Stacked Rapid Sand Filtration - Pilot Scale Operations

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Abstract

The stacked rapid sand filter has been proven to be an alternative to traditional rapid sand filtration systems, and their efficiency makes them an appropriate component in gravity powered municipal-scale water treatment facilities. In this study, a pilot-scale apparatus has been created as a model of the hydraulic controls throughout a full-scale stacked rapid sand filter system. After installation and field testing at Tamara, it is vital for the backwash segment of filter operation to be controlled for a more efficient use of the system. The purpose of the current experimentation and lab procedures are to determine the optimal backwash cycle time necessary for the filter to remove as much particulate matter as physically possible with a short filter-to-waste cycle, thus reducing the overall rinse cycle time. Further research will be needed in determining how to lessen bubble formation, be it in the inlet box or filter itself, and in measuring the change in flow distribution throughout filtration and backwash. A four-layer rapid sand filter was created to test filter efficiency versus monetary compensation from using less sand in the filter box, but was shown to have less than optimum particulate matter removal when compared to the tested six-layer.

Literature Review

Belkin, N., Bar-Zeev, E., Berman, T., and Berman-Frank, I. (2012). "Two Innovative Devices for Depth Sampling in Granular Filtration Systems." J. Desal., 286, 115-119.

In this article, two new sample-collecting devices in rapid sand filtration are discussed. The first device is able to obtain a sample, either an interstitial water sample or sand granule, from within the filter bed during filtration. The second device is able to measure levels of dissolved oxygen (DO) from within the filter bed. Both require the use of individual peristaltic pumps during operation. Because electricity is required, these devices cannot be used in AguaClara plants due to the strict "no-electricity" sustainability requirement, but these devices can provide very useful information in the laboratory, i.e. at the pilot and bench scale. These devices are mainly used to deliver biological data, which is not a primary concern of the SRSF Pilot scale team at this time, but future research topics may require and benefit from this technology.

Chuang, Y., Wang, G., Tung, H. (2011). "Chlorine Residuals and Haloacetic Acid Reduction in Rapid Sand Filtration." Chemosphere, 85(7), 1146-1153.

This journal discusses the relationship between chlorine levels within the sand filter and bioactivity levels. Specifically, this research targets the amount of biodegradation due to haloacetic acid (HAA). Not surprising, this research concluded that with higher amounts of chlorine the amount of bioactivity decreases. This research is informative because, given the current AguaClara plant design, the water is chlorinated after it contains less than a specified value of turbidity. Bioactivity is known to increase with a decreasing presence of chlorine, so we may have to concern ourselves with biodegradation within our filter bed. If this phenomenon is deemed a topic of concern for future, we may be able to use the research from "Two innovative devices for depth sampling in granular filtration systems" above to collect and analyze data.

Han, S.J. (2009). "Simulation on Combined Rapid Gravity Filtration and Backwash Models." Water Science and Technology. 59, 2429-2435.

Amirtharajah, A. (1984). "Fundamentals and Theory of Air Scour." Journal of Environmental Engineering. 110, 573.

These two journals discuss a tried-and-true component of filter backwashing: air scouring. Air scouring is the process of using air, in addition to water, to agitate and fluidize the filter bed during backwash. Currently, the AguaClara Stacked Rapid Sand Filters use only water during backwash to fluidize the bed. Air scouring has been proven to greatly reduce backwash times as it causes greater forces to dislodge particulate matter from the filter media. There are different ways to incorporate air in the backwash cycle. The design can either incorporate either keep a constant flow of air along with water, or it can implement pulsed air, creating a "collapsing" effect on the filter bed. "Collapsing pulses" are said to be the most effective in quickly cleaning filter beds during backwash. The air breaks up what are called "mudballs," a large agglomeration of particles that occasionally form in the filter.

It would be interesting to consider the effect of incorporating air scouring in an AguaClara plant. This process can potentially optimize current backwash cycles of the stacked rapid sand filter. However, it may be difficult to implement this process as AguaClara plants by design run without electricity. Nonetheless, experimenting with this process may lead to decreasing the amount of wasted water during backwash. This is an interesting topic and some people (i.e. grant reviewers) have asked questions about it with regards to stacked filtration. The way air scouring works is that compressed air is pumped in at the top of the filter bed before the backwash water flow starts.

D.S. Bhargava, C.S.P. Ojha (1989). "Theoretical Analysis of Backwash Time in Rapid Sand Filters." Water Research, 23(5), 581-587.

This journal provides mathematical support for one of the current research objectives of the SRSF Pilot Scale team. Using a derived mathematical model and experimental data, this source postulates and supports the idea of an "optimum" backwash time. For any given filter, the longer the backwash cycle, the more particulate matter will removed from the filter bed. However, after a certain amount of time, there is a sharp decrease in marginal removal. At the beginning of our work this semester we believed there was an ideal backwash time – one that is long enough to remove enough particulate matter for appropriate filter performance while still remaining short enough as to not waste clean, filtered water. This journal article supports our ideas in a more detailed and formal manner; however it does not recommend specific conditions (ideal backwash time or filtration velocity), because these are specific to the physical system of interest.

Background

Traditional rapid sand filters are backwashed at high velocities to sufficiently clean the media bed, which requires large flow rates that are delivered by costly and complicated equipment such as elevated tanks or electrical pumps. This technical complexity makes it impractical for small communities due to the high capital costs that are required. The stacked filter system significantly reduces the amount of water necessary for backwash and the amount of space required for the filter.

It is possible to have fully hydraulic filters in the traditional design, but the design is flawed due to the filters needing to be in parallel with each other. This requires the filter boxes to handle the increase in velocity when one box is taken off-line and backwashed, diverting the flow from the other boxes with a velocity proportional to the numerical count of filter boxes. Unlike the Stacked Rapid Sand Filter (SRSF), which has all these components in one unit, the parallel filter configuration requires a large amount of space to build each filter box along with a complete set of plumbing for each filter box. The SRSF overcomes this drawback by using simple fluid dynamics and geometric manipulation.

The SRSF requires only one filter tank to accomplish both filtration and backwash, and it uses the same total flow for both processes. As shown in Equation 1, the filtration velocity is directly related to the flow through the system divided by the number of layers and the area of each layer. The flow pattern through the SRSF depends on what cycle it is currently in, changing from parallel in filtration to series during backwash.

$$V_{Filtration} = \frac{Q_{Filtration}}{N_{Layer}A_{Layer}} \tag{1}$$

The difference in the two system states is shown in Figure 1. When backwash is fully engaged, the flow is solely entering the filter from the base of the column, flowing up through the entire sand bed to exit the filter through the backwash siphon and weir.This weir/siphon piece is important in controlling the cycle of operation of the filter: during filtration, it maintains a high water level in the column with an air trap, and throughout backwash it is the sole way of removing

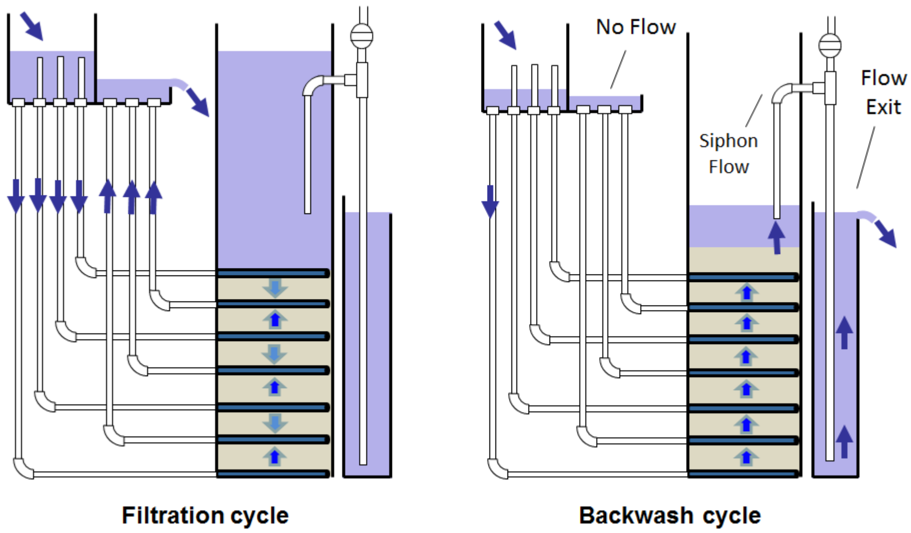

Figure 1: Figure showing the difference in flow directions during filtration, the figure on the left, and the backwash, on the right. During backwash the flow direction is all upwards and results in a more rapid velocity that is proportional to the amount of layers present.

the high turbidity waste water. The backwash velocity ($V_{Backwash}$) experienced in the bed is the only a function of the flow $Q_{Backwash}$and the area (A_{Layer}) of one layer (Equation 2).

$$V_{Backwash} = \frac{Q_{Backwash}}{A_{Layer}} \tag{2}$$

If the same flow $Q_{Filtration}$ is used in both backwash and filtration, this formula is simplified further to Equation 3, which shows how $V_{Backwash}$ is directly influenced by the number of layers and the initial $V_{Filtration}$ value:

$$V_{Backwash} = N_{Layer} V_{Filtration} \tag{3}$$

There are four inlet pipes that carry water into the filter and distribute it to layers above and below, and three outlet pipes remove water that has passed through a layer of sand, theoretically giving the filter bed six layers. Once the filters bed is clogged with contaminant particles, it must be backwashed to regain particle removal efficiency. A stacked filter system can initialize backwash by fluidizing the layers in a cascading fashion from the top down, accomplished by increasing flow through successively lower inlets. Equation 3 states that velocity through the system during backwash will be equal to six times the normal velocity when filtering.

Velocity during backwash is increased without the requirement of additional flow simply because the effective area is decreased. Equation 3 implied that a configuration of stacked layers can be designed so that the same amount of flow during normal filtration operation can also be utilized to fluidize the entire sand bed. For example, a filter with six layers could be operated at a filtration velocity of 1.83 mm/s, but then have a velocity of 11 mm/s for backwash. Both of these velocity values are within the acceptable range of typical design values for rapid-sand filtration.

When the configuration of the filter is changed, such as by decreasing the number of active layers, the filtration velocity will proportionally increase if all other variables (such as $Q_{Filtration}$ and A_{Layer}) are kept constant. A decrease in layer number from six to four layers will increase the filtration velocity to 2.745 mm/s. Even though the number of layers is decreasing, the backwash velocity remains constant at 11 mm/s because of its fundamental connection to the constants noted above. The increase in filtration velocity through the layers could lead to poor performance due to scouring of contaminant particles off of sand grains, forcing the high turbidity water through the layers and not allowing contaminant particles to be trapped and thus filtered out.

Additionally, with only one valve it is possible to change from filtration mode to backwash mode and vice versa. This new design uses less water during backwash, reduces the cost of infrastructure as the amount of filter beds needed is reduced, and also eliminates the requirement for expensive electric pumps.

Materials and Methods

Pilot-Scale Apparatus

The pilot-scale apparatus was designed to offer a set-up which models the municipal-scale SRSF. This pilot-scale design consists of four inlets which, during filtration, direct the flow of influent water through a layer of the sand filter bed, and out through the outlet. During backwash, the flow is directed from the filter column above the bed of sand filter media to the siphon and out through the backwash outlet. The influent water enters through the "inlet box," a 4" diameter, 76 cm tall clear PVC pipe fastened 2.9 meters off of the ground. The Fall 2011 Team used a bucket instead as this inlet box, and changes to the design can be seen in Figure 2. The U-shaped backwash siphon design, depicted on the right side of Figure 2is a modification of last semester's design which included a siphon submersed in a pipe. Observed water levels are consistent with theoretical hydrostatics, so this simple change to the design has made the backwash of the system much easier to complete.

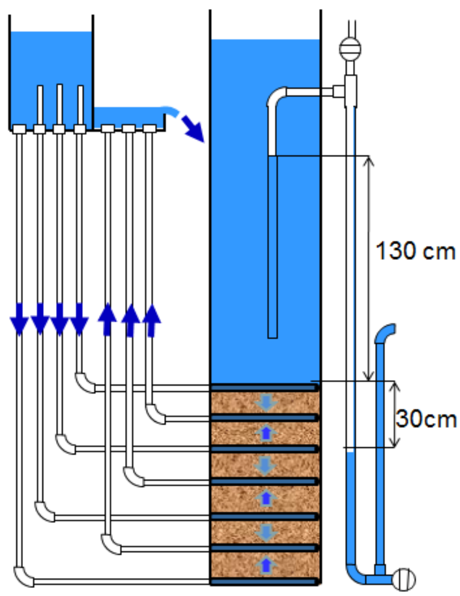

Figure 2: Current apparatus setup of SRSF system at pilot-scale. Curved siphon on the right is used to break air trap to commence backwash cycle. The filter displayed is in filtration mode, which is why the water level in the inlet box is high enough so there is flow through all four tubes connected to the filter.

There were two advantages to using the clear PVC pipe inlet box: firstly, it facilitates the operator's observation of the water level during the filtration and backwash modes; secondly, its comparatively smaller diameter allows for a reduced volume of water to be stagnant in the inlet box during filtration and backwash modes. Open at the top, the PVC pipe is capped off on the bottom with four stub connectors integrated into the cap. Three of the connecting points have PVC pipe stubs to control flow during filtration and backwash.

Each stub connector has a hose attached that runs downward to connect to the filter column at the bulkhead fittings. Three of the bulkhead fittings on this side of the filter column defines the top of either the first, third, or fifth layer in the sand filter. This is with the perspective that the "first" layer is that which is at the top of the stack. The three outlet bulkhead fittings on the opposite side of the filter are spaced so that the bottom of the second, fourth, and sixth layers are marked by the height of these bulkhead fittings. The entire filter column consists of a vertical 4" diameter clear PVC pipe which extends from the floor to 3.7 meters above the ground. It includes the sand bed of filter media at the bottom of the column, consisting of six layers, each 20 cm deep and is filled with water.

During filtration, the height of the water in the column usually levels out above the T-pipe connection between the filter column and the siphon. Water flowing through the first, third, and fifth layer moves downward one layer to the respective slotted pipe and through an outlet pipe. Water traversing through the second, fourth, and sixth layers of the sand filter flow upward toward toward the slotted pipe shared by the water flowing through the layer above. The three outlet hoses travel upward to the pipe stubs at bottom of the outlet box, a 5 gallon bucket. A hose from the top of the outlet box facilitates flow from the bucket down into a sink. As mentioned previously, the top of the filter column is connected by a T-pipe to the siphon, a vertically-standing 1" diameter, 3.6 meter tall clear PVC pipe.

At this connection, an elbow pipe internalized in the filter column is attached to a long clear PVC pipe which extends to a height just above the sand bed. The siphon on the outside of the filter column is connected to another vertical PVC pipe of the same diameter. The two are connected at their bottoms by a similar clear PVC pipe. The siphon is designed to maintain appropriate air pressure within its two main vertical pipes during filtration. Turning the valve at the top of the siphon releases air trapped in the siphon pipe during filtration, which forces the water to exit through the outlet box. This changes the flow so that is is directed up through the long pipe in the filter column and out through the siphon, as opposed to the flow being directed through the outlet hoses, as it is during filtration.

Control of Parameters and Data Acquisition

For our experimental methods and materials, we must calculate certain quantities and control important parameters to meet our experimental goals. We must first be sure that the flow rate through the entire filter is correct. Overall,

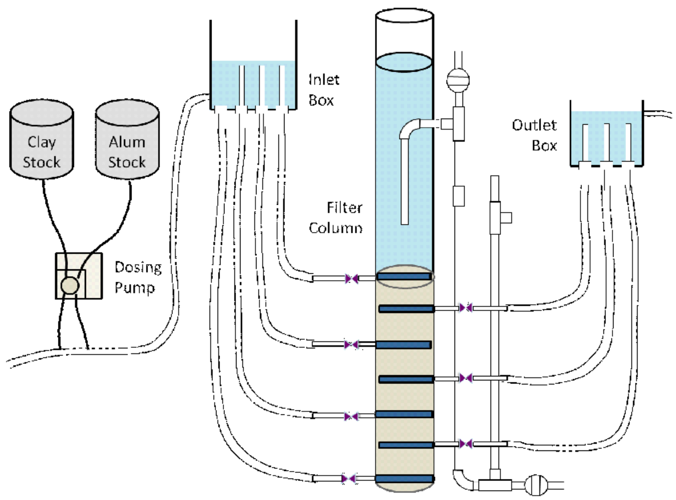

Figure 3: Figure showing locations of alum and clay stock tanks, along with dosing pump, in relation to the rest of the apparatus. The difference in heights in the inlet and outlet boxes

the filter has a flow rate of 5.3 L/min. This is adjusted by measuring the flow coming out of the outlet box tube and either opening or closing the flow valve that is supplied with water from the reservoir. At 5.3 L/min, the velocity during backwash is calculated as 11 mm/s and during filtration it is 1.83 mm/s, as used in the field-scale designs.

The next set of appropriate values to be determined are the concentrations and dosing rates of the influent water additives: Aluminum sulfate (alum) solution and clay solution. Clay is added to the influent water to create the desired influent turbidity of 5-10 NTU, in the high range of expected effluent turbidities from sedimentation. The alum is a coagulant that improves the effectiveness of our layers of sand filtration, and 1.5 mg/L of coagulant (as alum) are added to the influent water just downstream of the clay addition to simulate residual alum in the settled water. Both the alum and clay are individually added to the influent water at a rate of 3.49 mL/min using two peristaltic pumps with size 13 tubing. The alum and clay solutions are in their own stock reservoirs that continuously keep the solutions mixed. The alum solution stock has a concentration of 2.632 g/L and the clay stock solution has a concentration of 20 g/L. These values are obtained by using the "Stock Size Calcs Flow Tests" MathCad file found in the SRSF Spring 2012 group folder.

Data readings are taken every 5 seconds, and logged into an Excel file for each day. A new Excel file is created every time a new filtration cycle is started or stopped by Process Controller. MathCad is used to compile and analyze the collected data. The MathCad file is programmed to read and gather the data for a specific time period from the Excel datalog files, governed by an Excel 'Meta' file. All files are stored on a central server within the Stacked Rapid Sand Filtration folder.

Total Backwash Time Tests

Initially, a test was conducted to determine the performance of a 6:00 minute backwash run, as opposed to the 10:00 minute time used in the field. This was prompted by the indication from Spring 2011 data that the turbidity was low enough in the water coming from the backwash outlet just 6:00 minutes into the backwash cycle. Examining the minimum amount of time for the system to backwash properly is essential in conserving as much clean water as possible. The experiment was designed so that it ran in 12 hour backwash cycles for a total of 48 hours. Every 12 hours, the air valve on the siphon was turned to break the air seal and begin the backwash cycle. The valve was closed once there was consistent flow through the siphon, allowing the draining and fluidization of the layer to commence. After six minutes, the valve was opened and closed again to conclude the backwash cycle and to restart filtration. The influent and effluent turbidity were recorded by datalogging turbidimeters.

High Turbidity Tests

Following the 12 hour cycle backwash experiments, another experiment was conducted to observe the performance of the filter media over less time, but with proportionally higher turbidity running through the system. Loading the filter with as turbid water as possible for a shortened time period allowed for cycles to run for a total of an hour and a half rather than 12 hours. With many glitches occurring while the apparatus was left to run unattended, many of the test run results were unable to be analyzed as applicable data. This shorter time frame for filtration allows the system to be observed throughout the entire cycle for air bubbles, leakages, server errors, turbidity fluxes, and the like, and for these issues to be addressed as they occur.

To emulate the clay load of the previous 12 hours cycles, but in a shortened time, the clay was pumped in at 500 NTU during filtration. Before backwash was performed, the turbidity of the influent water was decreased to 10 NTU to return to more typical influent conditions. This was able to be implemented because the product of the filter run time and influent turbidity is roughly constant, so the overall "NTU-hr" of the filter capacity will be similar running 10 NTU over 12 hr (120 NTU-hr) or 500 NTU for fifteen minute to have the same filter head buildup (125 NTU-hr) .

The valve is opened to break the air seal, because a large enough amount of head will have be built up at this point, and the time for the water level in the filter column to drop and stabilize above the fluidized bed was recorded as the fall time. The ensuing timed portion is the altered variable of interest in this test, the flush time, and it is the amount of time the filter will actually be backwashing. The experimental runs varied with 10 minute, 8 minute, 6 minute, 4 minute, and finally to 2 minute time frames. The runs began with 10 and 8 minutes, since these were known to effectively and completely remove particulate matter from the bed, thus allowing for a successful subsequent filtration cycle. These times were decreased by 2 minutes each run so that the data would show which backwash time does not adequately clean the filter media to prepare it for the next filtration cycle.

Exiting backwash, the valve is turned again to resume the filtration cycle. The rise time is recorded, which is the amount of time it takes for the water in the filter column to climb until it begins exiting the outlet box. The time period it took the filter to get to 90% contaminant removal efficiency was known as the rinse time. This percent-removal is determined by noting the mostly stable influent turbidity and observing at what time the effluent turbidity is 10% of the influent reading. Immediately following this, the remaining time required for the effluent turbidity to decrease to that of U.S. drinking water standards, or 0.3 NTU, was also recorded. This concluded data collection for the backwash cycle.

The flush time used for each run is directly transferable to another stacked filter, due to the nature of the media and the influent being used. The rise and fall times will change depending on the hydraulics and configuration of each specific system. This is how the data collected and analyzed in the laboratory setting can be transferred to real world implementation. It is possible with smaller backwash periods, such as under 4 minutes, that there may be excess headloss at the beginning of the filter cycle. Flush times that showed initial head buildup, like an additional 4-8 cm over and above the clean bed head loss, were performed multiple times to find any patterns and to determine an average value.

Four-Layer SRSF

After the high turbidity tests were analyzed, the focus was redirected toward minimizing the amount of sand used as filter media while still providing an efficient filter. This study explored the performance and overall efficiency of a four-layer filter in comparison to the efficiency of the six-layer filter bed, with both filters designed with equally deep layers. As might be obvious, a filter comprising four layers, 20 cm each, would be less financially burdensome on the municipal scale than a filter with two additional layers of sand, also 20 cm each. Since the six-layer apparatus provides an acceptable filtration performance, it is worth considering whether or not the performance of a less-costly filter will be sacrificed for its lower cost. Because efficiency of a stacked rapid sand filter is complex, the amount of wasted water, which is influenced by the backwash time, the rinse time, and headloss buildup, and removal of particulate matter, are all variables which need to be compared to those of the six-layer filter.

The clay was loaded into the system at 10 NTU so that the results may be comparable to those of the tests run over 12-hour cycles through a six-layer filter. As in previous tests run through the six-layer filter, the apparatus was turned on so that clay and coagulant mix with influent water and enter the apparatus through the inlet box. When an appropriate amount of head is built up in the inlet box, which is to say that the water level rises 30 cm after turning the filter apparatus on, the siphon valve is turned to break the air seal and begin backwash, as was executed in previous experiments. The procedure for operation continued to remain identical to that used to execute filtration cycles using a six-layer filter. A backwash time of 3 minutes was employed, as our previous testing offered this as the optimal backwash time. The rise, rinse, and fall times were recorded as in previous testing. The focus, however, was on the rinse time, as this determines how much water must be used to remove contaminants from the influent water, and thus deeming it unavailable to drink. After a certain amount of time, the filter becomes saturated with particulate matter and the effectiveness of the filter media decreases exponentially. This causes the effluent water's turbidity to become essentially stable. The value of the effluent water's turbidity was also a key consideration to characterize the overall performance of the four-layer filter.

Results and Discussion

Continuous Testing

The plotted turbidity and water height data shown in Figure 4 follows a specific observable trend. When the system is not in backwash mode, which only occurs once every twelve hours, turbidity of the influent should be fairly constant and the effluent turbidity should be lower than the influent. The plot in between these spikes, especially observable in the first and third 12 hour cycles, depicts the filtration cycles between backwashing. Backwashing expels particles in the sand bed, and the filter performance following this action results in an increase in efficiency due to scouring of captured particles.The low effluent turbidity under 1 NTU suggests that a total backwash time of 6:00 minutes thoroughly cleanses the sand bed to allow it to filter particles sufficiently.

Also seen in Figure 4 is the change in height in the system through out the filter and backwash cycle. The blue line is an indicator of water height in the filter column and the red line is the height of water in the inlet box. Linear head loss with a constant upward slope in the filter is an indicator of effective depth removal while in operation. There is a plateau in the inlet box height at the end of some cycles due to overflow being removed by an additional tube to prevent flooding.

After 40+ hours cycling, there is not a great increase in bed height, possibly due to air bubbles throughout the system. These bubbles were present in the tubing leading into the filter, at the base of the inlet box, or in the lower sand bed "layer". During filtration, the appearance of bubbles prevents the full flow

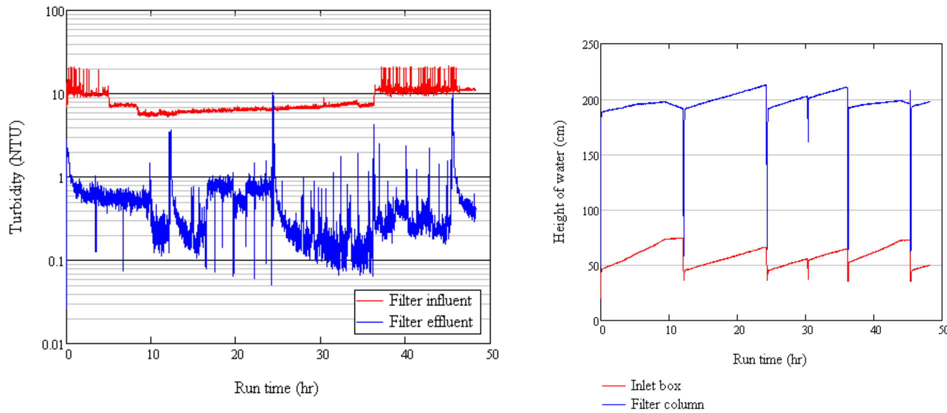

Figure 4: Influent and effluent turbidity of the system for Trial 1. Backwash cycles are shown by a sudden dip in the height of water, with a peak in effluent turbidity as the filter undergoes the filter-to-waste cycle.

of water from entering the filter, limiting both the filter water height and clay introduction to the system. It can also redistribute flow among the layers so the performance of the filter itself is compromised. The bubbles during backwash introduce a unique problem in that the bubble is often at the lowest layer in the filter column, closest to the only flow present in the system. To remove the bubbles, the valve for the hose is closed, which allows them to rise to the water surface in the inlet box.

The layer flow sensors in the system measure the increase in height at equidistant intervals thought the unfluidized filter bed. As the bed becomes more clogged with particulate matter, the velocity increases because the pore space between sand particles is decreasing. This leads to head building up in the system and recorded by the sensors. Theoretically, there should be a similar trend in all layer data, where all six sensors show a linear increase before dropping steeply during the backwash cycle.

The sensors reflect the water height increase and troubles found during the experiment. Five of the six sensors showed correct relations to height, but Layer 1 sensor data seems skewed. It is possible that in previous trials this sensor was incorrectly viewing data because sand was removed from the top sand layer. Also, because this layer is serviced by the inlet that is closest to the base of the inlet, and does not have a pipe stub, the flow may have a slight increase compared to the other layers serviced due to there being less minor head losses along this path.

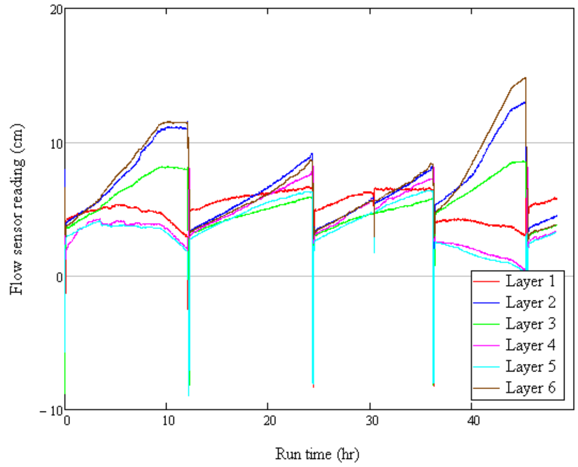

Figure 5: Sensor data for the first SRSF trial. Note how during backwash all six sets of sensors drop, due to their only being flow through the system from one point at the bottom of the filter.

At hour 30 of this trial, computer failure caused the filter to shut down for a short period of time. Our water level plots reflect this occurance.

After a base line observation was seen of how the filter performs and backwashes, it was decided that a shorter backwash cycle time would be attempted. Though five minutes would be the new "total" backwash cycle time, the period recorded is the added values of the fall time, the flush time (when the filter is in actual backwash) and the time it takes for rise to be completed.

Continuous Testing - Human Errors in Experimentation

For the next trial of filter/backwash cycles over 2 days, difficulties were experienced with the clay solution dosing system. At some point during the run, the clay inlet became clogged, preventing the addition of clay to the influent water. As Figure 6 indicates, we experienced a sharp drop in influent turbidity. This caused our effluent turbidity to be around the same value as the influent because with just an alum solution and very few particulates present, the effectiveness of our filter decreases significantly. This problem also causes issues with our backwash cycles and filter column water heights. Without the clay present in the filter, the interstitial spaces within our sand layers does not decrease. With a relatively clean filter, filter column water heights are not able to reach appropriate levels during filtration as Figure 6 indicates. These errors can be easily determined by observing turbidimeter data in real time while running experiments. With no clay particles, as shown in Figure 6, the turbidimeters dropped and were at such a low level for an extended period of time. In the future, there should be a combination of checking/re-calibrating turbidimeters

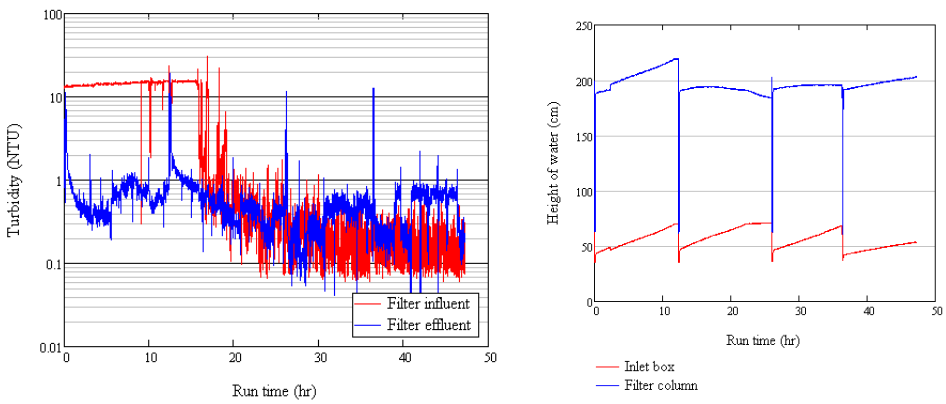

Figure 6: Influent and effluent turbidity of the system for Trial 1. Backwash cycles are shown by a sudden dip in the height of water, with a peak in effluent turbidity as the filter undergoes the filter-to-waste cycle. This trial was plagued with a sudden decrease of alum in the system due to a blockage in the transport line.

before, throughout, and after experiments to prevent such errors.

The sensor data for this trial has been severely flawed due to air entrapment in the inlet box lines. Layers that are served by the same inlet will “track” together on the graph, and the addition of an air bubble causes a marked decrease in the amount of flow to the two layers. The system will attempt to balance the overall flow throughout, so if one layer is getting less flow another will have more flow through it to balance.

During the first and last 12-hour filtration cycles of the next experiment, the aluminum sulfate stock was severely depleted. The lack of this chemical in the influent water entering the filter debilitates the coagulation of the particulate matter. As is depicted by Figure 8, during the first and last filtration cycles, the effluent turbidity began to climb, rather than decrease, as the alum ran out. This lack of coagulation caused complications in backwashing and unclogging the filter media. Because it is harder for these small particles to be expelled when the bed is fluidized during the backwash cycle, the turbidity of the effluent water was many times higher than has been observed during other backwash cycles.

Additionally, the lack of large particulate matter stuck in the sand filter allows water from the inlet box and filter column to flow relatively smoothly, even at the end of the filter cycle, through the sand bed. With particulate matter

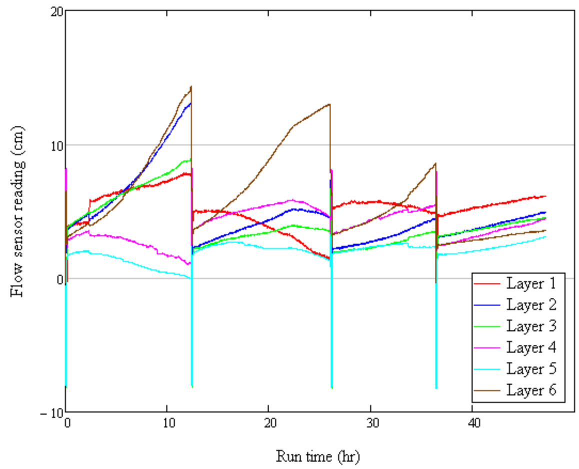

Figure 7: Sensor data for SRSF Trial 2. Note how during backwash all six sets of sensors drop, due to their only being flow through the system from one point at the bottom of the filter. This data shows a large amount of variance in the sensors due to no clay influent, so there was little to no uniformity in the data.

accumulating in the filter media, water in the inlet box and filter column should ideally face more resistance to flow in the sand bed and building head. As Figure 8 illustrates, the height of the water in the filter column did increase linearly, but not nearly as quickly or as high as previous trials.

During the second and third filtration cycles, particulate matter appeared to be filtered properly, as can be observed in Figure 8. According to Figure 9, the flow of the water through the filter column during these relatively smoothly running trials, while it does not increase as quickly as flow rates in previous experiments, is consistent and linear throughout the filter bed, as it should be.

There are apparent discrepancies in the flow readings acquired during the first and last filtration cycles of the experiment. Noting that layers 2-3 and 4-5 track together, though, suggests that air bubbles have again been affecting the inlet box tubing that supplies water to the sand filter.

High Turbidity Testing

High turbidity testing allows a larger amount of tests in a shorter period of time. Estimates were made of the total rinse time, which is calculated by adding the times needed for the effluent to drop to 10% of the influent and then how long

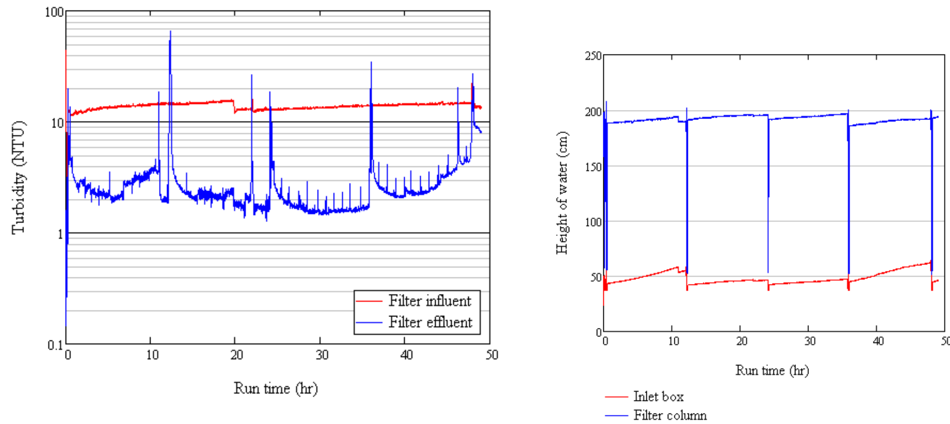

Figure 8: Influent and effluent turbidity of the system for Trial 3. Backwash cycles are shown by a sudden dip in the height of water, with a peak in effluent turbidity as the filter undergoes the filter-to-waste cycle. This trial did not have the addition of alum, so the clay did not stick and form semi-flocs. Thus it was harder to build head and backwash.

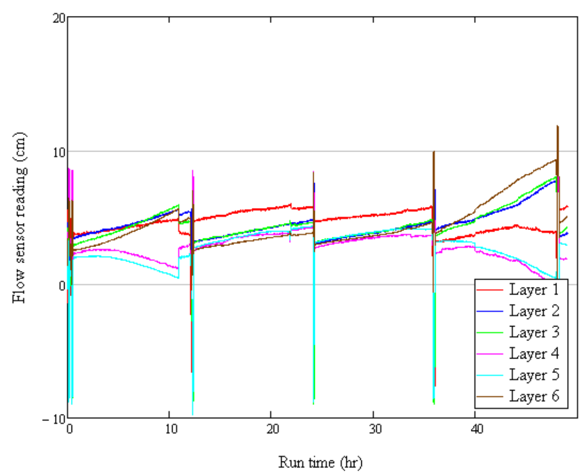

Figure 9: Sensor data for SRSF Trial 3. The second and third backwash cycles have sensor data that may be valuable, due to the linear nature, but the Layer 1 sensor seems to be incorrect in its recorded values.

Run	BACKWASH CYCLE			FILTRATION CYCLE					
Flush(min)	Fall (sec)	Flush (sec)	Rise (sec)	Rinse (sec)	Rinse USStd (sec)	Total Rinse (min)	Excess HL (cm)	Influent (NTU)	Effluent (NTU)
10	62	600	332	1419		40.22	0	~17	1
8	59	480	127	800	312	29.63	0	~11	1.1
6	54	360	138	518	873	32.38	0	~16	1.5
4	65	240	138	495	303	20.68	0	~23.4	2.3
3	60.5	180	149	587	551	25.46	0	15	1.5
2	65	120	137	601	427	22.50	4	~28.9	2.9
2	65	120	121	731	430	24.45	8	~37.5	1.01
2	62	120	166	558	415	22.02	5	~16	1.6
2	64	120	141.33	630	424.00	22.99	5.67	Average values calculated here	
1	59	60	312	3522		65.88	0	~17	

Figure 10: Table showing the results of high turbidity testing. For longer periods of backwashing there was a marked increase in the total rinse time. Since there were multiple tests performed for flush periods of 2 minutes, to see if the excess initial head was cumulative or not, averages of those runs were taken.

it takes for the effluent to reach US standards or to level out at an agreeable level. These rinse levels usually decrease to 0.3 NTU-0.5 NTU depending on the backwash cycle time depending on the influent turbidity. As shown in Figure 10a pattern can already be inferred from the results.

It had been hypothesized that a 2 minute backwash time, with an overall backwash cycle of around 3 minutes give or take, should be sufficient to fully clean the filter and have a short enough rinse time overall. Though the rinse time has been decreased with the shorter flush periods, it has been noted that there is an increase in excess headloss. This is a negative result, because an increase in excess headloss means that backwashing will have to be performed again sooner in the future. Also, when two experiments testing the 2 minute flush time were performed one after the another, it was showed that the headloss did not remain stagnant and actually "stacked" one on top of the other.

The total rinse time is the total amount of time it takes until the filter is performing at an acceptable level again. It is required to calculate the total amount of water that is "wasted" from the plant in this period of time, because this unsatisfactory water will not be sent to the distribution tank. As shown in equation 4, the height wasted in the column during this period of time is easily calculated using values that are either observed (T_{Rinse}) or known constants ($Q_{Filtration}$and A_{Pipe}). This will give us the total wasted height in meters through the system, but this is an example calculation of wasted height determined by converting measured times. Here, we used the "wasted height" parameter because it can be scaled to larger filters.

$$H_{Wasted} = \frac{Q_{Filtration} * T_{Rinse}}{A_{Pipe}} \tag{4}$$

Figure 11 displays the water that is wasted in the column throughout the entire backwashing cycle. It should be noted that as the flush time decreases,

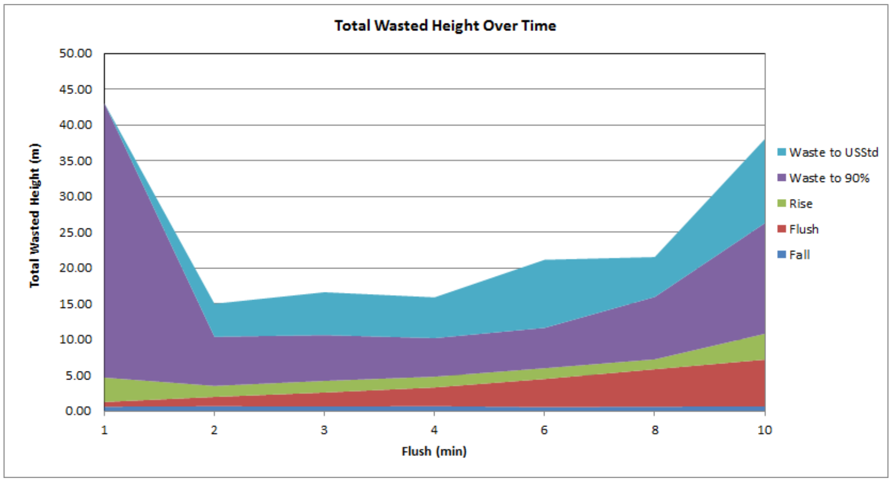

Figure 11: Graph showing wasted height of water in the filter column for each section of the backwash cycle. The fall and rise periods are the same for each flush time, due to it being dependent on the filter column hydraulics.

so does the water wasted. The "waste to US standards" time is where the highest amount of wasted water is usually found, as a result of trying to get the effluent turbidity down to 0.3 NTU. It was determined that 3 min flush periods are the best overall, because they have the lowest time period for the treated effluent to return to acceptable levels after backwash, and they did not result in any additional head being added to the column after the backwash period had finished. No additional head building up in the inlet box following backwash is an easily observable consequence of how effectively contaminants are removed from the filter media. The more contaminants that remain in the bed, the more head that will build up in the inlet box over and above the clean bed head loss. So when there is no excess head formed in the filter after backwashing it can be assumed that all contaminants in the sand bed were effectively removed.

Four-Layer SRSF

Figure 12 shows the times at which the system was in filtration mode, which is approximately until the 6th hour, and then after the 6th hour until about the 13th hour. The height of influent water in the inlet box follows an expected trend, as the water is not able to flow through the filter as easily with the filter continuing to capture particulate matter. The rinse periods provided very disappointing effluent turbidity values and trends.

There was hope that the four-layer filter would perform comparably to a six-layer filter. After the 5th hour backwash, the trend appears promising. Unfortunately the turbidity spike after 2 or 3 hours is concerning. After the

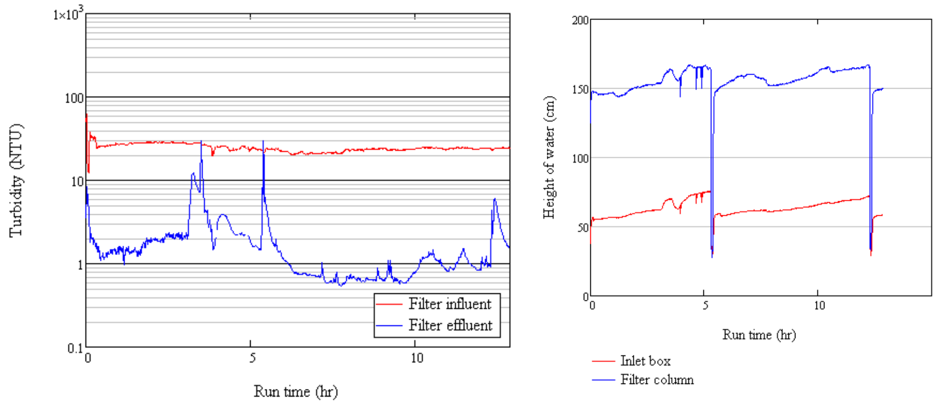

Figure 12: Turbidity and head increase in the system during four-layer SRSF testing. The head built up much quicker in the four-layer system, resulting in shorter run times than the 12-hour test. The system was backwashed whenever the height of water stabilized from exiting the inlet overflow hose.

12th hour, signaling the beginning of a new rinse period, while the effluent turbidity should be decreasing as the run continues, the turbidity values are sporadic at points and overall increase in value before the system had to be backwashed again. Considering that the filter did not perform to a pC* of 1 for a significant portion of the last rinse cycle, these results are a clear indicator that the four-layer filter is significantly less efficient than the six-layer filter. Its inefficiency for particle removal far outweighs the cost reduction it would provide.

As depicted by figure 13, the first backwash cycle provides flow distribution data that suggests that flow followed a similar trend among all the layers; however, that trend is not linear, as it is expected to be for effective depth removal of particulate matter. The second run appears to follow a generally acceptable trend, with the exception of of Layer 5 in the beginning, but the increase in flow is shown to be at a much steeper slope when compared to the six-layer data. The data collected from filtering turbid water through the four-layer system has made apparent two main disadvantages. The turbid water flows through the filter at an increased velocity due to the decrease in the number of layers. The increased filtration velocity does not allow enough contact time for the particulate matter in the influent water to latch on to the filter media and particulate matter previously captured in the filter. The increased filtration velocity also causes the head in the inlet box to build more quickly, so the head loss at the end of a run is greater, thus leading to shorter filtration cycles. The four-layer filter appears to be causing sporadic and unanticipated changes to the hydraulics of filtration and overall, does not appear to be a reliable or efficient filter.

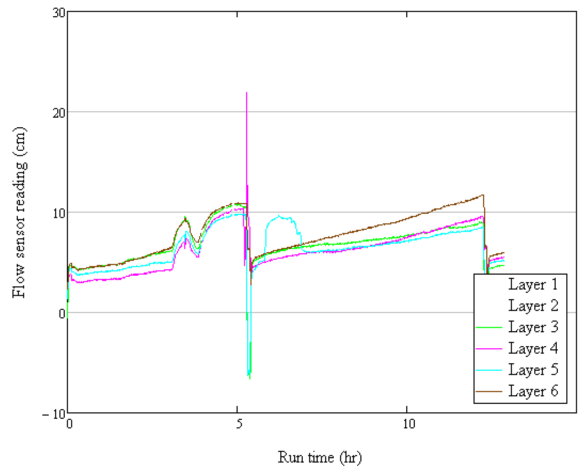

Figure 13: Flow sensor data for four-layer SRSF. The sensors showed zero flow through Layers 1 and 2, due to them being shut off, and throughout the testing period flow was shown to increase linearly, at a much higher rate than in six-layer testing.

Conclusion

While more backwashing runs may be performed for a more substantial set of data, the current turbidity readings after backwashing for 6:00 minutes highly suggests that 10:00 minutes, the previous estimated time for a sufficient backwashing time, is excessive. By reducing the time for such a run, a large volume of potable water could be kept from being flushed out of the system. However, this is not to say that 6:00 minutes is an assumed minimum time that the AguaClara stacked rapid sand filters can be backwashed. More experiments may be run testing runs at 3:00 and 4:00 minutes, decreasing the time until backwashing is no longer performing up to standard.

Uniform flow readings and consistent trends in the performance of filtration suggest the integrity and reliability of the apparatus. Despite these results, there are more discrepancies between the pilot-scale stacked rapid sand filter and its counterpart on the municipal scale. Due to the difference in size, the transition time from filtration to backwashing modes are noted to be longer in the field than it is in the pilot-scale apparatus. This subsequently affects what percent of the backwash time is actually time used to flush particles out of the bed. This suggests that future work must consider multiple dimensions of the backwash time and efficiency than previously presumed.

The creation and residual effects of bubbles in the system, be they in the inlet box or the sand bed itself, has led to problems during the backwash and filtration cycles of the experiment. The inlet box, because of the bubbles present, cannot transfer the correct amount of flow into the filter and artificially increases the amount of water in the box leading to more overflow. When bubbles are present during backwash, the bed cannot properly fluidize and thus it is no longer efficient. This leads to a reduced amount of particulate matter actually being flushed from the system, so the filter bed is not actually clean once filtration is started again.

Sensor data is confusing and may not be correctly recorded, due to the large amount of failed experiments changing the sand bed height and conformation. It would most likely be better for both data collection and analysis if the sensors were calibrated before each trial, so the values recorded are proportional to each other. This calibration must also be carried over to the turbidimeters due to a level of accuracy needed when performing tests that rely on the values.

Currently, the high turbidity tests show that 4 minutes and higher backwash times are suitable for particulate removal in the system while having a fairly low rinse cycle, with 4 minutes being the clear winner out of 4-10 minutes tested. It may be possible for the rinse time to be decreased to 3 minutes, to see if the minute decrease will efficiently clean the filter while avoiding the excess headloss that becomes a variable in shorter rinse periods.

After further research into decreasing the flush time, and seeing if there was an adverse affect from such actions, it was noted that 2 minute flush times consistently led to the filter having initial head buildup when switched back into filtration state. From running multiple tests, and consistently seeing that 3 min flush times resulted in a fairly quick return to 1 NTU effluent turbidity and no excess head, this was determined to be the "optimal" flush time to be given to the Tamara plant.

The four-layer sand filter, though a wonderful idea in principle because of the decrease in sand and inlets and outlets needed, did not perform up to the standards required for the plants. The higher velocities through the diminished number of layers led to a poor filter efficiency and effluent turbidities that were consistently higher than usual with odd peaks throughout the filtration run.

Future Work

Groups in the future SRSF Pilot Team have many more things to test and discover in the coming semesters. A more updated particulate matter removal curve will need to be created based off of the new lower backwash time, which will be sent to Honduras to implement new operating protocols. Another graph that could be created is a graph that determines the headloss in the filter system as a function of influent turbidity and velocity, which would require analysis of current data and supplementing it with additional data as needed.

The use of pressure sensors has not been used fully to their potential this semester, and next semesters could use pressures sensors to determine the amount of particulate matter in the filter bed. This could be implemented by two pressure sensors for continuous data collection during filter runs, one at the top of the filter bed and one at the bottom. To separate pressure effects from varying filter column water height, subtracting the top sensor pressure from bottom sensor pressure can quantify filter bed pressure at the bottom. In the end, this will allow a "clean" bottom filter pressure to be determined, which can be used in testing to determine if particulate matter has been removed efficiently or not.

Creating plots of the bottom filter bed pressure over time during filtration and backwash cycles can show how particulate matter builds up in the filter bed over time. This would allow different mechanical setups to be created if it shown the pressure builds in a linear fashion, increasing for the base upwards. Particulate matter is removed a varying efficiency due to the pressure buildup, so it would be helpful to see how this changes with different backwash cycles.