Research Report Summer 2013

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Abstract

The Surface vs. Subsurface Injection for Sand Filtration Team will find the parameters at which the subsurface injection filter becomes clogged. Using the experimental apparatus built in spring 2013, the team will continue research comparing the surface and subsurface sand filters. There are two columns of sand side-by-side, one modeling a surface injection sand filter and the other modeling a subsurface injection sand filter. The team will run experiments and change the filter velocity and coagulant dosage to observe the effectson head loss and effluent turbidity.

Literature Review

Both surface and subsurface injection systems utilize depth filtration, which rely on two categories of particle removal: surface and attachment. In surface removal, particles settle onto a flat surface via gravity or, if they are bigger than the sand pore, get caught between sand grains in a process called interception. In attachment removal, particles stick to sand grains due to either added coagulant or charge attraction. As a result of these particle removal processes, sand filters used in water treatment experience a build-up of particles in the media (called "clogging") and need to be periodically cleaned via backwashing. During backwashing, the flow of water is reversed and the sand bed fluidizes, causing particles to detach from the sand grains and be transported to waste along with the effluent water.The frequency and duration of backwash then depends on how clogged the sand filter is; thus, our research will not only compare the resulting head loss and effluent turbidity of the two injection sites, but also help determine when clogging occurs and whether backwashing is a sufficient method to unclog the filter.

Different factors, including influent turbidity (a measure of the amount of solids in solution), flow rate, PAC dosage, and filter media type, affect head loss and effluent turbidity. The most effective floc size is 0.1 to 0.3 mm because flocs outside of this range may not settle in the filter media. On the other hand, if a floc is too large, it may break up during flocculation ("Coagulation and Flocculation"). After the filter becomes clogged with particles, more head is required to push the water through the filter. Although this resistance to flow decreases the flow rate, turbidity breakthrough will occur if there is enough head and solid particles trapped in the filter bed are pushed through by the water and enter the filtered water (EPA). Since head loss is directly proportional to the square of velocity,we expect head loss to be higher at higher velocities. In addition, higher velocities will break up flocs and does not allow particles to settle easily in the media (Filtration). PAC dosages depend on the quality of raw water, as measured by the influent turbidity. Coagulation does not reduce turbidity itself, but the resulting larger particles help in filtration. (EPA) For low influent turbidity, research shows that coagulant was ineffective. For higher turbidities, it would then be tested how much coagulant was necessary. Filter media design, which refers to grain size, grain type, and bed depth, affects head loss and effluent turbidity. In rapid sand filters, the smaller sand is usually at the top of a pore size gradient, allowing particles to be caught in the first few layers of sand. This allows for depth filtration to occur throughout the filter. Other types of filters use multiple medias, including sand, anthracite coal, and garnet. Having larger particles at the top of the filter allows for longer run times because particles are allowed to settle to the bottom (Filtration). However, in an Stacked Rapid Sand Filter, as defined later in this section, different media cannot be used.

There are three types of head loss: clean bed, clogging, and straining. Clean bed head loss is the initial, unavoidable head loss due to physical factors such as friction from the filter media. Clogging head loss occurs with filtration throughout the filter bed and follows a linear increase over time. Straining head loss is from filtration at the surface due to size and follows an exponential increase over time. With the subsurface injection of water, this straining head loss should be reduced so that only the linear increase remains. Straining head loss can also be reduced by increasing filter media size or decreasing floc size (Hendricks).

The following graph 1 shows expected head loss and turbidity trends over time for a typical water treatment plant filter, given an influent turbidity of around 5 NTU. Head loss follows a linear trend, while turbidity decreases and then increases after turbidity breakthrough occurs. These sort of trends are expected from our own pilot filters, given a long enough run time.

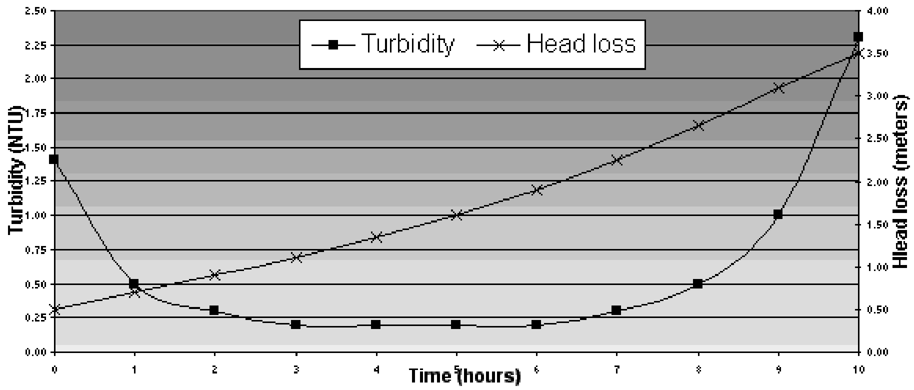

Figure 1: Sample Filter Results (McGregor)

In rapid sand filters (RSF), the coarser nature of the sand (grain size ranging from 0.4 to 1.2 mm) used requires a higher filtration rate and allows for depth filtration. This device is conventionally run in a down-flow direction in order to remove solids from influent water. Thus, once the filter bed is loaded it requires cleaningwith a process called backwashing, which requires a high-rate flow of water back up through the filter bed to remove deposited material that clogged the filter. While slow sand filters use the upper layers of the filter for removal, the RSF is designed to utilize the entire portion of the filter bed efficiently to attain a higher output of water for a given surface area. The RSF requires similar quantities of sand and is equally sensitive to changes in turbidity as compared to the SSF. However, the complexity of the RSF, electricity requirements and high pricing of its pumps deem the rapid sand filter inappropriate for developing countries and areas with limited resources. The amount of the wash water used limits backwash, since wash water comes from filtered water. The filter has a high cost of maintenance and releases large volumes of waste-matter during one cycle. The larger pore size of the filter also fails to remove harmful pathogens smaller than 20 microns. (di Bernando)

The AguaClara team designed a significantly improved method of rapid sand filtration: Stacked Rapid Sand Filters (SRSF). This innovative device is a self-backwashing system that utilizes its stacked geometry to operate using gravity rather than electricity. The SRSF has lower operating and maintenance costs with its simple design and can lower the effluent turbidity to below the US EPA standard of 0.3 NTU (Stacked). The SRSF reduces the amount of filters used and requires fewer materials to be constructed, therefore reducing material costs. In addition to saving money the SRSF also utilizes space more effectively because instead of six filters side by side, the filters are stacked on top of each other. The self-backwashing system of SRSF allows all of its six filter layers to be backwashed in series with the same water, saving resources. The fact that the filters are stacked on top of each other also greatly increases the efficiency of backwashing; in a SRSF, pressure difference produced by closing all but the bottom valve supplies the necessary backwash flow through all of the layers. The system is then backwashed with settled water and does not require any pumps. In conventional rapid sand filters, all six filters need to be backwashed with filtered water and often require pumps to do so. Lower costs and space efficiency make the SRSF more attractive to smaller communities and it is necessary to investigate possible failure modes with this method of filtration. One concern is that the slotted pipes of the SRSF will become clogged easily, and our goal is to determine precisely under which conditions this occurs and how to remedy the situation (i.e. is backwashing alone enough to unclog the filter?).

Background/Introduction

Continuing AguaClara's mission to provide safe drinking water at lower costs, the Surface vs. Subsurface Injection for Sand Filtration team highlighted the potential areas to explore with regard to discovering the conditions that clog sand filters and comparing subsurface to surface injection filter. Suspected variables that are factors for clogging include influent turbidity, filter velocity, and coagulant dosages. The team will test the performance of the Stacked Rapid Sand Filter (SRSF), an AguaClara invention which relies on its unique geometric design for efficient backwashing and uses subsurface injection of water to facilitate depth filtration. The team's goal is to determine the conditions of clogging by varying PAC and flow rate, and ascertain whether backwashing is sufficient in cleaning the clogged filter. Clogging is defined as when headloss starts to increase exponentially in surface injection, or when headloss reaches 1.5 times the sand depth in subsurface injection. Head loss is given by

$$h = f(\frac{L}{D})(\frac{v^2}{2g}) \tag{1}$$

where f is friction factor,D is diameter of the pipe, L is length, v is average velocity, and g is acceleration due to gravity. The team predicts that the subsurface filter will clog more quickly at low filter velocity, where the water is not able to force the particle through the sand bed, and at high coagulent doses, which increase the stickiness of the particles and lodges them to the sand bed. In addition to analyzing head loss, the team will also collect data on the effluent turbidity to compare the performance of the two filters. It has been established by previous research that effluent turbidity will decrease and then increase exponentially when the filters fail. The team will test various filter velocities and coagulent doses to pinpoint more closely the conditions under which the filter will clog, and also record qualitatively the states of the filters and whether backwashing is sufficient in cleaning the filters. By finding concrete and specific values as to when the SRSF clogs, it may be easier to avoid clogging and to prepare for cleaning the clogged fitlers in water treatment plants.

Methods

The previous semester, an apparatus was constructed in order for tests to be run that compare the differences between surface and subsurface injection sand filtration. In order to demonstrate the two types of filtration, two pipes are set next to each other. One pipe has water injected from the top in conventional downflow (surface injection) while the other has water injected into the sand bed, facilitating depth filtration (subsurface injection). The water that is injected into the pipes is amended with varying doses of clay and coagulant. The coagulant used is polyaluminum chloride (PAC) and the clay used is kaolinite clay. The flow rate of the water running through the pipes was also varied in order to test different circumstances. Generally, a set of experiments is run where one variable, such as flow rate, is changed while the other variables, including PAC dosage and clay dosage, are held constant. Since we initally did not have a sense of how long a set of experiments would take over the course of the summer, we would then move on to changing a different variable, such as PAC dosage. By changing different variables, we would be able to get a broader idea of what conditions would cause the sand filters to clog.

The ranges of influent turbidity and coagulant dosages were based off of values from actual functioning AguaClara plants. There is a range of four filter velocities that will be tested. The upper range of filter velocities is based on the backwash velocity of an AguaClara plant divided by six because there are six subsurface filters. The lower range is 50% of this upper range value, and two intermediate velocities were also chosen to test. The clay dosage is going to be kept constant at 100 mg/L for these experiments while the PAC dosage is varied for each set of experiments at each velocity. In order to test if PAC dosages may also cause clogging due to the sand sticking together, a set of experiments will be run where no clay will be added but the PAC dosage will be varied. We decided on a standard run time of two hours because the previous team also ran several of their experiments for two hours and were able to get adequate data demonstrating filter performance. As we want to find when the filters clog, we are going to run these experiments until the filters clog, so run times as long as twelve hours are to be expected. After running through the sand filters, the effluent turbidity and head loss of each column was measured, graphed, and compared. For each experiment, the following variables were recorded: influent turbidity; effluent turbidity of each column; head loss measured through pressure sensors; pump speed for influent water, clay dosage, and PAC dosage; stock concentration of PAC and clay; desired dosage of PAC and clay; and run time.

A few changes have been made to the experimental apparatus and the process controller commands. Instead of inputing a value for the clay pump fraction and PAC pump fraction in order to get a certain desired dosage of clay or PAC, we used method files written for the chemical dose controller to calculate these pump fractions for us. The information needed for this method file was the tubing size, stock concentration, and desired dosage concentration, and with this method file we no longer had to account for a change in dosage due to a change in flow rate or calculate a new stock concentration for the PAC and clay tanks.

In the Process Controller method file are the following states:

- Off: All pumps are off; all solenoids are closed
- Filter: Coagulant pump, clay pump, and the two filter pumps (one for each column) are on; the two solenoid valves near effluent turbidimeters are open, the other two solenoids for backwash are closed
- Backwash: Backwash pump is on (pumping water up through both columns); the two solenoid valves near effluent turbidimeters are closed, the other two solenoids for backwash are open
- Test: The two filter pumps are on at full speed; the two solenoid valves near effluent turbidimeters are open, the other two solenoids for backwash switch between closed and open every 0.5 seconds
- Calibrate: The pumps are on as necessary for calibration purposes
- Toggle: All pumps are off; solenoid valves switch closed and open every 0.5 seconds to check functionality.

The off, filter, and backwash states are the same as used in the previous semester. The calibrate and toggle states were added this semester, while the test state was altered to have filter pumps run at full speed.

Several valves were added in the pipes in order to better control water flow. During the filtration state, the water flow out is greater than the water flow in when the flow rate is low, so valves were added to the pipes leading out of the filters and then partially closed so that the water in the filter wouldn't drain out too quickly. Since this issue occurred so often, we repeated an experiment holding all variables constant where the flow accumulators were taken out in one experiment and then added back in the next experiment to see if the water would keep from draining out without the flow accumulators. The water actually drained without the flow accumulators as well, so we have continued with flow accumulators. The air in the columns indicate that there is a leak somewhere that would allow air to enter an otherwise closed system, but no leaks have been found. The solution to ridding the air out of the columns has been to raise the effluent water pipe to a height above the the sand filter columns. A T-pipe connector is added to the top with one end left open to the air and the pipe then follows down the sink, allowing the water to free-fall out to drain. Allowing the air in the top of the effluent water pipe creates positive pressure in the column, forcing the air in the columns out and keeping them filled with water. The valves in the pipes leading out of the filters are no longer necessary and were removed.

Another issue was clay accumulating in the bottom of the flow accumulator bottles, which lowered the turbidity entering the pipes after the influent turbidity had already been measured. To account for this issue, a T-pipe connector were added so that the water flowed directly into the columns without losing most of its turbidity and there is no longer any exit out of the flow accumulator. The T-pipe connecters allowed the flow accumulators to absorb the force of the pulse caused by the peristalic pump so that the flow into the columns remained steady.

When backwashing, there were two issues. The first issue was that sometimes water would enter from the filters to the flow accumulator bottles, causing them to overflow. The second issue was that water would also flow through both the backwash pipe and the pipe leading to the rapid mix chamber. Valves were added at the pipes connecting the flow accumulator bottles to the filters and the pipe leading to the rapid mix chamber and these valves are closed during backwash. The columns were taken apart so that mesh could be glued onto the top of the column so that during backwash, sand would not be lost in backwashing into the pipes. Sand was also added into the columns at appropriate heights since some sand had been lost - for the subsurface injection, the height is significantly above the water injection site; for the surface injection, the height is the same as the height of the water injection site. The top and bottom of the surface injection column were also tightened to fix leaking that had occurred there.

We had changed the pipe connecting to the clay stock tank to a quarter-inch pipe so that there would be less clogging, which had happened in the pipe with the smaller diameter. However, this method was incorrect because the larger pipe allowed the clay to settle out of the water and into the pipe, changing the intended influent turbidity and causing influent turbidity to fluctuate significantly from ranges of 50 NTU or higher over and under the average turbidity. It is essential to have a small tubing size leading from the clay stock concentration to the pump and from the pump to the rapid mix chamber or else the clay will settle out of the water. In order to solve the issue of clogging, the clay stock concentration was lowered to 5 g/L and the peristaltic pump is run at a higher revolution per minute (RPM) to achieve the same desired clay dosages as before. By running the pump at a higher rate, the water and clay mix is pulled through the system faster and is less likely to clog the small pipe. If there is visible clogging (i.e., the pipe is full of clay and is not translucent), then the pipe should be disconnected after the clay pump and the pump should be run at full speed to fix any clogging.

In order to get a better idea of what occurs in the filtration and backwashing process, pictures and video will be taken of the columns to see how the sand and clay interact during these processes.

Description of Testing Setup

The components of the test setup fall into three catagories: input system, sand columns, and sensor system. The input system components determine the composition of the water that we need for a specific filtration test. It is able to vary filter velocity, coagulant dosage, and clay dosage (i.e. how dirty the water is before filtration). The two sand columns are where the sand filtration occurs. Dirty water flows down through the sand beds and clay flocs are filtered out. The sensor system allows us to measure influent and effluent trubidities, as well as head loss across the columns.There have been slight changes in how water flows throughout the plant since the design from Spring 2013, which are included in the explanation below.

More specifically, the components of the test setup are described in the following two figures, the first of which is a labeled diagram, and the second is a labeled photo of the test bench. The purpose of each component is described in the following list:

(a) Clean water is taken from the temperature controlled (Temperature set to 20ºC) and aerated clean water supply tank in HLS 160.

(b) Water mixed with clay is stored in a stock tank. This stock is constantly being stirred by an electric mixer. The concentration of clay in this stock tank was varied according to the test we were currently running. We would vary the clay concentration and the clay pump (d) speed until we achieved the desired NTU on the influent turbidity.

(c) Water mixed with PAC coagulant is stored in a stock tank.

(d) Two separate peristaltic pumps were used to pump the clay stock solution and the coagulant stock solution from their stock containers to the influent water tubing. The speed of each could be varied to achieve the desired level of coagulant or clay concentration in the influent water solution.

(e) A rapid mix chamber was used to mix the coagulant solution with the clay water solution. This chamber created high turbulence water that mixed the two separate solutions into one uniform solution, most likely forming small clay flocs in the process.

(f) An influent turbidimeter measured the turbidity of the water/clay solution before it passed through the sand filters.

(g) Two peristaltic pumps pump water through the sand columns in the downward direction.

(h) Two flow accumulators are used to smooth out the water flow from the peristaltic pumps. The flow accumulators are closed containers and water does not actually flow through the bottles.

(i) Pressure sensors are installed across the sand columns. These sensors measure the difference in head between the top and the bottom of the sand columns. These sensors are zeroed before each test, when the water is not flowing.

(j) A fitting with a small tube is used to inject water into the middle of the bed of sand. Due to the small diameter of the tube, the water velocity through it is very high. This subsurface injection fitting allows us to create conditions similar to the slotted pipes in the AguaClara SRSF. A diagram of water through each of the two sand columns is provided in a following figure. We have chosen the diamater of the tube so that the velocity of water exiting from the subsurface injection fitting into the sand bed is very close to that of the velocity of water exiting the slotted pipe in the AguaClara SRSF.

(k) Two solenoids control the flow out of the bottom of the columns. These solenoids are open during filtration, and closed during backwash.

(l) The effluent turbidity of both sand filters is measured.

(m) A peristaltic pump is used to backwash both columns between tests. This pumps water up through the columns, fluidizes the sand beds, and flushes all the deposited clay from the previous test.

(n) Two solenoids control the flow of water out of the top of the sand columns. These solenoids are open during backwash and closed during filtration.

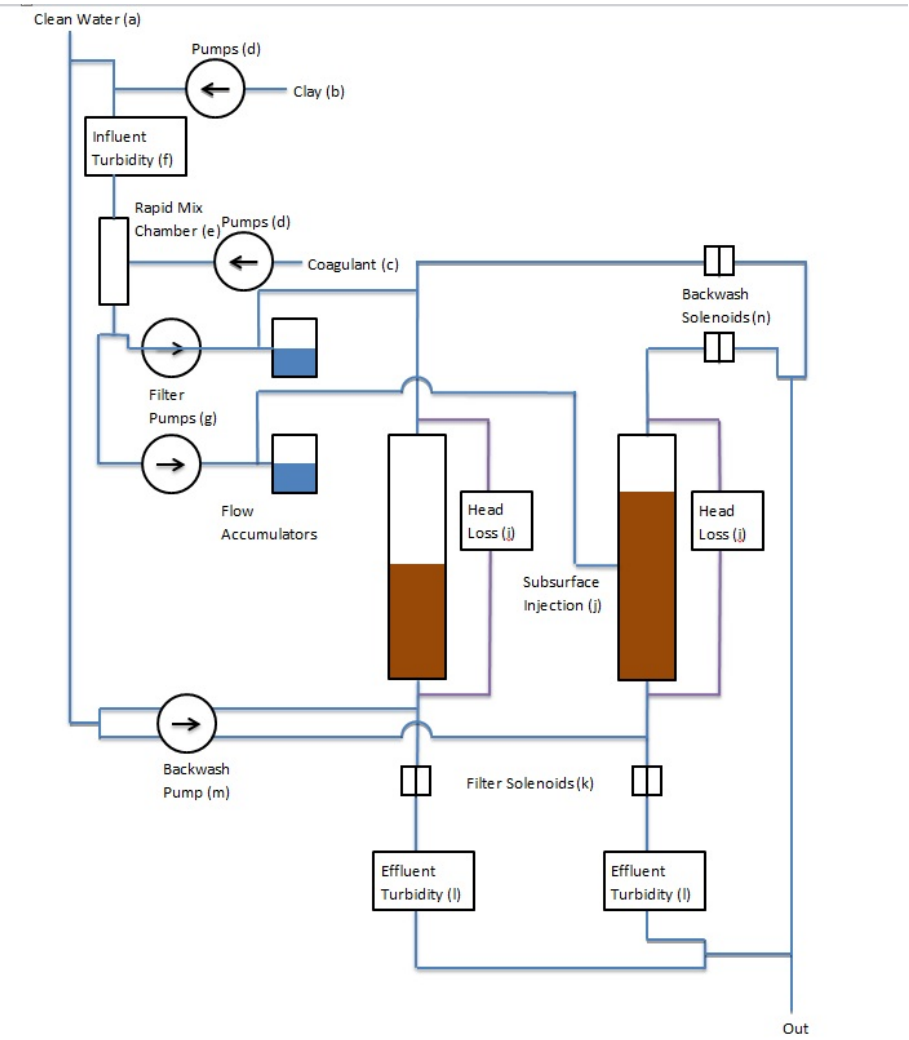

Figure 2: Schematic of Experimental Apparatus

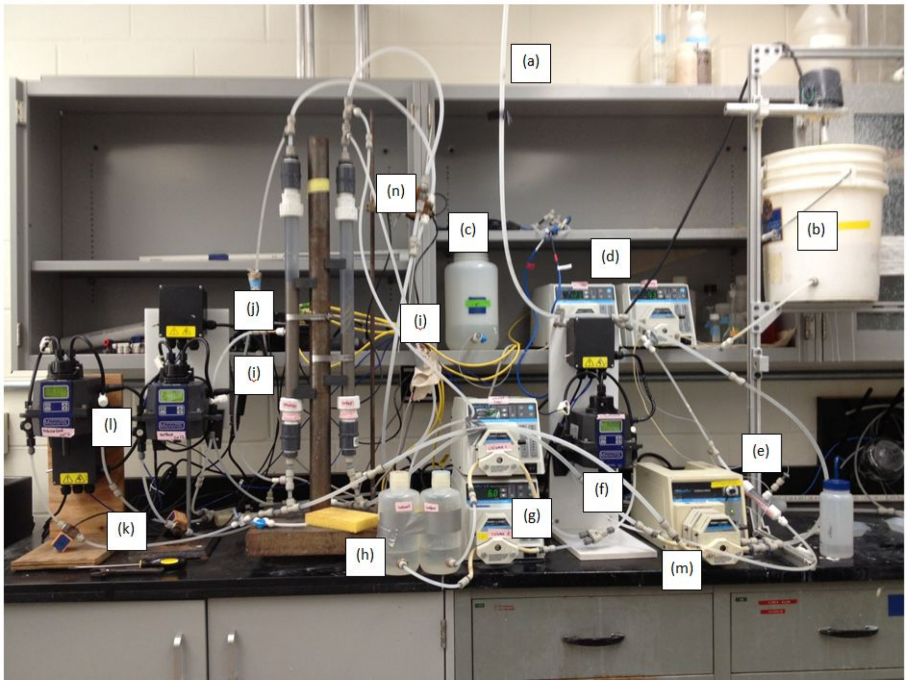

Figure 3: Photo of Experimental Apparatus

Qualitative Observations

During filtration, the water entering the surface filtration column by conventional downflow is turbid and clay particles can be seen floating down through the water. These clay particles form a blanket of clay on top of the sand and tends to form flocs as the clay builds up. There is depth filtration in the surface injection filter as white clay particles can be seen dispersed throughout the upper layers of sand, but most of the clay is filtered out on the surface. In the subsurface injection column, white clay particles could be seen throughout the sand filter beneath and around the injection site. The water above the sand in this column was not as turbid, as most of the clay was trapped in the sand and orm smaller flocs in nature than those in the surface column. Shown below are the subsurface (left) and surface (right) columns after running an experiment at filter velocity 1.2 mm/s and PAC dosage 15 mg/L for 17 hours.

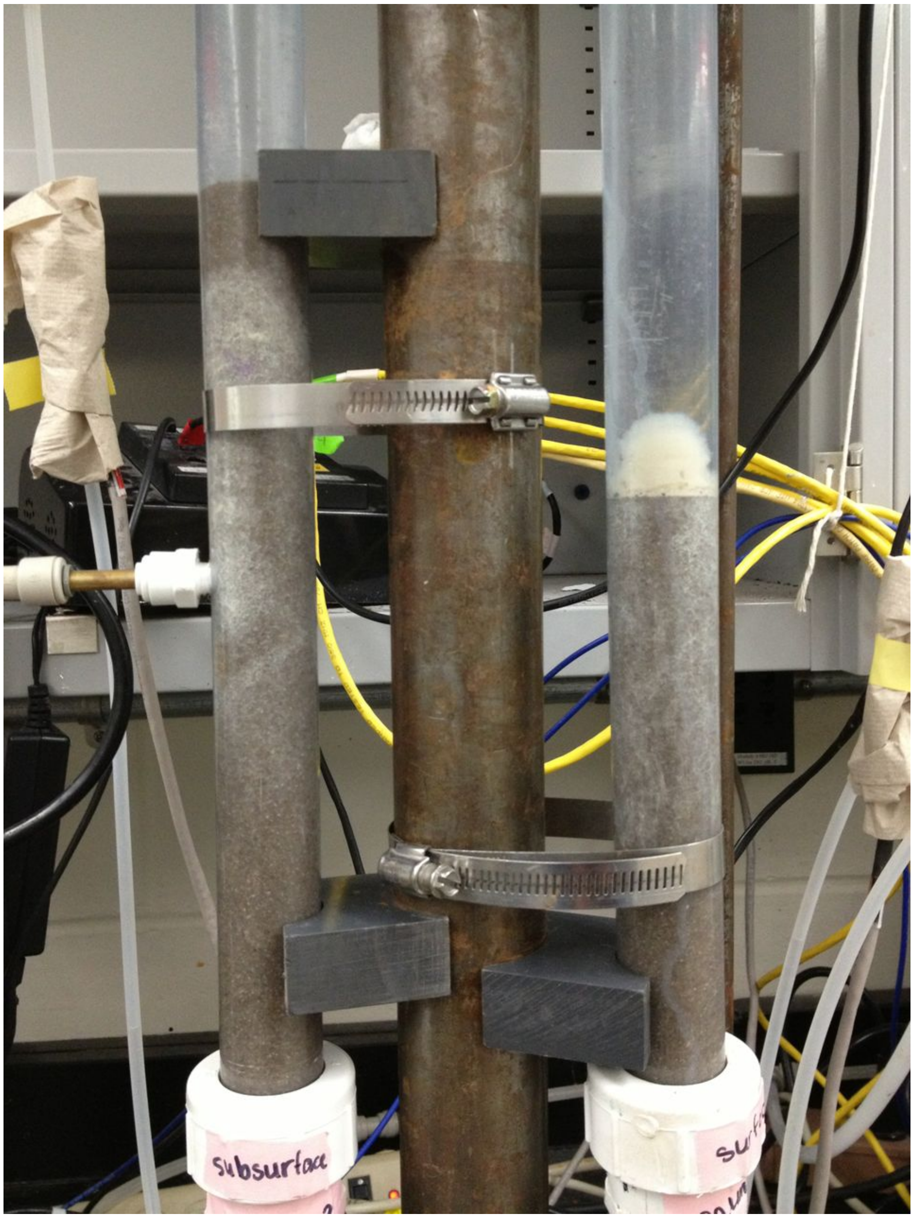

Figure 4: Influent Turbidity: 120 NTU; Filter Velocity: 1.2 mm/s; Coagulant Dosage: 15 mg/L

Low filter velocities and high PAC dosages increase the amount of particles settling in the sand filters because those conditions make it harder for the water to push through.

An experiment with a PAC dosage of 80 mg/L, filter velocity of 1.8 mm/s, and no clay added, there was a build-up of translucent white material on top of the sand in the surface injection column. The substance appears different from the usual solid white clay and we suspect that this substance is coagulant mixed with water settling on top of the sand. The flow accumulator for the subsurface accumulator overflowed, which might have been because the coagulant clogged the sand at the injection site and would not allow water to pass through.

While backwashing, it is noted repeatedly that the subsurface column experiences far less difficuly than the surface column in removing flocs. The subsurface sand bed fluidizes well and the particles are small enough in nature that they exit to waste with the effluent water, leaving no visible clay particles in the column after cleaning. In the surface column, a layer of large clay particles (estimated to be as large as 0.7 mm in diameter) stay suspended above the fluidized sand bed and does not exit with the effluent water. In attempts to break up the clay particles, we have increased backwash pump speed from the usual 300m to up to 1000m and also increased backwash time from the usual 5 minutes to up to 30 minutes; however, the clay particles don't break up easily and we often had to run new experiments with small paricles of clay already present in the column.

Quantative Analysis

Head Loss

Note on head loss: In several of the experiments, the flow rate out of the column was greater than the flow rate into the column. As a result, the water drained partially in the column. Although the filter was still functional if there was some water above the sand level, the pressure sensors would read the pressure difference between air and water as head loss, resulting in inflated head loss values. In the apparatus, we tried to rectify this issue by inserting valves in the pipes leading out of the columns and partially closing the valves, forcing the flow rate out to lessen. However, this method was mostly used after the column had already drained. We have tried to account for the pressure difference in the head loss graphs by normalizing the data around a zero that would be closer than the observed zero in order to find true head loss values as well as calculating the difference between the maximum and minimum head loss after the time it appears that the column drained. In other experiments though, the water drained gradually and resulted in a graph of a steadily increasing head loss at an extremely high rate. According to theory we suspect there to be a trend with the influent turbidity and head loss, but occurence of air in the filter prevents us from observing this trend.

Head Loss and Influent Turbidity

As seen in Figure 5, at this time there does not appear to be a distinct relationship between the influent turbidity and the amount of head loss within the columns. However, column 2, the subsurface injection column, has demonstrated consistently lower head loss than column 1, the surface injection column, at every value of influent turbidity tested.

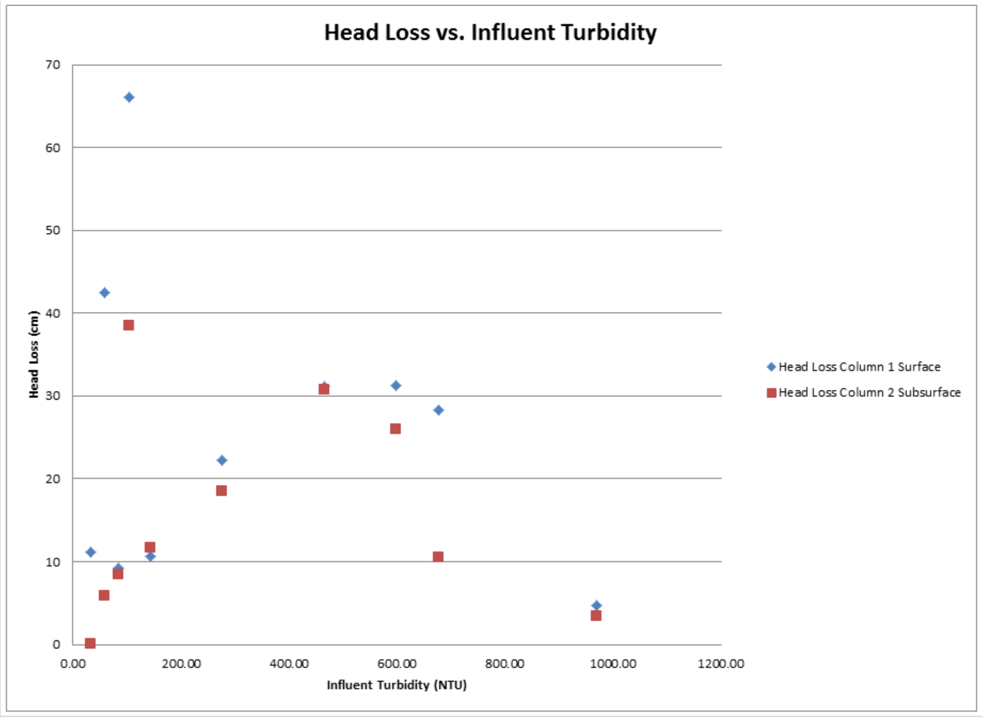

Figure 5: Filter Velocity: 5 too many figures!!! mm/s; Coagulant Dosage: 5 or 15 mg/L

Head Loss and Velocity

The general trend as shown in Figure 6 is that head loss increases as velocity increases. There are large spikes in the data, but these are due to the columns partially draining and allowing for a large pressure difference. It appears that the subsurface injection column experiences less head loss overall compared to the surface injection column, except for where these spikes occur.

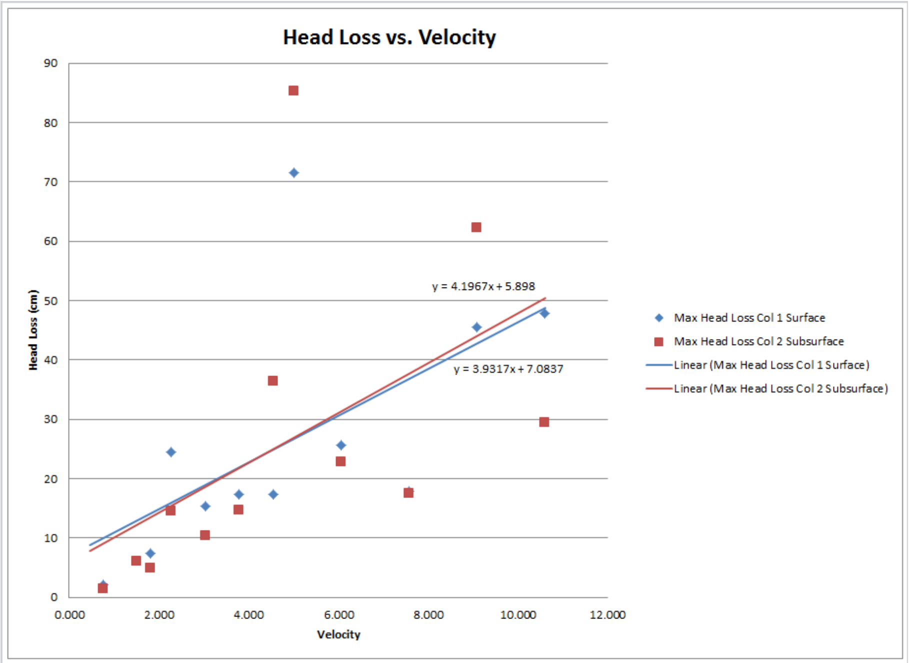

Figure 6: Influent Turbidity: ~120 NTU; Coagulant Dosage: ~15 mg/L

Head Loss and PAC Dosage

As the PAC dosage was increased the head loss increased linearly for both the columns at two different flow rates. The first data set, shown in Figure 7, shows the relationship as the velocity is kept constant at 4.5 mm/s. The second data set, shown in Figure 8, shows the relationship with the velocity kept constant at 10.6 mm/s. At the higher flow rate the second column appeared to have the sharper increase of head loss as the PAC dosage was increased. At the lower flow rate the first column experienced the sharper head loss.The precise relationship between PAC dosage and head loss is still unknown and further tests should be run to understand how PAC dosage factors into the relationship for both surface and subsurface injection filtration.

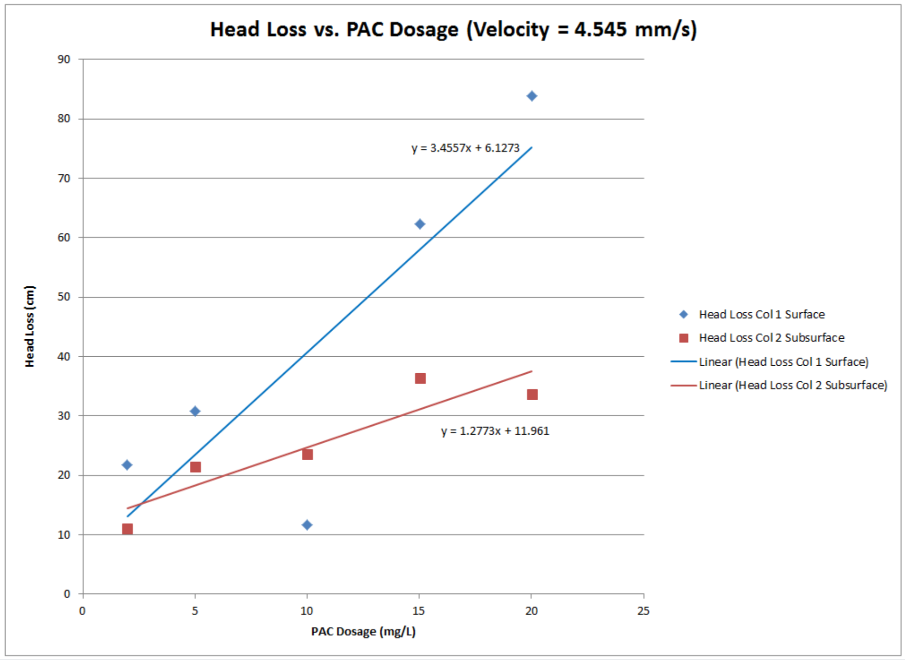

Figure 7: Filter Velocity: 4.5 mm/s; Average Influent Turbidity: 170 NTU

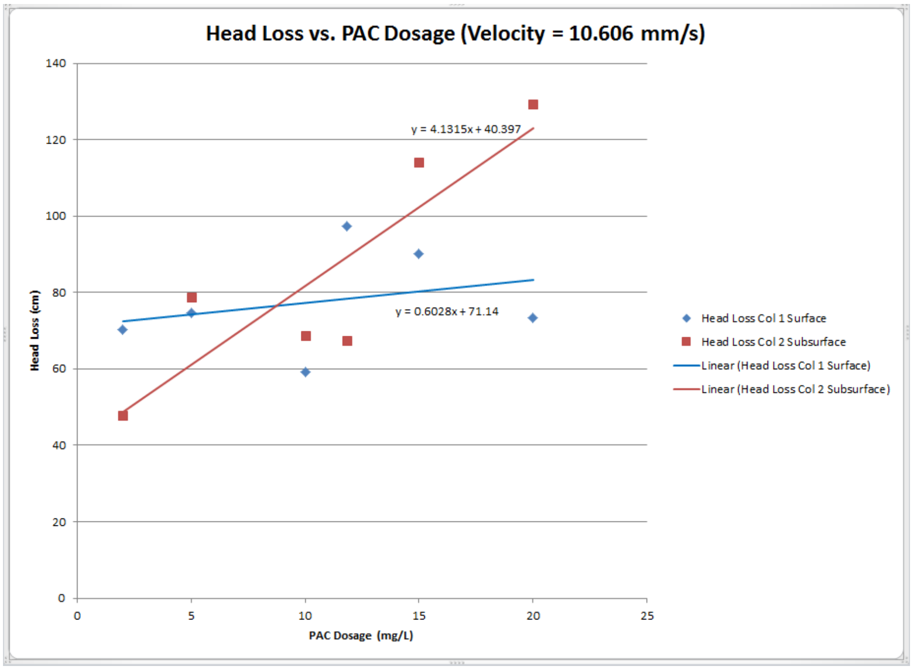

Figure 8: Filter Velocity: 10.5 mm/s; Average Influent Turbidity: 170 NTU

Head Loss Over Time (For Various Influent Turbidity Levels)

At very low (32.93 NTU) and very high (969.94 NTU) turbidities, shown in Figures 9 to 12, subsurface headloss remained constant while surface headloss steadily increased over time, at rates of 2.3 x 10^-3 cm/s and 3.3 x 10^-3 cm/s respectively. In addition, at these 2 turbidities subsurface headloss is generally lower than surface headloss. At middle turbidities (ie 104.92 NTU and 598.1 NTU), although subsurface injection site experienced more headloss than surface overall, the rate of headloss increase is lower for subsurface, suggesting that if the plant is kept running surface headloss will eventually be higher than subsurface headloss. The head loss is different for higher turbidities due to the presence of more amounts of clay.

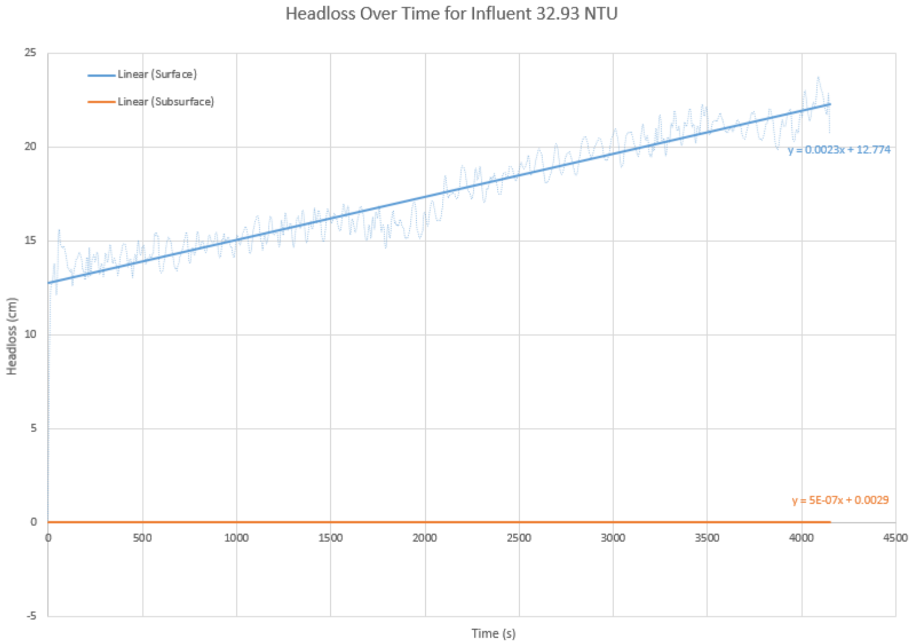

Figure 9: Influent Turbidity: 30 NTU; Filter Velocity: 5 mm/s; Coagulant Dosage: 5 mg/L

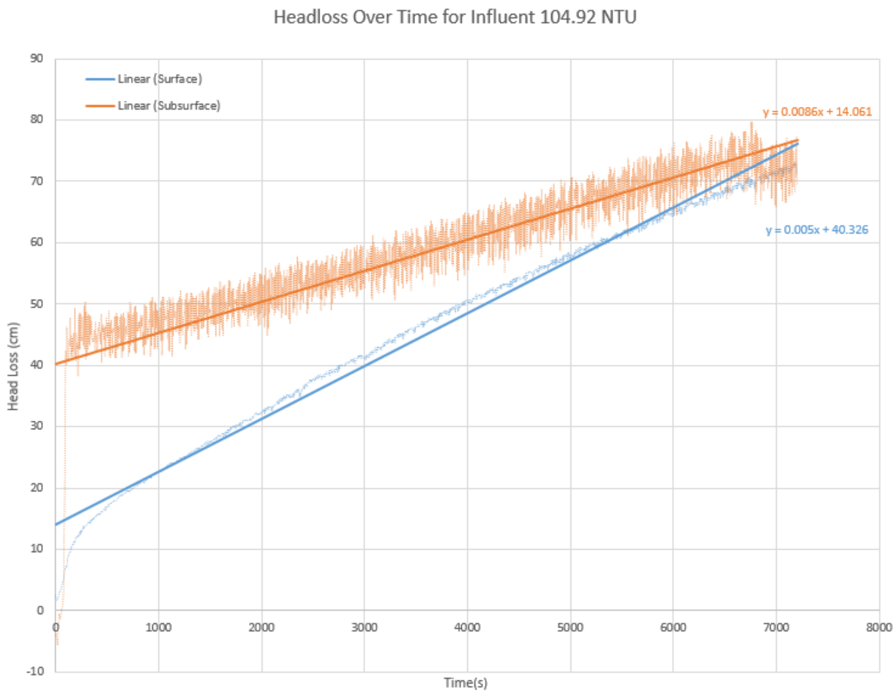

Figure 10: Influent Turbidity: 100 NTU; Filter Velocity: 5 mm/s; Coagulant Dosage: 15 mg/L

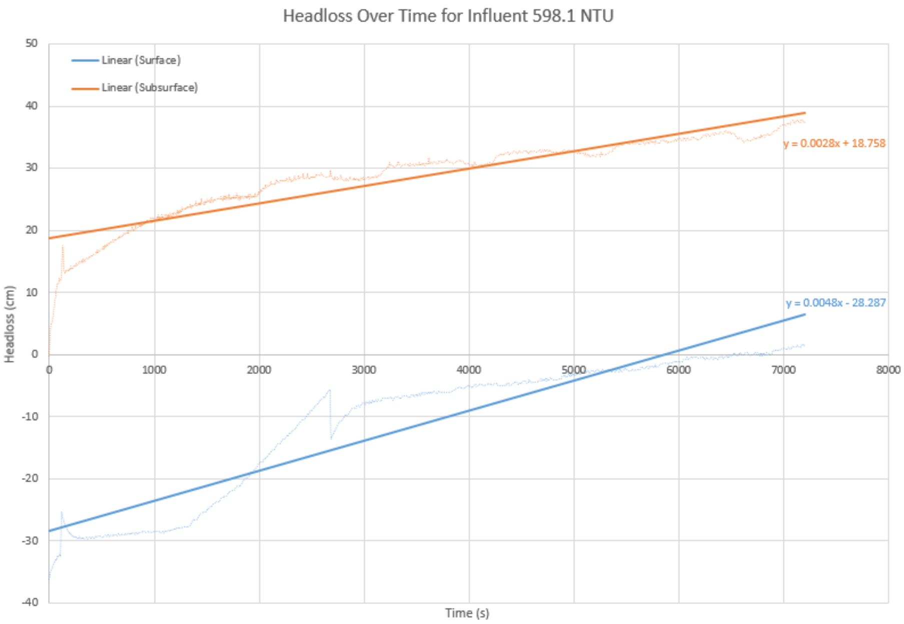

Figure 11: Influent Turbidity: 600 NTU; Filter Velocity: 5 mm/s; Coagulant Dosage: 5 mg/L

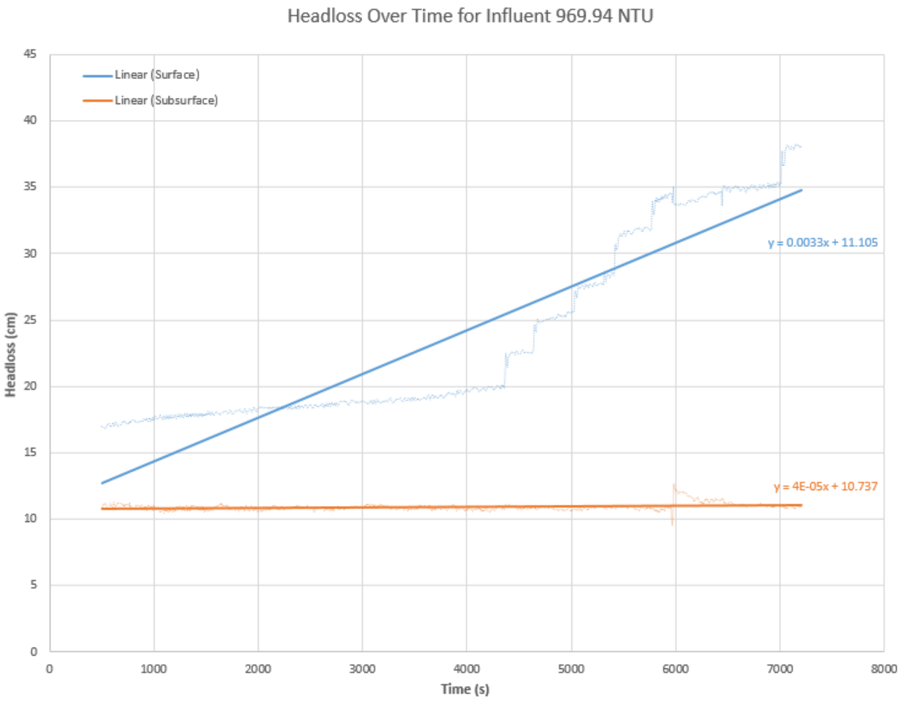

Figure 12: Influent Turbidity: 970 NTU; Filter Velocity: 5 mm/s; Coagulant Dosage: 15 mg/L

Head Loss Over Time (For Various Velocities)

In all three representative velocities(1.5 mm/s, 3.8 mm/s, 11 mm/s), as shown in Figures 13 to 15, subsurface head loss is generally lower than surface head loss. In addition, subsurface head loss increases at a slower rate than surface head loss. This discrepancy is most drastic in the lowestvelocity (1.5 mm/s) where the surface head loss increases at a rate of 0.011 cm/s while subsurface increases at a rate of 0.0009 cm/s.

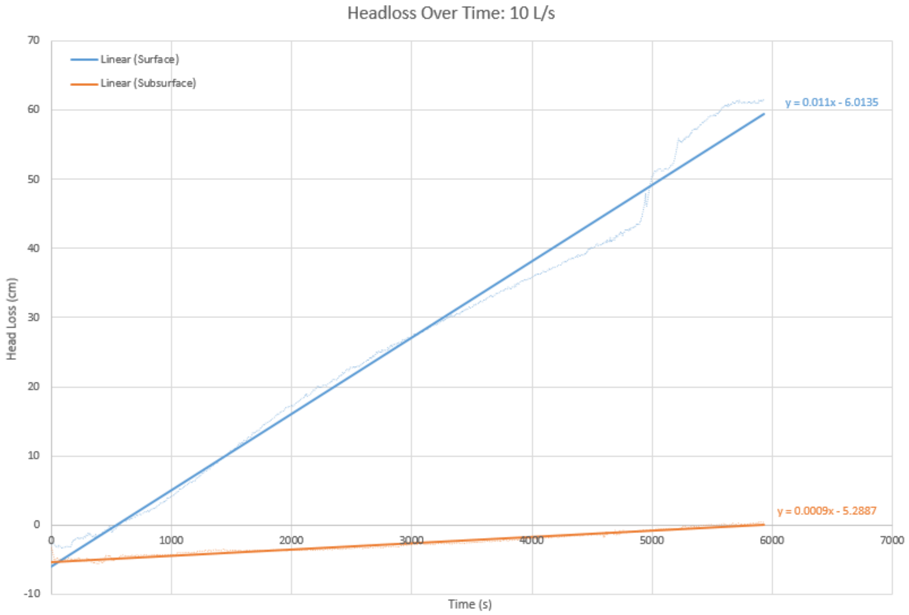

Figure 13: Influent Turbidity: 100 NTU; Filter Velocity: 1.5 mm/s; Coagulant Dosage: 15 mg/L

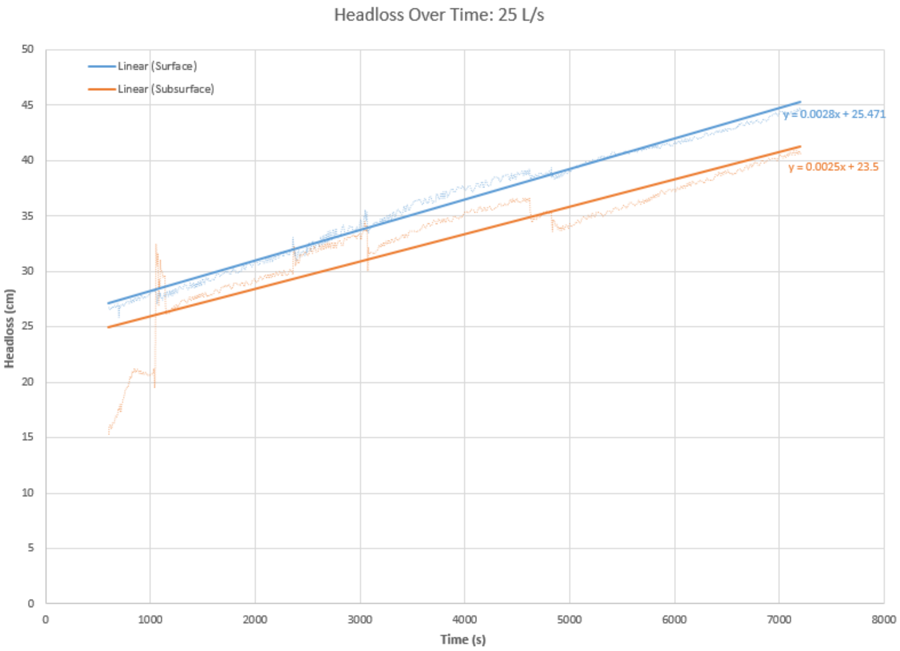

Figure 14: Influent Turbidity: 170 NTU; Filter Velocity: 3.8 mm/s; Coagulant Dosage: 15 mg/L

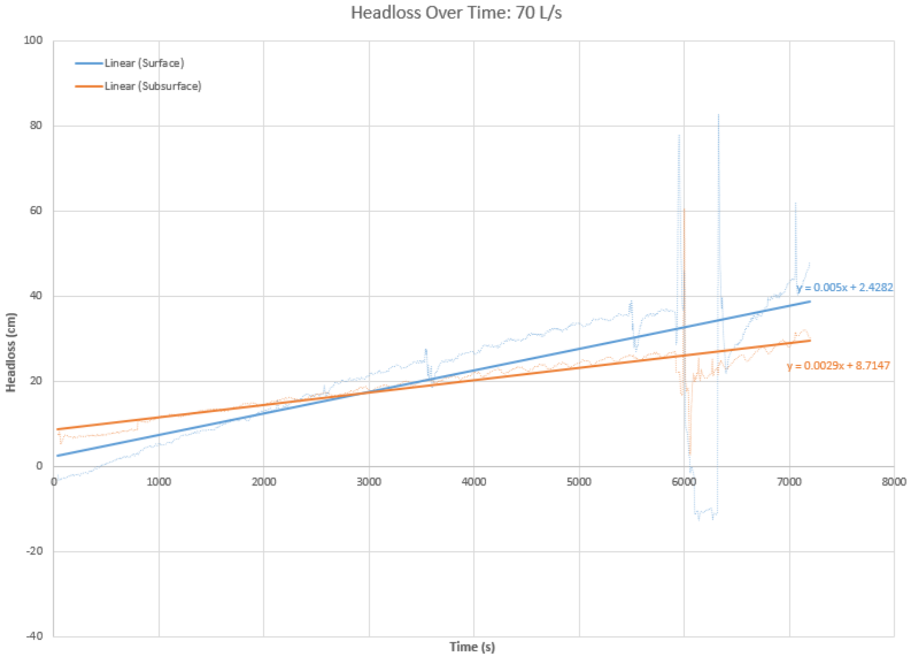

Figure 15: Influent Turbidity: 200 NTU; Filter Velocity: 11 mm/s; Coagulant Dosage: 13.8 mg/L

Head Loss Over Time (For Various PAC Dosages)

As shown in Figure 16, head loss followed a linear trend even after a run time of over 22 hours. Clogging did not occur in the sense that the head loss trend never became exponential, so more experiments should be run with an even higher PAC dosage to induce clogging. However, head loss had increased to over 40 cm, rendering the filters mostly ineffective as the elevated head eventually creates enough shear force to push clay particles attached to the sand through to the effluent water. The experiment was thus ended due to this condition.

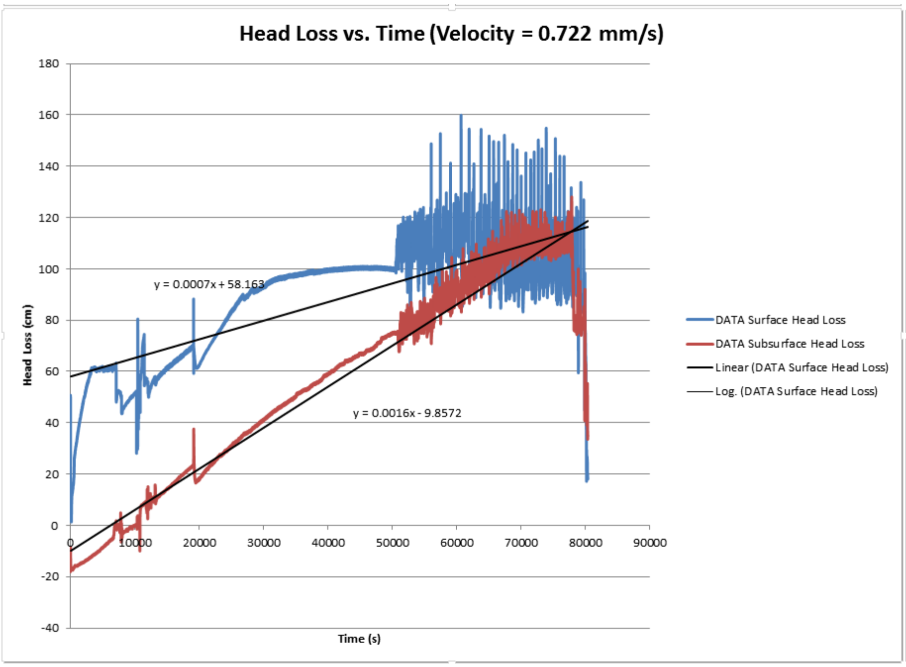

Figure 16: Influent Turbidity: 820 NTU; Filter Velocity: 1.833 mm/s; Coagulant Dosage: 15 mg/L

Experiments Run at 0.7 mm/s

The following graphs (Figures 17 to 24) all represent the same five experiments on different x-axis in order to demonstrate which parameters affect head loss. These experiments were all ran at a filter velocity of 0.7 mm/s and a clay dosage at 100 mg/L. Since the turbidimeter had recorded the turbidity of influent water after the coagulant was added to the mixture in this set of experiments, the influent turbidity is not actually known but is estimated to be 170 NTU after running several other experiments which had influent turbidity recorded before the coagulant was added to the mixture. There is not an apparent trend among these five experiments as to how these factors affect head loss. It is also important to note that these experiments were ran before it was discovered that the surface backwash solenoid valve was broken, which may explain certain spikes in the data as the open valve could have allowed water to flow out of the column.Adjust the x-axis on Figure 24 so that you don't have so much unused graph space. Also, try normalizing the time axis on Figure 17 so that the runs are easier to compare (divide all of the times by the total run time so that your x axis becomes a fraction of the experiment run time)

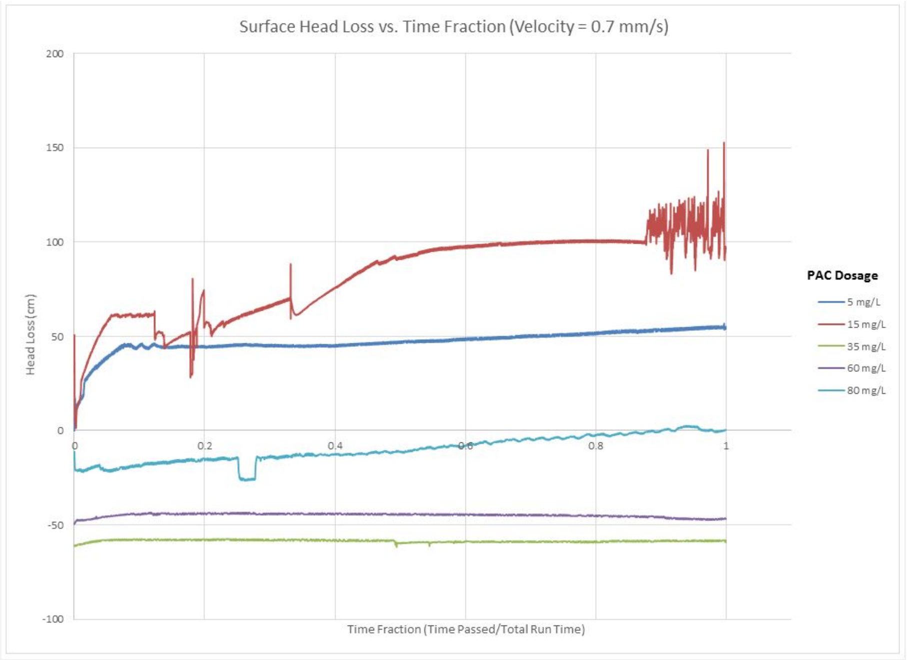

Figure 17: Influent Turbidity: 170 NTU; Filter Velocity: 0.7 mm/s

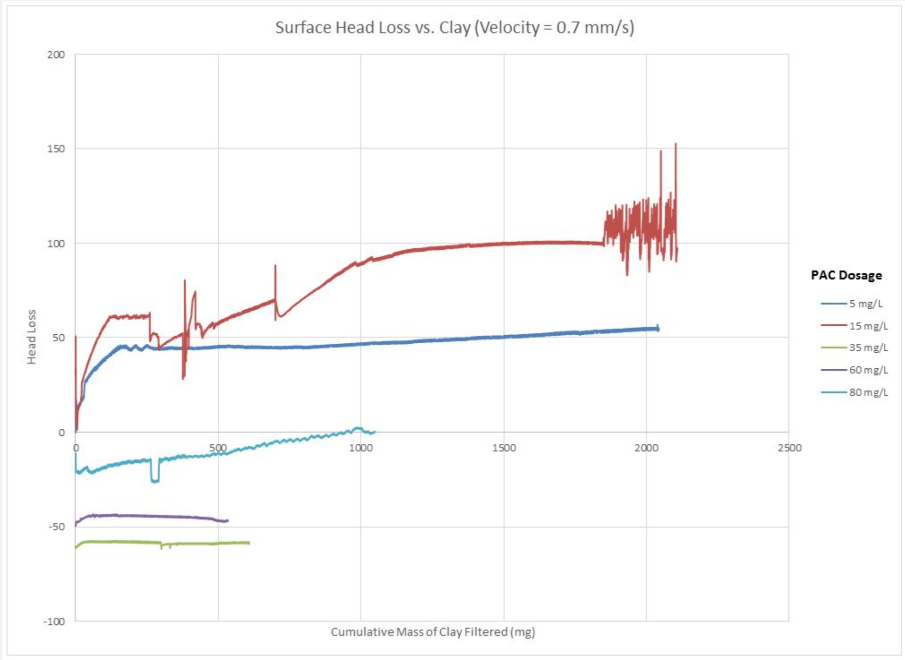

Figure 18: Influent Turbidity: 170 NTU; Filter Velocity: 0.7 mm/s

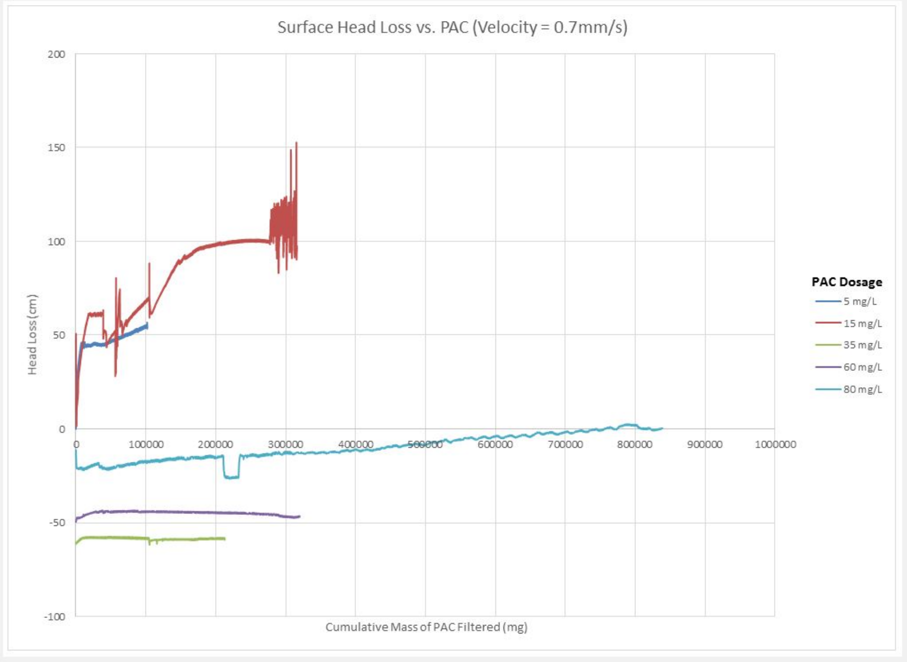

Figure 19: Influent Turbidity: 170 NTU; Filter Velocity: 0.7 mm/s

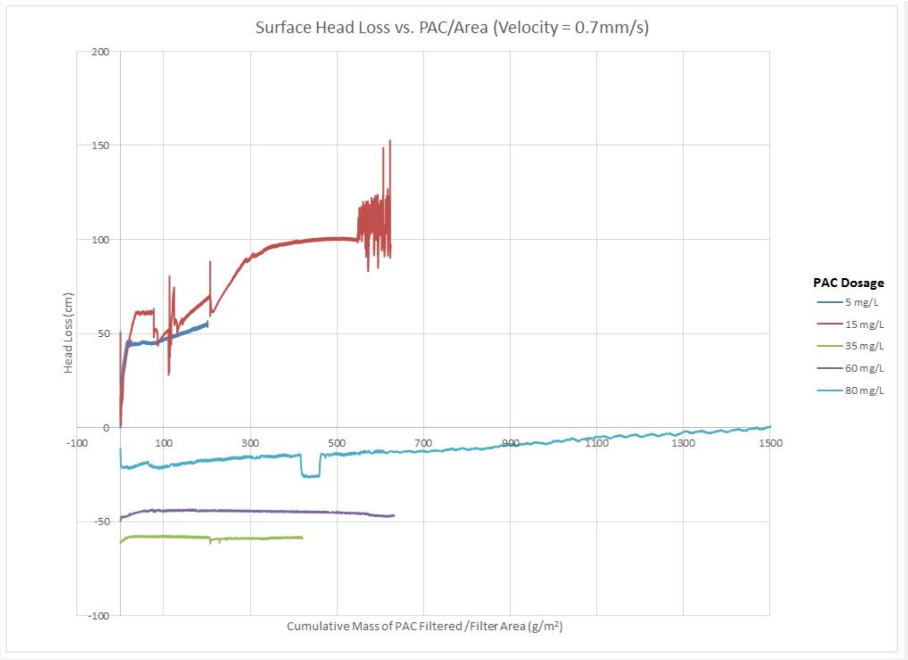

Figure 20: Influent Turbidity: 170 NTU; Filter Velocity: 0.7 mm/s

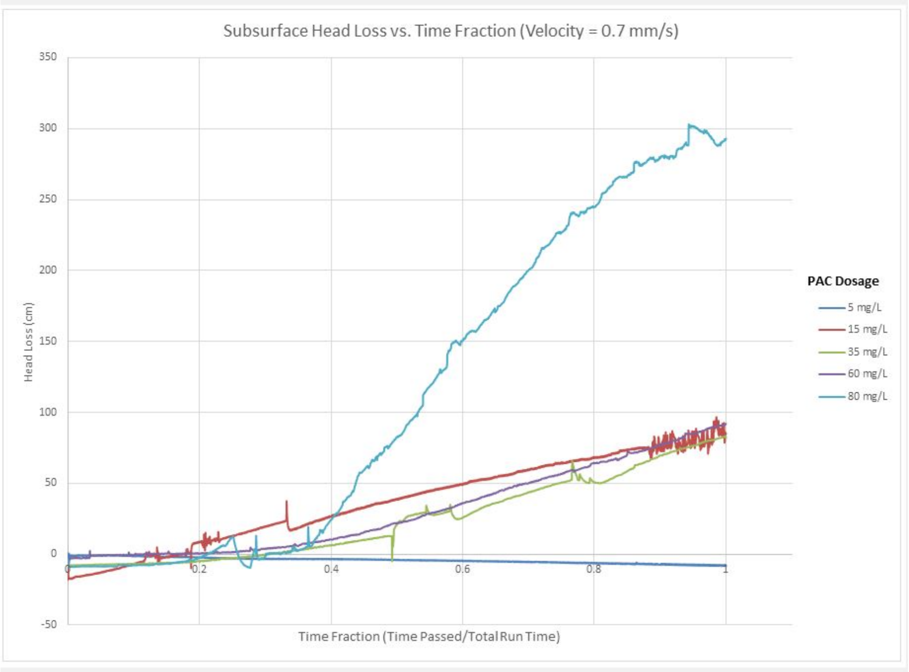

Figure 21: Influent Turbidity: 170 NTU; Filter Velocity: 0.7 mm/s

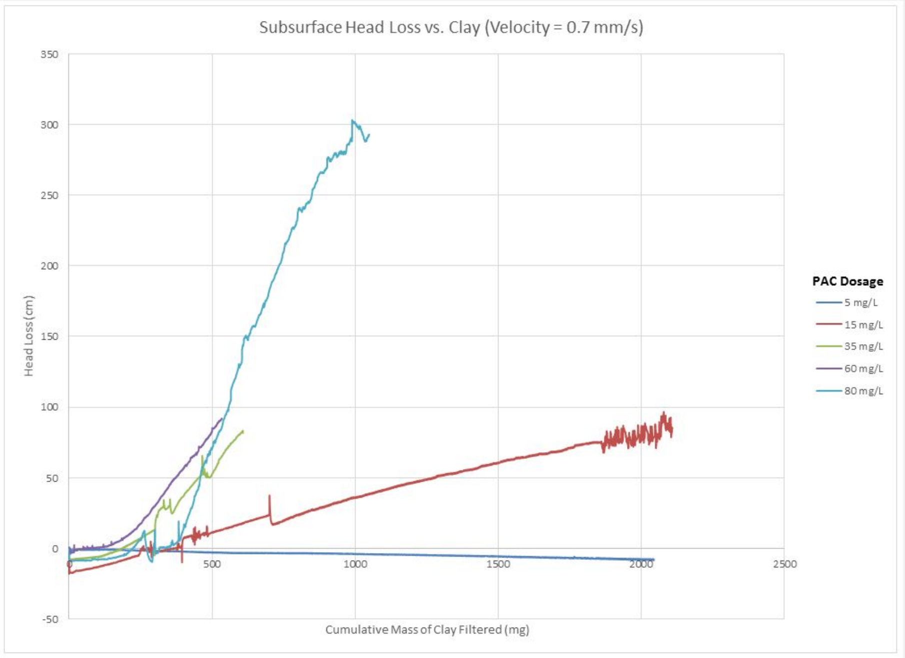

Figure 22: Influent Turbidity: 170 NTU; Filter Velocity: 0.7 mm/s

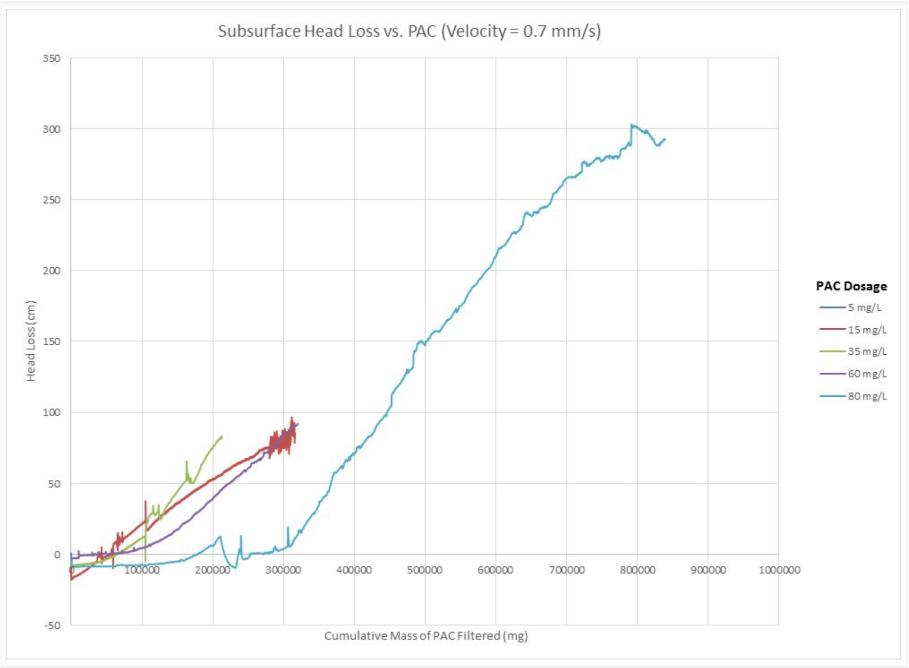

Figure 23: Influent Turbidity: 170 NTU; Filter Velocity: 0.7 mm/s

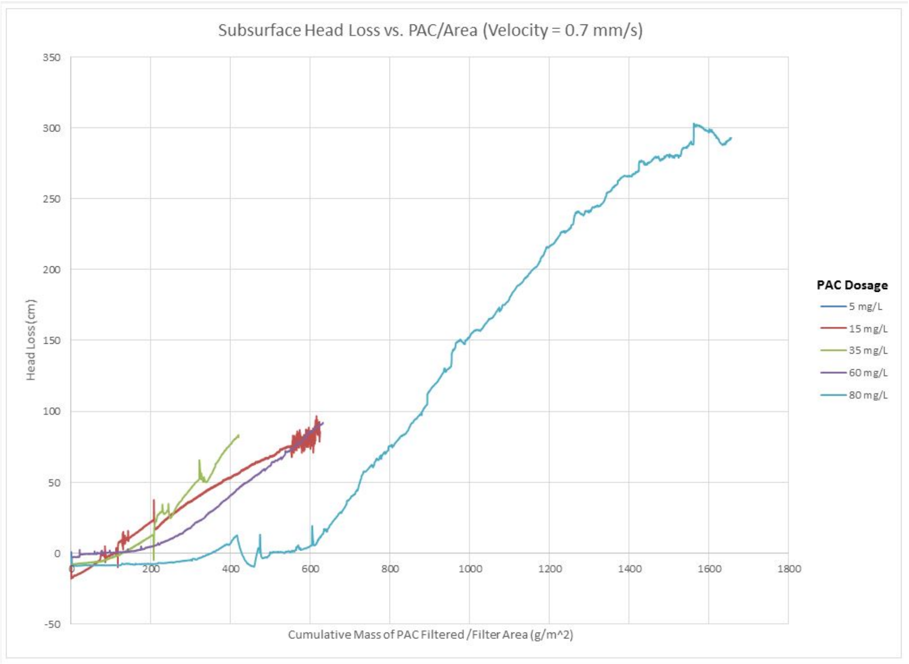

Figure 24: Influent Turbidity: 170 NTU; Filter Velocity: 0.7 mm/s

The following graphs (Figures 25 and 26) show the turbidity levels over time for these same five experiments. There is not any apparent trend of filter performance for these five experiments. It is noted that subsurface injection filter performs significantly better than the surface injection column, though subsurface injection tends to clog faster than surface. Try normalizing the time on the below graph as well. Also, be sure to make the x-axis cross the y at the lowest value (which may not be zero for your log plots)

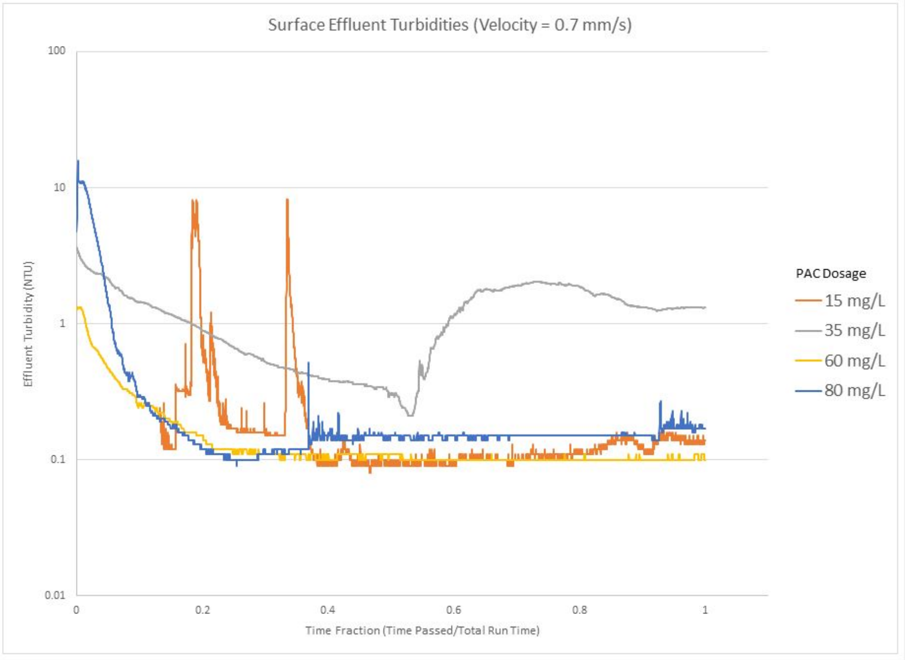

Figure 25: Influent Turbidity: 170 NTU; Filter Velocity: 0.7 mm/s

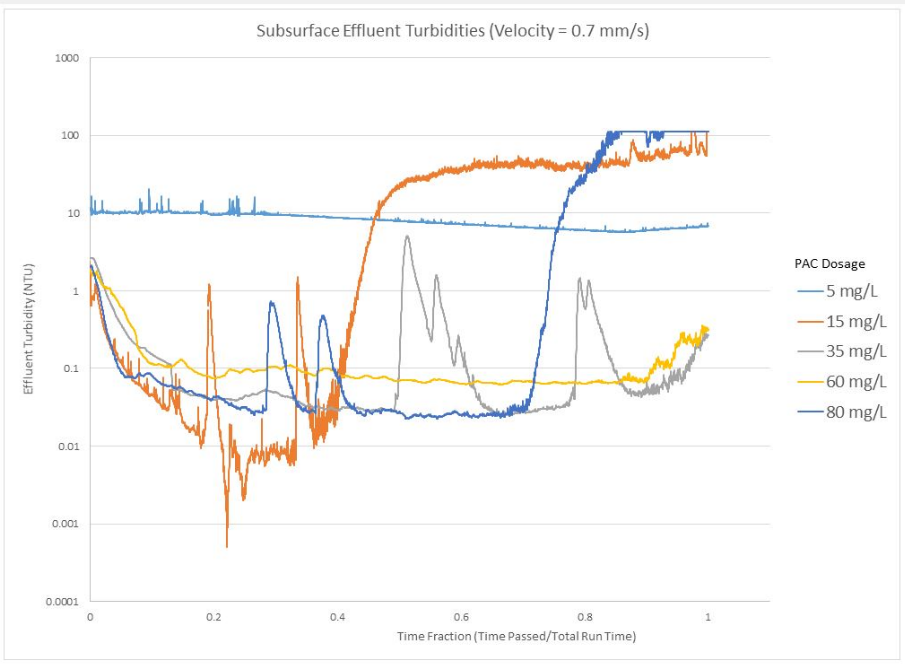

Figure 26: Influent Turbidity: 170 NTU; Filter Velocity: 0.7 mm/s

Effluent Turbidity

We define the value pC* as:

$$pC* = -log(\frac{effluent}{influent}) \tag{2}$$

The negative log of the effluent turbidity over the influent turbidity gives us a dimensionless parameter in which to compare turbidity. The less effective the filter is and more turbid the effluent water is, the smaller the pC* value.

Turbidity Over Time (For Various PAC Dosages)

Figure 27 shows the turbidity over time at a velocity of 1.8 mm/s and PAC dosage of 15 mg/L. For the subsurface injection column (column 2), turbidity suddenly rose after about seven hours, while the surface injection column (column 1) stayed relatively low. We suspect that the surface injection column performed so well because over time, any incoming clay would have continued to settle on top of the established clay layer on top of the sand bed. This clay layer is evident in backwashing, as there are large flocs of clay that are very difficult to backwash.

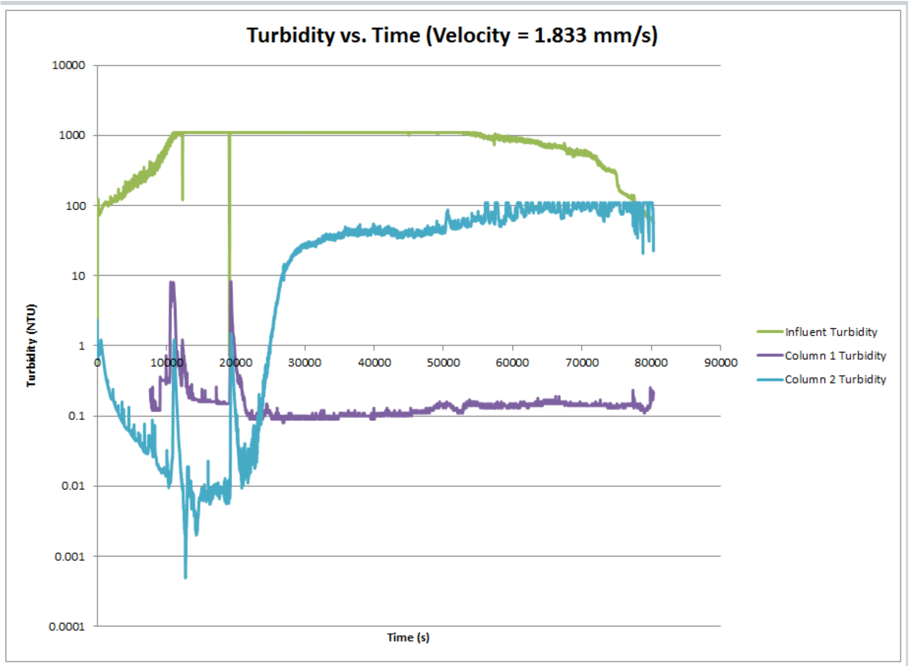

Figure 27: Influent Turbidity: 820 NTU; Filter Velocity: 1.833 mm/s; Coagulant Dosage: 15 mg/L

Effluent Turbidity and Velocity

There is a distinct relationship between velocity and average effluent turbidity of both columns, as seen in Figure 28. An increase in velocity clearly displays a marked increase in the turbidity of both these columns creating a positively sloping trendline. After crossing a certain velocity, the turbidity levels of the surface injection, column 1, increases at a faster pace than that of subsurface injection, column 2.

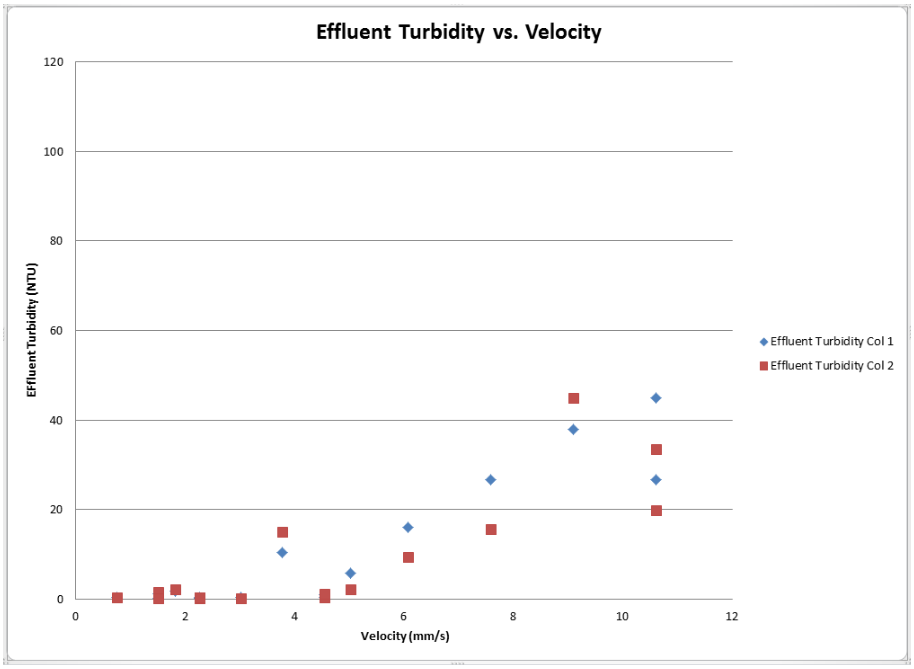

Figure 28: Influent Turbidity: 2 to 970 NTU; Coagulant Dosage: 2 to 20 mg/L

pC* and Velocity

The data, graphed in Figure 29, shows that pC* value of both the surface and subsurface injection columns decrease logarithmically as velocity increases. This decreasing efficiency could be explained in that as velocity increases, more particles are forced through the filters and thus accumulate more quickly. Shear forces also increase as velocity increases, which may be strong enough to push particles right through the filter and stay in the filtered water. Based on the projected trendlines, subsurface injection is shown to be more effective than surface injection in decreasing turbidity. However, there were certain experiments where the pC* value of the subsurface injection was less than that of the surface injection, meaning that subsurface inejection was less effective than surface injection, but the significance of these experiments remains to be seen. The R^2 for surface injection is 0.6239 while the R^2 for subsurface is 0.5194.

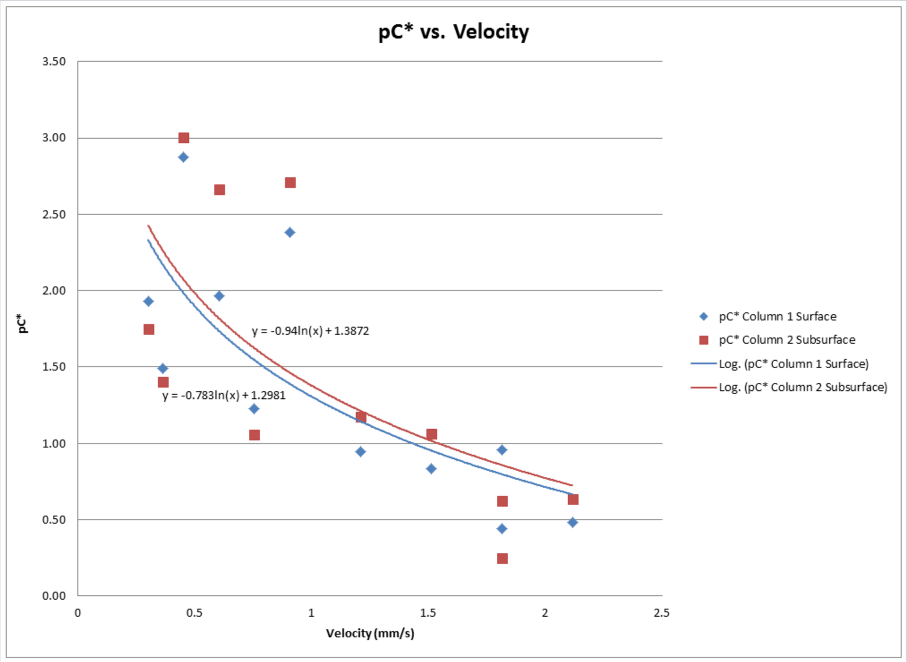

Figure 29: Influent Turbidity: ~120 NTU; Coagulant Dosage: 15 mg/L

pC* and PAC Dosage

At a velocity of 4.5 mm/s, as shown in Figure 30, the surface injection column indicates that pC* values are inversely proportional to PAC dosage, while the subsurface injection column shows a directly proportional relationship. This proportional relationship in the subsurface injection column conflicts with other results though, and more tests should be done at this velocity if a relationship between PAC dosage and effluent turbidity is to be defined.

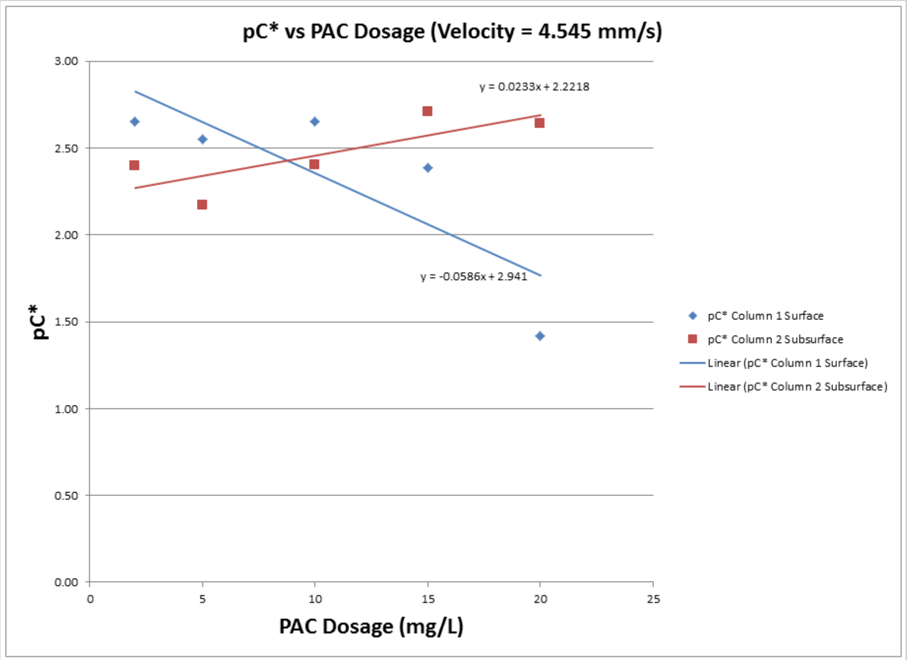

Figure 30: Filter Velocity: 4.5 mm/s; Average Influent Turbidity: 170 NTU

For the velocity of 10.6 mm/s, as shown in Figure 31, the general trend of both surface and subsurface injection columns indicate that their pC* values are inversely proportional to PAC dosage. The subsurface injection column exhibits a greater decrease in pC* value as PAC dosage increases. Since higher pC* is an indicator of higher efficiency, as PAC dosage increases, the efficiency decreases at a velocity of 10.6 mm/s. This inefficiency can be explained by the high rate of floc formation during higher levels of PAC dosage.

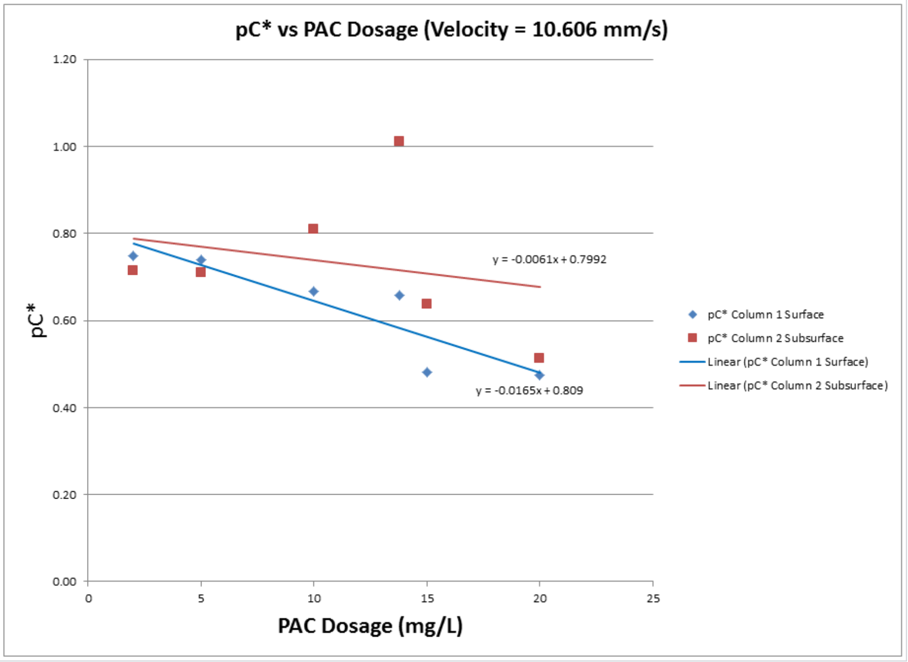

Figure 31: Filter Velocity: 10.5 mm/s; Average Influent Turbidity: 170 NTU

Results/Conclusions

We conducted numerous experiments by varying influent turbidity and velocity; the resulting effluent turbidities and head loss were then recorded. From the collected data, it is convincing that subsurface injection sites (as used in Stacked Rapid Sand Filters) are more beneficial than surface injection sites because in subsurface injection sites, head loss rates are lower and filter efficiency (shown through pC* values) is higher.

It was found that a linear relationship exists between time and head loss. At various influent turbidities, although the subsurface filter does not always experience lower head loss than the surface filter, its trend line has a consistently lower rate of increase suggesting that in the long run it will be more efficient. Similar results were obtained over a range of various plant flow rates; the rate of head loss increase is generally lower for subsurface filtration. Due to the variable data, especially with head loss, it is recommended that some of these tests be run again to confirm these numbers or discover a trend closer to what actually occurs in the filters. In addition, since we are running the experiments until the filters clog, longer run times are necessary in order to see an exponential head loss trend, which indicates clogging.

Although the experiments ran were at a much lower range of velocities than the range of velocities in actual plants, these experiments demonstrated that clogging is not really an issue for the subsurface injection filter in terms of backwashing ability. It is expected that clogging would happen faster at lower velocities, so these experiments show that even at extremely low velocities, there is not much of a clogging problem. However, more experiments should be done at the velocities used in actual AguaClara plants in order to get a better idea of the clogging conditions and backwashing results.

Observations demonstrate that the subsurface column initially produces lower effluent turbidity measurements than the surface column. However, once the subsurface injection site has been clogged its effectiveness decreases and the surface column produses lower effluent turbidity. Although the subsurface column tends to clog sooner than the surface column, it is also proves easier to backwash and unclog than the surface column. This suggests that the SRSF would perform more efficientally than a conventional rapid sand filters. Both subsurface and surface injection achieve the same level of particle capture and removal, but the subsurface injection site filter proves easier to maintain. Out of 17 experiments with various coagulent and clay dosages the subsurface column never proved difficult to backwash. However, the surface column often required long backwash processing to break up accumulated layers of clay that hindered its performance.

Hence, the SRSF is more space- and energy-efficient than conventional rapid sand filters and it also has lower rates of head loss increase and comparable effluent turbidities as shown by our research. The overall durability of the SRSF also appears to be more promising than the standard rapid sand filter.

Future Work

The future team should follow the experiment template already in use and complete the experiments listed in our inventory. In addition, the team should consider rerunning the latest experiments where headloss displays a decreasing trend (this error was caused by a broken backwash solenoid valve on the surface column that interfered with readings by the pressure sensors). After collecting and analyzing all the data, the team should then create a model that specifies the conditions for clogging based on influent turbidity, PAC dosage, and filter velocity. This model will seek to better predict when backwashing is necessary, since currently AguaClara plant operators can only identify clogging when water overflows due to high head. The team should also investigate methods for cleaning the surface filter of its clay build-up since backwashing hasn't been sufficient. Lastly, another field to investigate is the duration or velocity of backwash necessary to clean the filter columns.

If influent turbidity continues to fluctuate, the team can consider implementhing a pinch valve clay-delievery system rather than the pump currently in use.

Team Reflections

The team worked well together and there was great communication between us and our team leader. However, the purpose of our research was vague until we met with Monroe about halfway through the program, resulting in a great amount of time wasted on poorly designed experiments. Much time was also spent on making adjustments to the apparatus in order to troubleshoot: replacing solenoid valves, turbidimeters, dosing tubes and connectors; adding in air vents to reduce the amount of air in the columns; rerouting the path of water so it passes by and not through the flow accumulators to prevent clay settling, etc. Nevertheless, after meeting with Monroe, we have redesigned our experiments, fixed the apparatus so it functions properly, and grasped the rudimentary fluid theory pertaining to this area. Regretfully, we do not have enough time to finish the proposed experiments before the end of the summer program.

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