Field Validation of Sequencing Batch Reactor and Cloth Media Filtration Technologies To Attain Ultra-Low Nutrient Levels

Terence K. Reid[1*], Al Zerbato[2], Rungrod Jittawattanarat[1], Lloyd W. Johnson[1], Kenneth A. Mikkelson[1], Matthew Castillo[1]

[1]Aqua-Aerobic Systems, Inc, Loves Park, IL, 61111, USA
[2]Lee Wastewater Treatment Facility, Lee, MA, 01238, USA
*Email: TReid@aqua-aerobic.com

ABSTRACT

Sequencing batch reactor (SBR) technology coupled with cloth media filtration (CMF) has been used extensively to achieve low levels of total nitrogen (TN) and total phosphorus (TP) in wastewater treatment. Practical resource considerations for cost, energy, chemicals, personnel and analytics typically prohibit the pursuit of treatment goals that are substantially lower than the prevailing regulatory requirements. Demonstration of systems achieving ultra-low levels of both nitrogen and phosphorus is further complicated if the discharge permit requires one but not the other. This study was facilitated by a municipality's concern for an impending 0.2 mg/l TP discharge limit and a permit obligation to implement TN removal.

A validation test program was defined and executed on the 5,679 m^3/day (1.5 mgd) SBR and CMF system at the Town of Lee, Massachusetts. A 0.1 mg/l TP and 3.0 mg/l TN effluent was achieved through step-wise monitoring and adjustment of key operational parameters and activities.

KEYWORDS: Activated sludge, phosphorus, nitrogen, nutrient removal, sequencing batch reactor, cloth media filtration.

INTRODUCTION

Water quality impairment by nutrients represents one of the greatest environmental challenges we face in our nation's lakes, streams, rivers, estuaries, bays and coastal regions. Nutrients, algal growth and ammonia collectively represent the second leading cause of impairment for 303(d) listed waters in the United States. Significant efforts have been made by the Water Environment Research Foundation (WERF) and others to classify performance levels and identify technologies on metrics such as capability, operational attributes, cost, carbon footprint and reliability (WERF, 2010). WERF-designated Level 4 effluent 0.1 mg/L TP and 3.0 mg/L TN concentrations approach the practical limits of technology (LOT), warranting extensive new and emerging technology review. SBR and CMF technologies are often referenced in enhanced nutrient removal (ENR) technology reviews, but their performance characteristics are either generalized or referenced to installations with substantially different discharge requirements.

The SBR process has been demonstrated to offer significant advantages over conventional activated sludge processes due to its high degree of operational and control flexibility (Ketchum, 1997). Utilizing time-managed reactor controlled environments to create independent anaerobic, anoxic and aerobic conditions under varying substrate levels has been effective in establishing active nitrification, denitrification and biological phosphorus removal within a single reactor.

In order to achieve an effluent quality that approaches the ≤ 0.10 mg/l LOT TP objective, a combined biological and chemical phosphorus removal strategy must be established. The SBR process offers a unique configuration that can create an anaerobic condition during the treatment cycle's initial Mix-Fill phase. As shown in Figure 1(a), the aeration system is typically turned off during the first 45-90 minute Mix-Fill phase, resulting in a reactor that is completely mixed in the absence of dissolved oxygen (DO). In a system achieving a low effluent TN concentration, the background nitrate (NO_3-N) and nitrite (NO_2-N) levels at the beginning of the cycle are typically between 1-2 mg/l (Figure 1(b)). During the Mix-Fill phase, the reactor is filled with screened primary sewage which is reflected by a slight rise in the influent ammonium-nitrogen (NH_4-N) as illustrated in Figure 1(c). The anaerobic stated is reached once the oxidized nitrogen (NO_2-N and NO_3-N) depletion occurs, resulting in short-chain volatile fatty acid (VFA) generation by facultative bacteria that ferment soluble organics.

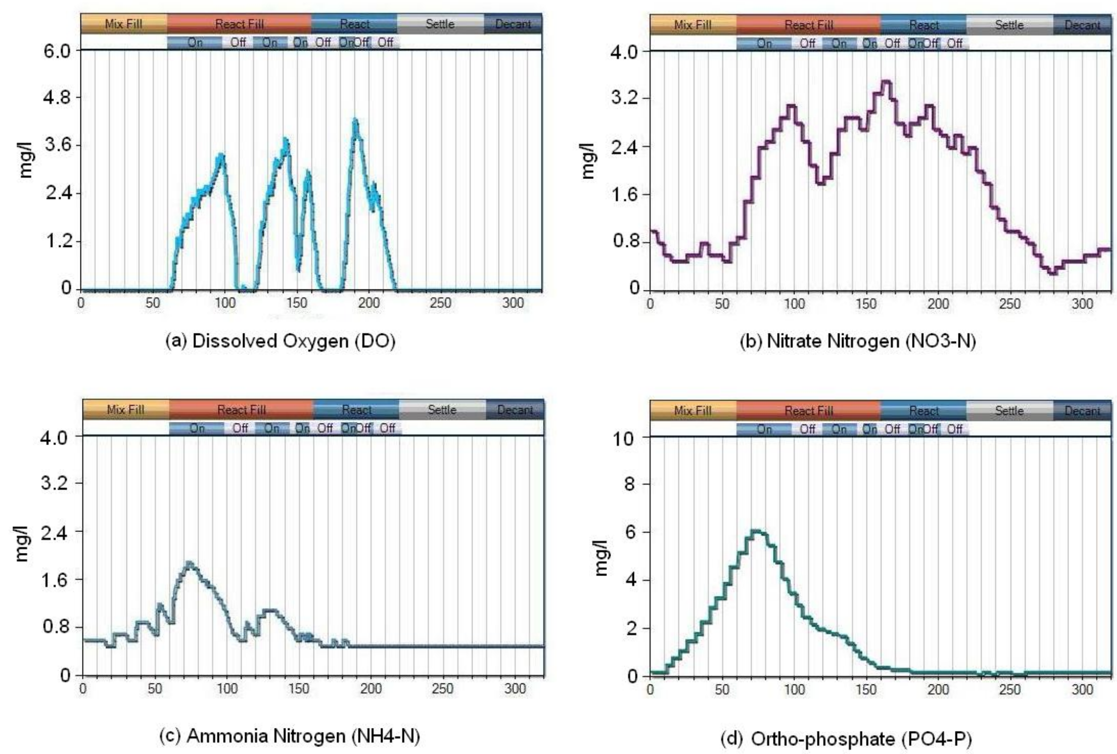


Figure 1. Data illustrating profiles of (a) DO, (b) NO_3-N, (c) NH_4-N and (d) PO_4-P typical for an SBR configured for ultra-low nutrient discharge levels.

The fermentation products are assimilated by phosphorus accumulating organisms (PAO) such as *Acineobacter*, *Aeromonas* and *Pseudomonas*. The energy requirements for the PAO bacteria are derived from poly-phosphate compound hydrolysis within the cells, resulting in an increase in soluble phosphorus (Danesh, *et al*., 1997) as shown in Figure 1(d).

Upon completion of the 45-90 minute Mix-Fill phase, the anaerobic reactor environment is converted to an aerobic state in the React-Fill phase. The DO rapidly increases while influent organic substrate continues to fill the reactor once the aeration system is operated. The PAO's exhibit an elevated phosphorus uptake in the oxidative state (Figure 1(d)) as the bacteria metabolizes stored fermentation products. Subsequent anoxic steps during the React-Fill and React (non-fill) phases represent discrete, short intervals needed to establish later denitrification. As exhibited in Figure 1(d), the secondary anoxic steps (after the initial Mix-Fill phase) will inhibit the rate of phosphorus uptake, but will not result in secondary orthophosphate release if the anoxic period is kept sufficiently short (typically less than 30 minutes) to prevent anaerobic activity. However, once aeration is reinitiated during the React-Fill phase, phosphorus uptake will continue (Figure 1(d)), allowing the reactor to reach low soluble orthophosphate levels prior to the start of the React phase.

As the biological phosphorus release and uptake mechanisms have been completed mid-way through the cycle, the SBR reactor offers an ideal location for coagulant addition near the end of the React phase. Introducing a coagulant at this point in the cycle allows the biological process to remove the bulk of the phosphorus, resulting in lower chemical dosing requirements. Metal salt mixing followed by a quiescent settle phase also provides effluent clarity and minimized chemical solids loading to the downstream filter system.

To achieve a 0.1 mg/l final effluent TP, the SBR discharge concentration should be approximately 0.2-0.3 mg/l with a phosphorus speciation profile that permits further filtration. As the effluent total suspended solids (TSS) from a nutrient removal SBR is typically 5-10 mg/l, particulate phosphorus must be removed further. Tertiary filtration with provisions for coagulant and polymer addition with flocculation may be necessary to provide system reliability.

In this field investigation, the SBR and CMF system operating at the Town of Lee, Massachusetts was evaluated for the purpose of determining if both a 3.0 mg/l TN and a 0.1 mg/l TP discharge limit could be realized.

The Lee Wastewater Treatment Facility (WWTF) is located in the southwest corner of Massachusetts and discharges into the Housatonic River at segment MA21-19. The Housatonic is classified as a “Class B” water by the State of Massachusetts which identifies it as a habitat for fish and wildlife, as well as a designated use for primary and secondary contact recreation. In 2000, the Lee WWTF was issued a 1.0 mg/l TP discharge permit. Upon a subsequent permit evaluation, the Environmental Protection Agency (EPA) determined that this discharge requirement could not ensure adequate protection of the downstream receiving water under critical flow conditions. To mitigate further eutrophication, a 0.2 mg/l point-source discharge concentration was determined necessary to meet water quality standards based upon a recommended 0.1 mg/l downstream concentration. An interim effluent 0.55 mg/l TP discharge requirement was issued until the 0.2 mg/l requirement was to take effect on April 1, 2012.

Figure 2. Aerial view of the Lee, MA WWTF and the Housatonic River.

While phosphorus has been identified as a significant cause for impairment of the Housatonic River, the Lee WWTF discharge permit required evaluation of alternative methods to optimize TN removal (EPA, 2008). The suggested operational modifications included anoxic and aerobic time adjustments as well as evaluation and management of side-streams and septage input to the plant.

PURPOSE AND OBJECTIVES

The primary purpose of the study was to evaluate the Lee, MA WWTF's ability to meet the impending 0.2 mg/l TP discharge limit as well as its responsiveness to efforts made to improve TN reduction.

Another major objective was to evaluate the potential for a specific SBR configuration to meet respective 0.1 and 3.0 mg/l TP and TN values when coupled with CMF technology. A primary goal of the study was to determine if deliberate operational manipulation of key variables could yield the LOT results with an established process technology to avert the need for the added cost, equipment and complexity often associated with emerging technologies.

METHODOLOGY

System Components

The Lee WWTF is designed to treat 7,192 m^3/day (1.9 mgd) as a maximum-month, average flow (MMAF) with the ability to process 14,991 m3/day (3.96 mgd) during maximum daily flow (MDF) conditions. The system must also process 18,474 m^3/day (4.88 mgd) on a peak hourly basis.

The plant's headworks include grit removal and a 6 mm (¼ inch) coarse screen, two raw wastewater wet wells, a septage storage tank and a recycle tank. The septage is also processed through a dedicated 6 mm (¼ inch) coarse screen, stored and co-thickened with waste activated sludge through a rotary drum thickener (RDT). The thickener's filtrate is routed to the reycle tank and combined with the filter backwash in the raw wastewater wet wells. As part of the multi-point chemical injection design, coagulant can be added to the reycle tank and the reactor influent as necessary (Figure 3).

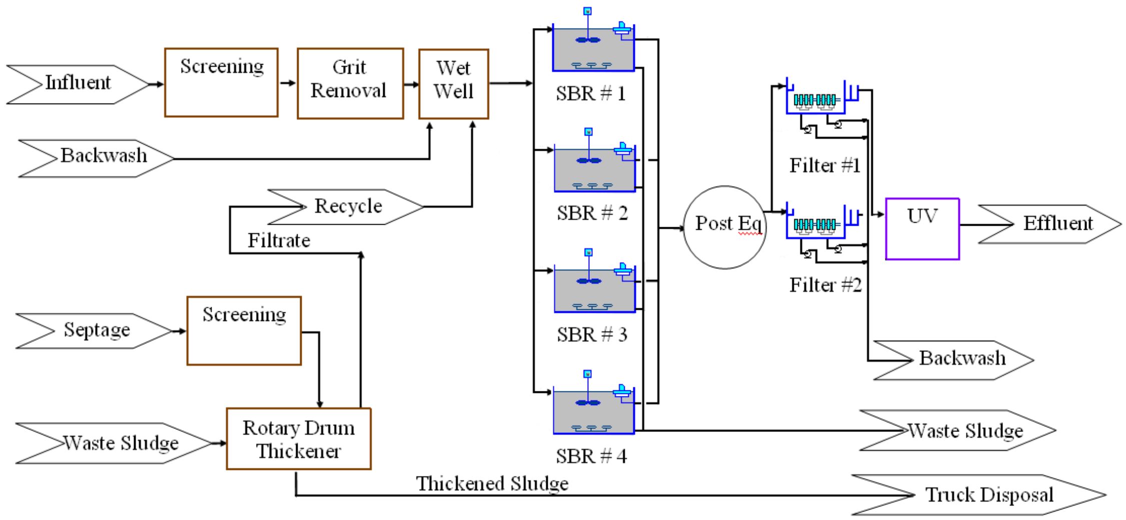


Figure 3. Lee WWTF Process Flow Plan.

The facility is equipped with four SBR reactors, each 24.4 m (80 ft.) in diameter with an operational depth ranging from 5 m (16.5 ft) to 7 m (23.0 ft) providing a 23-day solids retention time (SRT) and a 3,500 mg/l design mixed-liquor-suspended-solids (MLSS) concentration at the low water level. Each reactor contains a direct-drive mixer which can operate independently of the fine-bubble aeration system to develop fully-mixed aerobic, anoxic and anaerobic conditions. Dedicated coagulant feed lines are provided to each reactor to offer the ability to inject chemicals prior to the sedimentation phase. The control system integrates on-line feedback that allows the system to maintain DO levels within an operator-defined range. The design cycle structure utilizes four 6-hour cycles in a ¼-point filling sequence, allowing only one reactor to fill or decant at any time. The cycle structure is presented in Table 1.

Table 1. Design cycle structure (4-basins).

Mix-Fill	60	Minutes
React-Fill	30	Minutes
React	150	Minutes
Settle	60	Minutes
Decant	60	Minutes
Aerobic Fraction	0.40	Cycle
Anoxic Fraction	0.11-0.13	Cycle
Anaerobic Fraction	0.13-0.16	Cycle

The treated water is discharged to a post-equalization basin with a gravity-assisted, flow controlled discharge to the tertiary filtration system. A chemical mixing system allows direct addition to the post-equalization as part of the multi-point dosing system.

The equalized flow is introduced into two identical 8-disk AquaDisk® CMF units manufactured by Aqua-Aerobic Systems, Inc. Each disk provides a 5 m^2 (53.8 ft^2) effective filtration area, for a total of 80 m^2 (861 ft^2) resulting in a design filtration rate of 3.75 m/hour (12.2 ft/hour). The units employ OptiFiberPA-13® nylon pile cloth media which offers a 10µm nominal rating.

Preliminary Investigation

The study was preceded by a preliminary investigation to assess, evaluate and characterize historical performance. This was done by reviewing operational data from the previous two years. Data provided by the plant's Discharge Monitoring Report (DMR) as well as daily records of influent, effluent and reactor parameters from the Operations Monitoring Report (OMR) provided the inputs to statistical modeling software (JMP, V6.0). The data were represented graphically to better illustrate seasonal variability while each parameter was summarized by a cumulative distribution function and defined by a quantile framework to benchmark performance.

The operating conditions including the cycle times, phase times, aeration cycling, and MLSS concentrations were incorporated with influent characteristics into the process simulation software (BioWin, V3.1). Monthly performance was modeled over a six month period spanning 2009 and 2010 when all four SBR reactors were online. A composite simulation report was generated based upon the operational period to confirm general agreement between the model's output and the actual performance results (Figure 4).

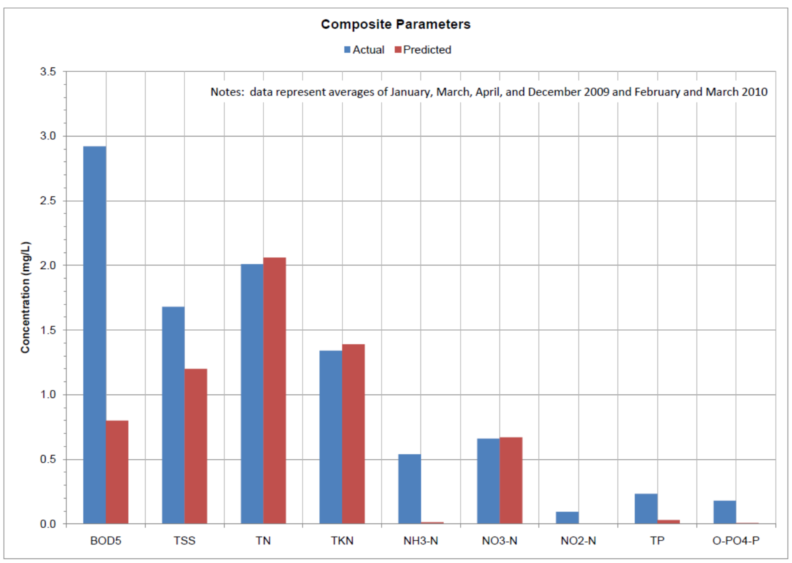


Figure 4. Comparison of Lee WWTF's actual and predicted performance.

Evaluation of Current Operation

At the time of the scheduled field evaluation, the Lee WWTF system was achieving results lower than the requirements outlined in the design specifications and current effluent permit. Due to the reduced flows and increasing temperatures, one of the four SBR reactors was previously taken off line. The resulting organic loading to the three remaining reactors placed the system at 70% of design capacity during the testing program.

As suggested by the simulation tool, effluent TN levels were already below the 3.0 mg/l objective identified as a practical limit of technology. The effluent nitrogen performance suggested that the current cycle structure was appropriate with respect to aeration and anoxic staging (Table 2). Therefore, no changes were made.

Table 2. Field test cycle structure (3-basins in operation).

Mix-Fill	70	Minutes
React-Fill	45	Minutes
React	110	Minutes
Settle	60	Minutes
Decant	60	Minutes
Aerobic Fraction	0.43	Cycle
Anoxic Fraction	0.10-0.15	Cycle
Anaerobic Fraction	0.06-0.10	Cycle

TP removal resulted in 50%-tile and 90%-tiles below 0.19 and 0.36 mg/l, respectively. While the system performance had approached the future 0.2 mg/l permit requirement, the modeling software provided insight with respect to the need for further phosphorus speciation. Specifically, the model suggested that additional reductions in soluble orthophosphate could be attained in order to approach the 0.1 mg/l TP target.

The 1,600-1,800 mg/l low water level basis) MLSS concentrations were appropriate for the flows and temperatures, resulting in a 20-25 day SRT that matched the design basis. As a result, no changes to the solids-wasting schedule were planned.

Effluent jar testing with a variety of coagulants including aluminum sulfate (alum) and polyaluminum chloride (PACl) had been performed. Prior to the newer and more stringent permit requirement, alum had been found suitable to achieve a 0.2 mg/l level. However, the residual reactive orthophosphate wasn't being driven low enough to achieve the 0.1 mg/l objective. In lieu of increasing the alum dosage, a change to add PACl (Epic WW-58) containing 5.5% Al^{+3} proved to be effective.

The system was designed with flexibility to support multiple-point chemical injection. A review of the possible injection points and historic performance identified two areas with the greatest potential for optimization as:

1. Raw wastewater wet-well: A significant source of phosphorus was determined to be reintroduced by the RDT system filtrate. Chemicals were dosed to the influent to this tank, but were limited to periods when RDT flows were received within this tank.
2. SBR: Establishing proper biological phosphorus removal (by release and uptake) within the first 50% of the cycle was expected to produce low background dissolved total phosphorus (dTP) in the latter portion of the cycle. Coagulant was dosed to each reactor in the final 30 minutes of the React phase for a four minute pumping period. This method provided proper mixing, coagulation, flocculation and sedimentation prior to filtration.

Despite the ability to add chemicals to the post-equalization basin and the filter inlet, these locations were purposely not used in the testing program. By avoiding chemical use after the SBR reactors, the solids loading to the downstream cloth media filters was reduced resulting in prolonged filtration runs between backwash events and a corresponding reduction in the volume returned to the wet well.

The Lee WWTF accepts septage as a revenue source to help offset costs. In 2010, the facility accepted an estimated 7,571 m^3 (2.0 mg) of hauled septic waste which generated approximately $200,000 (USD) in revenue. The septage at the plant is screened, stored and co-thickened with the waste activated sludge (WAS) in the RDT system. Elevated TP is an obvious concern in the liquid that passes through the septage screen as well as the filtrate from the RDT device. For the testing period, the septage input was restricted to 38 m^3/day (10,000 gpd) and the raw influent, SBR feed and recycle tank were monitored independently for TP content.

Sampling and Analysis

Once the Lee WWTF demonstrated the ability to meet the LOT objectives for TN and TP for a 60-day period, an augmented sampling and testing program was undertaken to validate performance. In addition to the sampling and testing required by the plant's national pollution elimination discharge system (NPDES) permit, a sampling and analysis regimen was defined to quantify nutrient loadings at the following locations:

A. Raw Influent – Wastewater prior to primary screening or grit removal.
B. Raw Wastewater Wet-Well – Degritted and screened influent mixed with backwash flows from filtration system and filtrate recycled from the RDT process.
C. Filter Influent – SBR effluent after the post-equalization basin.
D. Final Effluent – Filtered effluent after UV disinfection.
E. Recycle tank – Filtrate from the RDT.

A weekly sampling and testing schedule was created and executed by the plant's staff over a 5-6 week period. All analyses were performed by either the Town of Lee WWTP staff or a local independent lab (Berkshire).

RESULTS

Prior to the study, the Lee WWTF was performing within their 0.55 mg/l effluent TP requirement and was compliant in reporting effluent TN levels. With only the requirement to report effluent TN, the SRT was initially maintained below critical levels necessary to promote nitrification. In anticipation of future seasonal nutrient limits, the SRT was increased to 20-25 days which promoted active nitrification and denitrification that produced 3-5 mg/l effluent TN despite the lack of a formal numerical objective.

In June 2011, the Town of Lee submitted a letter to the EPA in accordance with Administrative Order Docket No. 09-042 which outlined the plans and modifications necessary to enhance TP removal to a level of 0.2 mg/l. By this time, the coagulant dosing to the SBR effluent (feeding the CMF) had been terminated in favor of direct dosing to the SBR reactors. Additionally, coagulant addition to the raw wastewater wet-well only during sludge dewatering had proven successful.

The decision was made at this point to limit the septage input to approximately 1.4 % (or 37.8 m^3, or 10,000 gpd) of the total daily flow.

Based on historical performance, aluminum sulfate coagulant was replaced with PACl containing 5.5% Al^{+3}. By the end of August, the 0.1 mg/l TP LOT objective had been achieved for 60 days and the TN had reached the 3.0 LOT target, allowing the test program to begin (Figure 5).

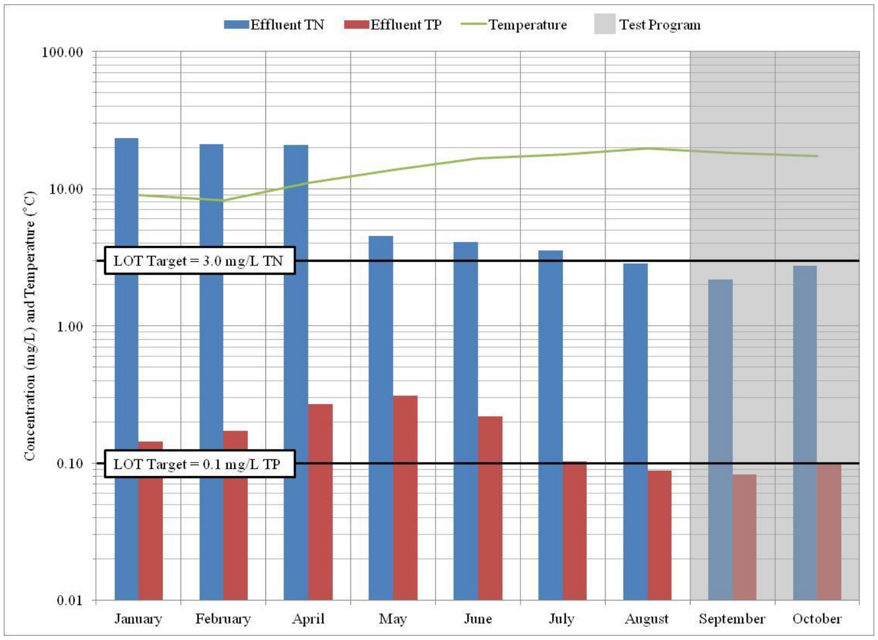


Figure 5. Reported 2011 monthly average effluent TN and TP

The average daily flow during the field validation testing was 3,521 m^3/day (0.93 mgd) requiring daily average 38 L (10 gal.) PACl addition to the raw wastewater wet-well and 246 L (65 gal.) dosed to the three on-line SBR reactors. The summary conditions are presented in Table 3.

Table 3. Summary conditions for the Field Validation Study

Location	Flow (m^3/day)	BOD_5 (mg/l)	TSS (mg/l)	TN (mg/l)	TKN (mg/l)	TP (mg/l)
Raw influent	3,521	126	156	-	24	5.5
Raw wastewater wet-well	-	171	239	-	35	5.4
Filter influent (SBR effluent)	-	-	4.4	-	-	0.12
Final effluent	-	1.3	3.4	2.88	1.38	0.09
Reycle tank	123	-	1,231	-	10.0*	34.8

*Reported as NH_3-N.

The 0.1 mg/l (or less) targeted final effluent TP was attained in 69% of the composite samples with a maximum value of 0.13 mg/l and a minimum of 0.05 mg/l (Figure 6). Despite the lack of chemical precipitation following the SBR and the low inlet TP the CMF system demonstrated a 25% average removal.

The total 284 L/day PACl dosing represented a 1.15 molar equivalent of moles of Al^{+3} applied per mole of TP removed. As the anticipated dosage for this level of phosphorus removal could be more than 3 to 10 times higher than that typically observed (Sedlak, 1991), stoichiometry suggests that a significant amount of phosphorus removal is occurring biologically, producing a low soluble PO_4-P concentration in the reactor during chemical addition in the React phase.

The final effluent TN during the study averaged 2.88 mg/l, with about 80% of values falling below the 3.0 mg/l LOT objective (Figure 6). The influent BOD_5:TKN ratio averaged 5.2 and supplemental carbon addition was not required to facilitate denitrification.

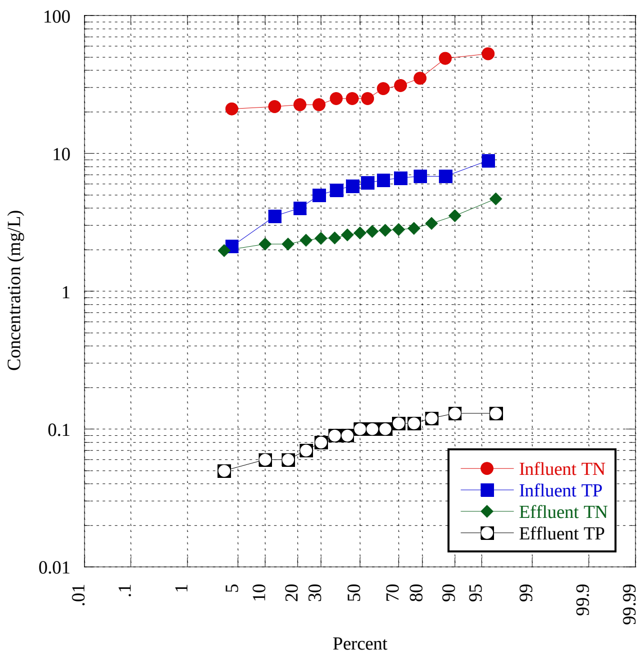
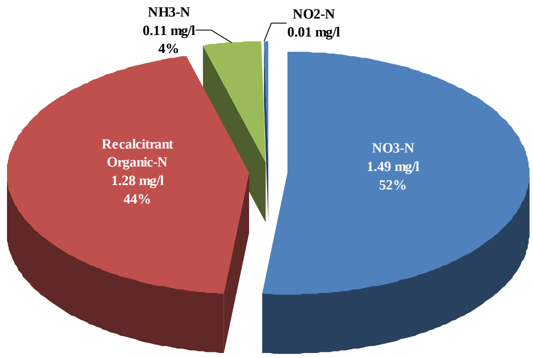


Figure 6. Results from Field Validation Study (09.18.11 through 10.24.11).

As outlined in the analytical protocol, TN and TP speciations were performed to identify potential limits to reach ultra-low levels of these nutrients. Approximately 52% (1.49 mg/l) of the the effluent TN was comprised of NO_3-N while 44% (1.28 mg/l) was present as recalcitrant organic nitrogen (Figure 7(a)). While there may be a slight opportunity to achieve further NO_3-N reductions, the study confirms the 3.0 mg/l LOT objective as a practical limit.

Similarly, TP speciation suggests a slight possibility to achieve further reductions without substantial changes in technology and chemical dosing. Soluble, non-reactive phosphorus comprised 33% (0.03 mg/l) of the TP over the testing period (Figure 6(b)). The remaining 67%, (0.06 mg/l), comprised of soluble reactive and particle-associated species, represents a potential opportunity for further limited reduction by precipitation, adsorption and complete removal of TSS.



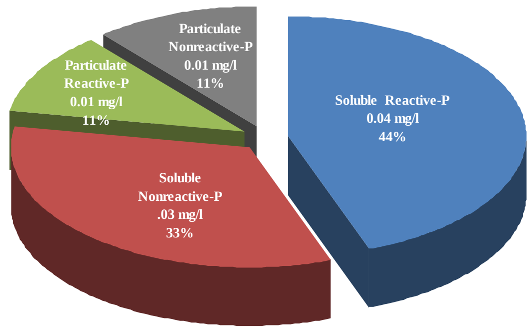


Figure 7(a). Effluent TN Fractions **Figure 7(b). Effluent TP Fractions**

In the preliminary investigation, concern for the system's ability to reliably achieve the 3.0 mg/l TN LOT objective during wintertime operation could not be addressed in the scheduled study. A follow up plan was maintained to observe the SBR and CMF's performance over the following months. Throughout the winter of 2011/2012, Lee WWTF produced a 2.0 mg/l average effluent TN, with all monthly reported effluent TN levels below the 3.0 mg/l LOT objective (Figure 8). Temperatures during the 8-month period ranged from 8°C (46.4°F) in February 2012 to 19°C (66.2°F) in June of 2012.

The 0.2 mg/l NPDES permit requirement became effective on April 1, 2012. Lee WWTF reported a 0.14 mg/l average effluent TP over the first three months of the new permit, with values ranging from 0.1 to 0.17 mg/l.

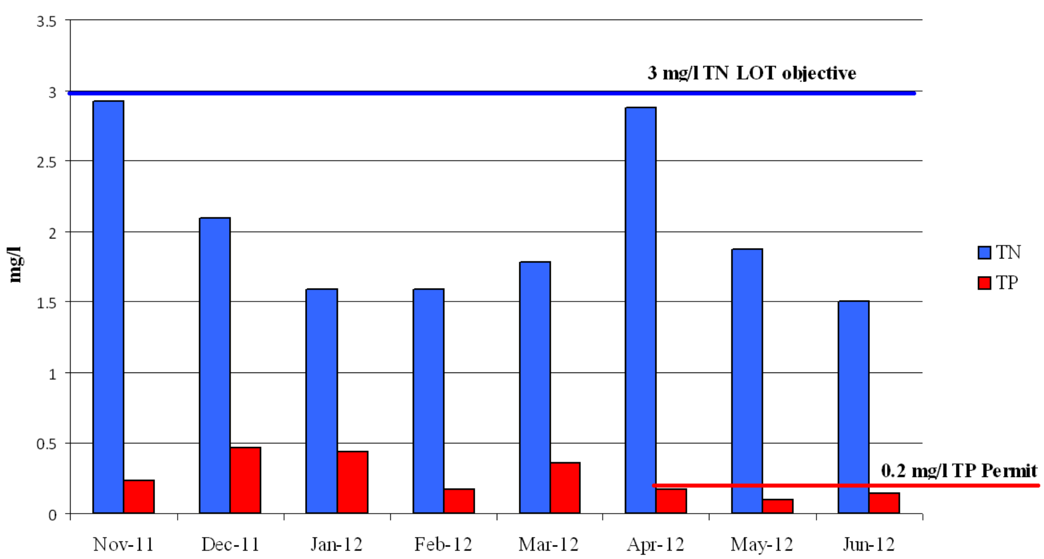


Figure 8. Reported Monthly TN and TP levels following the field study.

SUMMARY AND CONCLUSIONS

Of the approximately 16,500 permitted municipal wastewater treatment plants in the United States, only 44% provide some type of advanced treatment although more than 10,000 nutrient-related impairments have been reported (USEPA, 2009). As population growth and climate change affect our nation's water quality, impairment concerns will demand reliable treatment processes with proven nutrient removal capabilities. Technology choices will be limited to minimize energy, capital and construction costs, and operational complexity. Integrating SBR and CMF technologies has demonstrated performance consistent with LOT effluent limits while requiring a manageable investment of additional operational resources.

A 0.1 mg/l TP (98% TP removal) level was achieved by combining biological and chemical phosphorus removal strategies with SBR and CMF technologies. Chemical requirements were minimized by isolating phosphorus-rich recycle streams (such as filtrate from a RDT) and limiting coagulant dosage to match flows generated during solids-thickening events. SBR use to create an initial anaerobic state followed by aeration in the presence of incoming organic substrate resulted in significant biological phosphorus removal. Subsequent 5.5% Al^{+3} PACl dosing to the SBR for four minutes during the React phase resulted in a 0.12 mg/l SBR effluent of prior to tertiary filtration.

Chemical dosing to the SBR prior to the Settle phase eliminated the need for coagulant addition to the CMF influent and reduced the solids loading on the filter media. The CMF was effective in removing particle-associated phosphorus which resulted in a 0.09 mg/l effluent TP over the duration of the field validation study.

The SBR system met the 3.0 mg/l TN objective without supplemental carbon addition. Use of automatic DO control and time-managed aerobic, anoxic and anaerobic phases demonstrated 1.59 to 2.92 mg/l average monthly effluent TN levels throughout winter operation with temperatures as low as 8°C (46.4°F).

Septage waste treatment can provide revenue for municipalities to help offset operational expenses. However, septage represents a significant source of TP and TN that can be reintroduced into to the treatment system's influent. Limiting septage input to a maximum of 1.4% of the incoming sewage flow and dosing PACl to the associated recycle streams permitted the SBR and CMF systems to achieve the LOT objectives.

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