Stay in Control of Your Control Strategy Using Advanced Simulation Tools

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Abstract

The purpose of this paper is to illustrate the importance of simulating an existing plant's complex operational control strategy to accurately calibrate and model alternatives for a Kruger BioDenipho nutrient removal oxidation ditch, and to explain how to translate this complex operational control strategy into an aeration system model.

Introduction

The 12 mgd North Cary Water Reclamation Facility (NCWRF) is a nutrient removal plant located in Cary, North Carolina that has to meet stringent effluent total nitrogen (TN) and total phosphorus (TP) limits. Specifically, the TN limit is 3.9 mg/L on an annual average basis and the TP limit is 2 mg/L on a quarterly average basis. There is also a monthly maximum summer ammonia limit of 0.5 mg/L, and 1 mg/L in the winter.

The NCWRF has the following unit processes (see Figure 1): screening and grit removal, three BioDenipho oxidation ditches, secondary clarifiers, cloth disk filters, and aerobic sludge holding. No chemicals are added to the process for nutrient removal. For the past five years the average effluent TN and TP have been 2.1 mg/L and 0.56 mg/L, respectively.

Each oxidation ditch has an anaerobic zone upstream of the ditch and a second anoxic zone and reaeration zone downstream. The majority of the oxidation ditch volume can operate in a phased

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isolation configuration, which means the operators can select from ten different phases and set the duration of time spent in each phase. Four of the ten phases are currently employed, and Figure 2 shows a process flow diagram of the four phases and the time spent in each. Each ditch has two trains that mirror each other. In this paper these are referred to as the "upper" and "lower" portions of the ditch in reference to how they appear in Figure 2.

The mode of aeration is mechanical using 60 hp surface aerators on rotors. There are eight rotors per ditch. Presently, there is one DO probe per side of the ditch (two per ditch for a total of six at the NCWRF). The probes are located closest to Aerator 4. When the ditch is in an aerated phase, an operator-established target DO setpoint is maintained using the following logic:

- Aerator 1, which is farthest from the DO probe, turns on.
- If 3 minutes pass and the DO setpoint is not met, Aerator 2 turns on.
- If 3 more minutes pass and the DO setpoint is not met, Aerator 3 turns on.
- If 3 more minutes pass and the DO setpoint is not met, Aerator 4 turns on, which is closest to the DO probe.
- If 3 more minutes pass and the DO setpoint is not met, a small 25 hp jet aerator turns on.

Similarly, when the DO setpoint is exceeded for more than 3 minutes, the aerators and jet turn off in reverse order in 3-minute time steps. It takes a minimum of 12 minutes for all aerators to turn on, and 15 minutes for a jet to turn on.

The Town of Cary commissioned a study to identify strategies to increase capacity and maintain excellent nutrient removal performance. The Town suspected the aeration technology provided would be insufficient for flows beyond 12 mgd. It was apparent that developing a calibrated process model of the NCWRF would be an important tool in this evaluation. For example, only

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an accurate model could properly simulate at what flow and load the plant's current aeration system capacity would be exceeded. The modeling would need to be dynamic in order to simulate the aeration phases, diurnal variations in influent load, and accurately predict effluent quality.

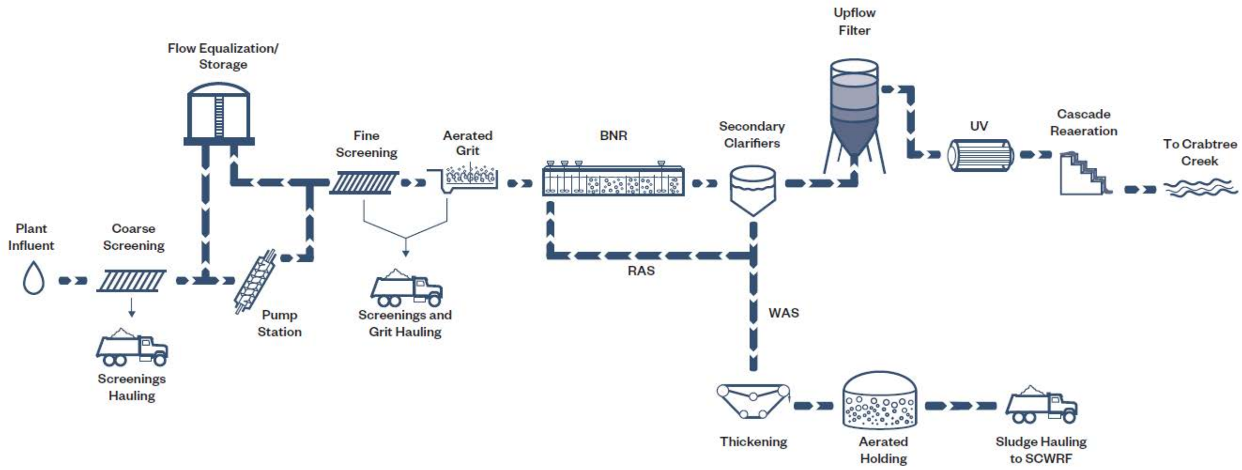

Figure 1. Process Flow Diagram

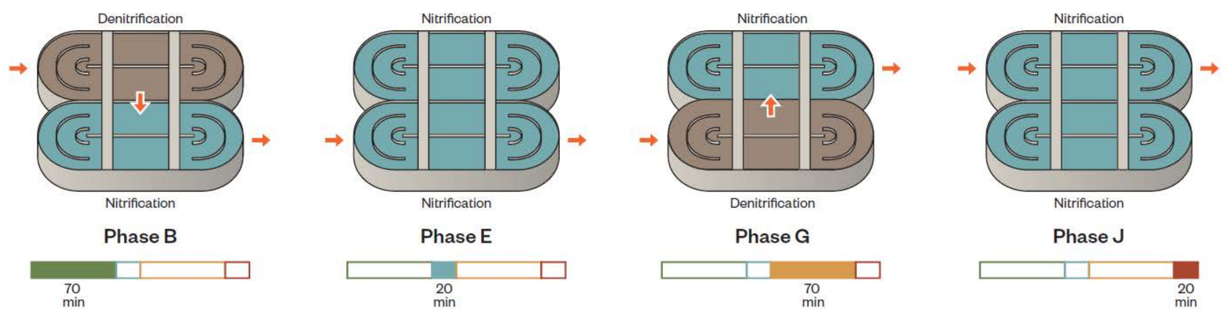

Figure 2: Phases Employed Currently

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Methodology

The wastewater process modeling software used in this evaluation is BioWin by EnviroSim. The objective of the model calibration effort was to develop a month-long dynamic simulation that closely matched the observed plant performance data. The well-calibrated model could then be used to evaluate capacity and alternatives with confidence in its ability to predict future plant performance.

Because of the inherent complexity of this system – four phases, finite oxygen delivery per rotor, and the three-minute wait time in between aerators turning on and off—it was necessary to use the BioWin Controller tool to properly simulate this process. EnviroSim developed the controller logic for this project to mimic how the BioDenipho process is currently operated. Figure 3 depicts the control logic that formed the basis of the controller program. Essentially, each aerator is in one of eight states shown and makes an action to either move forward one state or return to an initial state every minute. This controller turns the rotors in the basins on and off according to ditch cycle and a dissolved oxygen setpoint.

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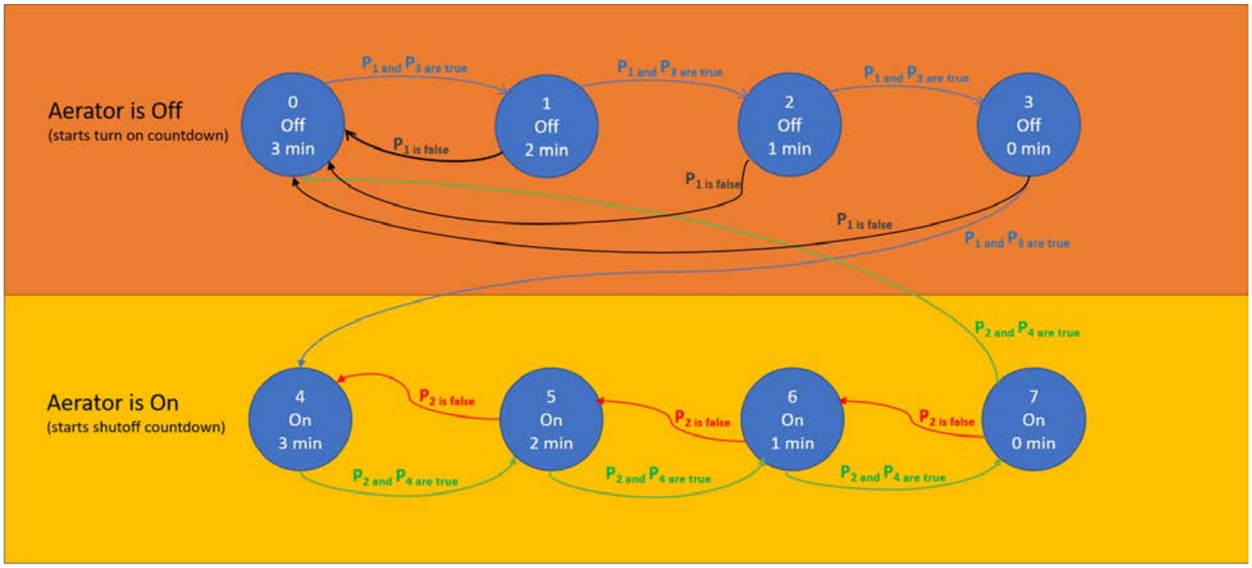

- P_1 DO < 1.3 mg/L
- P_2 DO > 1.5 mg/L
- P_3 = Previous aerator ON
- P_4 = Next aerator OFF

Figure 3. EnviroSim-developed control logic for the aerators showing the eight possible states for each aerator, and what conditions prompt a change of state. For example, when in State 1, if the DO is less than 1.3 mg/L and the previous aerator is on, move to State 2.

On top of this controller logic, there was also an overarching timer program that kept track of the current operational phase for the ditch. It was important to know when to initiate the aerator timing program as it is only active during an aerated phase. Figure 4 contains a snapshot of the main BioWin Controller screen. The list of controllers is described as follows, and instructions on the specifics of how to code the logic shown in the “controller formula” space can be found in the Biowin Controller User Manual. Each type of controller used in this application is a user-defined controller, which highlights the flexibility of the BioWin Controller tool to simulate any type of operational scenario.

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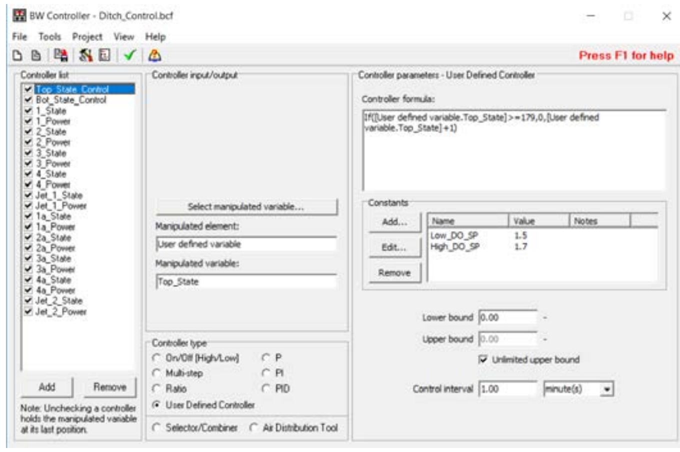

Figure 4. Main BioWin Controller screen.

- **Top_State_Control –** this is a timer that counts minutes for the top half of the ditch and resets the time to zero after each 180 minute cycle.

- **Bottom_State_Control -** this is a timer that counts minutes for the bottom half of the ditch and resets the time to zero after each 180 minute cycle.

- **1_State –** defines the state (from Figure 3) that Aerator 1 in the top half of the ditch operates. A similar logic applies to the **2_State**, **3_State**, **4_state**, and **Jet_1_State** controllers for the upper half of the ditch where the number or word "jet" denotes the aerator number. The lower half of the ditch has similar controllers with the extension "a" attached or "jet_2." Sublogic for this controller is as follows, and also illustrated by Figure 5.

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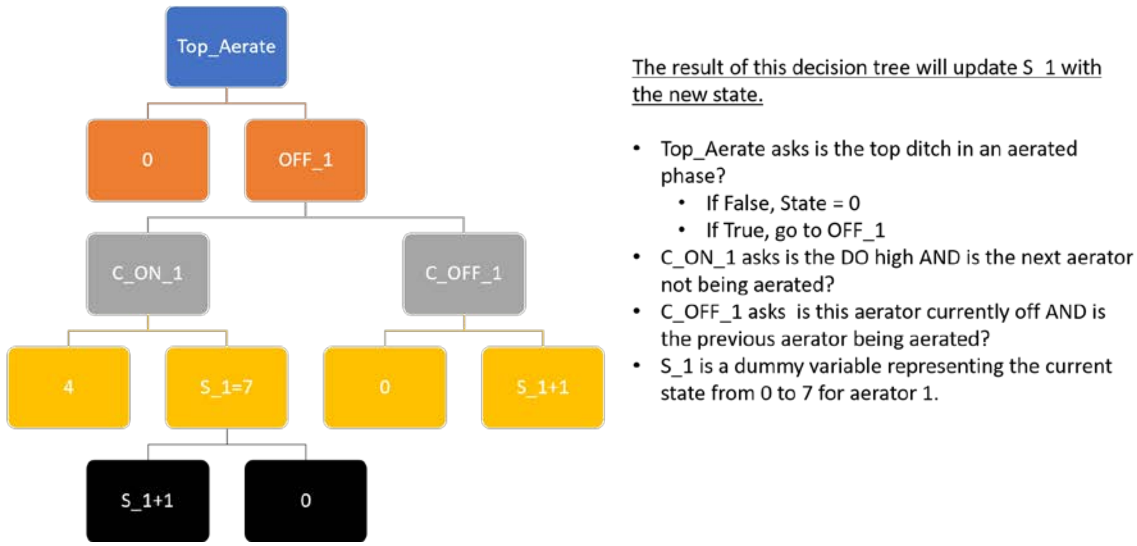

Figure 5. Decision Tree for the 1_State Controller

- While the aerator is off (C_OFF_1), if the DO is below the setpoint and the aerator is next in sequence to activate, then increase the state by a value of 1. Otherwise, return to state 0.
- While the aerator is on (C_ON_1), if the DO is greater than the setpoint and the aerator is next in sequence to deactivate, increase the state by a value of 1. Otherwise, return to state 4. If the state is incremented above 7, return to state 0.

- **1_Power** – identifies the horsepower of air to add to aerator if the program determines that it needs to turn on. The aerator is off while in states 0 to 3, and on while in states 4 to 7. A similar logic applies to **2_Power**, **3_Power**, **4_Power**, and **Jet_1_Power** for the upper half of the ditch where the number or word "jet" denotes the aerator number. The lower half of the ditch has similar controllers with the extension "a" attached or "jet_2."

A significant number of user-defined variables were also developed as part of this BioWin Controller application, as shown in **Figure 6**. This includes 12 state variables to track if the ditch is aerated or not, and to count the state of each aerator. These variables are: **Top_State**, **Bot_State**, **S1**, **S2**, **S3**, **S4**, **jet1**, and **S1a**, **S2a**, **S3a**, **S4a**, and **jet1a**.

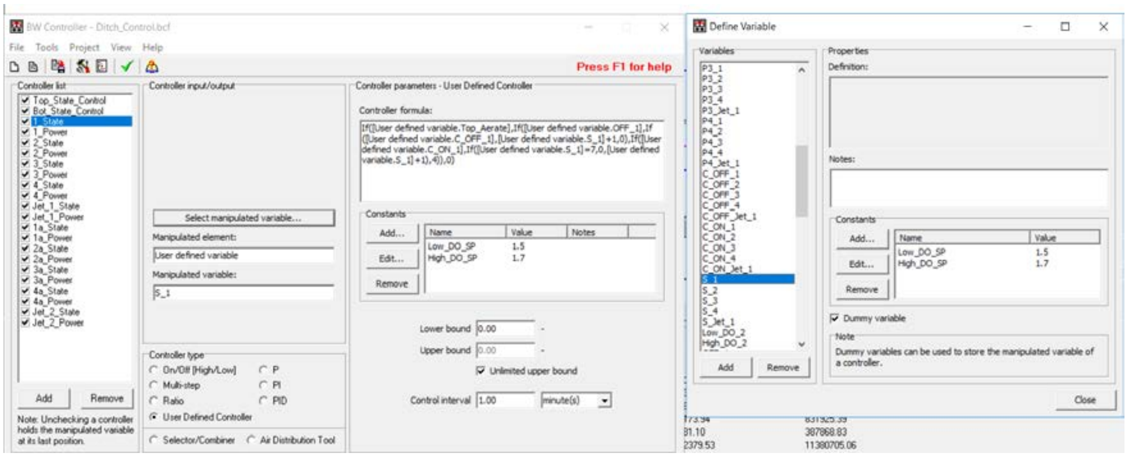

Figure 6. Main BioWin Controller screen (left) and variable definition screen (right).

The NCWRF BioWin model was run dynamically and calibrated to June 2017 (special sampling month) and April 2017 (high flow and cooler temperature month). The facility does not record historical DO concentration data, but the DO setpoint was discussed at a February 2017 meeting and thus the most recent months around that meeting were used for calibration as no significant changes to operation had been made.

A screenshot of the NCWRF BioWin model is shown in **Figure 7**. Blue lines in the diagram indicate flows that are part of the main wastewater flow of the plant, brown lines signify solids streams, RAS flows, and sludge handling, and pink lines represent the interconnection between the oxidation ditches in each train. NCWRF has three BioDenipho® trains containing two oxidation ditches that alternate throughout a treatment cycle. In this BioWin model, only one oxidation ditch is modeled at a time.

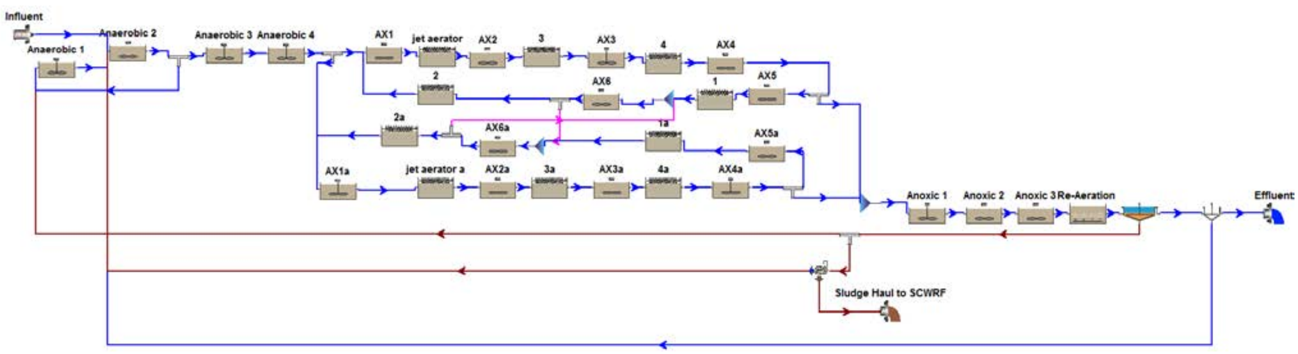

Figure 7: NCWRF Biowin Model Screenshot

The following historical data were input into the dynamic BioWin model:

- Influent wastewater characteristics such as COD, TKN, TP, and ISS.
- Cycle times and operational parameters such as which side of the ditch flow enters at a given time, and whether the ditch is aerated or mixed at a given time.
- DO setpoints per oxidation ditch.
- Secondary clarifier underflow/RAS flow rate.
- WAS flow rate.

Results

Detailed results for the July 2017 and April 2017 calibrations are included below. The following parameters are provided as model output based on the wastewater fractions and influent characteristics selected, and were compared to historical records to demonstrate the model was well calibrated:

- Influent TSS and $cBOD_5$
- MLSS concentrations.
- WAS load (a mass balance was performed to estimate WAS load)

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- Effluent nitrogen and phosphorus concentrations
- Number of rotors operating at any given time during an aeration cycle

This section presents a series of figures that illustrate that the calibrated dynamic model matched the actual observed process parameters for June 2017 and April 2017. Less detail is provided for the April model in the interest of brevity. In each figure, modeled values are depicted as a line, while observed values are shown as points.

June 2017 Dynamic Calibration Results

Influent $cBOD_5$, TSS, TKN, TP and NH_3-N concentrations are presented in **Figures 8** and **9** and **Table 1**. The modeled influent COD concentration was based on the $cBOD_5$:COD ratio from special sampling. Overall the historical average values match well with the modeled average values for all parameters.

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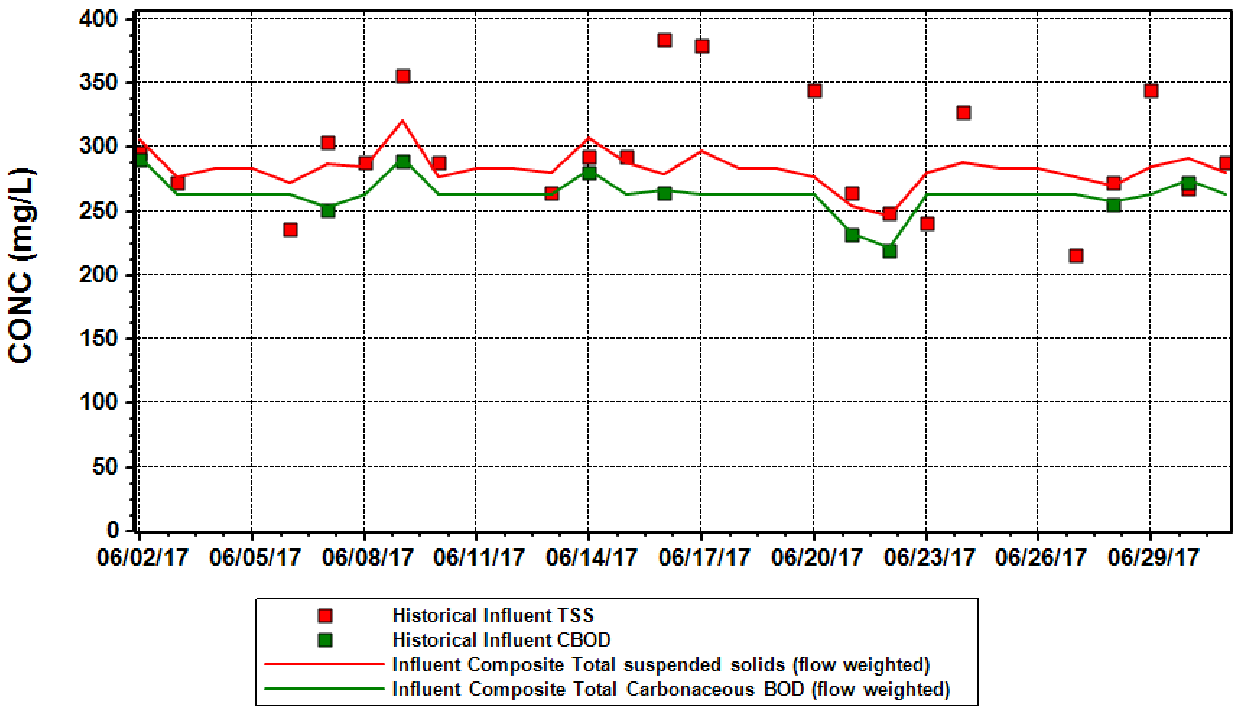

Figure 8: June 2017 BioWin Model Results: Influent TSS and cBOD5 Concentrations

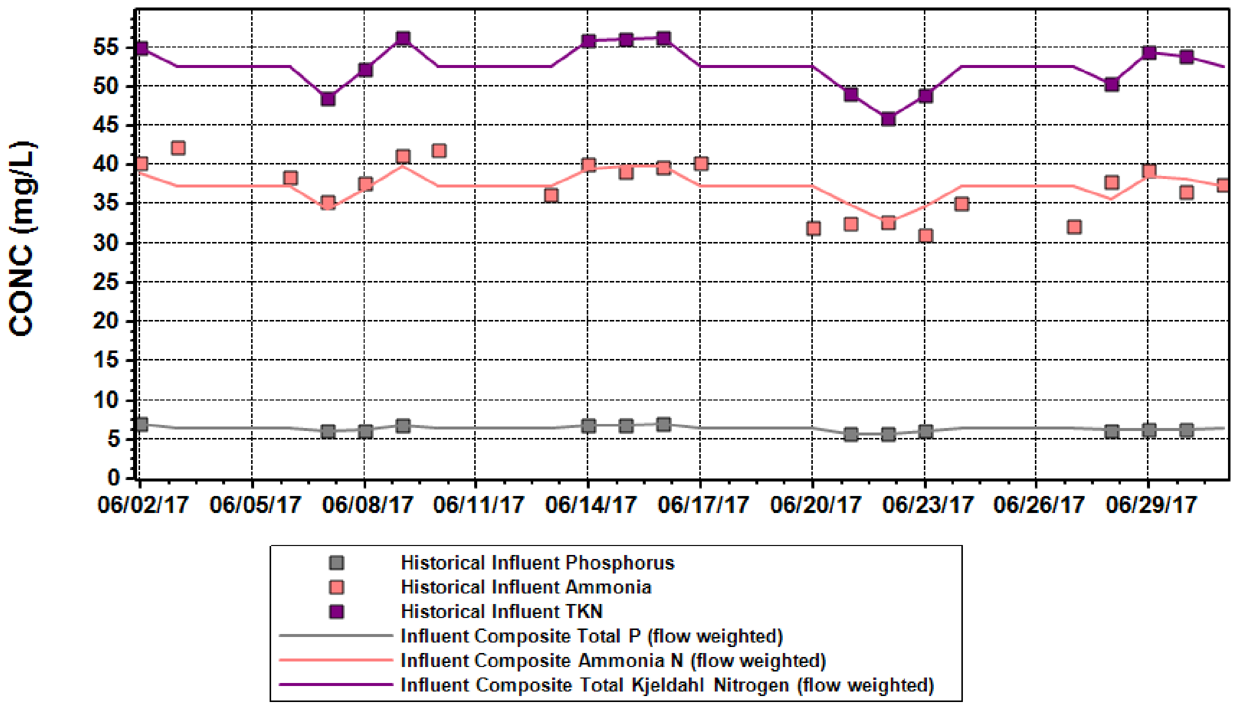

Figure 9: June 2017 BioWin Model Results: Influent TP, TKN & Ammonia Concentrations

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Table 1: June 2017 Historical vs. BioWin Model Results: Influent Concentrations

Parameter	Historical June 2017	Modeled Avg.
TSS, mg/L	294	283
$cBOD_5$, mg/L	261	263
NH_3-N, mg/L	37.2	37.2
TKN, mg/L	52.5	52.5
TP, mg/L	6.3	6.3

The average MLSS and MLVSS concentration is presented in **Figure 10** and **Table 2**. The model prediction for MLSS and MLVSS matched well with observed data from June 2017. The model predicted that three to four rotors would be necessary during all phases for full nitrification, which is similar to what was observed in the field.

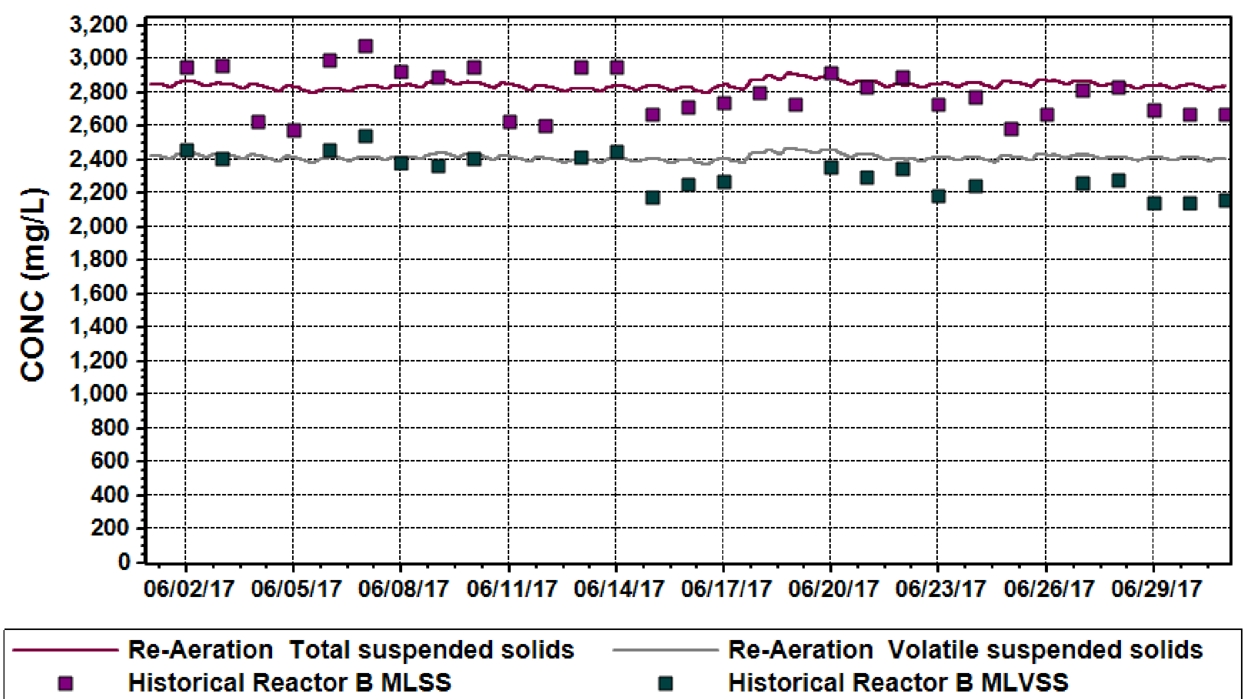

Figure 10: June 2017 BioWin Model Results: MLSS and MLVSS Concentrations

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Table 2: June 2017 Historical vs. BioWin Model Results: MLSS and MLVSS Concentrations

Parameter	Historical June 2017	Modeled Avg.
MLSS, mg/L	2,800	2,800
MLVSS, mg/L	2,320	2,400

The average WAS load is shown in **Figure 11**. The model prediction for WAS matched well with observed data from June 2017. The June 2017 historical WAS load was 11,800 lb/day. The historical value divided by two (since two trains are in service, and only one was modeled in BioWin) was 5,900 lb/day while the modeled average was 6,200 lb/day. In the model, the wasting flow rate was increased approximately ten percent higher than the reported values to better match reported MLSS and WAS load.

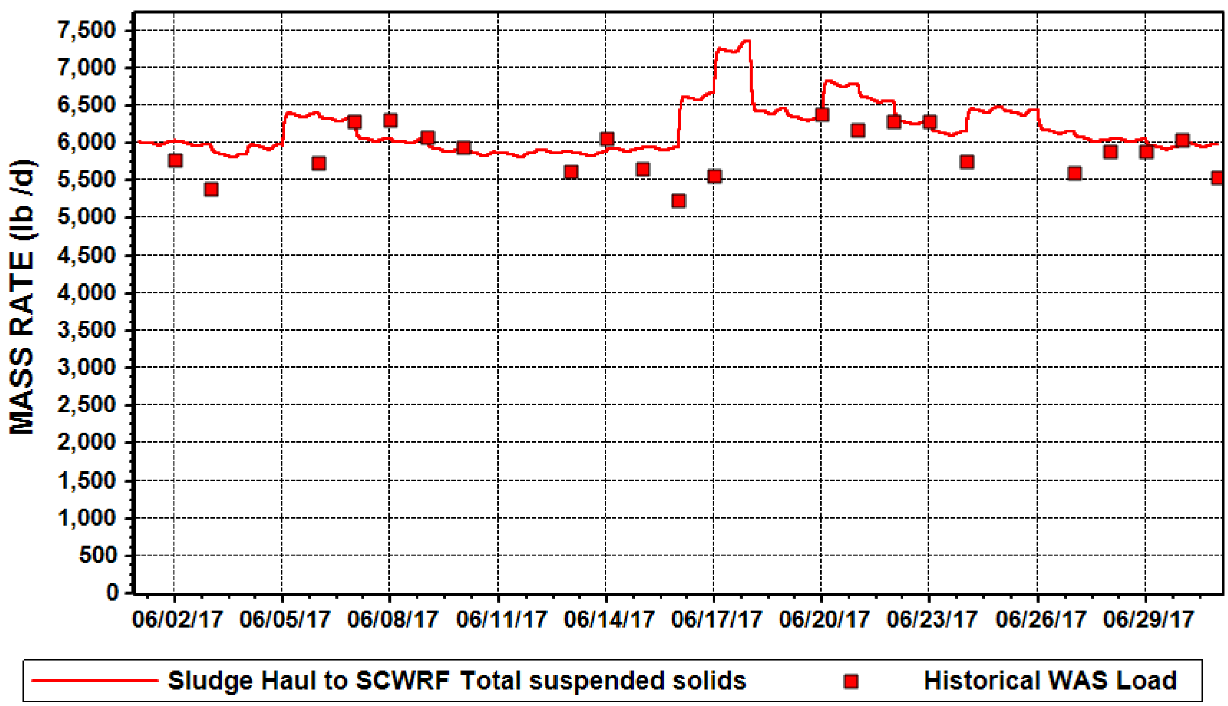

Figure 11: June 2017 BioWin Model Results: WAS Load

Effluent nitrogen species and TP concentration are presented in **Figure 12** and **Table 3**. The model prediction for nitrogen and TP matched well with observed data. There are a few times when the modeled NO_x-N concentration increases above the historically observed values. This is due to low $cBOD_5$:TKN ratios in the BioWin model. Historical influent NH_3-N is recorded five days per week, while influent $cBOD_5$ is recorded two days per week. Because of this, there are days when historical data for NH_3-N is available, and higher than average, but the average $cBOD_5$:TKN ratio for the month is used for the BioWin model, since there is no historical $cBOD_5$ data available for that day. This leads to a lower than typical $cBOD_5$:TKN ratio, and a slight increase in effluent NO_3-N concentration.

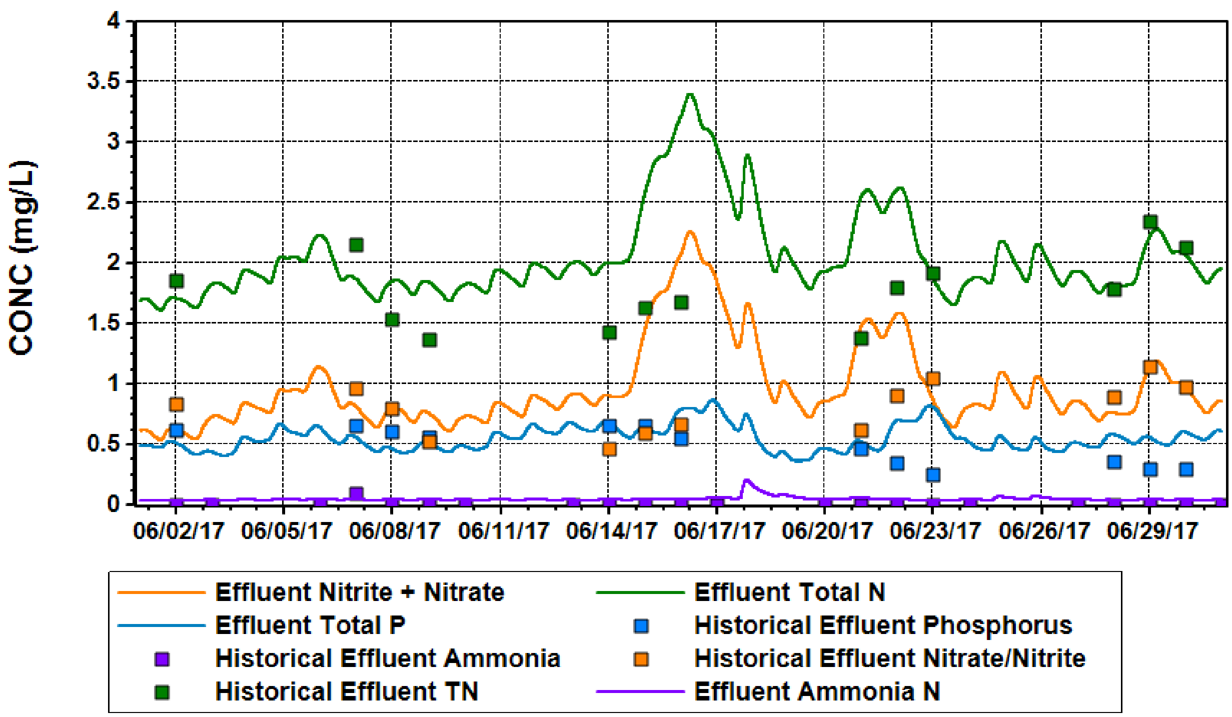

Figure 12: June 2017 BioWin Model Results: Effluent Ammonia, TN, TP & NO_x-N Concentrations

Table 3: June 2017 Historical vs. BioWin Model Results: Effluent Ammonia, TN, TP & NOx-N Concentrations

Parameter	Historical June 2017	Modeled Avg.
NH_3-N, mg/L	0.01	0.05
NO_x-N, mg/L	0.80	0.97
TKN, mg/L	0.97	1.1
TP, mg/L	0.49	0.55

A representative DO profile for one three-hour cycle is shown in **Figure 13**. Influent loads vary hourly, explaining some of the variability in DO concentration by aerator location. Results for April were comparable as well.

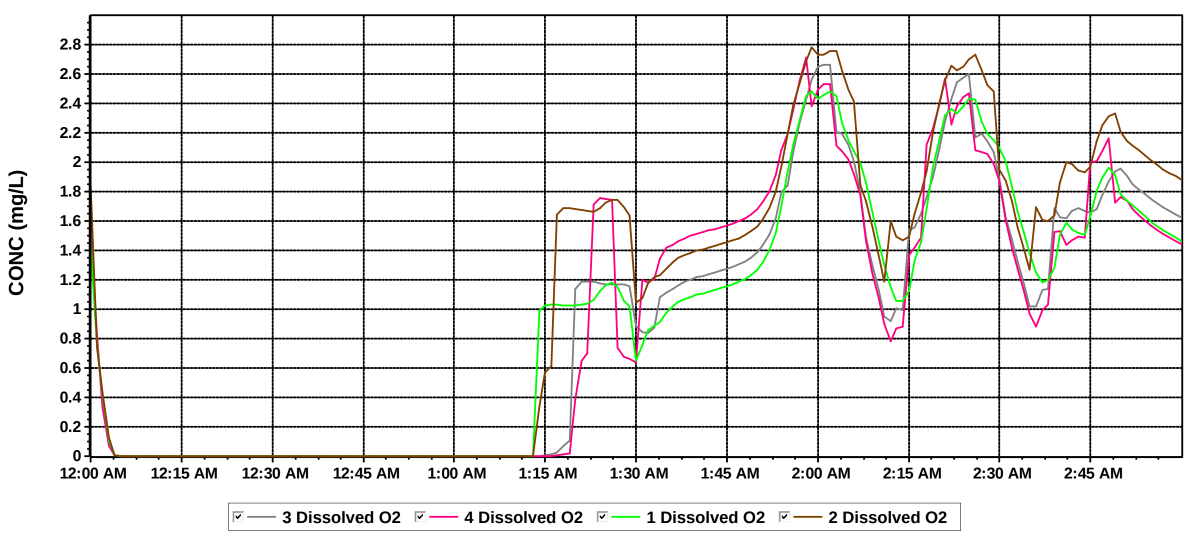

Figure 13. DO Profile for one 3-hour cycle. Note the 12-minute difference between when the first aerator (1) starts and when the fourth turns on (4).

<u>April 2017 Dynamic Calibration Results</u>

April 2017 was also used for calibration to represent a wet-weather condition where there was a small nitrification challenge to verify the model was sufficiently sensitive to modeling nitrification. Limited influent nutrient concentrations were recorded during the storm (April 26-

30th), therefore influent concentrations during the storm were calculated using the average April 2017 $cBOD_5$ and TSS load and dividing it by the flow during the storm. The TKN concentration was calculated using the $cBOD_5$ concentration and the April 2017 average $cBOD_5$:TKN ratio.

Effluent nitrogen and TP concentration are presented in **Figure 14** and **Table 4**. The model prediction for nitrogen and TP matched well with observed data. The model predicted the increase in NH_3-N at the beginning of the storm on the 24th and 25th, confirming the calibrated model is sensitive to the increase in flow and decrease in wastewater temperature.

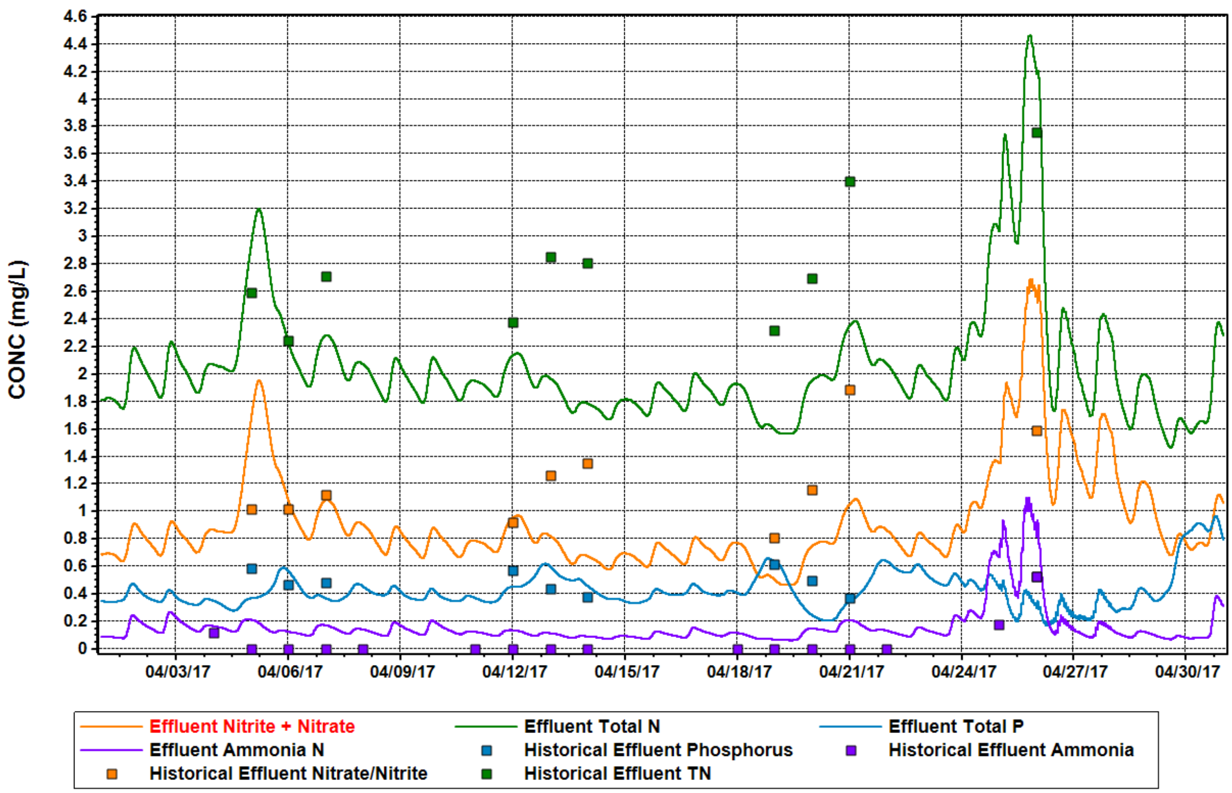

Figure 14: April 2017 BioWin Model Results: Effluent Ammonia, TN, TP & NOx-N Concentrations

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Table 4: April 2017 Historical vs. BioWin Model Results: Effluent Ammonia, TN, TP & NOx-N Concentrations

Parameter	Historical April 2017	Modeled Avg.
NH_3-N, mg/L	0.05	0.16
NO_x-N mg/L	1.21	0.92
TKN, mg/L	1.56	1.13
TP, mg/L	0.50	0.43

Summary

The BioWin model was calibrated using two different months of data and the BioWin Controller extension to accurately predict solids production, and effluent nitrogen and phosphorus species. The model was also used to evaluate alternatives to expand the NCWRF to 15 mgd.

Conclusions

The alternatives for expanding beyond 12 mgd did require additional air and thus included: converting the ditches to plug-flow reactors, or replacing the aerators with fine bubble diffusers and maintaining the BioDenipho operating phases. Both options could meet the effluent objectives, but the phased isolation option was significantly lower in cost and is being pursued. A layout of how the fine bubble diffusers would be distributed is shown in **Figure 15**. The exact operating configuration of the fine bubble diffuser grids has not been determined, but was simulated using a fixed DO setpoint for a specified cycle time to achieve the desired effluent ammonia concentration. The controller was not used for simplicity in this part of the analysis.

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Mixers would continue to maintain solids in suspension during the anoxic phases. Representative effluent quality is shown in **Figure 16**. **Figure 17** shows the recommended time spent in each phase as the plant expands. The increased aerobic cycle times are necessary to reliably meet the monthly average effluent ammonia targets. Supplemental carbon will be needed as a result of the reduced anoxic detention time. No additional BNR volume will need to be constructed. The Town was pleased with this analysis and plans are moving forward to replace the mechanical aerators with fine bubble diffusers.

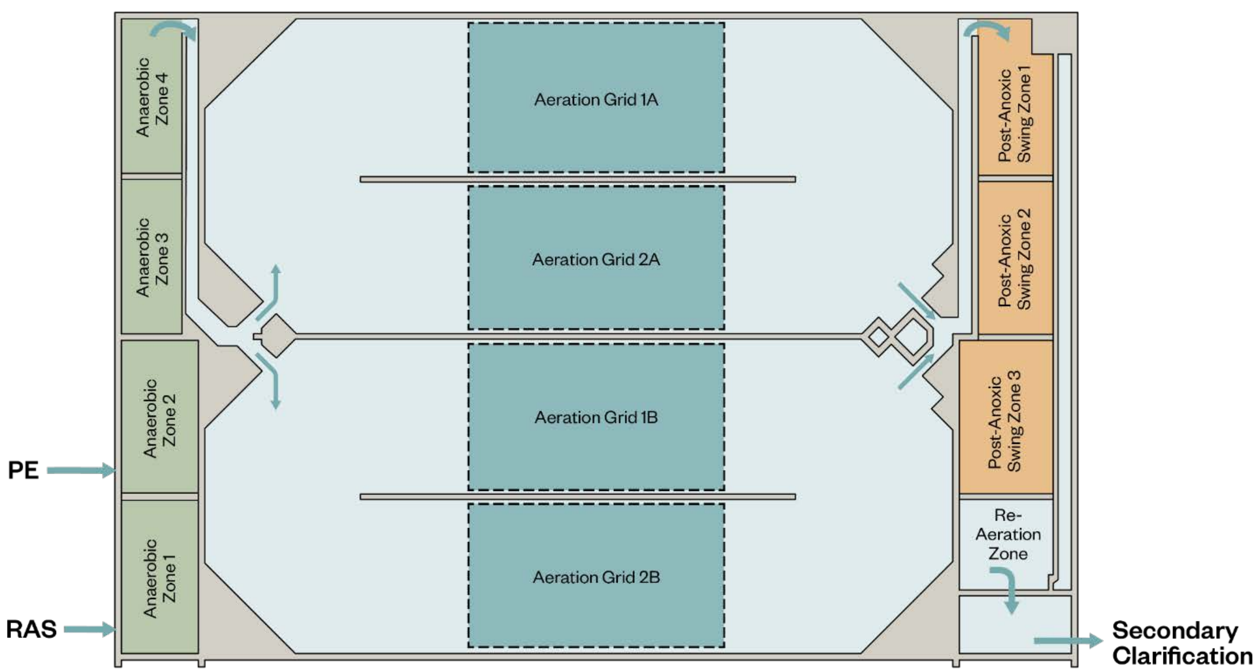


Figure 15. Layout of fine bubble diffuser grids to replace mechanical aerators.

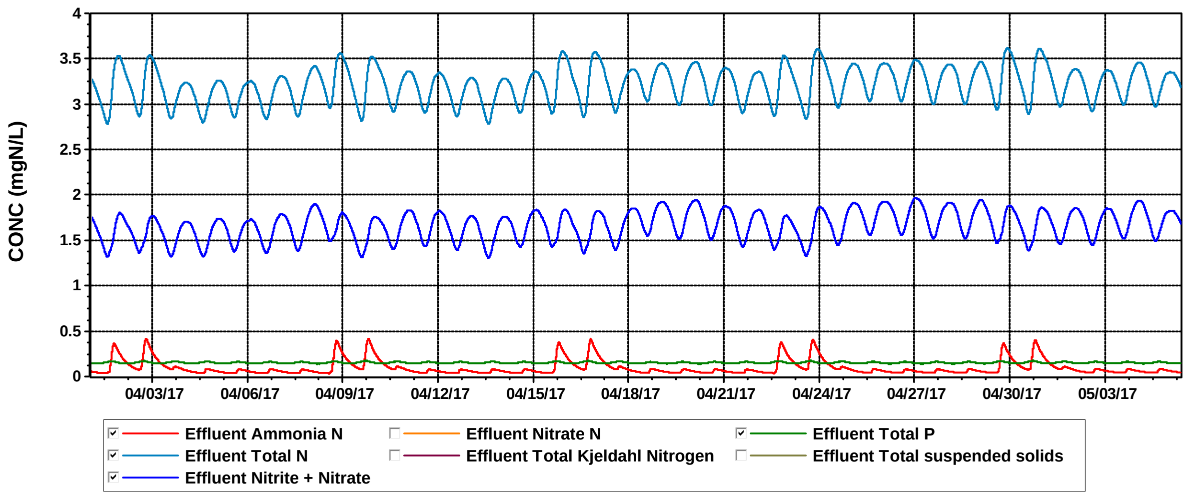
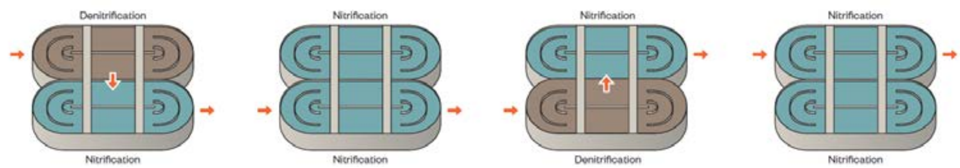


Figure 16. Effluent TN, NOx-N, Ammonia, and TP at 15 mgd.



Condition	% Aerobic	Phase B (min)	Phase E (min)	Phase G (min)	Phase J (min)
Current	61	70	20	70	20
12 MGD	72	50	40	50	40
13.5 MGD	78	40	50	40	50
15.0 MGD	83	30	60	30	60

Figure 17. Proposed Phases and Time Allocated to Each to Maintain Effluent Nutrient Targets

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