Energy Reduction and Nutrient Removal in WWTPs Using Feed-Forward Process Control

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ABSTRACT

Aeration is by far the largest electrical consumer in a wastewater treatment plant (WWTP), accounting for greater than 50% of total energy consumption. Typically, DO set-points are based on peak loading and are therefore much higher than what is needed for the majority of the day. Lowering DO set-points can have a significant impact on total energy consumption of a plant. A real-time, model-based process control system that calculates optimal DO set-points to treat the incoming loading without compromising effluent quality can reduce aeration and hence energy requirements. The process control system can also control mixed liquor recycle in a BNR plant, to maximize denitrification in the anoxic zone, thereby maximizing Total Inorganic Nitrogen (TIN) removal.

Pilot projects in Phoenix, Arizona and Enfield, Connecticut demonstrated aeration energy savings of 15% to 17% and improved TIN removal by over 35%.

KEYWORDS

Energy conservation, process control, process optimization, nutrient removal, real time control, model based control, set point control, ammonia/nitrate analyzer, aeration, DO control.

INTRODUCTION

Numerous studies have shown that aeration is by far the largest consumer of energy in a municipal wastewater treatment plant (WWTP), independent of treatment process, level of treatment, and plant size. The proportion of energy used for aeration of activated sludge in the plant typically varies between 50% and 70%, sometimes even higher (Figure 1). The total energy used in the plant per volume treated varies by plant size, treatment level and process, with typical numbers range from 385 to 450 kWh per ML (1,300 to 1,800 kWh per million gallons) for conventional activated sludge plants and from 400 to 500 kWh per ML (1,600 to 2,000 kWh per million gallons) for oxidation ditches and extended aeration plants (WEF, 2009).

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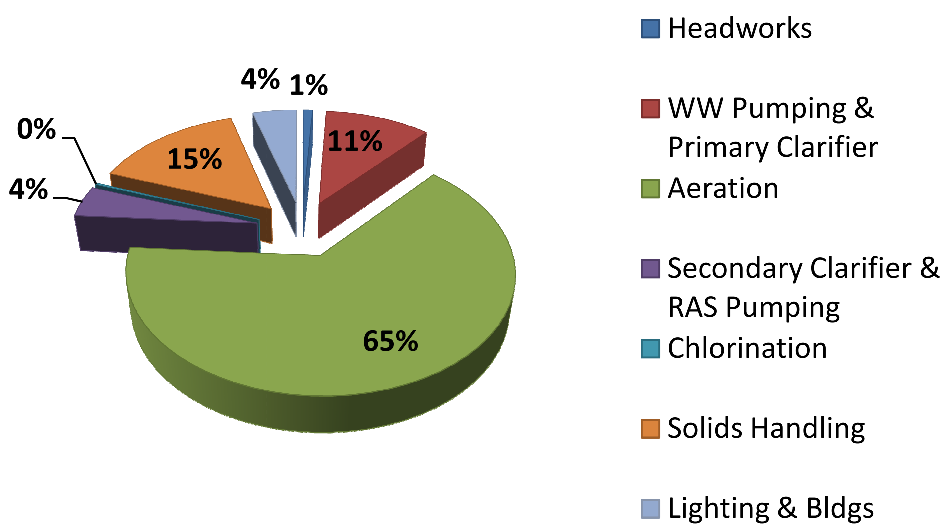

Figure 1. Breakdown of Energy Requirements in an 80 ML/d (20 mgd) Plant with Nitrification (data from WEF, 2009)

There is a hierarchy of actions that can and need to be taken to reduce total aeration energy in a WWTP:

1. The aeration blowers must be sized correctly. A legacy of rapid investment in infrastructure during a time of rapid growth, abundant funds and cheap energy is that aeration blowers were sized for anticipated future needs with a large margin of safety. The result is that there are currently numerous WWTPs in the country that only use a fraction of the installed aeration capacity and have oversized blowers that cannot be controlled to meet actual aeration demand. These plants either blow off excess air or over-aerate their secondary treatment tanks.
2. Aeration blowers need to have enough control capability ("turn down") to adjust their output (and thus their energy consumption) to the actual oxygen demand of the system. There are a number of mechanisms available to achieve turn-down, depending on the type of blower, such as variable frequency drives (VFDs) that reduce the motor speed, variable inlet vanes or inlet flow restrictors. Modern high-speed turbo blowers use VFDs to achieve turn down.
3. The air needs to be efficiently delivered to the location in the treatment process where it is needed. As a rule of thumb, recommended air distribution is 50% of total air to the first third of the tank, 30% to the second third, and 20% to the last third. Pipes and flow control valves need to be proportionally sized, and diffusers need to be distributed to balance airflow and pressure losses in the system. Fine bubble diffusers are well accepted as the most efficient means of transferring oxygen to the mixed liquor.
4. The system needs to be able to automatically adjust the amount of air to the metabolic needs of the process, typically measured as the level of dissolved oxygen in the aeration basins. Dissolved oxygen (DO) is consumed by the microorganisms that break down carbonaceous dissolved and suspended solids (BOD) and ammonium in the wastewater. The respiration rate (oxygen consumption) of the microorganisms changes with the contaminant loading of the wastewater. DO control measures changes in DO as a result of loading changes (normally measured as a deviation from a DO set point) and adjusts the blowers to maintain the set

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point. An even supply of DO to the microorganisms also helps stabilize the biology of the system and thus improve overall performance.

In a biological nutrient removal (BNR) environment, the sizing of the first anoxic (or pre-anoxic) zone and correct mixed liquor recycle flow rates can provide additional aeration energy savings. In the pre-anoxic zone, fresh primary effluent, rich in BOD and ammonia, is mixed with return activated sludge (RAS) that is rich with microorganisms and internal mixed liquor recycle (IRQ) rich in nitrates from converted ammonium. In the absence of free dissolved oxygen, the microorganisms take oxygen from the nitrates to metabolize BOD. This has the effect of simultaneously removing BOD and nitrates from the wastewater, and reducing the DO demand in the aerobic zones of the tank by the amount of BOD already metabolized in the pre-anoxic zone.

A BNR plant with a pre-anoxic zone, subsequent aeration zones and internal nitrate recycle is known as a Modified-Ludzak-Ettinger (or MLE) process. This also describes the core treatment process for most other four and five stage BNR processes. The layout and process flows of the MLE process are shown in Figure 2.

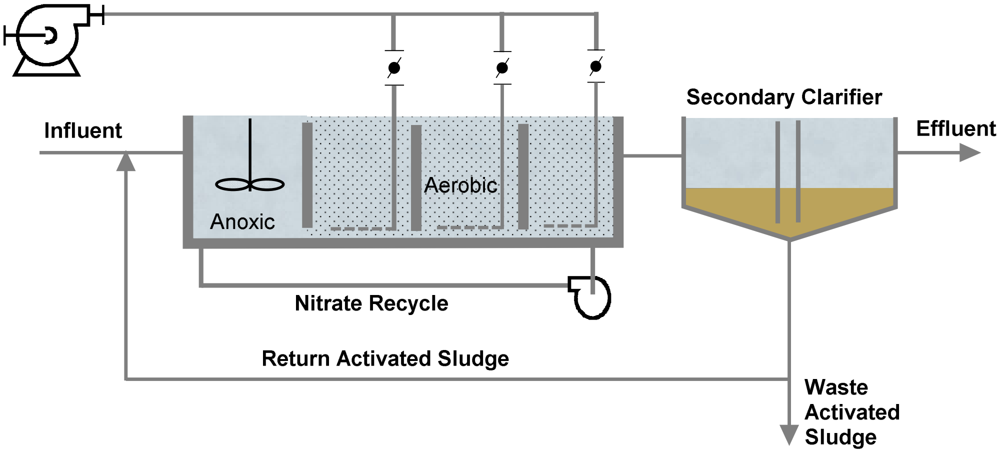

Figure 2. MLE Process Schematic

It can be shown that after implementation of all of these optimization measures, real time control of the treatment process can provide significant additional aeration energy savings and improve the nutrient removal process. This paper discusses the control methodology and shows results from sample installations.

OBJECTIVES

Modern activated sludge plants are set up to maintain a constant DO in the aeration basins, modulating the air supply to the basins to match the loading of the influent flow. The rate of nitrification in the basin is largely determined by the DO level, so the operator will determine the DO set point needed to safely meet the permit limits under the maximum anticipated loading

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conditions. Note that it is commonly accepted that BOD removal occurs much more rapidly than ammonia removal, so ammonia removal becomes the defining kinetic rate. Since the loading varies significantly (and more or less predictably) throughout the course of the day, the DO set point is higher than necessary for a large part of the day. At the same time, the oxygen transfer efficiency, as described in Equation 1 (EPA, 1989), decreases with increasing DO.

Figure 3 shows the aeration savings that can be achieved at a constant oxygen transfer rate (at a given diffuser type and depth) by varying the DO. The graph shows that at a DO of 1.0 mg/L the oxygen transfer rate is the same as at 3.0 mg/L with 30% less air flow.

$$OTE_f = \alpha F\,(SOTE)\,[\beta(C_{s,T}) - C]\,/\,C_{s,T} \qquad \textbf{(1)}$$

where: α, F are constants, $\beta = 0.95$, $C_{s,T} = 9.08$ mg/l saturation concentration at 20˚C,
C = DO concentration and SOTE is the Standard Oxygen Transfer Efficiency for a given diffuser, depth and flow rate ($SOTE = 0.3q^{-0.15}$ for a membrane disk diffuser at a depth of 4.57 m (15 ft)).

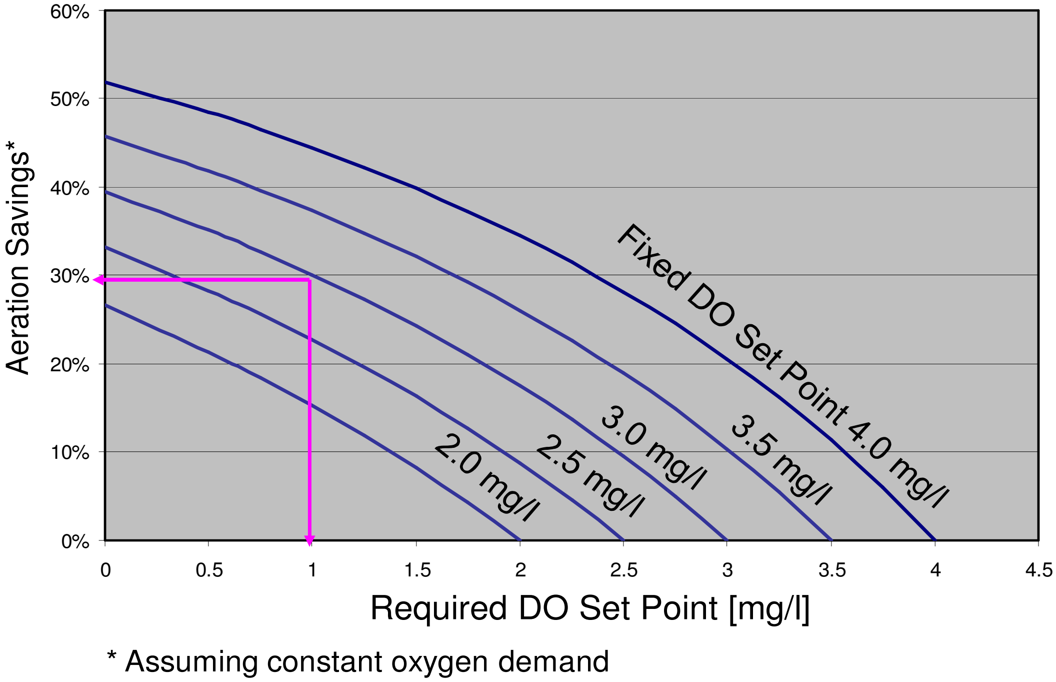

Figure 3. Aeration Energy Savings as a Function of DO Reduction

The nutrient removal process is managed by the internal recycle flow (IRQ) of nitrate rich mixed liquor to the pre-anoxic zone. The IRQ rate is measured as a percentage of influent flow and is normally operated at or near 400% of influent flow rate. That means that about two thirds of the nitrates generated in the ammonia removal process in the aerated portion of the reactor are returned to the beginning of the tank, while one third is released to the secondary clarifiers or a denitrification process. The fixed IRQ rate does not take into account the actual capacity of the

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pre-anoxic zone to convert nitrates to nitrogen gas. If the denitrification capacity is higher than the IRQ rate, then available capacity is wasted; if it is lower, the anoxic zone is overloaded and the IRQ pumps work without providing a benefit.

The objective of the real time process controller is to determine the optimum DO set point and IRQ rate in real time for minimum energy usage and at the same time maximize nutrient removal.

METHODOLOGY

The Bioprocess Intelligent Optimization System (BIOS) determines the optimal operating settings for the secondary treatment based on actual operating conditions and influent loading. It communicates with the plant SCADA (or DCS) to determine influent and recycle flow rates, DO, operating temperature, mixed liquor suspended solids (MLSS) and waste rates. It also communicates with on-line nutrient analyzers that measure the ammonia level in the anoxic zone and ammonia and nitrate at the end of the reactor. The tank geometry is programmed into the system, and ammonia utilization rates and denitrification rates are measured with a bench scale batch reactor prior to system installation. The BIOS uses a customized version of the Activated Sludge Model (ASM 1) (Henze, 1987) to create a simulation model of the plant. It uses the model to calculate in a feed-forward mode system outcomes (effluent levels) in real time based on the system inputs. In an optimization loop it then determines the operating parameters (DO set point and IRQ rate) that optimize the system outcomes. These data points are communicated to the SCADA for implementation. Figure 4 shows the process schematic.

If kinetic rates (ammonia utilization rate and denitrification rate) deviate over time, due to changes in process, season or wastewater composition, the program will recognize the changes by measuring the ammonia at the end of the train and it will self-correct.

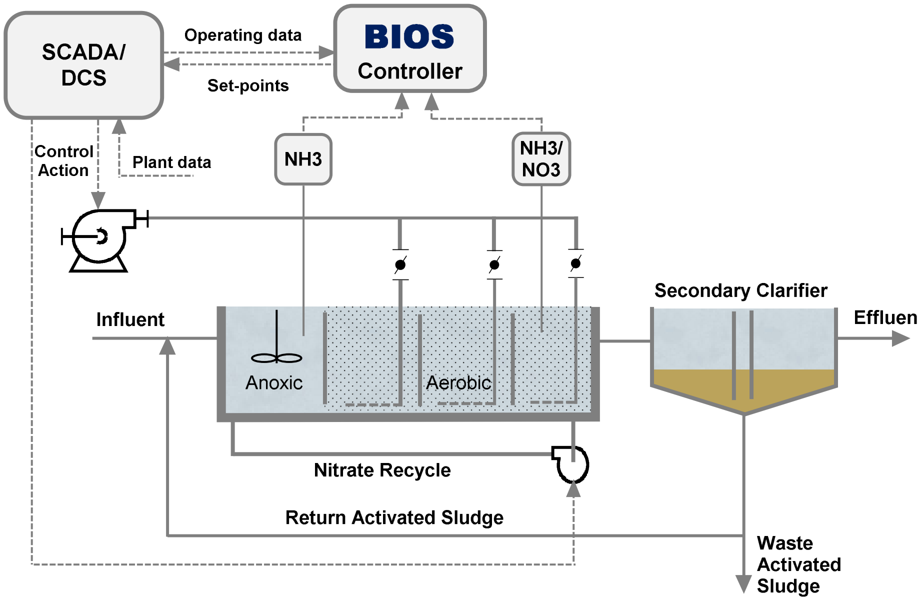

Figure 4. BIOS Process Schematic

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Feed-back control systems that are designed to achieve the same objectives based on measuring deviations of the effluent conditions (ammonia, nitrate or total nitrogen) from the target have two inherent problems:

1. The time lag between the cause of the deviation and the time that the measurement takes place causes the system to respond well after the disturbance has occurred, and can therefore at best only partially compensate for the deviation.
2. Since the feed-back controller measures a deviation, but does not have information about the nature of the disturbance, it can only be tuned to respond to an "average" disturbance and thus the control response may be inadequate, causing instability in the control response.

DO Optimization

The objective of the DO optimization is to achieve the desired level of effluent ammonia at or near the end of the tank, but not significantly before. As is common practice in activated sludge plants, the BIOS uses degressive DO set points along the length of the tank, i.e. the highest set point will be in the first aerobic zone, and the lowest is at the last aerobic zone. Under high loading conditions, the controller will adjust the DO set points upwards, and under low loading conditions it will lower the DO set points. The range of set points can be limited to operator-defined upper and/or lower set points, for example to manage filamentous growth and/or facilitate mixing.

Optimization of the DO set point has multiple benefits:

1. Energy usage is minimized, because the minimum amount of air needed to convert BOD and ammonia is used.
2. Under low loading conditions the loading is moved down the length of the tank instead of being used up in the early stages, so the microorganisms only receive respiration oxygen when they also have food, stabilizing the biology.
3. Because loading is moved to the end of the tank, air in the last zone, which is typically needed for mixing even in the absence of loading, will be used by the biology and the DO will be kept low, preventing a spike in the DO which will cause oxygen to be recycled to the anoxic zone, causing inefficiencies in the anoxic zone.

IRQ Optimization

Neither the denitrification potential of the anoxic zone nor the total mass of nitrates in the internal recycle flow are a constant, so current control strategies that use a constant recycle flow ratio will underutilize and/or overload the anoxic zone at different times of the day. A real-time control strategy that calculates the denitrification potential of the anoxic zone and measures the nitrates in the recycle flow can adjust the IRQ to always achieve the maximum possible total nitrogen removal.

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Simulation Results

The BIOS control strategy was simulated and applied to the IWA benchmark wastewater treatment plant (BSM1) (Copp, 2001). BSM1 is a mathematical model describing an MLE treatment process and 14 days of influent loading. It is designed to allow comparisons of process control strategies. The results of the BIOS simulation over a three day period are shown in Figures 5 to 8:

- Figure 5 shows the influent ammonia loading and the BIOS optimal DO set point response vs. a fixed set point of 3 mg/L. The BIOS DO set point is constrained in the simulation to between 1.0 and 3.0 mg/L. Over a 24 hour period, the BIOS set point is at the lower limit more than 50% of the time.

- Figure 6 shows the nitrate concentration at the end of the aeration tank and the resultant optimal IRQ set point vs. a fixed set point of 400% of influent flow.

- Figure 7 shows a comparison of the calculated aeration energy for the BIOS control vs. the fixed DO set point control. BIOS control provided aeration savings of 20.5%.

- Figure 8 shows the total inorganic nitrogen (TIN) in the effluent for the two control strategies. TIN removal was improved by 9.6% using the BIOS control.

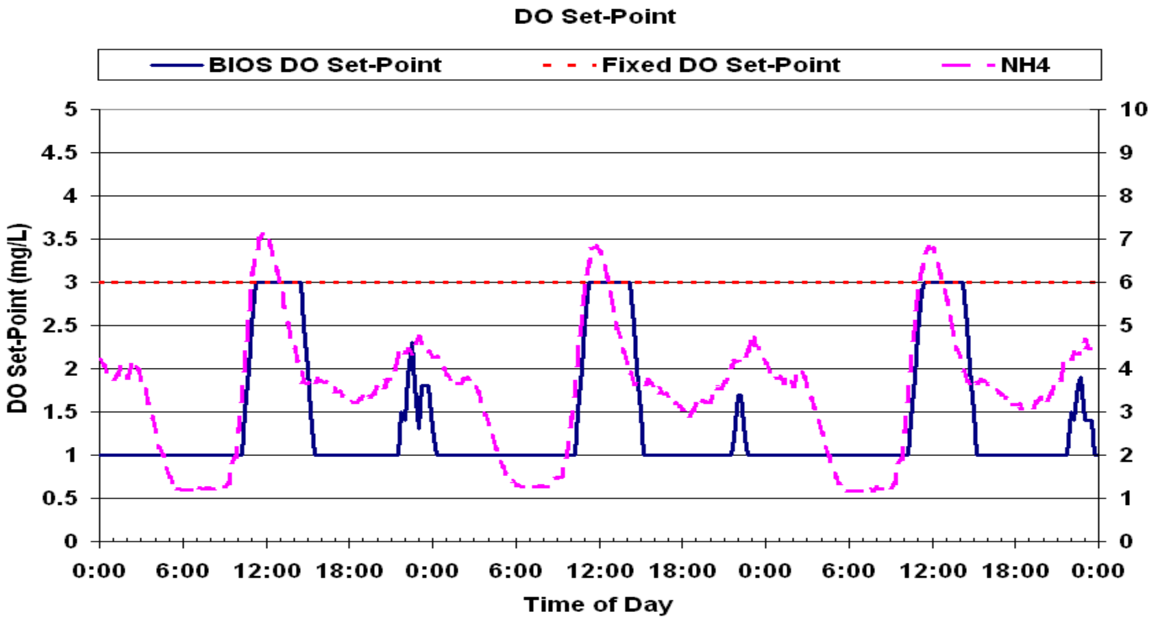

Figure 5. Simulation of BIOS DO Set Point Control Using the IWA Benchmark

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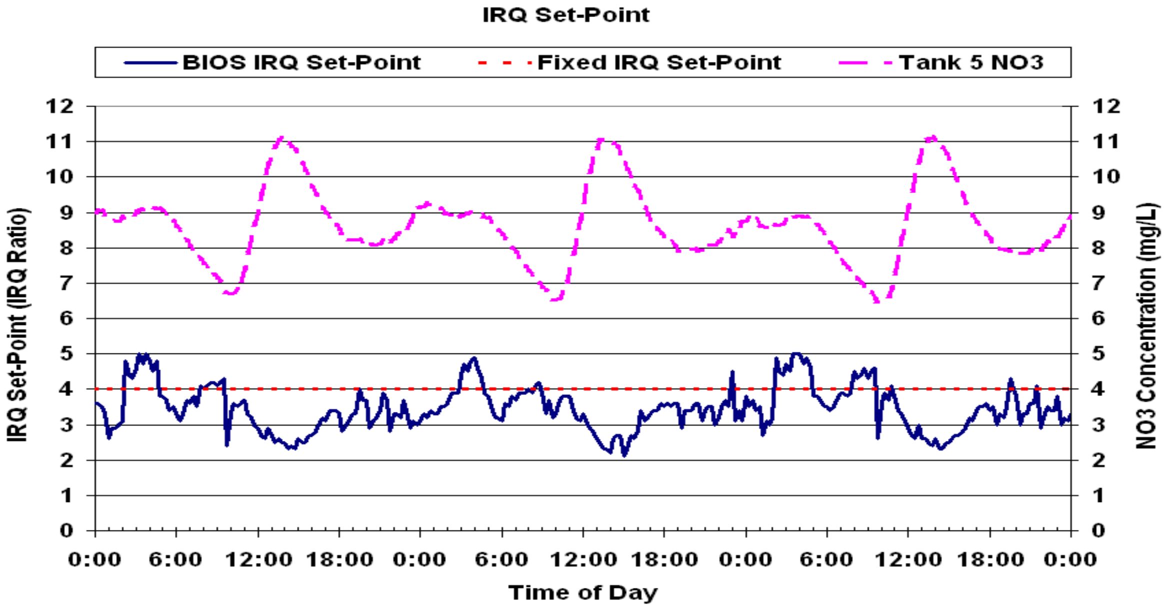

Figure 6. Simulation of BIOS IRQ Control using the IWA Benchmark

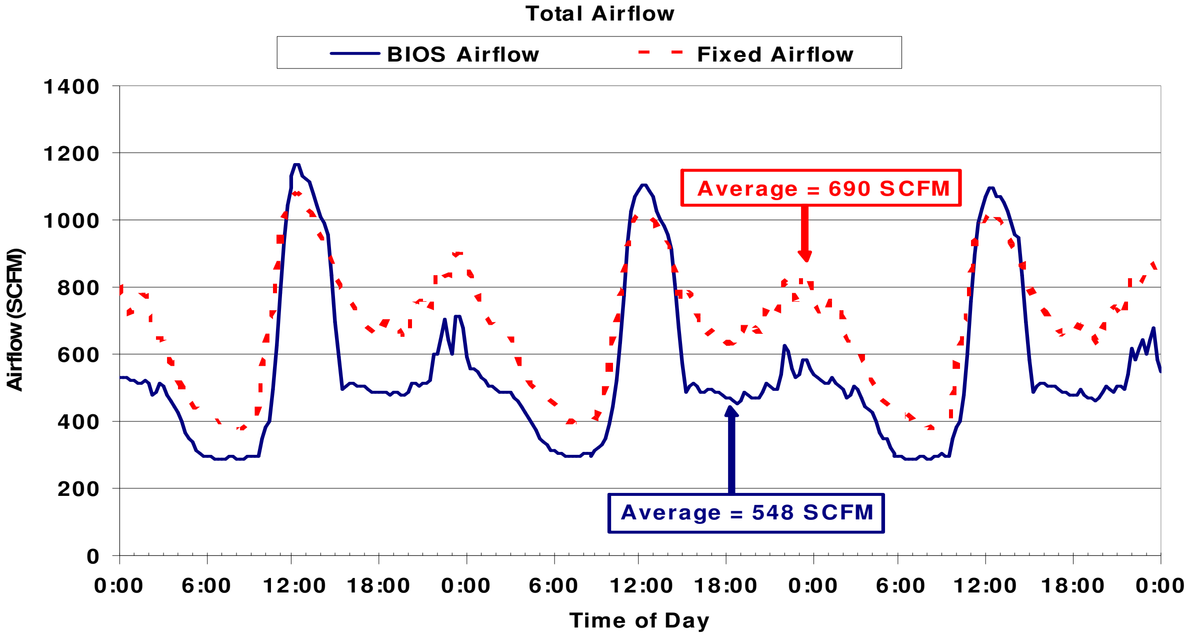

Figure 7. Comparison of Airflow Rates Using BIOS Control vs. Fixed DO Set Points in the IWA Benchmark. BIOS Control Used 20.5% Less Air.

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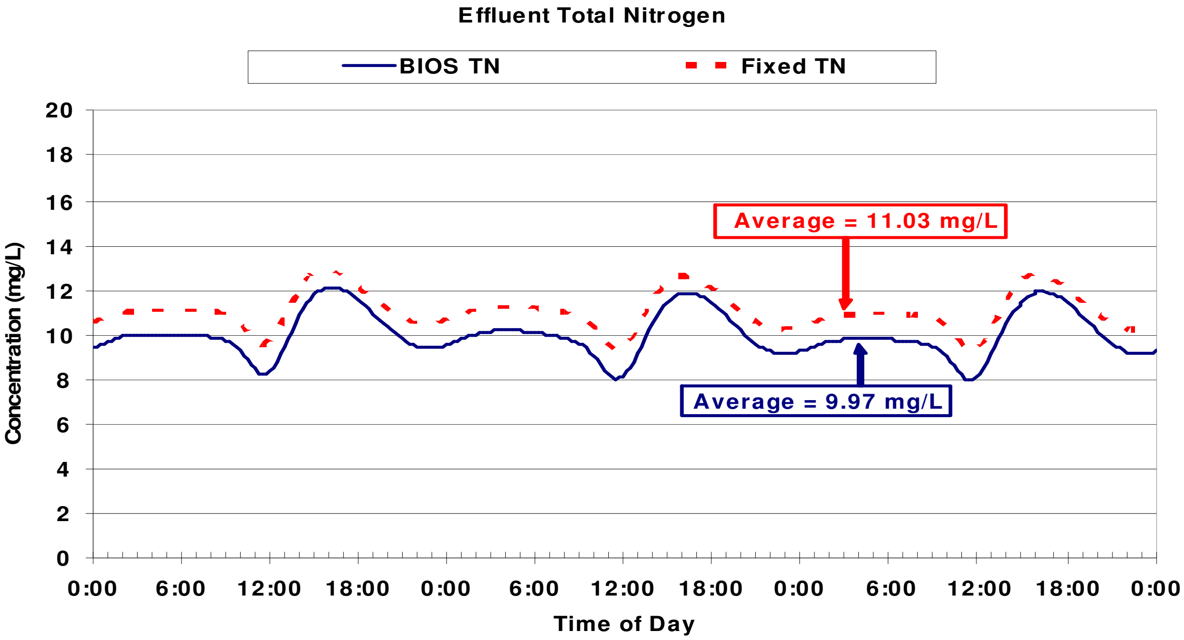

Figure 8. Comparison of Effluent Total Inorganic Nitrogen Using BIOS Control vs. Fixed IRQ Control in the IWA Benchmark. BIOS Control Improved TIN Removal by 9.6%.

CASE STUDIES

Enfield, Connecticut

The Town of Enfield Water Pollution Control Facility (WPCF) is subject to Connecticut's Nitrogen Control Program, which has the goal of reducing nitrogen discharges to the Long Island Sound. In 2002 the Town of Enfield and SEA Consultants investigated opportunities to meet the new discharge limits while maintaining the design capacity of 40 ML/d (10 mgd). As a first step, the plant was converted to an MLE process. To operate the plant at maximum capacity, BioChem Technology Inc. was invited to demonstrate and test the BIOS. In order to quantify the performance of the BIOS, a side-by-side comparison was conducted.

The Enfield WPCF has four parallel trains with one anoxic zone and three aeration zones (Figure 9). The BIOS was installed in Train 4, while Train 2 was fitted with an ammonia/nitrate analyzer in the effluent to measure total inorganic nitrogen (TIN) in the effluent. The manual set points used to operate Train 2 were DO levels of 2.75 mg/L, 2.0 mg/L and 0.5 mg/L for zones 1, 2 and 3 respectively, and the IRQ ratio was set at 275%.

The comparison was run from January 2004 to May 2004, with the BIOS controlling the DO set points and the IRQ ratio of Train 4. The study demonstrated that the aeration requirements were reduced by nearly 18% (Figure 10) and TIN removal was improved by 36% (Figure 11). The BIOS has been controlling the plant since June 2004. In 2009 the process was upgraded to a four stage AOAO to include a post anoxic zone with carbon addition for additional nitrate removal without increasing tank size and without downgrading the plant capacity.

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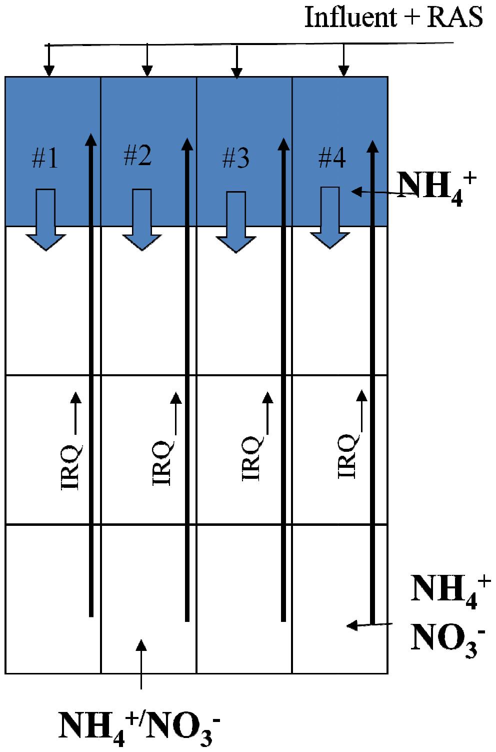

Figure 9. Enfield WPCF Layout with Location of NH4+ and NO3- Analyzers

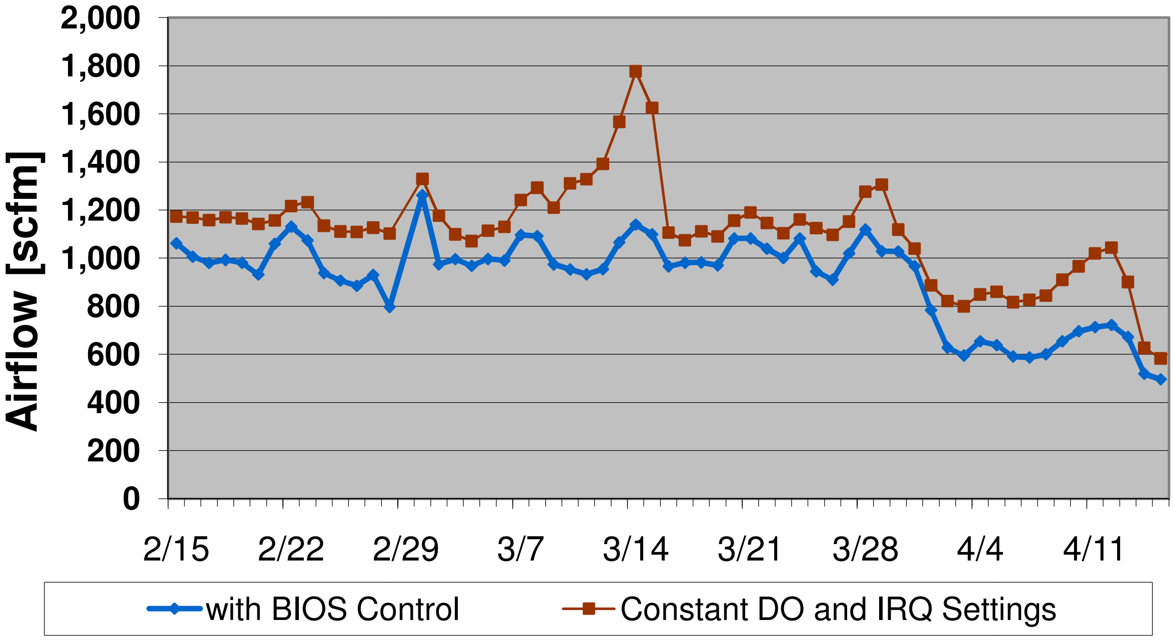

Figure 10. Enfield, Connecticut. 17.8 % Aeration Savings Achieved During the Pilot Project

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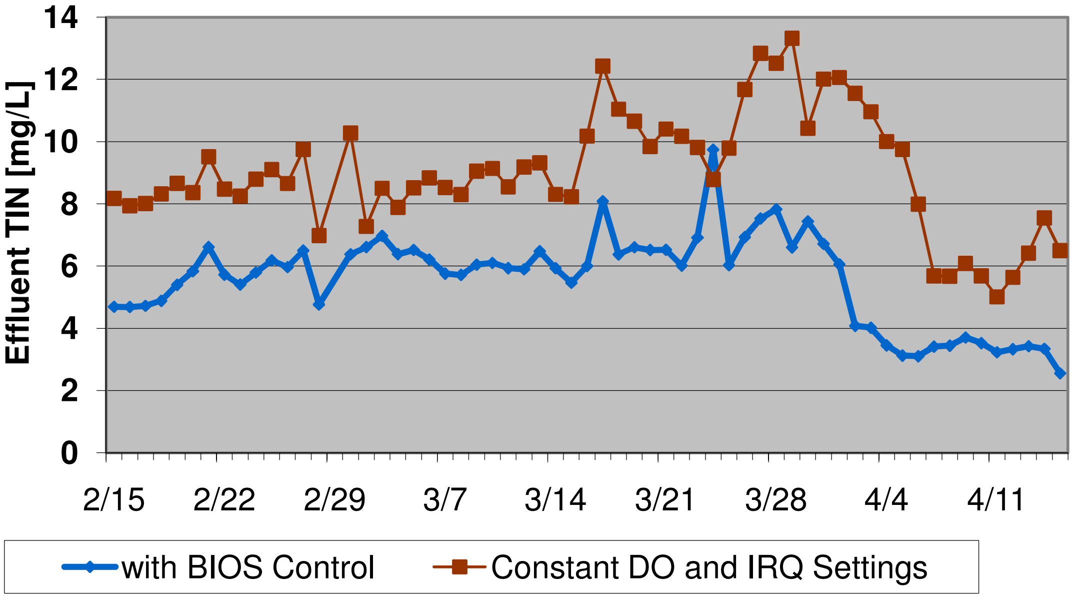

Figure 11. Enfield, Connecticut. 37.6% TIN Reduction Improvement During the Pilot Project

In early 2008 US EPA Region 1 conducted an energy benchmarking survey of activated sludge plants. Enfield was ranked first for WWTPs between 20 and 40 ML/d (5 and 10 mgd) with similar processes. In 2010 Enfield WPCF received the NEWEA Energy Management Award.

Phoenix 23rd Avenue WWTP

In 2006 the City of Phoenix Energy Management Division decided to fund a pilot project to evaluate the energy savings provided by a real time process control system at the 23rd Avenue WWTP.

The WWTP has a capacity of 256 ML/d (64 mgd) and an average daily flow (ADF) of 192 ML/d (48 mgd). It has four parallel treatment trains using the MLE process, each with three anoxic zones and nine aeration zones. Figure 12 shows the layout of one of the trains.

The DO optimization module of the BIOS was installed in 2007 in one of the trains. Total nitrogen removal was not an objective of the pilot so the IRQ module was not installed. To quantify the energy savings generated by the BIOS, the plant was operated under BIOS control for a series of days, and then subsequently operated with fixed DO set points for a similar number of days. Total energy use of the blowers was measured daily, and energy use data were compared for the periods when the plant was operating under BIOS control vs. fixed DO set points. The energy saved with one train under BIOS control represents one quarter of the potential energy savings when applied to four trains.

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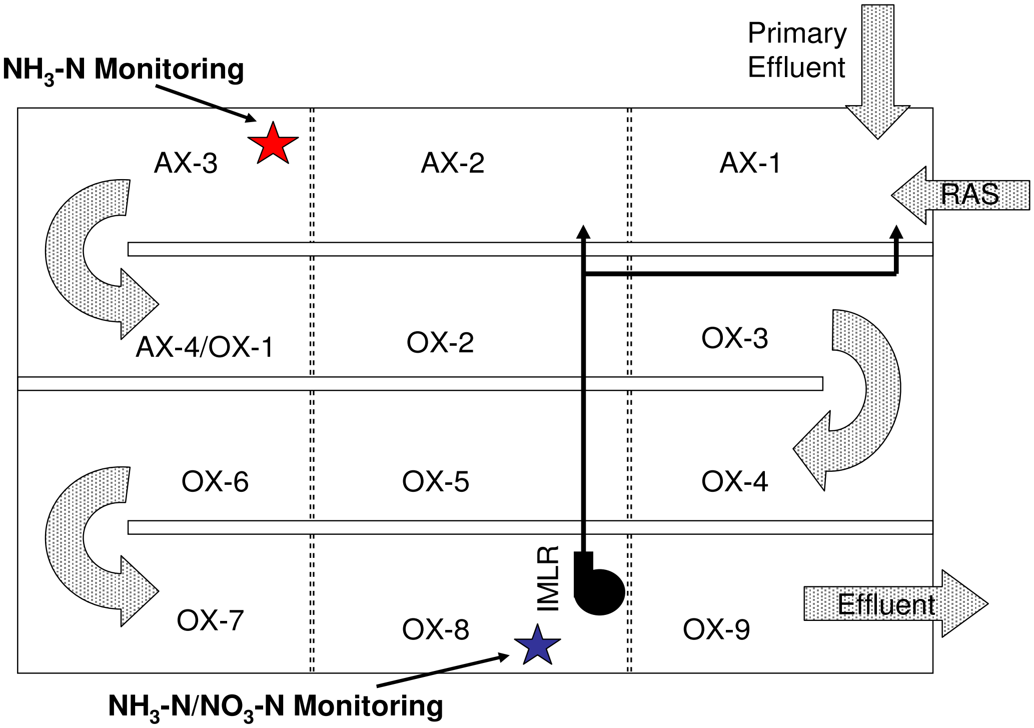

Figure 12. Layout of 23rd Avenue Treatment Tank with Location of Nutrient Analyzers

A summary of the collected data showing energy use by the blowers for the periods with the BIOS on and off are shown in Table 1. Measured energy savings ranged from 11.5% to 18.3% when applied to all four trains, with an average savings of 15.3%. The savings can also be expressed as 117.6 kWh per million gallons of treated flow.

Table 1. Energy savings using automatic control at 23rd Ave WWTP

Trial	BIOS	Duration [Days]	Measured kWh/MG	Difference kWh/MG	Savings One Train	Calculated Savings Four Trains
1	ON	8	725.8			
	OFF	7	760.6	34.8	4.6%	18.3%
2	OFF	11	772.8	22.3	2.9%	11.5%
	ON	11	750.5			
	OFF	11	781.7	31.2	4.0%	16.0%
Average				**29.43**	**3.82%**	**15.3%**

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This represents an energy savings of 2,000 MWh per annum and a carbon footprint reduction of 1,400 metric tons.

Note that at the 23rd Avenue WWTP the operator set lower DO limits of 2.0 mg/L at the front of the train, 1.3 in the middle and 0.5 at the end of the train. The BIOS operated at the lower limits for most of the day, so the savings would have been greater if the limits had been lowered.

During the test, effluent ammonia and nitrates were measured, and it was determined that the effluent quality was not compromised by the BIOS control.

CONCLUSIONS

Dynamic DO set point control using a model-based feed-forward control strategy in wastewater treatment plants can provide aeration energy savings on the order of 15% to 20% without compromising effluent quality. In addition, dynamic control of the internal recycle flow can improve total nitrogen removal by over 35%. Results were consistent across different climate zones and plant sizes (Phoenix, Arizona 23rd Avenue WWTP and Enfield, Connecticut WPCF) and they conformed closely to simulation results.

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