Magnetic Ion Exchange as a Pretreatment Step at a Surface Water Treatment Plant With Seasonally Variable Water Quality

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The City of Tampa Water Department (city) currently owns and operates the David L. Tippin Water Treatment Facility (DLTWTF), which is permitted to withdraw an annual average quantity of 82 mil gal per day (mgd) and a maximum daily quantity of 120 mgd from the Hillsborough River. The overall goals of the DLTWTF are to provide safe drinking water by removing the vast majority of total organic carbon (TOC) in order to reduce formation of disinfection byproducts (DBPs), improve the aesthetic quality of the water by eliminating color, and reduce taste- and odor-causing compounds. Due to the DLTWTF's raw water supplies, there is significant seasonal variability in water quality, specifically in regard to TOC, which has historically been as high as the low 30s (measured as mg/L).

Figure 1 depicts the existing process flow diagram for the DLTWTF. Water withdrawn from the Hillsborough River is screened through a grass bar rack and mechanical screens downstream for debris removal. The raw water is then pumped to the four conventional (coagulation, flocculation, and sedimentation) treatment trains: Trains 5, 6, 7, and 8. Together, these trains receive approximately 70 to 80 percent of the total plant flow. The remaining flow is treated in parallel through the Actiflo™ Trains 1 and 2. Both systems (conventional and Actiflo) use ferric sulfate as a coagulant. Before the Actiflo and conventional treatment trains, coagulant is added, which depresses the pH of the raw water. The pH is further adjusted using sulfuric acid in order to achieve a target pH to about 3.8 to 4.5 to maximize the efficiency of the enhanced coagulation process, specifically for TOC adsorption onto the floc.

After sedimentation, pH adjustment is required before ozonation. Lime is added to the conventional treatment trains at the combined Trains 5 and 6 and Trains 7 and 8 effluent flumes. Additional pH adjustment occurs at the low lift intermediate pump station before ozonation using caustic soda when the target pH (6.3 to 7) cannot be achieved using lime alone (due to lime-induced high turbidity). The flow is then directed to the ozonation process for primary disinfection.

After primary disinfection, the flow is treated with caustic soda to achieve a prefiltration pH of between 6.5 and 7.3 and then conveyed to the biological activated filtration (BAF) process, which consists of 30 gravity filters. The filters' design maximum hydraulic loading rate is 3.5 gal per minute/sq ft (gpm/ft^2), and all filters have 12 in. of sand and 22 in. of granular activated carbon (GAC). The water is then chloraminated and the finished water is stored in the clearwells before high-service pumping into the distribution system.

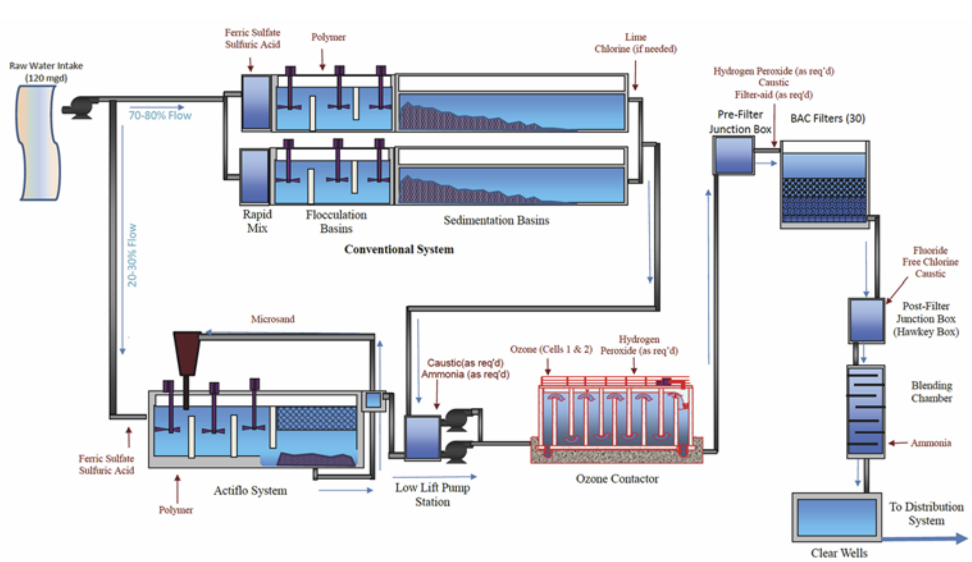

Figure 1. David L. Tippin Water Treatment Facility Existing Process Flow Diagram

The city requested that Carollo Engineers Inc. conduct a six-month pilot study on the magnetic ion exchange process in conjunction with efforts for finalizing a comprehensive master plan for the DLTWTF. The process was tested as a pretreatment option for the facility's existing conventional and Actiflo processes, with the purpose of removing the bulk of the TOC in order to reduce operational expenses (OPEX) and extend the infrastructure life for the basins.

This article details the pilot plant design, goals, operations, and results of the study conducted from September 2017 to March 2018, specifically with respect to TOC removal. Due to the DLTWTF's source of raw water, dissolved organic carbon and TOC vary seasonally, which is typically dependent on rainy and dry seasons.

Historical Raw Water Quality and Chemical Usage

Historical raw water TOC for the DLTWTF (herein referred to as a full-scale plant) and for the pilot plant is shown in Figure 2. Raw water TOC ranged from 2.8 to 26 mg/L from December 2015 to April 2018, which is a typical seasonal trend seen by the plant. For purposes of this study, high

TOC (above 15 mg/L) season is assumed to occur every year from June 15 to December 1, and low TOC (below 15 mg/L) season from December 1 to June 15. Figure 2 also shows the raw water TOC for the full-scale and pilot-scale systems for the duration of the pilot study to illustrate the similar influent water quality, which allows for TOC removal comparisons discussed later.

Currently, the enhanced coagulation process requires coagulant doses that can range from 50 to 266 mg/L as ferric sulfate (along with pH adjustment chemicals) in order to remove the amount of TOC needed through the existing treatment processes. This magnitude of TOC reduction allows the full-scale plant to consistently meet the finished water TOC goal (with minor exceedances during exceptionally high TOC periods) regardless of the season, albeit with significant chemical costs.

City staff has noted that enhanced coagulation treatment becomes difficult during low TOC season. Even when TOC is low (again, considered to be below 15 mg/L for this plant), a large amount of coagulant is still required and the enhanced coagulation process is less efficient. Based on historical data, the average TOC removal during high TOC season ranged from 78 to 87 percent, with an average of 83.2 percent, while during low TOC seasons, removal ranged from 67 to 82 percent, with an average removal of 75.5 percent. It's suspected this is due to changes in the type of organics between high and low TOC seasons.

In regard to chemical usage, a significant amount of sulfuric acid, lime, and caustic are required. During high TOC season, little or no acid addition is required because the coagulant dose is generally capable of lowering the pH adequately without the need for acid. During low TOC season, acid addition is required and subsequently results in the need for additional caustic and/or lime to raise the pH to the desired range before ozonation.

Lime use over caustic use is preferential in terms of chemical cost, but due to the high alkalinity and hardness of this water, lime alone cannot be used for pH adjustment during this season. This is because the required dose of lime needed would result in increased turbidity and calcium carbonate precipitation. From March 2017 through March 2018, the addition of coagulant, acid, lime, caustic, and polymer cost the city over $6.7 million.

Although the city's finished water goals are consistently achieved with current operations, it comes at a significant cost stemming from high chemical use, resulting in accelerated wear/corrosion on the exposed surfaces (concrete and equipment), and high volumes of solids/residuals that require processing and disposal. Therefore, the ultimate goal of this study was to determine if, with magnetic ion exchange as a pretreatment step, OPEX within the conventional and Actiflo treatment systems could be reduced without compromising overall TOC removal efficiency (and finished water quality goals), even with highly seasonal variations in water quality.

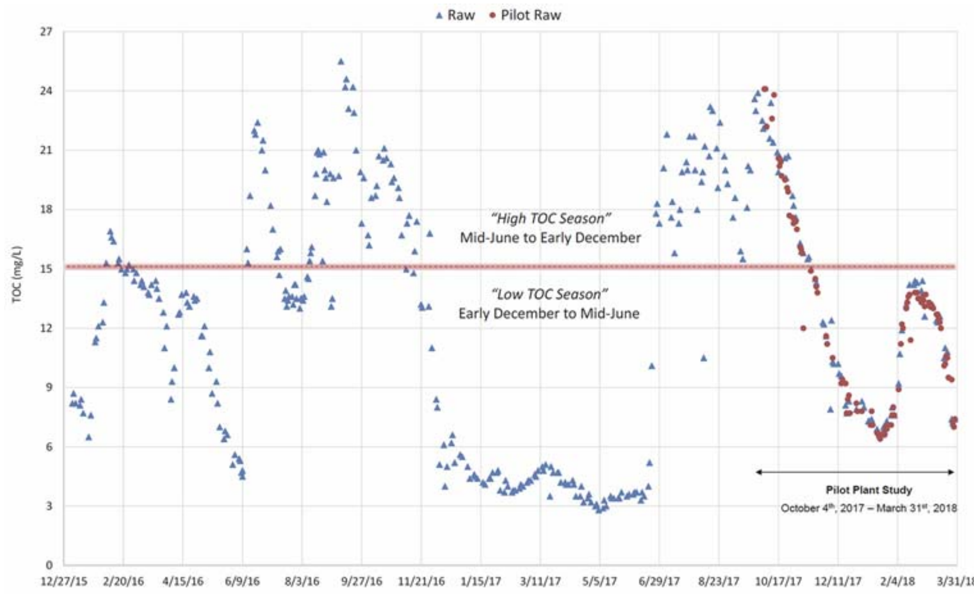

Figure 2. Full-Scale and Pilot-Scale Raw Water Total Organic Carbon

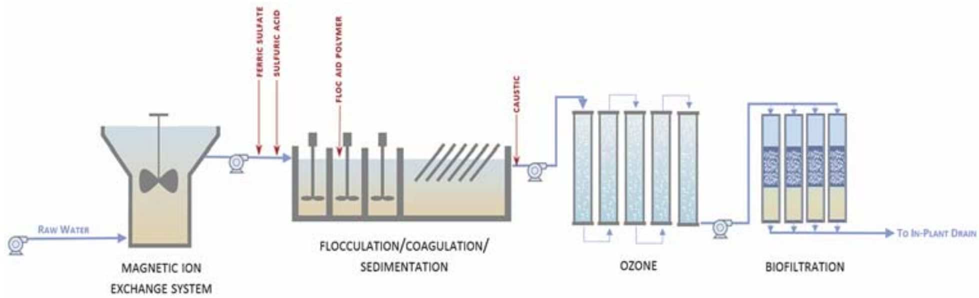

Figure 3. Pilot Plant Process Flow Diagram

Pilot Plant Configuration and Design

The study consisted of four pilot treatment skids: magnetic ion exchange system, flocculation/sedimentation (further referred to as floc/sed unit for brevity), intermediate ozone, and filtration. Figure 3 details the process flow for the pilot study.

The raw water was supplied at a rate of 10 gpm by an existing air-operated double-displacement pump and feed piping system, which is pulled from the Hillsborough River and services other areas in the plant. During times when magnetic ion exchange was tested, after pumping, the raw water would flow up through the resin-filled contactor, through a set of inclined plate settlers (to separate any remaining resin), and through the collection launder pipes before flowing to the break tank and being pumped to the floc/sed unit. After pumping, ferric sulfate and sulfuric acid would be added prior to rapid mixing. Floc aid polymer addition (when magnetic ion exchange was off) occurred between the first and second stages of flocculation, and caustic was used to adjust the pH after settling and prior to ozonation. The settled water was then treated through the ozone unit, followed by filtration in each of the four filters. The filters were operated in biologically active mode to mimic full-scale operations. During times when enhanced coagulation was piloted, the raw water flow was processed through the magnetic ion exchange contactor, which would be void of resin, so no organic treatment occurred through the unit.

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Pilot Plant Operation

The pilot units were typically staffed Monday through Friday from 6:30 a.m. to 3:30 p.m. Remote access and online data logging for the skids were utilized to help facilitate continuous operation, including overnight and weekends, without the presence of an operator. Operations were conducted in a manner to fully test a number of treatment scenarios across the entire pilot treatment train throughout seasonal water quality variations, as illustrated in Figure 4.

In summary, the magnetic ion exchange system was operated as a pretreatment step to the coagulation process and was operated during times of high and low TOC as follows:

- Oct. 7 to Nov. 24, 2017
  - 600 bed volume (BV)
  - Chlorine (started November 1), ferric sulfate
  - High TOC season
- Nov. 27, 2017, to Jan. 5, 2018
  - Magnetic ion exchange system off
  - Ferric sulfate, sulfuric acid, caustic
  - Mid to low TOC season
- Jan. 8-21, 2018
  - 600 BV
  - Chlorine, ferric sulfate
  - Low TOC season
- Jan. 22 to March 8, 2018
  - 1000 BV
  - Chlorine, ferric sulfate
  - Low TOC season
- March 9-31, 2018
  - Magnetic ion exchange system off
  - Ferric sulfate, sulfuric acid, caustic
  - Low TOC season

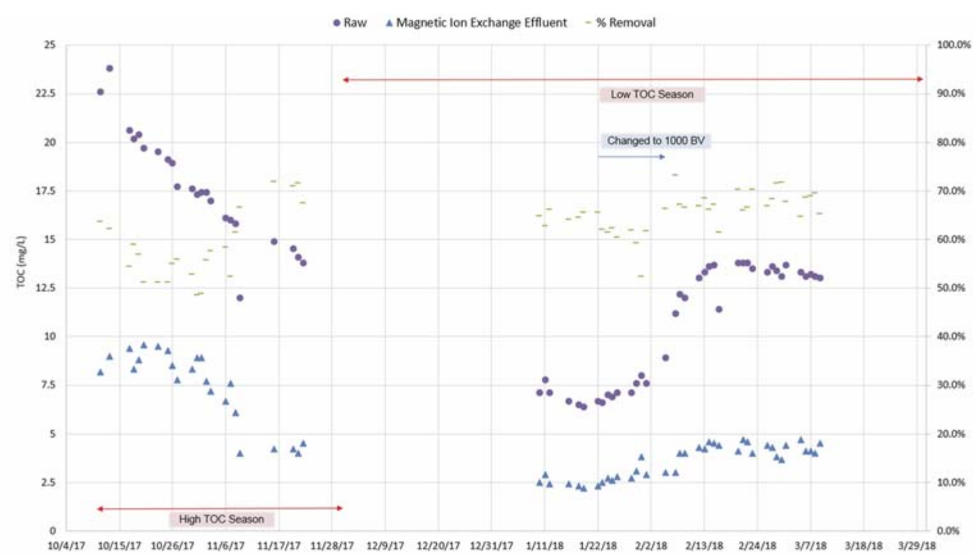

Figure 4. Pilot Plant Operations Summary

In order to confirm the scalability of the pilot plant results when the magnetic ion exchange system was not in operation, enhanced coagulation within the floc/sed unit was employed through the use of ferric sulfate, sulfuric acid, and caustic addition to mimic full-scale operations.

A number of water quality parameters were monitored continuously on the pilot skids, and grab samples were collected and used in the data analysis for this study; however, TOC was the primary parameter of interest. Considering process control needs in regard to TOC removal performance, the city implemented an online ultraviolet $(UV)_{254}$ analyzer to monitor settled water UV_{254} (floc/sed effluent). For the city's source water, there is a strong correlation between UV_{254} and TOC, allowing this method to help forecast expected TOC removal and implement, on a daily basis, any needed process modifications. The city also conducted periodic jar testing to help determine appropriate dosing schemes based on changing influent water quality throughout the study, much like it does for full-scale operations.

Results

Magnetic Ion Exchange System Performance

Although many other water quality parameters were monitored and considered when evaluating the viability of the magnetic ion exchange process as a pretreatment for the DLTWTF, the primary interest was on organics removal, and it's the focus of the discussion in this article.

The magnetic ion exchange system was operated during the high TOC period from Oct. 10 to Nov. 27, 2017. During this time frame, the pilot plant operated at a bed volume treatment rate (BVTR) of 600 BV. Figure 5 shows the raw and magnetic ion exchange-treated TOC values and percent removal throughout the study. The raw water TOC ranged from 13.8 to 23.8 mg/L during the high TOC period and declined steadily into low TOC season. Despite this decline in raw water TOC, the magnetic ion exchange unit achieved steady TOC removal, with an average removal of 58.1 percent during this time.

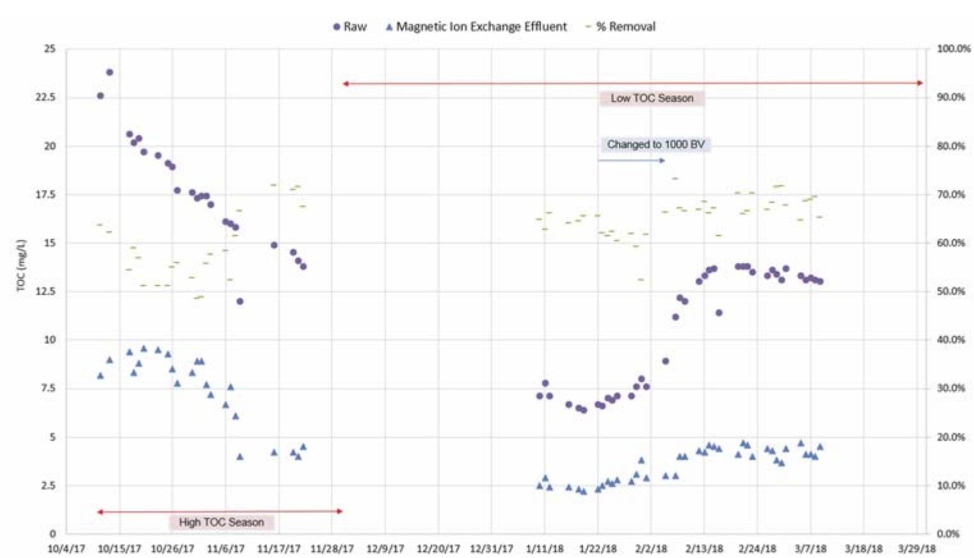

Figure 5. Pilot-Scale Total Organic Carbon Removal Through Magnetic Ion Exchange Pretreatment

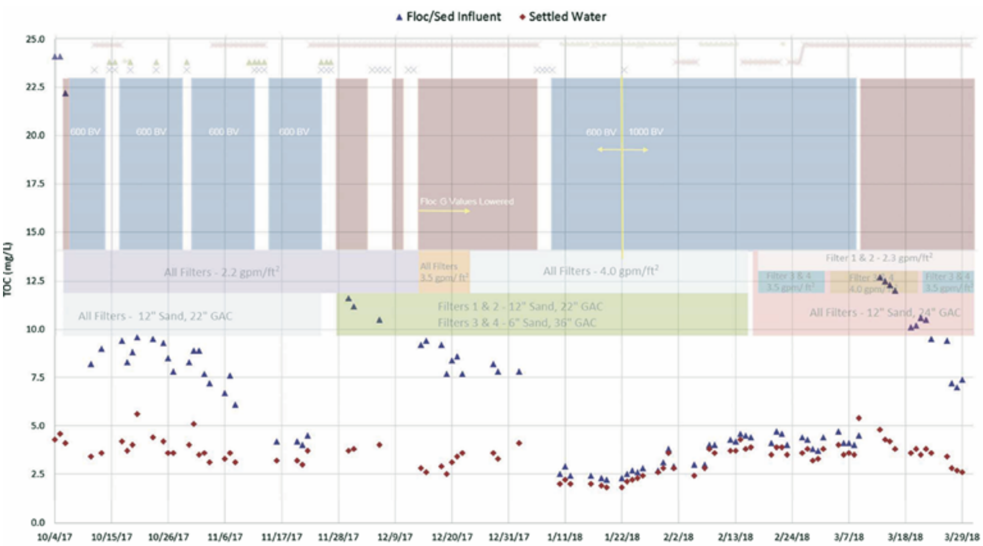

Figure 6. Pilot Plant Flocculation/Sedimentation Unit Total Organic Carbon Removal

During the low TOC period, magnetic ion exchange was operated from Jan. 8 through March 9, 2018. Initially, the unit was operated at 600 BV; however, multiple load jar testing was conducted and showed that there was limited benefit in terms of organics removal operating at 600 BV compared to 1000 BV. Therefore, on January 22, the pilot plant BVTR was changed to 1000 BV. During this time frame, the raw TOC ranged from 6.4 to 13.8 mg/L. Despite the change in BVTR, the removal was higher (average 65.7 percent removal) and more consistent across the lower range of raw water TOC concentrations. Although limited testing was performed during this period, the results consistently show that when the raw water TOC is below 7 mg/L, the magnetic ion exchange effluent TOC fell below 3 mg/L, meeting the current finished water goal prior to the downstream coagulation and filtration processes.

These results demonstrate that the magnetic ion exchange process is capable of producing low TOC effluent under dynamic conditions of widely varying and quickly changing influent water quality. The improvement in performance during low TOC season is likely due to the difference in the type of organics. The magnetic ion exchange treatment process is known to remove smaller (low-molecular-weight humic substances and humic acids) nonaromatic-type organics, while the enhanced coagulation process removes larger, aromatic-type organics. During low TOC seasons, it's likely the former type of organics are more predominant, and during high TOC seasons, the latter.

Coagulation, Flocculation, and Sedimentation System Performance

Figure 6 shows the influent TOC concentrations to the floc/sed skid, as well as the settled water TOC (floc/sed effluent prior to ozonation). An overlay of the operations on this figure is provided for reference. As shown, and as expected, the influent TOC to the floc/sed unit was greater during times when magnetic ion exchange pretreatment was not employed (since the influent would be the same as the raw water supply). There is little difference in settled water TOC concentration when comparing magnetic ion exchange pretreatment versus no pretreatment; however, when observing high TOC season versus low TOC season, the enhanced coagulation process (following magnetic ion exchange) is more efficient in TOC removal in high season, and significantly less efficient in low season. In fact, the average TOC removal through coagulation during magnetic ion exchange operation and high TOC season was 3.8 mg/L (48 percent), compared to only 0.5 mg/L (15 percent) removal in low TOC season (Table 1).

Finished Water and Full-Scale Performance Comparison

An important consideration and driver for this study was the ability of magnetic ion exchange pretreatment in conjunction with coagulation to provide similar or better overall TOC removal and finished water TOC concentrations at less than 3 mg/L.

Figure 7 shows the pilot plant TOC effluent per unit process. Overall, TOC removal was greater during times of magnetic ion exchange pretreatment for both low and high TOC seasons. Of significance is also the fact that the magnetic ion exchange system removed the vast majority of TOC during low TOC season. The magnetic ion exchange system removed 65.7 percent of the TOC, with only an additional 15 percent removed through coagulation. This percent reduction related to a less than 1 mg/L of TOC removal through the coagulation system, which is significantly different than high TOC seasons where coagulation removed an average of 48 percent (an additional 3 to 4 mg/L TOC removal). The filters consistently removed about 1 mg/L of TOC in both high and low seasons.

Table 1. Total Organic Carbon Removal Through Pilot Plant Flocculation/Sedimentation With Magnetic Ion Exchange Pretreatment

	Average TOC Removal	
	mg/L	%
High TOC Season	3.8	48
Low TOC Season	0.5	15

The TOC removal via magnetic ion exchange was not as originally expected with this source water. Initially, it was thought that the magnetic ion exchange system would be most beneficial during high TOC season; however, the pilot study results indicated the opposite to be true. The magnetic ion exchange as a pretreatment to the existing downstream processes was found to be more effective overall in the low TOC season with respect to reducing chemical demand, while meeting finished water TOC goals.

When comparing to existing full-scale treatment, Figure 8 shows the percent TOC removal for full-scale and pilot-scale plants over the duration of the study. As depicted, finished TOC concentrations were similar in the full-scale and pilot-scale systems, with the pilot plant performing slightly better, especially during low TOC periods when the magnetic ion exchange system was in operation. During periods of high TOC, the pilot plant was capable of removing over 85 percent of the influent TOC, and consistently removed more TOC than the full-scale plant when the magnetic ion exchange was in operation.

Considering full-scale flow rates and TOC removal in mg/L, an approximate pounds of TOC removed per day was calculated. The results showed a high correlation ($R2=0.90$) between pilot-scale and full-scale performance. These findings suggest that the pilot plant produced the same or better finished water TOC as the full-scale system. Thereby, it would be expected that full-scale implementation of magnetic ion exchange could warrant similar results.

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Chemical Usage

The chemical dosing scheme within the floc/sed unit varied according to raw water quality and whether magnetic ion exchange pretreatment was in use. Throughout the study, chemical dosing was adjusted based on online UV monitoring results and full-scale plant chemical doses. The required coagulation pH was much lower when magnetic ion exchange pretreatment was offline (for enhanced coagulation treatment), thereby requiring higher coagulant, acid, and caustic doses for pH control.

Figure 9 shows box plots for comparison of each chemical between full-scale and pilot-scale operations to illustrate the distribution and variability of chemical additions over the course of a year. As shown, there was a significant reduction in chemical usage when magnetic ion exchange pretreatment was in use at the pilot scale. When magnetic ion exchange was not in use (shown as Pilot Scale – Enhanced Coag), ferric sulfate dosages closely mimicked full scale. Sulfuric acid dosage was higher than full scale when using enhanced coagulation only. This could have been due to overdosing because of issues with process control at the pilot scale. Additionally, caustic usage was also higher in this mode of operation, but that is due to the fact that caustic alone was used, whereas the full-scale facility utilizes lime and caustic for pH adjustment.

When magnetic ion exchange pretreatment was in use, caustic alone was capable of adequately adjusting the pH before ozonation and at dosages less than the full-scale plant. This was especially the case during the low TOC season when, in full scale, sulfuric acid is needed to lower the pH in conjunction with ferric sulfate, thereby requiring the use of both lime and caustic for pH control. Although caustic is more costly than lime, there would still be cost savings due to the decrease in caustic usage and elimination of lime usage with magnetic ion exchange pretreatment. Additionally, sulfuric acid was not required during times of magnetic ion exchange pretreatment due to the shift away from enhanced coagulation.

The pilot-scale polymer dose (not shown) averaged 0.25 parts per mil (ppm) to match full-scale operation during times of enhanced coagulation. When magnetic ion exchange pretreatment was in use, polymer was turned off. Biological growth on the resin was witnessed early in the study and required prechlorination to prevent resin fouling, ineffectiveness, and carryover. With prechlorination of the raw water there is the risk of formation of regulated DBPs, specifically total trihalomethanes (TTHMs) and haloacetic acids (HAAs). The DBPs were not monitored during the study; however, due to the raw water TOC levels (up to 25 mg/L) and required chlorine dose (average 2.9 mg/L), it can be assumed that DBPs could be a significant issue. Overall savings in chemicals with the magnetic ion exchange pretreatment process is estimated to be approximately $2.5 million per year.

While chemical dosing was significantly reduced during low TOC season with magnetic ion exchange pretreatment, the additional 0.5 mg/L removal offered by the enhanced coagulation process comes at a significantly higher cost when considering the dollars spent per pound of TOC removed. Therefore, if chemical dosing could be modified to focus on producing a settleable and filterable floc, as opposed to removing as much TOC as possible, then additional cost savings could be realized.

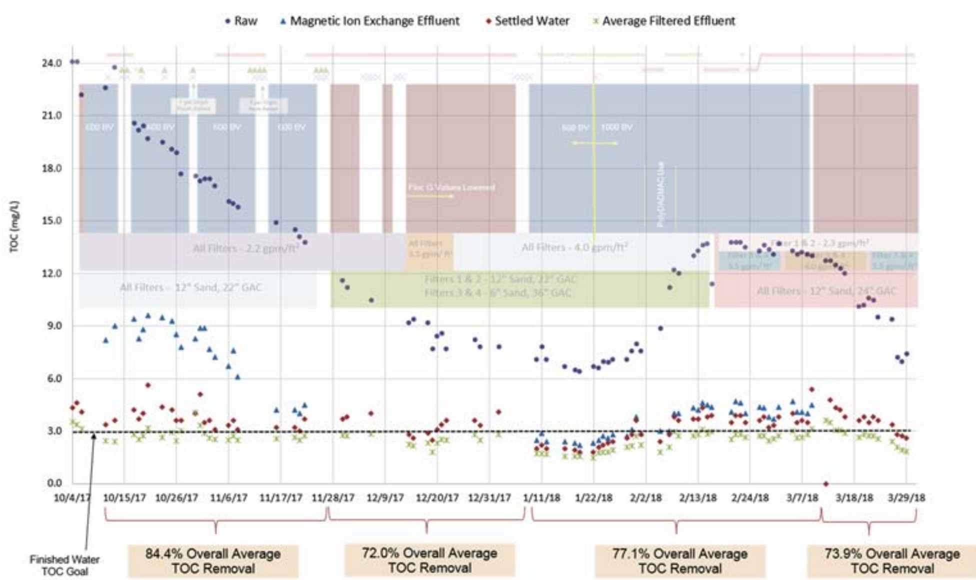

Figure 7. Pilot Plant Total Organic Carbon Removal

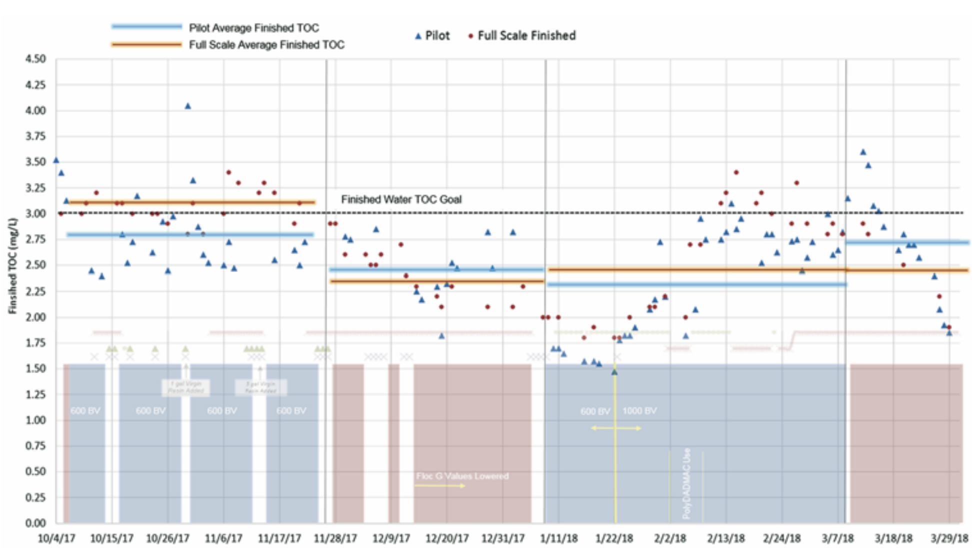

Figure 8. Pilot Plant Versus Full-Scale Plant Total Organic Carbon Removal

Conclusions

It was confirmed that the magnetic ion exchange process was capable of producing low TOC effluent under dynamic conditions of widely varying and quickly changing source water quality. The results of the pilot study found that magnetic ion exchange pretreatment could produce the same or better finished water

TOC as the full-scale DLTWTF (average values less than 3 mg/L), thereby meeting the city's finished water quality goals.

Due to the efficiency of the ion exchange pretreatment process, downstream chemical demand was significantly reduced, lowering the ferric sulfate dose by an average of 70 mg/L and eliminating the need for sulfuric acid and lime (75 mg/L and 33 mg/L average reductions, respectively), which could result in combined chemical cost savings of over $2.5 million annually at average annual flows.

Surprisingly, the magnetic ion exchange pretreatment process was most effective and valuable during relatively low TOC season (< 15 mg/L), which has historically been a time where the DLTWTF struggles to efficiently treat the water, and is likely due to the seasonal change in the type of organic compounds present in the source water. Research has shown that the magnetic ion exchange process is effective in removing low-molecular-weight and nonaromatic hydrophilic-type organics, while the enhanced coagulation (currently employed at the DLTWTF) process removes larger, aromatic hydrophobic-type organics.

There is the possibility that the DLTWTF may be required to process and treat up to 50 mgd of alternative water supply as part of the Tampa Augmentation Project (TAP), which will utilize a source water with significantly lower effluent TOC concentrations than the Hillsborough River. Therefore, there is potential that the duration of the low TOC season could be greatly extended in the future. Based on the type of organic compounds in the new water supply, magnetic ion exchange pretreatment could become even more effective, providing the additional cost savings and water quality benefits determined from this pilot study.

Acknowledgments

It's essential to acknowledge the work, commitment, and endless hours of many of the city's staff, operators, and equipment suppliers put forth for this effort. The success of this study would not have been possible without the city's dedication to the pilot's mechanical and process operations, extensive water quality testing, and optimization of varying treatment scenarios.

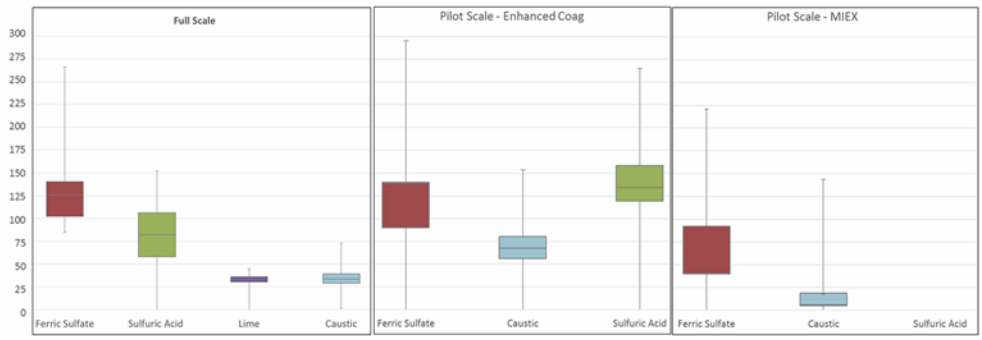

Figure 9. Pilot-Scale and Full-Scale Chemical Dosing Box Plots