Enclosed Stacked Rapid Sand Filter (EStaRS)
Fall 2014

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Abstract

The ultimate goal of the EStaRS (Enclosed Stacked Rapid Sand) Filter team was to develop an appropriate configuration for the stacked rapid sand filter system that could be implemented to treat groundwater in India. The stacked rapid sand filter is an excellent choice for treating water near the city of Ranchi, India, as the primary water source there is groundwater. The low turbidity of groundwater means that the full AguaClara treatment process is not required and filtration with dosing will suffice. After testing the current apparatus, the goal was to improve the design so that modular EStaRS filters can be run in parallel efficiently and sand bed fluidization can be detected. This team set up a system to allow for extended backwash times, proposed a weir design to run multiple EStaRS Filters in parallel, and set up a manometer system to analyze bed fluidization during backwash.

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Introduction

The goal of the 2014 Fall EStaRS team was to develop and test a fully functioning enclosed stacked rapid sand filter that can be utilized in countries such as India where the source of water is groundwater and the full AguaClara process is therefore not necessary.

The filter apparatus built by the former LFSRSF (Low Flow Stacked Rapid Sand Filter) team was used throughout this semester's research. The design of the filter was improved by setting up an organized way to test the efficiency of the filter, creating a backwash flow storage system, designing a model for running filters in parallel, analyzing the pressure on the filter cap, and developing a method to determine if the sand bed is fluidizing sufficiently.

This semester's work sheds light on several different aspects of the filter design. Results from the backwash efficiency tests show that it consistently takes about 10 minutes in filtration before the filter clogs (at which point the filter efficiency drops below a pC* value of 2), demonstrating that backwashing between filter periods is consistently effective. Development of the weir design generated a new way of potentially running EStaRS filters in parallel. Construction and analysis of a manometer attached to the filter gave a potentially effective way of measuring sand bed fluidization.

Literature Review

As discussed in the article "Stacked Filters: Novel Approach to Rapid Sand Filtration" by Adelman, et al., in the *Journal of Environmental Engineering*, the AguaClara stacked filter design has been "introduced as a more robust and sustainable alternative" to conventional sand filters (2012). Conventional sand filters require elevated tanks or electrical pumps to generate flow rates high enough for backwash, while a stacked rapid sand filter "can backwash itself with no additional flow, which eliminates the need for pumps or other expensive equipment" (Adelman, et al., 2012). An enclosed stacked rapid sand (EStaRS) filter design has been fabricated and tested in the AguaClara lab. Last summer, members of the team were able to devise a way for the filter to effectively switch between forward filtration and backwash cycles. Backwash removal of contaminants in the sand (caused by fluidization of the sand particles) was successfully demonstrated, but the process leaves much room for improvement.

For example, the fluidic control system that controls the switch between filtration and backwash, can be improved to run more smoothly. As the article “A Novel Fluidic Control System for Stacked Rapid Sand Filters” explains, “The water level in the filter is regulated by a siphon pipe, which conveys flow during backwash, and which contains an air trap to blow flow during filtration… controlled by one small-diameter air valve” (Adelman, et al, 2013). Controlling the air valve and the siphon pipe currently requires two people and often results in overflow of some water in the process of creating the siphon; this is one aspect of the filter that this semester’s EStaRS team aimed to improve.

Other initial ambitions for the semester included: 1) obtaining test data indicating how effectively the sand filter works and how effectively it cycles between forward and backwash, 2) devising a way to monitor the fluidization of the sand bed during backwash, and 3) designing a way for multiple EStaRS filters to run in parallel. Challenges faced when running the filters in parallel include ensuring all filters are level. If the filters are not situated at the same height, determining which filters to backwash and backwashing at the designed flow rate will be very difficult.

According to the “Novel Fluidic Control System” article cited above, an effective EStaRS filter could result in “reduced complexity of implementation and operation; savings in capital and operating costs; and possible reductions in water lost to backwashing” when compared with conventional sand filters (Adelman, et al., 2013).

Methods

Backwash Storage System

A backwash storage system was created to allow the team to run the filter in the lab. The purpose of this system is to extend the filter’s backwash run time by creating a buffer of storage before the slow sink drain. Clean water from the tap enters the filter during backwash, moves through the filter column and fluidizes the bed, is siphoned out into the “kiddie-pool”, and then pumped into the 500L black drum. The first run demonstrated that the black drum provides approximately 12 minutes of backwash run time before it is filled. After the run (or even during the run), water can be pumped from the black drum into the sink at a much lower flow rate to allow the sink ample time to drain.

During regular filtration mode, clean water that has been taken from the tap is pumped from the red bucket (bottom left of Figure 1) at 0.8 L/s into the entrance tank (Step 1 of Figure 1). As this tap water is moving to the entrance tank, it is mixed with both clay and coagulant. Water then flows into four circular orifice weirs within the entrance tank and into the filter column, where it travels through slotted pipes and then into the sand filter body (Step 2 of Figure 1). Water moves both upwards and downwards through the sand filter bed and towards the nearest slotted pipes of an exit channel. Finally, clean water exits the sand filter body through these slotted pipes and empties into the exit tank (Step 3 of Figure 1). Clean water coming out of the exit tank then comes right back into this red bucket at 0.8 L/s to allow us to recycle water through the filter.

During Backwash, a tall weir is placed over the exit tube of the entrance tank to raise the height of water in the sand filter column. Once this water level is raised to the height of the siphon (Step 4 of Figure 1), the siphon valve is opened to allow water to flow out of the filter column. Ideally this siphon creates an upward velocity through the sand filter bed that fluidizes the sand bed to some degree and cleans the filter. Dirty water coming out of the siphon is then pumped into the backwash storage system (Step 5 of Figure 1), where it can provide a buffer for the slow sink drain time, and its turbidity can be measured for a mass balance test.

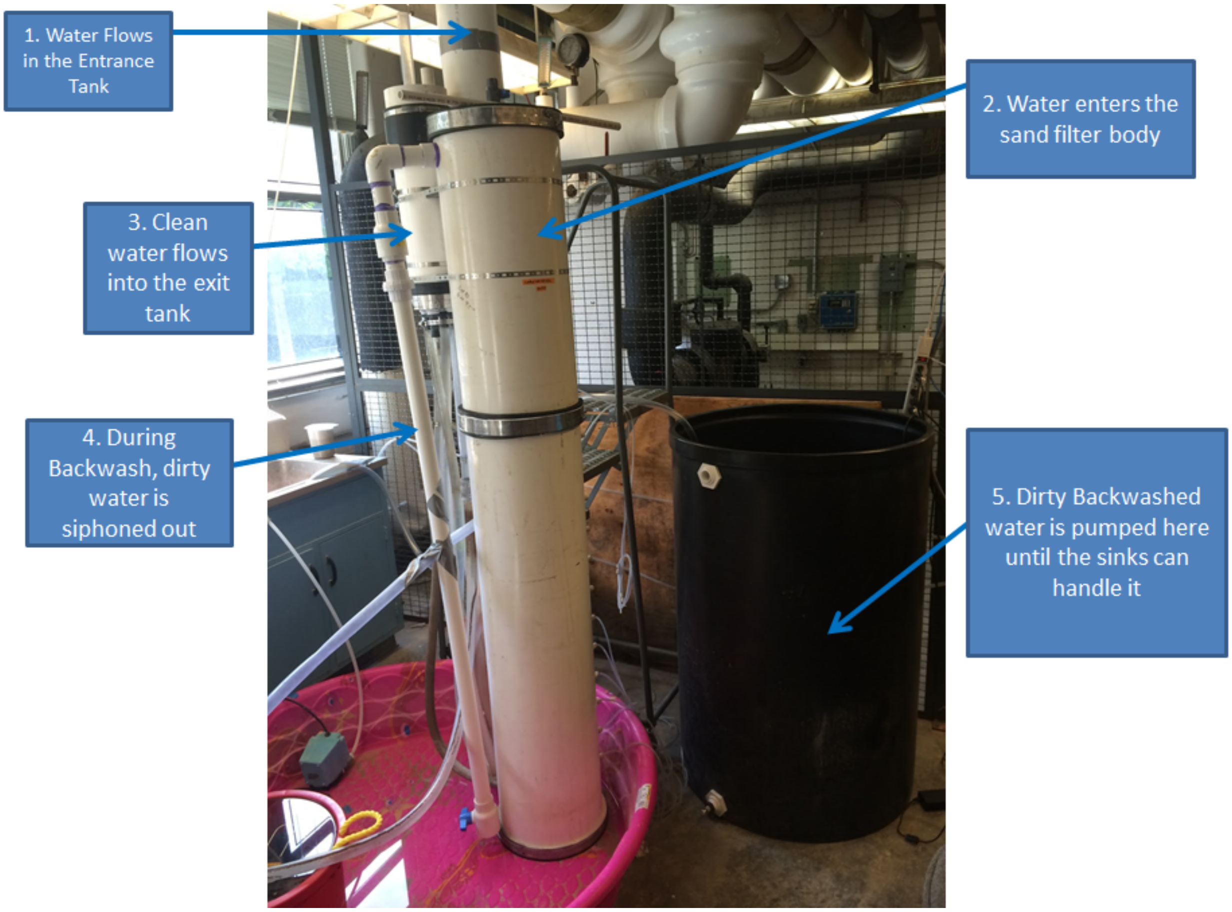

Figure 1: Filter System

Weir Design

AguaClara in India has been working on designing an efficient system to run multiple filters in parallel while ensuring that 0.8 L/s would be available to each filter when it needed to be backwashed. After consulting with the team in India, a new weir was designed to allow for an easy way to switch between filtration and backwash when running multiple filters in parallel. The new design uses one pipe with two sets of orifices (one set on each end of the pipe) that can be flipped when a filter needs to be backwashed so as to maintain a minimum 0.8 L/s flow into the backwashed filter, while splitting the remaining flow between the other filters. Below is the preliminary design, where each weir would be in the entrance to one filter. The weir orientation on the left models the system running in filtration mode, while the weir orientation on the right models the system running in backwash mode.

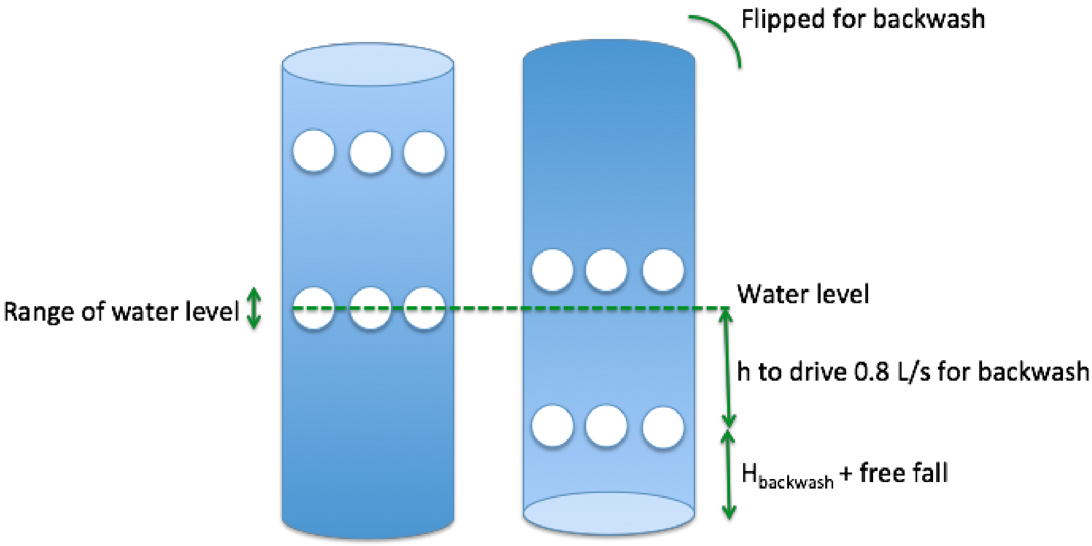

Figure 2: Weir Design

This system was originally designed with the assumption that each filter would have its own individual entrance tank. This would require that each entrance tank be at the same elevation to avoid uneven distribution of flow. Ensuring that each entrance tank is at exactly the same elevation poses a difficulty, since the entrance tanks would need to be easily moved vertically. With this in mind, and after consulting with Monroe, the team decided that perhaps having one large entrance tank for the entire plant would be a more reasonable design, but the team in India had reservations about this idea.

The AguaClara team in India pointed out that building one large entrance tank for any given treatment site would increase construction costs and make the filters less modular. Furthermore, there have been difficulties in constructing large tanks with level bottoms in the field. Since the goal is for new filters to be added or removed with ease, the team in India overall preferred the multiple small entrance tank configuration. Further design consultation is recommended.

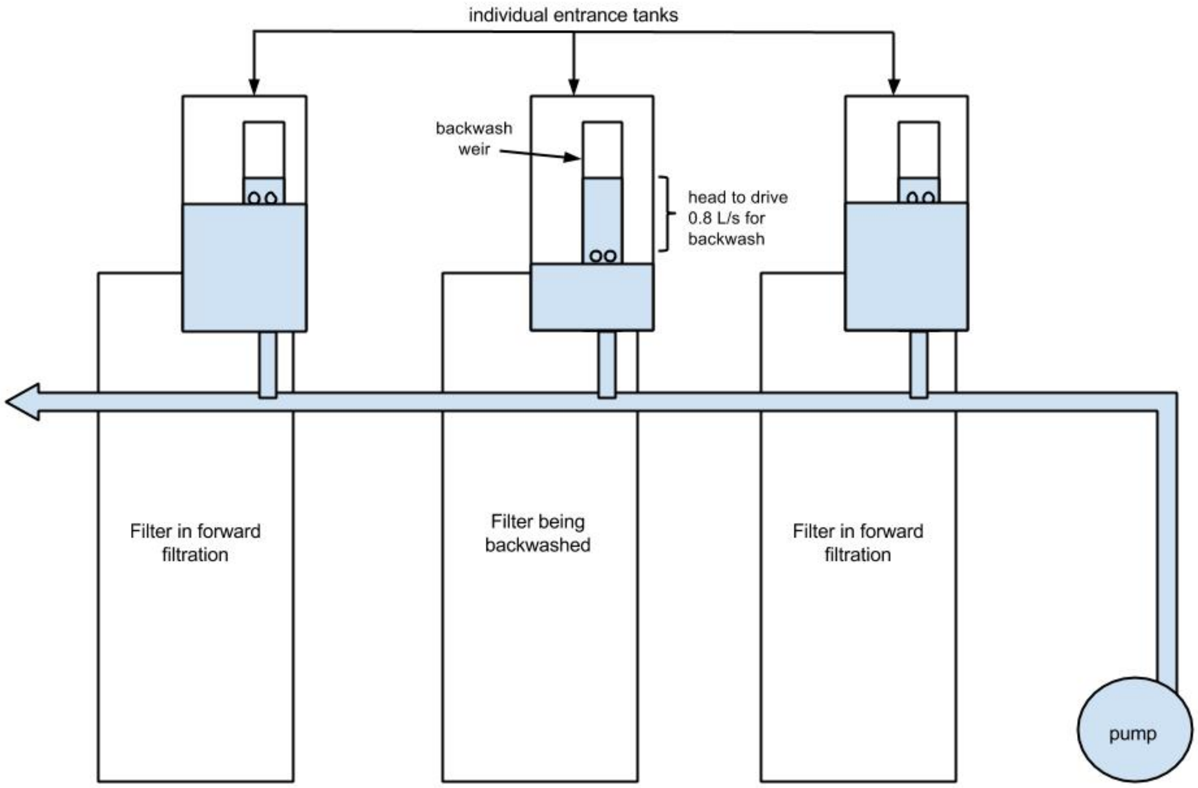

Figure 3: A diagram of three filters in parallel with one filter in backwash mode and the other two in forward filtration

Backwash Effectiveness

The EStaRS Team has run the filter several times without problems switching from filtration to backwash. The team's goal in these filter trials was to determine (indirectly) how effective the backwash cycle was at cleaning the filter. The metric used to determine how effective the backwash cycle performed was how long successive filter runs lasted at similar conditions for both influent turbidity during filtration and volume of water backwashed. The team sought to keep the influent turbidity at around 500 NTU, and the volume of water backwashed through the filter at a 0.8 L/s flow rate at 480L (about the volume of the black drum used to buffer the flow going into the sink drain). The team defined filter run time as the time before turbidity spiked above 10 NTU. The initial results are shown in Table 1 (in Results and Discussion), with more trials needed to confirm the progress.

Cap Design

Over the summer of 2014, the cap of the filter column was observed to have blown off twice. The reasons for the high pressure in the filter column are undetermined, but the filter cap blew off again on November 19th while being run in forward filtration. The filter system had last been run and backwashed on the 18th, and no differences from the usual backwash practices were noted. Though the reasons for cap failure are still undetermined, it was a goal of the team this semester to address this recurring problem.

The cap currently installed on the filter is made out of a PVC plate (cut in a circle with a diameter of 32.4 cm), a rubber gasket, stainless steel shim stock, and hose clamps. The pipe it caps - the filter column - has an outer diameter of 32.4 cm and an inner diameter of 30.5 cm.

To calculate the worst case scenario for pressure in the filter column, the situation in which the entire column is filled with air during forward filtration was considered. This situation could occur if the filter were ever drained (for example to clean the sand) and then filled again without having the filter column open and the filter manifolds blocked off. However, it would be unlikely that at the same time the entrance tank would be overflowing. As the reason for cap failure is yet to be determined, the most extreme scenario was considered. In this case the inlet channels would be full of water, and the the main air-water interface would be at the base of the filter column, at the bottom of the filter bed. The pressure at this interface was assumed to be equal to the head from the height of the water in the entrance tank, and this pressure was further assumed to be acting upon the filter column cap (because at this stage the filter would be full of air, which has a low density and has essentially the same pressure throughout as at the air-water interface). If the water in the entrance tank is near overflowing and the area upon which the pressure within the column acts to blow the cap off is defined by the inner diameter of the filter column pipe, the force of air on the filter column cap during the situation in which the filter bed would be completely dry is 1826 N. This value was reached using the following equations:

$h_t = \text{height of water in entrance tank} = 258\ cm$

$h_b = \text{height of water in bottom of filter column} = 3\ cm$

$P_i = pressure\ at\ water-air\ interface = \rho_{water} g(h_t - h_b) = 25016\ Pa$

$d = inner\ diameter\ of\ filter\ column = 30.5\ cm$

$A_{cap} = area\ of\ filter\ in\ contact\ with\ air\ in\ the\ filter = \pi\left(\frac{d}{2}\right)^2 = 0.073 m^2$

$F_{cap} = Force\ on\ the\ filter\ cap\ from\ pressure\ in\ the\ filter = A_{cap} P_i = 1826\ N\ (410.5\ lb)$

This force (minus the weight of the PVC plate filter cap piece) must be less than the force of friction between the PVC filter column and the rubber gasket, and this force of friction is a result of the force exerted by the hose clamps. The pressure required of the hose clamp can be calculated in the following manner:

$t_{cap} = 1.27\ cm$

$A_{contact} = area\ of\ contact\ between\ Fernco\ fitting\ and\ the\ filter\ column = t_{cap} * \pi d = 121.7\ cm^2$

$\mu_{static} = coefficient\ of\ static\ friction\ between\ Fernco\ fitting\ and\ PVC\ sheet = 0.6$

$P_{required} = pressure\ required\ = \frac{F_{cap}}{A_{contact} * \mu_{static}} = 250090\ Pa$

This force, in turn, is dependent mainly on how tightly the hose clamps are attached, which could be modeled as a function of how much torque is applied to the screw tightening the hose clamp. A torque wrench was used in the lab to tighten the screw to 40 inch-pounds. This torque is converted to a force exerted on the gasket by the hose clamp in the following manner:

$F_{clamp} = \frac{torque\ from\ wrench}{radius\ of\ screw} = \frac{40\ in-lb}{0.156\ in} = 256.4\ lb = 1140 N$

$P_{clamp} = F_{clamp} / A_{contact} = 91492\ Pa$

The pressure from the hose clamp is nearly three times less than the pressure required in the extreme scenario. While this difference seems very high, the situation in which the filter column is empty and the entrance tank is near overflowing is very unlikely. As the cap has been seen to blow off in cases where the column is over half full with water, it is plausible that the current pressure exerted on the cap by the clamp is far less than the worst-case scenario.

The theoretical value for the force of friction necessary to oppose the air pressure in the filter does not, however, take into account some potential weak spots in the filter cap design. For example, the stainless steel shim stock that is placed between the rubber gasket and the hose clamps tends to buckle when the hose clamps are tightened, and because the pipe for the filter column is not cut exactly level at the top, the filter cap rests unevenly upon the top.

Implementing a stronger cap may potentially expose other problems with the filter column or even cause new problems. For example, once the cap is made to keep from blowing off, the middle gasket that keeps the two halves of the filter column together may become the most vulnerable to pressure in the filter. If this middle gasket were to fail, the consequences of having the filter column open at its middle (sand and water would most likely come out), would be more difficult to deal with than the process of re-attaching the filter cap (this would be a problem specific to the filter in the lab - the filters in India are bolted together at the middle.

Bed Fluidization

In order for the backwash process to effectively clean the filter, it is necessary that the sand bed become fluidized. Currently it is impossible to see what is occurring in the filter, because it is built from non-transparent PVC. The main indication of bed fluidization is from the difference in water height between the entrance tank and the water levels in the inlet and outlet tubes to the manifolds in the column. The team added a series of manometers to the side of the filter in order to better assess whether the bed was being fluidized. Currently the filter column has been tapped and fitted at 10 cm intervals with twelve 6.4 mm (¼”) brass values to which 6.4 mm (¼”) outer diameter flexible tubing sections were attached using push-to-connect fittings. The Summer 2014 EStaRS team had been using this set-up to test for bed fluidization as well. However, the summer’s results from this set-up proved variable and inconclusive. Because this may have been a result of using thin tubing where the manometer readings were extremely sensitive to small air bubbles, the push-to-connects and 6.4 mm (¼”) tubing were removed and replaced with barbed fittings with 9.53 mm (⅜”) outer diameter clear, flexible tubing. The tubes were arranged so that comparison between the water levels in the tubes would be easy.

The team was able to run the filter in filtration mode successfully without air bubbles and operate the manometers. The manometers revealed pressure changes that are consistent with what the team expected.

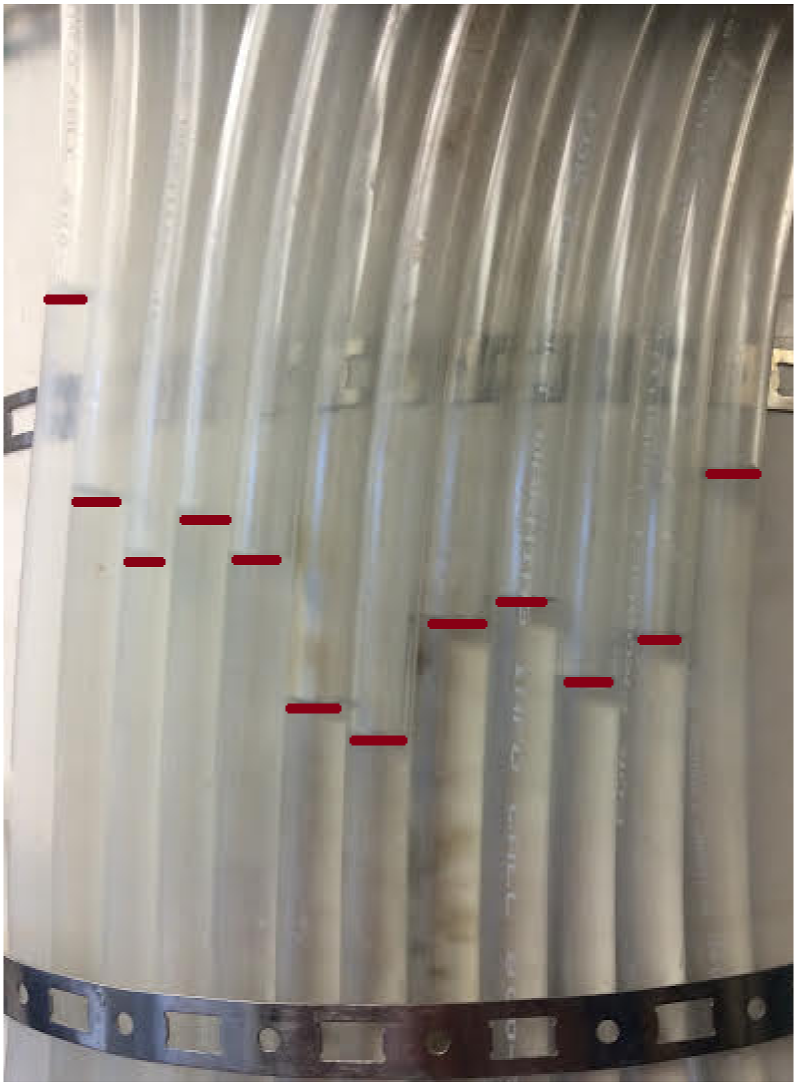

Figure 4: Manometer water levels during filtration

The manometers reflected that water was moving from the inlet manifolds at high pressure towards the exit manifolds at a lower pressure, and there was an evident change of pressure from positive to negative somewhere in the middle of the filter. Additionally, it was observed over an extended filtration period that the manometer level corresponding to the higher-pressure side of each sand layer rose more quickly than the level corresponding to the lower-pressure side of each sand layer. This makes sense considering that flocs build up in the sand during filtration, especially near the high pressure inlets, and demonstrates the effectiveness of the manometer system during filtration.

The team was unable to get a reliable reading from the manometers during backwash due to the air bubbles that continually enter the sand filter body from the entrance tank during backwash. In order to reliably use the tubes as manometers during backwash, it is necessary to first make sure there are no air bubbles in the tubes and/or the filter manifolds. Once the issue of air bubbles is no longer a hindrance to obtaining manometer readings for backwash mode, this could be a means of confirming fluidization of the bed by measuring the difference of water heights between two manometers and comparing it to the actual distance between those two manometer taps. For instance, two manometers placed 20 cm apart should have a water height difference of less than 20 cm if the bed is fluidized, since a fluidized sand would decrease the the pressure and would not be simply a 20 cm water column.

An alternative method of recognizing bed fluidization besides using manometers, involving the addition of windows into the filter column, has been considered. However this method would involve complete disassembly of the filter column and help from the machine shop staff, so this method would best be implemented during “down-time”, such as winter break. To create windows, once the 30.48 cm (12”) PVC filter column pipe has been separated from its contents, several (tentatively, three) 7.62 cm (3”) diameter holes would be opened in the PVC pipe so that the sand towards the base of the filter, the sand toward the middle of the sand bed, and the sand close to the top the approximated height of the fluidized bed would be seen. These holes would be covered by adhering and screwing 6.4 mm (¼”) thick clear PVC sheeting over them. This procedure is possible but time-consuming and furthermore, if the EStaRS system were to include bed fluidization checks in the field as well, manometers would be easier to widely implement than windows.

Results and Discussion

The fall 2014 EStaRS team improved the setup of the filter system in the lab so as to allow for a greater range of testing conditions. By adding an additional pump and an intermediate holding tank with a storage capacity of about 550 L, the filtering system was able to run in backwash for a longer period of time. At a rate of 0.8 L/s (the design filtering and backwash rate), the disposal set-up allows for at least 9 minutes of backwash time beyond that of the duration handled by the sink drain alone. This additional time is particularly beneficial in the event that the current or future teams attempt to more critically analyze bed fluidization. With the current recycle system (with water flowing through the filtration system, exiting, and then re-entering the process), there exists the potential for a slight buildup of residue (either coagulant or sediment particles that make it through the filter), which requires effective monitoring of both the influent and effluent turbidities so as to understand the extent of the difference between the two.

The results from the three filter runs that have been performed (shown in Table 1) are encouraging. As shown in the data, it took roughly 10 minute each trial for the pC* value to fall below 2. Given the filter's opaque wall, it is hard to say how well the filter bed is actually fluidizing during backwash. However, the data the team did generate on backwash efficiency suggests that the backwash cycle is effective at cleaning the filter and fluidizing the bed, because it produces similar filtration run times. More data, and more consistent data between run times are needed to further extend this claim.

Table 1: Filtration Trial Results

Trial (at 0.8L/s)	Influent Turbidity Average NTU	Effluent Turbidity Average NTU	Previous Backwash Volume at (0.8L/s)	Filter Run Time (before NTU>10)	Headloss at trial end	Filter Percent Cleaned During Backwash	pC* at start of trial	pC*at end of trial
1	633.19	5.30	(first trial)	8 minutes	N/A	-	2.1	1.8
2	565.73	4.10	480L	9 minutes	N/A	-	3.1	1.8
3	481	4.15	480L	8 minutes	68.58 cm	0.74	2.1	1.7

Future EStaRS teams should continue to experiment with the design of filters running in parallel as an improvement to the capacity of the system. It is expected that there will be an associated increase in head loss throughout the system. Previous teams focused their attention on the slot sizes of the manifolds enclosed in the filter as a way to decrease head loss (by making the pipes slotted on both sides as well as increasing the slot width). This year, the Alternative Backwash subteam is looking further into changing the geometry of the filter manifolds in order to remove the need for slotted pipes and thus decreasing the risk of clogging in the manifolds.

Conclusions

After setting up a backwash storage system, testing the EStaRS system in filtration and backwash mode, and observing several trial runs, the team's backwash process has proven successful at producing consistent run times during subsequent forward filtrations. To further observe fluidization effectiveness during backwash, the team implemented a grid of manometers on the length of the filter sand bed that have confirmed the theoretical flow of water between sand bed layers. Although the team has been unable to reliably quantify to what degree the backwash system was fluidizing the sand bed (due to air bubble interference), the manometer system could be used in the future to analyze the effectiveness of the backwash. Finally, a rough draft of the weir system designed to allow for multiple filters in parallel has been sent to Maysoon in India, and dialogue about the implementation of this weir system should be continued.

Future Work

Now that the filter system is running smoothly in both forward filtration and backwash (as well as smoothly transitioning from one to the other), future EStaRS teams should continue to repeat runs of the filter at a high turbidity to better determine the necessary amount of backwash time, while keeping the backwash intensity constant. This will enable them to run the filter in forward filtration mode for equal periods between backwashes without losing filtering capacity. In addition, future teams should conduct further mass balance tests to determine the inflow and outflow of floc mass through the filter column as well to obtain a reliable pC* number to analyze backwash efficiency. Using this mass balance and backwash efficiency, the necessary backwash frequency could be determined by setting limits on the allowable mass of floc in the filter at any given time and calculating the time over which the mass of floc accumulates in the filter column to the point of exceeding the set limit.

With the general concept of the new weir system fairly set, the next team should dedicate time to calculating the proper dimensions and spacing of the pipe and orifices. Once the calculations have been made, the next step will be to fabricate a set of weir pipes so that their functionality can be tested; the weirs must channel the right amount of flow individually and also work properly when being run in parallel.

The decision of whether each filter will have its own entrance tank or whether there will be a single large entrance tank distributing flow to each filter is yet to be made. In order to make more definitive designs for the weirs, the next team must communicate further with the group currently in India in order to decide what design is preferred. For example, if the filters are to have separate entrance tanks, the team will also need to design a way to adjust entrance tank heights between filters.

More calculations must be made to better understand the situation in which the filter column cap blows off, as well as to better understand how to prevent the problem. After the current cap design is analyzed for its capacity, a design for a cap that can withstand the calculated force from pressure in the column must be established. This work however, is less crucial to the overall goals of the team, and these calculations and potential fabrication should be considered if there is sufficient time.

While manometers were installed to analyze bed fluidization, they were unable to be used as a means of determining bed fluidization. This could be a simple and effective method if the issue of air bubbles was able to be resolved. Future teams should work on this, as well as more rigorously investigating the exact difference in water levels between manometers that should be observed to correlate to the desired 30% bed expansion. In the future it may also be interesting to make the more permanent addition of windows into the filter column to directly assess whether the sand bed is fluidizing. Windows may provide insight into the possibility of dead zones in the filter where sections of the sand bed aren't fluidizing, as well as into the potential for shear along the filter walls causing uneven flow distributions through the filter.

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