Stacked Rapid Sand Filtration

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Abstract

Stacked filters have been demonstrated as a novel alternative to traditional rapid-sand filtration, and their efficiency makes them an appropriate process for sustainable municipal-scale drinking water facilities. In this study, a pilot-scale apparatus was set up as a model of the hydraulic controls for the stacked filter system. This pilot-scale system was used to develop and provide experimental justification for stacked filter design equations. In addition, a bench-scale apparatus was developed with a single-layer rapid-sand filter to study fundamental questions such as removal efficiency in upflow and downflow filtration. Results to date have successfully clarified aspects of the hydraulic design and provided some insight into flow within the layers of the filter.

Background

Rationale

Traditional rapid-sand filtration is a familiar and widely-used water treatment process, but its technical complexity makes it impractical for small communities especially in the developing world. Since the backwash cycle requires high velocity, expensive equipment such as elevated tanks or electric pumps must be used to provide backwash flow. It is possible to have fully hydraulic filters in traditional design, but the number of filter boxes would need to be the same as the backwash velocity over the filtration velocity, so that all of these parallel filters could backwash an additional one. The Stacked Rapid Sand Filter (SRSF) overcomes this drawback. It requires only one filter tank to accomplish filtration and backwash, and uses the same total flow rate for both cycles. Additionally, with only one valve, it can change from filtration mode to backwash mode and vice versa. It saves water during backwash, reduces cost of infrastructure, and eliminates requirement for pumps.

Our SRSF research team has conducted several experiment at both the pilot scale and the bench scale. We have studied the siphon system, flow distribution in the sand layers, control system configuration, upflow and down performance comparison, as well as a proposed sand removal systems. Our goals for this semester were to gain insight into important design and operating parameters for the SRSF, and investigate questions of fundamental importance to the viability of this technology.

Literature Review

Mayer, V. (1983). "Rapid Sand Filters for Advanced Wastewater Treatment: Upflow or Downflow?" GWF, Wasser-Abwasser, 124(5), 213-220. This article comments on the upflow vs. downflow debate in rapid sand filtration design and operation, and compares the performance of rapid sand filters operating in upflow or downflow based on pilot-scale and full-scale data. The author concludes that downflow filtration is advantageous for the particular application of tertiary suspended solids removal at a wastewater plant. The effectiveness of filtration performance in the upflow and downflow directions is a question of great significance for the SRSF, which has both upflow and downflow layers during the filtration cycle.

Han, S., Fitzpatrick, C.S.B., and Wetherill, A. (2008). "Mathematical Modelling of Particle Removal and Head Loss in Rapid Gravity Filtration." Separ. Sci. Technol., 43(7), 1798-1812. This paper presents a model that describes particle removal mechanisms and the development of head loss in the bed of rapid-sand filters. The model consists of three "stages" of particle removal that are manifest during the course of a filtration cycle. The results of the model were compared with full-scale data from a working water plant.

O'Connor, J.T. and O'Connor, T.L. (2002). "Rapid Sand Filtration." In Control of Microorganisms in Drinking Water. Reston, VA: American Society of Civil Engineers, 127-148. This article discusses the prevalence of rapid sand filtration as a means of removing microbial pathogens from drinking water. It discusses the role of rapid sand filtration, following flocculation and sedimentation, as the last barrier between suspended particles and the public drinking water distribution system. The article also discusses the importance of using coarse-grain filter media for meeting drinking water turbidity standards.

Lin, P.-H. (2010). "Filter media modification in rapid sand filtration." Thesis (Ph.D.)–Cornell University, May 2010. This thesis focuses on developing improved operating methods for rapid sand filtration. It discusses several different coagulants like alum, ferric chloride and poly-aluminum chloride which are applied to modify the sand filter medium, concerning their dosage and pretreatment. Moreover, it introduces a novel fluidized-bed pretreatment process which enhances the efficiency of turbidity removal. In addition, the thesis discusses and explains the mechanism related to the improvement of the filter performance by the presence of coagulants.

Materials and Methods

Pilot-scale Apparatus

First, the pilot-scale control system was set up to test the siphon. This pilot-scale apparatus includes a bucket representing the filtration inlet channel with four pipe stubs connected to hoses through the bottom of the bucket. Each of the four hoses runs from the bottom of the inlet bucket to one of the four filtration column inlet manifolds. The hose connected to the bottom inlet manifold is connected to the shortest pipe stub, and the hose connected to the top inlet manifold is connected to the second shortest pipe stub. The two hoses connected to the middle inlet manifolds are connected to the tallest pipe stubs. This configuration allows the water level in the inlet bucket to fall below the top of the higher pipe stubs during backwash initiation, thereby cutting off flow to the middle inlet manifolds. The siphon is configured to hold an air trap during filtration mode, and then backwash mode can be initiated by releasing the air trap and allowing the siphon to transport the total system flow to the backwash outlet. The control system was run in cycles beginning with filtration mode, followed by initiating backwashing by breaking the air trap, followed by steadstate backwashing, followed by initiating filtration by forming the air trap, and so on and so forth. Particular attention was paid to the water level in the inlet bucket and flow of air and water through the siphon during these cycles. A diagram of this apparatus is found in 1.

Second, the pilot-scale apparatus was modified for subsequent pilot-scale studies. The inlet bucket has been replaced by a clear 4" pipe with the same

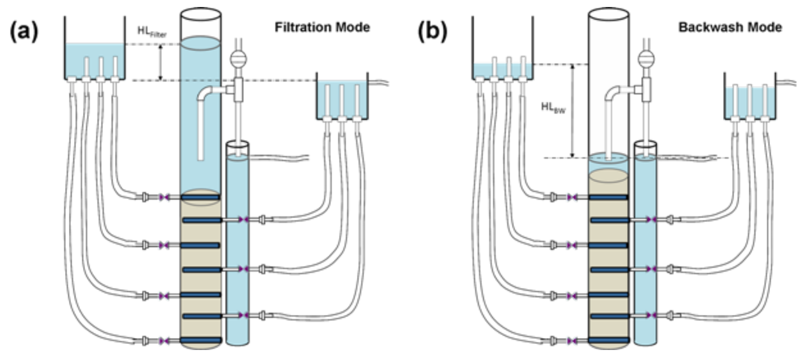

Figure 1: Diagram of the pilot-scale apparatus for the control system study, showing the water levels during (a) the filtration cycle and (b) the backwash cycle along with important head losses.

configuration of stubs and hoses. The goal of the new clear 4" pipe is twofold: first, it will allow for visual monitoring of water level in the inlet channel and second, it provides a reduced diameter of the wetted perimeter in the inlet channel and reduces the volume of water that sits in the inlet channel during filtration mode.

It is worth mentioning that the bottom of the backwash siphon-capture pipe has been replaced with clear PVC to allow for the visual monitoring of flow through the siphon. The goal is to visually identify whether air is completely trapped in the siphon or if some bubbles flow out through the bottom of the siphon as the water level in the filtration column rises.

Pilot-scale Experiments

Specific experiments required certain specific modifications to the pilot-scale apparatus, as described below.

First, a test was conducted to demonstrate the sand removal system. The test apparatus was modified to model the full-scale sand removal system that has been constructed in Tamara, which is intended to allow filter media to be readily removed for maintenance as needed. The modification required the drilling of a hole in the filtration column at the arbitrarily selected place of about 10 cm higher than elevation of the backwash exit weir. A bulkhead fitting was installed in hole in the filtration column, and a 1/4" ID tube was connected to the bulkhead fitting on the interior of the filtration column. The tube ran lengthwise all the way down the filtration column so that the end of the tube was embedded in the sand at an elevation about 5 cm higher than the lowest filter column inlet. The tube was installed during backwash because the tube can only be inserted into a fluidized bed. A tube of the same diameter was connected to the exterior of the filtration column by the bulkhead fitting, and that tube was run to the sink, with the tip having an elevation of 76 cm below

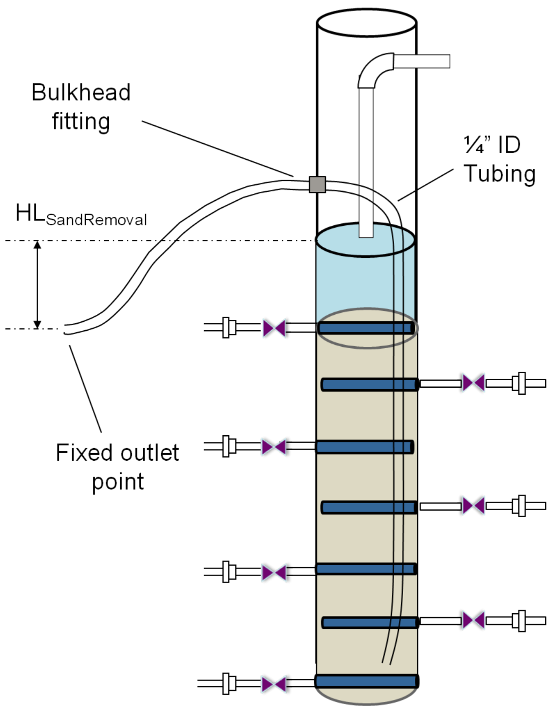

Figure 2: Diagram of sand removal study apparatus and key dimensions.

the backwash exit weir to provide the driving head for this system. The sand slurry was discharged into a sieve in the sink to collect the data for this study.

The following diagram (2) shows the schematic for this test on the pilot-scale. The design for the selection of ID for the sand removal tube is dominated by the need to achieve flow velocity in the tube within the range between the minimum scour velocity of sand and the maximum allowable velocity, which is the highest velocity that will not affect the normal performance of the system in backwash mode. This maximum allowable removal velocity can be calculated by solving for the removal flow rate that would bring the backwash velocity in the filter column to its threshold of 5 mm/s. This algorithm helped us select a tube of OD 3/8", which provides a sand removal flow rate of 1.277 L/min and a removal velocity of 0.672 m/s, while maintaining an upflow velocity of 7 mm/s in the filter to keep the sand fluidized.

Another modification was made to test the possibility of an alternate design for the backwash pipe, basin, and weir that has been constructed in Tamara. The backwash basin was completely removed from the test apparatus, and the lower end of the backwash siphon pipe was connected to a series of two additional elbows and two additional pipes to create a U-shaped plumbing trap, or water seal. This modification is motivated by the need to investigate affordable alternatives to the initial design used in Tamara. The large diameter of the

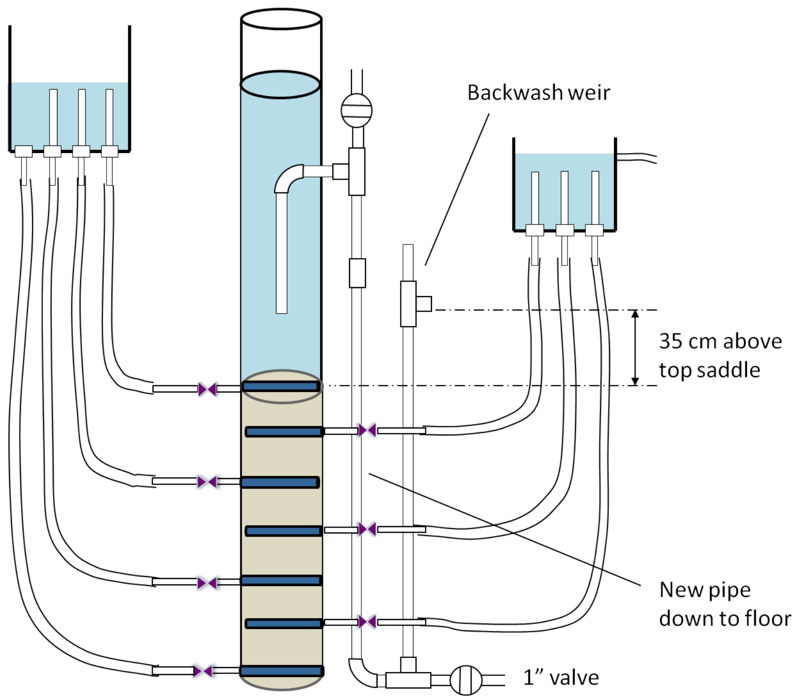

Figure 3: Diagram of water seal apparatus in the pilot-scale experimental system, with key dimensions.

backwash basin incorporated by the initial design comes at a higher cost than a U-shaped water seal configuration made of pipe with the same diameter as the backwash siphon. The new configuration for the U-shaped water seal maintained the same final backwash weir elevation as had been implemented by the prior apparatus configuration. A diagram of this modification to the pilot-scale equipment is found in 3.

A third modification was made to the pilot-scale apparatus to measure and compare the flows through the six individual sand layers of the filtration column. The filtration column pipe was tapped, with two holes and fittings installed on each of the six layers. The holes were oriented so that they lined up with the vertical axis of the filtration column, and the holes were spaced regularly such that they each had 10 cm elevation spacing between them, centered on each sand layer. The spacing was selected to include an area with only vertical flow in the sand, and exclude the area of influence of the inlet and outlet slotted pipes in the sand bed. Pressure sensors were installed across each of the six pairs of tapped holes, and the sensors were calibrated so that when calculations were applied, they reported positive flow in each layer during filtration mode. The motivation for this test is to analyze the uniformity of flow distribution between the six layers during filtration mode. The setup of these pressure sensors is

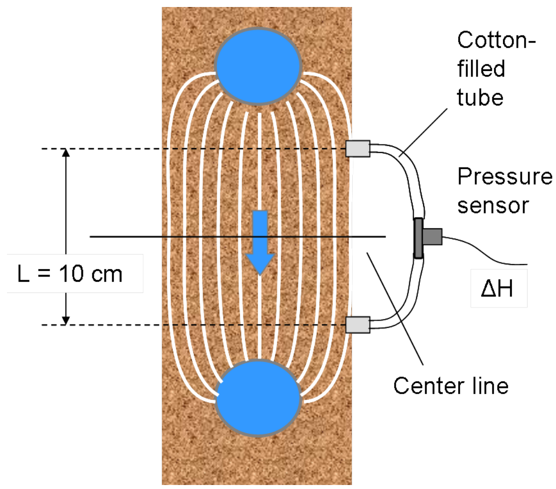

Figure 4: Diagram of showing the setup of pressure sensors to measure flow in each layer of the SRSF. The white lines are conceptual flow lines in the sand, and the pressure sensors were placed to keep the pressure sensor outside of the area of influence of the inlets and outlets.

shown in 4.

Bench-scale Apparatus

A filter has been set up at the bench scale to test turbidity removal performance of upflow versus downflow. This has involved rigging a series of tubes and valves to pump water, dose alum, dose clay, and monitor influent and effluent turbidity. Each dose and sampling system has a pump which requires calibration, and solenoid valves are controlled by the process controller software to control the system in upflow and downflow. The bench-scale apparatus to compare upflow and downflow performance is shown in 5.

This apparatus was modified to study the self-healing capabilities of nonuniform flow among layers in a stacked filter. Two parallel filter columns were set up, each with a flow sensor and turbidimeter. Standard rapid-sand filtration sand (effective size 0.5 mm, uniformity coefficient 1.65) was passed through a #30 soil sieve to create coarse and fine fractions, and one column was loaded with each fraction. Water with 10 NTU influent turbidity and 1.5 mg/L of coagulant as alum was passed through these filters, and the distribution of flow between the columns was logged throughout the test. Flow sensors and turbidimeters were placed in this system downstream of a drop tube, so that the head loss in the sensors would not affect flow distribution between the columns. It is hypothesized that a scenario like this might be seen in an SRSF with insufficiently uniform filter media, but we further expect that the problem of uneven flow will be self-correcting as increased solids loading to one column will increase

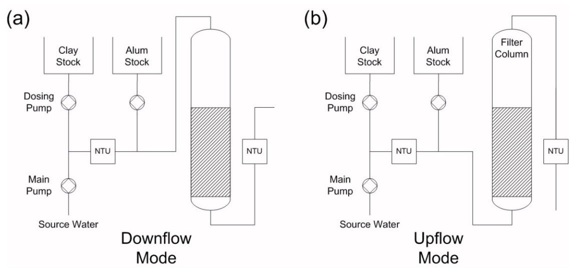

Figure 5: Process-flow diagram of the bench-scale apparatus for (a) upflow and (b) downflow filtration.

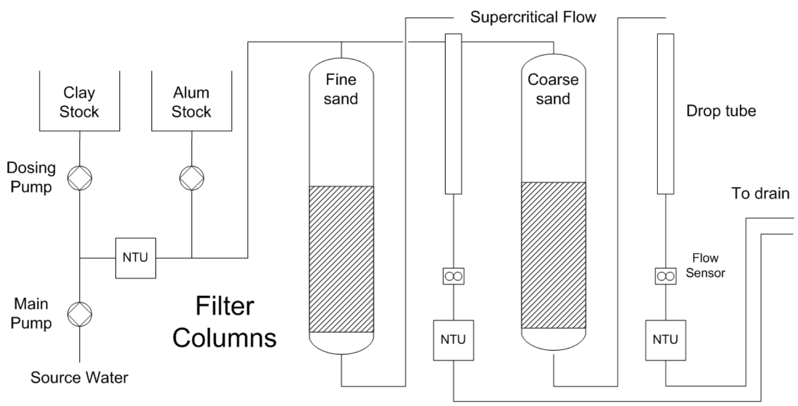

Figure 6: Process flow diagram of the bench-scale apparatus to study flow distribution and the self-healing nature of uneven flow in filters.

head loss and re-allocate flow to the other column.

Results and Discussion

Siphon Failure Limits

The first pilot-scale experiments involved putting the siphon through control system tests, which has shown siphon failure in the system. When the system is in filtration mode, the water rises in the filter column and increases pressure on the air trap that is in the siphon. What we have found, through simple visual observation, is that this pressure becomes too much for the air trap and the water begins to flow into the siphon pipe. Our experimentation consisted of putting the system through its normal filtration and backwash cycle, while carefully taking measurements of the heights of the water in the inlet bucket as well as in the column when the siphon just began to leak. Water elevations at the failure point are shown in 7.

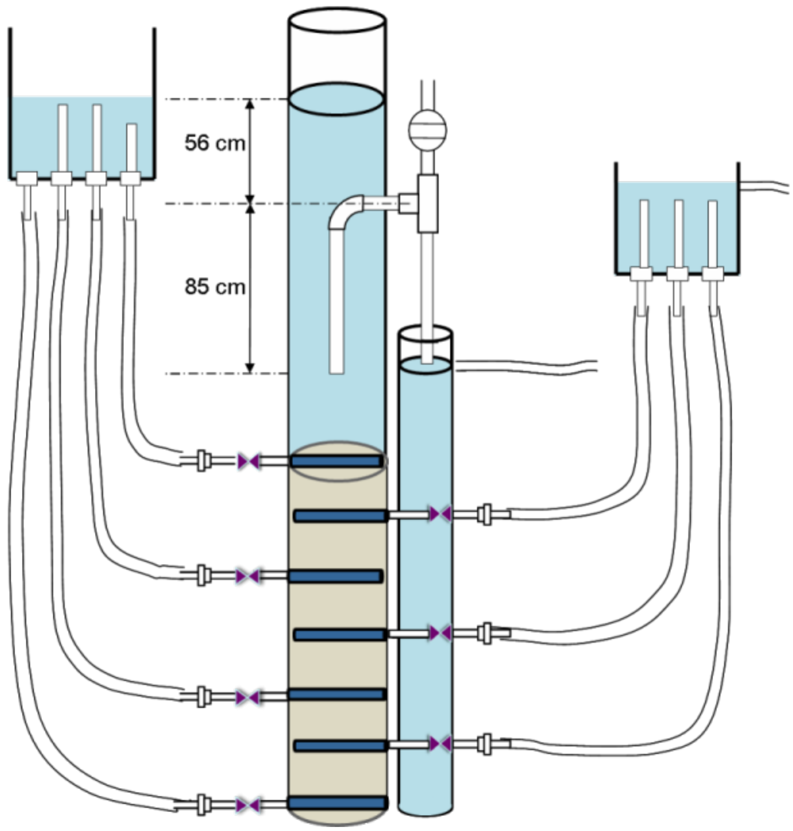

Figure 7: Diagram showing water levels observed at siphon failure, when water began leaking into the siphon.

All of our data in this part of the experiment was pretty consistent, and also coincides with the predictions from the design equations that tell us the water is supposed to go over the siphon only about 56 cm. The air trap at equilibrium is described by the following system of equations:

$$P_{Air} = \rho_{Water} g \left(H_{Rise} - H_1 \right) + 1atm \tag{1}$$

$$P_{Air} = \rho_{Water} g H_2 + 1atm \tag{2}$$

$$P_{Air} = \frac{n_{Air} RT}{V_{Air}} \tag{3}$$

where P_{Air} is the gauge pressure of the air; H_{Rise} is the height that water has risen in the filter column over the inlet of the siphon; and H_1 and H_2 are the heights of water in the siphon, within the filter column and in the backwash box, respectively. For a water rise as shown in 7, these equations predict that the water in the siphon pipe will rise sufficiently to begin spilling over into the horizontal part of the siphon. The experimental observations show that these equations are valid for the purposes of siphon design. They also allowed us to select a higher position to place the siphon pipe so that it would not leak during the filtration cycle.

Riser Pipe Configuration Test

Three possible configurations were proposed for the riser pipes in the filter inlet box. Configurations tested with the pilot-scale apparatus are illustrated in 8, and include:

- Configuration (a): three riser pipes of the same height, to automatically turn the top three filter inlets on and off during the mode switch
- Configuration (b): the reduced size of the riser pipe for the topmost inlet allows most water to drain from the inlet box and exit the filter without passing through the sand and possibly causing excess fluidization
- Configuration (c): staggered inlet pipes to fluidize the layers of the filter two at a time instead of all at once, possibly reducing the initial head requirement during backwash

After testing the three different pipe stub configurations in the pilot scale model, we have come to the conclusion that Configuration (a) is the most effective configuration. We have concluded that the necessary height for the three variable pipe stubs lies between the steady water height during filtration mode and the steady water height during backwash mode. As to what the heights of the individual pipes should be has proven to be irrelevant. With Configuration (b), there was little excess fluidization observed with the pilot-scale system at the beginning of backwash. This leaves us with little reason to put much time

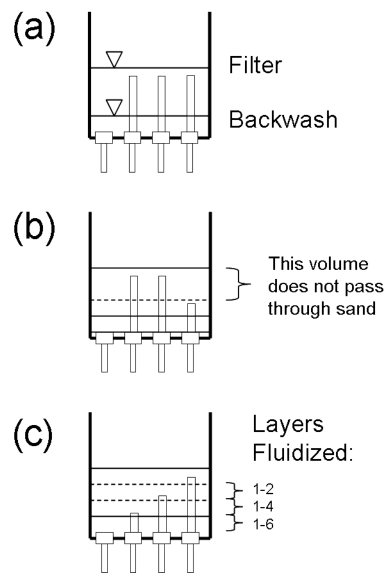

Figure 8: Proposed configurations of inlet box riser pipes and rationale for each.

into the testing of this configuration. Likewise, Configuration (c) shows a water level behavior similar to that of (a), but with more activity between the filtration and backwash water levels, which gives no further effect to the system. Therefore, the simplest and most effective configuration would be the one which puts three equal-height pipe stubs at a level happily between the water levels during filtration and during backwash.

Water level logs are shown in 9, which plot the height of water in the inlet box and the height of water over the top of the sand in the filter box. These results show that both cycles of operation work effectively with the control system configured as in (a) or (b). The equilibrium heights of water and head losses, both for backwash and clean-bed filtration, are the same with either configuration. The major difference can be seen in the data from the inlet box water level during the transition to filtration mode, where the flat lines on the curve reflect the heights of the pipe stubs in the inlet.

Water Seal Siphon Study

It was conceived to implement a U-shaped water seal instead of the backwash basin for holding the siphon's air trap. The expectation is that in full scale implementation, the U-shaped water seal, consisting of a length of pipe with two elbows, will cost less to construct than a concrete basin. Furthermore, draining a pipe will prove to be simpler than draining a basin in the field, especially if the backwash effluent contains sedimentary particles.

The pilot-scale apparatus was adjusted to implement the water seal by com-

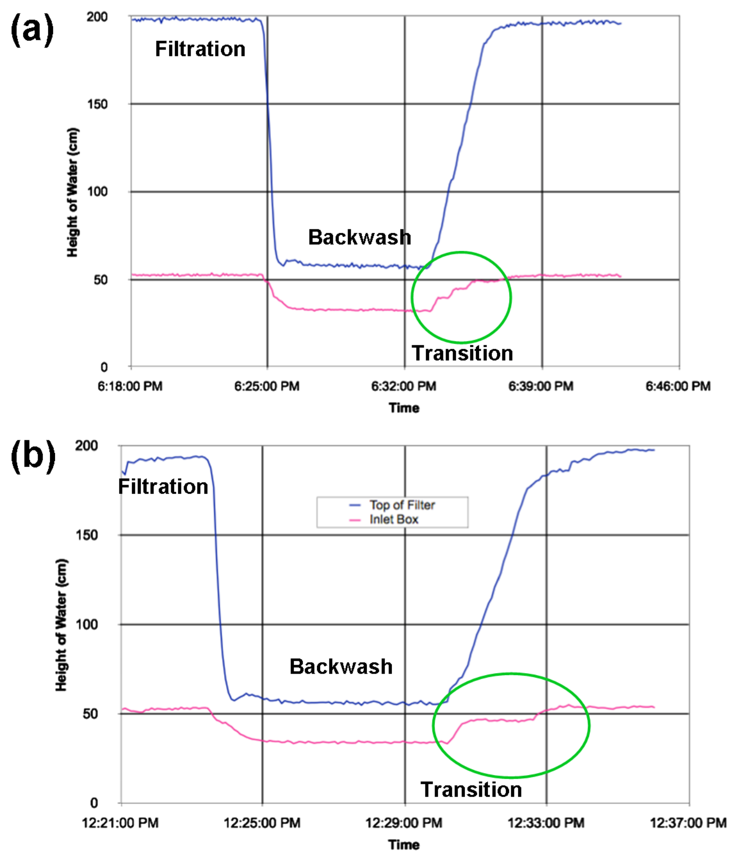

Figure 9: Water level data for the filtration and backwash cycles, for (a) pipe stubs of equal size and (b) pipe stubs of staggered size in the inlet box.

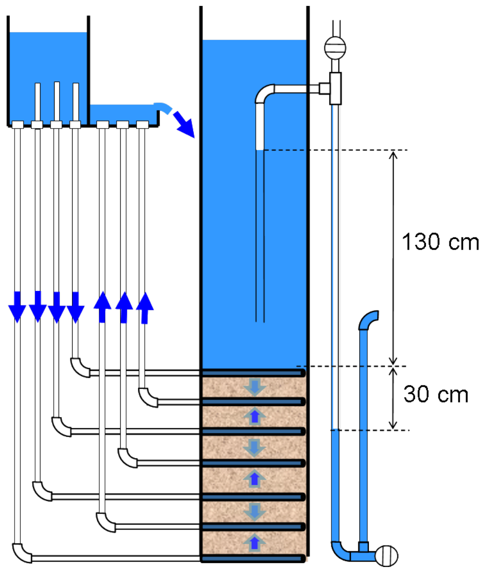

Figure 10: Steady-state equilibrium in filtration mode for the water-seal siphon study.

pletely removing the backwash basin and extending the siphon pipe down to the floor, adding two elbows, and running the pipe back up to the elevation required for the backwash weir. The new water seal configuration successfully held the air trap and allowed for cycling between modes. Since the new water seal pipes in the pilot-scale apparatus are clear, it allowed for direct observation of water levels in the siphon pipe during filtration mode, while the air trap was in place.

Measuring from the datum at the top of the sand during filtration, it was observed that at the beginning of filtration, the top of the water in the siphon pipe within the filter column reached 130 cm above the datum. Simultaneously, the top of the water in the siphon pipe leading to the backwash weir reaches 30 cm below the datum. These results are shown in 10.

These observations concur with the expected water levels based on the prediction from theoretical hydrostatics. The pressure head from the water level in the filtration column over the water level in the adjacent siphon pipe equals the pressure head from the backwash weir over the water level in the water seal pipe. This hydrostatic equilibrium holds the air trap in place because air has negligible density. Equations (1)-(3) can be used to show that the observed steady-state equilibrium for filtration was consistent with our hydrostatics model.

Sand Removal System Test

During the sand removal system experiment, we have successfully removed the sand down to the end of the pipe, which is halfway between the inlet and outlet

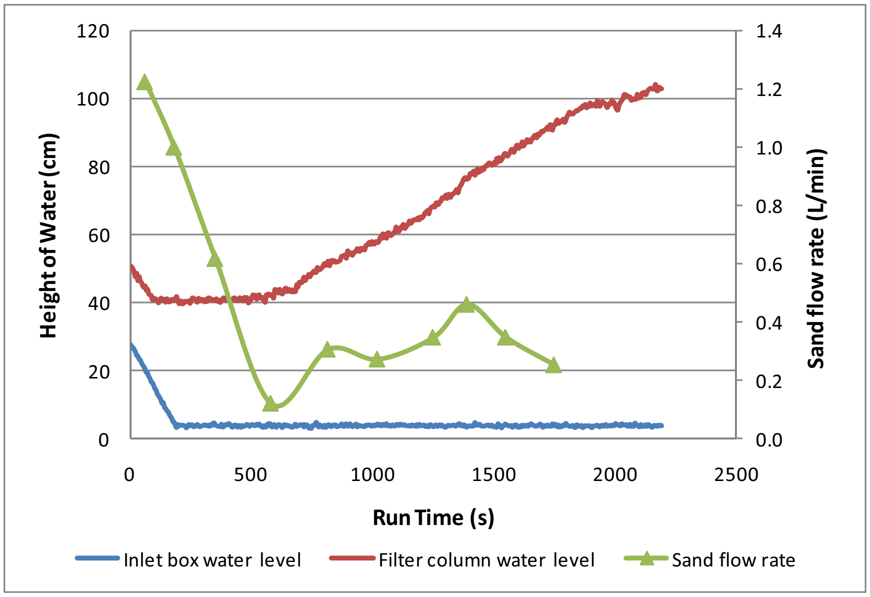

Figure 11: Water levels and sand flow rate over time during the sand removal system test.

pipes of the lowest layer. We notice that the bed remains fluidized during the process and sand is removed as a slurry. However, we also encounter problem related to the air entering the siphon. As sand being removed, water level in the inlet falls, it goes below the bottom of the inlet box and entrains significant amounts of air. The air goes into the siphon system and increases its head loss dramatically and creates a risk of breaking the siphon.

According to the calculation, the sand removal flow rate at the beginning should be 1.27 L/min. In our experiment, we measured the flow rate one minute after the removal system started, and we observed a 1.22 L/min flow. The initial value we measured was almost the same as the design prediction. As we observe in the test that the flow rate decreases during the process, there is a great possibility that the little difference between the predicted and observed value was due to time difference. The data taken through the course of a test of this sand removal system is shown in 11.

When sand is being removed from the filter, the aggregate density of the filter bed volume is decreasing while the density in the sand removal tube is roughly constant. This density difference reduces the net available head driving the sand removal system, and therefore causes the sand flow rate to decrease during the test at the beginning. However, as shown in 11, sand flow rate stops decreasing near 600 s into the run, at the same time the water level in filter column starts to rise. That is because the air trapped in the siphon causes the water level in the filter column to rise, thus increasing the driving head on the sand removal system. As a result, the sand flow increases.

As more head loss in the siphon system increases the sand flow rate, we suggest that adding a screen over the inlets in order to add more head loss. This may be required to effectively use the sand removal system in the field.

Flow Distribution Study

The flow distribution among layers of a stacked filter plays an important role in the performance of the filtration cycle. We have successfully measured the flow distribution among each of the six layers of the pilot-scale SRSF and logged data by Process Controller. The interpretation of our flow data will be based on Darcy's Law. Darcy's law is a simple proportional relationship between the instantaneous discharge rate through a porous medium, the hydraulic conductivity of the medium, and the pressure drop over a given distance. By simplifying the origin equation, we derive the equation below:

$$v = K\nabla P = K\frac{\Delta H}{\Delta L} \tag{4}$$

Where v is flow velocity to hydraulic gradient, ∇P is hydraulic gradient and K is hydraulic conductivity. Note that the hydraulic conductivity$K$ is a material property of the porous media that describes the ease with which water can move through pore spaces or fractures. The hydraulic conductivity of the sand we are using in the pilot-scale SRSF is estimated to be about 5.3 mm/s.

Before each run of the filtration and backwash cycles, we zeroed each of the six layers. This must be based on the condition that there is no flow (zero flow) in the SRSF column. Assuming flow is uniformly distributed across all layers, the sensors should show a near consistent pressure drop during filtration mode, and a pressure drop of around 3.4 cm is expected to be observed. Due to the upflow through all the six layers during backwash, the sensors installed on Layers 1, 3 and 5, which normally experience downflow, will record negative head losses whereas the sensors installed on Layers 2, 4 and 6 still show positive head losses. We expected that the measured head loss should spike to just under 10 cm in absolute value. By switching between the filtration mode and backwash mode, we obtain a beautiful diagram as shown below (12). Note that we usually run the filtration longer than backwash, which is also consistent with the SRSFs in reality. In addition, we periodically shut off flow during the test to check whether the sensors maintain zero as expected. It appears from this data that flow is relatively well distributed among layers during filtration, at least initially.

Additional tests were carried out where 5-10 NTU influent water with 1.5 mg/L coagulant as alum was loaded into the SRSF, and the distribution of flow among the layers was tracked during the course of a 7-hour filtration cycle. Data is shown in 13 below. The results of this test are consistent with our hypotheses. First of all, head loss in all layers increased steadily over the course of the experiment as contaminants filled the pores in the filter and lowered the effective Darcy K. Secondly, even though one layer started out receiving more flow than

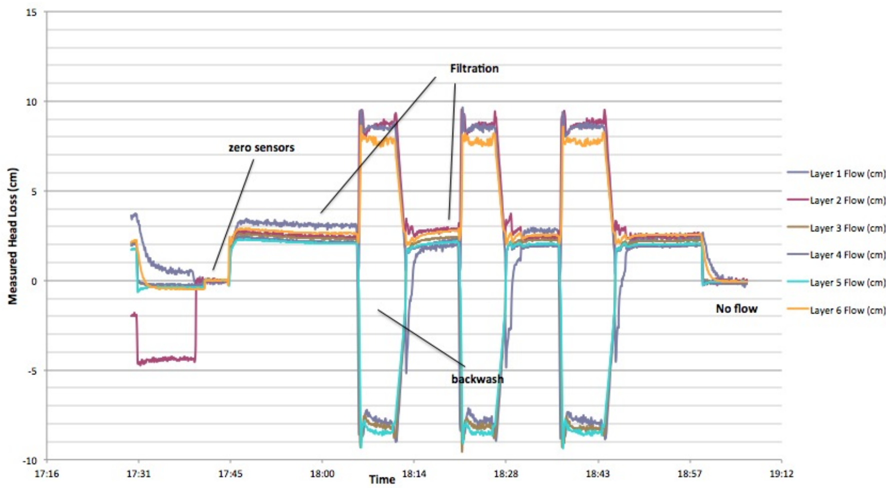

Figure 12: Plot of flow sensor readouts for the clean-bed tests.

the others, the flow became more uniform over the course of the cycle as solids loading pushed the system closer to a uniformly-distributed equilibrium. Note also that performance was good, with effluent turbidity generally below 0.3 NTU.

Upflow-Downflow Performance Comparison

In our bench-scale study of the effectiveness of upflow and downflow through the layers of stacked sand, we measured the turbidity of the influent/effluent water in both modes. This experiment is meant to show us whether or not the assumption of equality of the upflow and downflow in the pilot-scale was correct. Each run of the experiment was preceded by backwash and vibration-assisted settling to a 20 cm bed depth. We collected 6 hours of data for downflow, followed by an automatic switch to a 6 hour data collection for upflow.

As you can see in 14, there is a clear and systematic difference between the downflow and upflow cycles, with downflow performance significantly better. The major difference is the "spikes" of turbidity in the upflow effluent, as the baseline of the effluent and pC* graphs appear to be similar in upflow and downflow.

We hypothesized that the spikes in 14 are due to contaminants that settled out on top of the sand during the downflow cycle, then were carried into the effluent from time to time during the upflow cycle. Therefore, an additional upflow/downflow comparison test was run with a backwash cycle to clean the filter bed and remove any settled contaminants between cycles. The results of this test are shown in 15 and 16.

These figures show that, under comparable operating conditions and using an entire filtration cycle of data, there does not appear to be a significant difference

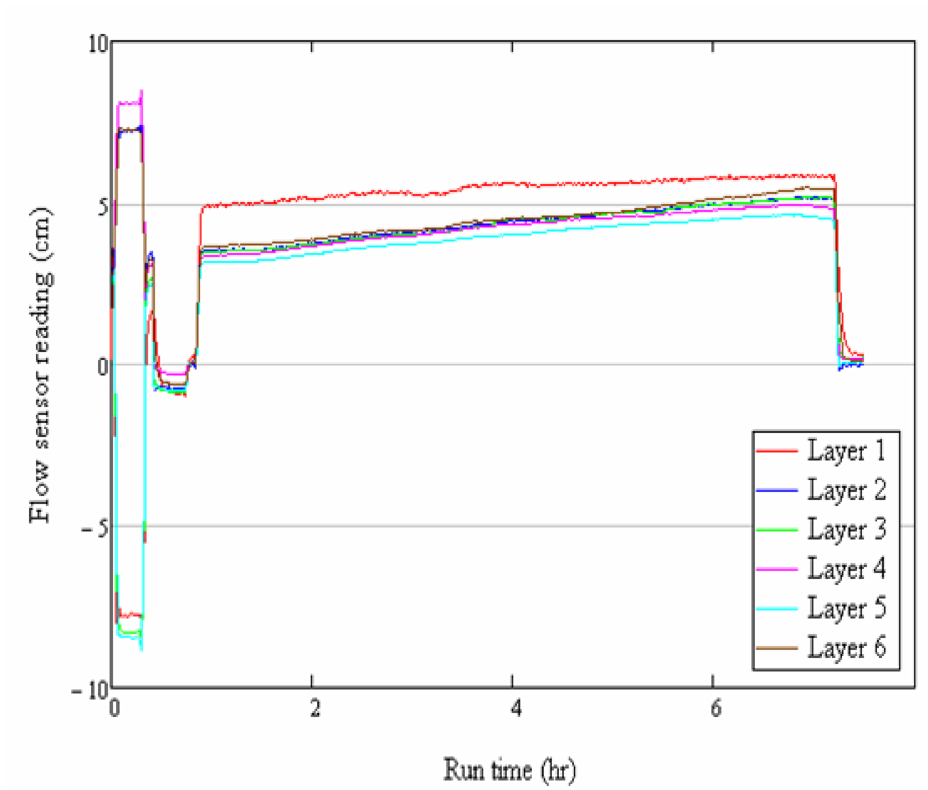

Figure 13: Plot of flow sensor readouts from the tests with 5-10 NTU influent over a 7-hour filtration cycle.

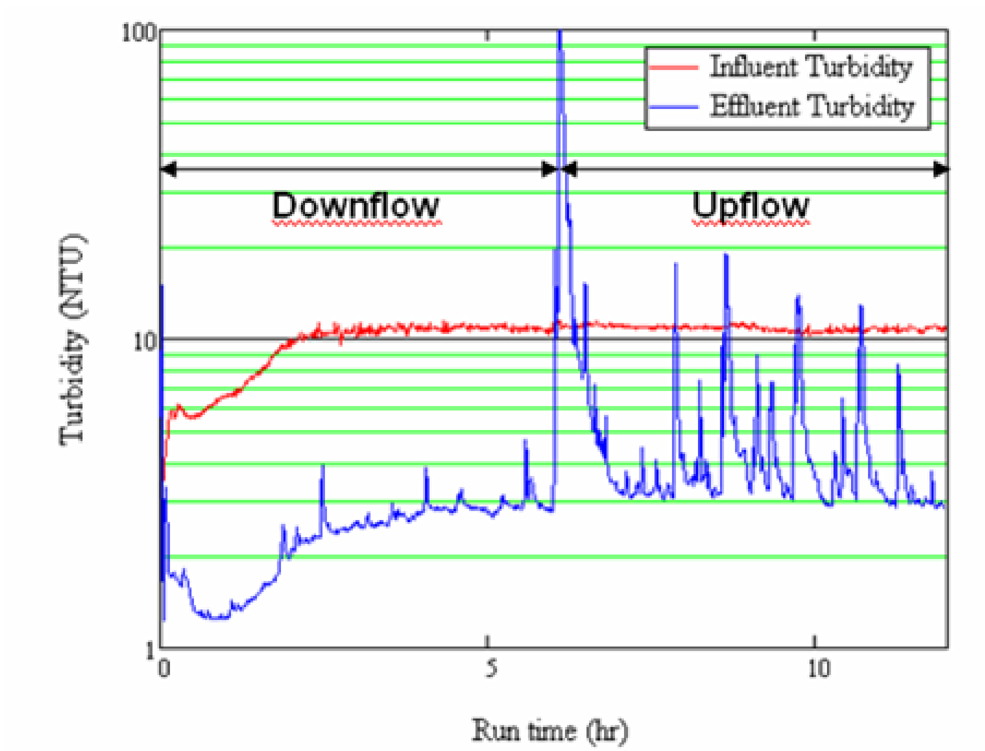

Figure 14: Upflow/downflow comparison results with spikes of turbidity in the effluent during the upflow cycle.

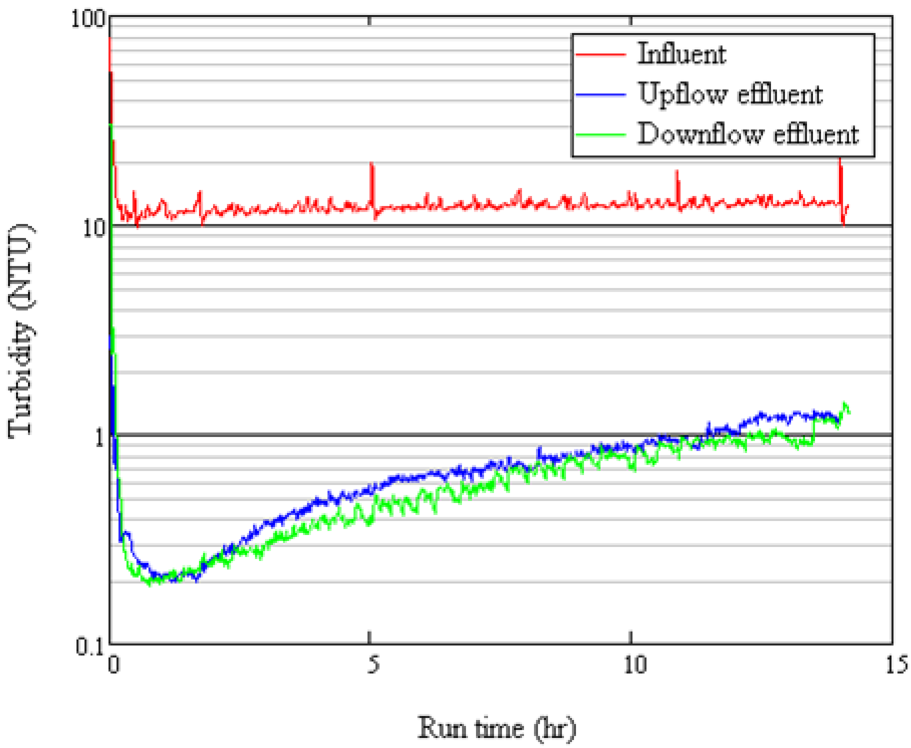

Figure 15: Upflow/downflow turbidity removal data for a 14-hour test with a backwash between cycles

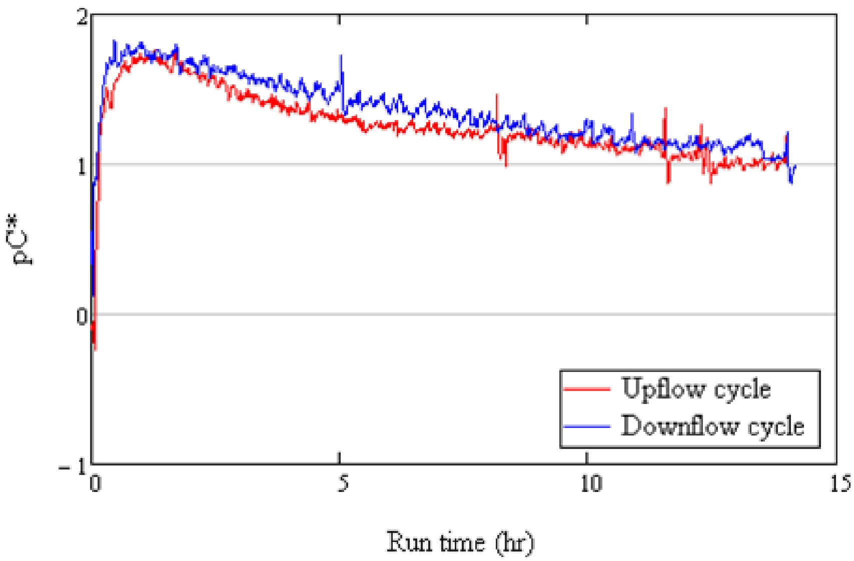

Figure 16: Upflow/downflow performance as pC* during a 14-hour test with a backwash between cycles

in particle removal performance between upflow and downflow filtration. This is an important result for the viability of the SRSF concent.

Conclusions and Recommendations

- The placement of the siphon pipe through the walls of the filter is an important design constraint to make sure that the air trap will work correctly during the filtration cycle. The design equations used for the field-scale filter appear to be valid for the failure modes of concern.
- The riser pipes in the inlet box should be placed between the steady-state backwash water level and the clean-bed water level during the filtration cycle. Within this window, either pipe stubs of a constant size or staggered size appear to be viable.
- The sand removal system, which has already been implemented in the field, is functioning properly and effectively removes all sand from the column. The only problem with the system is that the flow rate of the sand decreases significantly as sand is removed from the filter. A head loss element may be required for the siphon in the field to increase the flow of sand.

- At the bench scale, there does not appear to be a significant difference between the upflow and downflow filtration performances.

- Our tests of the flow rate using the sensors in the pilot scale show that the flow during clean bed conditions is relatively uniform, and the flow in each layer converges during the course of a filtration cycle.

Future Work

In the bench scale, we are in the process of adding a second column to the system. This second filter will be filled with sand of a different grain size than is in the current bench-scale filter. The purpose of this test is to find whether the flow distribution evens out in the two parallel filters over time. We expect that the flow within these two parallel filters will experience a somewhat "self healing" effect, distributing the flow proportionally through each filter. We expect that reducing the sand grain size will lower the range of filtration and backwash velocity, and work better for filtration at low flow rates. Other future priorities for the SRSF research will include:

- Experimental studies to specify the optimal filter medium, in terms of sand grain size and uniformity.

- Tests of a 4-layer instead of 6-layer SRSF configuration, to investigate the possibility of using higher velocities with deeper sand layers.

- Test of an air elimination system for the filter inlet channel, to address a problem that has been observed in the field.