Laminar Tube Flocculator Team

Final Report

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Part I

Introduction

Flocculation is used to decrease the turbidity of raw water by causing suspended particles to collide and form flocs that are large enough to be removed by sedimentation. Flocculators are used to cause the collisions, and in the presence of a coagulant, these encounters result in an aggregation of particles to create flocs. These flocs can then be removed by sedimentation or filtration to decrease the effluent turbidity. In our system, the coagulant used is an aqueous polyaluminum chloride, or PACl,that is used by the Cornell Water Treatment Plant and turbidity is measured in units of Nephelometric Turbidity Units. The turbidimeter measures the influent water's turbidity by shining a light through a glass vial. The amount of light that reaches a sensor after reflecting off of particles in the water determines the turbidity of the suspension. The turbidity of the effluent water is controlled by regulating the capture velocity of a tube settler. Where capture velocity is defined as the settling velocity of the slowest settling particle that experiences 100% removal. In these experiments the tube settler angle was set at 60° from the horizontal (this tube angle is the same as is used for full scale plate settlers in AguaClara water treatment plants), and the capture velocity was controlled by varying the flow through the tube settler using a peristaltic pump. The assembled tube settler, flow control and measured effluent turbidity are referred to here as the Settled Water Turbidity Analyzer (SWAT).

The purpose of our research this semester is to validate the results obtained by the Summer 2014 research team's research, and to determine if it is possible to obtain data that matches the fractal flocculation model developed by Weber-Shirk, Swetland, and Lion. The fractal flocculation model predicts that the log of fractional effluent turbidity NTU varies with dose. The trials conducted over the summer had exemplary results in lowering the turbidity below 0.5 NTU, but the effectiveness of the coagulant did not increase as the dose was raised. Using this data as a starting point, experiments this semester will consist of a base case and experiments that continue to vary the PACl coagulant dose. The difference is that the doses will be highly reduced from those of the summer, and will be increased in much smaller increments. The goal of these trials will be to see if a higher effluent NTU can be achieved. A higher effluent turbidity will allow characterization of PACl particle size using the fractal flocculation model. Changes in the coagulant and turbidity measurement system were made between Swetland's doctoral research and Summer 2014, so those differences could be accountable for the new findings from summer 2014. If the SWaT system and the new coagulant cannot be found to match the the fractal flocculation model , then a new relationship between coagulant, flocculation, and sedimentation must be explored.

Part II

Literature Review

Throughout the flocculation process, clay particles covered with PACl coagulant collide, leading to the creation of flocs. Because the flocs are much larger in size than the original clay sediments, they can be removed by a tube settler, lowering the turbidity of the effluent flow. In order to compare the new residual turbidity monitoring system, SWaT, to the system prior teams including Karen Swetland utilized, FReTA, the SWaT flow rate was set to achieve a 0.12 mm/s capture velocity (Jain, 2014).

Previously, it was believed that the performance of the SWaT system would follow the same trend as the earlier FReTa data obtained by Karen Swetland; however, in the past laminar tube flocculator design conducted by the 2014 summer team, the trends were significantly different. From Figure 1, we can see that similar amounts of PACl in the SWaT system produced markedly lower residual turbidities than those obtained using FReTA . In the FReTA experiment, performance measured as pC* increased as colloid coverage with PACl increased. With SWaT, the optimal performance was achieved at a middle dosage and there was little change in performance with change in coagulant dose (Jain, 2014).

The changes from the FReTA system to the SWaT system could have produced some discrepancies in results, but we do not believe that the distinct methods of measurement would produce the large differences that we have seen. The FReTA system consisted of three parts: an inline turbidimeter, a transparent column, and an electrically actuated valve (Chou 8). SWaT, which consists of a tube settler held at a 60 degree angle and a turbidimeter, runs through a very different, and what we believe to better, system then FReTA. In the Fall of 2013, FReTA had issues with water upflow that led to altered turbidity measurements (Chou 8). The Fall 2013 team tried to correct the system by increasing the ramp down time from 14 seconds to 31 seconds. Experiments still yielded results with fluctuations, showing that there was an with the turbidimeter system itself (Chou 9). Therefore, it is not surprising that the SWaT system has achieved better turbidities than those taken with the FReTA system. However, the real problem lies in why performance within the Summer 2014 team's trial did not improve as dose increased.

For the Fall 2014 Laminar Tube Flocculation team, suspicions center on the type of PACl utilized. Recently, AguaClara research teams began using PACl coagulant obtained from the Cornell Water Filtration Plant. The previously used granular PACl coagulant was obtained from a supplier in China. This change in PACl could have a large impact on the calculations done to compute a theoretical pC* for a given dosage. With the new, uncharacterized liquid PACl coagulant, coagulant precipitate size is unknown, potentially leading to an incorrect calculation of the coverage of clay particles by PACl. It is possible that the almost identical performance independent of coagulant dose occurred because the coagulant precipitate was much smaller in diameter than the previous PACl and thus perhaps the coagulant coverage of the clay had reached close to 100%. With further experiments, the Fall 2014 team expects to be able to more accurately characterize this new coagulant as well as explore the range of PACl dosages where pC* and dosage may have a similar relationship as seen in Karen Swetland's work. The research will evaluate arrange of coagulant dosages that goes from no response to the maximum pC* attainable with the given flocculator.

As a result of the many issues we have encountered with process controller, one of our other main focuses for this semester is to optimize the method file we use. Most of the major problems in our trials were observed in our method file, so we believe that the Summer 2014 team may have had some errors in their method file to begin wit. Since we used their file as a starting point for our experiments, any problems that they had were carried over to our trials. The summer 2014 team did at one point have to shut down the automatic system and run it manually, in order to monitor the process more effectively (Jain, 15). They ended up changing several of the variables, including capture velocity and loading time. This resulted in eliminating the the initial spikes seen in their effluent turbidities, as well as creating larger physical flocs than when it had been created with the automatic system (Jain 17). Therefore, based on this difference between the process when run manually and when it is run automatically, we need to look into the effectiveness and precision of process controller.

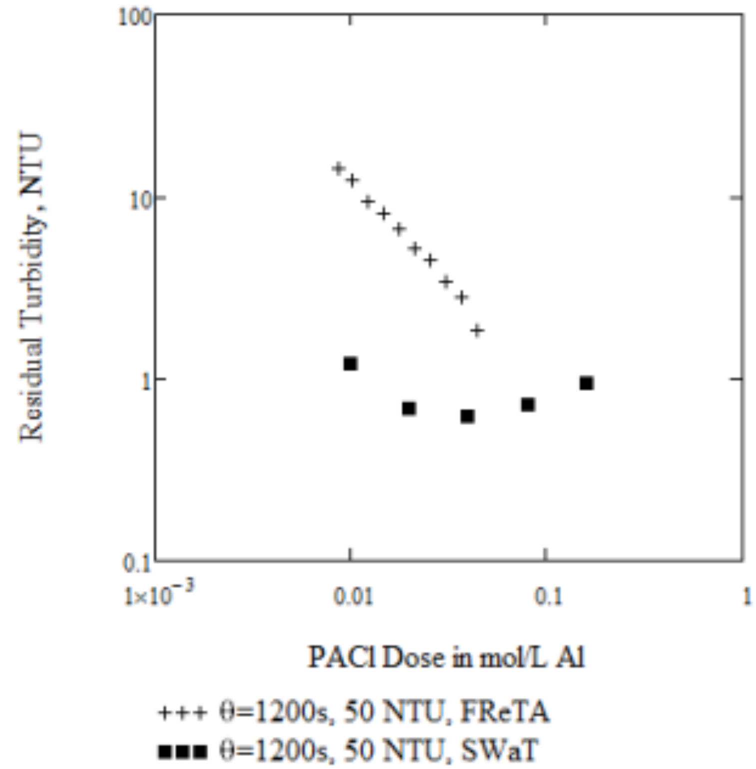


Figure 1: Residual Turbidity for various PACl dosages in both FReTA (Karen Swetland's data) and SWaT. For both systems, the capture velocity was 0.12 mm/s (Jain, 2014).

Part III

Methods

Apparatus

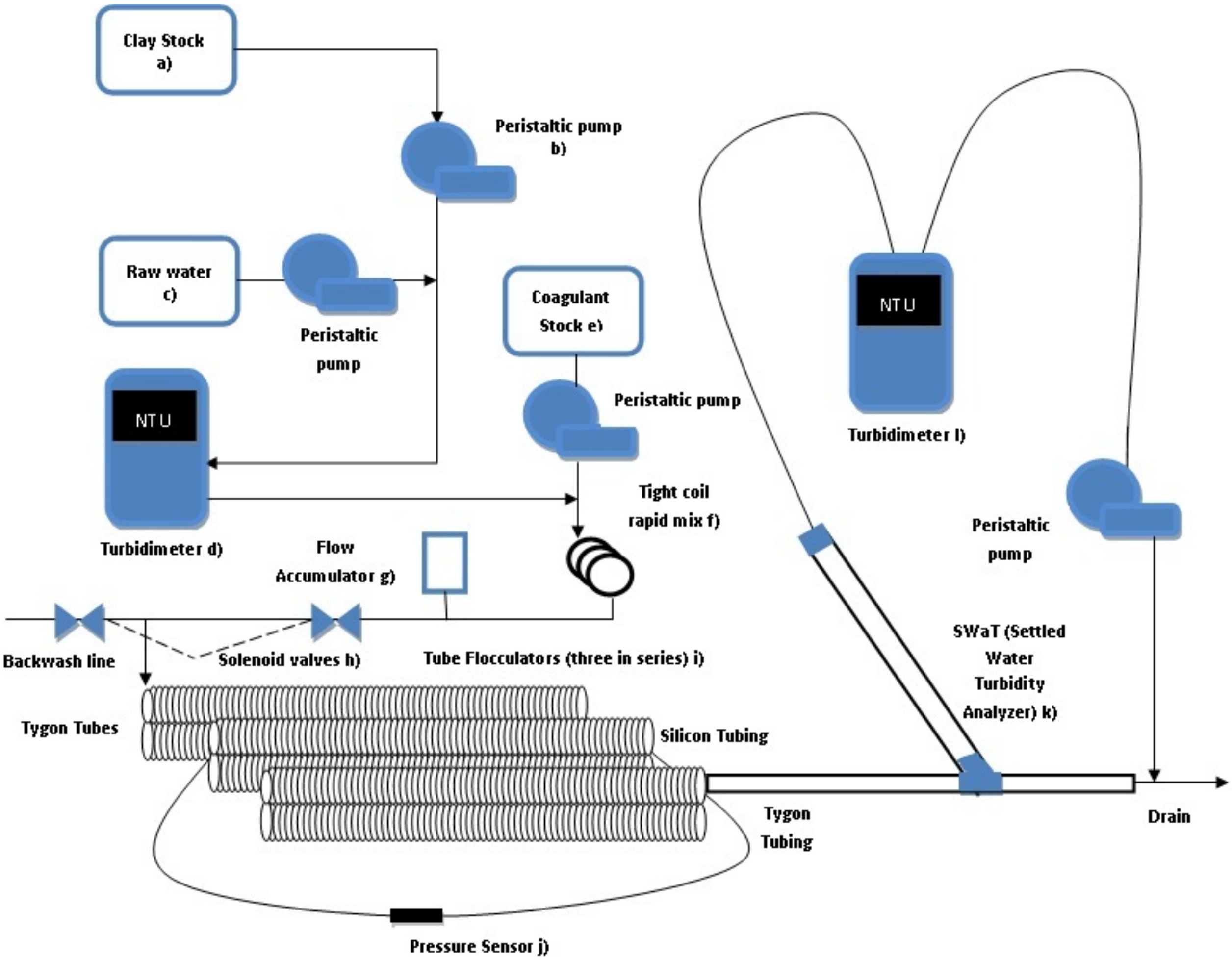


Figure 2: Laminar Tube Flocculator Schematic

A schematic for the Laminar Tube Flocculator can be seen above in Figure 1. Each part of the plant was labeled with a letter, and each letter will be detailed below.

a. The Clay Stock tank is kept at a concentration of 5 mg/L and kept from settling by a constant mixing system.
b. The clay is pumped into the system using a peristaltic pump that is controlled by Proportional-Integral-Derivative controller, or PID, a process controller program. PID works to control the clay flow rate using the turbidity taken at point d and adjusts the speed of the clay pump to increment the influent turbidity towards the desired value. The P in PID stands for proportional and

represents to what degree the system should change in response to a high or low variable reading, using the discrepancy or error value to calculate the proportion. The integrative value, I, determines how the system responds to the amount of past error based on the integral of this error over a certain amount of time. The D is derivative value and represents how much the system is affected by the rate of change of the turbidity value. Process controller utilizes these variables to adjust the clay pump speed and, therefore, the influent turbidity that is achieved.

c. Raw water is pumped into the system using another peristaltic pump. This water is temperature controlled in the Hollister B60 lab in order to avoid temperature gradients that might cause flocs to recirculate when in SWaT, as this would jeopardize the integrity of the residual turbidity readings.
d. Influent turbidity is measured in the turbidimeter by a light shining through a glass vial of water. The amount of scattered light that reaches a sensor after passing through the vial corresponds to the measure of suspended particles in a sample in units of NTU (Nepholometric Turbidity Units). This reading of the influent turbidity is used by process controller adjust the flow rate of clay stock.
e. The coagulant stock is kept at a concentration of 60 mg/L. Process controller adjusts the speed of the peristaltic pump depending on the desired dosage of the coagulant.
f. The tight coil rapid mix consists of tubing wrapped tightly into a coil around a plastic cylinder. Right after water and coagulant are combined, they are fed through the rapid mix coil to enhance attachment of the coagulant to the clay particles. Ideally, the clay particles are covered by the coagulant so that they can form flocs once they have reached the flocculation tubing. In practice some coagulant is lost to the walls of the tubing in the rapid mix and the tubing in the flocculator.
g. The flow accumulator was put in place to dampen flow pulses created by the peristaltic pumps, as a smooth flow of water is desired for the flocculator tubing.
h. Two solenoid valves are used in the system, one after the flow accumulator and before the backwash line, and another between the backwash line and the flocculator tubes. To open the valve, Process Controller applies a current to the solenoid valve, inducing a magnetic field. When there is no current applied, the valve remains closed.
i. The three tube flocculator sections each consist of ½" tubing wrapped in a figure eight design around two parallel 11 cm outer diameter cardboard tubes. The figure eight design is used to prevent flocs from settling at the bottom of the flocculator. The first and third flocculators use 30 m long Tygon tubing, while the second flocculator uses 23 m of silicone tubing.
j. A 7 k Pa pressure sensor was arranged to measure the head loss across the silicone flocculator during the Summer 2014 trials.
k. SWaT (Settled Water Turbidity Analyzer) is the current system used to measure the effluent turbidity. SWaT consists of a tube settler with an outlet that leads to a turbidimeter. The tube settler is a 1.04 m long PVC pipe with an

inner diameter of 26.65 mm that is tilted at an angle of 60 degrees. This angle prevents floc roll-up and allows for a capture velocity between 0.1 and 0.5 mm/s. The flow rate is controlled by a peristaltic pump attached to the outgoing side of the connected turbidimeter.

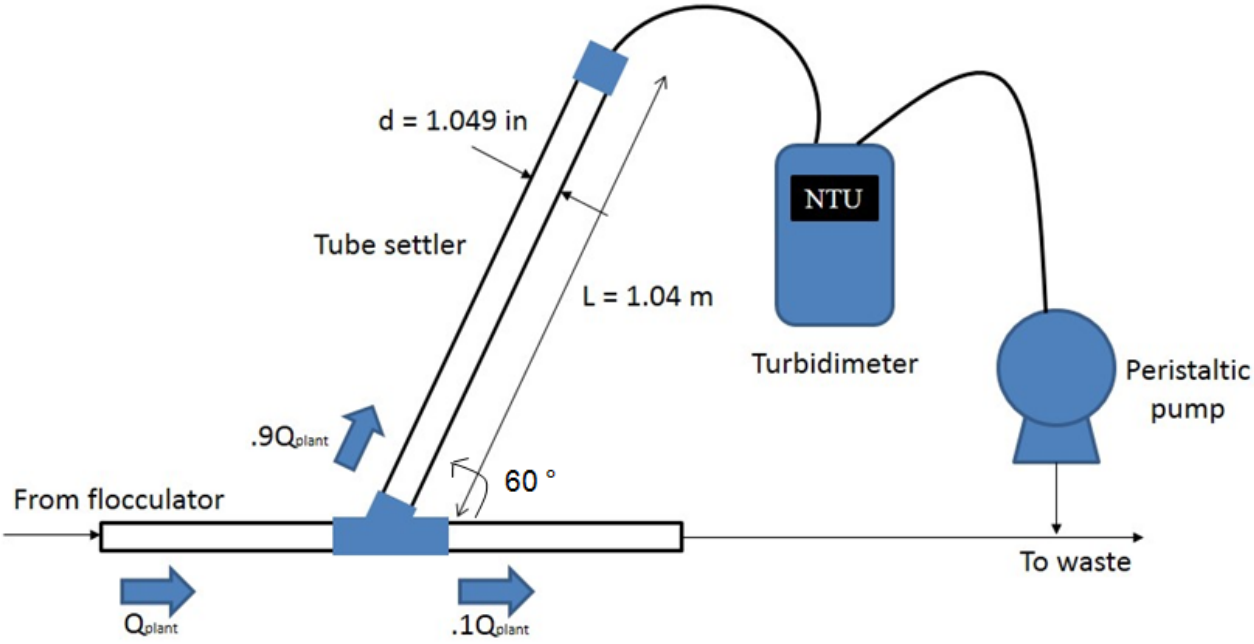


Figure 3: Schematic of the angle of SWaT

1. The turbidimeter attached to the tube settler measures the residual turbidity after the flocs have been settled out.

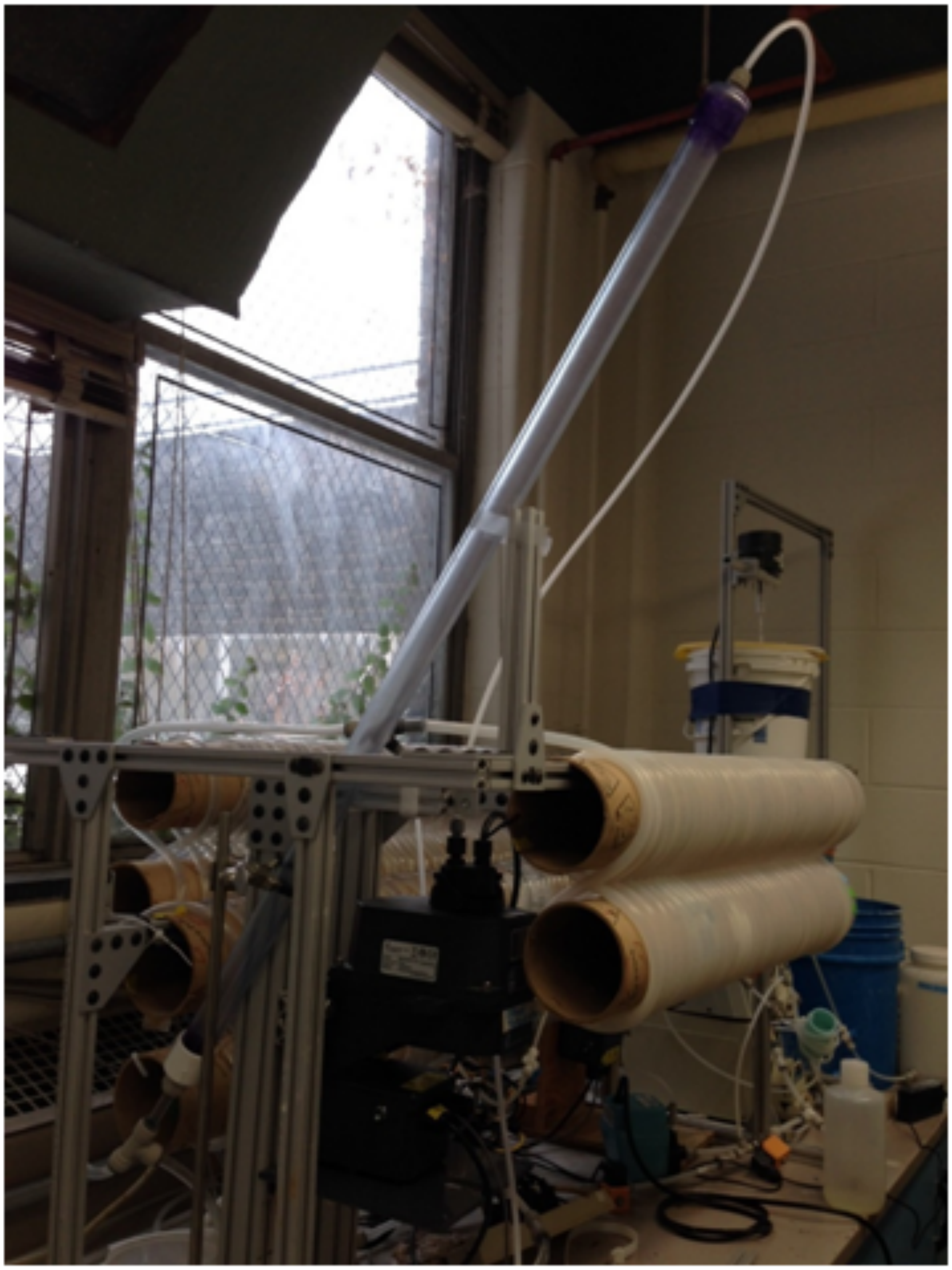


Figure 4: SWaT system

Method File

A team objective is to explore the characteristics of the new liquid PACl obtained from the Cornell water filtration plant. For our initial experiments, the flocculator ran through an automatic cycle consisting of five separate states: Off, Loading, SWaT, Backwash with Tube, and Backwash without Tube. After several adjustments of the experiment procedure, it was determined that the Loading state should be eliminated, as the full-scale plants would never cycle through such a stage. A more complete description of each state is as follows:

a. Off: All pumps and valves are closed in this state. No water, clay or coagulant flows through the system.
b. Loading: This state was initially included so that the system could reach the desired turbidity and coagulant levels before the actual experiment was run with the Settled Water Turbidity Analyzer. Tap water, clay and coagulant all flow through the system, except for the tube settler. The raw water solenoid valve is opened so that water passes through, the backwash valve is left closed. Tap water flows through a peristaltic pump at a rate of 5 mL/s, while the clay flow rate is controlled by PID, in order to give PID time to establish a good baseline turbidity.

    This state is included to account for the fact that at every new cycle. the turbidity spikes dramatically. The loading state lasts for 35 minutes.

c. SWaT: This is the state in which the tube settler is opened and effluent turbidity is measured. The tube settler pump is turned on to allow for settling within the SWaT system, and tap water flows in at a rate of 5 mL/s. Clay is injected with PID control, and PACl is dosed at a flow rate determined by the desired PACl dosage. The influent turbidity is maintained at approximately 50 NTU, with deviations of about 2 NTU. The water through the tube settler is pumped with a flow rate of 1.4 mL/s in order to achieve a capture velocity of 0.12 mm/s. The system is in the SWaT state for 40 minutes.
d. Backwash with Tube: This state is used to flush the system of any flocs and pass them into the drain in the sink. This is done using water from the backwash tube that flows forward through the flocculator. In the state, the solenoid valve is closed to prevent backwash water from moving back through the system, and the tap water, clay and coagulant pumps are all turned off. Only the peristaltic pump after the tube settler was turned on to move water through the system. This state lasts for ten minutes.
e. Backwash without Tube: This state was designed to allow flocs at the bottom of the tube settler to simply flow out and be drained away. The tube settler is turned off, and tap water is pumped forward through the system. Tap water is pumped through the flocculator using a peristaltic pump and water passes through the drain without flowing up the tube settler. Clay and coagulant are turned off in this state. This flushing state lasts for five minutes.

Originally, during the first runs of the experiment, the system began in the loading state and then proceeded to cycle through the SWaT and backwash states. The system would iterate through the SWaT state five times, but once the SWaT state counter in Process Controller reached five, the system would shut down. After several trials however, it was determined that the loading state was unnecessary. Instead, the SWaT state was extended to 75 minutes, so that the time required for the clay and coagulant doses to equilibrate was still included, but the adjustments were still made with the tube settler turned on.

System Methods

We began by locating the method files in Process Controller that were present in the Summer 2014 team folder on the AguaClara server. After selecting a file from the summer, we ran Process Controller to test that the apparatus was still performing properly. The bucket that controls the stock concentration of the clay-water mixture was filled with 5 liters of clay suspension at a concentration of 5 g/L. We used the diluted liquid PACl from the summer team's trials, which was at a concentration of 60 mg PACl per L water.

After the test run, our team created a process called “SWaT counter” that would count every time Process Controller entered the SWaT stage. The system was then adjusted to turn all processes off before it entered Backwash No Tube if the SWaT counter reached five. After the PACl stock container was refilled with PACl of 60 mg/L concentration, the flocculator was then run again at the lowest PACl dosage of 1.05 mg/L that the summer team used.

Part IV

Results

From the test run set to determine whether the flocculator was performing properly, we were able to discern a fault in the Process Controller method file. The file left by the summer team continued to run the entire process until the PACl stock was depleted or until it was manually turned off. In order to automatically shut-down the experimental apparatus after a set number of experiments, the SWaT counter was implemented.

The experiment was run again with the automatic shutdown implemented. Five trials were conducted with influent turbidity constantly oscillating between 40 NTU and 60 NTU. This variability in influent turbidity was too high and prevented us from accurately measuring pC*. PACl dosage was kept constant at 1.05 mg/L. The Raw Water Pump was calibrated to generate a flow rate of 8 ml/s throughout the plant. This flow was also measured by hand using a stopwatch and graduated cylinder to ensure accuracy. The Clay Pump was also checked to make sure it was constantly generating about 50 NTU of influent turbidity. We set the capture velocity of the tube settler to 0.12 mm/s to remain consistent with previous tests using FReTA and the summer team’s parameters. In the method file, the loading and SWaT states were adjusted to be identical to simulate the conditions of an actual AguaClara hydraulic plant.

Results of the 1.05 mg/L Trials

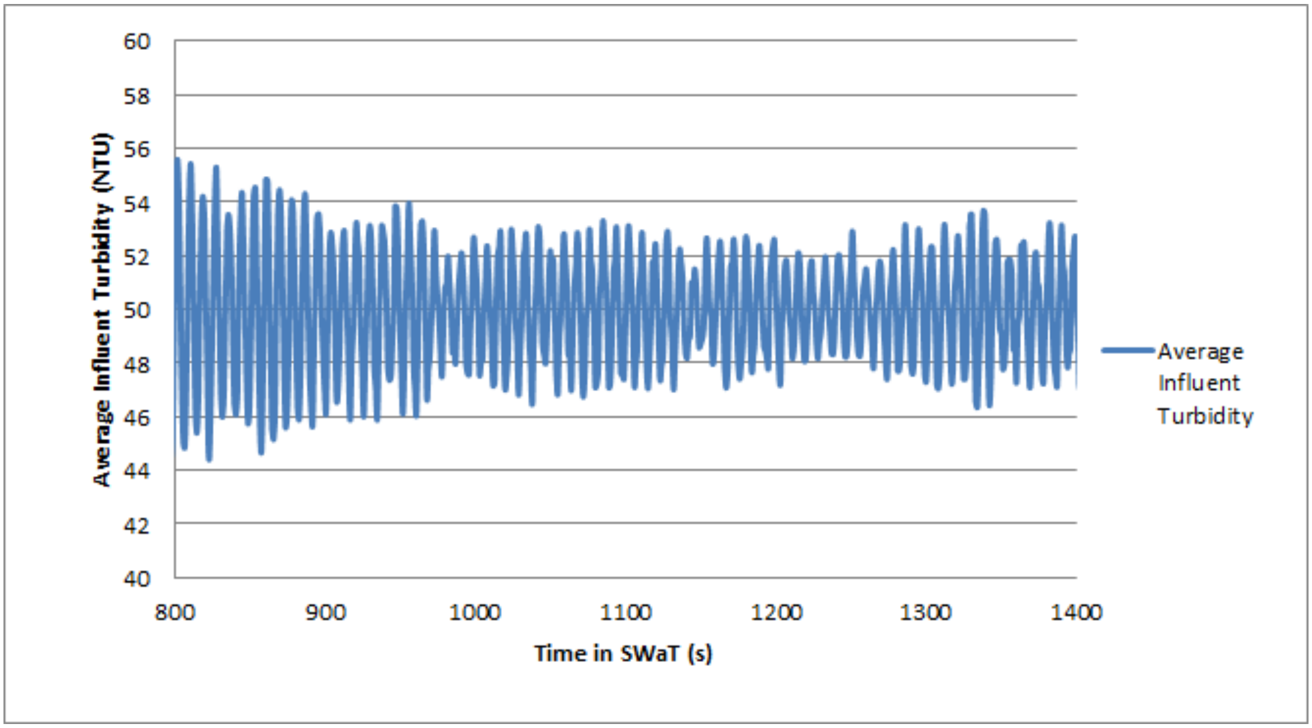


Figure 2 - Average influent turbidities for the 1.05 mg/L PACl dose during SWaT. The time interval selected is 800s to 1400s into SWaT. This was done to observe the effects of influent turbidity on effluent turbidity levels particularly in trial 1. Performed on 11/5/14.

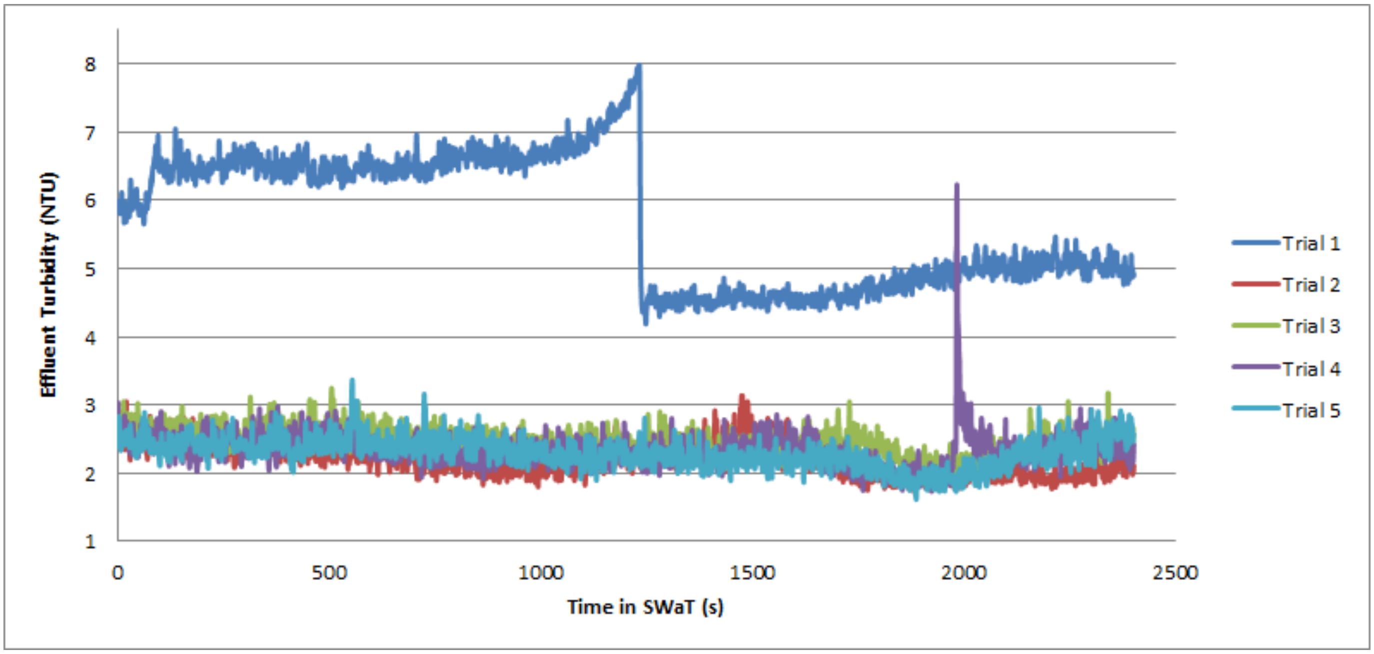


Figure 3 - Effluent Turbidities measured in Trials 1-5 for 1.05 mg/L PACl dose. All times during SWaT are displayed. Performed on 11/5/14.

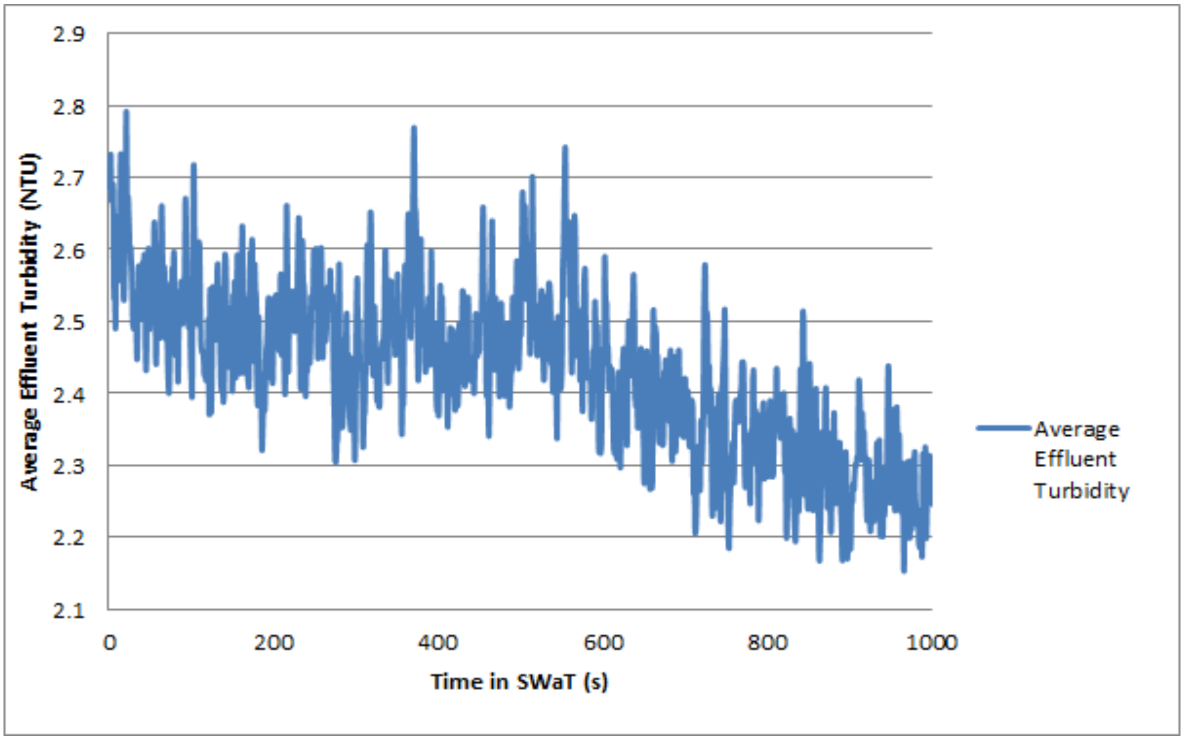


Figure 4 - Average effluent turbidities measured in Trials 2-5 for 1.05 mg/L PACl dose. The first 1000 seconds are displayed, at which point the effluent turbidities seem like they could continue to drop. Performed on 11/5/14.

Results of the 0.1, 0.05, and 0.03 mg/L Trials

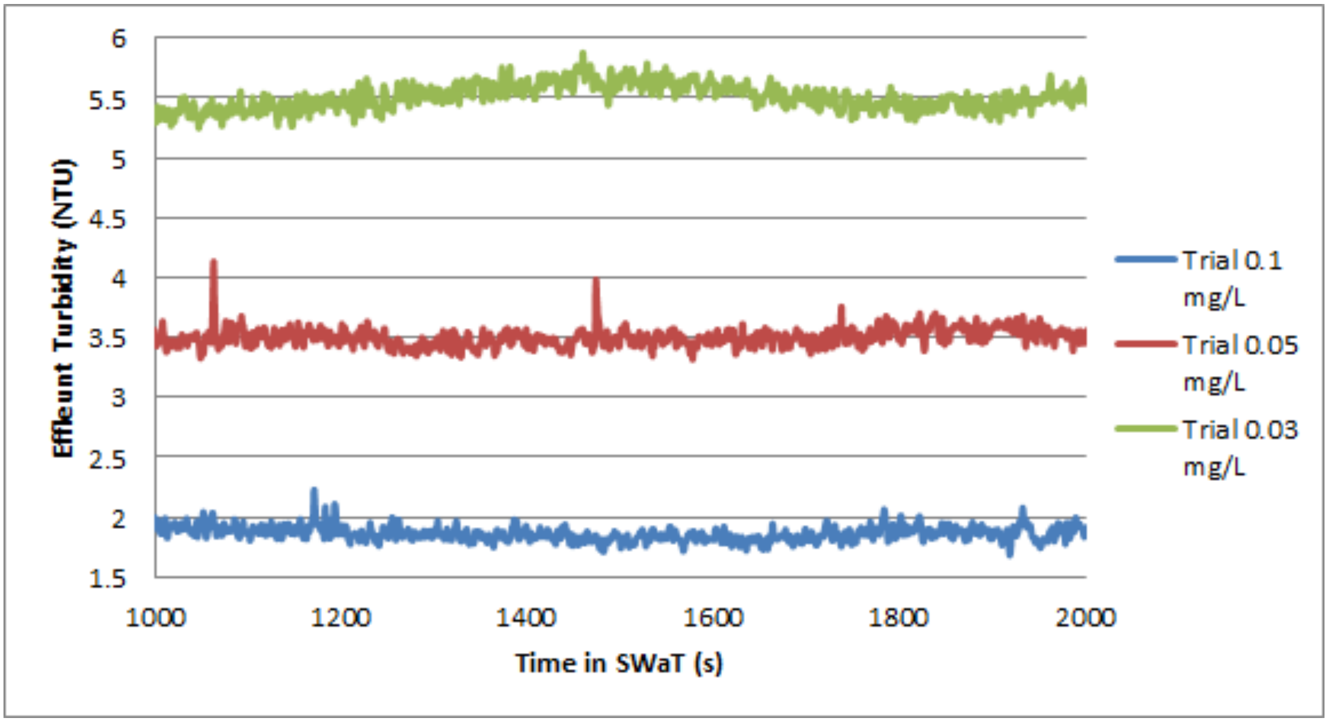


Figure 5 - Average effluent turbidities measured for the 0.1, 0.05, and 0.03 mg/L PACl dose trials. Each dosage was repeated for 6 trials. The time interval between 1000s and 2000s during SWaT is displayed, at which point the effluent turbidities seemed to have settled to a steady value. Performed on 11/10/14, 11/12/14, and 11/16/14.

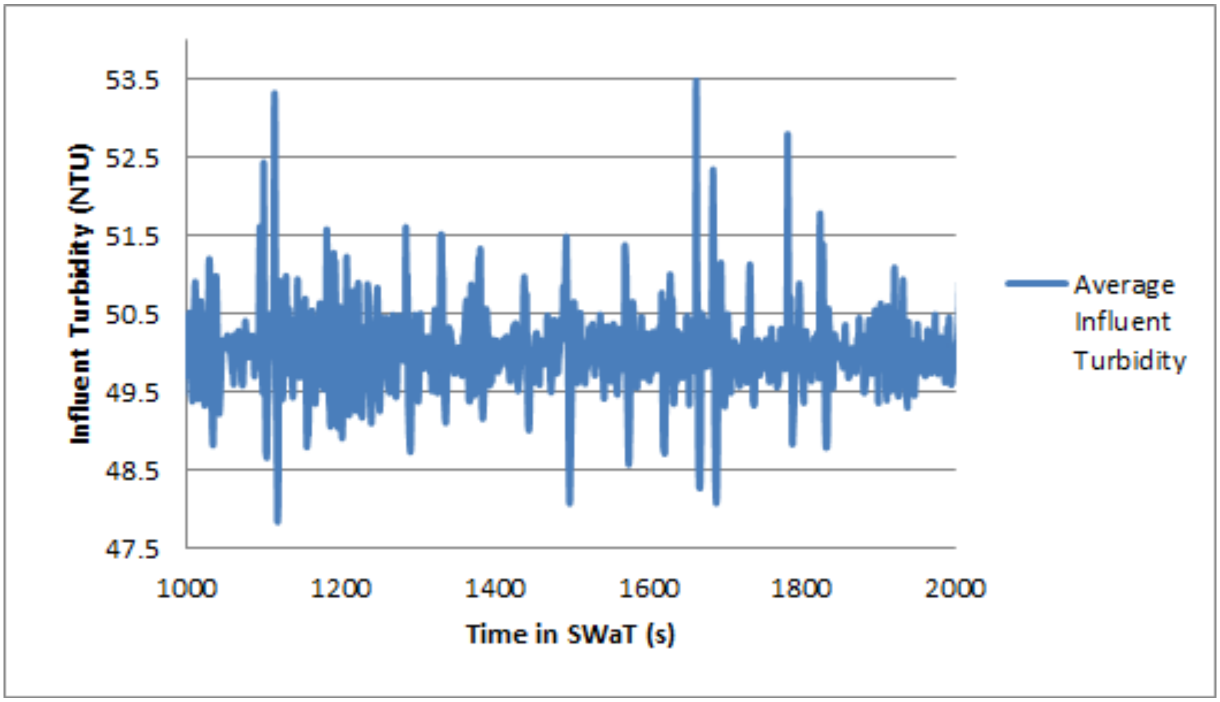


Figure 6 - Average influent turbidity levels for the 0.03 mg/L case. The time interval taken is 1000s to 2000s into SWaT. This is the same time window taken for the effluent turbidities in Figure 5 above.

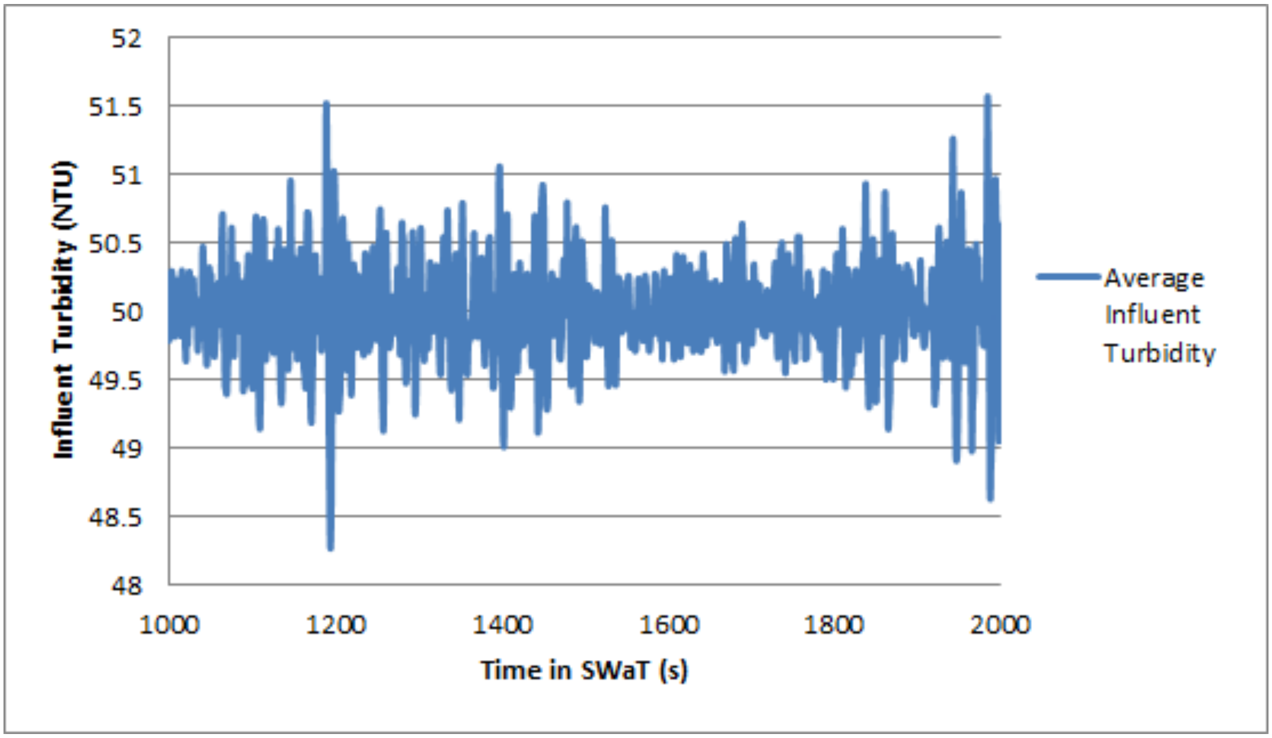


Figure 7 - Average influent turbidity levels for the 0.05 mg/L case. The time interval taken is 1000s to 2000s into SWaT. This is the same time window taken for the effluent turbidities in Figure 5 above.

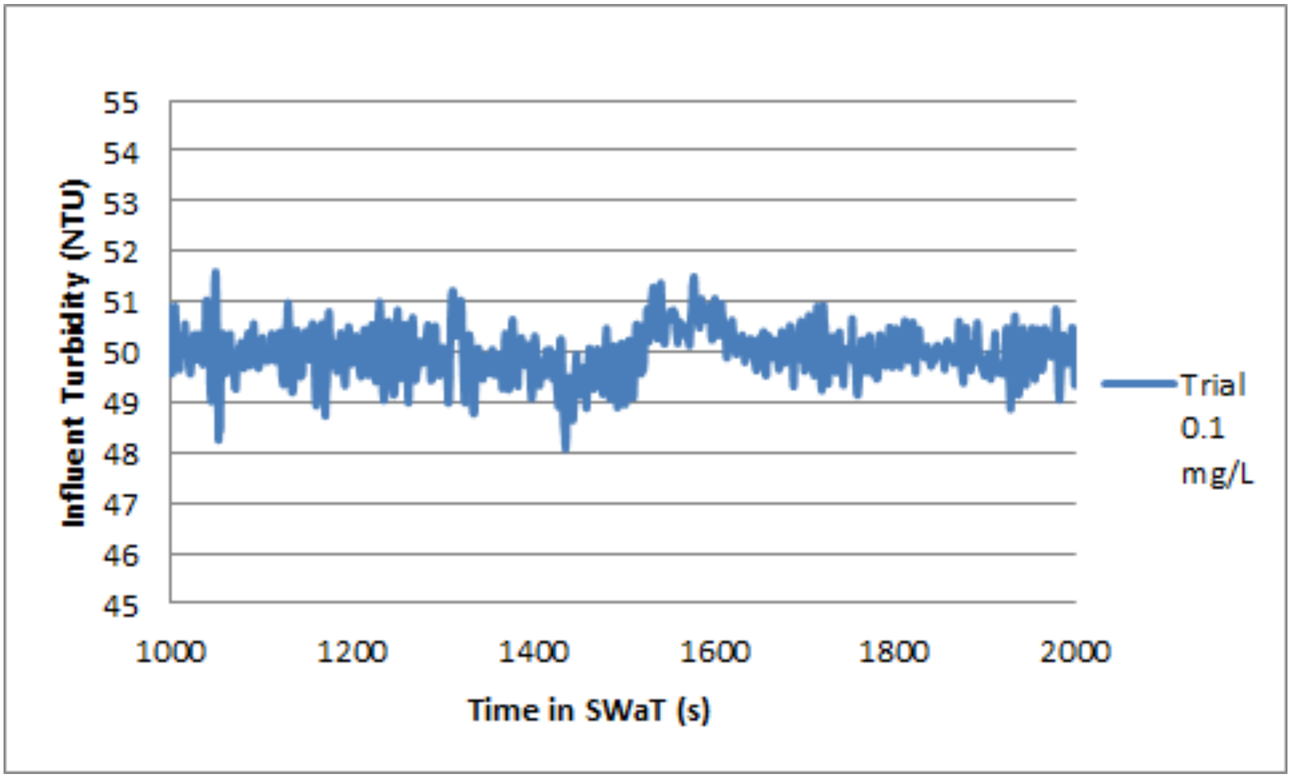


Figure 8 - Average influent turbidity levels for the 0.1 mg/L case. The time interval taken is 1000s to 2000s into SWaT. This is the same time window taken for the effluent turbidities in Figure 5 above.

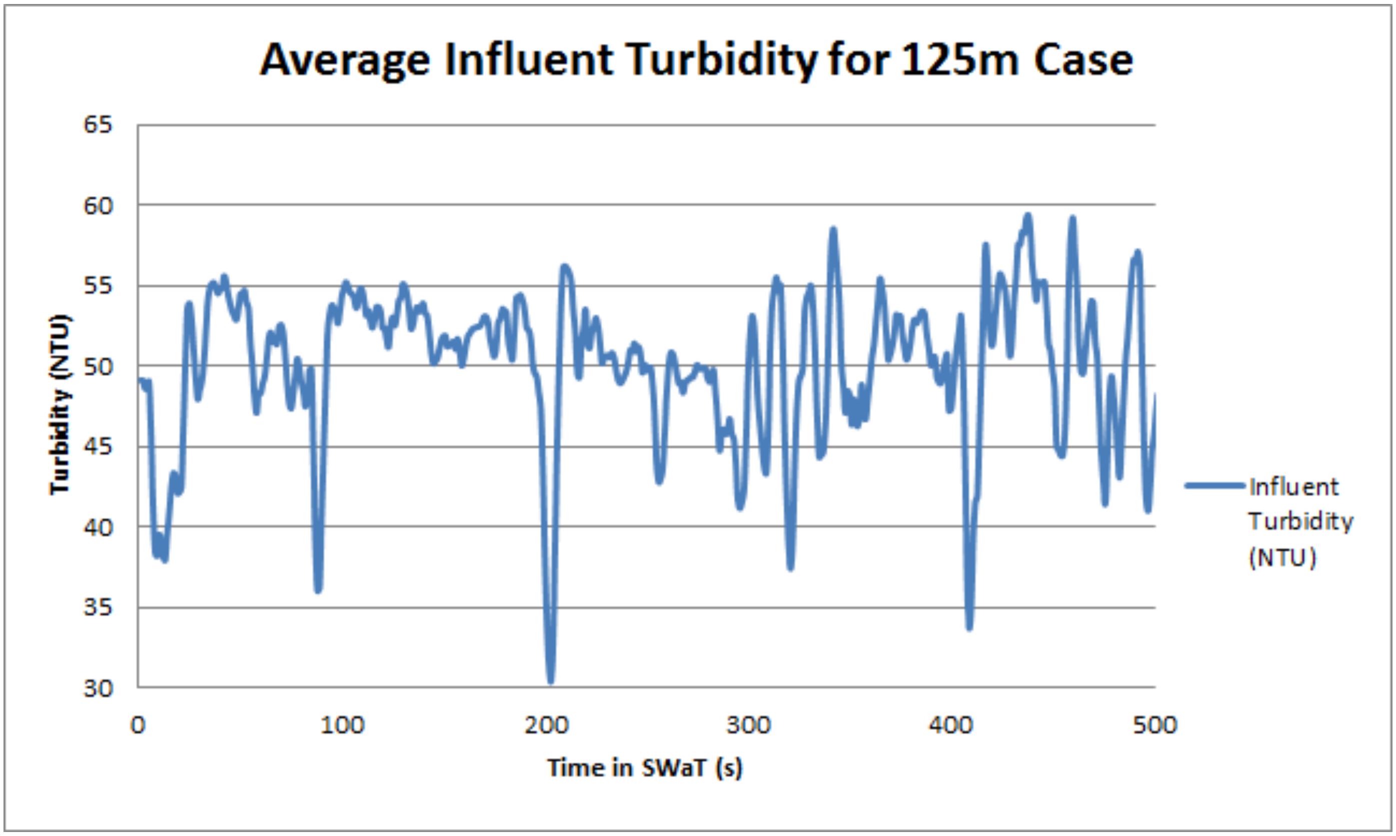


Figure 9 - Plot of average influent turbidity against Time in SWaT. The first 500 seconds are displayed where we can begin to see fluctuations in the influent turbidity levels. This trial was done at a P value of 125m. The mean turbidity level is 49.85 NTU with a standard deviation of 5.83. This was performed at a 0.03 mg/L PACl dosage.

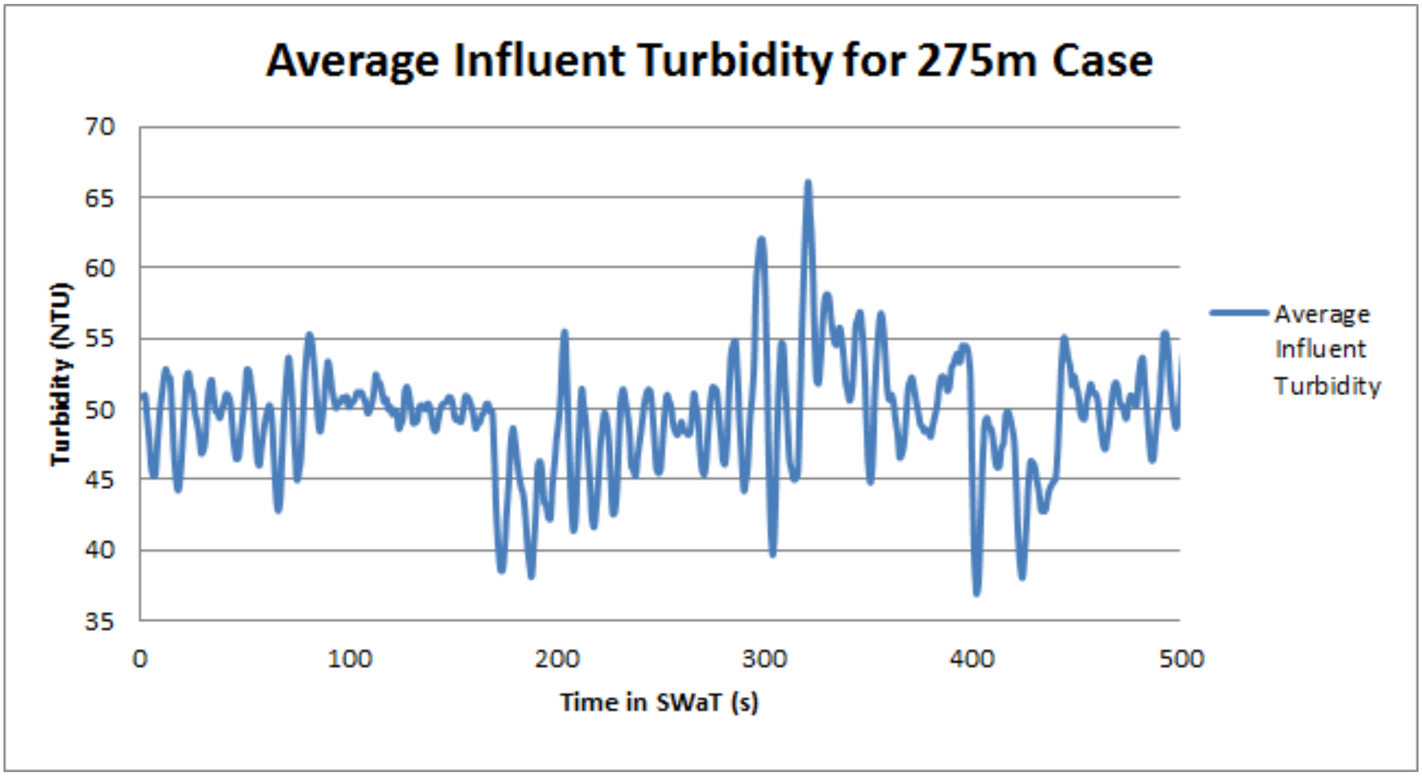


Figure 10 - Plot of average influent turbidity against Time in SWaT. The first 500 seconds are displayed where we can begin to see fluctuations in the influent turbidity levels. This trial was done at a P value of 225m. The mean turbidity level is 49.86 NTU with a standard deviation of 2.52. This was performed at a 0.03 mg/L PACl dosage.

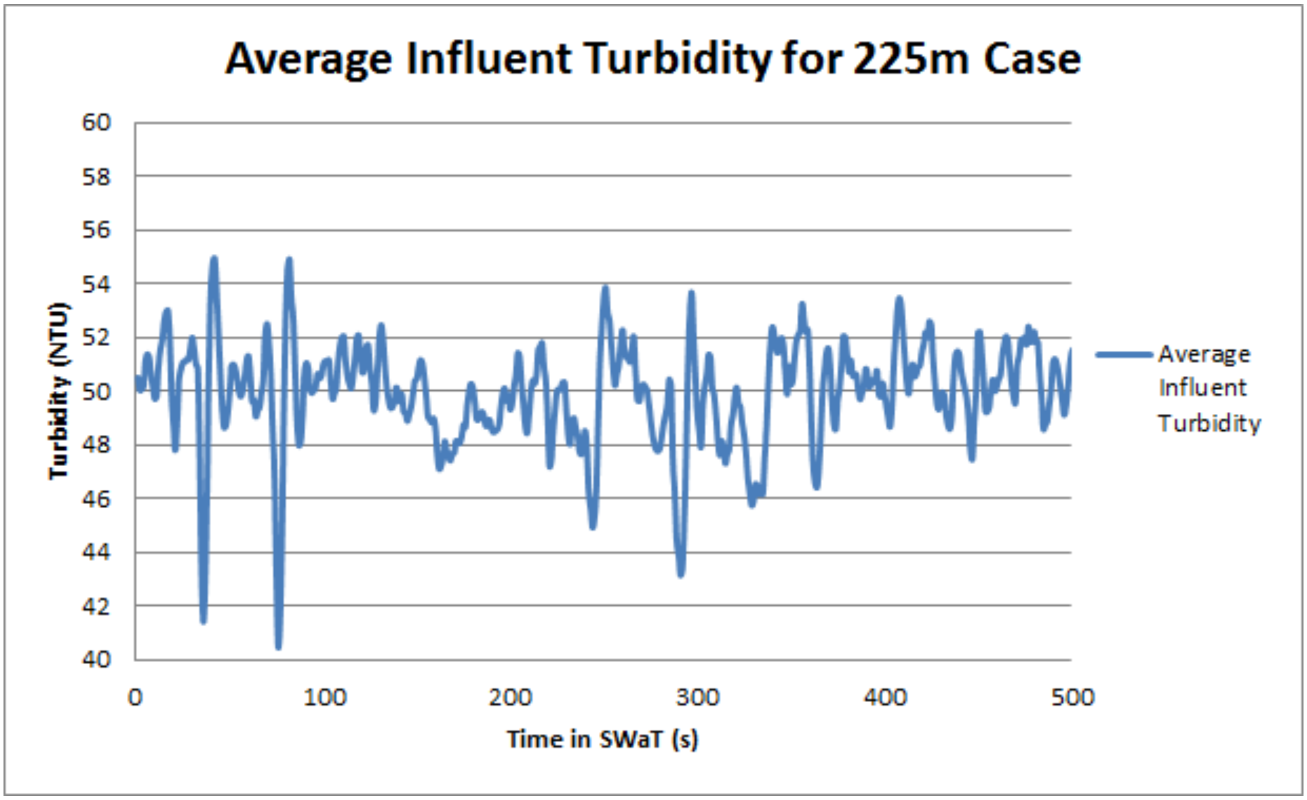


Figure 11 - Plot of average influent turbidity against Time in SWaT. The first 500 seconds are displayed where we can begin to see fluctuations in the influent turbidity levels. This trial was done at a P value of 275m. The mean turbidity level is 50.04 NTU with a standard deviation of 3.35. This was performed at a 0.03 mg/L PACl dosage.

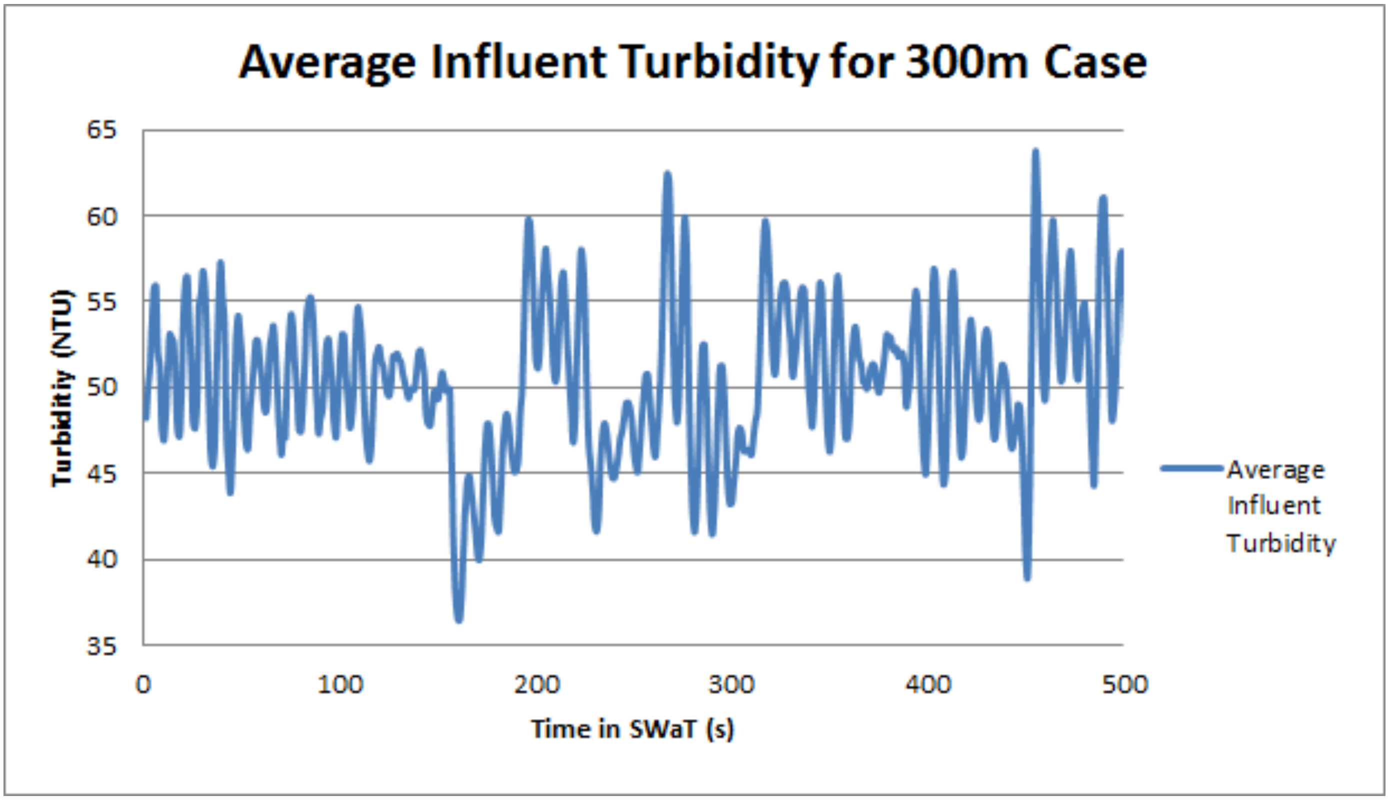
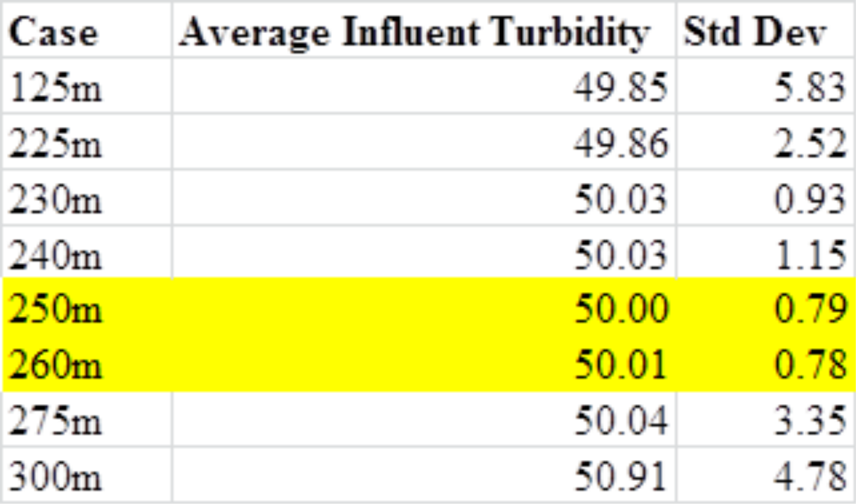


Figure 12 - Plot of average influent turbidity against Time in SWaT. The first 500 seconds are displayed where we can begin to see fluctuations in the influent turbidity levels. This trial was done at a P value of 300m. The mean turbidity level is 50.91 NTU with a standard deviation of 4.78. This was performed at a 0.03 mg/L PACl dosage.

Table 1 - Table of average influent turbidities (NTU) and standard deviations for cases where the P value is 125m, 225, 275m, and 300m.



Case	Average Influent Turbidity	Std Dev
125m	49.85	5.83
225m	49.86	2.52
230m	50.03	0.93
240m	50.03	1.15
250m	50.00	0.79
260m	50.01	0.78
275m	50.04	3.35
300m	50.91	4.78

Part V

Analysis

Results of the 1.05 mg/L Case

Issue	Correction
Erratic influent turbidity in 1.05 mg/L trial (50 ± 6) resulting in erratic effluent turbidity (± 0.4)	Erratic influent and effluent turbidities did not repeat itself (disappeared) in next trials for no known reason.
Sudden plummets in effluent turbidity	Looked at kPa record in datalog and found corresponding drops. This issue did not repeat itself for no known reason.
Spikes in effluent turbidity	Unclear of cause. One possibility might be found in the kPa measurement. This issue did not repeat itself for no known reason.

Results of the 0.1, 0.05, and 0.03 mg/L Trials

Issue	**Correction**
Undulations in effluent turbidity when it should have settled to a steady value	This issue did not repeat itself for no known reason.
“Tubing Size” parameter for PACl Pump in Process Controller set to a value of 100m instead of 14.	Set “Tubing Size” to its correct value of 14 and run a test at 0.03 mg/L to obtain a correction factor.
Obtaining a constant influent turbidity	Alter P parameter in PID and test by trial and error which P value gives the steadiest values

Determining a Correct P Value in Process Controller

After running the experiments at varying dosages, we observed that the influent turbidity levels were still not completely under control and varied slightly around our target of 50 NTU. In order to better constrain the range of values that influent turbidity fluctuates between, we began experimenting with the P parameter in Process Controller. This P value represents to what degree the system should change in response to a high or low variable reading, using the discrepancy or error value to calculate the proportion. By adjusting the P value, we make the system more or less sensitive to changes in influent turbidity levels.

Originally P was set at a value of 250m. In our trials we experimented with P values of 125m, 225m, 275m, and 300m. From Table 1, we can observe that the 225m trial has the smallest spread in values with a standard deviation of 2.52 and the 125m case has the largest spread with a standard deviation of 5.83. The 275m case has a mean closest to the target influent turbidity value of 50 NTU with only a standard deviation of 3.35. Currently, in our trials the 225m and 275m cases are the closest to the desired target influent turbidity of 50 NTU and range of about ±0.5; however, they still are quite lacking in precision and we must look towards trials done at P values between 225m and 275m.

Subsequent trials done at P values of 250m and 260m showed much more accurate and precise results. At a P value of 250m, the mean influent turbidity value is virtually the target turbidity value. Also, the standard deviation is much lower than most of that of the previous trials as well. Rivaling the results of the 250m trial is that of the 260m trial. In this next trial, the mean influent turbidity was also virtually the target turbidity value; however, it resulted in a slightly lower standard deviation associated with higher precision. Both P values were only run for two trials, but yielded virtually the same result. We decided to utilize the 260m P value in future experiments due to its slightly higher precision.

Part VI

Conclusions

So far, we have gone through a huge learning process. Since we came in with no knowledge of the system or of process controller, we had to go through a period of adjustments and explorations. After our first trial in which process controller ran 12 times when we had only wanted it to run once, we learned how to change and adjust the rules and methods of process controller. Because we were struggling to use process controller, we have only been able to run a few experiments testing four different PACl dosages. We know now that we have to change the process controller for every experiment we do, based on what PACl dose we want, how it should be adjusted in each run of the system, and how many iterations there should be. With this knowledge, we will be able to run our process more effectively in the future.

Our data still has some major errors associated with it. At very negligible PACl dosages, we were still seeing good performance from the flocculator which does not make sense because if we did not add any PACl into the apparatus, the influent turbidity readings should match the effluent turbidity readings. Our experimental results were also showing that decreasing the PACl dosage does not necessarily mean flocculation performance will worsen. This indicates that we need to do additional experiments to establish a clearer relationship between decreasing PACl dosage and flocculation performance and graphing out the effects of changing one dependent variable. As we have previously mentioned, there are a lot of errors in the method file we are using from the summer team so we will continue investigating all the parameters within the method file to make sure they match with the real apparatus. After making these changes, we hope that the data we get will make physical sense. If we add a negligible amount of PACl into the system, we should see effluent NTU readings close to the influent NTU readings. However, as mentioned earlier, we recently discovered that our actual tubing size had an error associated with the tubing size in the pump control method file. Because of the incorrect input, the effluent turbidity readings could have been much different than we expected, because the pump was trying to pump a different amount based on the input tube size. Although the relationship between the data points should be unchanged by this, the effluent values themselves could be a lot larger. This would mean that what we thought were negligible dosages could have been substantial, leading to the high performance in lowering the effluent turbidity.

As we look back at this semester, we now recognize that many of our problems arose from process controller issues. Most of our data is either invalid or needs to be adjusted due to errors that we had in our method file or that existed in the system itself. For this reason, we have created a Laminar Tube Flocculator Manual so that our errors will not be repeated by future teams. The biggest conclusion that can be made from our work this semester is that the system is not as accurate as it may seem. Even if process controller and the method file, or even the pumps themselves, say that they are running a certain way, there is no guarantee that they actually are. The system has to be checked and adjusted manually to ensure that the data is the best it can be.

Part VII

Future Work

The first thing that the Spring 2015 team should do is to continue to verify if the system is working the way believe it should be. As the Fall 2014 team encountered so many problems with process controller and pump accuracy, the Spring 2015 team should read the Laminar Tube Flocculator User Manual very carefully before conducting experiments. The pumps should be checked to make sure that the actual plant flow rates are at the desired value from process controller. A good thing to do would be to measure manually measure the flow rate of the PACl pump itself, by disconnecting it from the system and seeing what volume is being pumped. If the pumps are not working properly, then they need to be recalibrated and the PID states should be checked.

Other things in the system that need to be checked are whether both turbidimeters are actually accurate by disconnecting them from the system and instead directly connecting them to each other. This should produce nearly identical influent and effluent turbidities, since there would be no real way for flocs and sediment to settle out. Karen Swetland's system had the ability to check turbidity after the flocculator, before settling. This could be compared to the influent turbidity and insured that both turbidity meters were giving comparable readings.

Once the system has been verified, the most important thing to do would be to obtain the ten points of data that we had been trying to obtain. Those points are three points of poor performance, five points along the linear relationship of increasing performance with increasing PACl dose, and two points of maximum performance. The first dosage used would depend on how the system verification went, since the those results would greatly affect the accuracy of data we had obtained. Since the system still performed so well for us when we were putting in nearly negligible amounts of PACl, we are dubious that our results were very accurate. Therefore, once the system is working properly, we suggest starting with the base case that both the Summer and Fall 2014 teams used, which was 1.05 mg/L. Depending on what the results are from that trial, it is up to the discretion of the Spring 2015 team to choose how to increment their dosages.

If the Spring 2015 team is able to obtain these ten points and they can establish Karen Swetland's results, the next step would be to see how capture velocity affects the system. It would be best to use dosages that have already been used, and then vary the capture velocities at those dosages to see whether we have been working at an optimal capture velocity.

Part VIII

References

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