Phosphorus Removal from Industrial Wastewater Using Dissolved Air Flotation to Meet Discharge Requirements for the Chesapeake Bay Watershed

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ABSTRACT

Dissolved air flotation (DAF) is a feasible tertiary treatment technology for the removal of total phosphorus (TP) and total suspended solids (TSS) preceding a NPDES permitted outfall. In 2009, a pilot study was conducted to determine the efficacy of using this technology for the removal of TP from the wastewater of a poultry processing facility that discharged into a tributary of the Chesapeake Bay watershed. In 2010, a full-scale, tertiary DAF system was installed to remove chemically flocculated TP from the effluent of an activated sludge system providing treatment for a wastewater from a poultry processing facility. Pilot data and two years of full-scale operational data indicate that the technology can provide effluent TP concentrations in the range of 1.0 to 2.0 mg/L provided that adequate dosing control and flow management systems are in place.

KEYWORDS: Dissolved Air Flotation, DAF, Tertiary Treatment, Phosphorus Removal, Poultry Processing, Solids/Liquids Separation

INTRODUCTION

Over the last thirty years, there have been a number of state and federal efforts to quantify and limit the amount of nutrients and sediment entering the Chesapeake Bay. By 2010, water quality issues in the Bay had reached a point where the U.S. EPA issued Total Maximum Daily Load (TMDL) limits for the watershed and specific direct dischargers within the watershed (U.S. EPA, 2010). This included a Virginia poultry processor that discharged wastewater to an affected stream under a National Pollution Discharge Elimination (NPDES) permit.

The poultry facility processed roughly 30,000 turkeys per day and discharged 3,028 to 4,542 m^3/day (0.8 to 1.2 mgd). The facility operated a wastewater treatment system which consisted of fine screening, equalization, dissolved air flotation (DAF), biological treatment (activated sludge), biological nutrient removal, and disinfection. The processor consistently met the limits established under an NPDES permit through the Virginia Department of Environmental Quality.

In 2010, the facility was issued a TMDL TP limit of 622 kg/yr (1,371 lbs/year). The plant's NPDES permit did not contain TP limits; however, limits were expected with the renewal of the permit in 2014. Based on the TMDL limit, the plant expected inclusion of a permit limit for TP in the range of 0.3 to 1.0 mg/L. With discharge TP concentrations in the range of 5 to 12 mg/L, it was evident the plant would not meet the TMDL limit or future NPDES limits for TP.

The facility, with the help of their engineering consultant, evaluated and tested a number of TP removal technologies, including:

- Precipitation and Sedimentation. This option involved dosing of a coagulant to precipitate TP and settle within the existing clarifier for the activated sludge process. This option was discarded due to concerns over the disposal of the precipitate with the waste activated sludge (increased volume and limited avenues for disposal) and the limited settleability of the TP precipitate.
- Precipitation and Filtration. The plant evaluated a sand filter process which required TP precipitation of the clarified effluent from the activated sludge process. The concept was dropped as testing indicated the size and cost of the sand filters would be prohibitive due to the high TP precipitant solids loading on the filters.
- Precipitation and Flotation. Like the filtration option above, this option involved the precipitation of TP from the clarified effluent from the activated sludge process using a metal salt coagulant prior to separation in a dissolved air flotation (DAF) system. The plant already used DAF with chemical flocculation for pretreatment of TSS and O&G, and plant personnel were comfortable with the technology. This was the last technology evaluated.

Based on an initial evaluation, the plant decided to conduct a pilot study to better assess the potential for using chemical flocculation followed by DAF to remove TP from the clarified effluent from the biological treatment system. The processor contacted Environmental Treatment Systems, Inc. (ETS) to arrange for a pilot study to make this assessment.

PILOT STUDY

Pilot Study Goals

ETS conducted a dissolved air flotation (DAF) pilot study at the poultry processing facility in April 2009. The study had the following primary goals:

1. Evaluate the treatment performance of a DAF system for the removal of phosphorus from biologically treated wastewater prior to disinfection and final discharge.
2. Determine a chemical program that would be effective and economical for coagulation and flocculation prior to flotation.
3. Determine the approximate chemical consumption requirements using a DAF system.
4. Approximate the amount of solids generated using a DAF system.
5. Confirm the initial design parameters of the system.
6. Develop the process design for a full-scale DAF system for tertiary phosphorus removal.

Methodology

The ETS pilot DAF system was deployed at the processing facility on April 13, 2009 and installed with assistance from facility personnel. The pilot system consisted of a small DAF with two mix tanks (flash mix and flocculation mix) and associated chemical feed components mounted on a skid. The DAF was an ETS Model RT-3 of 304SS construction with a contact chamber, float cell (0.28 m^2 of actual surface area), a float (sludge) hopper, and an effluent clear well. Whitewater (dissolved air-in-water solution) was provided by a recycle pump that recirculated clarified effluent from the clear well to a contact chamber at the influent end of the DAF. Air was injected into the pump which operated in the range of 5.2 to 6.1 bar (75-88 psi) to force the air into solution. The air injection was controlled through a rotameter with a needle valve while the pump pressure was controlled by an adjustable pressure valve just prior to the contact chamber. As the whitewater passed through the valve, air would come out of solution in the form of micron-size bubbles and begin rising within the contact chamber.

DAF influent passed through a flash mix tank where coagulant was added. The wastewater then flowed by gravity into a flocculation mix tank where a flocculent (polymer) was added. The flocculated stream then flowed by gravity from the flocculation mix tank into the contact chamber of the DAF where the resulting floc made contact with micron-size air bubbles from the whitewater stream. The floc-and-bubble matrix would rise to the water surface within the flotation cell forming a float bed which was removed by a chain-and-flight skimmer system into the float hopper. Clarified effluent would pass under an internal baffle into the DAF clear well prior to discharge (Figure 1). Any solids that did not float would generally settle in the V-bottom of the DAF unit for discharge by periodic blow-down.

For the pilot study, the DAF influent was clarified effluent from the existing activated sludge biological treatment system. This wastewater was pumped to the pilot skid from the existing chlorine contact chamber prior to the introduction of chlorine using two small submersible pumps. To minimize the number of variables over a short study period, it was decided to maintain a constant flow rate to the DAF at 2.27 m^3/hr (10 gpm) which translates to a hydraulic loading of 8.1 $m^3/hr/m^2$ of surface area (3.0 gpm/ft^2), well within generally accepted hydraulic loading for a pretreatment DAF (Ross *et al.* 2000). The recycle system operating conditions

Figure 1. DAF Pilot Setup and Operation

were also held fairly constant, operating at 5.2 to 6.1 bar (75-88 psi) with an air injection rate of 0.020 to 0.025 m^3/hr (0.7-0.9 scfh). Float from the DAF was collected in a container to collect samples and to determine the float volume and solids mass produced. DAF effluent was discharged back to the headworks of the wastewater treatment plant.

Chemical Program

Chemical processes for phosphorus removal commonly rely on phosphate precipitation through the addition of metal salts that form sparingly soluble phosphates (Jenkins and Hermanowicz, 1991). The most commonly used for this purpose are: lime ($Ca(OH)_2$), aluminum sulfate or alum ($Al_2(SO_4)_3$), aluminum chloride ($AlCl_3$), sodium aluminate ($NaAlO_2$), ferric chloride ($FeCl_3$), ferric sulfate ($Fe_2(SO_4)_3$), ferrous sulfate ($FeSO_4$), and ferrous chloride ($FeCl_2$). While each of these salts have specific advantages and disadvantages, the chemical programs chosen for the pilot study focused on the use of $Al_2(SO_4)_3$ (alum) and $AlCl_3$.

Theoretically, it takes one mole of Al to precipitate a mole of TP, or 0.87 kg Al per kg TP. For example, an alum solution of 49% concentration would require a dosage of 15 liters of solution per kg TP precipitated (1.8 gal/per lb). In application, this ratio can be 2-6 times higher due to various process conditions (e.g., alkalinity, pH, the presence of other contaminants, temperature, etc.). The actual ratio can be determined through bench-scale or pilot-scale testing.

The flocculents used in the study included both cationic and anionic polymers. A polymer solution was blended (0.1-0.2% concentration) prior to dosing through a variable speed peristaltic pump. The coagulant solution was dosed using an electronic metering pump on the DAF skid which was set to manually dose at a constant rate. It was determined early during the study that the influent alkalinity was too low to sustain the required dosages of coagulant without the wastewater pH decreasing below an optimum level. Therefore, a pH control system was added to adjust the pH in the flash mix tank using a 50% solution of sodium hydroxide (NaOH). The pH control system was set to maintain DAF effluent between pH 6.4-6.8 to optimize the removal of TP with the aluminum-based coagulants.

Pilot Study Results

The pilot study was conducted over a three-day period from April 14 to April 16, 2009. Each morning during the study period, initial influent samples were taken from the wastewater source to determine benchmark TP levels for that test day. The samples were analyzed on-site using a Hach - PhosVer® 3 ascorbic acid test (Hach Method 8048) to determine reactive phosphorus concentrations which were converted to TP concentrations. These results were used to determine the initial dosages required to precipitate TP. Once determined, a test run was initiated where the pilot was operated for a period of 1-2 hours. Since it was not possible to visually confirm the efficacy of coagulant dosages in removing TP, coagulant dosages were adjusted as additional TP data were collected. Flocculent dosages were made based on both effluent quality and visual observation of the floc formed in the flocculation mix tank.

A total of sixteen (16) test runs were conducted over the three day study. During each test run, DAF system operating conditions were recorded (Table 1) and system influent/effluent samples collected for analysis. Each sample was analyzed using the Hach method mentioned previously and the analytical results plotted (Figure 2).

Discussion

The results of the pilot study are summarized as follows:

Table 1. DAF Pilot Study Operating Conditions

Test #	Coagulant Type	Coagulant Dosage	Polymer Type	Polymer Dosage	Influent pH	Effluent pH	Influent Phosphorus	Effluent Phosphorus	Removal	Total Solids Produced [2]
Units		**ppm**		**ppm**	**SU**	**SU**	**mg/L**	**mg/L** [1]	**%**	**kg/hr**
1	$AlCl_3$	950	anionic	1.60	6.63	12.01	9.83	0	100%	0.33
2	$AlCl_3$	660	anionic	0.60	6.83	7.02	9.93	0	100%	0.39
3	$AlCl_3$	660	anionic	0.60	6.89	7.27	9.93	0	100%	0.33
4	$AlCl_3$	660	anionic	0.60	6.73	7.68	9.06	0	100%	0.33
5	Alum	475	anionic	0.70	6.85	4.38	7.53	3.50	54%	0.47
6	Alum	396	anionic	0.70	6.85	5.81	7.53	0.63	92%	0.37
7	Alum	396	anionic	0.70	6.85	6.40	7.53	0.49	93%	0.37
8	Alum	396	anionic	0.70	6.85	6.49	7.53	0.86	89%	0.37
9	Alum	528	anionic	0.70	6.85	6.43	7.53	0.77	90%	0.47
10	Alum	528	anionic	0.70	7.06	6.29	7.53	0	100%	0.47
11	Alum	528	anionic	0.70	7.06	6.30	6.70	0	100%	0.47
12	$AlCl_3$	528	cationic	1.15	6.89	6.10	6.60	0.54	92%	0.26
13	$AlCl_3$	951	cationic	1.15	6.89	6.21	6.60	0.55	92%	0.33
14	$AlCl_3$	740	cationic	1.15	6.89	5.97	6.60	0.50	92%	0.33
15	Alum	528	anionic	0.95	6.89	7.02	6.60	0.37	94%	0.37
16	Alum	528	anionic	0.95	6.89	7.40	6.60	0.50	92%	0.37
Average Study	N/A	591	N/A	0.85	6.87	6.80	7.73	0.54	92%	0.38
Average $AlCl_3$	$AlCl_3$	736	N/A	0.98	6.82	7.47	8.36	0.23	97%	0.33
Average Alum	Alum	478	N/A	0.76	6.91	6.28	7.23	0.79	89%	0.41

[1] TP readings below detectable limit were assumed to be zero.

[2] Total solids are on a dry matter basis.

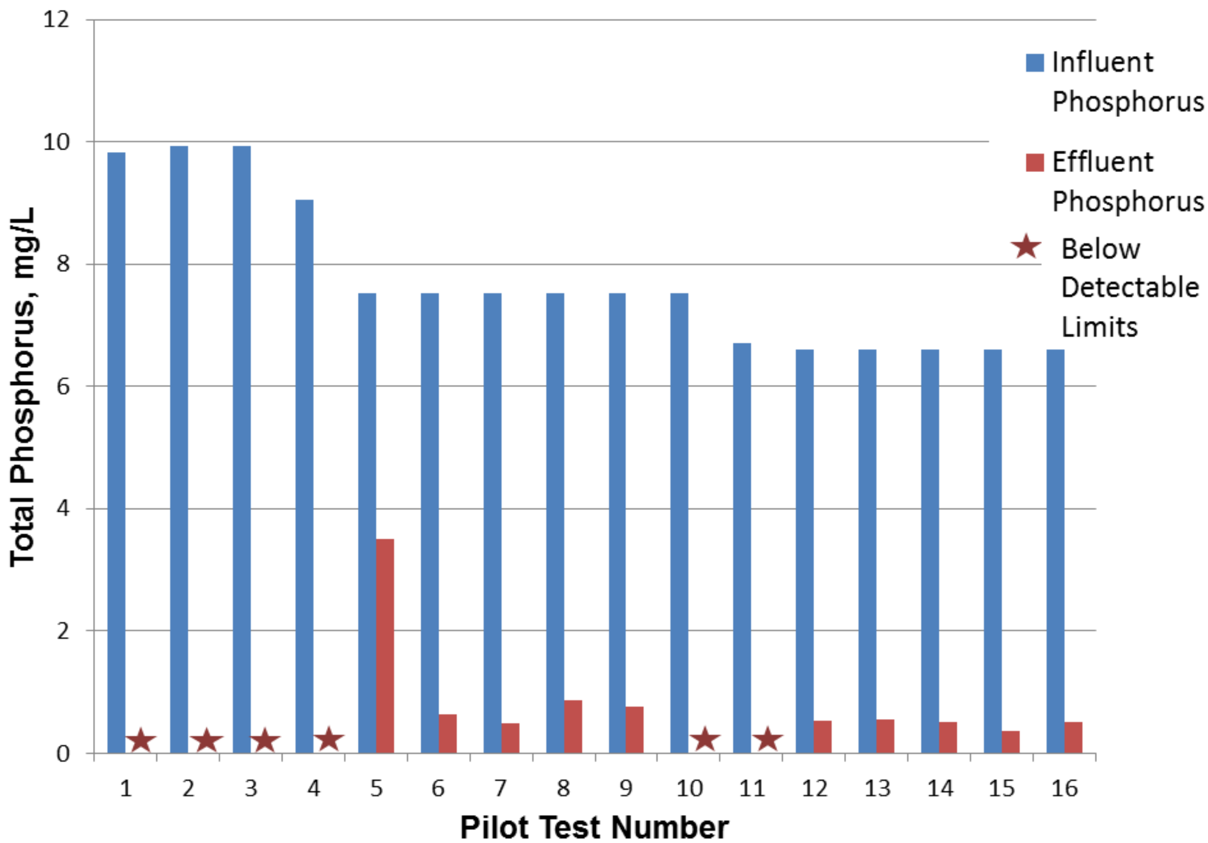

Figure 2. Pilot Study Phosphorus Removal Data

1. The performance of the pilot DAF system was relatively stable during all test runs. Overall, the system provided a high level (average 92%) of TP removal efficiency using an aluminum-based coagulant and a single flocculent prior to flotation.
2. Effluent TP concentrations averaged 0.54 mg/L with an average influent TP concentration of 7.73 mg/L.
3. The DAF was hydraulically loaded at a fairly constant 8.1 $m^3/hr/m^2$ (3.0 gpm/ft^2) of actual surface area. Based on the performance of the DAF, both from an effluent quality perspective and visual observations, this was well within the capability of the system to float and remove the flocculated solids.
4. The study confirmed that either $AlCl_3$ or alum was effective at precipitating phosphorus once dosage rates were optimized. Dosages during the study averaged approximately 600 ppm and varied with influent TP concentrations. The study also confirmed an optimum operating pH range of 6.5 to 7.0 SU. It was noted that dosing $AlCl_3$ or alum at these levels would decrease wastewater pH, possibly requiring the addition of pH control at the process to maintain pH in the optimum range or the use of another aluminum-based salt such as poly-aluminum chloride (PAC) which would be less acidic.
5. Both of the anionic and cationic flocculents were shown to be effective at creating a floc that could be floated within the DAF. Dosages averaged less than 1 ppm and were

believed to be sufficient for generating an acceptable floc. Dosages of 1 to 2 ppm were recommended for a full-scale system.

6. During the study, the DAF float solids generation averaged 0.38 kg of total solids (dry matter basis) per hour with a wastewater flow of 2.27 m^3/hr (10 gpm) or 0.167 kg solids per m^3 of wastewater flow. With a full-scale system operating at 3,028 m^3/day (0.8 mgd), the expected solids yield would be approximately 508 kg/day (1,120 lb/day dry matter).

FULL-SCALE TERTIARY DAF SYSTEM

DAF Design

The pilot DAF was operated at a fixed hydraulic loading of 8.1 m^3/hr/m^2 of surface area (3.0 gpm/ft^2). This is considered well within the hydraulic design criteria for a pretreatment DAF or one providing clarification of biological solids (Ross *et al.* 2003). With a design instantaneous flow of 193 m^3/hr (850 gpm), it was determined that a DAF with a minimum of 22.30 m^2 (240 ft^2) surface area or 8.66 m^3/m^2-hr (3.54 gpm/ft^2) would meet the hydraulic design requirements for this application (Table 2).

While the effluent TSS concentrations from the existing biological clarifier at the plant were fairly low (<20 mg/L), significant TSS would be generated by the precipitation of TP in the flocculation system. The TSS created by the flocculation process during the pilot study was not measured; however, based on the chemistry used and the influent TP concentrations, it was estimated that the TSS of the wastewater entering the DAF from the flocculation system would be less than 300 mg/L. With a design flow of 193 m^3/hr, this concentration would translate into a solids mass loading of approximately 58 kg/hr (128 lbs/hr, dry weight). With a DAF sized above at 22.30 m^2 (240 ft^2) based on hydraulic loading, this would result in a solids mass loading of roughly 2.60 kg/m^2-hr (0.53 lbs/ft^2-hr), which was well within a generally accepted range. The whitewater system fitted on the DAF would have a recycle rate of 34 m^3/hr (150 gpm) at an operating pressure of 6.55 bar (95 psig) with an air solution capacity of approximately 3.4 m^3/hr (120 scfh). Based on a solids mass loading of 58 kg/hr, this resulted in a fairly conservative air:solids ratio of 0.076.

System Design

Based on these design criteria, an ETS RT-240 DAF was proposed for full-scale installation. After a final review by the poultry processor of the other treatment options, the decision was made to install the DAF at their facility. One of the major factors in this decision was that the plant was already familiar with DAF technology as an identical DAF was being used as pretreatment process prior to biological treatment. Also, the DAF provided an additional means to capture TSS carryover from the activated sludge system and could produce a thickened sludge with lower volumes and disposal costs compared to the other technologies reviewed.

The initial system design is represented in the process flow diagram (Figure 3). Like the pilot study, the system was designed to provide tertiary TP removal of the clarified effluent from the activated sludge process just downstream of the existing clarifier and upstream of disinfection and stream discharge. As indicated in Figure 3, effluent from the existing secondary clarifier gravity flows into a flash mix tank (HRT approximately 45 minutes) where a coagulant is added

Table 2. Tertiary DAF Design Parameters

Parameter	Units	Design	Notes/References
Forward Flow	m^3/hr	193	Design flow provided by poultry processing facility
Total Suspended Solids	mg/L	300	Maximum estimated solids generated by TP precipitation
Solids Mass Loading	kg/hr	58	Calculated
Recycle Pressure	bar	6.55	2.76 to 4.83 (Metcalf & Eddy, 1991)
Air Solution Rate	m^3/hr	3.40	By design
Recycle Rate	m^3/hr	34	N/A
Recycle	%	18	5% to 120% (Corbitt, 1999)
Flotation Surface Area	m^2	22.30	By design
Hydraulic Loading	$m^3/hr/m^2$	8.66	0.50 to 9.8 (Metcalf & Eddy, 1991)
Solids Loading	$kg/hr/m^2$	2.60	4.0 to 9.8 (WEF MOP-8, 1992)
Air to Solids Ratio	kg/kg	0.076	0.006 to 0.070 (WEF MOP-FD-3, 1994)

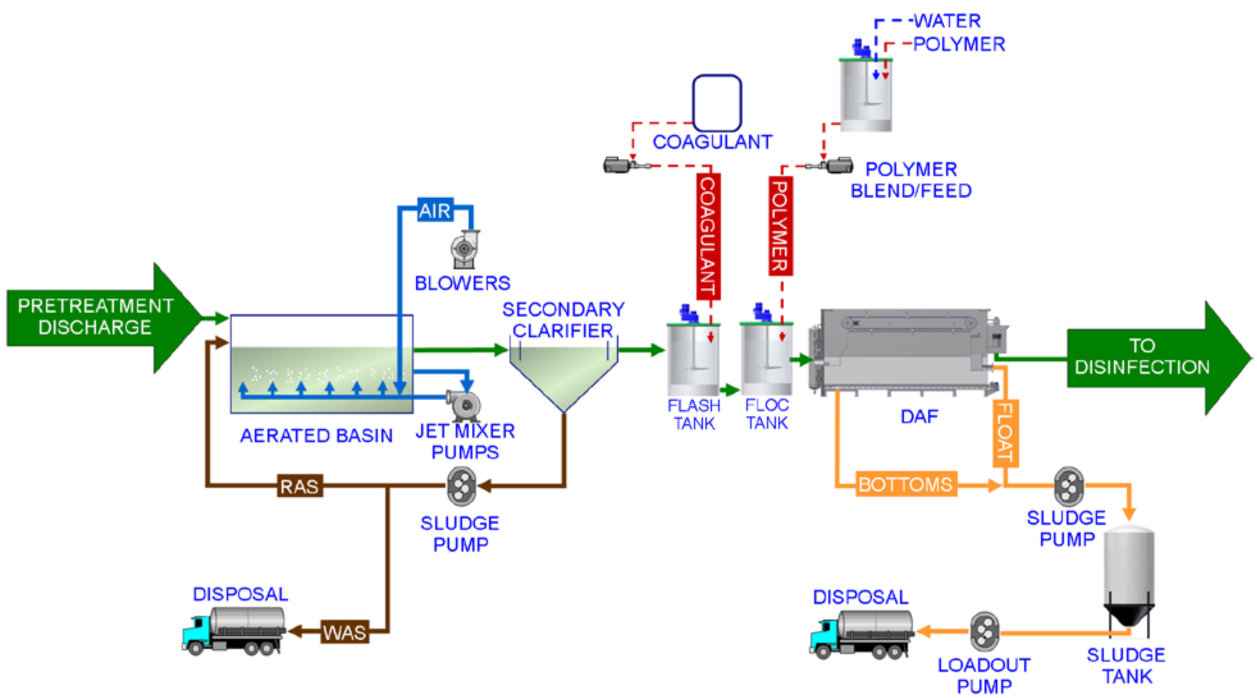

Figure 3. Process Flow Diagram of a Full-Scale DAF Phosphorus Removal System

to form a pin floc. Overflow from the flash mix tank flows into a flocculation tank (HRT approximately 11 minutes) where a polymer is introduced to create a larger floc. The flocculated stream passes into the DAF for flotation and removal of solids (float) with the clarified effluent discharging through an ultraviolet disinfection system prior to stream discharge. The float material removed by the DAF skimmer system is collected in a 30.3 m^3 (8,000 gallon) holding tank for decanting of free water prior to hauling for disposal. The hauled material is mixed with dairy cow manure for composting or land application.

Figure 4. Full-Scale Flash Mix Tank and Tertiary DAF

Figure 5. Full-Scale Tertiary DAF Effluent and Float Formation

DAF Operation and Performance

The DAF system was installed and placed into operation in June of 2010. The chemical program initially used included alum followed by a cationic polymer. In large part, the chemical dosages were held constant although there was some variation in both flow and incoming TP concentration. Plant operators periodically checked the TP concentrations of the DAF effluent using the Hach method to confirm TP removals. The graph in Figure 6 illustrates the final effluent TP concentrations and corresponding flows from compliance reporting by the plant in 2011. There were no corresponding influent TP measurements taken during this period; however, the plant typically had effluent TP concentrations in the 6-12 mg/L range prior to the installation of the teritiary DAF.

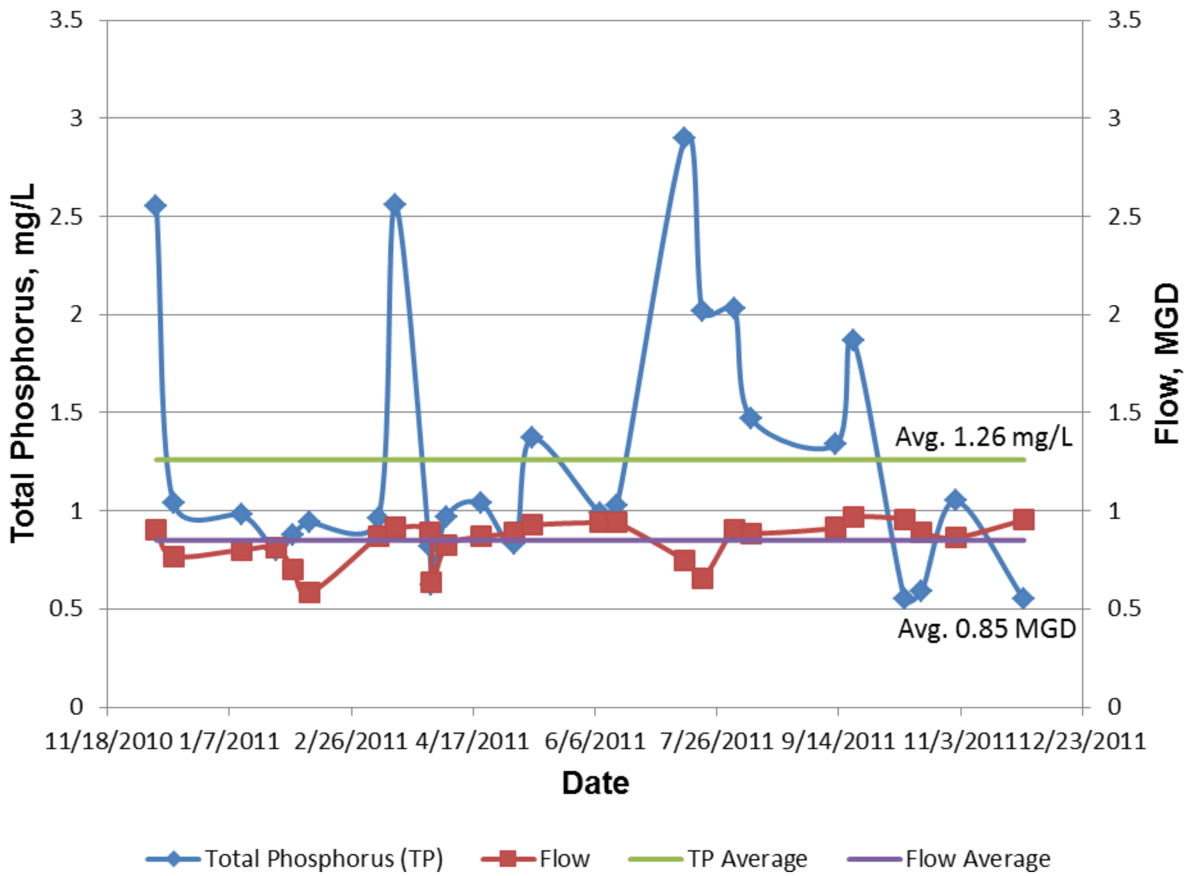

Figure 6. Tertiary DAF Effluent Phosphorus Concentrations (2011)

As indicated in Figure 6, the system typically provided effluent TP concentrations near the target of 1.0 mg/L (averaging 1.26 mg/L for the period shown). However, there were points where the effluent TP concentrations exceeded 2.5 mg/L, most likely due to a lack of chemical dosing control relative to variations in influent TP concentrations and instantaneous flow and issues related to floc carryover from the DAF.

The poultry production facility had set an internal deadline to meet a TP concentration limit as low as 0.30 mg/L with their pending NPDES permit renewal. Therefore, the plant opted to add a sand filter system to remove additional floc particles including precipitated TP from the DAF effluent. The sand filter system was installed and made operational in December of 2011. After system installation, the plant conducted a two year study (2012-2013) of the performance of the tertiary DAF and the sand filter system. A graph of TP concentrations of the tertiary DAF influent and effluent is provided in Figure 7.

As illustrated in Figure 7, the effluent TP concentration averaged 1.15 mg/L over the two-year study period, which was higher than the average effluent quality measured during the pilot study (0.54 mg/L) but lower than the average results observed during 2011 (1.26 mg/L). As seen in both sets of the full-scale data, it is evident that the system is capable of providing effluent TP concentrations at or below the original target of 1.0 mg/L; however, it has proved difficult at times to consistently meet this target. The reasons for this include:

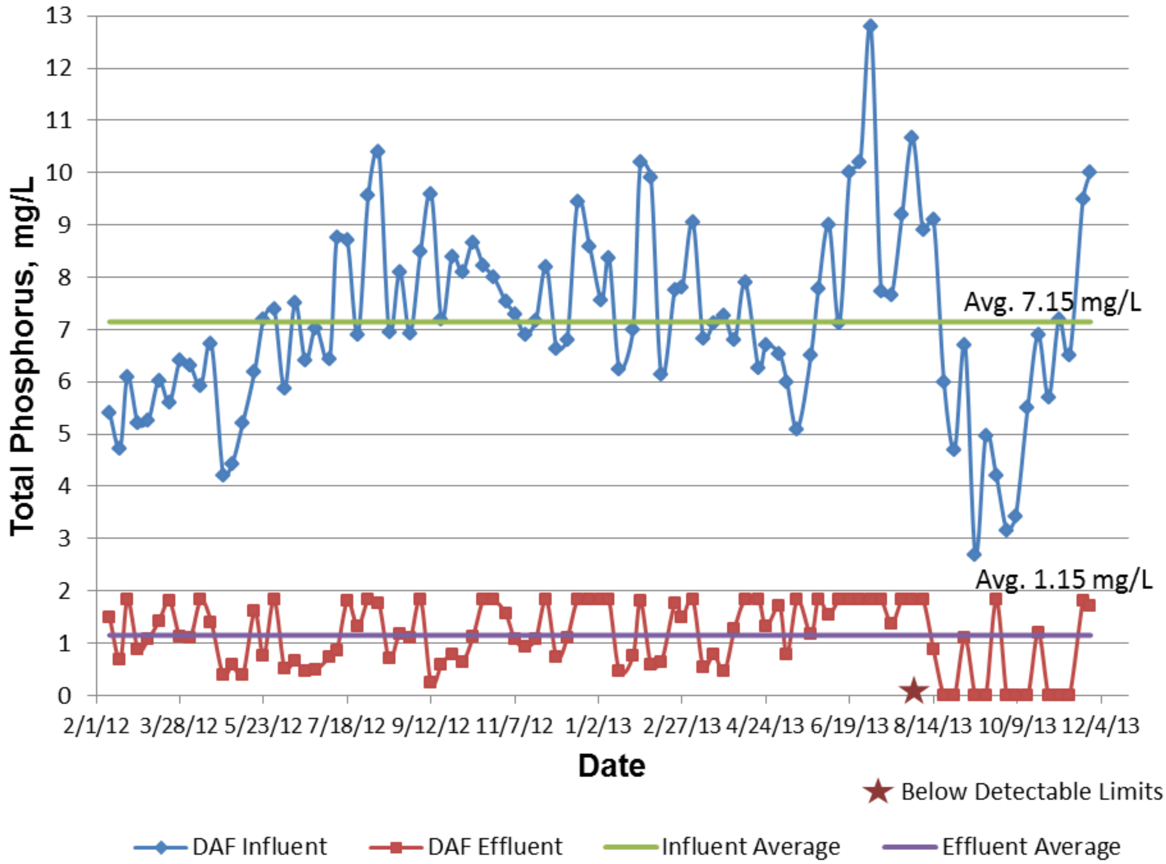

Figure 7. Teritary DAF Influent and Effluent Phosphorus Concentrations (2012-2013)

1. Influent TP Variations. As indicated in Figure 7, there was considerable variation (2.8-12.8 mg/L) in influent TP concentrations. Much of the influent TP variation resulted from cleanup operations around the live haul area which flushed phosphorus-laden poultry manure into the system. Without a near-continuous feedback of influent TP concentrations, it was difficult for the plant operators to manage a coagulant dosage to match the stoichiometric requirements for TP precipitation.
2. Flow Variations. Instantaneous flow through the tertiary DAF system varied from 182 to 273 m^3/hr (800 to 1,200 gpm), especially during rain events since facility stormwater also passed through the wastewater treatment system. Although the treatment system has some equalization, it frequently was inadequate for maintaining relatively constant flow through the secondary and teritiary treatment systems during storm events. Without automatic, flow-paced control of the coagulant and polymer feed systems, the system was unable to correct for rapid changes in the instantaneous flow rates and resultant mass rates of TP coming to the system.
3. DAF Carryover. In this application, the TP floc was very weak (lacking bulk and cohesiveness) and was susceptible to shearing in transition from the flocculation tank to the DAF and from the introduction of whitewater in the DAF contact chamber. Some of the weak floc characteristics likely derived from the two earlier operational issues

(influent TP and flow variations) which affected the quality of floc formed. However, some modifications were made to the whitewater injection ports on the DAF to minimize floc shearing and reduce some of the carryover of TSS, including precipitated TP, into the DAF effluent.

Performance Comparison

A comparison of the pilot study results and the 2012-2013 full-scale system study is presented in Table 3. In general, with the exception of the average effluent TP concentrations discussed previously, most of the performance criteria established by the pilot study have been observed with the full-scale system. Full-scale system coagulant dosages were lower than the average observed during the pilot study. Coagulant dosages relative to the removal of TP were also lower with the full-scale system (56.23 liters/kg TP removed) compared to what was expected from the pilot study (63.71 liters/kg TP removed). However, average flocculent (polymer) dosages for the full-scale system were significantly higher than that observed during the pilot study (5.4 ppm vs. 0.85 ppm). Much of this is due to the plant using both a cationic and anionic polymer in an effort to improve the floc quality and reduce carryover from the DAF. The total mass of solids generated (on a dry matter basis) relative to TP mass removal was also comparable between the full-scale and pilot-scale studies (29.23 kg TS/kg TP removed vs. 24.55 kg TS/kg TP, respectively).

CONCLUSIONS

A full-scale, tertiary DAF system installed at a poultry processing plant has performed well and been proven capable of providing an effluent TP concentration in the range of 1.0 to 2.0 mg/L. Like many wastewater treatment processes, it was susceptible to variations in influent flow and contaminant loading. Much of this can be mitigated with better flow and contaminant equalization, improvements in contaminant monitoring, and adjustments to the chemical program.

Table 3. Comparison of Pilot-Scale and Full-Scale Tertiary DAF Performance

	Influent Phosphorus	Effluent Phosphorus	Phosphorus Removal	Coagulant Dosage	Coagulant Use/Mass TP Removed	Flocculent Dosage	Total Solids Produced/Mass TP Removed [1]
	mg/L	mg/L	%	ppm	liters/kg	ppm	kg/kg
Average Pilot Study	7.73	0.54	92%	591	63.71	0.85	24.55
Average Pilot Study: $AlCl_3$ Coagulant	8.36	0.23	97%	736	71.68	0.98	18.35
Average Pilot Study: Alum Coagulant	7.23	0.79	89%	478	57.52	0.76	29.37
Average Full-Scale 2012-2013	7.15	1.15	93%	450 [2]	56.23 [2]	5.40 [3]	29.23

[1] Total solids are on a dry matter basis.
[2] The facility used a poly-aluminum chloride (PAC) coagulant through most of this period.
[3] Dosage value reflects the combined dosage of both an anionic and cationic polymer in the flocculation system.

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