Selection, Installation, Startup and Testing of the World's First Full-Scale CoMag Phosphorus Reduction Tertiary Treatment System

Elena Proakis Ellis[1*], Alan H. Cathcart[1]

[1] Concord Public Works, Water and Sewer Division, Concord, Massachusetts.
[*] Address correspondence to Elena Proakis Ellis at: eproakis@concordma.gov

ABSTRACT

The Town of Concord, Massachusetts has incorporated magnetically enhanced coagulation (CoMag™) technology for phosphorus removal into a 20-year old wastewater treatment facility. Brought online in November 2007, this tertiary treatment system is the first full-scale CoMag installation in the world. Within the first three days of start-up, the system was optimized to provide discharge of less than 0.05 mg/L TP on an average daily basis prior to its final polishing magnet. As operation has continued, the system has reached low phosphorus levels at a wide range of flow rates and influent loads. The full-scale system is operating better than anticipated based on pre-design data. The CoMag system has immediately proven its ability to meet Concord's upcoming phosphorus limits as well as the lower limits required in many NPDES permits nationwide, while providing additional benefits relating to a variety of other effluent quality parameters.

KEYWORDS: CoMag, phosphorus, ballasted flocculation, tertiary treatment, Concord.

INTRODUCTION

In accordance with recently established water quality standards and Total Maximum Daily Load assessments, wastewater treatment plants throughout the country are being required to meet increasingly low effluent nutrient limits where the introduction of nitrogen and/or phosphorus to receiving waters is contributing to environmental degradation. The US Environmental Protection Agency (EPA) recently issued a permit to the Metropolitan Syracuse Wastewater Treatment Plant with an effluent phosphorus limit of 0.02 mg/L, to be met by 2012, for its discharge to Onondaga Lake. In addition, extremely low phosphorus limits, reportedly as low as 0.01 mg/L, are currently being evaluated in many parts of the country, including the Great Lakes, Chesapeake Bay, Lake Coeur d'Alene, and the Spokane River. Locally, many treatment plants in Massachusetts have new phosphorus limits in their NPDES permits, including communities discharging to the Assabet River, who are required to meet a 0.1 mg/L monthly average total phosphorus (TP) standard in the coming years.

For the past decade, the Town of Concord, Massachusetts has been aware that stringent new phosphorus limits were being considered by local regulators that could dictate the direction of its wastewater treatment in the foreseeable future. Based on this knowledge, the Town undertook a collaboration with the developers of an innovative phosphorus reduction technology, which ultimately led to the design and construction of a full-scale CoMag tertiary treatment system. Concord's CoMag system, which came online in November 2007, is the first full-scale CoMag installation in the world. The information provided herein describes Concord's decision making process in the selection of the CoMag system and the results of its first seven months of operation.

Background

Concord, Massachusetts is a suburb of Boston with approximately 18,000 residents, about 35% of whom are served by a municipal sewer system. The collection system pumps all flow to a centralized 1.2 million gallon per day wastewater treatment plant (WWTP) which discharges treated effluent to the Concord River. The WWTP presently provides fine screening, grit removal, primary settling, biological treatment using trickling filters, CoMag tertiary treatment, and ultraviolet (UV) disinfection.

Concord's current National Pollutant Discharge Elimination System (NPDES) permit limits are summarized in Table 1. Since 2002, a seasonal phosphorus limit of 0.75 mg/L TP has been required during the summer months. Beginning in February 2007, a winter monthly average limit of 1.0 mg/L TP came into effect. Furthermore, the current NPDES permit stipulates a compliance schedule whereby the plant must meet a new seasonal monthly average phosphorus limit of 0.2 mg/L beginning in April 2009.

Table 1: Concord, Massachusetts WWTP NPDES Permit Limits

Parameter	Limit	Comments
Flow	1.2 million gallons per day	12-month rolling average
Biochemical Oxygen Demand	30 mg/L	Monthly Average
Total Suspended Solids	30 mg/L	Monthly Average
Fecal Coliform	200/100mL	Monthly Geometric Mean
Fecal Coliform (max.)	400/100mL	Monthly Maximum
Total Phosphorus (Apr.-Oct.)	0.75 mg/L	Through October 2008
Total Phosphorus (Apr.-Oct.)	0.2 mg/L	Starting April 2009
Total Phosphorus (Nov.-Mar.)	1.0 mg/L	Started February 2007
pH	6.0 to 8.3	Continuously Monitored
Ammonia Nitrogen	Report Only	Monthly Average
Aluminum	Report Only	Monthly Average

Phosphorus Reduction Technology Selection Process

In 1999, the Town first held discussions with Cambridge Water Technology (CWT, Cambridge, MA) which culminated in an agreement to host a 100 gallon-per-minute commercial demonstration of their innovative CoMag phosphorus reduction system. This Commercial Demonstration Plant (CDP) was constructed and placed into operation in 2002 with collaboration from Woodard & Curran, Inc. (Portland, ME), contract operators of the Concord WWTP. The CDP operated for several years to determine the viability and scalability of the technology, which had previously only been run at 10 gallons-per-minute. During this time, CWT was afforded the opportunity to challenge and modify their system, provided that the core operation of the WWTP would not be compromised and operational costs would not be borne by the Town.

The Town's interest in the CoMag CDP grew as it became apparent that the technology was achieving positive results. Three years of trial data from the CDP convincingly demonstrated that the CoMag system was capable of meeting any phosphorus limits anticipated in the foreseeable future and, should regulatory policies allow, could afford the Town with advantageous nutrient trading opportunities.

Yet even after the CoMag system had successfully proven itself capable and robust enough for full-scale installation, the Town embarked on an alternatives evaluation, performed by Woodard & Curran and peer-reviewed by Brown and Caldwell, Inc. (Portland, ME), to determine how the findings from the CPD compared to other treatment technologies. At that time, CoMag was evaluated alongside Actiflo, Densadeg, DualSand, cloth filters, membrane filters, membrane bioreactors, and some combinations of these technologies, when challenged with treatment goals of both 0.2 mg/L and 0.05 mg/L TP. Criteria considered included cost (both capital and operations), reliability, size, ease of operation, sludge production, safety, and community impacts. Figures 1 and 2 show the results of these evaluations.

Criteria	**Weight**	**Actiflo**	**DensaDeg**	**Cloth Filter**	**Membrane Filter**	**CoMag**	**CoMag Sidestream**	**Membrane Sidestream**	**Membrane Bioreactor**
Reliability and Flexibility of Process Performance	5	3	3	3	4	4	2	2	4
Safety	5	3	3	3	3	3	3	3	3
Visual, Odor, Noise, and Traffic Impacts on Community	4	3	3	3	3	3	3	3	3
Impact on Other Treatment Processes	4	3	3	3	4	4	2	2	5
Space Requirements	3	3	3	5	3	3	4	4	5
Relative Utility and Chemical Cost	3	3	3	5	2	3	4	3	1
Ease of Construction and Implementation	3	3	3	4	3	3	3	3	2
Maintenance and Reliability of Equipment	3	2	3	4	2	3	3	2	2
Relative Capital Cost	2	3	3	5	2	4	4	3	1
Staffing Requirements – Day-to-Day	2	3	3	3	3	3	3	3	3
Sludge Production, Quality, and Processing	2	3	3	2	4	4	5	4	4
Ability to Implement the Process in Phases	2	3	3	1	1	3	3	3	1
Proven Technology at Treatment Level	2	3	3	3	3	3	3	3	3
Total Unweighted Score		**38**	**39**	**44**	**37**	**43**	**42**	**38**	**37**
Total Weighted Score		**117**	**120**	**136**	**119**	**133**	**123**	**113**	**121**
Score as % of Maximum Possible Score		**59**	**60**	**68**	**60**	**67**	**62**	**57**	**61**

Figure 1: Phosphorus Removal Alternatives Evaluation Matrix for 0.2 mg/L TP. Excerpted from the Town of Concord's December 30, 2003 *Phosphorus Removal Options Analysis Final Report*. Cloth filtration and CoMag treatment scored higher than the other processes. The criteria for which these processes scored above average are highlighted above.

Criteria	Weight	Actiflo and Filter *	DensaDeg and Filter *	Dual Sand Filter *	Tertiary Membrane*	CoMag*	Membrane Bioreactor
Reliability and Flexibility of Process Performance	5	3	3	1	4	4	4
Safety	5	3	3	3	3	3	3
Visual, Odor, Noise, and Traffic Impacts on Community	4	3	3	3	3	3	3
Impact on Other Processes	4	3	3	3	3	3	3
Space Requirements	3	2	2	3	4	4	5
Relative Utility and Chemical Cost	3	3	3	3	3	3	3
Ease of Construction and Implementation	3	2	2	3	3	3	2
Maintenance and Reliability of Equipment	3	3	3	2	3	3	3
Relative Capital Cost	2	3	3	4	3	4	3
Staffing Requirements - Day to Day	2	3	3	3	3	4	3
Sludge Production, Quality, and Processing	2	2	2	2	4	4	4
Ability to Implement the Process in Phases	2	3	3	3	1	3	1
Proven Technology	2	3	3	3	3	3	5
Total Unweighted Score		**36**	**36**	**36**	**40**	**44**	**42**
Total Weighted Score		**112**	**112**	**107**	**126**	**134**	**130**
Score as % of Maximum Possible Score		**56**	**56**	**54**	**63**	**67**	**65**

* This process requires treatment at the secondary clarifier to lower the influent TP concentration.

Figure 2: Phosphorus Removal Alternatives Evaluation Matrix for 0.05 mg/L TP. Excerpted from the Town of Concord's December 30, 2003 *Phosphorus Removal Options Analysis Final Report*. CoMag and membrane bioreactor treatment scored higher than the other processes. The criteria for which these processes scored above average are highlighted above. MBR was subsequently ruled out because it would require replacement of the entire secondary treatment system.

The treatment goal of 0.2 mg/L was selected because the EPA had put the Town on notice that its next NPDES permit, which took effect in 2006, would include phosphorus limits of 0.2 mg/L or less. The second matrix evaluated technologies to meet 0.05 mg/L, which was considered to be the reasonable limit of currently available technology. Whereas the existing plant could not reach either limit without considerable investment, the Town ultimately decided that any system installed should be able to meet all possible future phosphorus removal goals. Therefore, the final selection focused only on the comparison of technologies to meet the 0.05 mg/L limit.

When the CoMag process was found to rank highly advantageous in the alternatives analysis, the Town invested approximately $125,000 for additional studies to determine how CoMag could be integrated and optimized for full-scale use in Concord, focusing specifically on flow variability, sludge management, pathogen reduction, and coagulant usage. While this research confirmed CoMag's site-specific applicability, the peer reviewers concluded that CoMag was not the only feasible technology to meet Concord's needs. Accordingly, a competitive request for bids was issued, ultimately resulting in the purchase of a full-scale CoMag system at a cost of $3M.

Since Concord and CWT had been working collaboratively for well over three years, third party review and oversight was deemed imperative by the Town. The technology selection process involved two different consultant teams, including operations specialists and nationally recognized nutrient removal experts, in addition to the technology developers at CWT. Furthermore, the installation of the CoMag system was incorporated into a larger facility upgrade project, which was required as some equipment within the 20-year old plant had reached the end of its useful life. Project design and construction services were performed by Camp Dresser & McKee, Inc. (Cambridge, MA). Ultimately, this degree of oversight and quality control provided a high level of confidence for the Town that, as an early adopter of an innovative technology, operational and financial risks had been mitigated to the maximum extent feasible.

METHODOLOGY

CoMag Process Description

The CoMag process operates using ballasted flocculation, with magnetite as the ballast. Aluminum sulfate (alum, 48.5% solution) and an anionic polymer are used in the coagulation process along with the magnetite, to create a very dense floc which settles rapidly as a result of the high specific gravity of the magnetite (SG >5.0, approximately twice that of sand). Due to the inherent properties of the magnetite, the ballast is easily recovered using a magnetic drum to which the substance adheres once sheared from the tertiary sludge. The magnetite is then recycled for repeated use, and phosphorus, which is bound in the precipitate, leaves the treatment stream in the tertiary sludge. The clarifier effluent passes through a final polishing filtration magnet to remove any carry-over of magnetite and to achieve even lower solids levels. Since the filter is electromagnetic, backwash to remove particles from the filter matrix is performed by simply turning off the power to the magnet and sending a slug of water across the course matrix for approximately ten seconds, once every five hours. Figure 3 illustrates the steps of the CoMag process, and Figure 4 shows the system as designed specifically for the Concord plant.

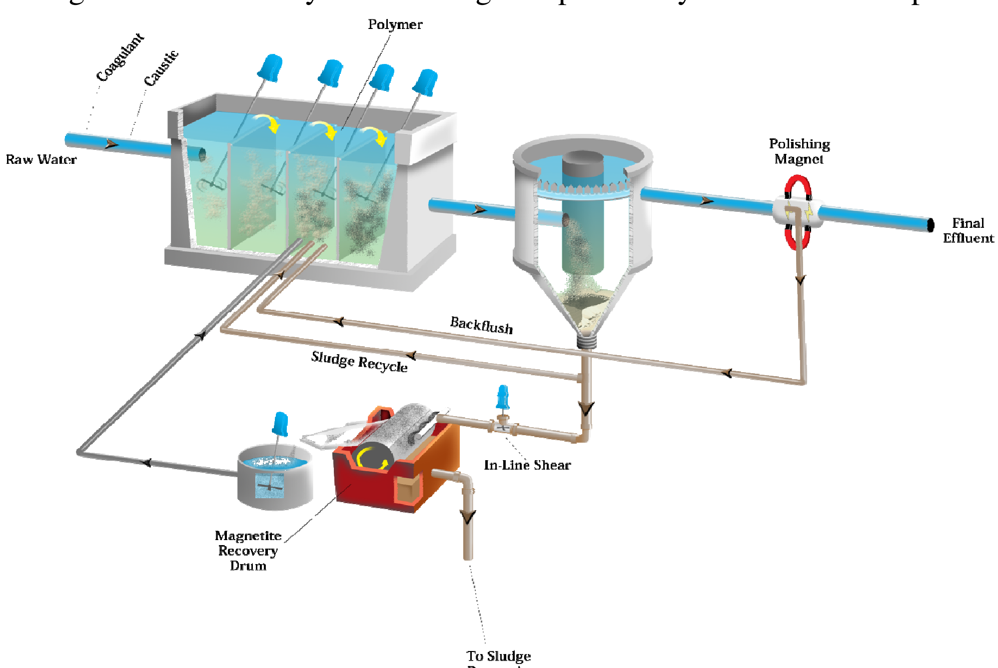

Figure 3: Flow Diagram of Cambridge Water Technology's CoMag Process

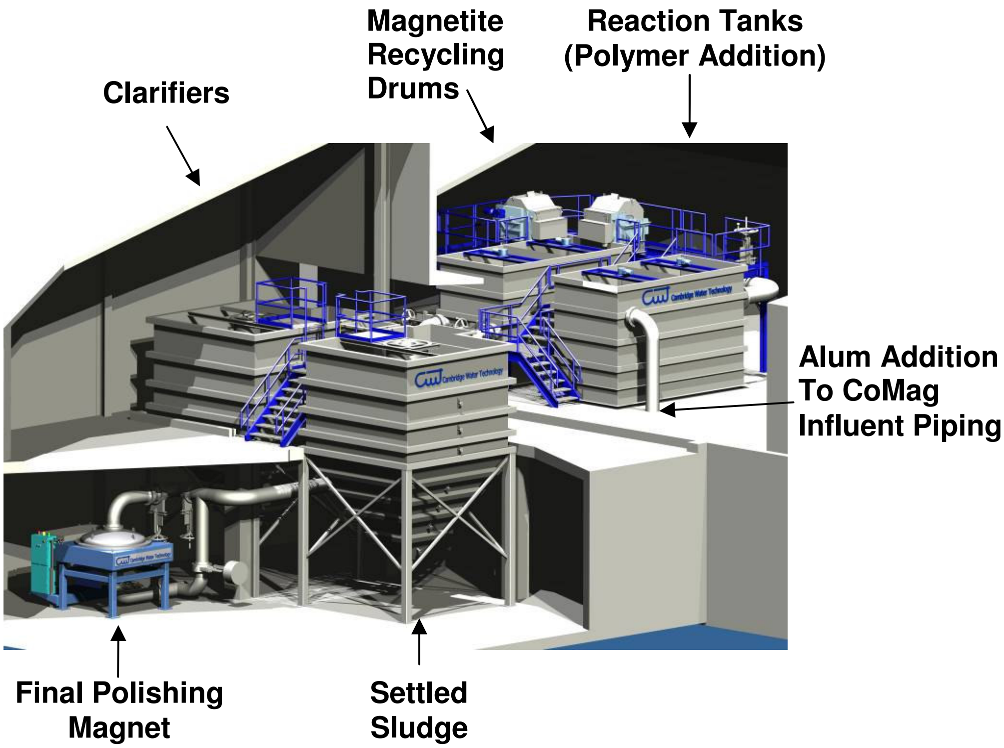

Figure 4: 3-D Depiction of Concord's Full-Scale 1.2 MGD CoMag System

Based on the CDP testing, CWT established that multi-point alum addition (in both the secondary clarifiers and the CoMag system) consistently resulted in more efficient phosphorus removal than single-point addition (only in the CoMag system). Therefore, all tests conducted using the full-scale installation have used multi-point alum addition.

CoMag Performance Validation Testing – December 10-21, 2007

The Request for Bids issued by the Town required rigorous performance testing following installation, to prove that the system, as installed, was capable of meeting a permit limit of 0.05 mg/L TP averaged over a predefined period. Accordingly, the validation test was conducted using full plant flow from December 10 through December 21, 2007. Composite samples were taken at the effluent end of the final polishing magnet every half hour for discreet eight-hour time periods and tested using Standard Methods 4500 P-E (EPA Method 365.2) to determine total phosphorus. Each period represented one sampling point, thus a total of 30 data points would be obtained over the course of a ten day test period. Due to circumstances unrelated to the CoMag process, three data points were eliminated from the data set. Therefore, in total, 33 data points were amassed over an 11-day period.

Routine NPDES Compliance Monitoring – January through May 2008

During the months that followed, the CoMag system was operated to meet the applicable NPDES permit phosphorus limits. In January through March, the permit limit was 1.0 mg/L TP, and in April through June, the limit was 0.75 mg/L. Final effluent sampling was conducted for all parameters pursuant to the NPDES permit, including those listed in Table 1 above.

Dose-Response Monitoring – June through July 2008
During the five week period of June 3 through July 10, 2008, dose-response testing was undertaken to correlate alum dosage with phosphorus removal capabilities. In all cases, alum addition was split evenly between the secondary clarifiers and the static mixer between the tertiary lift pumps and the influent to the CoMag reaction tanks. The coagulant addition protocol used for the dose-response testing is shown in Table 2.

Table 2: Full-Scale Coagulant Dose-Response Test Protocol, June - July 2008

Dates	Coagulant Dose [48.5% Aluminum Sulfate in mg/L as Al]*		
	Secondary Clarifiers	CoMag Influent	Total
June 3rd – June 6th	2.49	2.49	4.99
June 7th – June 12th	2.96	2.96	5.92
June 13th – June 15th	2.87	2.87	5.74
June 16th – June 22nd	3.97	3.97	7.95
June 23rd – June 29th	4.55	4.55	9.11
June 30th – July 6th	5.83	5.83	11.66
July 7th – July 10th	7.25	7.25	14.50

* Note that the alum dose in mg/L as Al may be divided by 0.058 to obtain parts per million by volume of the 48.5% alum solution.

RESULTS

Phosphorus Removal and Coagulant Use
During the three different testing scenarios described above, phosphorus removal goals, and thus coagulant dosages, varied. First, during the Performance Validation Test, CWT was challenged with immediately operating the system to meet an average limit of 0.05 mg/L TP. Figure 5 shows the TP levels in the CoMag influent versus effluent for each of the 33 8-hour periods examined. The resulting average effluent phosphorus over the 30 validated test periods was 0.0488 mg/L. Having passed this test, the CoMag system was formally accepted by the Town.

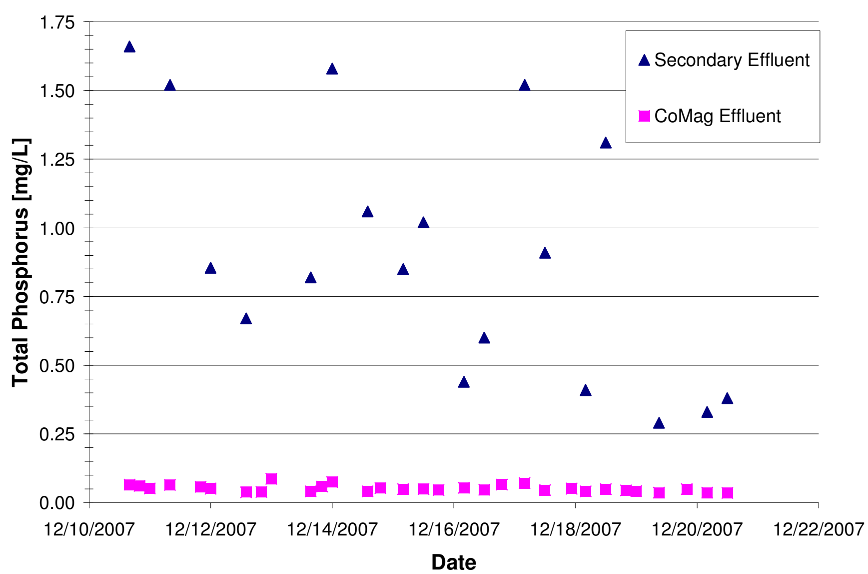

Figure 5: Results of CoMag Validation Performance Test

Since this was CWT's first attempt to meet a 0.05 mg/L TP limit with the full-scale system, CWT took a very conservative approach and dosed the CoMag with an alum concentration ranging from 6.67 to 22.39 mg/L as Al, averaging 13.75 mg/L, to ensure that the required performance standards would be met. Further operation of the process, however, has optimized system performance and shown that such high doses are not required to meet low TP standards.

Following the validation testing, the CoMag system was brought fully online in January 2008 and has been operating continuously ever since. In January, to meet the 1.0 mg/L TP winter standard, plant operators began multi-point addition by using the same total coagulant dose that had previously been used in the secondary clarifiers only, prior to CoMag's startup (approximately 4.64 mg/L as Al, or 80 ppmv of 48.5% alum solution). While this was the average dosage used without tertiary treatment to narrowly meet the 1.0 mg/L winter standard over the months of February, March, and November 2007, the same dosage, when divided into multi-point addition with CoMag running, resulted in TP values as low as 0.28 mg/L. This more efficient use of alum during CoMag operation allowed operators to scale back the alum concentration to 2.84 mg/L on average in March, to meet the 1.0 mg/L TP standard, with a resulting average effluent TP of 0.57 mg/L for the month. As septage deliveries have increased in the spring, alum dosage has increased to roughly 5.22 mg/L, with average monthly effluent TP falling well within the 0.75 mg/L seasonal standard. Figure 6 illustrates this more efficient alum usage when comparing phosphorus reduction results before and after CoMag came online.

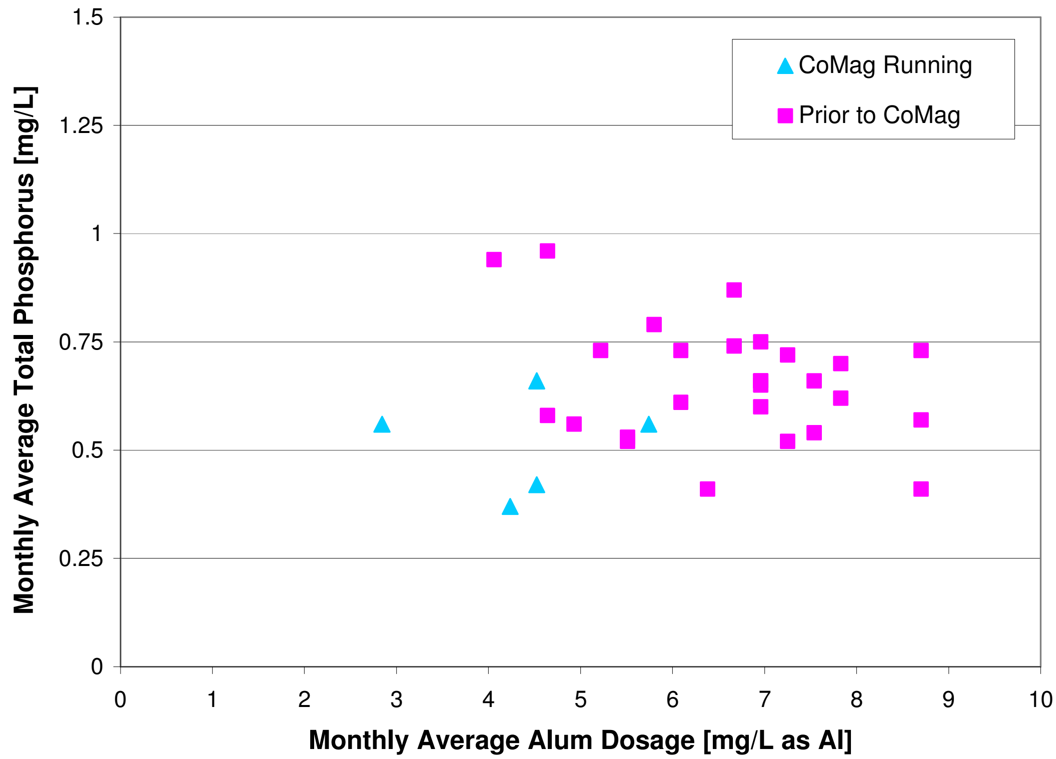

Figure 6: Alum Dosage Versus Total Phosphorus Before and After CoMag Came Online. This figure illustrates the reduction in monthly average alum dose required to meet the same 0.75 mg/L total monthly average phosphorus limit once CoMag was brought online compared to prior conditions.

Beginning on June 3, 2008, dose-response data was collected. These data are summarized in Table 3 and Figure 7. Operational data from the period of May 5th to 14th, which had a steady coagulant dose of 5.68 mg/L, were added to provide additional data points in this range.

Table 3: Full-Scale Coagulant Dose-Response Test Results

Date	Average Daily Flow [mgd]	CoMag Feed TP [mg/L]	CoMag Effluent TP (CWT) [mg/L]	CoMag Effluent TP (WWTP) [mg/L]	Multi-Point Alum Dose [mg/L as Al]	CoMag Polymer Dose* [ppmv]	CoMag Caustic Dose** [ppmv]
5/5/08	1.26	3.10	0.456		5.68	3.5	10
5/6/08	1.22			0.54	5.68	3.5	10
5/7/08	1.18	2.99	0.59		5.68	3.5	10
5/8/08	1.16	3.64	1.01		5.68	3.5	10
5/9/08	1.16	4.64	0.64	0.52	5.68	3.5	10
5/12/08	1.17	3.54	0.72		5.68	3.5	10
5/14/08	1.00	3.09	0.21	0.61	5.68	3.5	10
6/3/08	0.94			0.97	4.99	2.5	1.7
6/4/08	0.99	4.30	0.876		4.99	2.5	1.7
6/5/08	1.02		0.64	0.95	4.99	2.5	1.7
6/6/08	0.97	5.80	0.729		4.99	2.5	1.7
6/9/08	0.95	4.45	0.60	0.58	5.92	1.9	0.9
6/11/08	0.88			0.5	5.92	1.9	0.9
6/13/08	0.86	4.55	0.54		5.74	2.0	1.6
6/16/08	1.14	4.41	0.68		7.95	2.6	5
6/17/08	0.76	3.96	0.29	0.21	7.95	2.6	5
6/18/08	0.81	2.54	0.156		7.95	2.6	5
6/18/08	0.81	2.25	0.124	0.05	7.95	2.6	5
6/19/08	0.82	2.41	0.316		7.95	2.6	5
6/19/08	0.82	2.35	0.358		7.95	2.6	5
6/20/08	0.84	2.06	0.089		7.95	2.6	5
6/23/08	0.93	1.26	0.047		9.11	2.2	20
6/24/08	0.92	0.73	0.042	0.03	9.11	2.2	20
6/25/08	0.91	0.41	0.030	0.02	9.11	2.2	20
6/25/08	0.91	0.40	0.035		9.11	2.2	20
6/26/08	0.86	0.51	0.036		9.11	2.2	20
6/27/08	0.89	0.65	0.035		9.11	2.2	20
6/30/08	0.91	0.35	0.037		11.66	2.2	27
7/1/08	0.91	0.25	0.033		11.66	2.2	27
7/2/08	0.91	0.25	0.034		11.66	2.2	27
7/3/08	0.91	0.30	0.040		11.66	2.2	27
7/7/08	0.85	0.44	0.060		14.50	2.2	27
7/8/08	0.81	0.25	0.037		14.50	2.2	58
7/9/08	0.86	0.27	0.049		14.50	2.75	58
7/10/08	0.85	0.28	0.035		14.50	2.75	58

* Emulsion polymer used is 38% solids by weight.

** Sodium hydroxide (caustic) solution used is 50% NaOH.

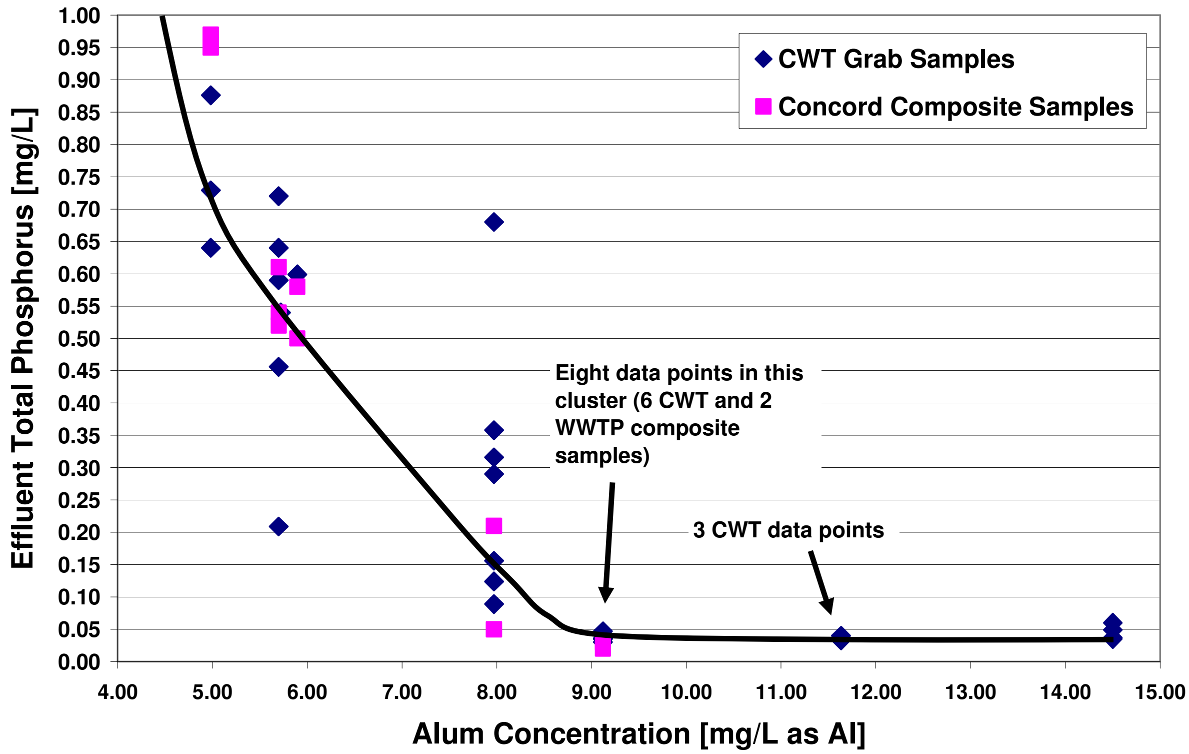

Figure 7: Results of Coagulant Dose-Response Testing. This figure illustrates the response of the full-scale CoMag system to variation in coagulant dose, to meet a range of effluent total phosphorus goals. All data presented in Table 3 above are shown here.

As shown in the resultant dose-response curve (Figure 7), incremental increases in total alum dose up to 9.11 mg/L correlate to measurable decreases in TP. Above 9.11 mg/L, with effluent phosphorus levels well below 0.05 mg/L, the addition of more alum did not result in a substantial further reduction of TP in the CoMag effluent. At concentrations of roughly 0.03 mg/L TP, the remaining phosphorus in Concord's wastewater appeared to be non-reactive.

Figure 8 illustrates the efficacy of the full-scale CoMag system as compared to the Commercial Demonstration Plant. This figure reveals that the full-scale CoMag system is operating far more efficiently in terms of coagulant usage, and thus more cost-effectively, than anticipated based on the CDP data. This figure also shows the overdosing of alum that took place during the initial performance validation test, as compared to the more efficient operation of the system after five months of full-scale optimization. The decline of removal efficiency at extremely high alum doses during the dose-response testing can also be seen in Figure 8, where the highest alum doses resulted in a lower percent TP removal. This is largely due to the extremely low secondary effluent TP, resulting from the equally high alum doses in the secondary clarifiers. With CoMag influent TP below 0.3 mg/L, and non-reactive P typically observed at 0.03 mg/L, reduction through the CoMag system above 90% is unlikely.

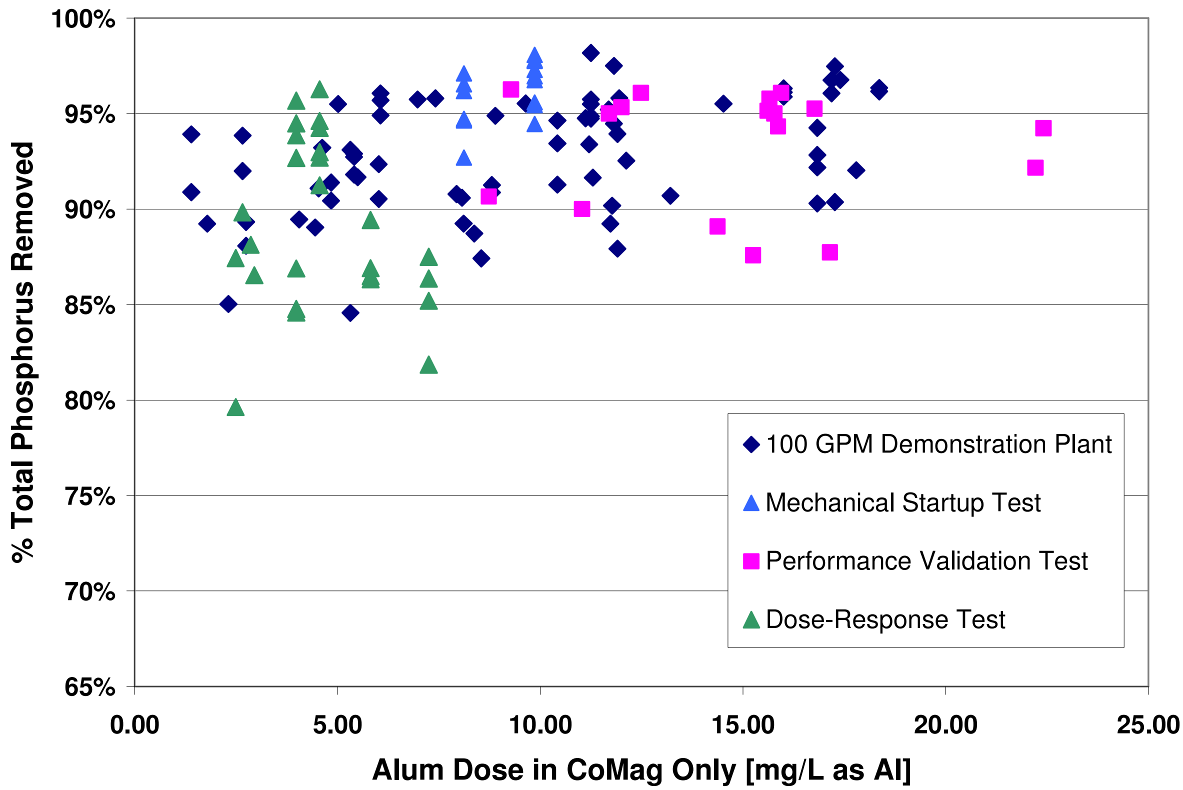

Figure 8: Percent Phosphorus Removed in CoMag System Versus Alum Dose. Only alum added to the tertiary treatment system is included, and the percent phosphorus removal compares TP in the CoMag influent flow to the system's effluent. Data are included from all periods during which both influent and effluent phosphorus measurements were taken, including a mechanical startup test performed in November 2007, the Performance Validation Test in December 2007, and the June-July 2008 dose-response testing. These data are compared to the percent removal measured during the operation of the 100 gallon-per-minute Commercial Demonstration Plant.

Polymer

The CoMag system uses an anionic polymer (Aries Chemical, Beaver Falls, NY; 38% solids by weight) to aid in coagulation in the tertiary reaction tanks. Polymer use in the secondary treatment system was discontinued two years prior to the CoMag installation, as it was deemed to have little effect on secondary treatment. Table 3 above shows the polymer usage during the dose-response testing. Polymer usage has gradually been reduced during the first few months of CoMag operation, as plant operators optimized tertiary treatment and established the minimum feed rate required. Under normal operating conditions to meet the 0.75 mg/L permit limit, the polymer is now being held at 2.5 parts per million by volume.

Sodium Hydroxide

Table 3 also shows the sodium hydroxide ('caustic') usage throughout the dose-response testing. Sodium hydroxide (50% NaOH solution) has been used for final effluent pH adjustment at the Concord WWTP for many years. Additional pH adjustment is now required in the CoMag system to reach the optimum pH for phosphorus removal using alum (6.0 to 6.2). As seen in Table 3, when large quantities of alum are used to reach extremely low phosphorus limits, caustic usage increases significantly, due to the depression of the pH by the alum. Caustic usage can be nearly eliminated at alum dosages close to 5.80 mg/L as Al, where the alum has brought the CoMag influent pH into the optimum range for phosphorus removal.

Turbidity

Turbidity was found to closely relate to phosphorus levels in the treated CoMag effluent. While there is no turbidity limit in the NPDES permit, effluent turbidity is monitored for process control, as it is easier and less costly to continuously monitor than effluent TP. During treatment to meet the 0.75 mg/L P limit with CoMag operational, effluent turbidity averaged 1.7 nephelometric turbidity units (NTU). Turbidity levels reached as low as 0.09 NTU during the dose-response testing, when the alum dose was set to 14.5 mg/L as Al. This turbidity measurement is well below the level required by EPA drinking water standards. Figure 9 shows effluent turbidity versus flow, illustrating the ability of the CoMag system to maintain a low average daily turbidity despite oftentimes wide variations in influent flows as measured over any given day.

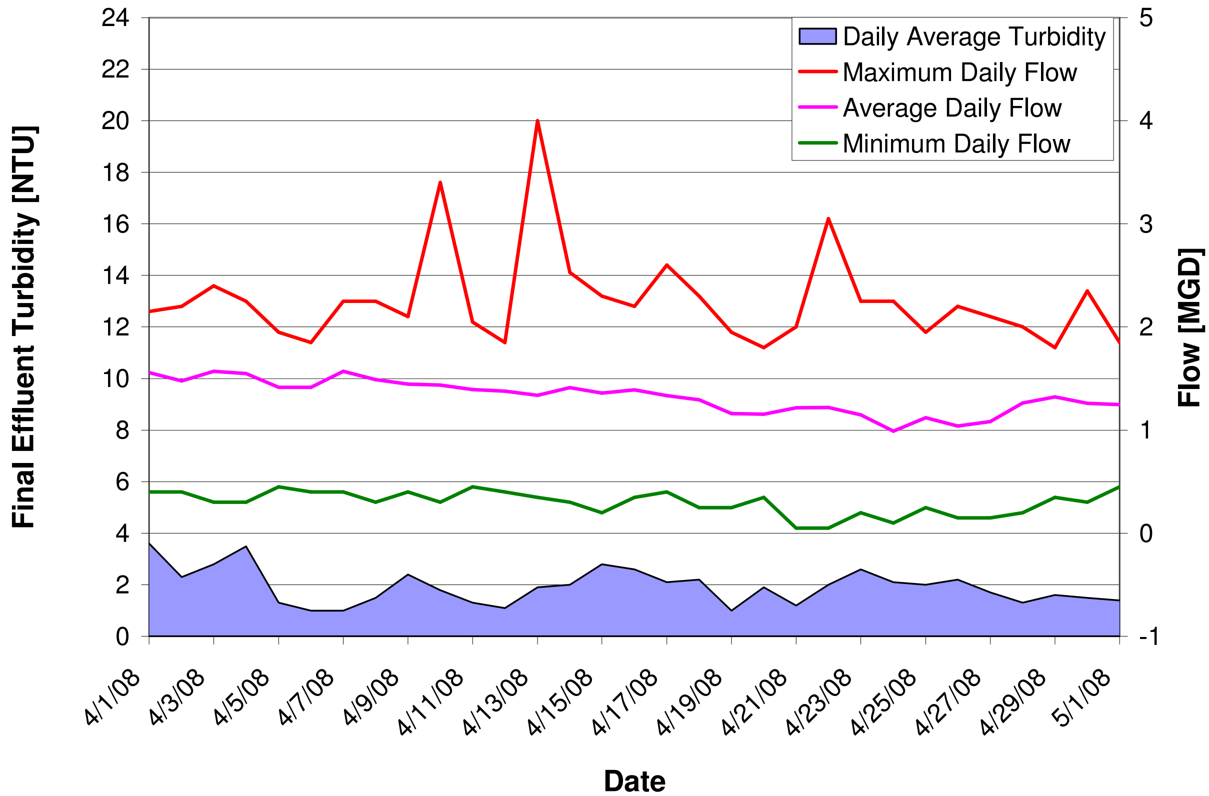

Figure 9: Final Effluent Turbidity, April 2008. Daily average effluent turbidity ranged from 0 to 4 NTU, while the plant flow experienced significant spikes during periods of high infiltration and inflow in early April and drastic nighttime drops as high groundwater subsided later in the month. Throughout this period, the CoMag system was operated to meet a permit limit of 0.75 mg/L TP.

Tertiary Sludge Production and Character

The CoMag sludge is typically thin, at approximately 0.25 to 0.5% solids during normal operating conditions. Tertiary sludge is blended with secondary sludge prior to being thickened to roughly 5% solids using a rotary drum thickener. The concentrated residuals are then trucked off-site to an incineration facility.

An increase in tertiary sludge is to be expected when increasing alum dose and thus forming more precipitate. Such an increase in sludge production was observed during the dose-response testing, although quantification was not feasible due to the difficulty of tracking the sludge through the various stages of handling over the short durations at each alum dose.

Most notable has been the decrease in sludge production when meeting the same permit limits using CoMag compared to using alum in secondary treatment only. Figure 10 illustrates the drop in sludge production that results from the increased efficiency of alum usage since the CoMag system was brought online.

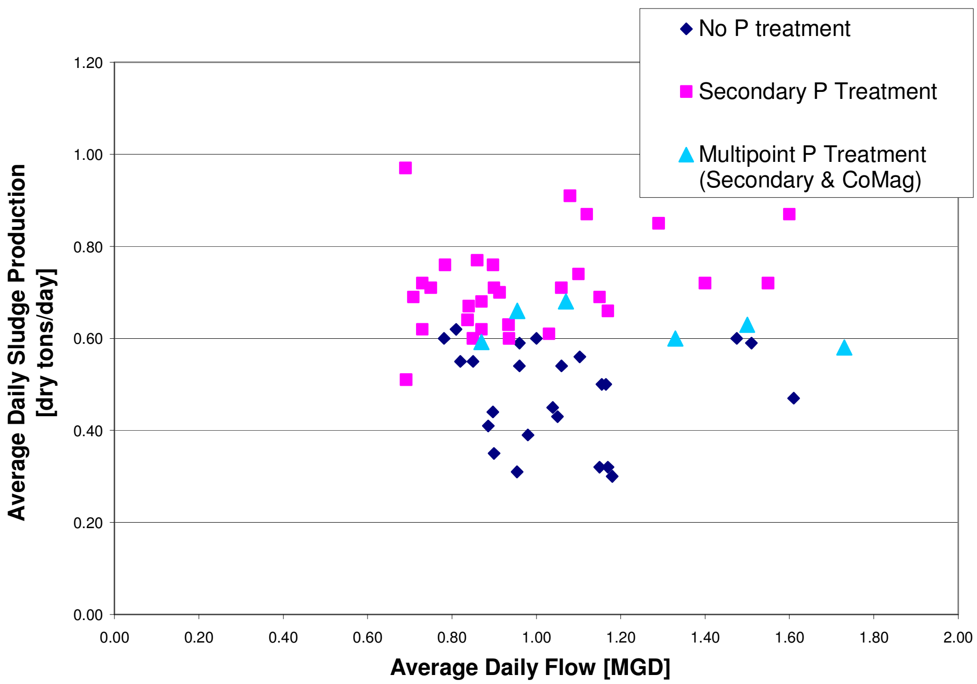

Figure 10: Average Daily Sludge Production Compared to Effluent Flows. Each multi-point and secondary P treatment data point represents a month when the WWTP was meeting a 0.75 mg/L total phosphorus standard, with and without CoMag, respectively. 'No P treatment' data points represent months when phosphorus treatment did not occur. Note that sludge production with CoMag in operation is low compared to sludge production to meet the same permit limits prior to CoMag installation.

Biochemical Oxygen Demand (BOD)

The majority of BOD removal takes place prior to CoMag within the secondary treatment system (trickling filters and secondary clarifiers). Still, further treatment provided through the CoMag system has resulted in a 32% reduction in average monthly BOD from January through June

2008 compared to the effluent quality during the phosphorus removal seasons of the previous five years, before CoMag was operational. Specifically, average BOD in the final plant effluent has dropped from 6.1 to 4.2 mg/L.

Total Suspended Solids (TSS)
Similarly, the final effluent TSS has dropped noticeably with CoMag online from January through June compared to the five previous phosphorus removal seasons. This 51% reduction has brought the final effluent TSS from 10.5 to 5.2 mg/L when averaged over each period. This is not surprising given CoMag's design goal of advanced solids removal.

Pathogens
During the optimization testing of the Commercial Demonstration Plant, CWT had shown positive results of CoMag's ability to remove pathogens, which become bound up in the settling flocs. This testing was performed using total coliform, fecal coliform and MS2 bacteriophage as indicator organisms for bacteria and viruses. Performance testing of the newly installed ultraviolet (UV) disinfection system further proved this ability.

Trickling filter effluent, prior to disinfection, typically contains fecal coliform counts in the tens of thousands per 100 mL range (Metcalf & Eddy, Inc., 1991). During the January 2008 UV performance tests, influent to the UV system following CoMag treatment was compared to UV system effluent, to determine the efficacy of disinfection. Due to CoMag's pathogen removal capabilities, the influent fecal coliform counts to the UV system ranged from less than 50 to 9,650 counts per 100 mL. These concentrations were measured over a three day test period, averaging 2,264 organisms per 100 mL from the 30 samples taken.

The UV transmittance (UVT) of the CoMag system effluent during this performance test ranged from 70 to 80%. With such low pathogen counts and high UVT, plant staff have turned the UV system down to its lowest power output setting. The system was designed with three banks (lead, lag, and standby), each bank having a turn-down capability of 50%. Even during peak spring flows, the UV system has been consistently run using only one bank set at 50% power.

Magnetite Consumption
CoMag continually cycles its ballast, the naturally occurring mineral magnetite, through the tertiary reaction tanks and clarifiers, recovering it using two magnetic drums. A small percentage of magnetite is lost each day, to either the tertiary sludge or the CoMag effluent. Since continuous CoMag operation began, an average of 5 kilograms (9 pounds) of magnetite per day has needed to be replenished. This amounts to a 0.06% loss of magnetite. Of the ballast leaving the system, magnetite concentration measurements have indicated that about 91% has been removed with the sludge, and the remainder has been carried into the CoMag effluent.

Due to its high specific gravity, the fraction of magnetite that is carried over the clarifier weirs into the CoMag effluent largely settles out in the finger weirs just downstream of the UV system, where it can be recovered periodically using a magnet. The fraction of magnetite that continues beyond the finger weirs has not been quantified. CWT continues to evaluate ways to enhance the magnetite capture to further reduce the loss of the ballast.

Metals
The use of aluminum sulfate as a coagulant inherently results in an increase in the effluent aluminum concentration. Concord's NPDES permit requires analysis of one sample per month for aluminum. During the past five years, in months when no alum was being added, effluent aluminum levels averaged 0.492 mg/L. In that same time period, when alum was added to the secondary clarifiers to meet seasonal TP limits, effluent aluminum averaged 1.755 mg/L. Since the CoMag system makes more efficient use of the coagulant, effluent aluminum has been reduced by 53% to 0.832 mg/L since CoMag was brought online.

Other metals of interest are measured quarterly during whole effluent toxicity testing, including zinc and copper. A marked reduction in effluent zinc concentration has been measured with CoMag in operation. Zinc levels previously averaged 0.047 mg/L without alum treatment and 0.027 mg/L with alum treatment in the secondary clarifiers. With CoMag online, a 47% further reduction has resulted, with average effluent zinc measuring 0.014 mg/L. Similarly, copper levels have experienced a 24% further reduction with CoMag online compared to secondary alum treatment.

Emerging Contaminants
Tests of the CoMag system's abilities to remove pharmaceuticals and personal care products have been minimal to date. Samples collected throughout the treatment plant during the Commercial Demonstration Plant's operation were analyzed by independent researchers for the presence of ibuprofen and aspirin (Hauri and Niece, 2005). Results of the CoMag system's removal abilities were limited because the trickling filters removed these constituents to a high degree, sometimes approaching the limits of reliable detection. Further research is needed to determine CoMag's efficacy in the removal or reduction of such substances.

Power Consumption
The electrical power used by the CoMag system is measured and recorded separately from the other WWTP equipment. Power consumption within the CoMag system includes the final polishing magnet, which has accounted for approximately 27% of the total power draw to date. Other electrical equipment includes mixers, sludge and recycle pumps, and chemical feed systems. Note that CoMag power usage does not include the tertiary lift pumps required to bring the plant flow to the system, as this is attributed to site-specific hydraulic constraints, rather than a function of tertiary treatment. Figure 11 illustrates the average daily power consumption for the CoMag system for the first five months of operation.

CoMag System Costs
The average daily power usage to date for the fully operational CoMag system is 150 kWh. At a rate of $0.12 per kWh, this equates to $18.00 per day, or $14.91 per day per million gallons of wastewater treated. While two tertiary clarifiers were installed to provide redundancy and increased hydraulic capacity at high flows, the use of only one clarifier, when feasible, reduces power usage by an average of 17 kWh per day, for a daily savings of $2.04. This savings results from the associated reduction in sludge and recycle pumping. Operating the CoMag system without the final polishing magnet results in a daily power usage of 112 kWh with two clarifiers running and 95 kWh with one clarifier running. Figure 12 shows the power costs associated with these various operational scenarios.

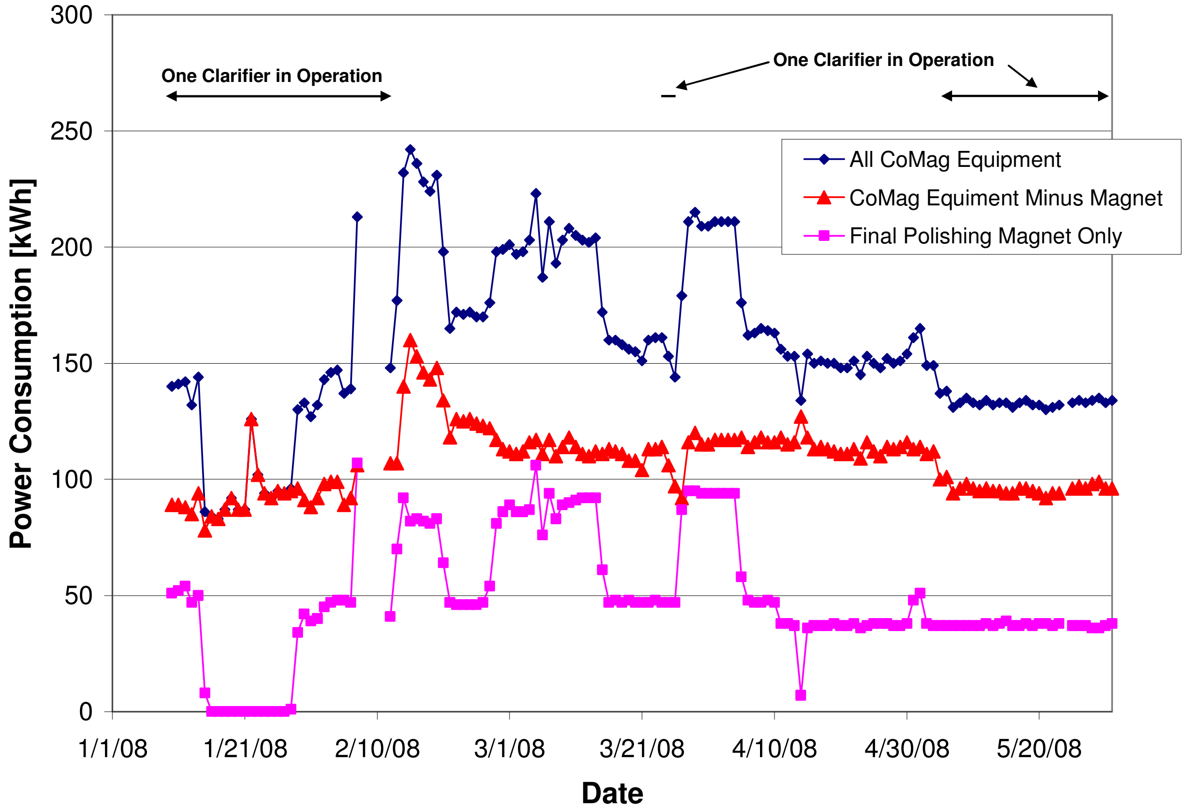

Figure 11: CoMag Power Consumption. Power consumption is shown for the entire CoMag system and is broken down into usage for the final polishing magnet and for the remainder of the CoMag equipment.

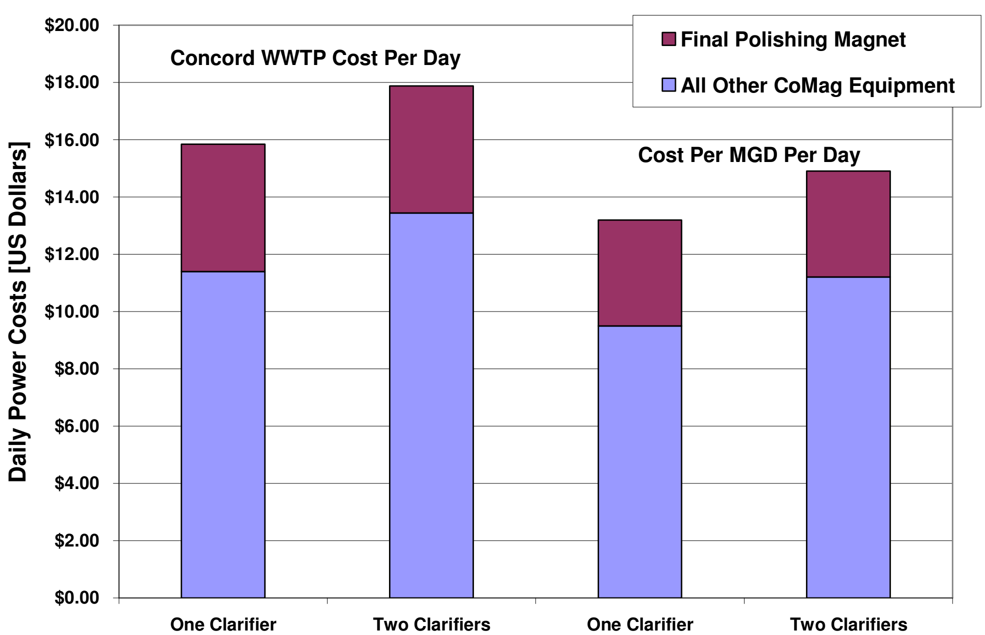

Figure 12: CoMag Power Consumption Costs. All costs are calculated using a rate of $0.12 per kWh. Both actual full-scale (1.2 MGD) costs and the cost per MGD treated are shown.

Figure 13 shows the alum, sodium hydroxide, and polymer usage, as well as sludge production, when comparing conditions with and without CoMag in operation to meet the same TP permit limit (0.75 mg/L). The periods of April through June 2006 and 2007 were used to represent conditions without CoMag, and April through June 2008 was used to represent CoMag operational data. Figure 14 shows the corresponding costs for each of these time periods for the parameters shown, as well as for magnetite.

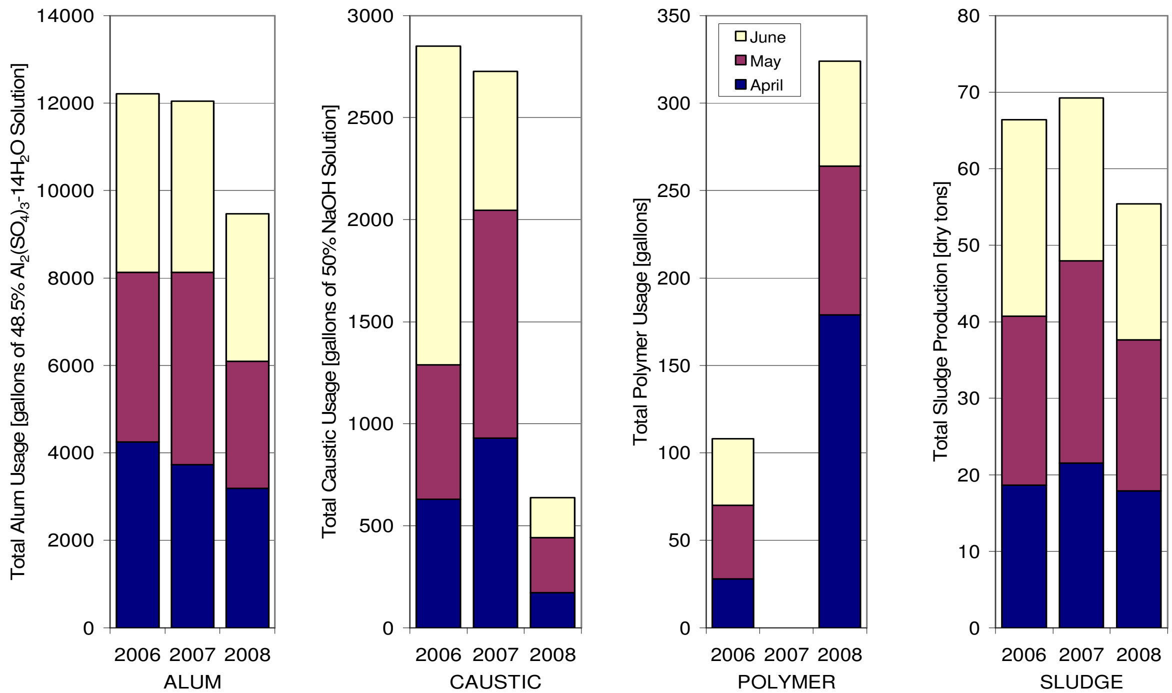

Figure 13: Chemical and Sludge Usage to Meet 0.75 mg/L TP. These charts compare months prior to CoMag installation to months with CoMag in operation, to meet 0.75 mg/L. Aluminum sulfate, sodium hydroxide, and sludge handling are all reduced with CoMag in operation, while polymer usage increases.

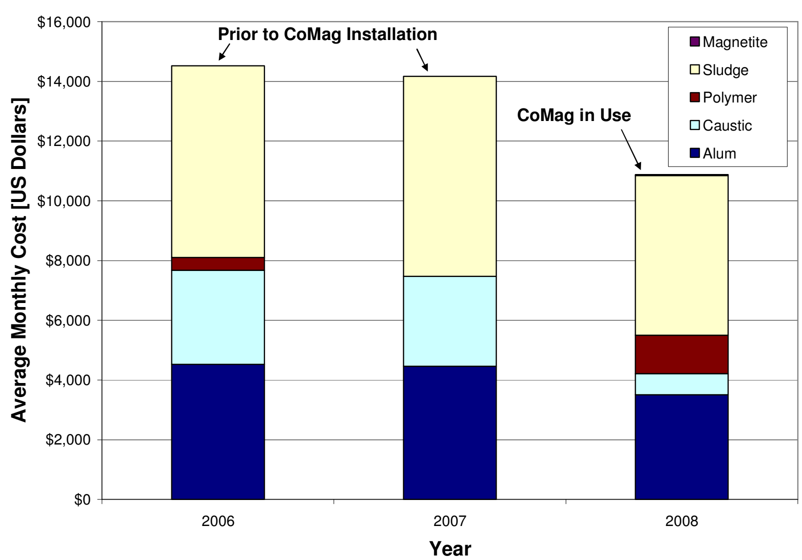

Figure 14: Costs for Phosphorus Removal. The April through June 2008 period represents the CoMag in operation, while 2006 and 2007 were prior to CoMag installation.

DISCUSSION

The results of the full-scale CoMag operation to date have revealed a number of interesting aspects of the operability, efficacy, and economics of this tertiary treatment system.

CoMag System Operability

After six continuous months of CoMag operation, the operators of the Concord WWTP have reported that the system has been relatively easy to operate and control. As described above, the system responds quickly to upsets in influent quality and surges in flow. The operators have not had any trouble meeting effluent permit standards, even during system startup and mechanical testing. After being turned off, the CoMag system can be reactivated to produce the desired results in a period of about fifteen minutes. A drawback of such a responsive process is that equipment or instrumentation upsets can create an equally fast deterioration in effluent quality. Potential upsets may include interruptions in coagulant chemical feeds or an undetected, rapidly rising sludge blanket in the tertiary clarifiers. Changes in effluent quality can, however, be easily detected with a properly designed and functioning Supervisory Data Acquisition and Controls (SCADA) system, allowing operators to quickly restore proper operating conditions. Furthermore, with permit compliance mostly calculated from composite and grab samples, rather than continuous monitoring, a very brief excursion in the continuous data would be unlikely to result in a measurable difference in overall effluent water quality.

While the adoption of an innovative treatment technology inherently generates some level of uncertainty, for the most part, the components that make up the CoMag system are standard equipment used for years in the wastewater treatment industry. These components include reaction tanks, cone-shaped clarifiers with no moving parts, static mixers, vertical shaft mixers, chemical feed pumps, tertiary sludge pumps, valves, and associated appurtenances and controls. The magnetite recovery drums had been used for decades in the mining industry prior to their application to wastewater treatment. The final polishing magnet is a more recent technology but its operation and backwash cycles are fairly simplistic, and the associated flow control valves are again common to the wastewater industry. Therefore, operators are familiar with the types of equipment used and are not required to spend time troubleshooting new or unanticipated problems based on the mechanics of the system's components.

Since the full-scale CoMag system is the first of its kind, the logic and controls strategies have required some learning and refinement to work out the inevitable bugs. The critical lessons learned from the startup of the CoMag SCADA system have been: 1) the importance of polymer system alarms, to quickly indicate any reduction in polymer feed or polymer makeup water quality, 2) the recognition that effluent turbidity correlates with effluent phosphorus levels, hence providing a valuable and easily monitored indicator for degradation of effluent quality, and 3) the need for accurate measurement and control of the sludge blanket level in the tertiary clarifiers. This last item is still being evaluated, because the first two attempts at instrumentation installation to accurately monitor sludge blanket level at all times have been unsuccessful. CWT continues to explore technologies to provide continuously accurate sludge level measurements.

During these initial months of operation, the successful functioning of the tertiary polymer system has proven to be both the most challenging and one of the most critical controls of CoMag performance. In addition to accurate and timely polymer system alarms, a fully redundant polymer system is necessary to ensure reliable effluent quality. Also, trace particulate matter in unfiltered plant water (used for polymer dilution and carrier water) has resulted in slime growth in the polymer feed lines to the CoMag reaction tanks, causing plugging and eventual failure of the feed system. The Town is presently evaluating the costs and impacts of conversion of the makeup water to municipal water supply, versus adding a filtration unit in the plant water feed to the polymer unit. Preliminary analysis has pointed toward filtration as the preferable option. Lastly, establishing the optimal polymer dose has required in depth experimentation and analysis, to strike the balance between adequate coagulation and polymer toxicity. CWT and plant staff continue to refine the nuances of the polymer system and its controls, to ensure its reliable operation.

CoMag System Efficacy

The positive impact of the CoMag system on the reliability of the treatment plant to meet all NPDES permit standards is apparent in the data pertaining to BOD, TSS, and pathogen levels. Upsets in upstream processes can easily be mitigated through the tertiary treatment system. Furthermore, CoMag treatment significantly enhances the UVT, thus facilitating disinfection. Based on regulatory requirements, the UV system was designed for a UVT of 65%, despite CoMag Demonstration Plant data that indicated higher UVT levels. With actual UVT in the range of 70 to 80%, the UV system as installed is oversized, preventing further turndown of the power usage. The owners of future CoMag installations should seek relief from this regulatory requirement to enhance overall treatment plant energy efficiency.

Most of the full-scale testing to date has been performed using equal doses of alum to the secondary clarifiers and the CoMag influent. While this multi-point alum ratio has proven successful, more research is needed to determine if different ratios are optimum for different treatment goals.

CoMag Operational Cost

The most poignant finding of the full-scale CoMag operation is that chemical usage (alum and caustic) is substantially lower using CoMag than just secondary treatment to meet the same permit limits. Accordingly, the dry tonnage of sludge produced is also reduced with CoMag in operation. Magnetite and polymer usage are added factors when using CoMag compared to prior treatment conditions, but the cost to replenish lost magnetite is minimal, and the costs for magnetite and polymer together are offset by the savings in alum, caustic, and sludge handling. This is clearly illustrated in Figure 14, which shows a reduction of over $3,000 per month to meet the same effluent permit limit. At an estimated $18.00 per day for power, CoMag power consumption is also offset by the costs associated with improved chemical efficiency.

Despite these lower operational costs to meet permit limits in the range of 0.75 mg/L TP, operation of a tertiary treatment system to achieve extremely low TP results becomes increasingly less cost-effective. Quantification of additional costs during the dose-response testing was difficult, due to the short duration of testing at each dose. However, each progressive step in alum dosage was estimated to result in over $2,000 in additional monthly operations costs, when accounting for sludge management, chemical usage, and power consumption. Operation to meet lower TP limits is also more labor intensive, with more sludge requiring thickening and increased process monitoring.

The water quality benefits of treatment to levels below 0.1 mg/L must be weighed against the potential detriments to economic viability and other environmental parameters. High costs can lead to escalating user fees and possibly the inability to adequately maintain other critical infrastructure. Higher TP removal also results in increased chemical transport and usage and increased sludge production. All of these factors must be considered in determining the appropriate level of treatment for a particular facility.

CONCLUSIONS

In summary, the first full-scale CoMag installation in the world has been a success from its first day in operation. The Town of Concord has found its treatment capabilities to be more than adequate to meet current NPDES permit limits and any anticipated future limits for the parameters presently regulated. This has been accomplished while using lower chemical dosages and less power than anticipated based upon the results of the Commercial Demonstration Plant. In fact, chemical dosages have been substantially reduced since CoMag was brought online to meet the same effluent phosphorus goals as in prior years.

Furthermore, the excellent performance of the CoMag system has allowed other treatment systems to operate more efficiently and effectively. The CoMag system provides a high level of comfort for the operators in its ability to respond quickly to change and rectify any upsets which may occur upstream in the plant.

Interest in CoMag has been high, with tour groups visiting from across the country and across the globe. Future visits are welcomed and encouraged. The Town of Concord is proud of the success of this project and looks forward to performing further research on the capabilities of this robust treatment system.

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