Flocculation and Sedimentation Optimization

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Introduction

As the Flocculation and Sedimentation Optimization Team, our goal for this semester is to improve the performance and efficiency of the flocculation and sedimentation process by incorporating floc recycle into the system. By increasing the number of particles in the influent water, there is a possibility that the coagulant will adhere more to the incoming particles than to the flocculator walls – resulting in a more efficient and economical use of coagulant. Also, the introduction of more particles into the flocculator should increase collisions between particles, thus prompting better capture of the minuscule particles so as to decrease the effluent turbidity. By recycling floc, in cases of influent raw water with low turbidity, the supplemental floc may help the development of a floc blanket as well. The Flocculation and Sedimentation Optimization Team is not new to Agua Clara, but this is the first time the team will implement and test the benefits of a floc recycle.

Literature Review

There have already been multiple studies of the flocculator and components of flocculation such as coagulant dosage and type, turbidity, and residence time. Karen Swetland, in her paper on predicting the performance of flocculator designs, develops a model of performance that is based on these parameters. Incorporated into the model of performance is the efficiency of the coagulant in covering the clay particles, and one sink of coagulant that Swetland mentions is the walls of the flocculator. In figure 2 of her paper - a graph of the fraction of coagulant that sticks to the particles' surface as a function of influent turbidity- it can be seen that the amount of coagulant that does not stick to the clay particles is lower when the influent turbidity is greater than about 150 NTU (Swetland, 2011). In this sense, floc recycle could aid in the efficient use of coagulant by increasing the effective turbidity of the influent raw water. In selecting coagulant dosage, another aspect to keep in mind is the effect of coagulant stacking on top of itself (which does not improve surface coverage of the influent turbidity, and is prone to occur at high coagulant levels).. In addition, as the influent turbidity increases, the floc volume fraction (the volume that the flocs and coagulant take up in the suspension) increases as well, which affects floc collisions.

Another possible benefit of incorporating floc recycle into the water treatment process is the easier production of a floc blanket. Matt Hurst, in his paper on floc blanket performance, discusses the effects of changing the upflow velocity, which, if too large, will result in flocs being swept through the plant without being able to settle out, but if too small will result in detrimental sedimentation (Hurst, 2010). For 100NTU influent turbidity, at which we are first building up the floc blanket, Hurst found the optimum upflow velocity to be between 1.0 and 1.3 mm/s. At an influent turbidity of 100 NTU, Hurst found the alum dosage of 45mg/L to be optimal, and that additional alum was not particularly beneficial. The residence time of floc in the sedimentation tank has a possible effect on the performance of the floc blanket as well, in the sense that the prolonged time in the blanket could cause the breakup of weakly formed floc from the stress of collisions with other particles. Through the use of floc recycle, a possible goal is to achieve optimum values for operating a floc blanket in a treatment plant without the use of excess construction materials.

Flocculator

The current experimental flocculator incorporates rapid mixing to induce the formation of flocs from the particles in the influent water. By coiling PVC tubing around a cardboard tube, differing velocities are created in the influent water and coagulant. The resulting shear forces mix the coagulant and influent so that the particles in the water are coated with coagulant and become “sticky.” In the flocculator, these particles experience laminar velocity gradients, and collide with other particles to form larger flocs. Although the recycled flocs would be added into the influent water before the addition of coagulant, it is expected that their influence will be in the flocculator where the increased floc volume fraction will increase particle collisions.

Coagulant

The turbidity of the effluent water, as well as the range of the turbidity of the effluent water, significantly decreases with the addition of coagulant followed by flocculation. However, the cost of coagulant requires that it be used efficiently. Even with previously tested optimal concentrations, some of the coagulant (due to its “stickiness”) is lost to the walls of the PVC tubing of the flocculator. By increasing the coagulant’s interaction with particles, there may be a decrease in that amount of coagulant that is lost to wall effects.

Hypothesis

By introducing flocs that have already been formed in the floc blanket to the beginning of the flocculator, it is thought that performance of the floc blanket and sedimentation tank will increase. These flocs will be taken from three separate locations, all of which could be optimal places for the flocs to be drawn, depending on the performance of the floc blanket. The first location is the floc weir, where the already "wasted" flocs are coming from the top of the floc blanket in the sedimentation tank, the second location is from the floc blanket in the middle of the sedimentation tank and the third location is near the inlet at the very bottom of the sedimentation tank.

A recycle flow rate of 10% of the flow into the sedimentation tank, Q , is used to transport flocs from the floc draw location back to the beginning of the system where recycle is introduced to the influent water before the coagulant is added. The introduction of already formed flocs to the turbid water should increase the formation of more flocs earlier on in the flocculator, thus capturing more clay particles, earlier on in the system.

It is possible that recycle of flocs may reduce the amount of coagulant to be used with certain turbidity levels. Our experiment starts with 45mg/L alum for 100NTU water, which is thought to be an appropriate ratio to be used in our system. However it is possible that there is a point where too much coagulant actually limits the efficiency of the system to build flocs. One of our goals is to reduce the coagulant to clay ratio to see if a lower coagulant dose can still be effective in turbidity removal.

Methods

Within the first experiment, the first cycle will build a floc blanket with 100 NTU water, 1mm/s upflow velocity and 45mg/L alum for one or more solids residence times. The second cycle will keep upflow constant (1mm/s) but step down both influent turbidity and alum dose to 30NTU and 13.5mg/L alum respectively (note: the ratio between NTU and alum is constant for each cycle in a respective experiment) with the goal of maintaining a floc blanket at the lower turbidity and dose for two solids residence times. The third cycle will keep consistent upflow velocity, turbidity and alum doses as the second cycle (in this example 30NTU and 13.5mg/L) but add in floc recycle at the beginning of the flocculator for two solids residence times. Floc recycle flow will be 10% of the upflow velocity in the sedimentation tank (1mm/s).

The second and third experiments are set up in the same way, everything is kept constant except for the alum dose. For the second experiment alum dose will be 30mg/L for the first cycle when the floc blanket is building at 100 NTU, and will drop to 9.0mg/L as the turbidity drops to 30NTU during the second cycle and then remain at the lower dose for the third cycle. Again, the ratio between alum dose and turbidity remains constant throughout one experiment.

The third experiment will have 15mg/L alum for 100NTU water during the first cycle, followed by 4.5mg/L alum and 30NTU water for the second and third cycles.

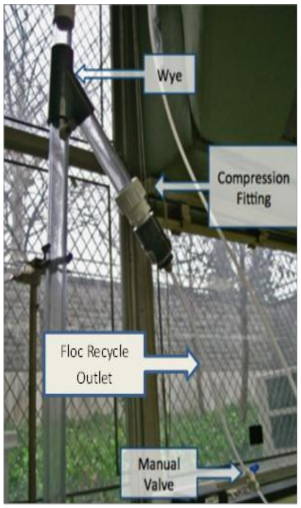
Cleaning the Apparatus

The first step taken in an effort to research the effects of floc recycle on the optimization of flocculation and sedimentation was to make sure there was a reliable baseline to compare the data to at the end of the experiment. First, the flocculator tubing was filled with a solution containing bleach and water and left in the tubing for 3 days. When the bleach solution was drained, the flocculator was left clean and free of the clotted flocs that were initially lining the length of the flocculator tubing. Likewise, a bleach solution was left sitting in the rest of the apparatus, mainly the sedimentation tank and floc hopper, in an effort to get rid of mold that had started growing inside and to clean the walls of the tubing that initially had a cloudy appearance. This bleach was left in the apparatus for 4 days and once drained, the apparatus contained little to no mold inside, however the walls of the sedimentation tank were still relatively unclear and cloudy. Clean water was run through the whole apparatus once more to wash out any additional loose debris. Overall, the apparatus ended up much cleaner than before, despite the cloudy walls of the sedimentation tank; however, it was concluded that the clearness of the pipes should not affect the data. This is just an aesthetic nuisance that is impairs seeing the floc blanket clearly.

After each experiment throughout the rest of the semester the turbidity meters were cleaned out with distilled water and kimwipes so the effects of the previous experiment on our influent and effluent data were not included. In addition, clean water and small pieces of sponge were run through the flocculator to remove mold and collected flocs on the walls of the flocculator tubing.

Set Up

All team members learned how to use process controller so that everyone could run the apparatus and understand the technology behind the system. Additionally, the floc recycle outlet and inlet was rearranged so that flocs would leave the sedimentation tank at the bottom of the floc hopper as indicated in the following picture.



Another change we made to the set up was to create an automatic floc waste outlet so that waste can be removed automatically when the system is run for long periods of time; which is necessary since our the full cycle of one experiment is 39.4 hours. This time length was calculated using

$$\theta = \frac{V * C_r}{Q * C_{in}}$$

to determine floc residence time with V being the volume, C_r the concentration of floc in the sed tank, Q the upflow velocity and C_{in} the concentration of flocs coming into the sed tank. Since the system needs to be run for a large amount of time, the floc weir must be drained so it does not fill up and overflow. Therefore the waste outlet was made, which pulls waste water out of the floc weir when floc recycle is not on. The waste is pulled out at 10% of the upflow rate. To compensate for this adjustment, the raw water flow rate was increased by 10%, that way the desired flow rate Q, is present in the tubular sedimentation tank. This also leads to more comparable results between the control and floc recycle, because .1Q will always be being pulled out and added in. As shown in the picture, either the floc recycle, or waste water is being pulled out at .1Q.

To clean the workspace and avoid problems, we changed all of the unused solenoid valves to manual valves and set them to the closed position. It turned out that some solenoid valves were not operating correctly and proved to be open when they were set at closed, so they were labeled as faulty in order to alert future users.

Trials

Trial 1

The first trial was started on October 5th. The trial was programmed so that the plant would run for one residence time during the build up phase at 100NTU with a coagulant dose of 45 mg/L. Once that time cycle was completed the influent concentration was decreased to 15NTU with a coagulant dose of 6.73mg/L and input for two residences times. Once that sequence was complete the system switched over to floc recycle and ran for two residence times. Floc recycle was drawn from the bottom of the floc weir. Effluent turbidity data was reviewed and the apparatus was cleaned out to get ready for the next trial.

Upon reviewing the data and checking the apparatus it is uncertain whether or not a floc blanket was ever formed and definite that a floc blanket was not maintained at the 15NTU stages of the experiment, which was confirmed by visual observation. Another issue with the first trial was that the influent NTU was not consistently kept at 15NTU. After looking into the situation, the team concluded that there was too great of a lag time between the process control's reading of the influent turbidity and the drip valve that controls the turbidity of the water, which was set at 10 second intervals. Therefore, when the NTU dropped below 15NTU, more clay was added, and continued to be added until the next reading of the influent NTU took place. The result of the long lag time was that the drip valve was open until the NTU increase was eventually observed and, the NTU jumped much too high.

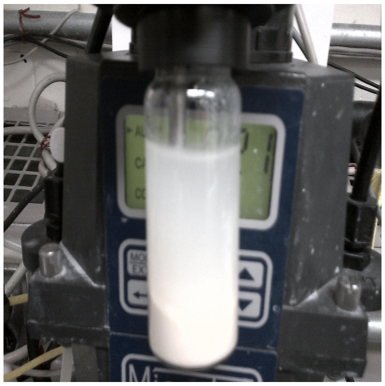
Before running more experiments, the apparatus must be working properly in order to get accurate data. What needs attention the most is the building of a floc blanket. The floc blanket is an essential component of the sedimentation system and needs to be maintained in order to reach low effluent NTU values. Our hypotheses of why a floc blanket was not created include:

1) 15NTU is too low of a turbidity to maintain a floc blanket
2) Upflow velocity of 1mm/s is too high.
3) Coagulant dosing is too high/low.
4) Floc blanket build up stage is not run for enough time

An experiment was run with the sole purpose of producing a floc blanket. The experiment was supposed to build and maintain a floc blanket for over a day, however two hours into the experiment, the influent turbidity was near 800 NTU. This brings forth warning signs of several different issues

1) Process Controller is not programmed correctly or working as expected.
2) The stock of clay mixture was improperly made and is too concentrated.
3) The drip valve going into the small clay stock is not functioning correctly.
4) The turbidity meter is not functioning properly.
5) The plant flow rate is too high, possibly not being regulated properly.

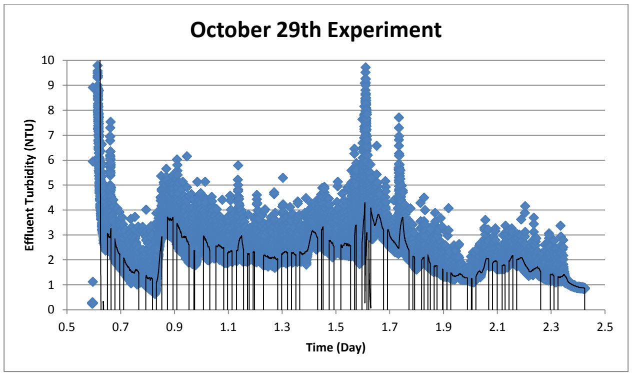
Other issues may exist, but these are the most probable. It was found that the vial in the influent turbidity meter was very dirty, as shown in the figure below, mostly due to such a high turbidity, however it may have gotten very dirty at the beginning of the experiment and then as the actual influent NTU decreased it may have kept reading high NTU. Nevertheless, the influent turbidity meter is now clean. It was also found that the tubing leading into the influent turbidity meter was very dirty and clogged with clay and this was leading to much higher turbidity when the system began running. These tubes were all cleaned out and replaced to fix this problem.



Trial 2

On October 29th a new experiment was started, the main goal of this experiment was to build a floc blanket successfully. During the 100NTU build up stage, a floc blanket was built; however, the floc blanket was not maintained when the experiment switched to stages 3 and 4 with an influent NTU of 15. This can be seen in the graph below of the effluent turbidity versus time, and it is apparent that at .81 days, which is where there was a change in stages, the effluent NTU spiked up from less than 1 NTU to 6 NTU. This suggests that the floc blanket was not maintained when the influent NTU decreased from 100 to 15.

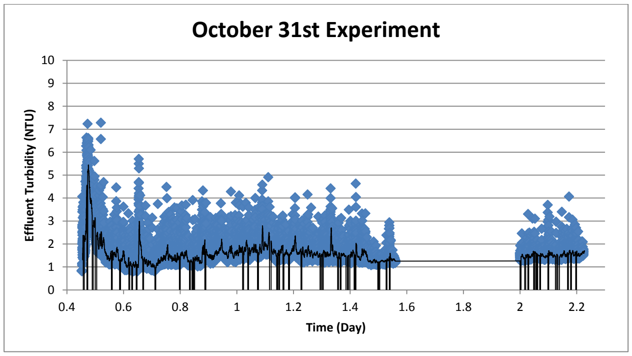
After looking over the graph, it seemed that 15NTU was too low to maintain a floc blanket, therefore it was decided to change the influent NTU in stages 3 and 4 (the control and floc recycle stages) to 30 NTU.



State	Time (fraction of Day)
State 1: 100 NTU Floc Blanket Build up Stage	0.57-0.81
State 3: 15 NTU Control stage	0.81-1.58
State 4: 15 NTU with Floc Recycle	1.58-2.345

Trial 3

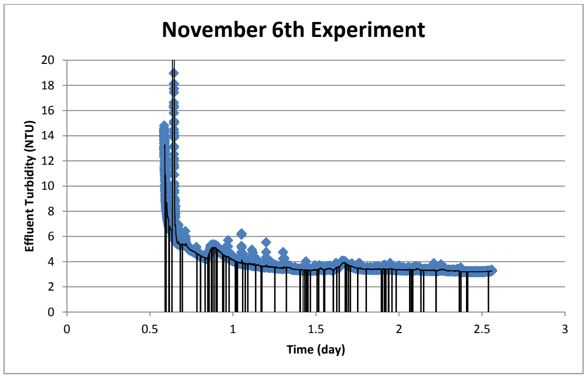
On October 31st another experiment was performed. This time with an influent NTU of 30 in stages 3 and 4 and the alum dose to NTU ratio was set at 45mg/L per 100NTU. Floc recycle was drawn from the bottom of the floc weir. A shown in the graph below, there did not seem to be a change in the effluent NTU between stages. A floc blanket was observed, so it is known that a floc blanket can be maintained at 30NTU. However, the floc blanket was not very dense or high, so it wasn't the most effective floc blanket. Since the floc blanket height did not reach the floc hopper, any floc recycle would not be expected to have a significant effect.



Stage	Time (Fraction of day)
State 1: 100 NTU floc blanket build up stage	0.454-0.696
State 3: 30 NTU control stage	0.696-1.460
State 4: 30 NTU with floc recycle stage	1.460-2.22

Trial 4

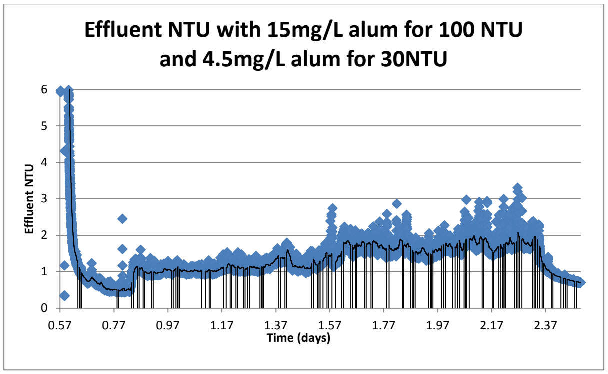
On November 6th, an additional experiment was started. This time the alum dose was set at 30mg/L per 100NTU and the influent NTU in stages 3 and 4 was 30NTU. Floc recycle was drawn from the bottom of the floc weir. Once again the results are inconclusive on the effects of floc recycle and the effluent NTU does not seemed to have changed much between stages.



State	Time (fraction of day)
State 1: 100 NTU floc blanket build up stage	0.586-.828
State 3: 30 NTU control stage	0.828-1.596
State 4: 30 NTU floc recycle stage	1.593-2.358

Trial 5

The last experiment for the 30NTU influent was conducted at a ratio of 15mg/L of alum per 100NTU. Floc recycle was drawn from the bottom of the floc weir. This experiment was cut short due to a power outage, however from the data obtained, the effluent NTU seems to have a significant difference between the stages completed - the effluent turbidity seems to increase with the introduction of floc recycle.



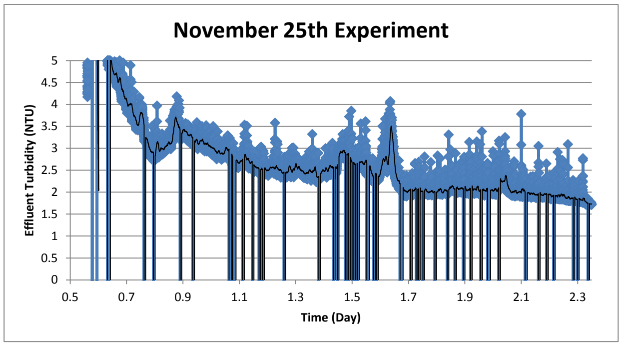
State	Time (fraction of Day)
State 1: 100 NTU build up stage	0.573-0.815
State 3: 30NTU control stage	0.815-1.579
State 4: 30NTU Floc recycle in middle	1.579-2.343

Floc Recycle from the middle of the floc blanket

The next experiments involved drawing flocs for recycle from the middle of the sedimentation tank. The decision to place floc recycle draw here was based on the visual observation that flocs are not being recycled from the end of the floc weir because the floc blanket isn't building up high enough for flocs to enter the weir. It is hypothesized that the probability of recycling a full stream of flocs is higher at a lower position in the system where there will definitely be flocs. By placing the floc recycle in the middle, flocs will be drawn directly from the floc blanket (assuming the floc blanket height is above this position). This should minimize room for error and ensure that flocs are being recycled. One concern is that by recycling from the center the mechanics of the floc blanket may be disrupted, also the floc concentration in the blanket will be lower than what would occur if the floc blanket height reached the floc hopper and flocs settled in the hopper. By drawing flocs from the middle of the sedimentation tank the upflow velocity in the remaining section of the sedimentation tank will be decreased by the flow velocity of the floc recycle line. In our experiments the floc recycle flow rate is 10% the upflow velocity in the sedimentation tank. After the floc recycle draw, the upflow velocity in the remaining section of the sedimentation tank will be 90% of what the original upflow coming into the sedimentation tank was.

Trial 6

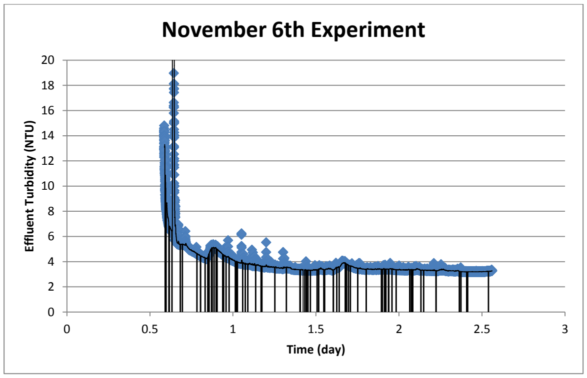
The next set of experiments was done with floc recycle placed in the middle. Instead of taking flocs from the end of the floc weir as before, now the flocs were taken from the middle of the sedimentation tank, about halfway up. This trial was done with an influent NTU of 30NTU in the control and floc recycle stages with a dosage of 13.5mg/L alum. As shown in the graph, there is a decrease in turbidity by roughly .5 NTU when floc recycle is introduced.



State	Time (fraction of day)
State 1: 100 NTU floc blanket build up state	0.5544-0.7964
State 3: 30NTU control	0.7964-1.561
State 4: 30 NTU with floc recycle in the middle	1.561-2.325

Trial 7

The next trial was done with an influent NTU of 30NTU in the control and floc recycle stages with 9.5mg/L alum. Here again the floc recycle was done in the middle. From the graph below, it can be concluded that floc recycle was not effective in this trial. The effluent NTU actually increased by about 1 NTU when floc recycle was introduced to the system.



State	Time (fraction of day)
State 1: 100 NTU floc blanket build up stage	0.586-.828
State 3: 30 NTU control stage	0.828-1.596
State 4: 30 NTU floc recycle stage	1.593-2.358

Conclusions

After having tested floc recycle at an influent turbidity of 15 NTU and not being able to maintain a floc blanket, the Flocculation and Sedimentation Optimization team ran the floc recycle tests on influent water with a turbidity of 30 NTU in order to be able to better discern the effects of floc recycle. While the change in influent turbidity allowed the formation of a floc blanket, not enough flocs were making it to the floc weir (where we initially pulled floc for floc recycle), so the placement of the floc recycle was moved to the middle of the sedimentation tank in order to actually have flocs in the floc recycle stage. The results obtained from the ensuing experiments were rather mixed as to whether floc recycle was beneficial however, as, for example, trial 6 with an alum dosage of 13.5 mg/L saw a decrease in effluent turbidity with the introduction of floc recycle, trial 7 with an alum dosage of 9.5 mg/L saw an increase in effluent turbidity. This could mean that a low alum dose does not coincide well with increasing the influent turbidity with floc recycle. On the other hand, these results suggest the need for further experimentation – although there is a chance that floc recycle makes the effluent water more turbid, there is now some data that supports that floc recycle can improve the system, and as a result this opportunity should be further evaluated.

Future Work

Future work for the Flocculation and Sedimentation team should continue the study of floc recycle. Many problems within the system were encountered throughout the semester and all of the tests necessary to fully understand the effects of floc recycle in the flocculation and sedimentation system were not completed.

Immediate work can include running the same experiments as described above with floc recycle placed at the bottom of the sedimentation tank. Timing this semester did not allow us to test the recycle draw from this location but if would be beneficial to be able to compare the results of floc recycle at three different locations and three different alum doses. It is important that the optimal location for the floc recycle to be drawn from is found so other variables can be tested.

Other variables in the system to consider once the location is solidified is the best alum dosage to use with specific turbidites of water. Three alum doses have been tested but they span a wide range and the dosing should be refined to a smaller range. The optimal alum dose will affect the formation of flocs and the floc blanket and ultimately where floc recycle can occur.

There are many variable to consider and the flocculation and sedimentation team next semester should persevere and continue the study of floc recycle to see if floc recycle can benefit the AguaClara plants.

References

[1] Hurst, Matt, Monroe Weber-Shirk, Leonard W. Lion. *Parameters affecting steady-state floc blanket performance.*Journal of Water Supply: Research and Technology-AQUA. Vol. 59.5, pg 312-323. 2010.

[2] Swetland, Karen A. *Predictive performance model for hydraulic flocculator design with polyaluminum chloride and aluminum sulfate coagulants.* Thesis. Cornell University. 2011