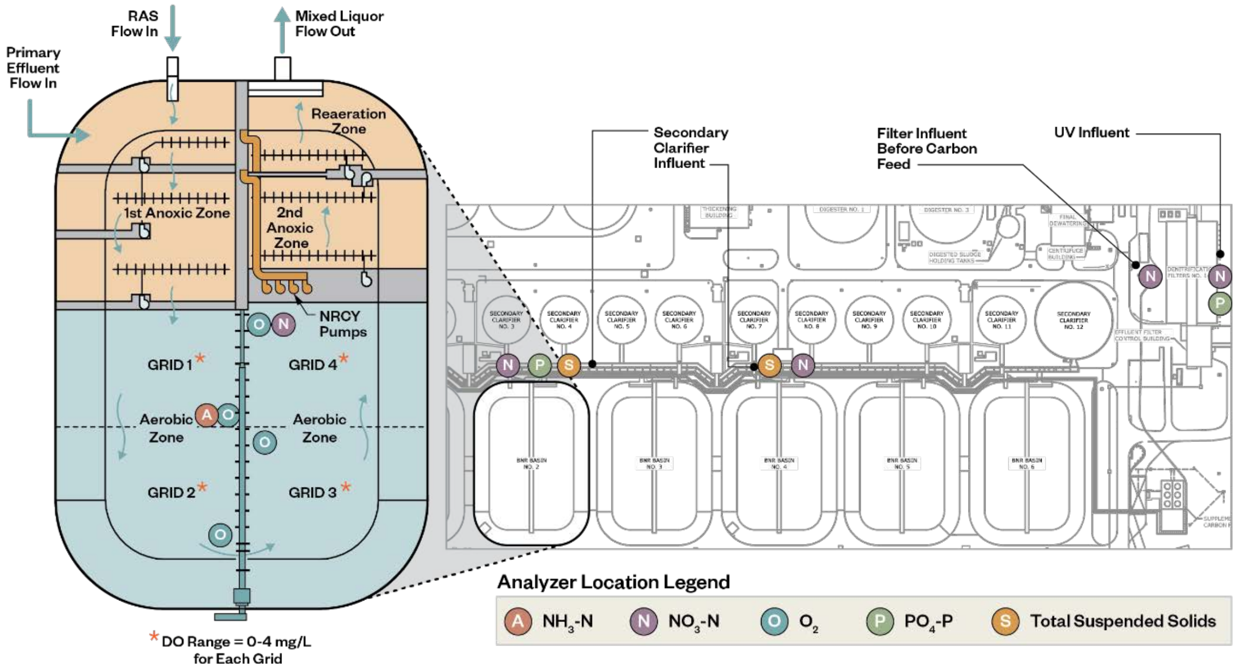

Figure 1: NRRRF Partial Site Plan and Instrumentation Diagram

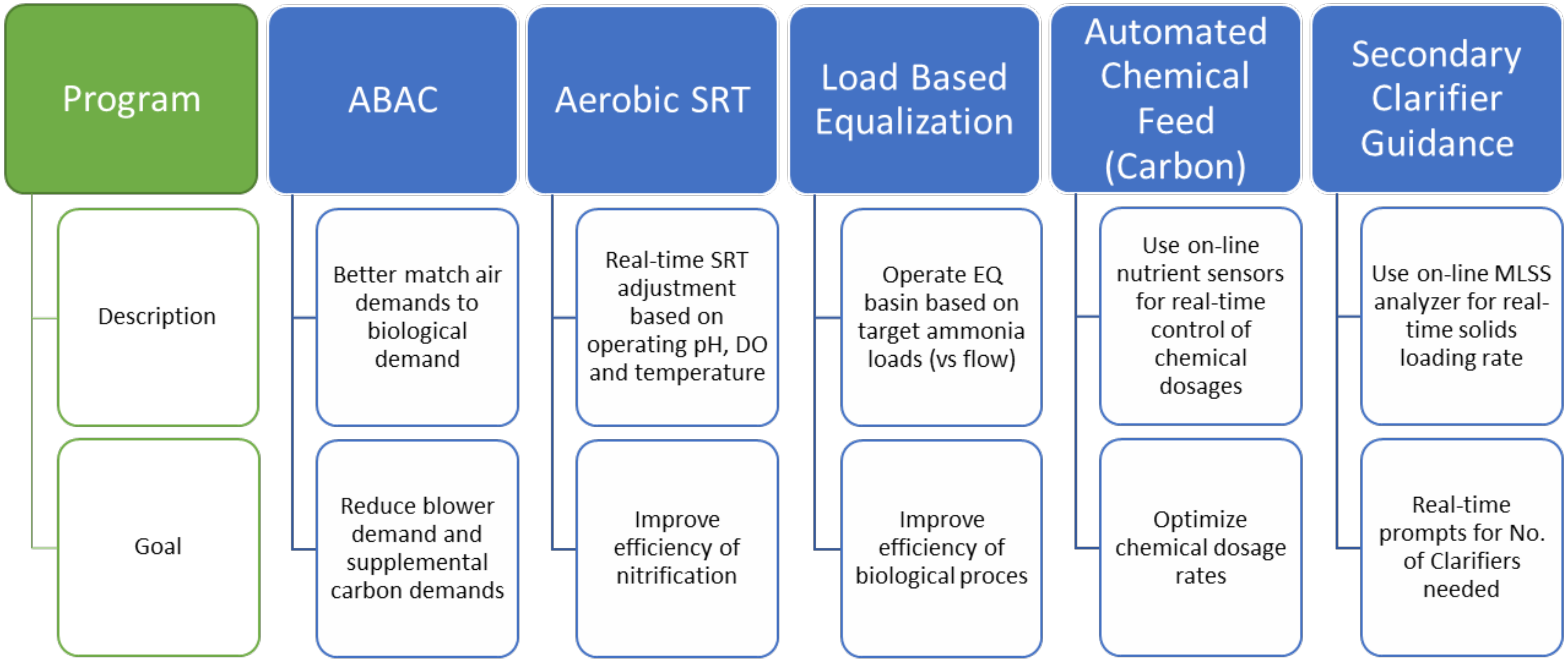

Figure 2: PTPC Program Summary

Instrumentation

On-line instrumentation is required for RTPC and monitoring to achieve challenging wastewater treatment objectives while minimizing operational costs. The on-line instrumentation required for the RTPCs in this paper include the following:

- Ammonia analyzers
- Dissolved oxygen probes
- Flow meters
- Nitrate analyzers
- Phosphate analyzers
- Total suspended solids analyzers

Nitrification

Process controls and measurements related to nitrification performance and reliability include temperature, flow, wasting rate, solids retention time (SRT), DO concentration, airflow distribution, DO control valve positions, DO probes, and any ammonia probe(s) in the BNR basins. This section will discuss several options for optimizing nitrification including ammonia-load-based equalization, ammonia-based aeration control, and SRT control.

Nitrification: Ammonia-Load-Based Equalization

Ammonia-load-based equalization allows facilities with diurnal equalization and/or wet weather equalization to control the filling and emptying of an equalization basin with the objective of maintaining a consistent ammonia load to the downstream process. This reduces the variability in required airflow, stabilizes blower operations and reduces peak energy demand for the aeration system. The stability of the nitrification process also improves as a result of the more consistent ammonia load. As a result, the load of nitrate to the anoxic zones is also equalized, thus making the anoxic zones perform more consistently to optimize TN removal.

The process controls and measurements that are related to nitrogen load equalization include an ammonia probe upstream of the point of diversion to equalization, and flow meters and valves associated with the following flows: to BNR process, to equalization basin, out of equalization basin.

In this mode of operation, the operator selects an ammonia mass target to the process. The algorithm to control the diversion of flow into and out of the equalization basin performs a calculation at regular intervals to compare the actual load and the desired load to the basins. Based on the degree of difference, the program determines whether flow should go into or come out of the equalization basin to achieve the desired ammonia load to the basins.

Nitrification: Ammonia Based Aeration Control (ABAC)

ABAC can reduce energy and supplemental carbon requirements while achieving simultaneous nitrification and denitrification (SND). In this mode of operation, an ammonia probe located in the aerobic zone is used to ensure that full nitrification is taking place within the aerobic volume. The DO concentration can fluctuate and be at the minimum possible value that still maintains the desired ammonia setpoint and achieves minimum mixing requirements. The DO concentration can be varied from almost zero to whatever upper limit the program will allow. The airflow rates can temporarily (on the order of 20-30 minutes) drop below minimum mixing if the ammonia concentration is acceptable. There is a periodic cycle that increases air flow to minimum mixing for three minutes to resuspend any settled solids. ABAC provides benefits including efficiently matching air to biological demand and reducing blower and supplemental carbon demand (see **Figure 3**).

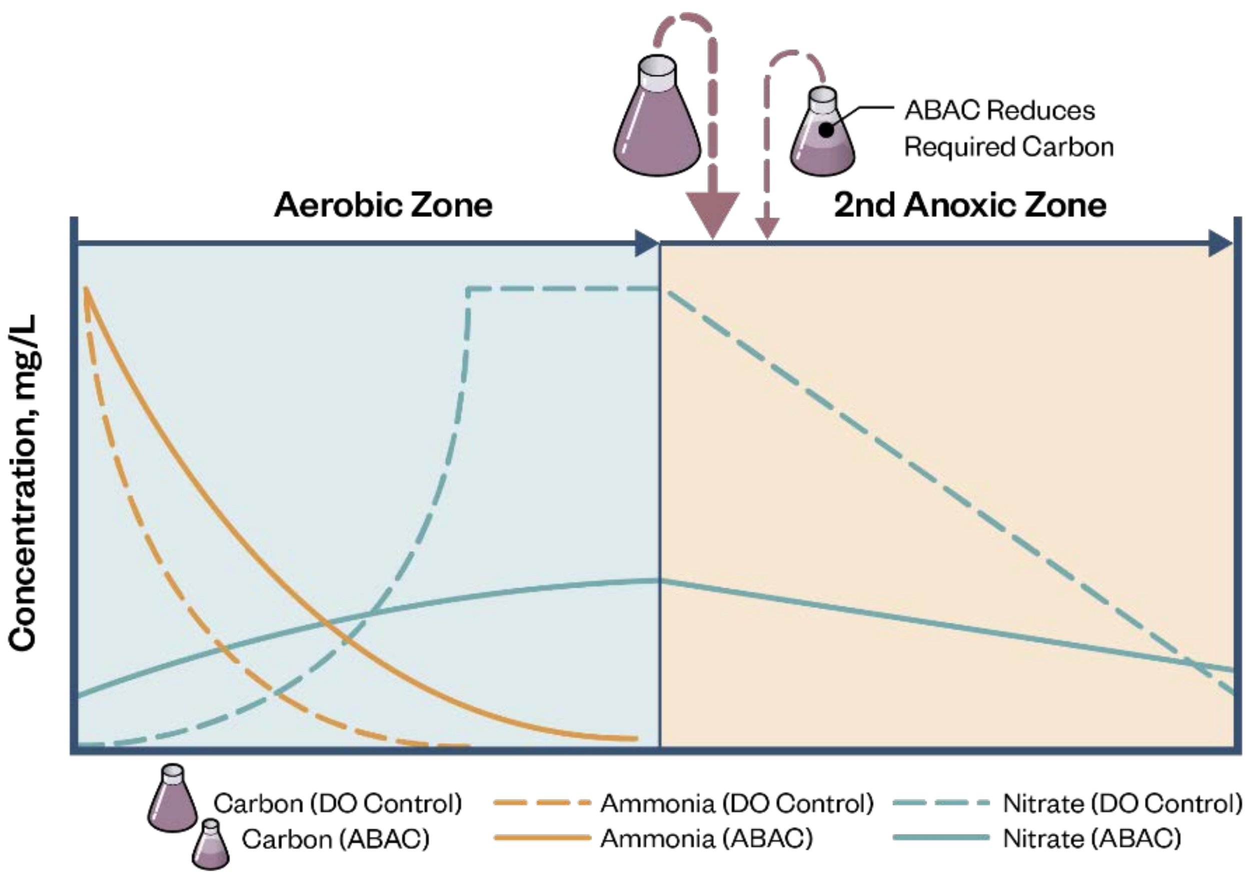

Figure 3: Ammonia Based Aeration Control

ABAC provides enough air for full nitrification, but during low loading conditions allows the DO to decrease to minimum mixing airflow if the ammonia setpoint is being met, which encourages SND as shown in **Figure 4.**

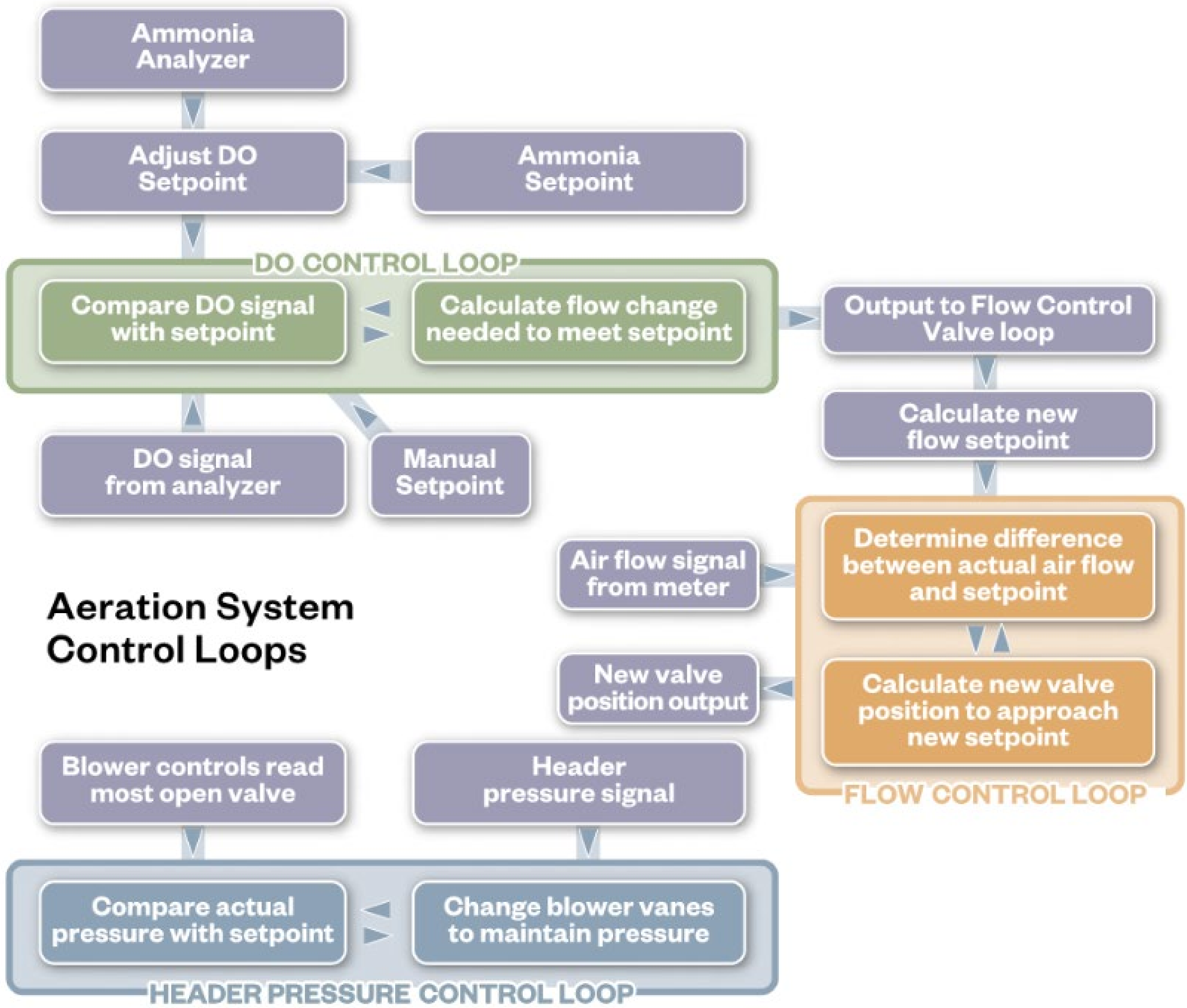

Figure 4: Ammonia Based Aeration Control Loops

Nitrification: Aerobic SRT Control

Assuming uninhibited growth and proper DO control; pH, DO and temperature determine the required SRT to maintain full nitrification. *BioWin™* modeling can be used to generate a table that presents minimum aerobic SRT as a function of pH, DO and temperature specific to each facility. On-line solids analyzers are used to calculate the actual SRT of the system knowing the aerobic volume online and mixed liquor suspended solids (MLSS) concentration. The required and actual SRTs are compared and feedback is given to the operator regarding the plant's position relative to the minimum required aerobic SRT. Wasting can be automated to maintain the desired aerobic SRT with some factor of safety.

Denitrification

Process controls and measurements related to denitrification include temperature, flow, WAS rate, SRT, the amount of DO entering the anoxic zones, the ratio of biodegradable COD to total

Kjeldahl nitrogen (TKN), the TKN concentration and load itself, the anoxic hydraulic retention time, and NOx-N and/or oxidation-reduction potential (ORP) probes in the BNR basins.

Denitrification: Carbon Nutrient-Paced Dosing

Chemical feed systems have traditionally had a manual and a flow-paced mode for delivery. On-line analyzers and accompanying feed programs allow a third mode, nutrient-paced mode, which is the most efficient mode. Nutrient-paced mode utilizes a feedforward and/or feedback loop to accurately pace chemical addition to demand.

The process controls and measurements that are related to supplemental carbon addition include plant flow meters and nitrate probes at the end of the aerobic zone, first anoxic zone, secondary clarifier influent channel, secondary effluent, and filter effluent.

The nitrate concentration at the end of the aerobic zone and the flow (influent, RAS, and internal recycle rate—if carbon is being added to the first anoxic zone) are used to estimate the mass of nitrate entering the first and second anoxic zones. Using this mass, the amount of carbon required to remove the calculated mass of nitrate is determined and used to set the carbon feed pump rate. The user also sets an effluent nitrate concentration setpoint for each anoxic zone, and the anoxic zone effluent nitrate probes are used to adjust the speed of the carbon feed pumps accordingly using a proportional integral derivative (PID) loop or similar approach.

Solids Separation

All activated sludge plants, regardless of whether they have a nutrient removal objective, must achieve adequate solids separation to perform well and meet their objectives. The solids separation process can be represented as a function of the following independent variables: mixed liquor suspended solids concentration, hindered settling coefficient, settling velocity, forward flow, RAS flow, and the number of clarifiers in service, represented by the total surface area.

Solids Separation: Secondary Clarifier Guidance Program

State point analysis (SPA) is commonly used to provide a simplified determination of whether a clarifier will fail under a given set of conditions. This approach was utilized to develop a RTPC program to monitor secondary settling at the NRRRF. This program is described as follows.
A series of SPAs using site-specific settling data for the NRRRF and a matrix of over 60 possible clarifier combinations and conditions were developed. The SPAs were then summarized using a multivariable linear regression (MVLR) equation to represent the required clarifier surface area as a function of the following variables: mixed liquor suspended solids measured by an on-line TSS probe (MLSS); plant flow (Q); RAS flow (Qras); and sludge volume index (SVI).

After simulation of the matrix of clarifier alternatives, the following equation was developed using MVLR.

$$\textit{Required Clarifier Surface Area, } ft^2 = -193{,}090 + 981 \times Q + 909 \times SVI - 530 \times Qras + 34.2 \times MLSS$$

This equation is plant specific and integrated into the SCADA system and provides real-time information as to the minimum number of clarifiers that should be in operation. This program is particularly useful during wet weather events when conditions are rapidly changing. For example, this equation prompts an operator that an increase in RAS capacity could reduce clarifier blanket levels since insufficient RAS flow can limit capacity during wet weather events.

Another feature of NRRRF's program is a built-in calculator that operators can use to determine the number of clarifiers needed in service based upon user-entered values for Q, Qras, MLSS concentration, and SVI (see **Figure 5 and 6**). This algorithm was low cost, did not require a calibrated process model, and provides useful guidance to operators during wet and dry weather conditions.

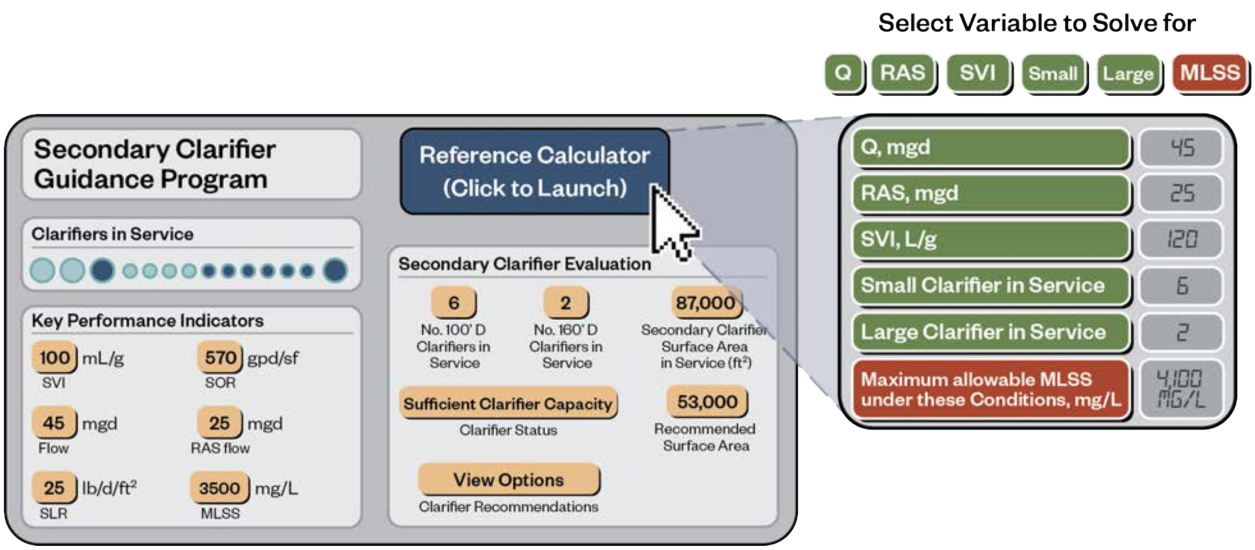

Figure 5: Sample of Secondary Clarifier Guidance Program Screen at NRRRF

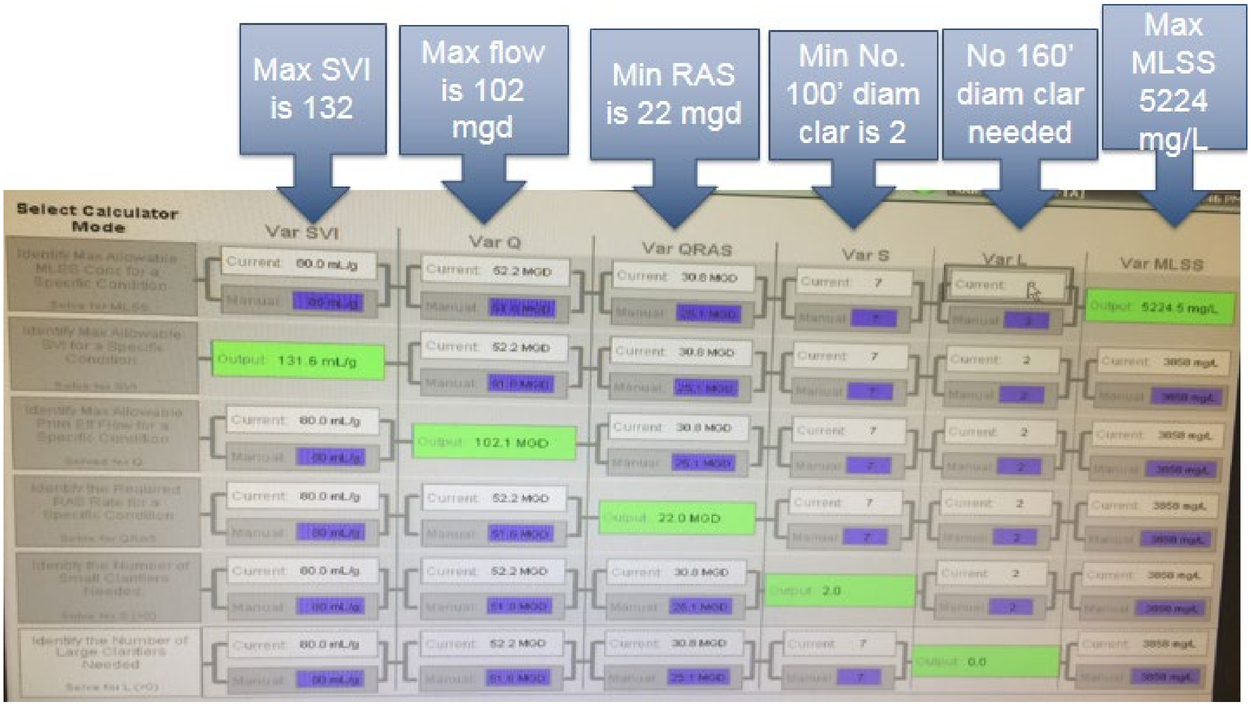

Figure 6: Sample of How the Calculator Works Showing Upper Limits Based on Current Clarifiers in Service

SUMMARY OF FACILITY RTPC OUTCOMES

This section presents RTPC outcomes for NRRRF, NDWRF, and SDWRF.

NRRRF Nitrification & Denitrification RTPCs

The NRRRF ammonia-load-based equalization program was installed in September of 2018. Since installation, NRRRF has found the program to be very useful in stabilizing the overall nutrient removal process.

Figure 7 shows a SCADA display of four consecutive dry weather flow days. The red line (Var C) represents the ammonia load entering the primary effluent distribution box. The load varies from 8,500 to 15,400 lb/d and has an average peaking factor of 1.18 (maximum to average for the four-day period). The lighter blue line (Var A) near the top of the graph represents the calculated mass of ammonia entering the BNR basins. This mass varies from 12,700 to 13,360 and has an average peaking factor of 1.02 (maximum to average for the four-day period). This figure indicates that on average, the program does a nice job of maintaining a constant ammonia load to the BNR basins.

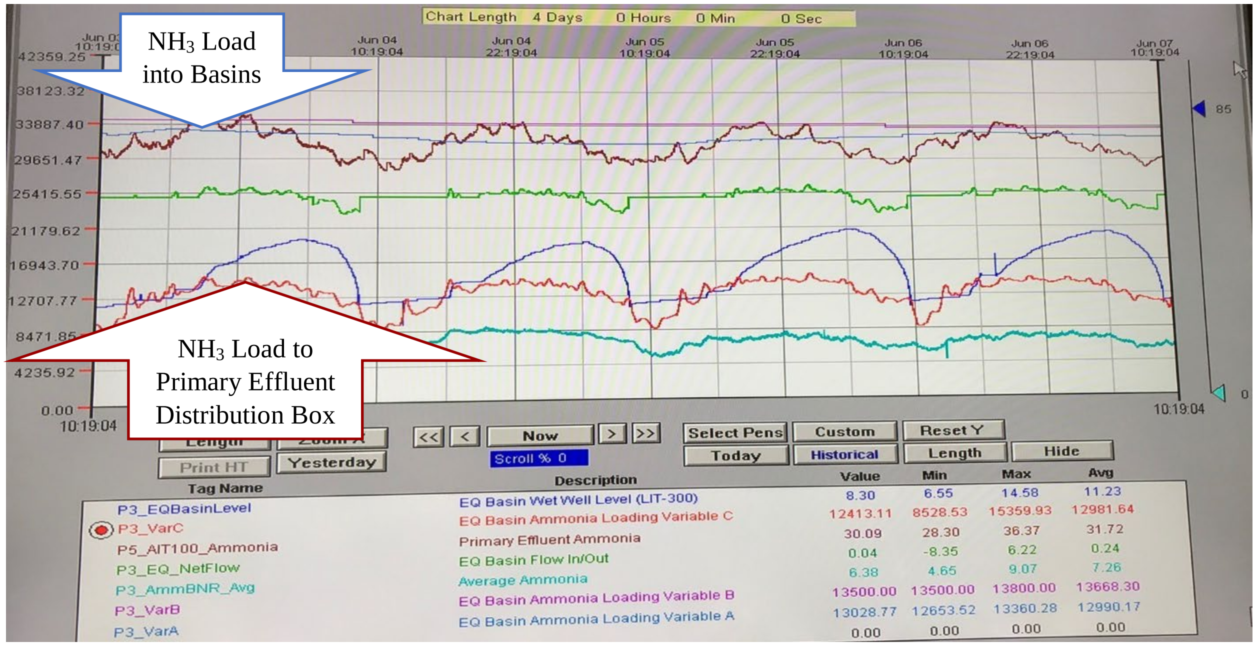

Figure 7: NRRRF Basin Ammonia Loading SCADA Screen During Dry Weather Conditions

When NRRRF experiences wet weather flows the equalization tank volume is repurposed for wet weather flow and the consistent ammonia values are not maintained, as shown in **Figure 8** where there is variability in the light blue line (Var A) near the top of the screen. Variable B, the target ammonia load (pink line) is no longer able to be maintained, but this is a short-term issue.

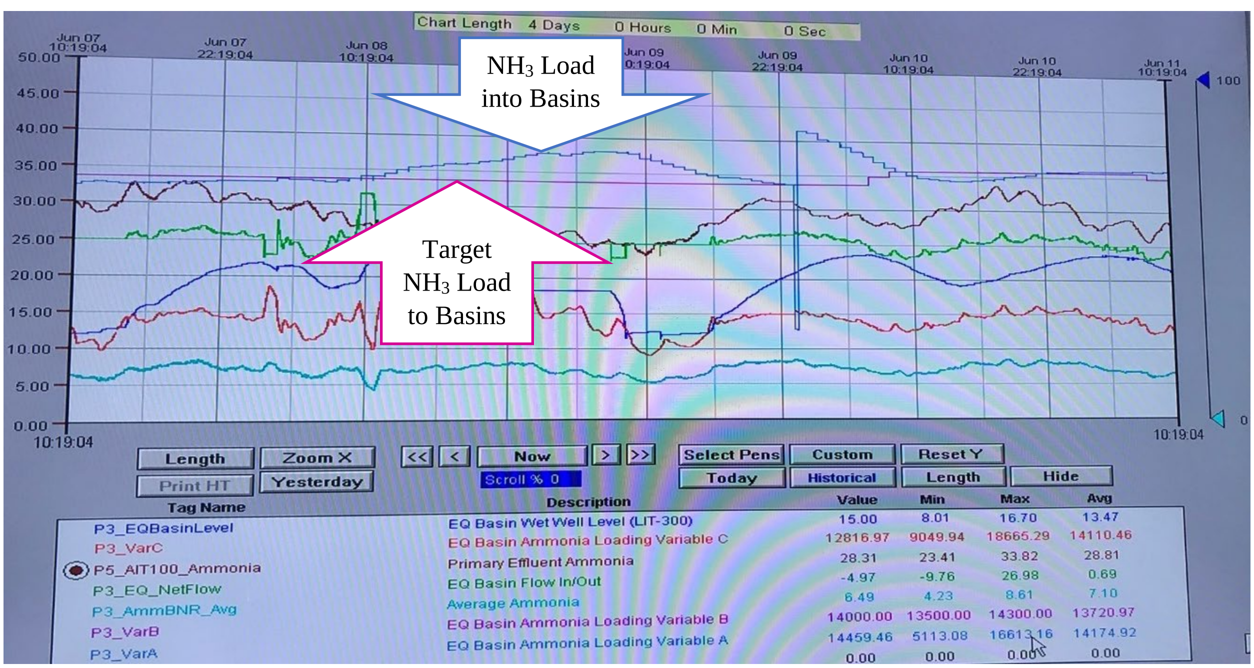

Figure 8: NRRRF Basin Ammonia Loading SCADA Screen During Wet Weather Conditions

NRRRF's ABAC program was initiated in February of 2018. Through a combination of the ABAC program, continued fine-tuning of target zone DO concentrations, and ammonia-load-based equalization, NRRRF was able to change from using two blowers to one blower in July of 2018. With the reduction to one blower in operation, the average blower power demand has reduced by 490 kW, which is estimated to save approximately $310,000 per year in energy savings.

NRRRF's nutrient-paced carbon feed program was initiated in November 2018. **Figure 9** illustrates NRRRF daily methanol usage before and after implementation of the ammonia-load-based equalization and nutrient-paced control programs.

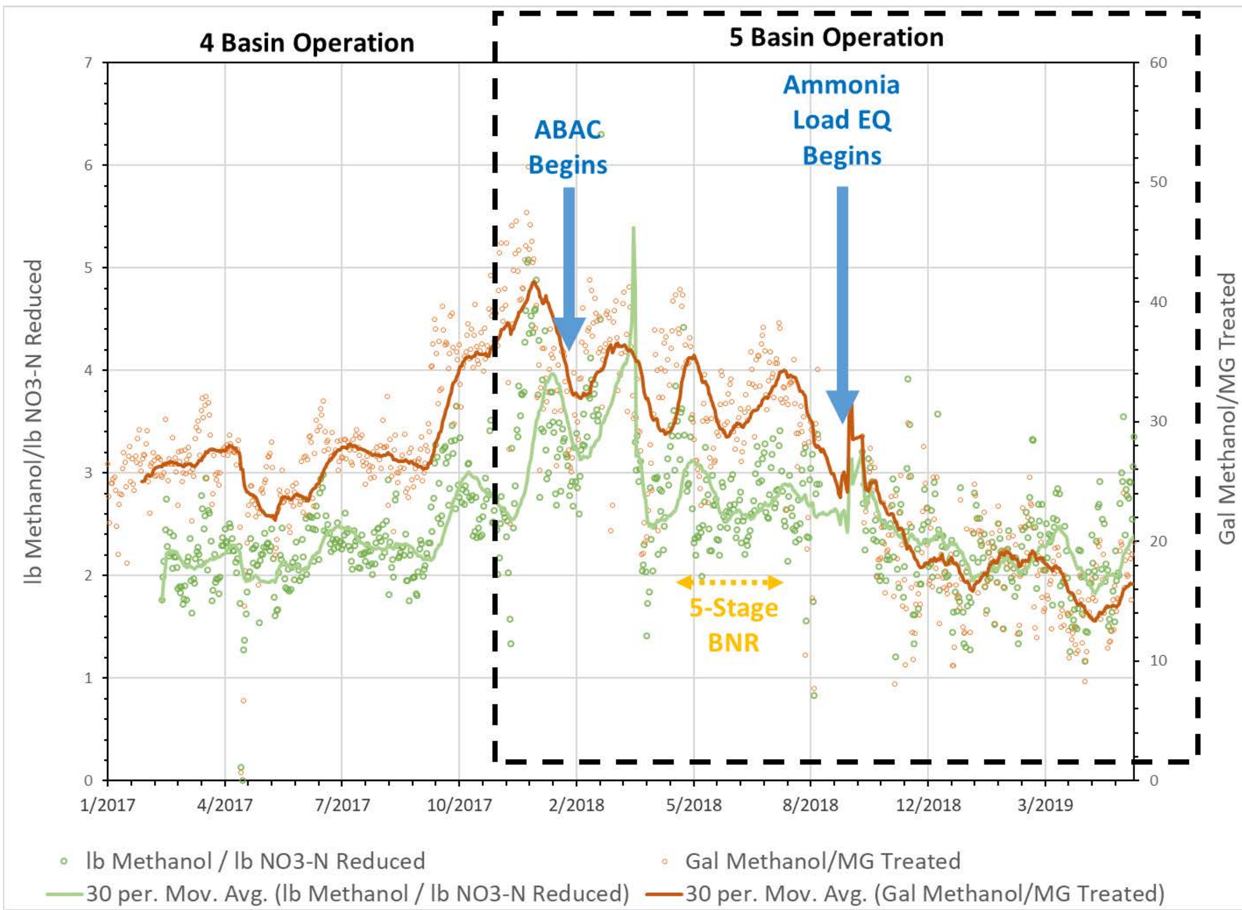

Figure 9: Supplemental Carbon Usage at NRRRF

It is to be noted that on December 2, 2017 NRRRF switched from a 4-basin to a 5-basin operation. During this time, the carbon nutrient-paced program had not been installed and carbon pumps were dedicated to each basin and set to flow at a constant feed rate. This resulted in an increase in total carbon usage because one additional pump was in use compared to the prior period.

The NRRRF also operated temporarily in a 5-stage BNR mode from later April until August 2018, to trial operations with enhanced biological phosphorus removal capabilities.

Supplemental carbon demands increased during this period compared to the month prior to conversion to 5-stage operation due to less carbon being available for denitrification.

Since the ammonia-load-based equalization and nutrient-paced carbon programs have been implemented, methanol use has decreased by 32%. The baseline for this percent decrease in methanol usage is 2017 carbon usage data compared to post-nutrient paced carbon dosing.

The overall reduction in methanol usage may be attributed to both lower NO_3-N to the post anoxic basin and efficiencies gained from the automated supplemental carbon feed system. Overall, The NRRRF has seen significant improvements in denitrification and carbon savings following implementation of ABAC, nutrient-paced carbon feed, and ammonia-load-based equalization.

Figure 10 illustrates nitrate trends and related control strategies at NRRRF. Overall, nitrate concentrations at the end of the aerobic zone have decreased from an average of 9.8 mg/L prior to ABAC implementation to 8.5 mg/L post ABAC implementation.

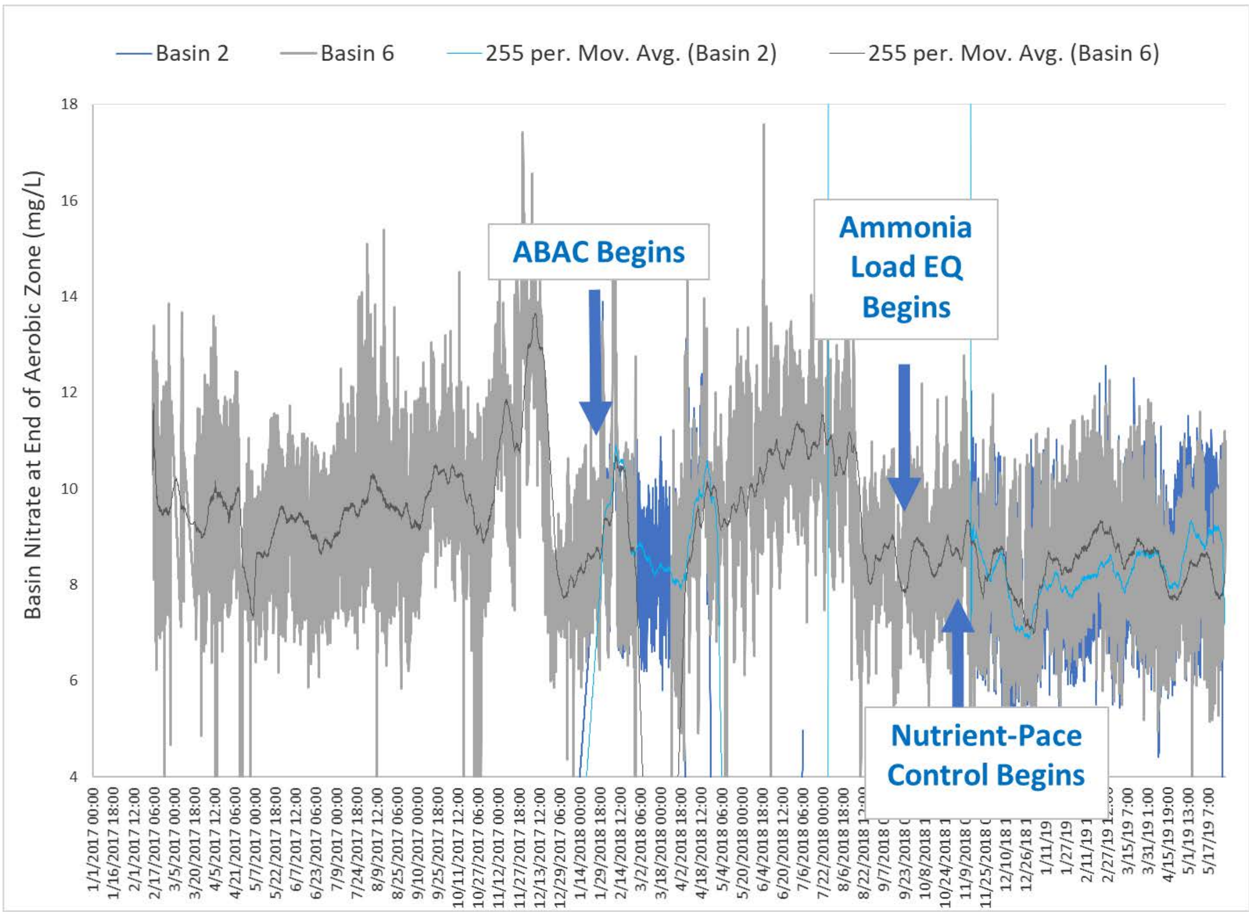

Figure 10: Basin Nitrate at the End of the Aerobic Zone at NRRRF (Two Representative Basins Shown)

NRRRF Solids Separation RTPCs

NRRRF has a Secondary Clarifier Guidance Program. The facility finds this particularly useful during wet weather events when conditions are rapidly changing and for daily use to maintain consistent clarifier SLR.

NDWRF Nitrification & Denitrification RTPCs

The NDWRF ammonia-load-based equalization program was initiated in March of 2016. Like the NRRRF, NDWRF has found the program to be very useful in stabilizing the overall nutrient removal process. Since 2017, the average target ammonia load to the basins was 3,848 lb/day and the ammonia-load-based equalization program maintained an average load of 3,849 lb/day.

Figure 11 illustrates ammonia loading at NDWRF which indicates that the ammonia load into the basins closely follows the ammonia load setpoints. The target ammonia setpoint is automatically increased or decreased to ensure the same portion of the equalization basin (e.g., 20%) is utilized for this diurnal storage program and the remainder reserved for wet weather capacity. Whenever this storage volume is exceeded the allowable ammonia load to the BNR basins increases by 10 percent daily until a new equilibrium is reached. Likewise, when the program is not fully utilizing the available capacity in the BNR basins for storage, such as might occur on weekends when dewatering does not occur, the mass to the BNR basins is decreased.

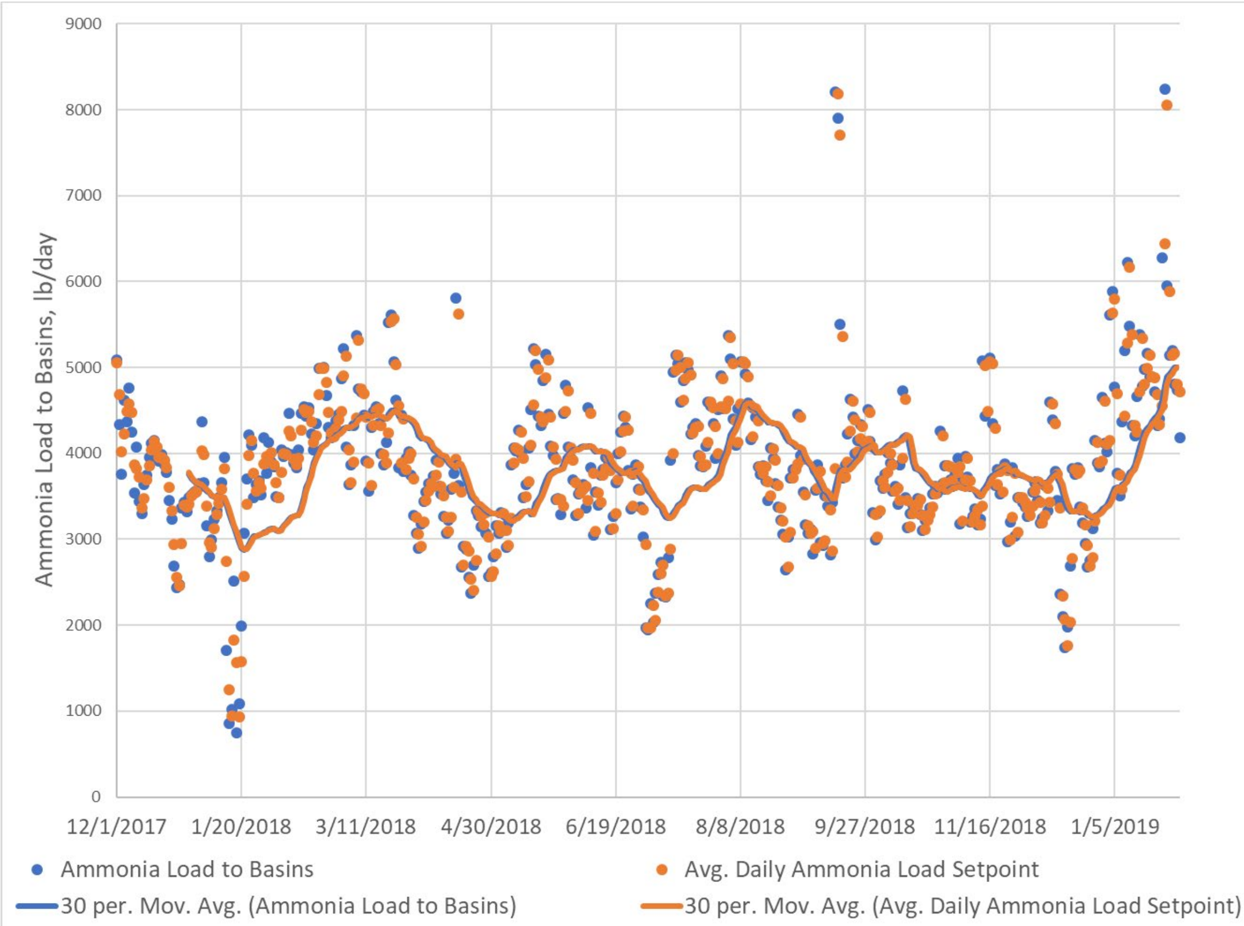

Figure 11: NDWRF Ammonia-Load-Based Equalization Data

NDWRF's ABAC and nutrient-paced carbon feed program was initiated in April of 2016. After implementation of ABAC, NDWRF optimized the ammonia setpoint to make nitrification in the BNR basins more reliable.

Dual zone DO control was also implemented at NDWRF to improve effluent TN. NDWRF BNRs have 10-cells as shown in **Figure 12**. DO Control Zone 1 includes Cells 5 and 6 and DO Control Zone 2 includes Cell 7. There is a DO sensor in Cell 5 and Cell 7, and an ammonia/nitrate sensor in Cell 7. As a result of ABAC and dual zone DO control, the average effluent ammonia concentration was reduced from 0.25 mg/L without ABAC control to 0.08 mg/L with optimized ABAC.

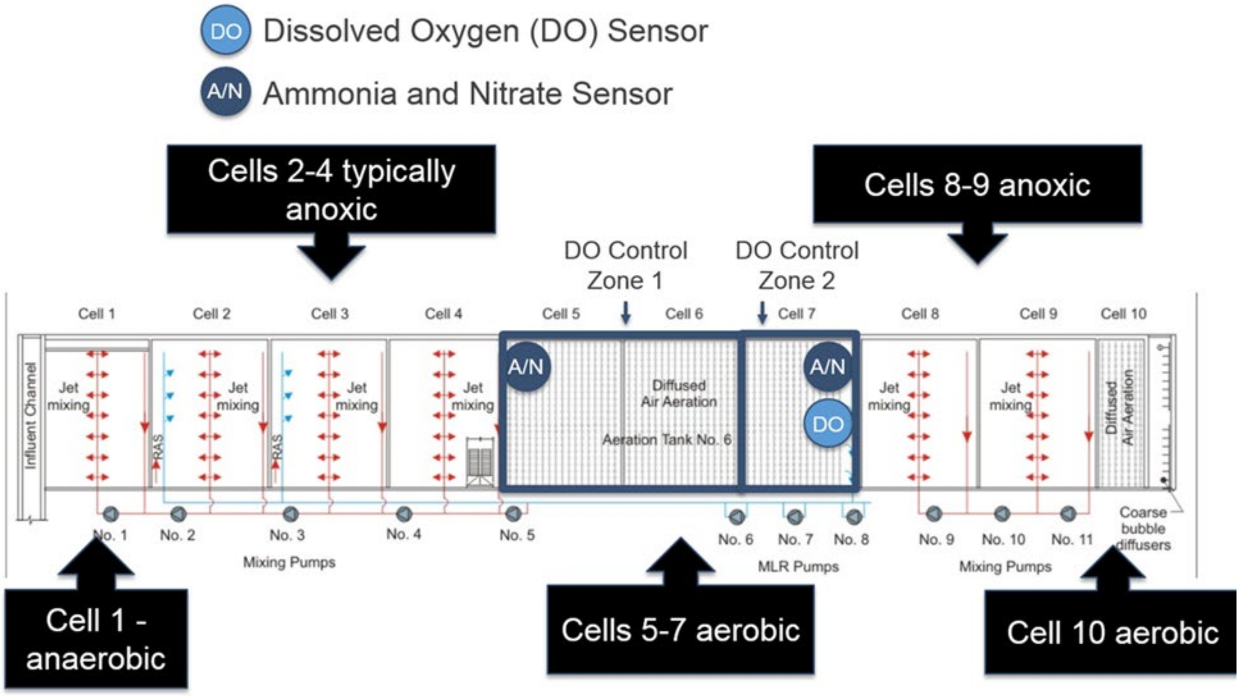

Figure 12: NDWRF BNR Zones and Instruments

As shown in **Figure 13**, the NDWRF also reduced its effluent TN by 0.5 mg/L from 2.9 to 2.4 mg/L by allowing for more SND and less DO entering the anoxic zones. It should be noted that the influent and primary effluent characteristics did not change during this period, illustrating that the improvements were due to the change to ABAC. In addition, the mass of nitrate removed in the second anoxic zone per pound of glycerin added increased from 2.1 to 3.4 lb nitrate/gal glycerin between 2015 and 2019, illustrating how ABAC also made denitrification more efficient.

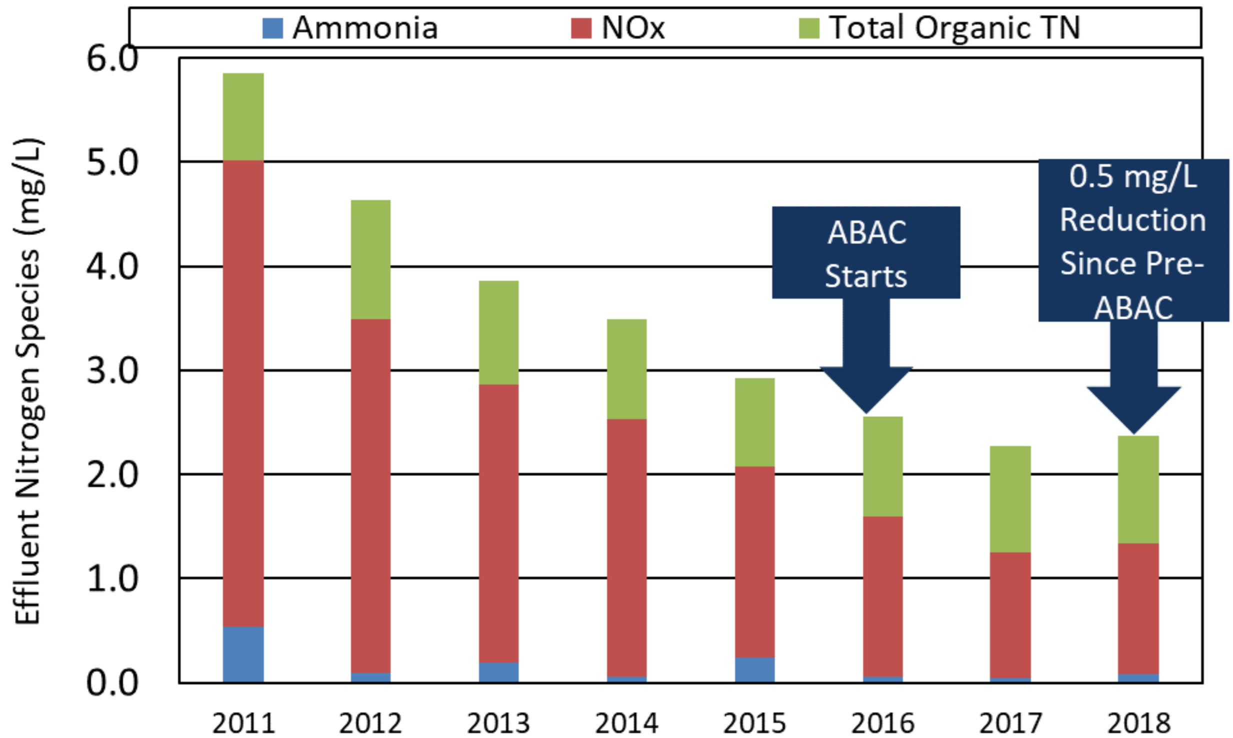

Figure 13: NDWRF Effluent TN

NDWRF's Aerobic SRT Control program was installed in 2016. **Figure 14** illustrates the NDWRF Aerobic SRT Control Program SCADA screen.

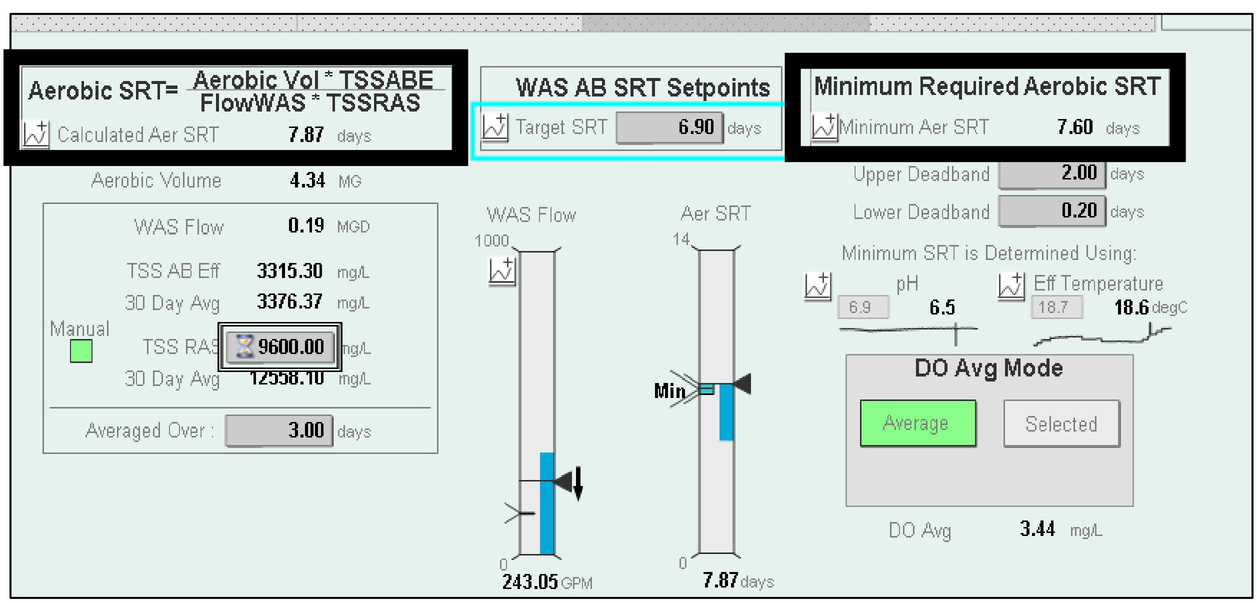

Figure 14: NDWRF Aerobic SRT Control Program

SDWRF RTPCs

The SDWRF has made several optimizations since the latest nutrient reduction improvements project which included RTPC installation. For example, instead of using ABAC, SDWRF reduced DO setpoints gradually without harming nitrification and found they could operate with less air than they had anticipated and one less blower. In addition, basin DO was optimized by installation of dual zone DO control and a waste air pipe to redirect excess air from the blowers when at minimum speed.

SDWRF also installed the ANITA™Mox Moving Bed Biofilm Reactor (MBBR) system for sidestream deammonification to reduce the nitrogen load to the BNR process by approximately 15 percent. In addition, baffle wall modifications improved scum movement and reduced back mixing of air from the aerobic zone into the first anoxic zone as part of the 2016 improvements.

As a result of these upgrades, SDWRF has reduced effluent TN by 2.0 mg/L since "Pre-Optimization" in 2015 as shown in **Figure 15**. These effluent TN concentrations are met without supplemental carbon addition. SDWRF's ability to reduce effluent TN is especially commendable considering the plant has received an average increase in TKN load of 30% since "Pre-Optimization".

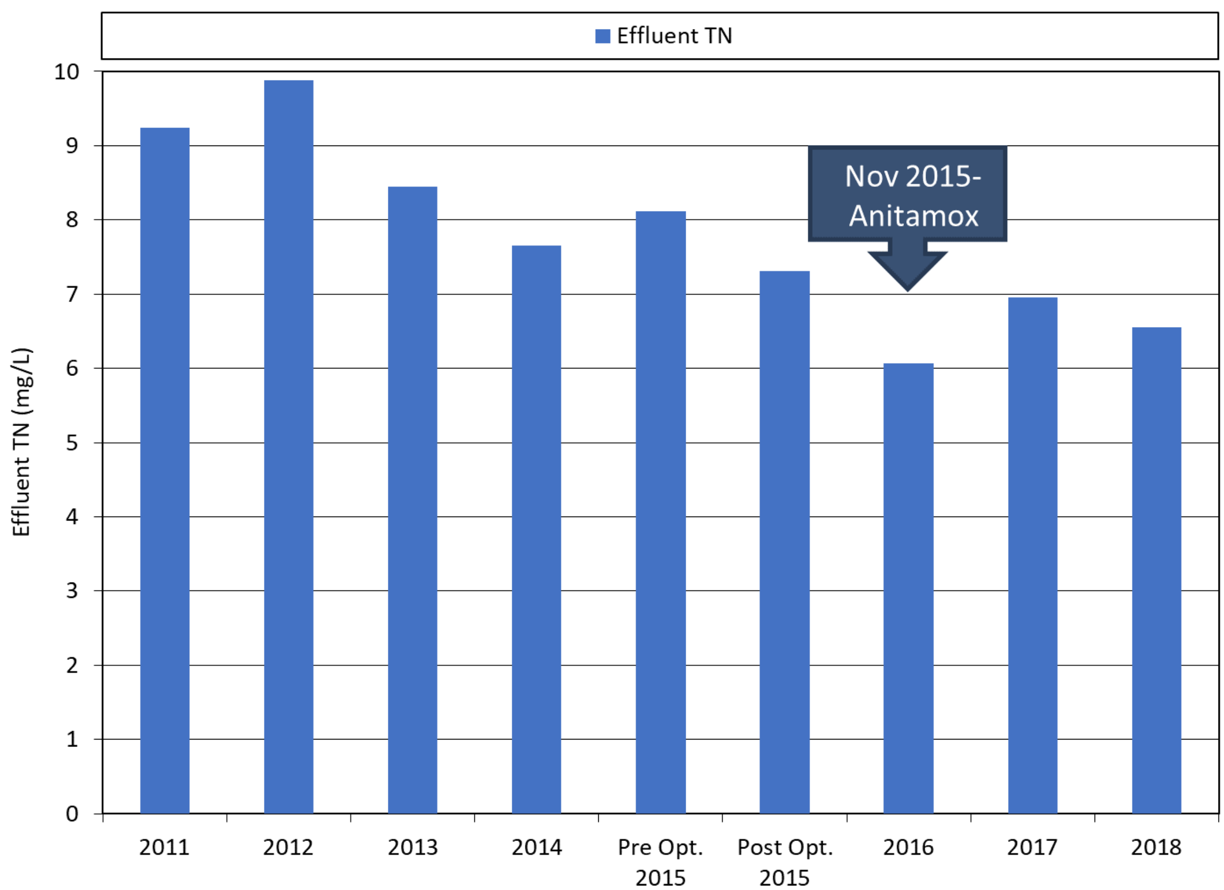

Figure 15: SDWRF Effluent TN Performance

As shown in **Figure 16**, SDWRF's electrical costs since the improvements were completed in 2016 have been $548K in 2016, $464K in 2017, and $400K in 2018 fiscal years. SDWRF has the capability to use any of their existing RTPC programs in the future to further enhance performance.

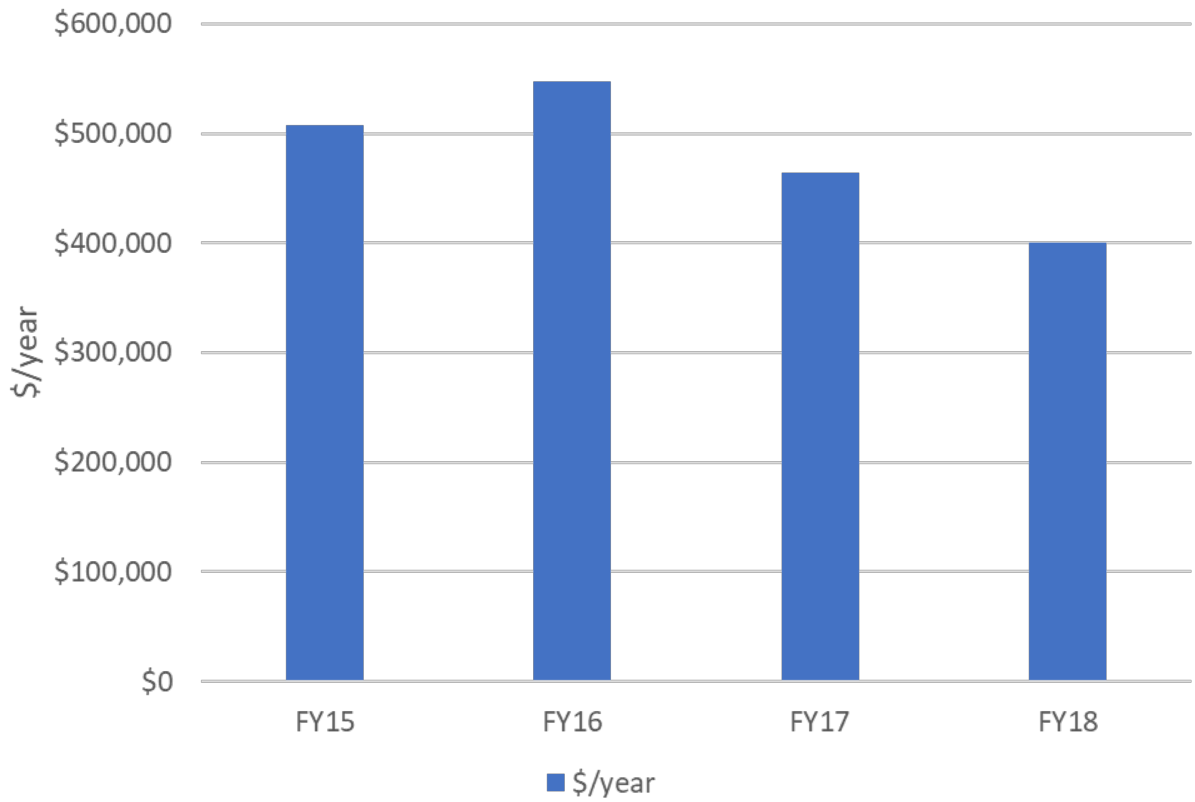

Figure 16: SDWRF Electrical Bill for 2015-2018 Fiscal Years

CHALLENGES WITH RTPC & AREAS FOR IMPROVEMENT

One of the challenges with RTPC operation has been ion selective electrode (ISE) ammonia probe drifting, which is typical for this type of instrument. Drifting typically precedes the need to replace the cartridge and is exacerbated when the probe is operating at routinely low ammonia concentrations (<1.0 to 2.0 mg/L). At the NRRRF these probes were placed in the first anoxic zone to provide feed forward control for ABAC in order to maximize the life of the cartridges. The NRRRF can get up to 6 months of operation between replacements with this configuration, but these results are site-specific.

In addition, the instruments associated with RTPC require consistent monitoring and calibration by plant staff to ensure that the RTPC programs are operating effectively. The wet chemical analyzers installed in Durham did cost more initially but remain accurate down to 0.1 mg/L of ammonia.

CONCLUSION

Three North Carolina BNR facilities including NRRRF, NDWRF, and SDWRF were able to achieve reduced effluent TN and/or TP concentrations and operating costs with RTPCs and/or optimization. As confirmed in this paper, these low-cost solutions are helping utilities operate more efficiently and achieve low effluent limits with reduced chemical and energy demand.

This paper illustrates that on-line instrumentation can be integrated with process modeling to provide a viable framework for RTPC. Many municipalities have invested in calibrated process models and nutrient analyzers to meet stringent nitrogen and phosphorus effluent standards. The integration of modeling and operations is promising option for routinely consistent and sustainable BNR operations.

REFERENCES

Bilyk, Katya, Joe Rohrbacher, Bill Balzer, Ron Latimer, Paul Pitt, Alan Stone, Charles Bott, and Rick Baumler. A Framework for Real-Time Process Control *Proceedings of the Annual Water Environment Federation Technical Exhibition and Conference (WEFTEC 2012 – National Conference of the Water Environment Federation)*, New Orleans, Louisiana USA.

Bilyk, Katya, Joe Rohrbacher, Paul Pitt, and David Wankmuller. Real Time Process Control Algorithms Combining Process Modeling and Instrumentation *Proceedings of the Annual Water Environment Federation Technical Exhibition and Conference (WEFTEC 2015 – National Conference of the Water Environment Federation)*, Chicago, Illinois USA.

Bilyk, Katya, Eric Polli, David Wankmuller, Tricia Drummey, Kyle Elliot, John Dodson, Charles Cocker, Damon Forney, Jeff Mahagan. Nutrient Removal Optimization *Proceedings of the 2018 NC AWWA-WEA NC Currents 97th Annual Conference Technical Session Recap*, Raleigh, North Carolina USA.