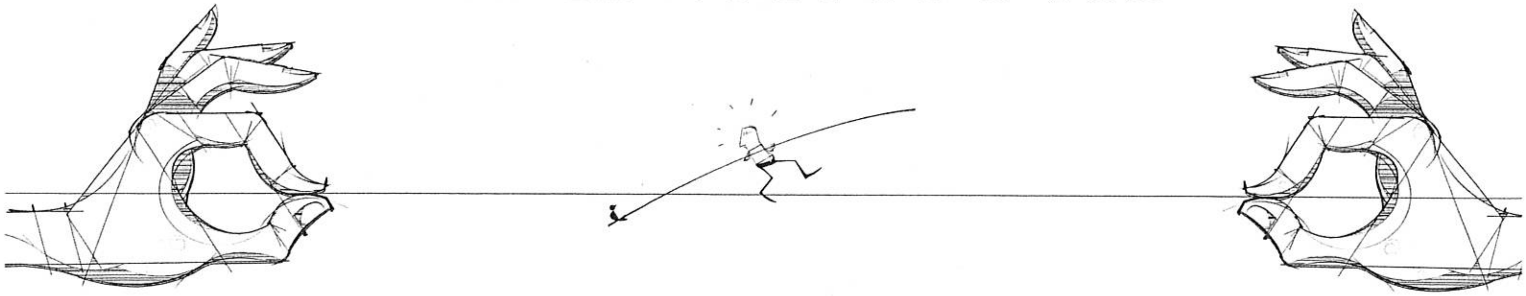
EXCEEDING EXPECTATIONS



The Town of Hillsborough, N.C., has managed to keep effluent total nitrogen below 1.5 mg/L for 500 days and counting – without supplemental carbon.

Jeff Mahagan and Katya Bilyk

Up against new nitrogen limits that are thought to be among the most restrictive in the nation and the world – the Town of Hillsborough, N.C., upgraded its water resource recovery facility in early 2014. At the town's permitted facility capacity, it will be required to comply with an annual average total nitrogen (TN) level of 1.43 mg/L.

When the upgrade was designed, both the town's staff and the design engineers believed that conventional biological nutrient removal (BNR) wastewater facilities could not meet these extremely low TN concentrations. However, by using a flexible design, the staff modified the five-stage BNR configuration and process control strategies, resulting in a 365-day average of 1.36 mg/L TN – without using additional carbon feed or any chemical feed. This TN removal exceeded everyone's expectations.

Falls Lake, located just north of the City of Raleigh, serves as flood control on the Neuse River and as the drinking water supply for Raleigh and several surrounding municipalities. Falls Lake is surrounded by state parkland and is the site of recreational activities such as fishing, boating, and camping.

To comply with the Clean Water Act and U.S. Environmental Protection Agency requirements, North Carolina monitors surface waters. Falls Lake was not meeting the water quality standard for Chlorophyll *a*. The North Carolina Division of Water Quality began developing new rules to reduce nutrients entering the lake from both point and nonpoint sources. The new Falls Lake Rules include a total maximum daily load (TMDL) for point sources that is designed to reduce total phosphorus (TP) and TN entering the lake by 40% and 20%, respectively. The rules were promulgated into state law in 2010, with point source requirements set to be implemented on January 1, 2016.

Design and performance

In 2008, the town initiated a preliminary engineering study to upgrade its 10,000 m^3/d (3 mgd) treatment facility to meet the Falls Lake Rules' speculative nutrient limits of 3 mg/L TN and 0.3 mg/L TP. To maintain the construction grant funding schedule, the report was completed before the final Falls Lake Rules were

Table 1. Historical effluent performance, speculative limits, and final nutrient allocations

	Permitted Allocations (prior to 2016)		Speculative Allocations (2008)		Final Allocations (Jan 1, 2016)	
	TN	TP	TN	TP	TN	TP
Mass Load (lb/y)	50,228	-	21,900	2,200	10,422	1,352
Concentration Equivalent at Design Flow of 2.4 mgd (mg/L)	5.5	2	3	0.3	1.43	0.185

issued. In 2009, the speculative nutrient standards were revised to values much lower than anticipated. The new speculative and final nutrient allocations are summarized in Table 1 (above), which also contains the permitted annual mass discharge limits before upgrade.

Conventional BNR technologies, like the processes proposed in the preliminary engineering study, typically reduce TN concentrations to 3.0 mg/L. Assuming 3.0 mg/L TN effluent concentrations and an annual TN discharge allocation of 4726 kg/yr (10,422 lb/yr), the upgraded facility would be able to discharge up to an annual daily average of 4200 m^3/d (1.1 mgd), as Figure 1 shows (see below). Figure 1 also indicates that at the design flow of an annual average influent flow of 9000 m^3/d (2.4 mgd), the maximum annual TN average would have to be 1.43 mg/L TN to stay in permit compliance, which is less than half of the proposed upgrade's TN removal capabilities.

The town conducted a study to determine whether the proposed upgrades would be compatible with additional unit processes that would be required to meet the Falls Lake Rules as influent flows increase. The study concluded that either reverse osmosis (RO) membranes or ion exchange (IX) could be added downstream of conventional treatment or a membrane bioreactor process to meet the Falls Lake limits.

The town chose a phased construction approach, with the first phase installing conventional BNR treatment and the second phase including RO or IX. The new BNR processes were designed for a TN and TP of approximately 3.0 mg/L and 0.3 mg/L, respectively. However, staff was optimistic that a TN of 2.0 mg/L was achievable.

Among the facility's most critical needs was construction of a dewatering facility, electrical upgrades, standby power, new secondary clarifiers, and tertiary filters. Improvements to the existing BNR process also were necessary.

The town and design engineers took a collaborative and innovative approach to the first phase that reduced the initial project construction cost, estimated at $30 million, to an actual cost of $16.4 million. The conventional BNR upgrade used the existing aeration basins, a mixture of surface mixers, fiberglass reinforced polymer baffle walls, and process instrumentation to create a five-stage BNR process out of aerated basins. Phase 1 construction began in 2011 and was completed in early 2014.

Phase 1 included reconfiguring the existing treatment basins to operate as a conventional five-stage BNR treatment facility (see Figure 2 on p. 57). The sizing criteria for each stage conforms to typical criteria and was developed using a calibrated model. The new configuration went online in 2013.

The effluent quality met the TN standard of 3 mg/L. However, staff observed significant variability in TN, suppressed pH, poor settling solids, and high TP concentrations. Caustic soda was fed at high doses to control pH. When the pH was raised above 6.7, the bio-P removal began to work, settling improved, and variability in effluent TN stabilized. Because pH had not needed adjustment before the upgrade, staff was concerned about the costs. They also felt that the biomass was over-oxidized, so they began looking for ways to improve process performance.

In-house modifications

Staff created a simple model to determine the detention time of each stage at various flows. Figure 3 (p. 57) shows these times and how they were calculated.

After reviewing the model, staff determined that at current flows, the aerobic zones' volume could be reduced, and that likely would result in better process control and improved effluent quality.

Figure 1. Maximum average daily total nitrogen concentrations at annual average daily effluent flow to comply with an annual allocation of 10,422 lb/yr

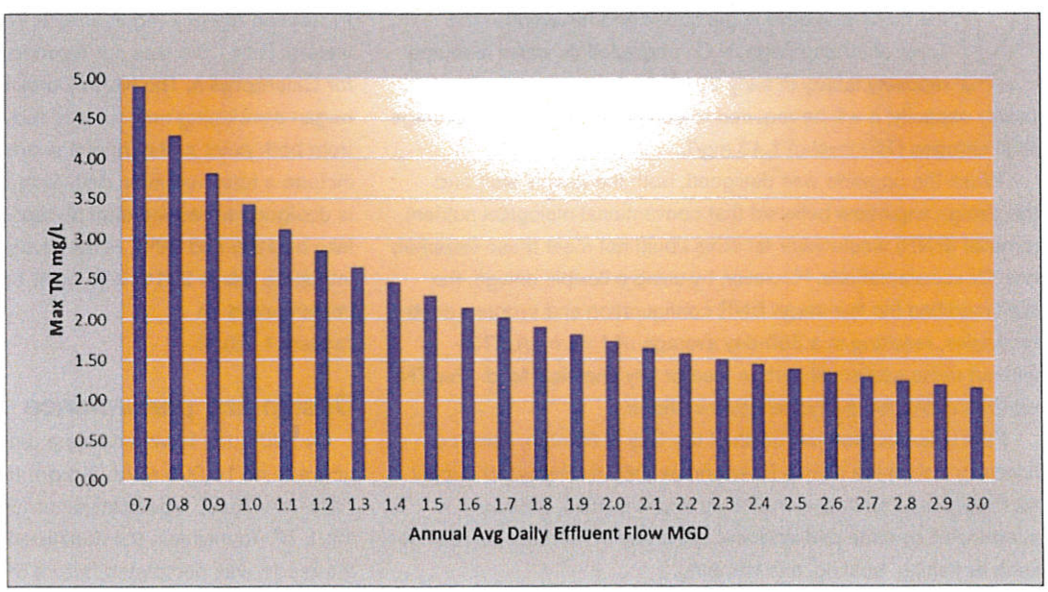
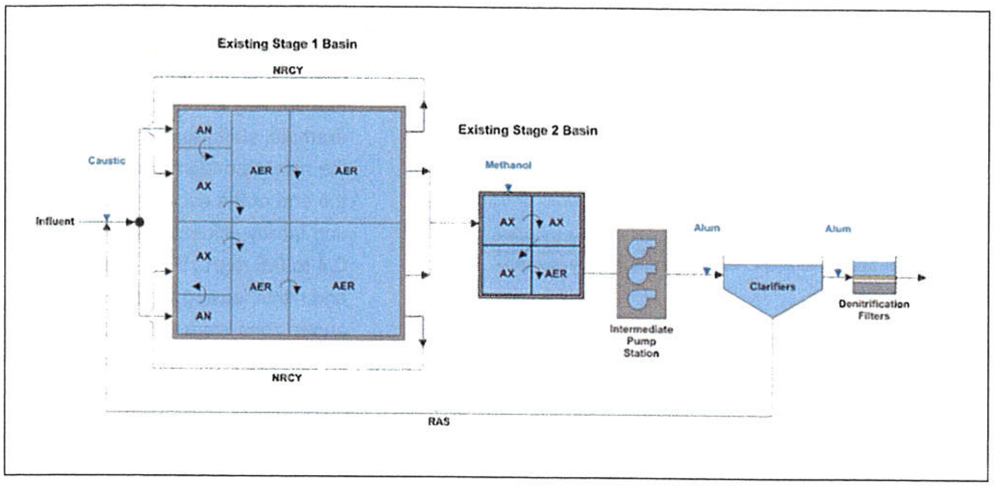


Figure 2. Phase 1 biological nutrient removal design concept



Process control methods and strategies

Both proactive process control (online instrumentation) and reactive process control (laboratory testing) must be implemented and strictly controlled to meet such low TN concentrations. The proactive process controls of the activated sludge process use luminescent/optical dissolved oxygen probes, nitrate probes, oxidation-reduction potential (ORP) probes, flow meters (water and air), and a programmable logic controller. This section highlights key design or operational strategies used to achieve the low TN values.

Tapered aeration. The first aerobic zone uses tapered aeration. The head of the aerobic zone receives by far the most air, and the dissolved oxygen (DO) decreases as it flows toward the effluent weir and NRCY pumps. The desired DO setpoints are entered into the supervisory control and data acquisition (SCADA) computer, and the blowers are modulated to maintain the setpoints. A DO target concentration at the head of the aerobic zone ranges from 2.2 to 3.0 mg/L, and 0.5 to 1.5 mg/L is desired at the end of the aeration tank.

NRCY control. This control is critical. Most BNR facilities control the NRCY pumps' flow pacing based on influent flow. Staff found that during storm events that produce high influent flow, the NRCY pumps would increase speed dramatically, which resulted in much

Staff modified the model to reduce the volume of the first aerobic zone and increase the volume of the first anoxic zone. After considerable review of the updated model (see Figure 4 on p. 58), staff implemented a plan to modify the existing BNR basins. Floating mixers were installed in the first section of the aerobic zone, and the air was turned off to that section. With this change, a significant increase in nitrogen recycle (NRCY) was needed to ensure the anoxic zone did not reach an anaerobic state. The model revealed that a NRCY rate of 900% should produce excellent results.

The modifications to the basins were completed in June 2014 and fully operational by July 2014. The results surprised everyone: Almost immediately, the effluent TN dropped to less than 1.5 mg/L and averaged 1.4 mg/L during the next 12 months. No pH adjustment was needed during that time, and no additional carbon source or coagulant was used. Figure 5 (p. 59) compares the percentile distribution of effluent TN before and after this change was implemented.

The modifications to the first anoxic and aerobic zones also improved the second anoxic zone's performance. The nitrate concentrations entering the second anoxic zone averaged 2.0 to 3.0 mg/L. The second anoxic zone effluent averaged 0.2 to 0.4 mg/L nitrate. The longer anoxic detention time in the first anoxic zone may have selected for a population of organisms better adept at hydrolyzing the slowly biodegradable biochemical oxygen demand (BOD) in the influent.

In late 2015, the TN numbers began to rise. However, the staff discovered that the increase was caused by the drinking water facility discharging large volumes of solids at night. Staff began working with the water facility staff on controlling this discharge. When the spike loads were reduced, the TN concentrations dropped back to their previous levels.

Figure 3. Initial detention time analysis (hours)

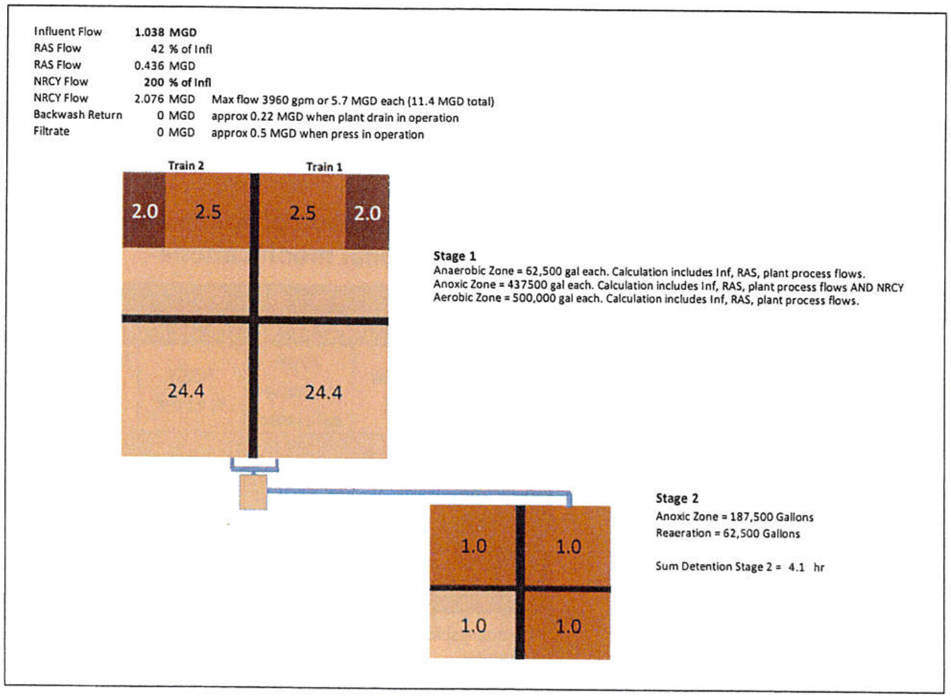
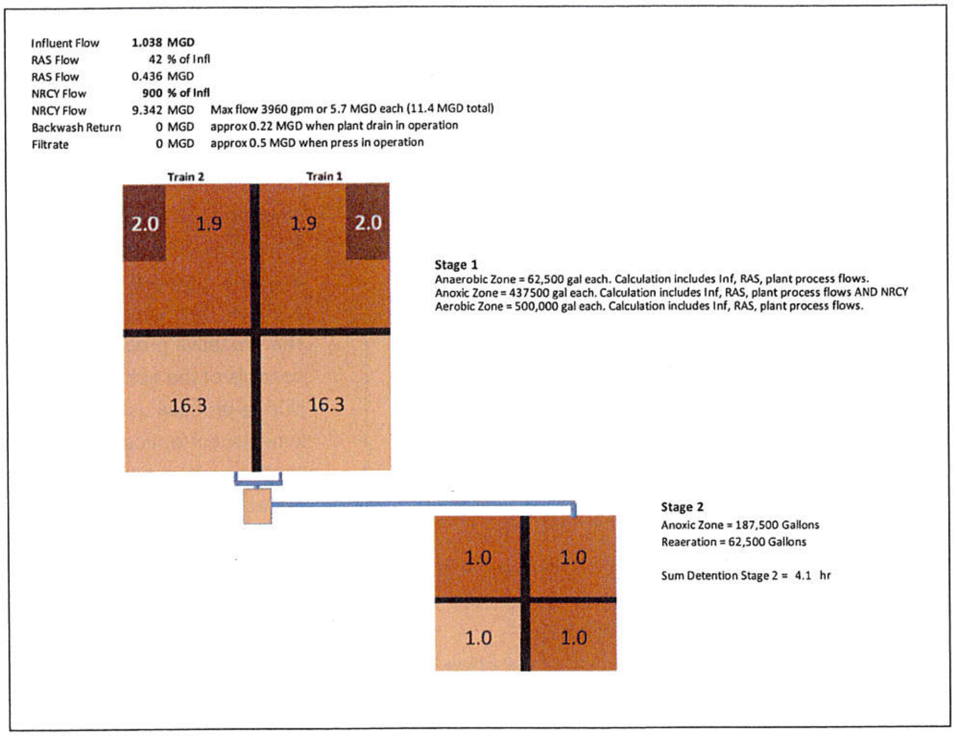


Figure 4. Modified detention time analysis (hours)



shorter detention time in the anoxic zones, and the TN would drastically increase. Staff began setting the NRCY pumps to manual control and reducing the pumps' speed in anticipation of storm events. They found that the spike in TN from the increased flow was significantly reduced. Then staff developed a new control strategy that paces the NRCY pump to maintain a desired anoxic zone detention time.

In the NRCY SCADA control, the mode for detention time control is selected, and the desired anoxic zone detention time is entered. The NRCY pump's speed can then be modulated to maintain the setpoint. The desired setpoint is determined by reactive process control. A sample of the activated solids at the end of the first anoxic zone is gathered and tested for the nitrate concentration, and the target concentration is 0.3 to 0.5 mg/L. If the nitrate is above the target, the detention time setpoint can be increased; if it is below the target, the setpoint can be decreased.

ORP control. Although ORP is not used for proactive process control, it is excellent for monitoring the basins to identify trends used for reactive process control. If large variations in ORP are found in the first anoxic zone, they likely indicate issues with the control strategy being used or the pumping capabilities. Also, monitoring the ORP in the return activated sludge is useful to determine whether the solids detention time in the clarifier is too long or too short.

Mean cell resistance time (MCRT). The MCRT is a critical control parameter for any activated sludge facility. Adjustments of even one or two days can make significant differences in nutrient removal, particularly with maintaining nitrification in cold weather. The Hillsborough facility staff had some interesting observations about what happens to nitrogen when striving to meet very low nitrogen limits. For example, staff found that at times, the nitrate concentration between the end of the second anoxic zone and facility effluent would rise by 0.4 to 0.6 mg/L. Both ammonia and nitrite leaving the second anoxic zone were undetectable, so nitrification in the reaeration zone did not explain the increase in nitrate. It was also thought that the secondary clarifiers could be releasing ammonia due to anaerobic conditions in the sludge blanket and subsequently nitrifying that ammonia to nitrate in the filters. The secondary clarifier solids retention time is about 1 hour, which is sufficient to result in a small degree of ammonia release.

In an effort to try alternative operational targets, staff decided to increase the MCRT by 2 days, and in about 2 weeks, the nitrate concentration increase between the second anoxic zone and plant effluent was significantly smaller. MCRT targets are high and typically set to 24 to 32 days. Although the exact cause of the nitrate increase was not identified, this experience underscores the challenges with removing ammonia and nitrate to undetectable levels in a biological process and that there are continued biological reactions that require nitrogen for growth even once ammonia and nitrate appear to be removed.

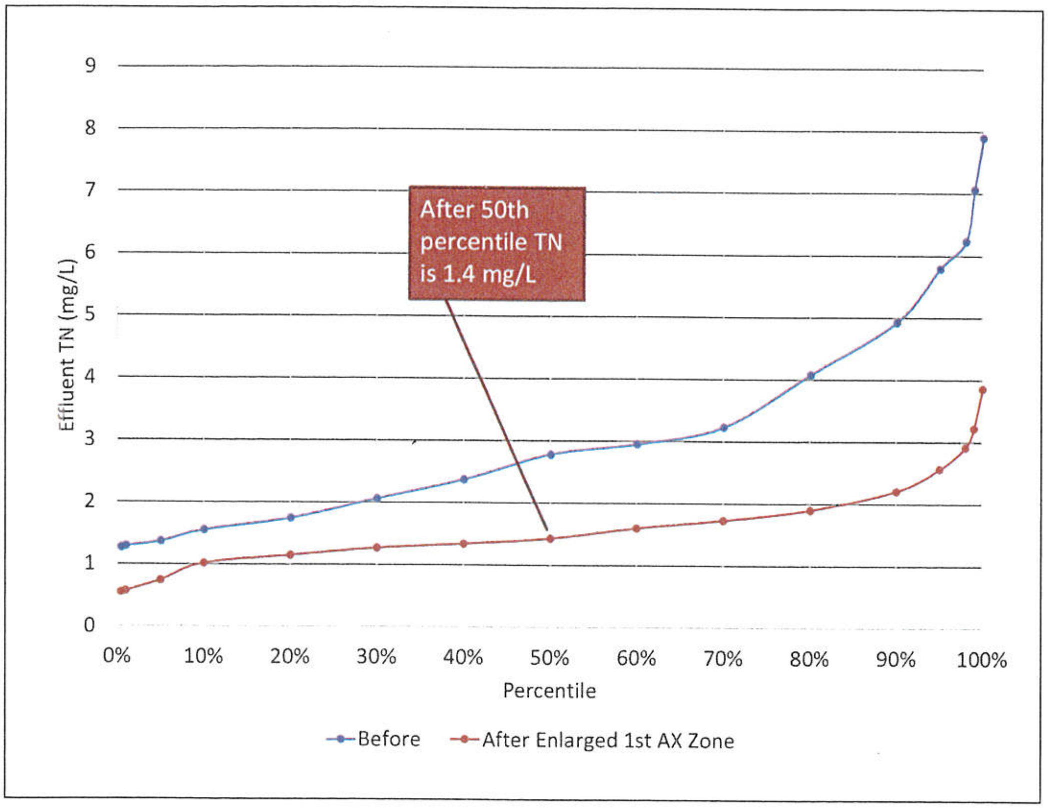
Solids management strategy. Often wastewater facility solids management strategies in this region include wasting to a digester, digesting the solids to reduce volume, implementing treatment to meet vector attraction reduction and pathogen reduction requirements, dewatering the solids, and land-applying the solids (now biosolids) at agronomic rates. Anaerobic digestion of volatile solids produces large amounts of ammonia

Table 2. Comparison of volume allocation and detention time before and after operational modifications

	Original (Nov-13 through June-14)				Modified (July-14 through Sep-15)			
Zone	Volume (MG)	% of Volume Allocated	NRCY % of Inf	Detention Time (hours)	Volume (MG)	% of Volume Allocated	NRCY % of Inf	Detention Time (hours)
AN	0.125	6%		2	0.125	6%		2
1st AX	0.375	17%	200%	1.9	0.875	39%	900%	1.9
AE	1.5	67%		24.4	1	44%		16.3
2nd AX	0.1875	8%		3	0.1875	8%		3
Reair	0.0625	3%		1	0.0625	3%		1
	*Avg Influent Flow = 1.038 MGD				*Avg Influent Flow = 1.038 MGD			

AN = anareobic.
AX = anoxic.
AE = aeration.

Figure 5. Comparison of effluent TN before and after modifications to enlarge the first anoxic zone and increase nitrogen recycle flow



and releases the phosphorus that was removed biologically. When the digested solids are dewatered, the ammonia and phosphorus are returned to the headworks, creating spike loads of nutrients that are difficult to remove.

During the upgrade's design, the town decided to take a different approach. The solids are wasted to smaller tanks and decanted daily. The decanted solids are transferred to a larger tank and dewatered, and then transferred to a compost facility. Staff tries to limit the time under aeration, to prevent aerobic digestion, and transport the wasted solids as quickly as possible. This practice greatly reduces the amount of ammonia and phosphorus in the filtrate and in turn reduces spike loads on the activated sludge process caused by the dewatering process.

Many facilities have implemented sidestream treatment to reduce the nutrients from the dewatering processes. The town's strategy is simply to eliminate the need for sidestream treatment by avoiding digestion and the related capital and operational expenses.

This approach to solids handling eliminates the need for additional capital expenditures such as on-site solids treatment processes needed to meet class A or class B land-application requirements, and it also eliminates the need for solids storage volume during inclement weather patterns. This strategy has proved cost-effective and very successful for Hillsborough.

Summary

The Phase 1 upgrade was designed to meet a TN of 3.0 mg/L. But with minor modifications, along with some inventive operational strategies, the facility achieved far better nitrogen removal performance. The effluent TN running average from July 1, 2014, through June 13, 2016, was 1.6 mg/L. Other than a short time with small doses of methanol, these results required no additional carbon source. Staff believes that the effluent TN average would have been below 1.4 mg/L if not for the spike loads related to the water facility solids management issues. The average effluent TN from March 2016 through June 2016 was an incredible 1.27 mg/L.

Conclusions

The town's original expectation that Phase 1 would defer Phase 2 by 5 to 8 years has been extended to beyond 8 years thanks to skilled operators. With an estimated cost of more than $70 million to build the advanced nutrient removal technology infrastructure needed to comply with the TN limit of 1.43 mg/L, the impending financial impact will cause significant hardship on the town's 3977 wastewater customers. Every year the massive debt is delayed, the number of customers will grow, and the impact on each customer will diminish.

Staff is confident in the facility's ability to achieve effluent TN of less than 2 mg/L year-round. The exact science behind this success is still being explored. However, the theory that the selected population of organisms are better adept at hydrolyzing the slowly biodegradable BOD in the influent under anoxic conditions is plausible. It is thought that the design and plug flow nature of the first and second anoxic zones also aids in promoting excellent denitrification.

The percent of volume allocated to the first anoxic zone and the first aerobic zone changed significantly with the modification. Staff believes this is a major reason for the process improvements. The town intends to use the modifications as a blueprint in future facility upgrades.

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