An Advanced Pollution Control Facility's Conversion to Four-Stage Bardenpho to Improve Biological Nitrogen Removal

Timur Deniz, Thomas W. Friedrich, and John Milligan

During the past decade, the city of Clearwater's Marshall Street Advanced Pollution Control Facility was operated as a five-stage Bardenpho process to achieve biological nutrient removal (BNR), along with the city's two other five-stage Bardenpho wastewater treatment facilities.

The Marshall Street facility was brought on line in 1930 and has been expanded and updated several times. In the late 1990s it was upgraded from a conventional secondary treatment plant to an advanced wastewater treatment facility with a five-stage Bardenpho process in response to state legislation requiring advanced wastewater treatment. Fermentation, anoxic and aeration basins were added by converting and/or modifying existing tankage.

The Marshall Street Facility is permitted to treat wastewater flows up to 10.0 million gallons per day (MGD annual average daily flow (AADF), using a process illustrated by the flow schematic shown in Figure 1. The facility consists of the following components:

- Preliminary treatment consisting of two mechanically cleaned fine bar screens
- A four-unit vortex-cyclonic grit removal system with an associated grit classifier
- Primary treatment consisting of eight rectangular sedimentation basins
- A biological treatment process consisting of three fermentation basins, three first anoxic basins, 13 aeration basins, four second anoxic basins, four re-aeration basins, and four 100-foot diameter secondary clarifiers

The plant's effluent limitations for total nitrogen (TN) and total phosphorus (TP) are 3.0 and 1.0 milligrams per liter (mg/L), respectively. Although the facility influent AADF ranged from 5.0 to 7.0 MGD AADF (50 to 70 percent of its design capacity), the BNR performance was not sufficient. The effluent TN concentration often exceeded 3.0 mg/L. In addition, the plant had to rely on chemical precipitation with alum to comply with the TP effluent limit of 1.0 mg/L.

Timur Deniz, Ph.D., is a senior wastewater process engineer in the Gainesville office of the consulting engineering firm Jones Edmunds & Associates. Thomas W. Friedrich, P.E., is a vice president in the firm's Tampa office. When this article was written, John Milligan was the wastewater technologies manager with the city of Clearwater Utilities Department. He currently is the operations manager for the Marion County Utilities Department. The article was presented as a technical paper at the 2008 Florida Water Resources Conference.

The purpose of this project was to identify performance limiting factors for BNR at this plant, make recommendations, prepare design documents for the required modifications,

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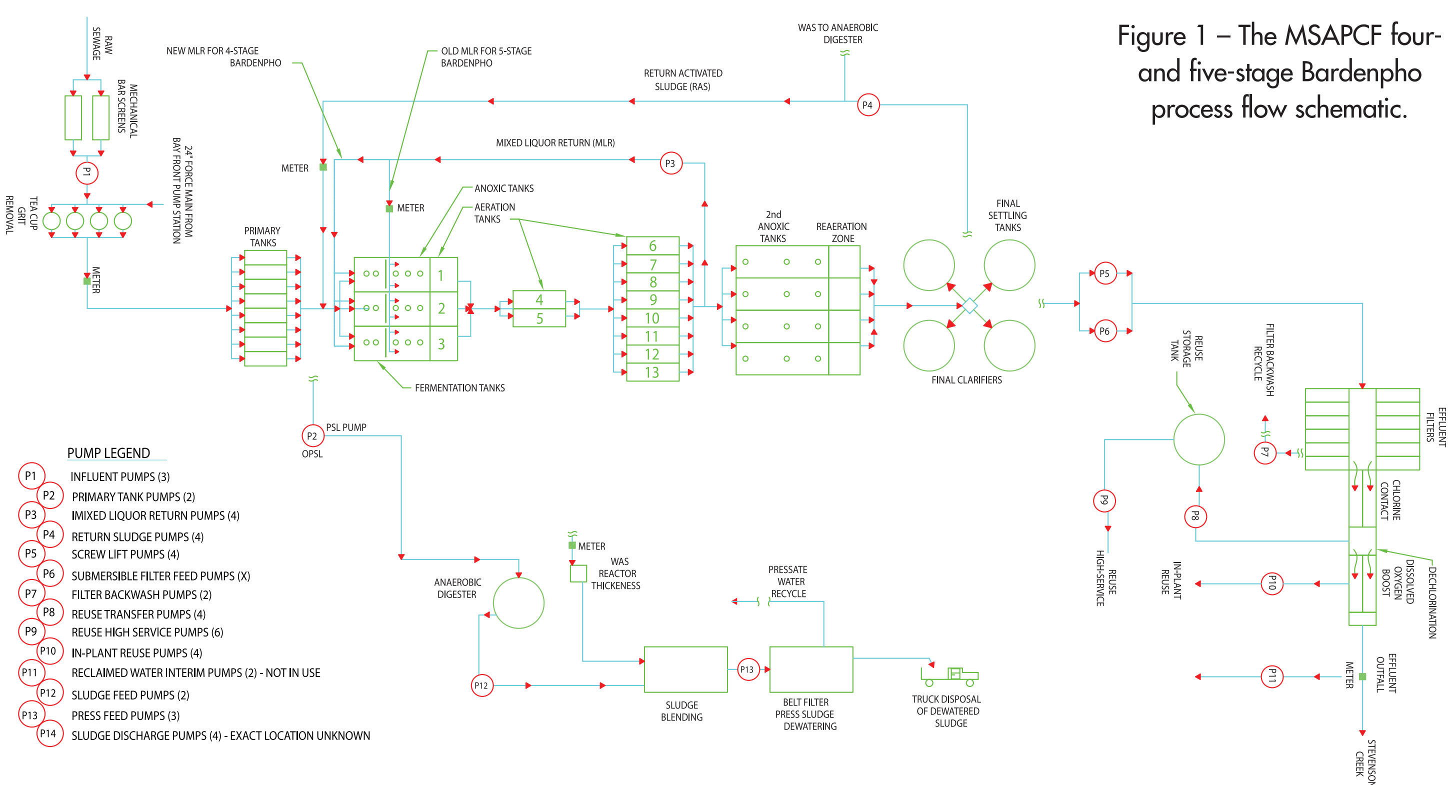

Figure 1 – The MSAPCF four- and five-stage Bardenpho process flow schematic.

Figure 2 – Picture showing the MLR flow input into the first anoxic basins at the Marshall Street Facility.

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and construct the required plant upgrades. This article summarizes the results of the initial evaluations and plant performance after the construction upgrades were completed to optimize the facility's ability to consistently meet the current effluent TN limit. The project required both operational process optimization and physical modifications.

Analysis of Operational Issues

Analysis of the Marshall Street Facility's performance began with workshops conducted with operators to discuss plant operation and performance under varying flows and loads. These workshops were followed by several plant inspections. The information provided by the staff and the facility inspections identified several operational and design issues.

The first issue identified was the re-aeration of the mixed liquor recirculation (MLR) flow. As the MLR flows were conveyed into the first anoxic basins, the turbulence of the flow caused by the design layout was re-aerating the mixed liquor. Such re-aeration is undesirable because it inputs a large mass of oxygen into the first anoxic zone, which reduces the efficiency of denitrification.

The most significant re-aeration impact appeared to occur from the discharge of the MLR pumps and during flow through the Parshall flume and stepped open channel (not shown), and again as the MLR flow "freefalls" into the head end of the first anoxic basins (Figure 2). This aeration impeded the denitrification process as oxygen was effectively introduced while the wastewater was entering a "theoretical" oxygen-free zone. During facility inspections, dissolved oxygen (DO) levels in the MLR flow were measured to be 3.0 mg/L before the cascade into the anoxic basins.

Each MLR pump is rated for 12 MGD and normal operations entailed the use of three MLR pumps providing an estimated total MLR flow rate of 36 MGD. It was estimated that the MLR flow added approximately 900 pounds per day (lbs/day) of oxygen to the first anoxic basins. To put this into perspective, the total average oxygen demand for the entire plant was estimated to be 10,500 lbs/day; therefore, about 8.5 percent of the plant's total oxygen demand was being provided by the oxygen contained in the MLR flow.

The operational staff found that the nitrate-N levels in the effluent fluctuated diurnally, with the highest levels found from 1 a.m. to 5 a.m. when the plant influent flows and loads are typically lowest and the DO load in MLR would have a more profound effect on the denitrification process. Three of the four MLR pumps were operating constantly, providing 36 MGD on a regular basis. This MLR flow rate exceeded the required amount, compared to the influent flows of 3.0 to 4.0 MGD at night. Ideally, MLR flow should be adjusted to be at 400 percent of influent flows at all times.

Based on DO measurements taken within the first anoxic basins, it is estimated that the oxygen introduced from this freefall essentially creates an aerobic zone within the initial portion of the first anoxic basins. This induced aerobic zone is estimated to occupy approximately one-third of the total volume of the first anoxic basins, leaving only two-thirds of the basin for actual anoxic treatment.

To counteract this situation, the plant staff used a common strategy to minimize the DO returned to the first anoxic basins with MLR. DO levels in Aeration Basins 6 through 13 were maintained between 0.5 and 1.0 mg/L. These DO levels also allowed simultaneous nitrification and denitrification to occur in those aeration basins. This operation did not affect nitrification efficiency at the plant, as evidenced by the average effluent ammonia-N concentrations of 0.10 mg/L.

The flows and loads analysis of 2001, 2002, and 2003 plant data clearly suggests that the plant influent may not contain sufficient concentrations of $CBOD_5$ during several months of the year to allow for optimal efficiency of the BNR process. The plant was designed for the influent $CBOD_5$ concentration of 220 mg/L, but the average daily influent $CBOD_5$ concentration was 166 mg/L for 2001, 2002, and 2003.

Complicating this issue is the fact that the plant operates primary clarifiers which remove a portion of the influent $CBOD_5$ associated with particulate material. The primary clarifier effluent had an average $CBOD_5$ concentration of 120 mg/L, which is relatively low and can be a limiting factor for BNR.

The operation of the primary clarifiers can not be halted because these units are necessary for the plant to reduce effluent copper levels effectively in order to meet licensing requirements. For modeling purposes, a primary clarifier effluent $CBOD_5$ concentration of 120 mg/L was used for the worst-case scenario simulations.

Wastewater Treatment Process Modeling

The five-stage Bardenpho process configuration of the Marshall Street Treatment Facility was set up in the BioWin wastewater treatment process model and calibrated using the plant operational parameters and effluent concentrations. The model was then used to evaluate the performance of the plant at the current and projected future flows and loads. Also, several alternative scenarios aimed at improving nitrogen removal performance under a variety of conditions were simulated with the calibrated model.

Table 1 summarizes the influent concentrations used for the plant design, the current influent concentrations shown in daily monitoring report (DMR) data, and the primary clarifier effluent concentrations used for modeling the BNR processes.

The calibrated model was able to closely simulate the observed conditions at the Marshall Street Facility, as evidenced by the agreement between the effluent concentrations predicted by the BioWin model and the DMR data (2001, 2002, and 2003), with a few exceptions.

Alum was added to the head end of the second anoxic basins because operational practice found that the biological process was unable to meet the effluent TP limit of 1.0 mg/L without chemical addition. Also, ferrous sulfate was added for odor control at the plant influent before the headworks structure and also enhanced the precipitation of phosphorus. Alum and ferrous sulfate were each added at a rate of 300 gallons per day.

These chemical precipitation processes were not accounted for in the model because the BioWin version used at the time did not have this capability. Given these factors, the apparent

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Parameter	Design Influent Concentrations	Current Influent Concentrations	Primary Clarifier Effluent Concentrations Used For Modeling
$CBOD_5$ (mg/L)	220.0	166.0	120.0
TSS (mg/L)	200.0	213.0	135.0
TKN (mg N/L)	31.0	30.0	30.0
Ammonia-N (mg N/L)	25.0	26.0	26.0
TP (mg P/L)	5.0	4.6	4.6

Table 1 - Summary of annual average influent concentrations used for BioWin modeling.

Effluent Parameter	Effluent Concentrations From Five-Stage Bardenpho Process	Effluent Concentrations From Four-Stage Bardenpho Process
Ammonia-N (mg/L)	0.07	0.10
Nitrate-N (mg/L)	3.97	0.94
Organic N (mg/L)	0.87	0.76
TN (mg/L)	4.91	1.80

Table 2 – The effluent nitrogen concentrations predicted by the BioWin model for the Marshall Street Facility five-stage and four-stage Bardenpho configurations at 10.0 MGD AADF treatment capacity.

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discrepancy of the model calibration for effluent phosphorus levels was not unexpected. As such, the model calibration to existing DMR data was determined to be sufficient to allow the model to be used for predictive purposes.

The discrepancy between the actual and predicted concentrations for TN most likely reflects the mode of operation of the plant. As noted previously, the staff found that nitrate-N levels in the plant effluent fluctuated diurnally, with the highest levels found from 1 a.m. to 5 a.m. during the lowest influent loads to the plant. To ensure that the facility continued to meet TN discharge limits, the operators adopted a policy to coordinate filling the on-site reuse water storage basin during these periods of high nitrate-N levels; therefore, while the nitrate-N levels recorded on the plant's DMRs are accurate for what is in the plant effluent flow (surface water discharge), the values would likely be higher if all the plant's effluent were discharged via the surface water outfall.

Steady-state simulations were run with the BioWin model that predicted average effluent concentrations for the specified conditions; however, the model does not take into consideration reuse water withdrawals or the nitrogen load that those flows contain. Since the model assumes all effluent is discharged via the surface water outfall, it is not unexpected that the level of TN predicted by the model is approximately 15 percent higher than the DMR data.

Currently, approximately 25 percent of the Marshall Street Facility effluent, on average, is sent to the reclaimed water system, so the TN level predicted by the model is likely a reasonably accurate reflection of what the effluent TN level would be if there were no reclaimed water use and all effluent were discharged to the surface water outfall.

After the model was calibrated, the effluent quality was evaluated under various plant configurations and operational improvements. The model simulation results suggested that the plant would be expected to struggle to meet its effluent TN limits at virtually any flow with the current plant configuration and assuming the worst-case scenario of low influent $CBOD_5$ concentrations. Although the model predicted effluent TN concentrations of 3.0 mg/L or higher under the old five-stage Bardenpho configuration, it should be noted that these TN levels did not take into consideration any nitrogen contained in effluent sent to the reuse water system.

The simulation results suggested that most of the TN in the effluent may be present in the form of nitrate-N, implying insufficient denitrification performance. The results also indicated that the effluent may contain about 0.10 mg/L of ammonia-N, suggesting excellent nitrification performance by the biological process. These results were consistent with plant operations data.

Based on the available information concerning the Marshall Street Facility, the following reasons were believed to be contributing factors to the poor denitrification and nitrogen removal predicted by the model:

- Low primary clarifier effluent $CBOD_5$ concentration of 120 mg/L.
- Oxygen mass input of 900 lbs/day to the first anoxic basins in the MLR flows of 36 MGD because of the design of the MLR system.

One alternative evaluated with the model simulations was the conversion of the plant process to a four-stage Bardenpho configuration by re-routing the MLR flow to the fermentation basins. The fermentation basins would then become additional first anoxic basins and the PAOs would be eliminated from the system.

This alternative seemed feasible. Since most of the phosphorus removal was accomplished with chemical precipitation, a five-stage Bardenpho configuration was not required.

Table 2 summarizes the effluent nitrogen concentrations predicted by the BioWin model for the Marshall Street Facility five-stage and four-stage Bardenpho configurations at 10.0 MGD AADF treatment capacity. The model simulations with four-stage Bardenpho configuration predicted that the plant's nitrogen removal capabilities would improve significantly and lower effluent nitrate-N levels could be achieved.

Plant Construction Modifications

Based on the results of the various model runs evaluating possible ways to improve TN removal, the city elected to implement the conversion of the five-stage Bardenpho process configuration to a four-stage Bardenpho process. This conversion was accomplished by redirecting the MLR flow to the fermentation basins. Also, the MLR piping layout was redesigned to prevent re-aeration and oxygen input to the first anoxic basins.

On-site construction modifications, including operation of a temporary MLR system, started in November 2006. The construction was substantially complete by March 2007 and the final plant modifications were placed in service.

During the construction, temporary MLR piping was used to pump MLR flow to the head end of the fermentation basins for operation as a four-stage Bardenpho, and some of the fermentation and anoxic basins were taken out of service to install recommended modifications. Grit accumulated in the fermentation and anoxic basins was removed during this time.

The new process configuration uses four existing axial flow MLR pumps and three splitter boxes with weir and discharge piping dedicated to each of the three anoxic/aeration treatment trains. The new MLR piping layout returns mixed liquor to the fermentation basins and minimizes re-aeration of the MLR flow.

Solid FRP baffles were installed at the head end of the first anoxic zones to allow primary effluent to completely mix with MLR

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flow. Equal flow split to each anoxic/aeration treatment train is achieved by three weir boxes located in the MLR pump box.

A firm capacity of 40 MGD of MLR flow is provided by three pumps, each operating at the re-rated capacity of 13.33 MGD when the plant is at the design capacity of 10 MGD. MLR pump flow rates can be adjusted to the required MLR flows to match the current annual average daily flow using the existing variable frequency drives. The fourth pump is an installed standby unit that can be used to pump to any anoxic/aeration treatment train.

Results & Discussion

The Marshall Street Facility effluent nitrate-N and TN concentrations for 2006 and 2007 are shown in Figure 3. These measurements were taken from the flow-weighted composite daily effluent samples for compliance with the surface water discharge limitations, which is 3.0 mg/L for TN.

These data do not represent the actual nitrogen removal performance of the plant, since the on-site reuse water storage basin is filled with the plant effluent containing high nitrate-N levels. Nevertheless, Figure 3 shows that the effluent TN exceeded 3.0 mg/L many times before plant modification construction started in November 2006. When some of the fermentation and anoxic basins were taken out of service during the five-month construction period, the plant's nitrogen removal performance was also negatively affected.

After construction was completed in March 2007, plant effluent nitrate-N concentrations were consistently less than 2.0 mg/L for the rest of 2007, except for a few days; however, effluent TN levels exceeded 3.0 mg/L for all of May 2007 after construction was completed. It was found that these high effluent TN concentrations were caused by elevated effluent ammonia-N concentrations in the range of 0.50 mg/L.

It was not clear what caused these abnormally high effluent ammonia-N concentrations. The effluent TKN concentrations were between 1.0 and 1.75 mg/L in May 2007. Historical plant effluent data demonstrate that usually the effluent ammonia-N concentration has been about 0.10 mg N/L and effluent TKN concentrations have been about 1.0 mg/L or less. This means that the effluent inert soluble organic nitrogen is about 0.9 mg/L, which correlates with the fact that the concentration of soluble inert organic nitrogen in domestic wastewater typically ranges from 1.0 to 2.0 mg/L.

It is clear from these data that the main objective for the Marshall Street Facility is to maintain effluent NO_x (nitrate-N and nitrite-N) concentrations below 1.8 mg/L and not to exceed effluent TN concentration of 3.0 mg/L.

The plant uses an online nitrate-N analyzer for monitoring purposes. Since this analyzer takes many measurements each day, it is possible to get a better idea about the nitrogen removal performance of the plant. Effluent nitrate-N data at three-hour intervals (presented in Figure 4) showed that the average effluent nitrate-N concentration was reduced to 1.5 mg/L after the modifications were completed at the end of March 2007. Also, the effluent nitrate-N had diurnal variations that exceeded 5.0 mg/L during night flows and loads. Following the design upgrades, diurnal variations of effluent nitrate-N concentrations are usually below 2.5 mg/L.

Figure 5 shows the alum feed rate that was added to the second anoxic basins at the rate of 300 gallons per day and effluent TP concentrations for 2006 and 2007. Ferrous sulfate was also added to the plant influent for odor control purposes at the rate of 300 gallons per day.

According to the data presented in Figure 5, effluent TP approached 1.0 mg/L toward the end of construction, but later in 2007 the effluent TP went below 0.5 mg/L while alum and ferrous sulfate feeding rates were maintained at 300 gallons per day. The data suggests that phosphorus accumulating

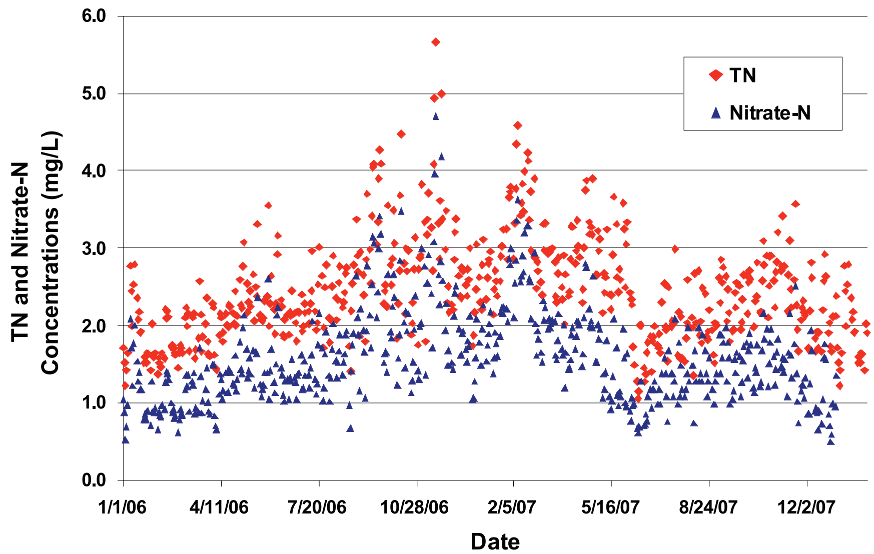

Figure 3 - Effluent Nitrate-N and Total N Concentrations measured at the Marshall Street Facility.

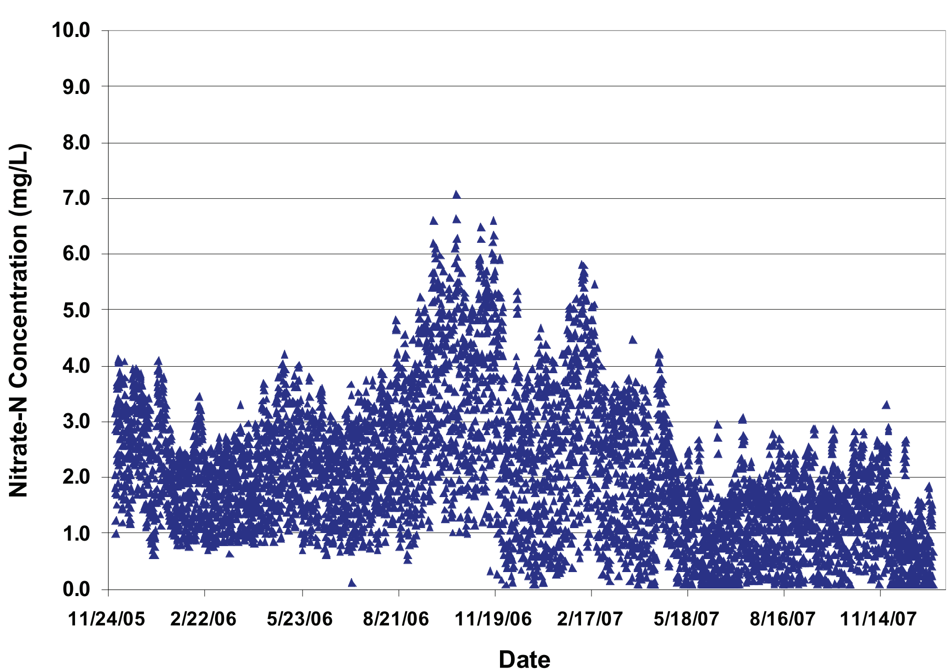

Figure 4 - Effluent nitrate-N concentrations measured by an online analyzer at the Marshall Street Facility.

organisms (PAOs) played a very minimal role in the removal of phosphorus.

Conclusions

The following results have been observed after the conversion of the Marshall Street Advanced Pollution Control Facility from a five-stage to a four-stage Bardenpho process:

- Conversion of fermentation basins to first anoxic basins increased the first anoxic basin volume, thereby increasing first anoxic SRT as well as providing volatile fatty acids to the denitrifying bacteria. This modification improved denitrification efficiency, which reduced effluent nitrate-N and TN.
- MLR modifications reduced aeration of the MLR flow and oxygen input to the first anoxic basins, which increased denitrification and reduced effluent nitrate-N and TN.
- After the plant conversion, the alum dosing rate was not changed to maintain effluent TP below 1.0 mg/L, suggesting that PAOs played a minor role in the removal of phosphorus before the process conversion.
- After the plant modifications, the average effluent nitrate-N concentration was reduced to 1.5 mg/L. Also, prior to the conversion the effluent nitrate-N had diurnal variations that exceeded 5.0 mg/L during night flows and loads. Diurnal variations of effluent nitrate-N concentrations usually have been below 2.5 mg/L since the design upgrades were completed.
- These modifications eliminated the need for adding external organic substrate (i.e. methanol) to improve denitrification performance.

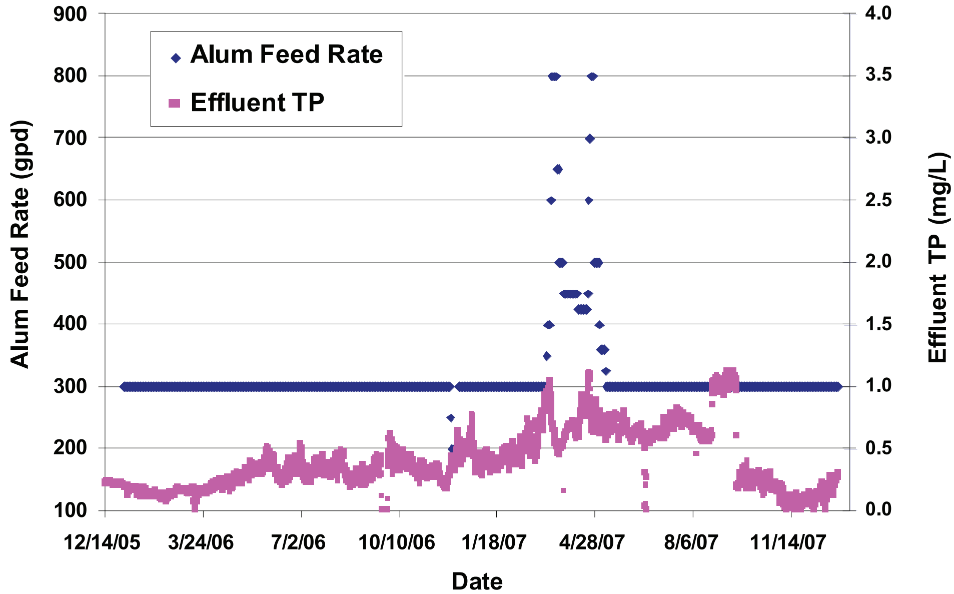

Figure 5 - Alum feed rates and effluent TP measured at the Marshall Street Facility.

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