Surface vs. SubSurface Inlet Systems for Sand Filtration

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Abstract

Through experimental analysis and observation, this research compares a conventional rapid sand filter, in which the raw water flows into the sand bed from above, with a stacked rapid sand filter, in which raw water is injected below the surface of the sand bed . To evaluate how head loss and particle capture efficiency are influenced by the inlet boundary condition, the influent turbidity, filter velocity, coagulant dosage, size of sand grains, and depth of the sand bed are varied.One current hypothesis is that during depth filtration, particles are unable to collect in regions of high shear between the sand grains because of a high filter velocity of the influent water which breaks up large flocs and pushes the particles deeper into the sand bed, essentially filling up the pores layer by layer from the top to the bottom of the bed. Consequently, we predict that head loss will increase linearly as a function of time when depth filtration occurs as opposed to an exponential increase when surface filtration occurs and the top of the filter bed becomes clogged with particles.

Literature Review

Contaminated water may enter sand filters from the top, from the bottom, or—as in AguaClara's stacked rapid sand filter—from within the sand bed. Since AguaClara is the first to inject water directly into the middle of the sand bed, there exists little to no research about the advantages or disadvantages of this method versus the typical method of flow into the top surface of the sand bed; we therefore plan to compare these two methods through various experiments. After the water enters the system, from either the top of the sand bed or injected below the surface of the sand bed, it flows through the bed at a velocity set by the flow rate.

There are four ways the particles in the water can be filtered by the sand grains: (1) they may be bigger than the pore size between grains, causing them to get trapped (a process called sieving); (2) they may stick to a sand grain due to their coagulant coating applied earlier in the water treatment process; or (3) their charge may draw them to a sand grain, to which they then attach (a process called binding); (4) they may settle to a sand surface due to gravity. Filters need to be periodically cleaned due to the build-up of particles in the sand bed over time. Filters that run at a low velocity often need surface washing, since the particles tend to collect at the top. Higher velocity systems generally do not need surface washing but instead undergo a process called backwashing (Balasubramaniam). In this process, the direction of flow is reversed, causing the sand bed to fluidize and particles to detach from the sand grains. Detached particles are then suspended and can be transported out of the bed with the effluent. The frequency of backwashing necessary depends on the the rate at which the filter pores are filled with particles. This in turn depends on several factors, especially velocity. What is of particular interest to our research is not how frequently the pores fill up but the distribution of the particles in the filter bed—at the surface of the sand bed or throughout it. A variety of sources have suggested but not completely confirmed that the following factors are significant: velocity of the influent water, amount of coagulant applied to the influent water, concentration of influent suspended solids, and size and type of filter media. We will conduct experiments to evaluate these parameters and their effects on location of head loss build-up. Rapid sand filters can be designed to not require a backwash pump if six filters are placed side-by-side, and five valves may be shut off to create a combined water pressure strong enough to propel a backwash in one of the filters. In a SRSF, six filters are stacked vertically, and a single valve is used to backwash the system. One advantage of the SRSF is that it accomplishes the same goals as a conventional rapid filter but reduces the number of filters required by a factor of 6; this translates into a large decrease in construction costs and makes the filter more practical for small communities, particularly in developing countries. If a single rapid sand filter is used as would be the case for small communities, then an additional advantage is that SRSF are backwashed without a need for pumps or storage of filtered water. A possible disadvantage of the SRSF that Professor Bisogni presented is the impossibility of using more than one type of filter media. The other sand filtration technology that can be operated without electricity is slow sand filtration. However, such a filter is approximately 260 times larger than an SRSF and thus its capital cost is considerably higher.

Introduction

The filtration process in water treatment plants significantly reduces the turbidity in drinking water produced by the plants. Different types of filter models and methods are available, including those that use membranes and various filter media. AguaClara's mission to produce energy efficient, low-cost treatment plants has led to the development of what is called a Stacked Rapid Sand Filter (SRSF). In this design, slotted pipes inject water into 6 different layers of the sand bed. Out of all of the AguaClara water treatment plants in current operation, only the Tamara plant has a SRSF installed. Turbidity measurements from this plant, compared to those from the other plants without filters, confirm that filtration substantially improves the quality of the effluent water. According to the data reported by monitor.wash4all.org for the month of March 2013, the average turbidity of filtered water from the Tamara plant was 0.14 NTU, while the average turbidity of the water after it passes through the sedimentation tank in this plant is 1.12 NTU. As this data suggests, filtration significantly improves the turbidity of the water. The goal of the Depth vs. Surface Sand Filtration research team is to learn what factors, such as filter velocity, coagulant dosage, and initial turbidity, may affect the type of filtration (surface or depth) that occurs within the SRSF. This experiment will hopefully expose which type of filtration occurs in the SRSF (surface, depth, or a combination of both) and how the flow inlet boundary conditions affects the overall efficiency and head loss of the filter over time. We compared different inlet boundary conditions, both by subsurface injection (the slotted pipe method, which is tested with the subsurface injection filter) and by the conventional downflow method in which influent water enters through the top of the bed and exits from the bottom, which is tested with the control filter. Evaluating the performance of both techniques led to a determination of which method to implement in future filter designs to reduce head loss and increase particle capture efficiency. This research will ultimately extend AguaClara's knowledge about the filtration process and may be used to help diagnose and fix clogging problems within the SRSF in the future if we are able to pinpoint what factors and capacities of such parameters determine surface or depth filtration. It is possible that a high coagulant dosage will cause large flocs to grow in the plant which could potentially clog the mesh used in the subsurface injection tube. If this phenomenon occurs, it would provide insight as to why there may be structural problems with the SRSF. Large flocs may accumulate on the ridges of the slotted pipes and potentially block the flow of water. This information can be used by the design team to minimize the size of the SRSF without losing efficiency and reduce production costs of future water treatment plants.

Our overarching goal of this research is to understand what causes the switch between surface and depth filtration. Our aim is to potentially reduce surface filtration effects by injecting water into the filter bed.This is critically important because if surface filtration occurred in a slotted pipe in the SRSF, it would result in rapid clogging. We will be investigating if it is possible that perhaps high dose of coagulant could cause the SRSF to switch to surface filtration. If that happened, it could have serious ramifications for treatment plants. This would lead to questions such as what would physically occur in the plant, how would the operator realize what is happening, and what would be required to fix the problem? This problem falls under one of the major themes of our research, which is to try and determine under what conditions might the slotted pipes in the SRSF clog? We know that the filter at Tamara needs to be cleaned every few months, but we think that is due to the fact that the fabrication system for the slotted pipes is resulting in sand leaking into the pipes and we think that sand is causing the clogging. But it could be possible that the pipes would be clogging even if sand weren't leaking into the pipes.We hope our research will help us better understand how often and to what extent the plant operators will need to perform routine maintenance on SRSF to clean the slotted pipes. Successful operation of SRSF will require that conditions leading to clogging of the slotted pipes be avoided and that appropriate methods be developed to clean the slotted pipes if necessary.

Our Theory

The regions in the sand bed in which the shear forces are the greatest are the regions in which the area between the sand grains (size of the pore) is the smallest because the water is forced to travel at a faster velocity due to this decreased area. We believe that surface filtration occurs when the particles collect in these regions and are likely to fill and clog the pore, preventing water from flowing through it (Figure 1). Our theory is that particles tend to build up in these regions because the shear forces acting on the particles by the water flowing through the pore are not strong enough to overcome the forces that bind the particles to the sand grains.

Shear in a pore is given by

$$\tau = \frac{4\mu\overline{V}}{r} \tag{1}$$

Where$\tau$is the shear,$r$is the pore radius,$\overline{V}$is the average pore velocity,$\mu$is the viscosity of the fluid. 1 assumes fully developed laminar flow. The velocity in a pore increases and the radius of the pore decreases as the pore fills with solids and thus the shear in the pore increases with solids loading. The attachment force is expected to be correlated with the surface coverage of the colloids with coagulant precipitate. Thus surface filtration is expected to occur at high coagulant dosages and low filter velocities.

In surface filtration the intraparticle forces are strong enough so that the particles are able to bridge across the pores.

Our theory is that depth filtration occurs within the sand bed because the particles tend to collect in regions of lower shear, which is near the base or top of the sand grains where the area between sand grains is greater than that of the narrow channel. Again, we hypothesize that this must be due to the relative forces acting on the particles. We suspect that the shear forces prevent the particles from collecting in the middle of the pores, and thus the passage for water to flow into the depths of the sand bed is left open. A lower coagulant dosage and a higher velocity of influent water are expected to produce this type of filtration (Figure 2).

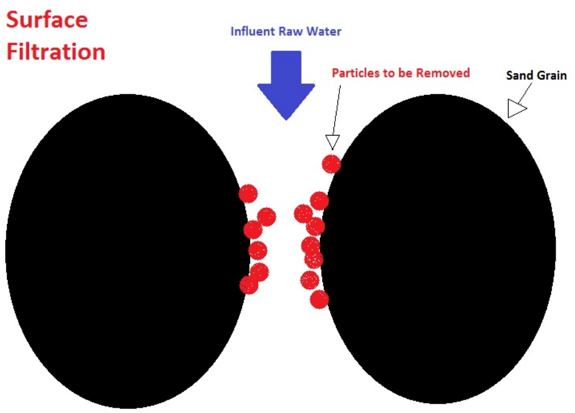

Figure 1: Our theory behind surface filtration is that particles stick to the sand grains in regions that are likely to clog the pore.

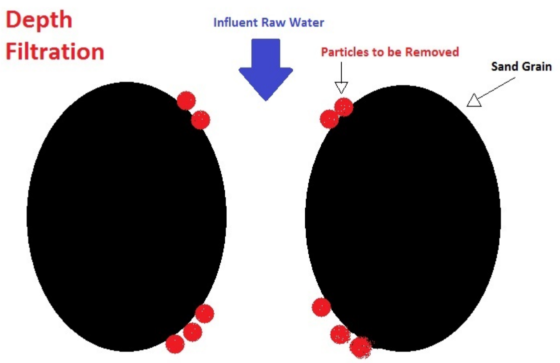

Figure 2: Depth filtration most likely occurs when particles are captured in regions of low shear in between sand grains, leaving the pore mostly open for water to flow through.

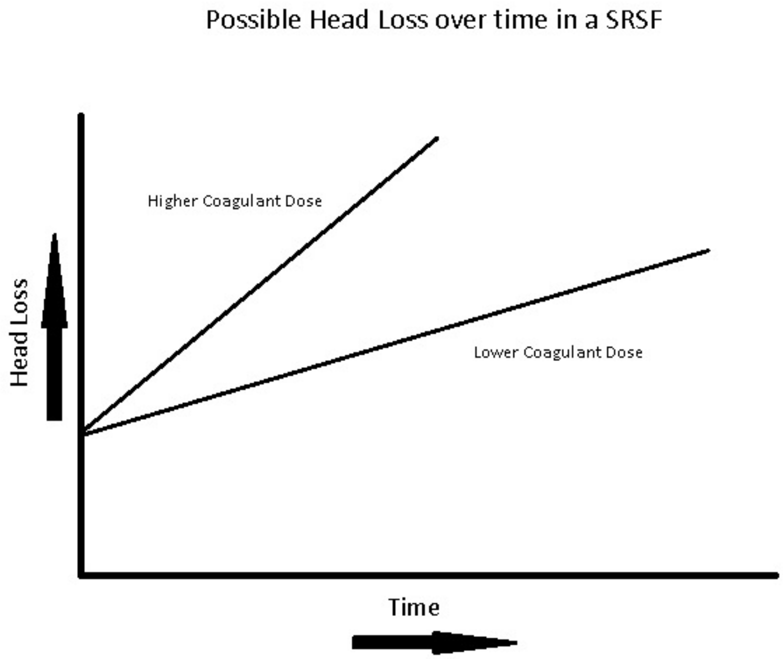

Figure 3:

We hypothesize that by injecting the water below the surface of the sand bed, we are forcing depth filtration to occur because of the higher velocity as a result of the smaller size of the inlet slots of the inlet pipe and the local higher velocity in the inlet region. In our initial experiement we will be recording head loss across the filter over time. We hypothesize that the head loss will increase at a linear rate over time, as this process continues throughout the depth of the sand bed as particles fill up successive layers of pores (though not completely clogging them) and the water is able to travel deeper within the bed and deposit their particles in these deeper pores.We also hypothesize that a higher coagulant dose will cause head loss to increase at a higher rate, as the filter will fill faster. Coagulant makes the particles stick to the sand grains, and shear forces attempt to remove the particles from these grains, so there is a critical interaction between these forces within the sand bed. These predictions are shown in Figure 3.

We believe that subsurface injection of the raw water into the sand bed will increase the particle capture efficiency and decrease the head loss during filtration.

The two major differences between the two methods of filtering will be where the water is loaded in the filter and with what velocity the water enters the sand bed (refer to Figure 4). In the case of the model SRSF, the constriction will

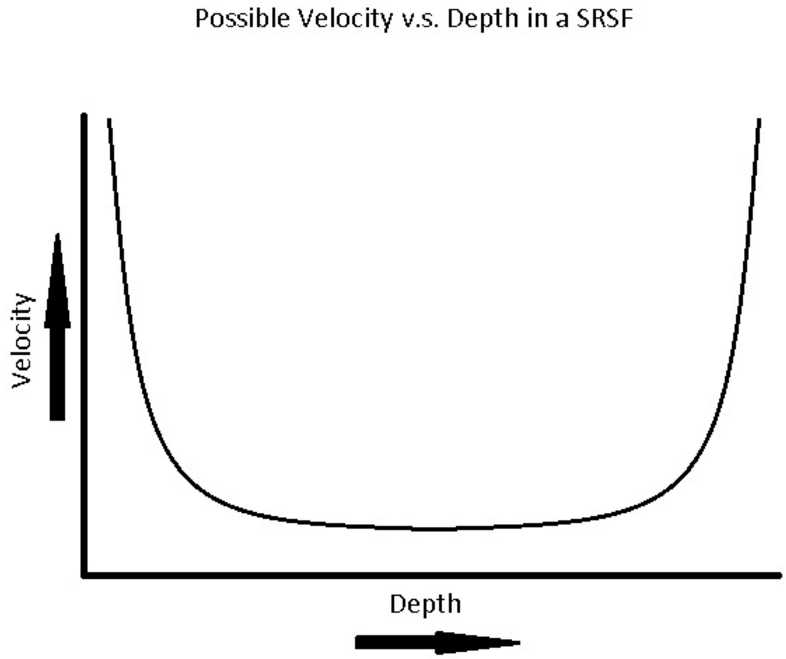

Figure 4:

cause the water to enter the filter at a signifcantly higher velocity, though the two filters will filter the same volume of water in the same amount of time. We hypothesize that this higher velocity will prevent surface filtration. This could lengthen the filter run time if conditions are such that surface filtration occurs in the control.

Methods

We have constructed an apparatus to perform various experiments on sand filtration. The test apparatus consists of two sand column filters. The first column filters water downward through the sand bed, consistent with a conventional rapid sand filter. The second column features a small fitting that injects water into the middle of the sand bed to create conditions of subsurface injection similar to those of the AguaClara SRSF. Tap water amended with clay and coagulant was run through the filters. The effluent turbidity and head loss of each column was measured and used to compare their overall performances. The influent turbidity, coagulant dosage, and filter velocity were varied to determine the effect of each on the efficiency of filtration and the accumulation of head loss.

Description of Testing Setup

In summary, 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 headloss across the columns.

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 20 C) 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. When choosing the concentration of coagulant in the stock tank, the following relation was used: (Coagulant concentration in the stock tank)*(Flow rate out of the stock tank) = (Coagulant concentration in the sand filters)*(Total flow rate through the sand filters). Thus, keeping in mind that the maximum flow rate out of the stock tank using a 100 rpm peristalic pump and size 13 tubing is 6 mL/min, we varied the stock tank coagulant concentration to achieve the desired coagulant concentration in the sand filters.

(d) Two separate peristalic 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/coagulant 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 that are filled halfway with water.

(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.

We ran several tests. For each test, a value for filter velocity, coagulant dosage, and influent turbidity was chosen. The test were run for a predetermined amount of time, measuring the effluent turbidities and head losses across the columns. The typical values for filter velocity (through a single column), coagulant dosage, and influent turbidity were 2 mm/s, 5 mg/L polyaluminum chloride, and 200 NTU respectively. However, values as low as 0.5 mm/s and as high as 5 mm/s will be used for filter velocity. Values between 0.5 mg/L and 15 mg/L will be used for coagulant dosage. Values between 80 NTU and 450 NTU will be used for influent turbidity. Our hypothesis is that head loss will increase over time (as the flocs collect in the filter). When the filter is backwashed, we expect head-loss to return to its original value (because the collected flocs are flushed out of the filter). By examing where the clay particles collect in the

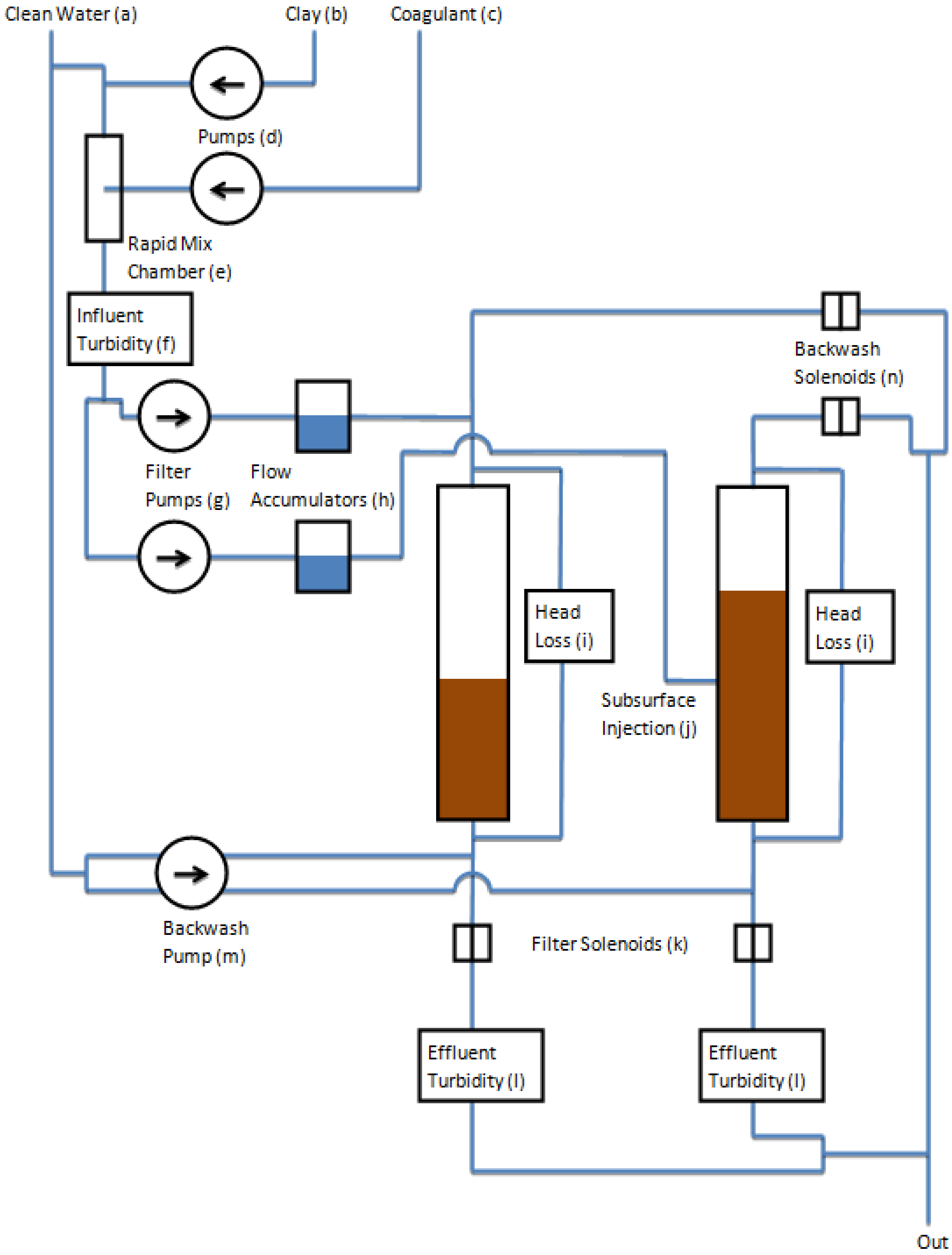

Figure 5: A schematic of our current experimental apparatus.

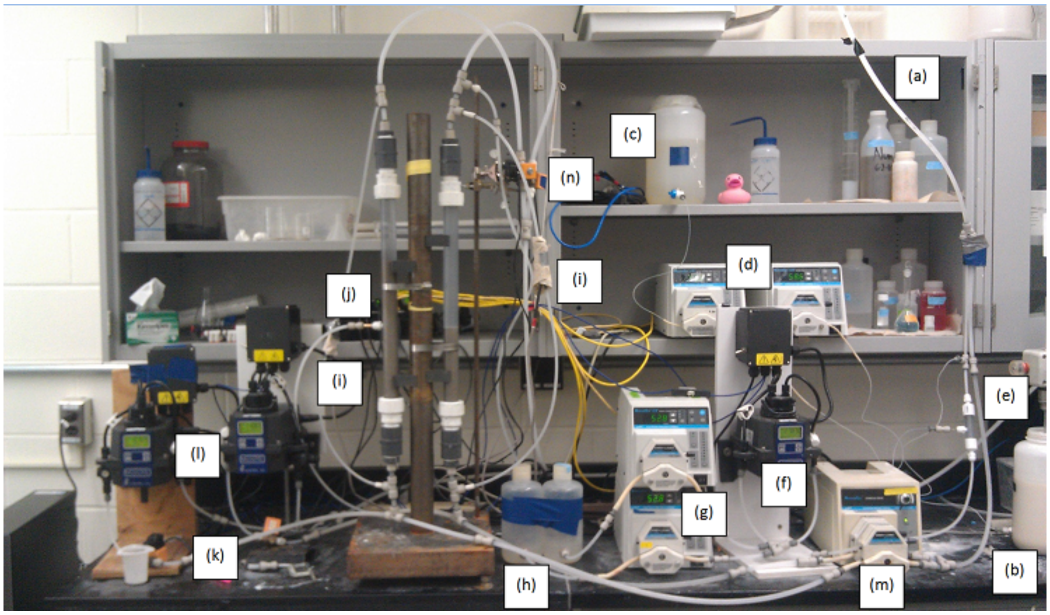

Figure 6: Photo of the experimental apparatus in the lab.

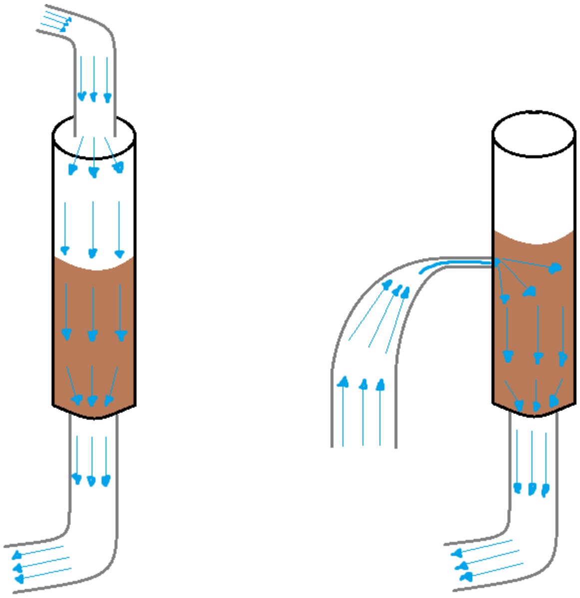

Figure 7: Left: Water flow in conventional downflow filter; Right: Water flow using subsurface injection fitting.

filter, we can see which cases produce surface filtration and which cases produce depth filtration.

It is important to note that the subsurface injection filter has a fitting that simulates the conditions for subsurface injection. Thus, since all other conditions are the same, we can compare subsurface injection to surface injection by comparing the turbidities and head loss between the two columns.

Process Controller Method Files and Software Setup

In our Process Controller method file we have 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 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 are open
- Test: A disposable state to test different pieces of equipment in the apparatus before making any changes to the other states

Each of the states includes a series of set points, some of which include:

- Off/On: Correspond to boolean 0/1 respectively. Can be used to turn pumps off/on.
- Turbidimeters: Includes an ID number (necessary for sorting the information gathered from each one)
- Pumps: Fractions and Flow Rates to dictate the speed at which each pump is run
- Run Time: Determines the length of time to run an experiment in the filter state before switching to the off state (this set point is only used when in automatic mode)

Qualitative Observations

There was a consistent difference in the location of particular capture between the two filters. The clay water that we ran through the system was a milky white color, and when particles got trapped in the sand, they appeared as little white specks between the sand grains that were observable with the naked eye. After running dirty water through the system for a period of time, a layer of flocs accumulated on the top of the sand band in the control filter (conventional downflow). A majority of the particles were trapped near the surface, as shown by the whiteness of this region of the sand bed. The lower depths of the filter did not show as much as a color difference, indicating that fewer particles were captured there. In the subsurface injection filter (subsurface injection), particles were trapped in the sand both above and below the injection site. because the water coming into the filter entered at such a high velocity, the clay and water particles collided with the sand grains and the opposite wall of the column, dispersing in all directions. Particles in the control column were filtered from top to bottom of the sand bed. Particles in the subsurface injection column were also captured in a similar "top to bottom" manner, but in the beginning of the experiment, the capturing of the flocs also spread in the upwards direction above the injection site as well as below it.

As noted above, thin layer of visible flocs formed on the top surface of the control filter (control), including some very large flocs that were similar in size to (or larger than) the sand grains. These larger, heavier flocs were difficult to remove with our standard backwash method, even when operating the backwash pump at a higher speed. No such large and heavy flocs were observed in the subsurface injection filter (subsurface injection), which may imply that subsurface injection prevents large flocs from forming during filtration, as opposed to surface filtration. Because of this difference, the subsurface injection filter could be backwashed at a lower backwash pump speed than the control filter, without large flocs remaining in the column afterwards. Because of the floc build-up observed on the surface of the control filter, the subsurface injection tube was also checked for similar build-up which could cause clogging. Before backwashing the system, the subsurface injection filter was drained and the influent tubing removed so that the metal tubing and mesh could be properly inspected. Both the tubing and the mesh were clear of any particles, which supports the idea that surface filtration does not occur during subsurface injection, even with very high turbidity. (Note: This inspection and these observations were made after filtering 400 NTU water (influent turbidity) for 2 hours (See Figure 8).)

Quantitative Analysis

Figures 8-14 show the measured headloss over time for different variables, including coagulant dosages, filter velocities, and influent turbidities.

Figures 15-19 display both the influent and effluent turbidities of each experiment which tested similar independent variables (coagulant dosage, filter velocity, and influent turbidity). The influent turbidity is measured on the primary axis, while the effluent turbidities of columns 1 and 2 is shown on the right hand secondary axis.

Note for Figures 13 and 18: If this test had been run for a longer period of time, we expect that the turbidities would have leveled out to become very close to one another as shown in the other experiments. Even though it may not be as clearly represented on this particular graph, it still shows that the headloss increases at a higher rate over time for the control filter.

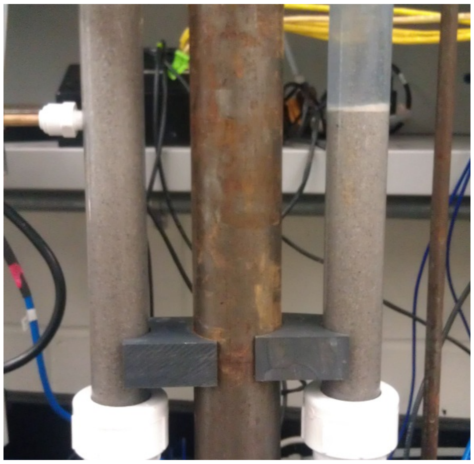

Figure 8: After filtering 400 NTU water for 2 hours. Notice how the sand bed is tinted white where the particles collected in both columns and the layer of build-up on the control column.

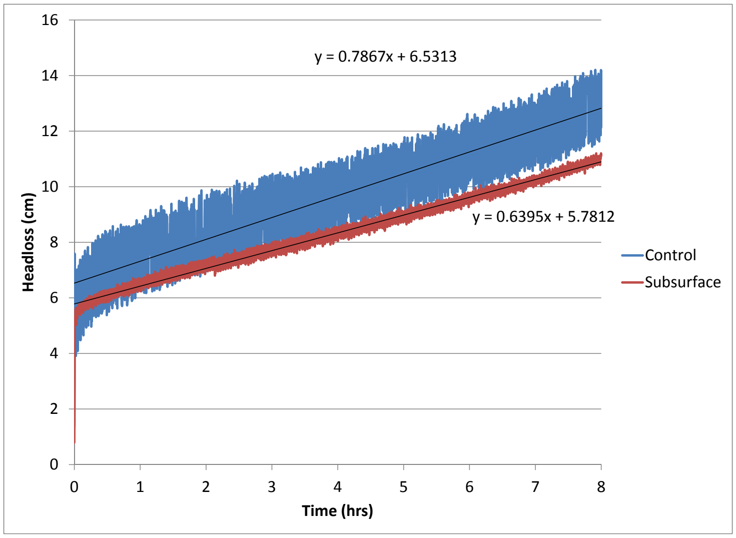

Figure 9: Influent Turbidity: 90 NTU; Filter Velocity: 2 mm/s; Coagulant Dosage: 5 mg/L

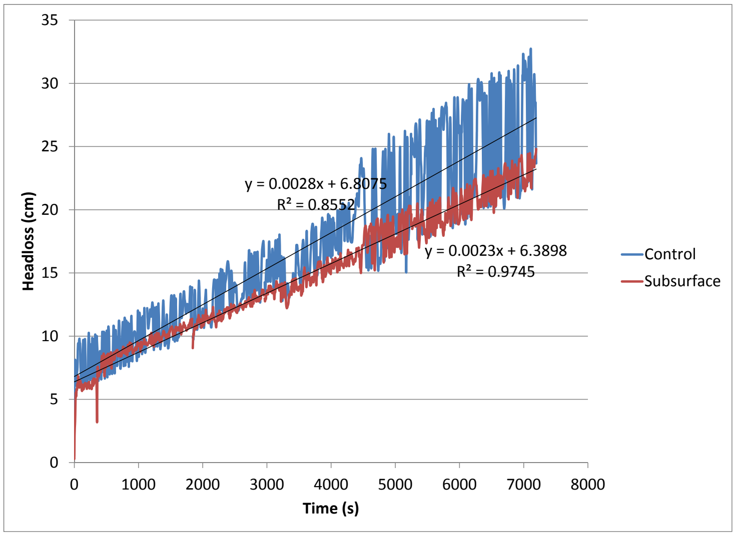

Figure 10: Influent Turbidity: 400 NTU; Filter Velocity: 2 mm/s; Coagulant Dosage: 5 mg/L

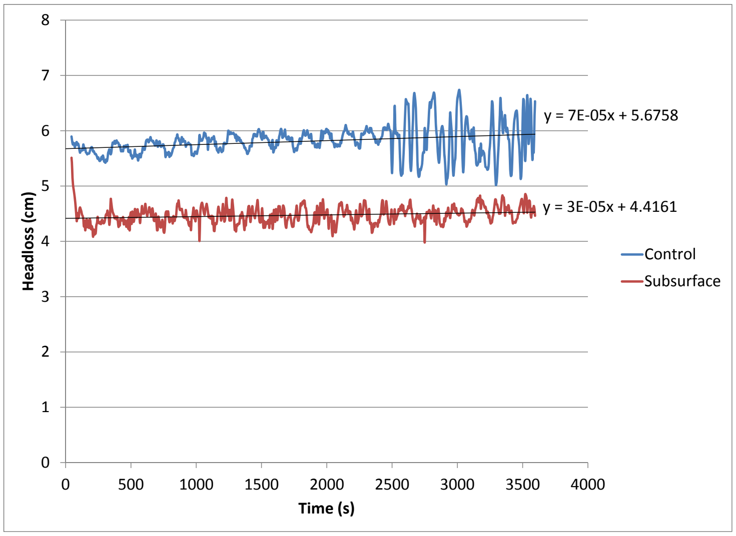

Figure 11: Influent Turbidity: 165 NTU; Filter Velocity: 2 mm/s; Coagulant Dosage: 0.5 mg/L

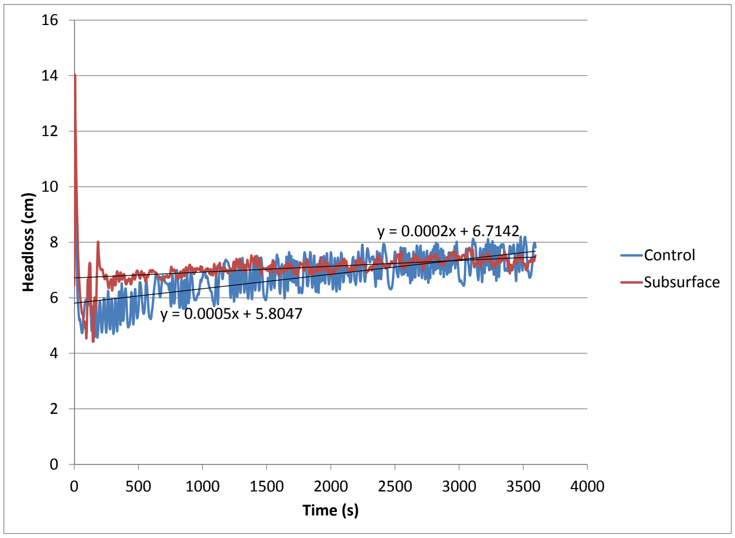

Figure 12: Influent Turbidity: 200 NTU; Filter Velocity: 2 mm/s; Coagulant Dosage: 15 mg/L

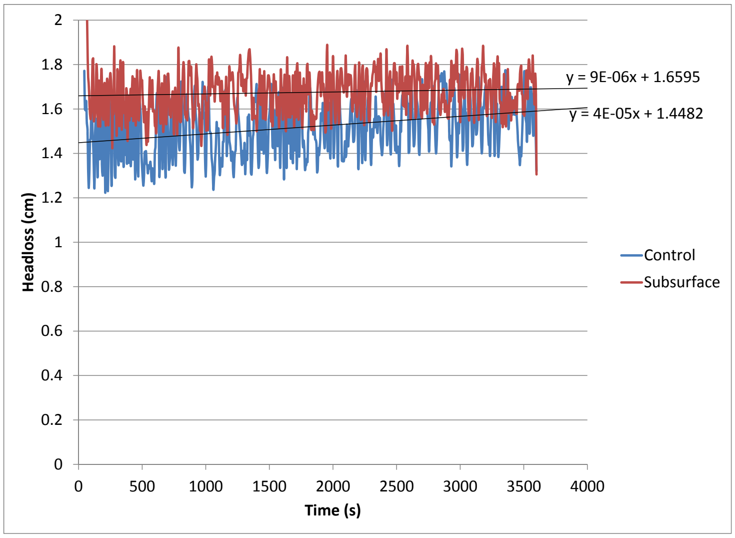

Figure 13: Influent Turbidity: 400 NTU; Filter Velocity: 0.5 mm/s; Coagulant Dosage: 5 mg/L

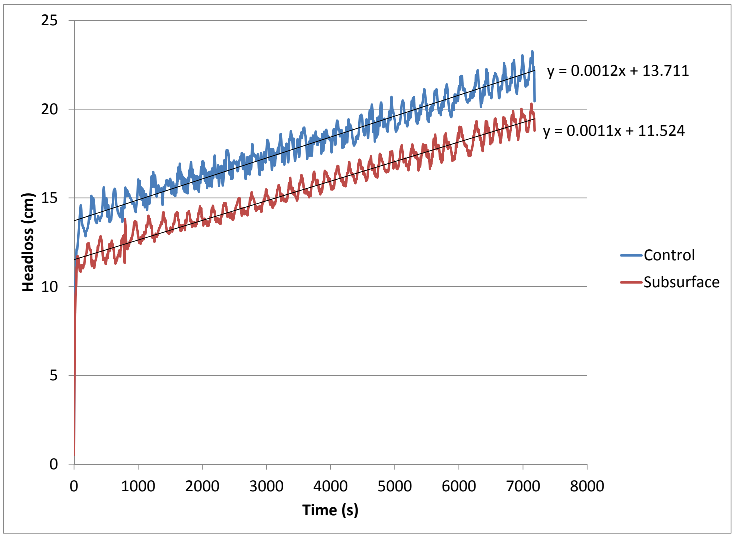

Figure 14: Influent Turbidity: 240 NTU; Filter Velocity: 5 mm/s; Coagulant Dosage: 5 mg/L

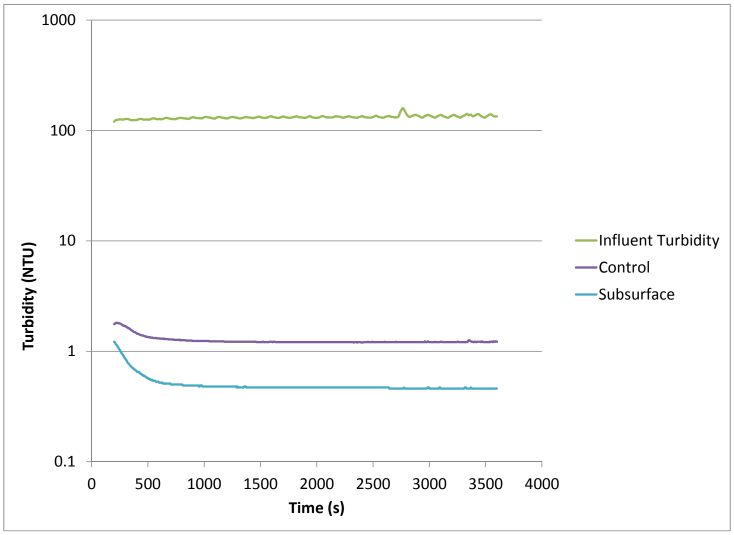

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Figure 15: Influent Turbidity: 130 NTU; Filter Velocity: 2 mm/s; Coagulant Dosage: 5 mg/L

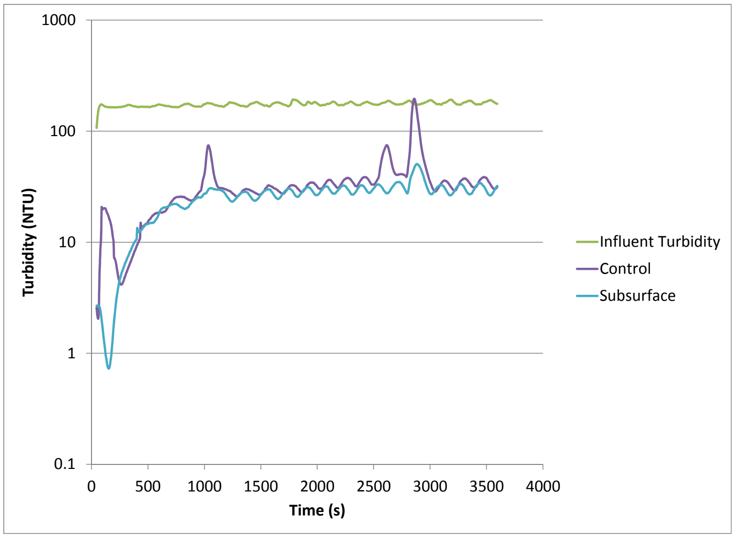

Figure 16: Influent Turbidity: 165 NTU; Filter Velocity: 2 mm/s; Coagulant Dosage: 0.5 mg/L

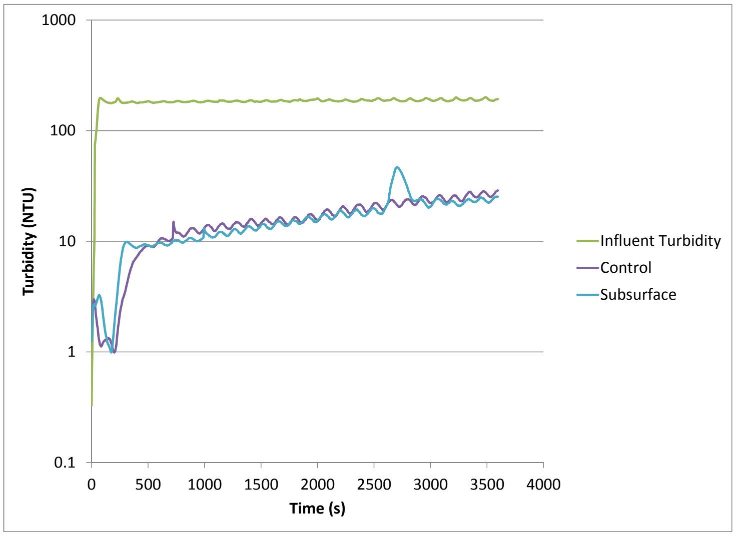

Figure 17: Influent Turbidity: 200 NTU; Filter Velocity: 2mm/s; Coagulant Dosage: 15 mg/L

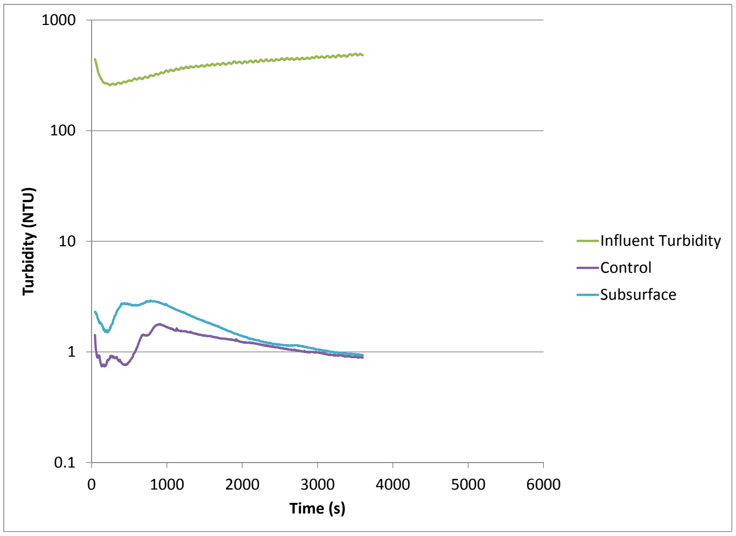

Figure 18: Influent Turbidity: 400 NTU; Filter Velocity: 0.5 mm/s; Coagulant Dosage: 5 mg/L

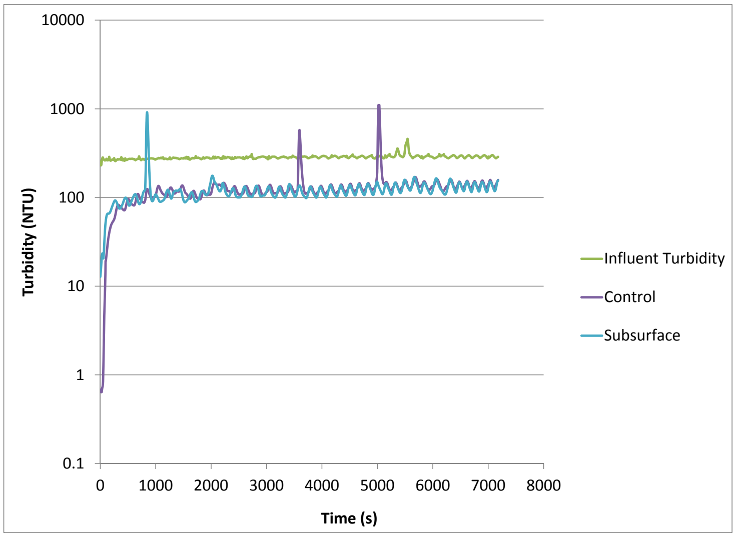

Figure 19: Influent Turbidity: 240 NTU; Filter Velocity: 5 mm/s; Coagulant Dosage: 5mg/L

Conclusions

From the data we collected at different influent turbidity level,s filtration rates and coagulant dosages, we observed a consistent trend that the headloss in both columns increased linearly over time. However, the rate of increase in headloss over time in the control filter was greater than that of the subsurface injection filter. The only exception to this trend was when the filter velocity for each column was at a high value of 5 mm/s. In this case, there appeared to be little difference between the rate of increase in headloss over time between the columns.

We believe there may be a connection between the influent velocity to the sand bed and the rate of increase in headloss over time. One clear connection that we found was that water entering the sand bed at a high filter velocity deposited smaller flocs on the surface of the control filter. This suggests that influent velocity substantially affects whether depth or surface filtration occurs within the filter. It appeared that at higher filter velocities, that depth filtration occured in the control filter because a top film of particles did not form, even at high influent turbidity values of 240 NTU. In the subsurface injection filter, because of the small diameter of the injection tube, the velocity is always relatively high, which would also explain why there was no floc build-up on the mesh of the tube. This supports that the SRSF design is better than a traditional downflow filter because the headloss builds up more slowyly over time, meaning that the filter can be run for a longer period of time before backwashing without needing to resort to surface washing the filter to properly clean it.

The effluent turbidities of each column were consistently similar to each other despite changes in influent turbidity and the difference in method of water injection. Minor discrepancies of about 1-2 NTU between the measured effluent turbidities of the columns is likely due to differences in calibration between the turbidimeters, which is an observation we made while testing the accuracy of the turbidimeters before running any experiments. After varying the coagulant dosage and filter velocity through the columns, the effluent turbidity was similar for both columns. So then it would appear as if the subsurface injection filter was not noticeably better at capturing or removing particles from the water than the control filter and there is no advantage to the SRSF design in this respect. The only advantage we can interpret from our gathered data is that the SRSF design has a slower increase in headloss over time.

Future Work

After analyzing the results of our initial experiments, we believe that further investigation into the effects of high filter velocities on each of the two types of filters may be beneficial to support our claim that at high filter velocities, depth filtration occurs to a certain degree even in the conventional RSF. Also, it would be interesting to try to run an experiment for the sole purpose of clogging the injection site of the subsurface filter. By determining what kinds of parameters may cause this (probably low flow rate and high turbidity) and recording these values, we may be better able to predict under what conditions the actual SRSF will clog. The head loss and effluent turbidity could continue to be monitored during this test as well to see what kinds of changes occur. By forcing the subsurface filter to fail we could simulate what kinds of physical implications this would have on the filter itself and on other components of the test apparatus connected to the filter. This information could inform plant operators of what signs to look for and could provide insight as to how to respond in situations in which it appears as the SRSF is clogging.

Other factors that were not tested but could also affect the headloss and effluent turbidities are different filter media or sand sizes. It would be interesting to see how changing this parameter would function in the SRSF and affect the headloss and effluent turbidities. Another idea to improve the particle capture efficiency of the SRSF design might be to filter the influent water twice through the filter to see if turbidity improves. It is possible that the remaining particles in the water after the initial filtering would be so small that they would not be captured during the second filtering, but we believe further investigation could possibly help improve the current SRSF model. Finally, the team may consider treating the water before and/or after the filtration process by . adding more coagulant to the raw water just before it enters the filter or installing a foam filter after the SRSF to potentially capture even more particles that were not removed in the filter. This plan would take some significant design changes to the apparatus used in the first round of experiments, and time does not permit us to test these new ideas.

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