Laminar Tube Flocculator, Spring 2015

Luyan Sun, Tanvi Naidu, Kevin Shao

5/13/2015

Abstract

Research on the Laminar Tube Flocculator in Spring 2015 aimed to validate the results obtained by Karen Swetland with the FReTA system and to further investigate factors that affect the overall turbidity removal. The past semester's team worked to test the new residual turbidity monitoring system, SWaT, in comparison to the FReTA system and verify that the new system can obtain similar results to those obtained with the old system. However, the actual coagulant tubing size used in the previous SWaT experiment was different from that in the pump control method file. Because of the incorrect input in tubing size, the PACl dosages were not accurate. The Spring 2015 research derived correction factors that would make the previous data usable. Then experiments were conducted in the SWaT system to finish verifying Karen Swetland's results. Future work includes experiments to determine if there is an optimal floc size which is small enough to combine with small clay particles yet large enough to be separated in the sedimentation tank. Also, future teams should study how dissolved organic matter (DOM) affects the performance of the flocculator and sedimentation tank. These findings will improve the performance of the flocculator and make it more effective for use in water supply.

Introduction

In water treatment plants, flocculation is an essential process that combines small colloidal particles into larger particles so that they can settle out in a sedimentation tank. The overall performance of a flocculator can be measured based on residual turbidity. Factors that affect the residual turbidity include but are not limited to coagulant type and dose, size of colloid particles in the raw water, concentration of dissolved organic matter, hydraulic residence time, and energy dissipation rate (Kawamura, 1991).

Built upon the work done by Karen Swetland and previous AguaClara teams, research in Spring 2015 aimed to validate the fractal flocculation model and investigate the effects of coagulant dosage, floc size, and concentration of dissolved organic matter (DOM) on overall improvement in turbidity removal. First, experiments conducted by Swetland showed a positive correlation between coagulant dose and turbidity removal. However, the results were obtained by using the Flocculation Residual Turbidity Analyzer (FReTA). FReTA has been replaced by AguaClara's new residual turbidity monitoring system called Settled Water

Turbidity Analyzer (SWaT). Based on previous research done by AguaClara teams, the results obtained by Swetland have not been thoroughly tested by the SWaT system due to system errors. Further testing of the flocculation model developed from Swetland's data would ensure that the model could be used under the new system and thus become a valid basis for future design and operation of hydraulic flocculators. Second, the AguaClara flocculation model predicts that colloids or small flocs tend not to attach to large flocs (Weber-Shirk, 2015). One possible reason is that as the floc size increases, the surface shear could be too high for a colloid to attach. Therefore, a low residual turbidity is hard to achieve as the process of effective collisions slows down when the number of colloids and non-settable flocs decreases. One hypothesis is that if flocs are routinely broken up, the process of effective collisions could be accelerated and hence improve the performance. Floc breakup experiments, which break flocs by local regions of high energy dissipation rate, could be utilized to explore if there exists a critical floc size that gives the maximum removal in turbidity. Finally, it is not clear how the concentration of DOM would affect the improvement in turbidity removal. It is proposed that natural DOM could act as a coagulant sink and increase the required coagulant dosage. Experiments over a range of DOM concentrations and a range of coagulant doses are needed to investigate 1) the relationship between concentration of DOM and required dose, 2) if DOM would cause any other changes besides an increase in required dose.

Literature Review

The flocculation process used by the Laminar Tube Flocculator Team involves the use of a coagulant (PACl) to facilitate the formation of flocs from clay particles. Flocs are clusters of small suspended particles that have been coated with coagulant, that are heavier than individual particles and thus easier to remove from the water through process of sedimentation. Water that has undergone this flocculation process followed by sedimentation thus has reduced turbidity. Factors such as coagulant dose, floc size, and dissolved organic matter affect the performance of the system in terms of residual turbidity and capture velocity.

The first part of the Spring 2015 team's research involves verifying the model based off of research conducted by Karen Swetland, originally developed by Monroe Weber-Shirk. This model reflects the effects of coagulant dose, raw water turbidity, flocculator residence time, and coagulant type (Swetland, 2012). The model can help predict settled water turbidity based on flocculator design and operation and is mechanistically scalable. It is described by the equation:

$$pC^* = \frac{3log(e)}{2} W \left[\frac{2}{3} \frac{\eta\, coag}{V capture} \right] \left(\Gamma\ G\ t\ \varphi^{\frac{2}{3}} - N_{c1} \right)$$

where C^* is the residual turbidity divided by the influent turbidity, W is the lambert W function, Γ is the fractional coverage of colloids by coagulant, G is the average velocity gradient, φ is floc volume, η_{coag} is the efficiency of the coagulant, N_{c1} is the collisions to make the first big flocs (=0.4), and $V_{capture}$ is the capture velocity (Weber-Shirk, 2015). The results of Karen's research indicate that higher coagulant doses lead to lower residual turbidity. Moreover, there is an optimum range for influent turbidity that provides the most efficient removal of turbidity: 50 to 150 NTU. Higher influent turbidity values are associated with lower fractional coverage of clay and higher floc volume fraction (Swetland, 2012).

These results were obtained using the FReTA system for measuring turbidity. The Spring 2015 team verified that similar results were obtained using the SWaT system. The past years' research found that the SWaT system yielded significantly different results from those obtained using the FReTA system, with lower turbidity values for each coagulant dose value (Jain et al., 2014). Another difference is that Karen Swetland’s experiments made use of granular PACl, while current research uses a purer liquid PACl solution. The research conducted by the Laminar Tube Floc team over Fall 2014 has some significant errors, however. The wrong coagulant pump tubing size was used as an input for the process controller, which might have led to substantial coagulant doses appearing negligible. This would make it appear as though low coagulant doses had very high efficiency.

The second area of research involves exploring if there is an ideal floc size to allow for optimal removal of clay particles in the system. It is known that flocs of too small a size will not settle during the sedimentation process, while flocs of too large a size will not combine with smaller clay particles. Smaller flocs are better suited to filtration, while sedimentation demands flocs of a certain minimum size (EPA, 2002). The team's aim is to conclude if an optimal size exists, and to determine its value if it does exist.

The final area of research is the effects of dissolved organic matter on performance of the system. The presence of dissolved organic matter increases the quantity of coagulant required to achieve the same results of residual turbidity. There are multiple hypotheses for why this is the case. Firstly DOM particles have a higher charge density than clay, thus requiring higher doses of coagulant to be neutralized. They also have have a larger surface area and greater diffusivity than clay, implying that they collide more frequently with PACl than do clay particles. Thus, all the DOM particles need to finish colliding with the coagulant before clay particles start to form flocs. The PACl particles become less polar when DOM particles attach to them, which reduces their ability to make clay particles coagulate. Consequently, the same dose of PACl is less effective at reducing turbidity in the presence of DOM (Weber-Shirk, 2015). The findings from the study of DOM would allow researchers to gain more insight as to how DOM affects the performance of the flocculator, such as through changes in size of flocs created and hence changes in capture velocity.

Methods

Experiment 1: Comparing SWaT and FReTA

Pump Calibration

In order to compare the new SWaT system and the previous FReTA system, it was essential to start by calibrating the various pumps utilized in the apparatus. These included the PACl Pump, the Clay Pump, the Raw Water Pump, and the Tube Settler Pump. Aside from the Raw Water Pump, the designated flow rates were met by each pump and calibrated correctly. The Raw Water Pump would consistently pump at a lower flow rate than the designated 5 mL/s flow rate of the apparatus. The pump head of the Raw Water Pump, which includes the peristaltic mechanism, was discovered to be damaged and would not clamp correctly. This made it difficult for the pump to reach its target flow rate. After replacing the head and successfully calibrating the pump according to RPM, it began to pump at a flow rate of about 6.5 mL/s. At the correct RPM, the Raw Water Pump was overshooting the plant flow rate. Instead of calibrating according to RPM measurements, the slope and intercept readings were manually adjusted in Process Controller under pump calibration in order to reach a proper flow rate of 5 mL/s for the apparatus. The manually adjusted slope and intercept for the Raw Water Pump were 0.84 and 0.01, respectively.

Correction Factor

Once all pumps were running at the correct flow rates, an experiment at a coagulant dosage of 0.05 mg/L as PACl and influent turbidity of 50 NTU was run to replicate an experiment from Fall 2014. This was done in order to obtain correction factors that would allow the team to utilize experiment results from Fall 2014 that were done at incorrect dosages. It was also helpful in testing the flocculator for proper performance. The correction factors were obtained by changing the coagulant tubing size in Process controller to Fall 2014's incorrect value of 0.1 , and by recording the RPM displayed on the pump. Subsequently, the tubing size was changed to a correct measurement of 14 and the displayed RPM was again recorded. For each PACl dosage, the old pump speed was divided by the new pump speed to obtain a correction factor as shown in Table 1 of the Analysis section. The correction factor was then multiplied by the old incorrect dosage to obtain an accurate dosage.

Determining P and I Value

After running the first experiment to test proper performance, the influent turbidity readings were found to fluctuate between 45 and 55 NTU. In order to obtain a consistent influent turbidity input, the Ziegler-Nichols method was implemented (Bennett, 2007). Previously P and I in Process Controller were set to values of 0.260 and 0.500, respectively. To implement the Ziegler-Nichols method, P was initially set to a value of 0.572, while I and D were set to 0. Influent turbidity was then observed for consistent amplitude oscillations, but damping trends were found. This indicated the controller gain K_c was too low. The K_c value was then set to a value of 0.800. At zero I and D, the gain K_c is the value of P. A much more consistent trend was observed, but small inconsistencies in amplitude were found as seen in Figure 1.

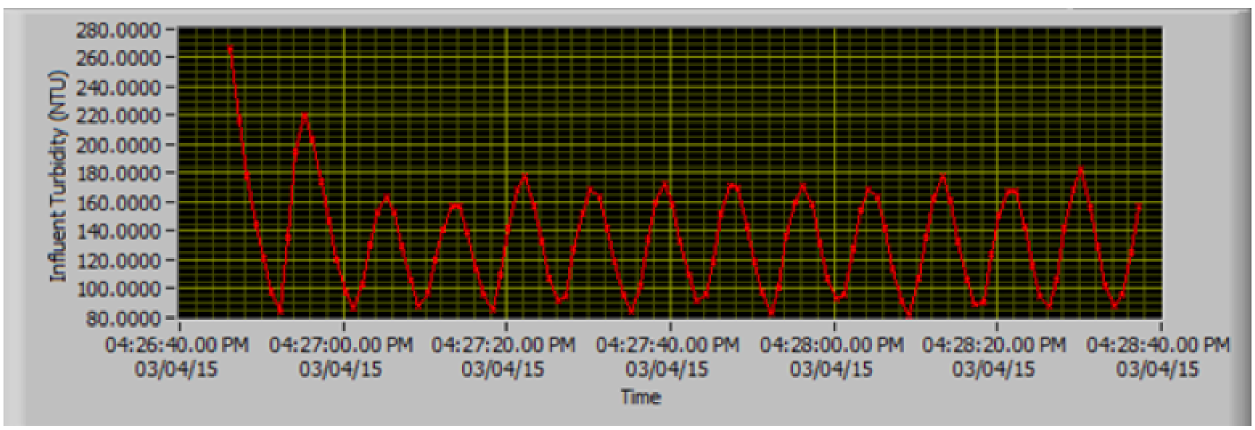

Figure 1 – Influent turbidity test run at a P value of 0.800 with I as 0. Performed on 3/4/2015.

The K_c value was then decreased to a value of 0.750. A more consistent trend in amplitude was observed in this trial as seen in Figure 2.

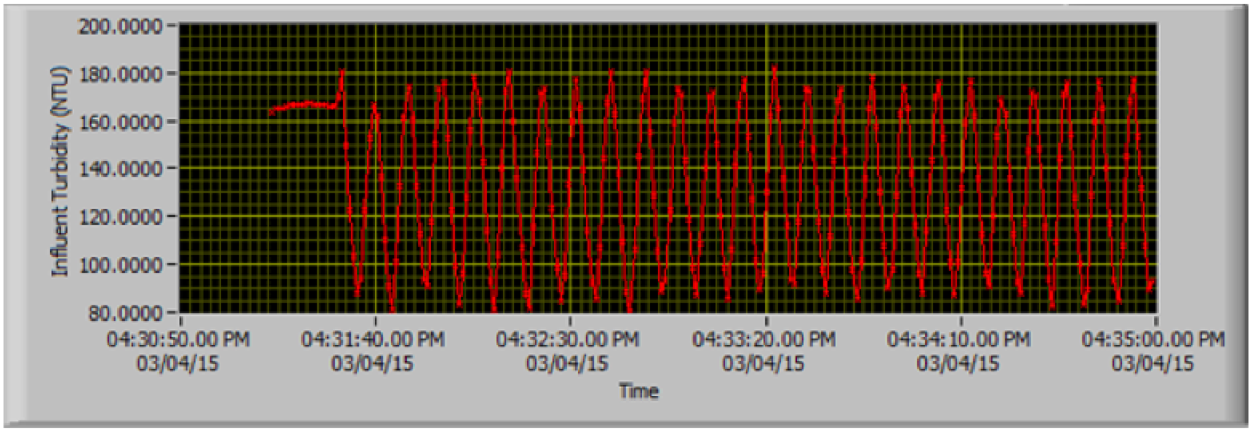

Figure 2 – Influent turbidity test run at a P value of 0.750 with I as 0. Performed on 3/4/2015.

The value of 0.750 was utilized as the value of the ultimate gain K_U, which was then divided by 2.2 to obtain a proper P value as described in the Ziegler-Nichols method. The value of I was obtained by dividing the period of the oscillation at steady state by 1.2.

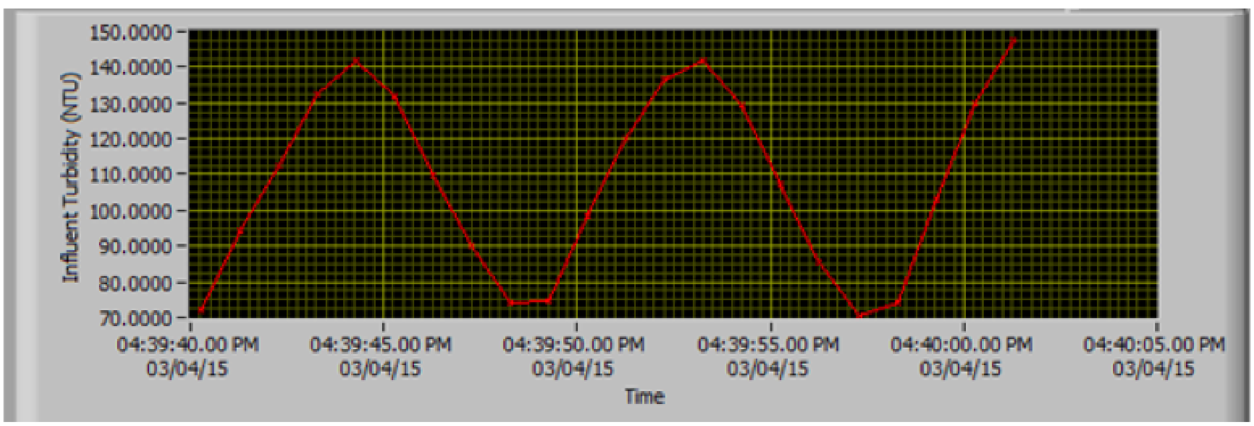

Figure 3 – Influent turbidity readings utilized to determine the period of oscillation in calculating an I value at a P value of 0.750. Performed on 3/4/2015.

As shown in Figure 3, when the system was at steady state, the time required to complete one full oscillation was approximately 8.70 sec or 0.145 min. The value of I is thus 0.145/1.2=0.121 min.

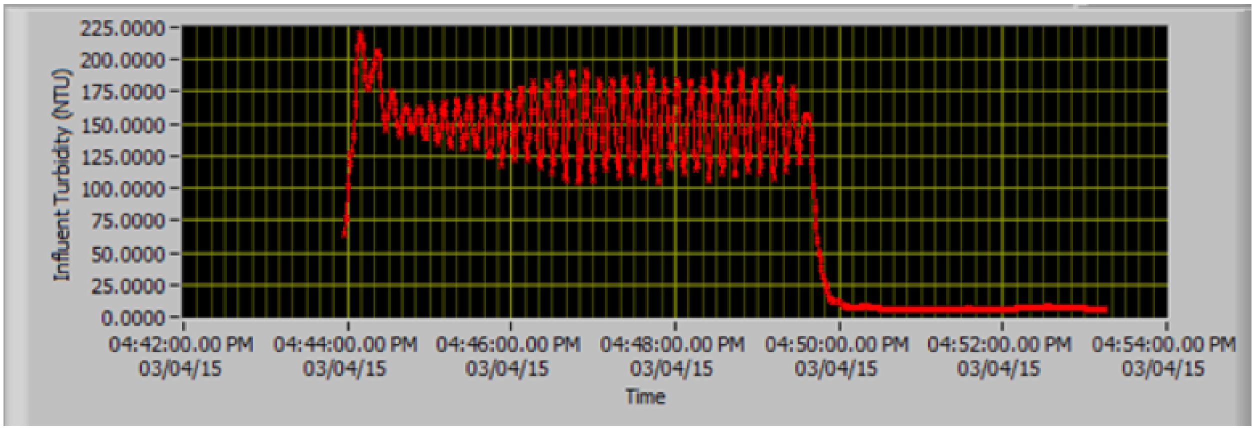

Figure 4 – Influent Turbidity test to observe control system behavior under a P value of 0.75/2.2=0.341 and I value of 0.145/1.2=0.121. Performed on 3/4/2015.

However, Figure 4 displays the results of an experiment that was run to observe the behavior of influent turbidity with the obtained P and I values. The significant variation in influent turbidity indicated that the K_U value was still too high. In the case when the gain is too high, the magnitude of oscillations increase with time and the response becomes unstable (Woolf, 2012).

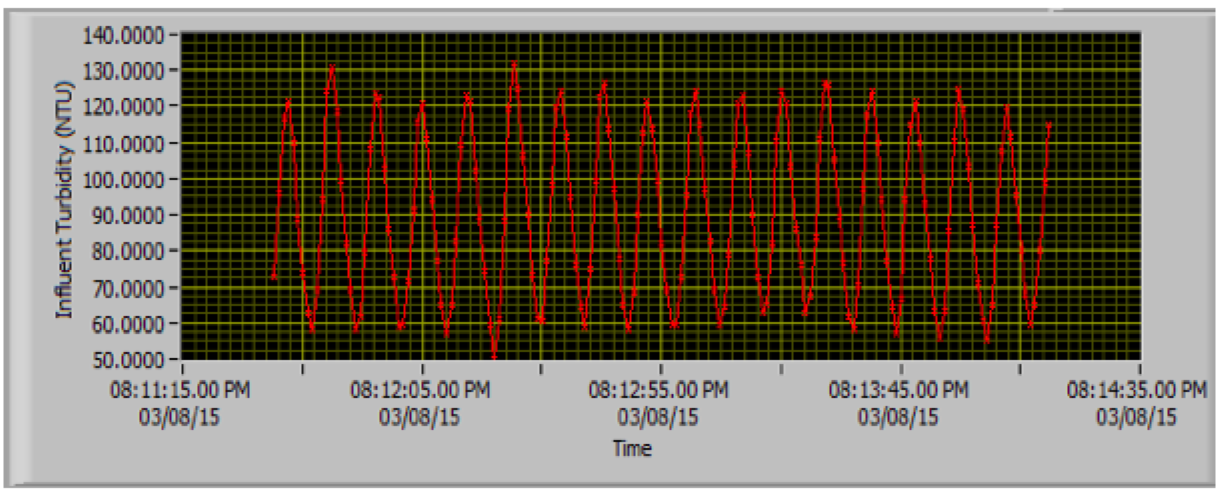

Figure 5 – Influent Turbidity test to observe control system behavior under a P value of 0.500 and I=0. Performed on 3/8/2015.

To control the turbidity, a smaller K_U value at 0.5 was tested. Figure 5 shows a relatively stable response of influent turbidity under the condition that K_U = 0.5 and P=0.5/2.2=0.227, and I =0. The new period of a full oscillation is 10.0 sec, or 0.167 min, and thus I= 0.167/1.2=0.139 min.

PACl concentration and PACl pump tubing size

The PACl concentration of the stock flowing into the set-up was originally prepared to be 60 mg/L as PACl. The PACl flows into the setup through a peristaltic pump, which regulates the flow rate so as to provide desired PACl concentration in the influent.

The following strategies were employed, in chronological order, to ensure steady PACl flow at the desired concentration.

i) The PACl stock bottle's cap was loosened to ensure that pressure stayed constant.
ii) A magnetic stirrer was added so that PACl particles were uniformly distributed through the stock. This was later removed, since it should not actually have much effect on a solution. The addition was made on the assumption that the solution is partly a suspension, which may be true, but not significantly so.
ii) The PACl concentration was increased from 60 mg/L to 500 mg/L based on Professor Monroe Weber-Shirk's suggestion. To complement this, the tubing size in the peristaltic pump was reduced to size 13 (same as the clay pump), to allow for a lower flow rate if necessary. However, it was found that 500 mg/L exceeded the maximum PACl concentration the system could have at the minimal flow rate. Calculations to find the maximum PACl concentration are as follows:

$$\text{Max PACl stock concentration} = Q_{sys} * D_{min} / Q_{min}$$

where Q_{sys} is the flow rate, D_{min} is the minimum dose, and Q_{min} is the minimum flow rate. Given Q_{sys} =5 mL/s, D_{min} =0.04 mg/L Aluminum dose, and Q_{min} =0.18 mL/min, the maximum PACl stock concentration was obtained as 67 mg/L as Aluminum.

It was decided that all concentrations relevant to PACl stock and PACl dose would henceforth be referred to in terms of mg/L as Aluminum, since values in terms of Aluminum are more accurate than in terms of PACl due to varying PACl polymer chain sizes in a solution. Since all concentrations from the beginning of the semester up to this point were referred to in terms of mg/L as PACl, the required conversions had to be made to change PACl stock and PACl dose values in the process controller and in the records.

It was discovered that the AguaClara PACl stock, which was originally thought to be 131 g/L as PACl, was actually 69.4 g/L as Aluminum. In order to obtain the new accurate concentration values in terms of mg/L as Aluminum, the values of PACl concentration obtained before were divided by the ratio (131/69.4).

Troubleshooting the experimental apparatus

Pressure Sensor

The pressure sensor at 200 kPa was plugged into Mod 1, 15. If the pressure in the flocculator was too high (i.e: greater than 101.325 kPA or 1 atmosphere) during backwash, the process controller shut down the pumps due to the sensor being out of range. In such a case, it would be necessary to transfer the pressure sensor plug to Mod 2 to allow for a greater pressure. In order to test if the pressure was too high, all stages of the experiment were set to 2 minutes and a test was run. It was observed that the pumps did not shut down, indicating that the pressure did not exceed 1 atmosphere during backwash.

One hypothesis for the unsteady effluent turbidity values as shown in Figure 10 was that pressure in the system was too high, thus not allowing the peristaltic pumps to draw out fluid at the required rate. It was noted during one meeting with Professor Monroe Weber-Shirk that a pressure exceeding 1 atmosphere (i.e.,101.325 kPa) would cause the pumps to shut down due to a sensor out of range error. The pressure sensor was also in the wrong outlet in the stamp box, which was why the pumps might not have shut down even with an excessively high pressure. After plugging in the pressure sensor to the right outlet and running a 2 min-per phase test trial, the pumps did not shut down, indicating that pressure did not exceed 100 kPa.

Clay Pump

The clay microbore tubing and clay pump tubing (size 13) were replaced earlier in the semester due the possibility of clogging, as well as wear and tear. It was still observed that clay did not seem to be flowing into the flocculator at the desired rate. While consulting Professor Monroe Weber-Shirk, it was found that running the pump backwards at a very high rpm for a short period of time allowed the clay to flow more easily when the pump was running forwards, indicating that there might have been a clog in the stock bucket orifice which was cleared.

Following this incident, the clay flow again seemed obstructed, indicating that there might be a large clay clump returning to the orifice. The clay stock bucket was cleaned and inspected for clogs. A clog was found and removed, following which the flow of clay was no longer obstructed.

Clay Clogging

It was hypothesised that the cause for unsteady influent turbidity was a clog in the clay tubing or the orifice of the clay stock bucket. While observing the influent turbidimeter visually during a test trial it was noted that little there was little or no visible clay in the influent (i.e: very low turbidity). During meeting with Professor Monroe Weber-Shirk, the clay pump was run backwards at a high speed for a short time period. Following this, during a test trial with standard settings, the fluid flowing into the influent turbidimeter contained clay (i.e, higher turbidity, as desired).

This confirmed that clay clogging was at least one of the problems leading to unsteady influent. In order to prevent frequent clogging in the future, the clay stock bucket was taken down and cleaned thoroughly. The clay tubing had been changed relatively recently and was assumed to be free of clogs. The solid clay used for making the stock solution was also changed. Previously, a solid clay used was highly compacted with dense clots that might have persisted despite mixing, and contributed to clogging. A finer, less compacted solid clay source was used from this point onwards. These measures have been effective at preventing clay clogging based on the results obtained from trials.

Raw-water Pump

The peristaltic pump tubing for the raw-water pump had a kink in it due to the difference in elevation between the pump and the turbidimeter, which forced the tube to turn at a very sharp angle. To address this, the pump was elevated by placing it on a large block of foam. The tube connecting the pump and the turbidimeter was also held down and stabilized using adhesive tape.

Disastrous Trial and Checking Serial Port

One trial conducted on April 6th, after meeting with Professor Monroe Weber-Shirk yielded very low influent turbidity values, in the single digits, and exorbitantly high effluent turbidity values (about 8001 NTU). It was found that the raw water pump plug had come loose, meaning that only clay was being pumped in. As a result, there was a huge build-up of clay which settled before even reaching the influent turbidimeter.

After cleaning out the necessary parts of the set-up and running a test trial, the effluent turbidity was still extremely high. Further inspection of the set-up showed that the connection to the back of the computer was loose, meaning that the system was not receiving information from the process controller. A new column was added to the pre-experiment checklist to remind people conducting experiments in the future that this is a possible source of error. The next trial yielded consistent influent and effluent turbidity values of expected magnitudes.

Addition of barbs & replacement of tubing

It was noticed that for several experiments, the first trial yielded a much higher effluent turbidity than the second and third, all other factors including influent turbidity being the same. Also, trials were run with a PACl dosage level of 0 mg/L as Al, which resulted in an average effluent turbidity of 70.75 NTU, which was lower than expected.

The causes of these two problems were believed to be related. It was observed that while the set-up was running the first trial, a significant number of air bubbles were flowing into the tube settler from the lower end. This was stirring up some of the flocs in the tube settler and sending them into the influent turbidimeter while they would have otherwise settled, leading to a higher effluent turbidity in the first trial. By the time the second trial began, most of these air bubbles would have passed through, allowing for lower, more accurate measured effluent turbidity.

Moreover, the presence of air bubbles in the turbidimeter itself would have led to less accurate readings of turbidity values. It was hypothesised that the bubbles were introduced to the system while it was off and not running due to the use of flexible tubing in the design. The seal formed using push-to-connects and flexible tubing was too weak to keep air out of the system, thus allowing the formation of air bubbles inside the tubes.

To improve the airtightness of the system, the flexible tubing leading into the tube settler was replaced with hard tubing to make it more airtight, and two barbs were added to the set-up: one near the influent turbidimeter and one near the effluent turbidimeter. As a result, the system should have become more airtight. These changes were successful at solving the two problems discussed. In the following 0 dosage trial the average effluent turbidity was ~87 NTU, which was closer to expected values. The three trials in each experiment were also consistent with each-other once these changes were made.

Replacement of Peristaltic pump-head

On two occasions (4/20 and 4/23), it was observed that the PACl level in the stock tank had increased from the previous level. This was highly baffling, and also raised the question of whether PACl was flowing into the system at all.

During a meeting with Professor Monroe Weber-Shirk on 4/29, the pressure sensor was placed directly after the PACl pump to observe the pressure in the tubing as the pump was running, starting from 100 rpm and brought rapidly down to 1 rpm. While observing the graph for pressure vs. time, it was noted that there was a periodic drop in pressure. There was good reason to believe that this periodic pressure drop was associated with the time when a particular part of the peristaltic pump rollers came in contact with the tubing. Over time, these periodic drops led to a significant cumulative pressure drop.

It was hypothesised that this pressure drop was causing fluid to flow from the flocculator to the stock tank instead of the other way round as desired. In order to combat this problem, the peristaltic pump-head was removed and replaced with another one, in the hope that the rollers of this pump would make more consistent contact with the tubing (ideally, a 6-roller pump head would have been used instead of a 3-roller pump head, but a 6-roller pump head could not be found). The same test was run once again to observe pressure vs time, and it was noted that periodic pressure drops did occur, but the pressure eventually started to stay near-constant at around 200 kPa as shown in Figure 6.

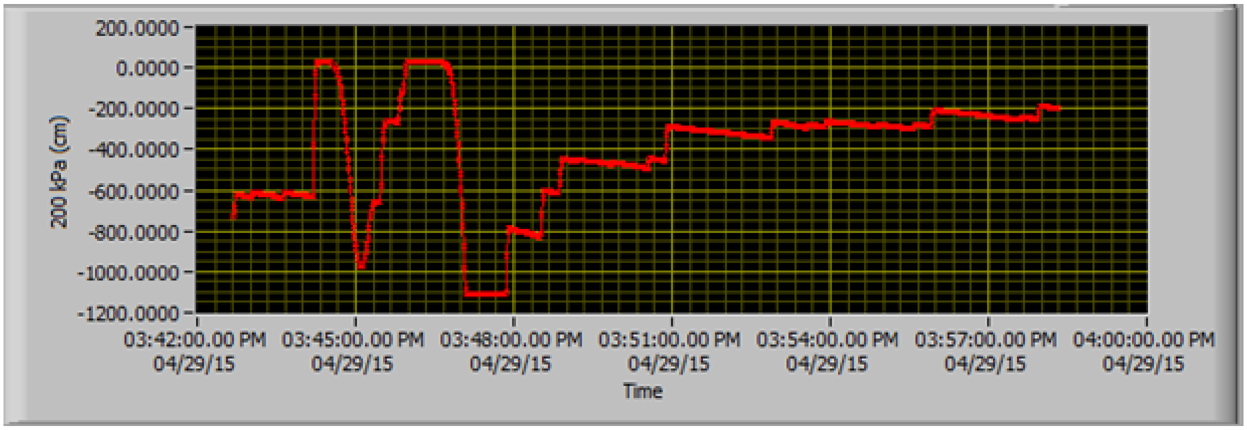

Figure 6-- Negative Pressure vs. Time while running PACl pump with new peristaltic pump-head (only partial graph: pressure stayed constant at 200 kPa for a much longer period than displayed)

After implementing this change and running a trial with new PACl solution, the level did drop by the expected level, indicating that the change of pump-head was helpful and successful.

Verifying Correct Dosages

In order to verify that the Aluminum dosages being applied were correct, the level of PACl in the stock tank was recorded at the start of the SWaT state on the bottle. A smaller bottle was also utilized for more accurate measurements. After the SWaT state, the new level of PACl in the bottle was recorded. The circumference of the bottle was measured as well as the drop in PACl level, which yielded a volume of PACl that was utilized by the apparatus during a SWaT duration of 3000 seconds. This method does not take into account the thickness of the walls of the PACl stock tank. In order to compare this actual value to a theorized value, the flow rate of PACl into the system was calculated using the following equation

$$Q_1 c_1 = Q_2 c_2$$

Q_1 = plant flow rate
c_1 = concentration of PACl in plant
Q_2 =PACl flow rate
c_2 = concentration of PACl stock tank

The calculated PACl flow rate into the system from the stock tank was then multiplied by the SWaT duration in order to find the theorized amount of PACl used in one SWaT duration. The actual value of PACl utilized in the system found from measuring the drop in PACl level yielded approximately 122 mL, while the theorized value calculated from flow rates yielded a value of about 140 mL. There is a small discrepancy between these values; however, it is not significant enough to cause large changes to the results.

Plotting in MathCAD

The coagulant used in Spring 2015 was liquid PACl whereas granular PACl was used in Swetland's research on FReTA. It was assumed that the diameter of liquid PACl particles was 20 nm. The performance graphs were plotted using Karen Swetland's flocculation model MathCAD files.

Analysis

Correction Factor

According to Fall 2014 research, the coagulant tubing size in the pump control method file was smaller than the actual size used. With a small tubing size, the process controller gave a higher flow rate and a higher coagulant dose. Therefore, the actual dose delivered was higher than the dosage reading from the process controller. The actual Aluminum dosages are shown in Table 1.

Table 1. Correction factors for different Aluminum dosages

Aluminum Dose (mg/L)	**0.01**	**0.03**	**0.05**	**0.1**
Old Pump Speed (RPM)	2.3	3	4.17	8.33
New Pump Speed (RPM)	2.3	2.3	2.3	2.9
Correction Factor	1	1.3	1.81	2.87
Actual Aluminum dose (mg/L)	0.01	0.039	0.091	0.287

Determining P and I Value

Based on the Ziegler-Nichols method, P value was set at 0.227 and I at 0.121 min. Figure 7 shows a relatively stable influent turbidity level under the P and I value. Figure 8 shows a stable influent turbidity level with variation within 10% of the targeted 150 NTU and thus confirms the P and I value used in the experiment. In Figure 9, it is clear that over the course of four trials, influent turbidity consistently hovered around the target value with its greatest fluctuations being slightly over 5 NTU.

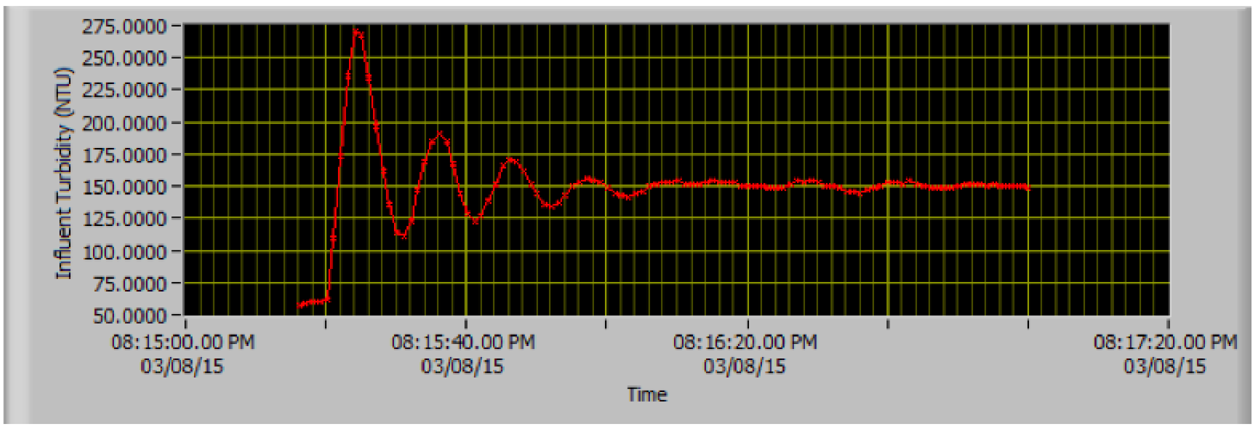

Figure 7 – Influent Turbidity test to observe control system behavior under a P value of 0.500/2.2=0.227 and I value of 0.167/1.2= 0.139. Performed on 3/8/2015.

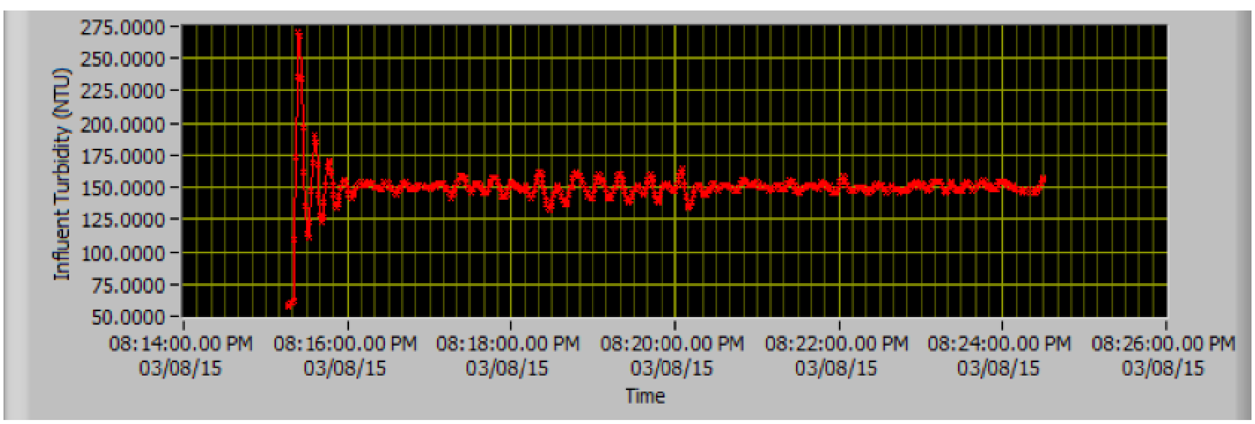

Figure 8 – Observed constant level of influent turbidity with small variation (less than 10% of the targeted 150 NTU) with P=0.227 and I=0.139. Performed on 3/8/2015.

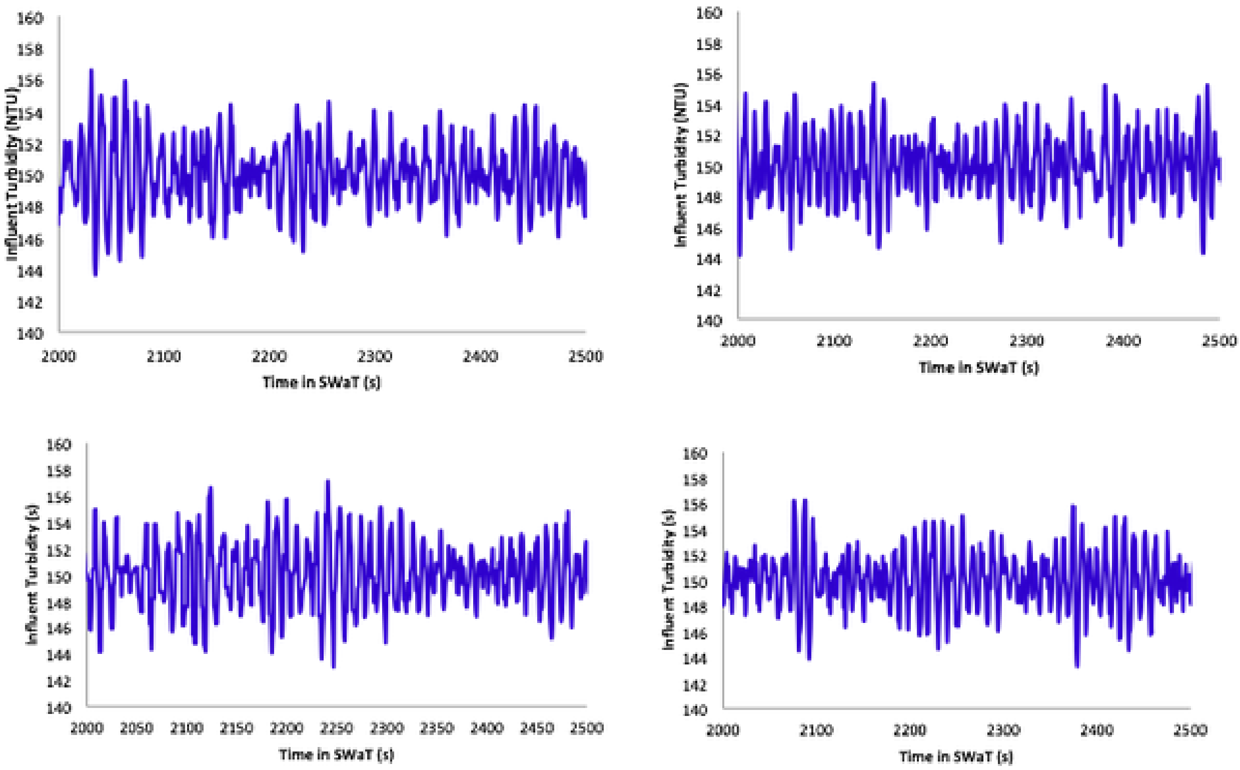

Figure 9 – Influent turbidity vs time for four trials in the SWAT state with a target value of 150 NTU. Performed on 3/2/2015.

Loading Time

Figure 10 shows that the effluent turbidity values steadily declined over the first 1000 seconds in the SWaT phase. One of the possible reasons was that the loading time was not long enough to reach a steady effluent turbidity value. In order to address this, both the loading time and SWaT time were increased from 2400s to 3000s. With the increased loading time, no initial drop in effluent turbidity levels was observed in subsequent trials.

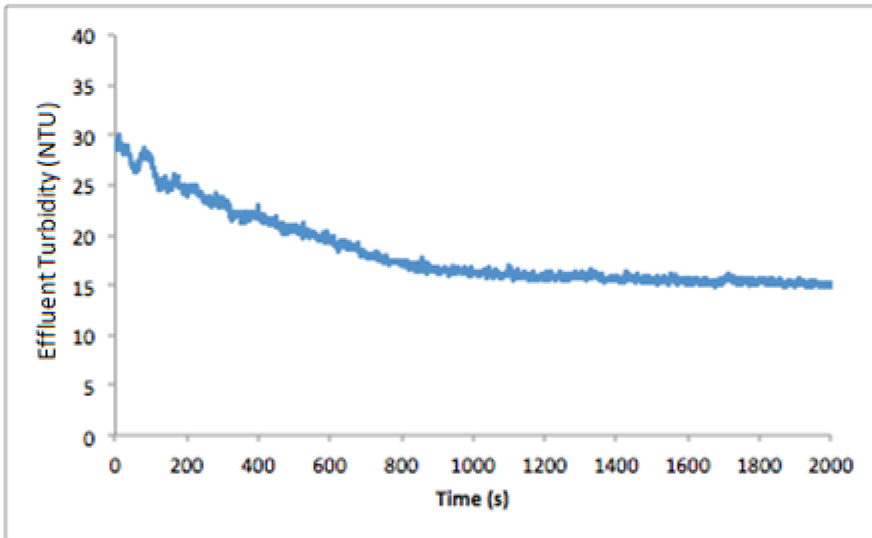

Figure 10 – Effluent turbidity vs time for trial conducted with a loading and SWaT duration of 2400s.

Trials with Inconsistent Effluent Turbidity

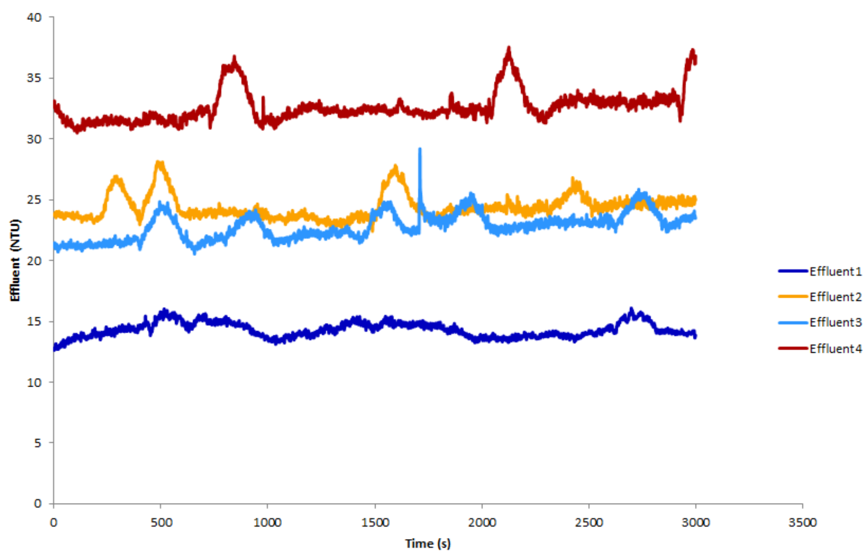

Figure 11 - Corresponding Effluent Turbidity values for trials 1-4 for consistent influent turbidity values.

In Figure 9 above, influent turbidities are observed to remain quite stable around the target value of 150 NTU and do not fluctuate to near 10 percent of the target influent turbidity. The largest fluctuations that can be seen in these time intervals is slightly more than 5 NTU around the target of 150 NTU. However, although influent turbidity values remained stable with small fluctuations throughout all four trials, effluent turbidity did not exhibit the same consistency. As seen in Figure 11, effluent turbidity values of trial one hovered around 14

NTU while that of trial four fluctuated at around 32 NTU. This was a difference of nearly 20 NTU. Trials two and three hovered around 20 to 25 NTU. Overall, a decrease in performance can be seen from trials one to four with a significant difference in effluent turbidity.

In order to resolve the issue of decreasing performance and effluent turbidity inconsistency, all parts of the apparatus were examined for any faults. The PACl stock tank was found to have its lid screwed on too tight. While Aluminum dosage is being drawn down into the apparatus from the stock tank, a vacuum might form in the air space above the liquid because of a tight lid. This would make it increasingly difficult for the pump to deliver an accurate coagulant dosage to the system, which would decrease the performance of the apparatus. Also, it was possible that there might have been Aluminum coagulant precipitating at the bottom of the stock tank, which would further decrease the performance of the apparatus by decreasing the concentration of Aluminum in the stock tank. In order to resolve these issues, the lid was unscrewed so that it fit loosely on the tank and a stirrer was added for the PACl stock tank. This was later found to be unnecessary because PACl is a solution and thus there was no settling of particles.

Trials with PACl Stirrer and Loose Cap

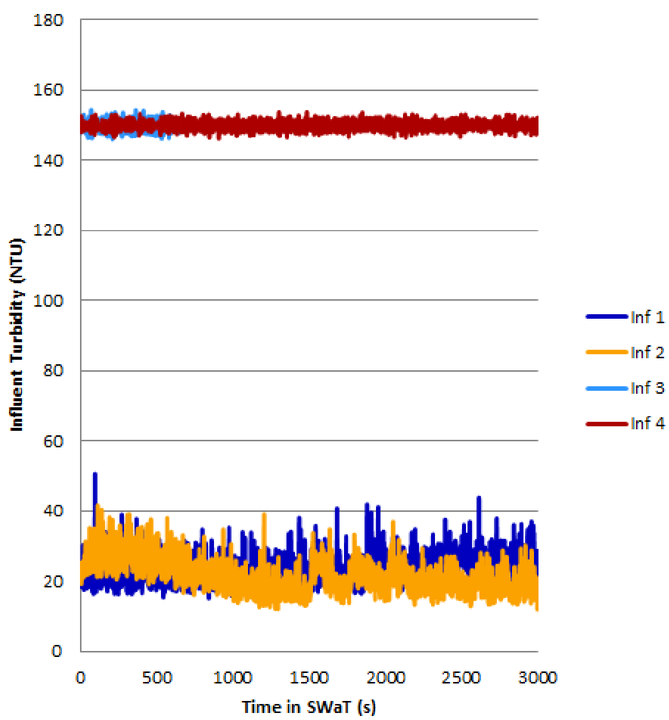

Figure 12 - Influent turbidity values for four trials with a PACl stirrer installed and a loose cap on the PACl stock tank. Performed on 3/10/2015.

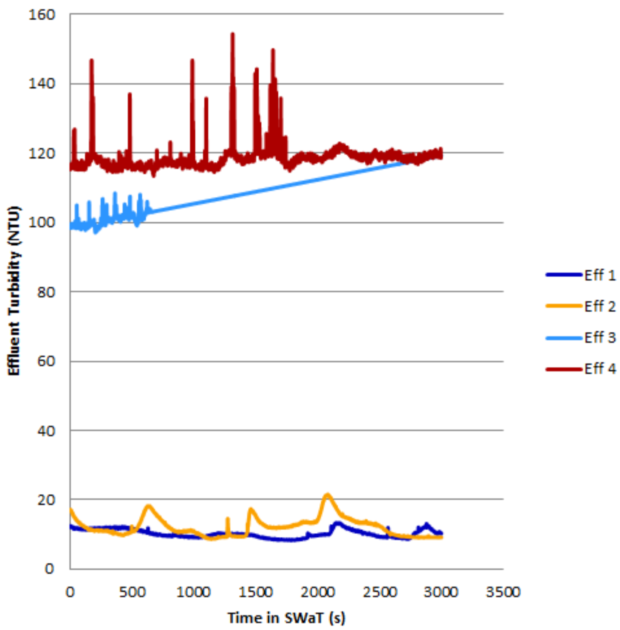

Figure 13 - Corresponding effluent turbidity values for four trials with a PACl stirrer installed and a loose cap on the PACl stock tank. Performed on 3/10/2015.

After adding a PACl stock tank stirrer and loosening the stock tank lid, another set of four trials were run and the influent and effluent turbidities are shown in Figures 12 and 13, respectively. Influent turbidity values for trials one and two were very low, fluctuating wildly between about 20 and 40 NTU. This was very far from the set target influent turbidity of 150 NTU. However, by the third and fourth trial, this issue resolved itself and influent turbidity rose to the target turbidity value of 150 NTU with very small fluctuations. The reason why trials one and two behaved this way is still uncertain. It is possible that there was clay clogging the inside of the nozzle of the clay bucket that leads into the tubing since the team had recently replaced the tubing.

In all four trials, although they were done at two different influent turbidities, they yielded similar performances. Trials one and two had influent turbidites at around 25 to 30 NTU and effluent turbidities of about 10 to 15 NTU. Trials three and four had consistent influent turbidities at the target of 150 NTU and effluent turbidities ranging between 100 and 120 NTU with large spikes in trial four. Effluent turbidities in all four trials are high relative to their respective influent turbidity for a system with a coagulant dosage. These effluent turbidities are similar in value relative to influent turbidities to trials done without coagulant that relied solely on clay settling. Because of consistently poor performance across all four trials, it appeared that the PACl might not have been injected into the system properly.

In this set of trials, two apparatus configuration issues were tested, which were the loose PACl stock tank lid as well as the PACl stirrer. In order to limit changes to one variable to determine which might have influenced performance, the PACl stirrer was removed. Also, in the Fall 2014 semester, no PACl stirrer was utilized and constant effluent turbidity values were still able to be obtained. It is unlikely but possible that the stirrer created a current inside the stock tank that made it more difficult for the PACl pump to draw out coagulant properly. It was later found that there was a certain orientation in the peristaltic pump head's rotation that allowed for depressurization of the system. This inefficiency may also be related to the poor application of PACl into the apparatus (see 'Troubleshooting the Apparatus').

Trials without PACl Stirrer

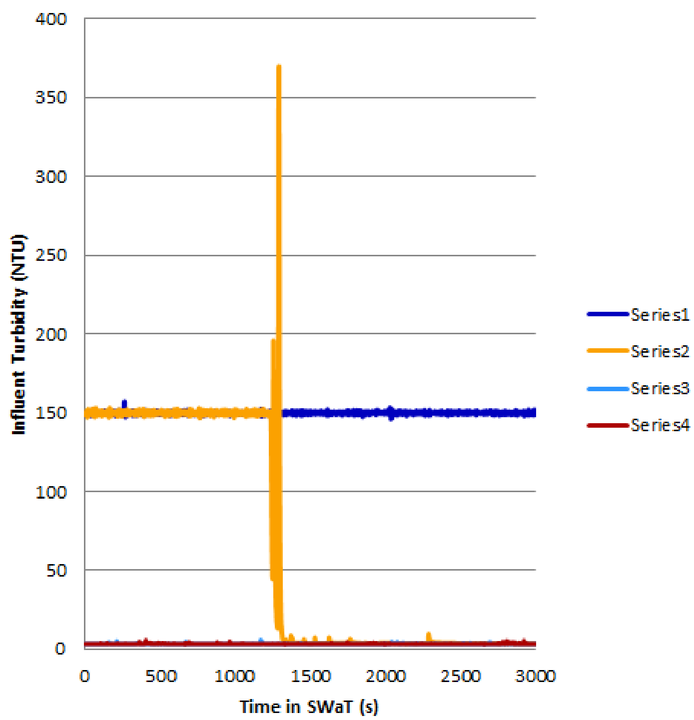

Figure 14 - Influent turbidity for four trials with no PACl stirrer in place. Performed on 3/17/2015.

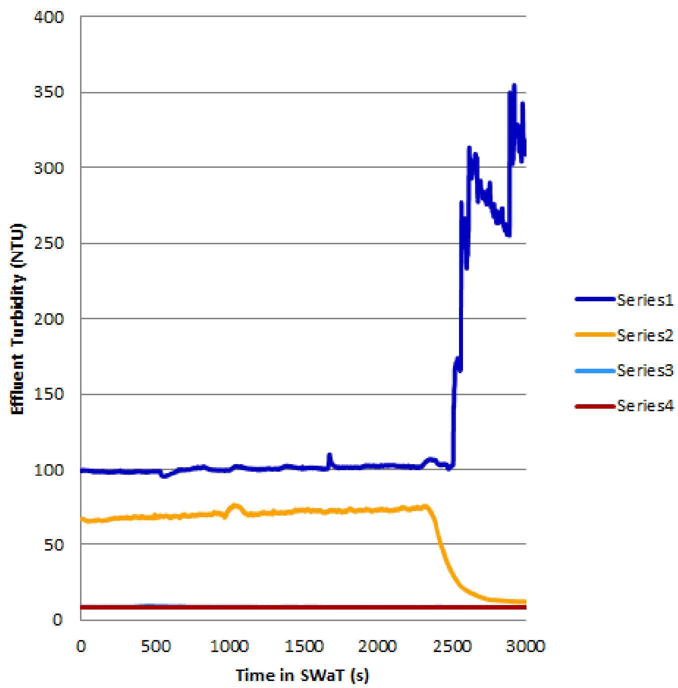

Figure 15 - Corresponding effluent turbidity for four trials with no PACl stirrer in place. Performed on 3/17/2015.

Figures 14 and 15 of influent and effluent turbidity were obtained upon removing the PACl stirrer to observe whether performance would increase. In Figure 14, influent turbidity of the first trial appeared to be steady at the target 150 NTU; however, in trial 2 at about 1300 seconds into SWaT, the influent turbidity spiked to over 350 NTU and then plummeted to nearly 0 NTU. Trials three and four remained at this very low influent turbidity. In Figure 15 of effluent turbidity, trial one had a relatively constant effluent turbidity of about 100 NTU until around 2500 seconds into SWaT when this value skyrocketed to about 350 NTU at its peak. In trial two, effluent turbidity appeared to decrease to about 70 NTU, exhibiting an increase in performance with a sudden decrease at about 2400 seconds into SWaT state, which corresponded to the influent turbidity value plummeting. Trials three and four remained at a very low effluent turbidity, which corresponded to the low influent turbidity.

Many of the issues were of uncertain origin, such as the large spike in influent turbidity in trial two and effluent turbidity in trial 1. The influent turbidity plummet in trial two was most likely caused by a clog in the clay delivery system, possibly at the nozzle of the clay bucket. Although in trial two, effluent turbidity did decrease compared to that of trial one, it still remained at about 70 NTU. This effluent turbidity was higher than expected for a trial with coagulant present. Effluent turbidity in trial one remained high at a value of about 100 NTU, which could solely be attained by clay settling in the apparatus. Even though it appeared that Aluminum was not being injected properly into the system, Aluminum dosage drawdown in the stock tank was observed.

It is possible that the pressure in the system was too high during these trials and that the PACl pump was unable to act effectively against this high pressure, lowering the actual coagulant dosage delivered. However, upon carefully examining the pressure sensor, it was found that Process Controller was attempting to obtain data on pressure from an incorrect outlet on the wall behind the apparatus. This problem was resolved so that the correct pressure data would be recorded and signs of high pressure might be observable. The system was run for two minutes in the loading state to see whether the pumps would shut down as a result of pressure exceeding 101.3 kPA (one atmosphere), which was the limit for the Mod 1 outlet. The pumps ran properly, suggesting that very high pressure did not exist in the apparatus. Nevertheless, pressure should be carefully monitored in subsequent trials. Also, precipitates of PACl inside the coagulant stock tank indicated that the stock concentration was much too low. The initial PACl stock concentration of 60 mg/L was changed to 500 mg/L. Additionally, the tubing in the PACl pump was changed from a size of 14 to 13 to obtain more accurate dosages. The Raw Water Pump was raised up by a foam block in order to smooth out a kink in the piping that might help create anomalous pressure gradients. Also, to temporarily resolve the issue of clogging in the clay system, the clay pump was manually run in the reverse direction. After making these new changes, the team proceeded with the next set of trials.

Results before improving airtightness

Trials with a dose of 0 mg/L Aluminum - Baseline

Baseline trials were conducted without coagulant at an influent turbidity level of 150 NTU. The average effluent turbidity across all four trials was about 70.75 NTU as shown in Figure 16.

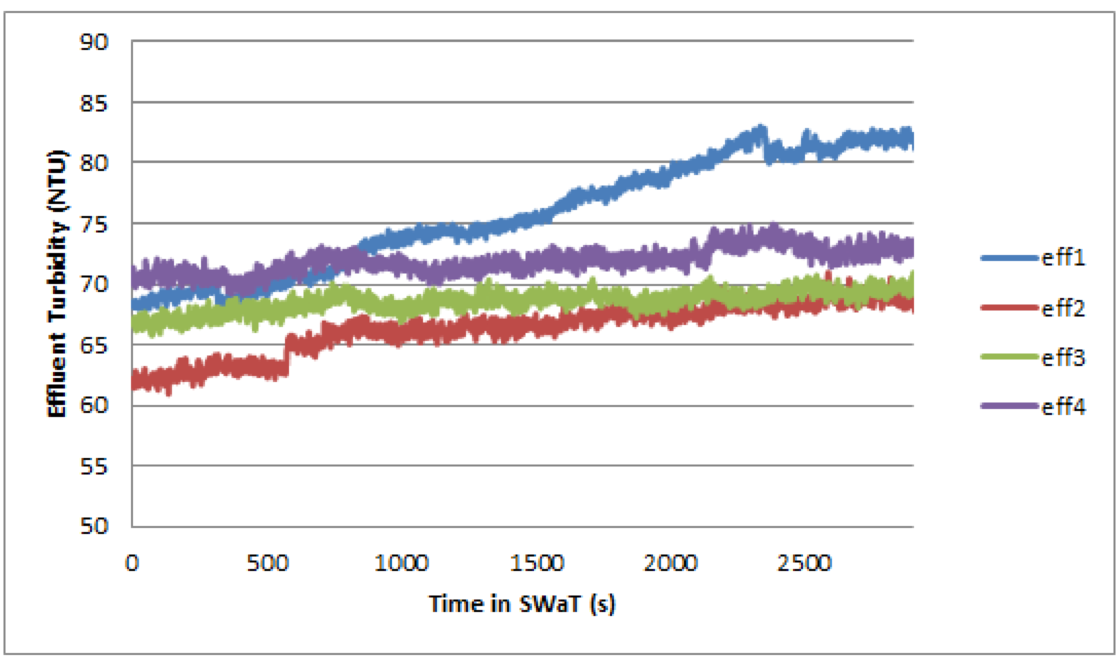

Figure 16 - Effluent turbidity measurements for an Aluminum dosage of 0 mg/L. Performed on 4/15/15.

Although there was an average of about 70.75 NTU across all four trials, within trials 1 and 2 individually, an obvious increase in effluent turbidity throughout time in SWaT was present. Trials 3 and 4 appeared to be much more consistent, only ranging about 5 NTU for each case. In the first two trials, it could be that the system was still equilibrating to the new input and was creating unsteady effluent turbidities. It is possible that latent bubbles that existed in the system before any trials are run were circulating through the system in trials 1 and 2, stirring up flocs on the bubbles' way up through the tube settler. These bubbles might have originated in the fittings and connections in the soft tubing. To combat this issue, barbed fittings near the tube settler "T" connection as well as near the influent turbidimeter were implemented to create a more airtight fit. Also, soft tubing was replaced with hard tubing near the tube settler. These latent air bubbles were a possible reason why trial 1's average effluent turbidity appeared higher than any other trial. Also, overall it appears that the values of effluent turbidity were quite high for performance relying solely on clay settling within the system. In previous trials it was observed that for an 150 NTU influent turbidity, an effluent turbidity of 120 NTU with a 0.1 mg/L aluminum dosage was obtained. Even if there were no aluminum dosage in those trials, the effluent turbidity results were much higher than those observed here. It is possible that there was some PACl still left in the system or alongside the walls that was helping to coagulate clay, but to what extent is unknown.

Trials with Aluminum dosage of 0.05 mg/L

The trial conducted on April 8th with a coagulant dose of 0.05 mg/L yielded consistent influent and effluent turbidity values for the first time this semester. The consistency of the influent values was believed to be in part due to a thorough cleaning of the clay stock tank and use of less compacted clay. The consistent effluent was most likely due to the new PACl stock concentration value, which allowed the PACl pump to run at a high enough rpm to actually inject coagulant at the lowest dosage (as described in the 'Troubleshooting the Apparatus' and 'PACl concentration and PACl pump tubing size' sections).

The influent turbidity was between 148 and 152 NTU as desired. Effluent turbidity had minor fluctuations, but was generally around 64 NTU. Compared with the next two trials, these effluent values seemed unusually high, but it was possible that in between the PACl dosages of this trial (0.05 mg/L) and the trial at 0.08 mg/L aluminum dosage was a dosage value at which the coagulant starts increasing in effectiveness. The average effluent turbidity of the three trials was 62.66 NTU.

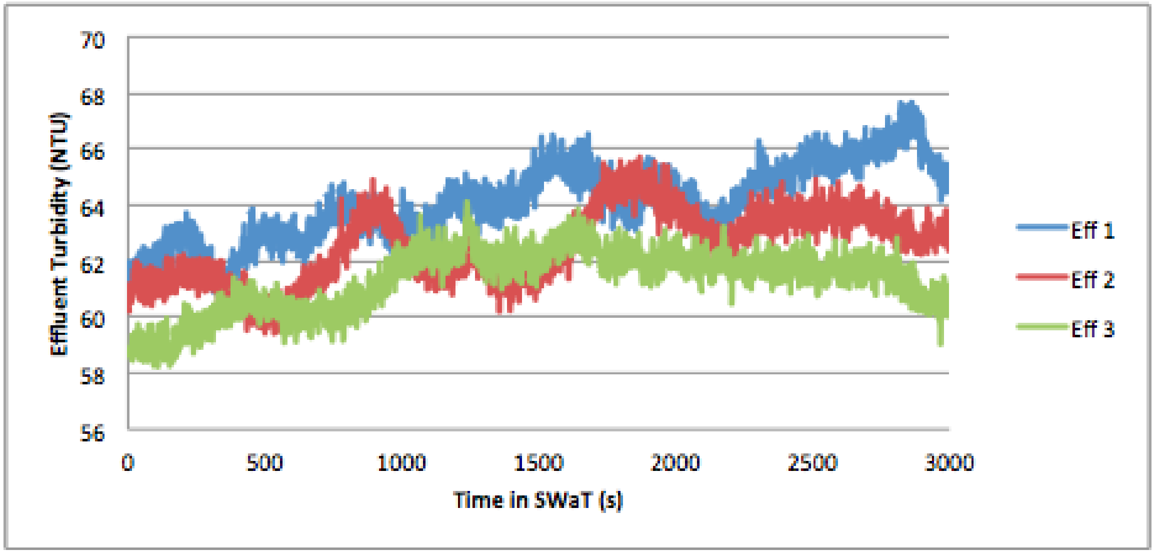

Figure 17 - Effluent turbidity measurements for the 0.05 mg/L Aluminum dosage. Performed on 4/8/15.

Trials with Aluminum dosage of 0.08 mg/L and 0.10 mg/L

The effluent turbidity levels from three trials with a 0.08 mg/L aluminum dosage are shown in Figure 18. The effluent turbidity level was particularly higher in the first trial than in the second and third trials. It was possible that the high effluent turbidity in the first trial was due to the air trapped in the SWaT system. Air trapped in the system would make it easier for flocs to be brought up the tube settler and into the effluent turbidimeter. The average effluent turbidity was 15.13 NTU based on results from the second and third trials.

When the 0.08 mg/L and 0.10 mg/L Aluminum dosage trials were compared, there were many similarities. These included the high effluent turbidity of the first trial as well as the consistent low turbidities of the second and third trials. The hypothesis concerning air bubble circulation in the apparatus applied to the first trial of this set of experiments as well. Disregarding the first trial's results, that of the second and third trial were quite consistent relative to each other as well as throughout each trial. The readings were also approximately as expected. There was a slight increase in dosage from the 0.08 mg/L trials to the 0.10 mg/L aluminum dosage trials and a corresponding slight increase in performance was observed. The average effluent turbidity readings in trials 2 and 3 for the 0.08 mg/L dosage case was 15.13 NTU while that of the 0.10 mg/L case was 9.24 NTU.

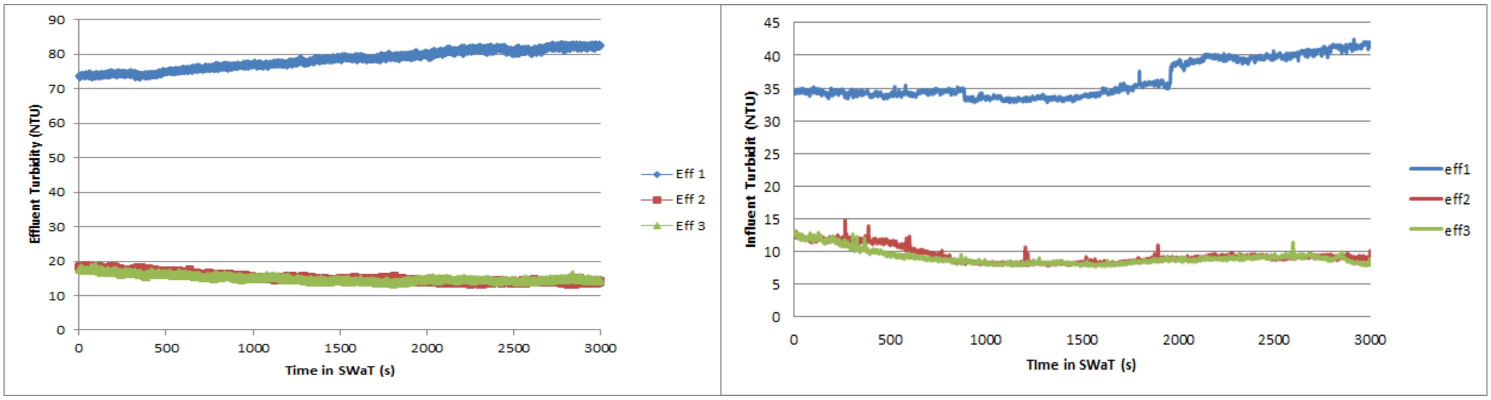

Figure 18 - Effluent turbidity measurements for the 0.08 mg/L (left) and 0.10 mg/L (right) Aluminum dosage. Performed on 4/9/15 and 4/13/15, respectively.

Results after changes were made to the apparatus

The following data were obtained after modifications were made to various parts of the apparatus. These changes included the addition of barbed connectors, the replacement of the peristaltic pump head for the PACl pump, and the replacement of soft for hard tubing.

New Trials with a dose of 0 mg/L Aluminum - Baseline

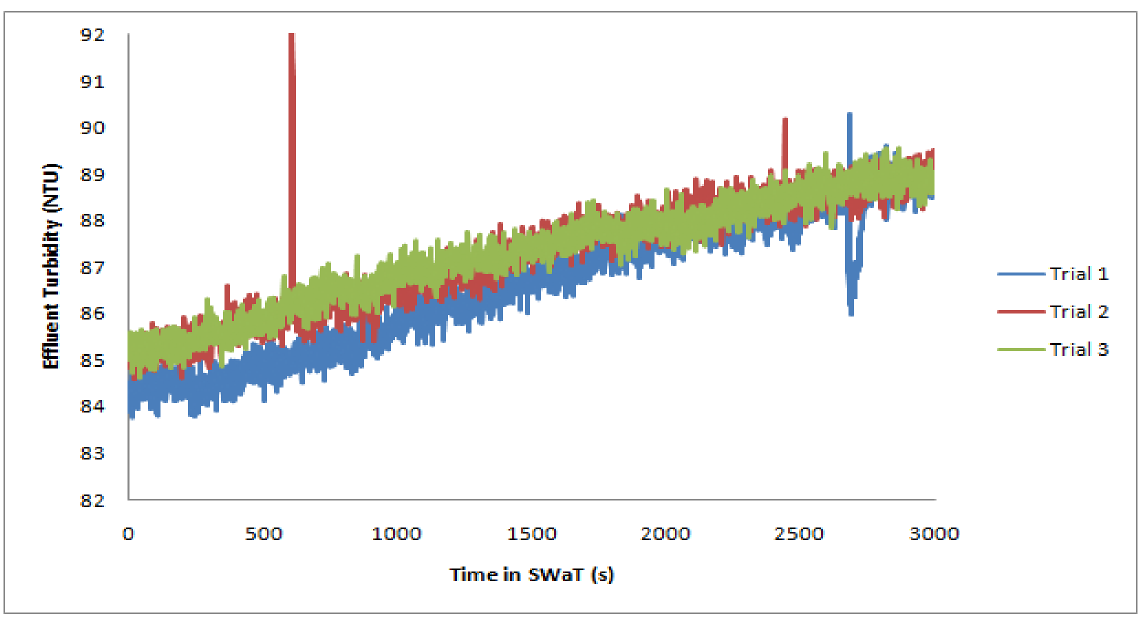

Figure 19 - Effluent turbidity measurements for an Aluminum dosage of 0 mg/L. Performed on 4/27/15.

After changes were made to the apparatus including the hard tubing as well as the barbed connections, the 0 mg/L Aluminum dosage trial was run again. The results are displayed in Figure 19. As can be observed, the values of effluent turbidity over all three trials ranged from about 84.5 NTU to approximately 89 NTU. All trials exhibited the same increasing trend as well. The average effluent turbidity value for the 0 mg/L case over all three trials was 87.05 NTU, which was significantly higher than the effluent turbidity of 70.75 NTU of the baseline done before modifications. It is possible that settling of clay became inefficient as more clay settled throughout the system leading to a decrease in performance as the SWaT state progressed. Also, it is possible that the system was not able to settle to a steady value in time; however, with a total loading and SWaT duration of 6000 seconds, this seems unlikely.

General Case for New Trials

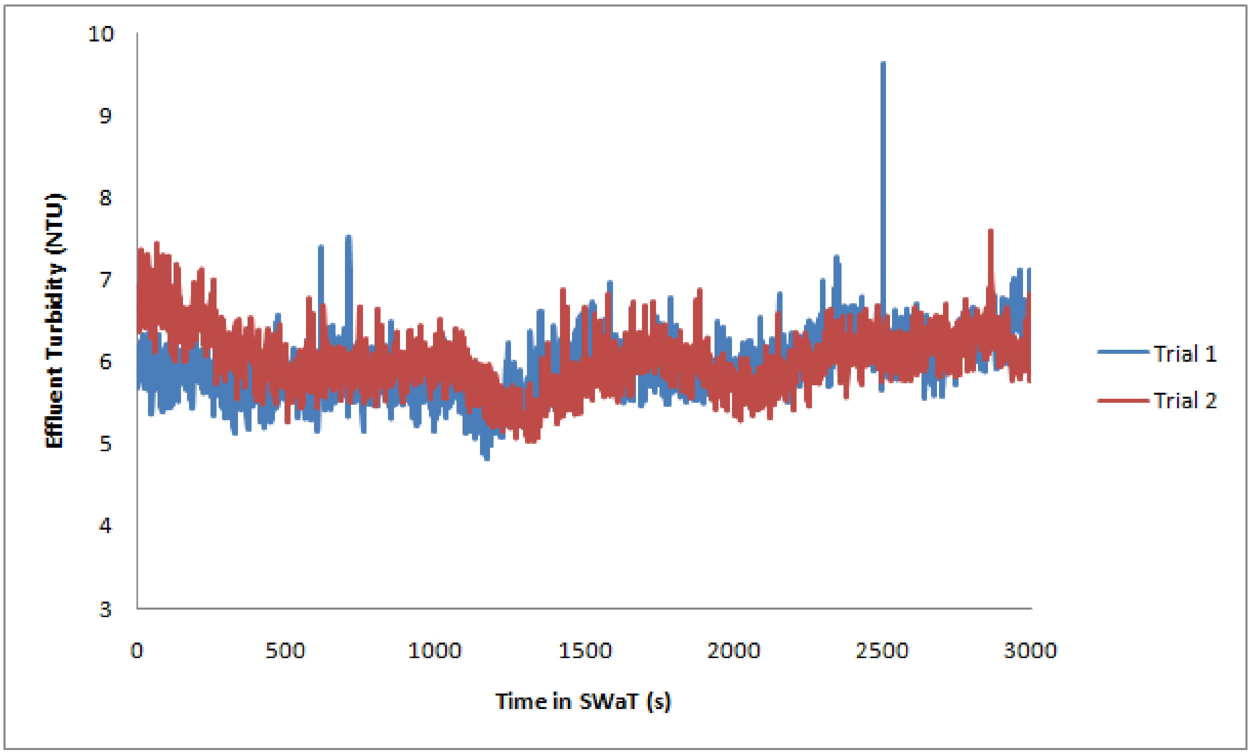

Figure 20 - Effluent turbidity measurements for an Aluminum dosage of 0.3 mg/L. Performed on 5/5/15. These trials represent the general trends of the experiments performed at various dosages after modifications were made to the apparatus. The trials were run at dosages between 0.1 and 0.7 mg/L at increments of 0.1 mg/L of Aluminum.

Figure 20 is representative of the trials done after modifications took place. Key characteristics included the elimination of an abnormally high effluent turbidity in the first trial of an experiment. Also, all trials displayed similar numerical values and steady trends. These trials were done at Aluminum dosage increments of 0.1 mg/L between 0.1 and 0.7 mg/L.

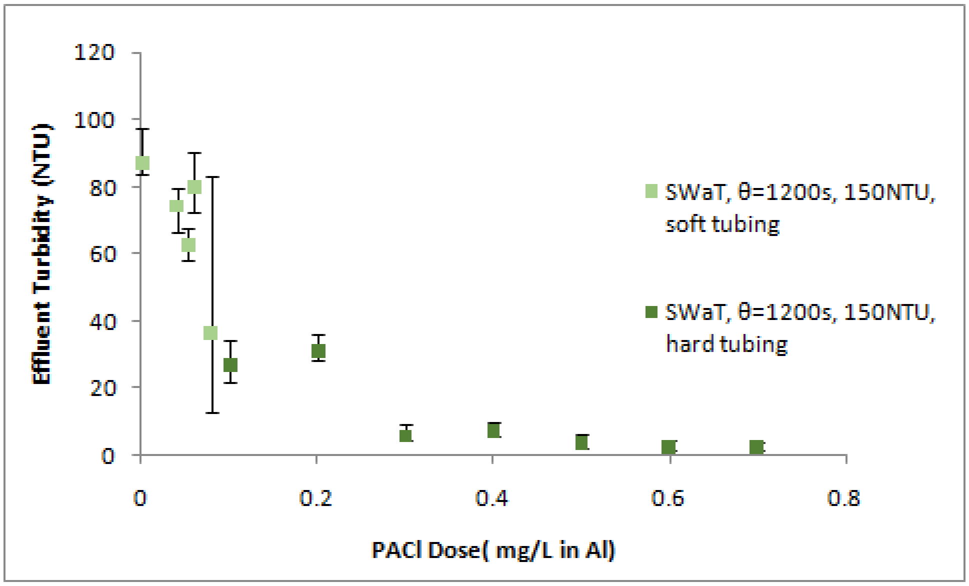

Figure 21- Effluent turbidity versus PACl Dose for SWaT systems at residence time of 1200 s and influent turbidity at 150 NTU. The first four data points in light green were obtained by using soft tubing, and data point in dark green were considered to be reliable by using hard tubing which improved the airtightness of the SWaT system. After changing soft tubing to hard tubing, the variance in effluent turbidity decreased.

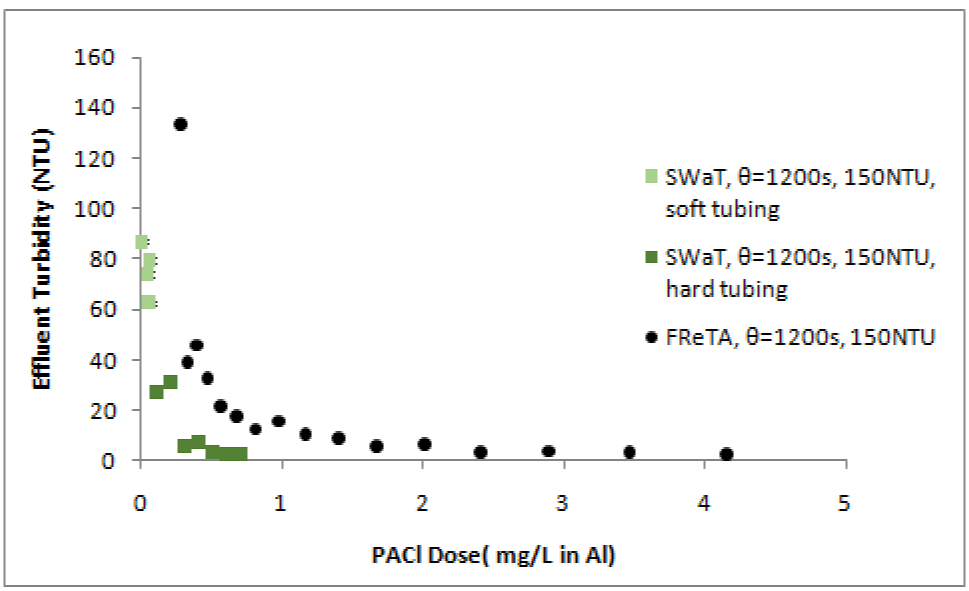

Figure 22- Effluent turbidity versus PACl Dose for FReTA and SWaT systems at residence time of 1200 s and influent turbidity at 150 NTU. The first four data points in light green were obtained by using soft tubing, and data point in dark green were considered by reliable by using hard tubing which improved the air tightness of the SWaT system.

Effluent turbidity decreased as PACl dose increased for both the FReTA and SWaT systems. As noted in Figure 21 and 22, at the same PACl dose, effluent tubidities were significantly lower in SWaT than in FReTA for all the dosages used from 0 to 0.7 mg/L in Al. It was also noted that as PACl dose became larger than 0.6, the decrease in effluent turbidity became smaller. The minimum effluent turbidity that SWaT system could achieve was approximately 2.6 NTU.

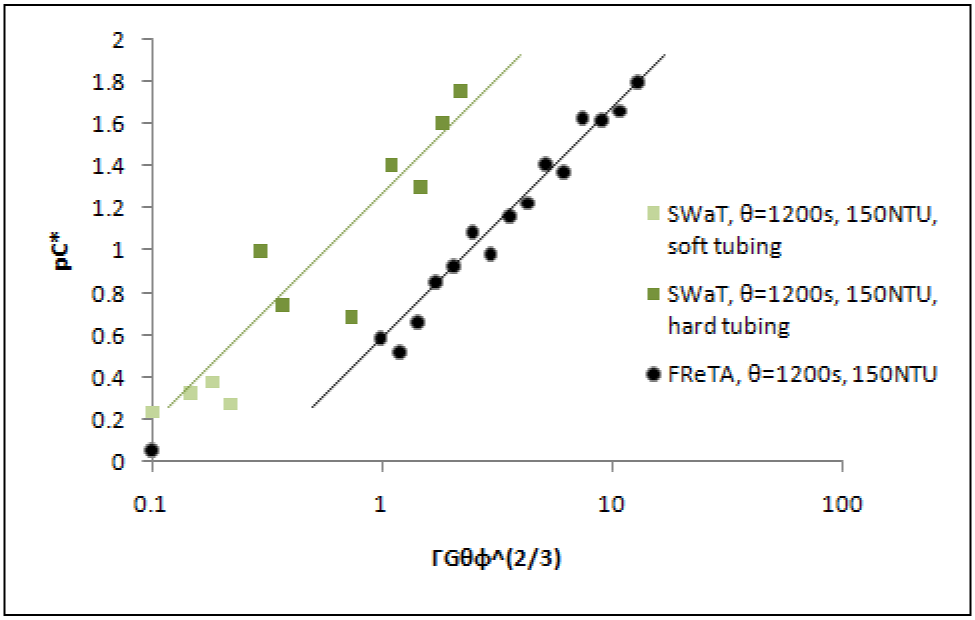

Figure 23 - SWaT performance plot in comparison with FReTA performance at residence time of 1200 s and influent turbidity at 150NTU. The first four data points in light green were obtained by using soft tubing, and data point in dark green were considered by reliable by using hard tubing which improved the air tightness of the SWaT system.

As shown in Figure 23, to achieve the same performance of the laminar flocculator, less PACl dosage was needed in the SWaT system than in the FReTA system. Figure 23 confirmed a linear relationship between pC* and the log of the effective collision potential ($\log(\Gamma G\,\theta\phi^{(2/3)})$) for SWaT system.

Conclusions

It is very important to the success of any experiments that the experimental set-up and the process controller work properly. The experimental system showed multiple unexpected problems ranging from clogged tubes to inconsistent influent and effluent turbidity levels. The 2015 research team finished troubleshooting the system and addressed all the system errors that presented themselves before conducting experiments.

Because the Fall 2014 team ran trials at an unknown coagulant dosage due to an incorrect PACl tubing size, the Spring 2015 team obtained correction factors in order to resolve this issue. These were found by taking the old pump speed with the incorrect tubing parameter and dividing it by the new pump speed using the correct tubing parameter. This correction factor was then multiplied with the inaccurate old dosage. These values along with the corrected dosages are displayed in Table 1. However this data from Fall 2014 was based on an influent turbidity of 50 NTU. Also, the data was obtained before the improvements in the experimental apparatus were made so it was questionable whether the results were accurate.

The Spring 2015 team was also able to obtain a steady and consistent influent turbidity with fluctuations of less than 10 percent around the target value of 150 NTU utilizing the Ziegler-Nichols method of calculating P and I in PID. When the system was run, trials indicated that there was not enough time for effluent turbidities to settle out to a steady value before the beginning of the SWaT state. The loading time and SWaT duration were increased to 3000 s from 2400 s.

Initially, trials with steady and consistent influent turbidity did not yield steady and consistent effluent turbidity, but instead, showed a decrease in performance. The lid on the PACl stock tank was loosened to prevent the formation of a vacuum in the tank. A PACl stirrer was also added to prevent the settling of PACl precipitates within the stock tank. In the next set of trials, influent turbidity was extremely low for the first two trials and reached the target value for the next two trials. However, throughout all four trials performance was very low to the extent that it could be largely attributed to clay settling within the system without the use of coagulant. The PACl stirrer was removed to rule out any issues with the new addition to the system. Throughout the semester, clay clogging was observed on three occasions and was fixed by cleaning the stock tank or running the clay pump backwards at a high speed. It was possible that high pressure existed in the system, making it difficult for the coagulant pump to deliver the correct dosage; however, subsequent trials to test whether the pressure was high enough to shut down the system indicated that pressure in the apparatus was not sufficient. (Later, however, a pressure drop in the PACl pump was observed which was believed to be interfering with PACl dosage. This was fixed by changing the peristaltic pump-head.) The pressure sensor was put into the correct outlet for Process Controller to read from and the PACl stock concentration was increased from 60 mg/L to 500 mg/L. Also, the PACl tubing size was changed from a size 14 to 13 and the Raw Water Pump was raised to smooth out kinks in the piping.

After this set of modifications were implemented, experiment results indicated that the first trials of many experiments had abnormally high effluent turbidity results compared to subsequent trials at the same dosage. This abnormality could have been linked to latent bubbles that entered the apparatus when the system was not running. To combat this possibility, hard tubing replaced soft tubing, and barbed connectors were utilized to create an airtight connection. The PACL pump head was replaced as well in order to avoid depressurization of the apparatus into the PACl stock tank. Subsequent trials then ran with consistent effluent turbidity values and with similar trends within each set of dosages.

This semester's results succeeded in confirming the results of Karen Swetland's work. The data obtained from the SWaT system confirmed a positive correlation between coagulant dose and turbidity removal. The results of the team's research this year indicated that either performance using SWaT is greater than performance using FReTA, or that the liquid coagulant currently in use performs better than the granular coagulant used by Karen Swetland. It was also possible that a combination of these factors were responsible for the difference in results.

It was expected that the performance using SWaT would be better than the performance using FReTA. FReTA made use of a glass column and an inline turbidimeter, thus results were significantly affected by recirculating flocs and effluent turbidity was higher. SWaT made use of an inclined tube settler (at 60 degrees) with a tube at the top leading to an external effluent turbidimeter, and was thus less heavily affected by recirculating flocs and effluent turbidity was thus lower than while using FReTA. Thus, one would expect performance to be higher using SWaT than while using FReTA, as observed in research conducted this semester.

A difference in PACl quality might also be partially responsible for the observed difference in performance. Karen Swetland made use of granular imported PACl, while research conducted this semester made use of liquid PACl produced in the USA. It is possible that the PACl currently in use is of better quality than that used by Karen Swetland, which would explain the higher performance observed this semester. Moreover, it is possible that liquid PACl performs better than granular PACl.

Future Work

The results of the team's research this year indicate that either performance using SWaT is greater than performance using FReTA, or that the liquid coagulant used performs better than the granular coagulant used by Karen Swetland. The difference in performance is significant, and further studies comparing the performances of SWaT and FReTA while using the same quality and variety of coagulant might be helpful at providing more conclusive results.

Now that some of Karen Swetland's experiments has been repeated utilizing the SWaT apparatus, work in the future can begin research on two additional areas: the effect of floc breakup on the performance of SWaT and the effect of dissolved organic matter on the performance of SWaT.

Floc breakup mechanisms will be placed at various points throughout the system, and their effect on performance will be noted. Further in the study, the effects of dissolved organic matter (DOM) will be explored as well. This will be done at various humic acid concentrations to observe their influence on system performance.

References

Bennett, J., Bhasin, A., Grant, J., Lim, W. (2007). PID tuning classical. Retrieved March 4, 2015, from https://controls.engin.umich.edu/wiki/index.php/PIDTuningClassical

EPA (2002). Water Treatment Manual: Coagulation, Flocculation & Clarification report. Retrieved March 5, 2015, from http://www.epa.ie/pubs/advice/drinkingwater/EPA_water_treatment_mgt_coag_flocc_clar2.pdf

Jain, S., Peifer, T., Shebaro, N., Zhu, L. (2014). Laminar Tube Flocculation Summer 2014 Team Final Report

Kawamura, S. (1991). Integrated design of water treatment facilities. Wiley, New York.

Shao, K., Dai, Y. (2014). Laminar Tube Flocculation Fall 2014 Team Final Report

Swetland, K., Weber-Shirk, M. L., Lion, L. W. (2012). Predictive performance model for hydraulic focculator design with polyaluminum chloride and aluminum sulfate coagulants. *Journal of Environmental Engineering.*

Weber-Shirk, M. L. (2015). Challenges Spring 2015. Retrieved March 6, 2015, from https://docs.google.com/a/cornell.edu/document/d/1lpYjj8CQ5fwHyrIneYqvs_Um1qc3cUknVOzWOFHCOzc/edit

Weber-Shirk, M. L. (2014). Lecture slides, CEE 4540, Flocculation Model. Retrieved March 25, 2015, from https://confluence.cornell.edu/display/cee4540/Syllabus

Woolf, P. (2012). Chemical Process Controls, PID Control. Retrieved March 24, 2015, from https://controls.engin.umich.edu/wiki/index.php/Recorded_Lectures