Demonstration Plant Team

Sahana Balaji, Muhammed Abdul-Shakoor, Thalia Aoki, Miree Eun, Diana Kelterborn, Mee

May 11, 2012

Abstract

The AguaClara water treatment process consists of coagulation, flocculation, sedimentation, and filtration, with flow/chemical dose control using gravity. The Demonstration Plant (Demo Plant) is an important educational tool to explain and publicize AguaClara technologies. Currently, a new Demo Plant has been constructed, tested, and documented. This version of the Demo Plant includes a sedimentation tank and a Stacked Rapid Sand Filter (SRSF) as well as a chemical doser and flocculator. The sedimentation tank design is based on the design from the ENGRI 1131 course and includes the formation of a floc blanket. The SRSF shows the new filtration method recently developed by AguaClara. There has also been emphasis on the systematic documentation of both theoretical calculations behind the design and operation of the Demo Plant.

Background:

Project Objectives

The goal of the Demo Plant team is to create a demo-scale version of the technologies used in full-scale AguaClara plants in several rural communities in Honduras. The Demo Plant is an important tool used to promote AguaClara in the Cornell community, at national conferences such as the EPA P3, and for community workshops in Honduras. The current Demo Plant effectively shows how water flows through the plant; however, there are technologies that have not been incorporated into the Demo Plant which would further aid the educational and outreach aspect of AguaClara.

Since many of the modules in the AguaClara plant are being updated and created anew, there is no reliance on the current Demo Plant for designs and measurements (such as the flow rate). New parts need to be machined and tested based on a new set of constraints that will inform the decision on allowable flow rates through the plant. The flocculator is going to essentially be the same and the team focus will be on the flow measurement through a Linear Flow Orifice Meter (LFOM), the chemical dose controller (CDC), the sedimentation tank with an operable floc blanket, and the Stacked Rapid Sand Filter (SRSF).

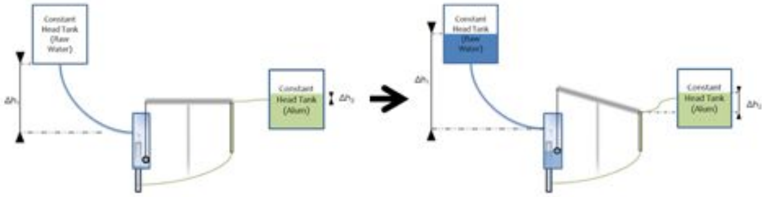

Figure 1: Schematic of the coagulant dosing system in flow and no flow conditions

Flow Control and Chemical Dosing

MathCAD files from the AguaClara design team are available to us for the full scale Linear Flow Orifice Meter (LFOM). The initial hypothesis, based on the output from the old MathCAD files, was that the LFOM at this small scale would not generate a linear relationship between flow rate and water height; however since it has been looked over and updated by Mickey, Professor Monroe, and another AguaClara team member, we have gotten usable results.

For the LFOM, a system was designed to simulate a Sutro Weir with a rectangular base, which will maintain a linear relationship between the height of the water and the flow rate of the plant. We have calculated the sizing for the LFOM based on the recent results we obtained from the MathCAD file. A chemical doser has been implemented using a lever, with a float attached and a slider (as the full scale plant does).

After much consideration of using the LFOM to measure the flow rate of water leaving the entrance tank, it was realized that at the Demo Plant Scale the size of the holes that comprise the area that creates the Sutro Weir effect are too small and thereby inapplicable. Laminar flow tubes are to be used to set the flow rate throughout the plant. Not only is this easier, but it is also more reliable on the small scale. Further developments have even informed setting the flow rate by adjusting the height difference between the entrance tank and the constant head tank for the raw water influent.

The lever doser will remain so that the dosing method in real AguaClara plants can still be observed at the Demo Plant scale. A schematic is shown below. Notice that while the flow rate is set simply by changing where the entry point is for the raw water, the lever allows the alum dose rate to change automatically based on the height of the water in the entrance tank. In order to reduce the chance of having clay settle in the bottom of the entrance tank, it is now being constructed as a pipe. This will reduce the area at the bottom of the sedimentation tank and increase the velocity, thereby reducing the chance for the clay to settle at the bottom. This is depicted in 1below.

Sedimentation Tank

The purpose of the sedimentation tank is to remove large particles from the water. The Demo Plant achieves this by using two functional sections: the floc blanket and tube settler, which are corollaries of the large-scale sedimentation tanks with plate settlers used in the real AguaClara plants. Although a full floc blanket has yet to be achieved in a full-scale AguaClara plant, floc blanket theory is the driving factor behind sedimentation tank design, and thus the illustration of a floc blanket and its functionality in the Demo Plant is a useful way to educate the public about AguaClara technologies. At the scale of the Demo Plant, tube settlers are more practical, and fully analogous to the full-scale plate settlers from the point of view of solids in the water.

The purpose of the floc blanket is to grow flocs, making them easier to capture. The tube settler acts to capture flocs grown in the floc blanket, cleaning the effluent water and feeding flocs back into the floc blanket. The floc blanket works by preventing flocs from settling out: water enters at the bottom of a vertical column, and flows upward, acting to counter the gravitational force on the flocs and fluidize them. The balance of the upward flow rate with the downward gravitational pull on the flocs means that flocs must circulate throughout the column, rather than simply passing through. This forced circulation causes increased particle collision, meaning that the flocs grow. Flocs that grow to the point where the gravitational force is strong enough to cause them to settle out are resuspended by the influent jet. The floc blanket thus consolidates particles in the water into large, capturable flocs.

The majority of those flocs are drained out by a floc weir at the top of the floc blanket column. The resultant, cleaner water then travels through the tube settler, an angled pipe of the same diameter as the floc blanket column. The angle of the tube settler's walls causes flocs traveling in the water to settle out on the sides of the tube. Gravity then rolls them back down into the floc blanket, where they will grow and be drained out. The combination of the floc blanket and tube settler effectively cleans water of a large portion of particles before it is processed by the stacked rapid sand filter.

Stacked Rapid Sand Filter

The purpose of the SRSF is to remove small particles that did not settle out in the sedimentation tank. The advantage of a stacked rapid sand filter over a traditional rapid sand filter is that the backwash process is more efficient. Since backwash of the layers occurs in series, the SRSF uses significantly less water to clean the filter. During filtration, water flows into the inlet tubes, out slotted pipes and through the sand layers. The purpose of the slotted pipes is to allow water to flow out but prevent sand from clogging the pipes. Therefore, the slots have to be smaller than a grain of sand for this to work. As water flows through the sand layers, any remaining particles stick to the sand effectively filtering the water. The water then flows back into a slotted pipe and through outlet tubes. After a while, the filter performance decreases due to particle buildup in the sand. At this point, it is necessary to backwash the filter.

During backwash, water only flows through the bottom inlet tube, creating a backwash velocity equal to the filtration velocity times the number of layers with the same flow rate used for filtration. This high water velocity fluidizes the sand bed, washing flocs out of the sand and through the backwash outlet.

In order to reproduce the SRSF on such a small scale, we will base our design calculations on the MathCAD worksheet used to design the full scale SRSF. Due to the size, several modifications will be made such as reducing the number of sand layers to four and using valves instead of a siphon system for backwash. Additionally, we must find some alternative way to replicate the slotted pipes which are impractical to fabricate on this scale.

Literature Review

AguaClara. (May 2009). "Plate Settler Sourcing." Retrieved from https://confluence.cornell.edu/display/AGUACLARA/Plate+Settler+Sourcing
This article summarizes relevant sedimentation tank designs and constraints that are applicable in current filtration plants.

Hurst, Matthew. (April 2010). "Evaluation of Parameters Affecting Steady-State Floc Blanket Performance." Retrieved from http://ecommons.library.cornell.edu/h
This paper describes variables affecting floc blanket performance, based on a laboratory water treatment simulation. It discusses the effects of varying hydraulic flocculation conditions, raw water turbidity, coagulant doses, upflow velocity through the floc blanket, floc blanket height, and the bulk density and solids concentration of the floc blanket.

Manrique, J. C. (October 2010). "Preliminary Design for NY, USA." Retrieved from https://confluence.cornell.edu/ download/attachments/127828383/Design+Spec
This article explains how the Chemical Dose Controller operates. Primarily, the water is treated by adding alum as the coagulant. The CDC was devised to make an accurate dosage of alum independent of the change in the plant flow rate. The CDC apparatus is capable of three dosage levels, which corresponds to changing the orifice sizes. The operator is at the liberty to pick an orifice size from a set of three based on the turbidity of raw water.

This article also explains how the sedimentation tank works. The sedimentation tank is used to provide a suitable adequate environment for the flocs to settle. It is necessary to design the inlet channel orifices so that they do not break the flocs or allow them to settle. We should ensure that the water is distributed uniformly and create a jet that re-suspends settled flocs. The sludge zone on the bottom of the sedimentation tank has walls at an incline. This sort of inclination is given to increase the upflow velocity at the inlet manifold so that the suspended flocs can be made to form as a blanket of flocs. Additionally, the sludge drain is provided so that the tank can be flushed and cleaned for any maintenance activity.

Buerman, L. and Weber-Shirk, M (December 2008). "Linear Flow Orifice Meter for Application in AguaClara Drinking Water Treatment Plants." Retrieved from https://confluence.cornell.edu/display/AGUACLARA/LFOM+S This article goes into detail about the LFOM. It is mainly placed at the entrance of the pilot scale drinking water plant. It is based on the concept of Sutro Weir. Evaluation was done on the LFOM to get accuracies over a range of flow rates from 20 to 140 L/min. The flow rate is directly proportional to the water height. The addition of LFOM was a momentous accomplishment in improving the productivity of the equipment and the ease of producing clean water without the need for electricity.

Adelman, Michael J., Monroe L. Weber-Shirk, Anderson N. Cordero, Sara L. Coffey, William J. Maher, Dylan Guelig, Jeffrey C. Will, Sarah C. Stodter, Matthew W. Hurst, and Leonard W. Lion. "Stacked Filters: A Novel Approach to Rapid Sand Filtration." Journal of Environmental Engineering (2012). American Society of Civil Engineers, 27 Feb. 2012. Web. This article explains how a stacked rapid sand filter works. It explains the basic geometry of the filter including how the inlet and outlet pipes create layers through which the water flows. Included are basic equations that can be used to calculate filter and backwash velocities, given the filter area, the number of layers, and the plant flow. Furthermore, the article describes how stacked filters can perform backwash using the same flow rate as filtration, as opposed to traditional filters that require different flow rates for the two operations. It also details successful laboratory experiments and field experiments which demonstrated that stacked rapid sand filtration is a viable water treatment method.

Mays, Larry W. "Headlosses, System Components." Water Resources Engineering. 2005 ed. John Wiley & Sons, Inc., 2005. Print. This textbook contains various minor loss coefficients for different valves and connectors used in the demo plant. In particular, values from Table 4.3.1 and 4.3.2 were helpful. We interpolated coefficients from these tables that were then used for head loss calculations throughout the plant. This source also contains formulas for contraction and expansion headlosses that were used to calculate head losses for different fittings.

Methods and Design:

Flow Control and Chemical Dosing

Other processes in the Demo Plant have required that the flow rate be adjusted to about 50 mL/min, so the MathCad code was used to come up with two different versions. The Demo Plant Doser Team worked on designing new and improved LFOMs that would match the range of flow rates we expect to encounter around 50 mL/min. Through this method we were able to design and fabricate two LFOMs that would be able to cover the necessary flow rates that we wanted. However, when we tested them, the flow rates coming out of the LFOMs were significantly lower than what they were made for. The applicability of the LFOM at the Demo Plant scale was found to be inadequate because the surface tension of water in the small holes was just too great for gravity to overcome. Therefore, we ended up replacing that plan with going back to the idea of long laminar flow tubes.

Designing the long laminar flow tube was much simpler than designing the LFOM because we only needed one equation that related the Inner Diameter of the tube used, the length of this tube, the flow rate desired, and the head level from the top of the entrance tank to where the tube releases the water:

$$Q_{Plant} = \frac{h_f g \pi D^4}{128 v L} \tag{1}$$

where Q_{Plant}corresponds to the flow rate though the Demo Plant, h_f is the head difference between the source and destination, D is the inner diameter of the tube, v is the viscosity of the fluid, and L is the length of the tube. Through this, we were able to have many options because it was possible to alter any of the other three variables (length, inner diameter, head difference) to get a certain desired flow rate going out of the entrance tank into the flocculator. Thus, we set the head level to be around 10 cm and the tube size to be 1/8" Inner Diameter, and then solved for the necessary length of the tube to get flow rates approximately 50 mL/min. However, for some reason, when we fabricated the new laminar flow tube and tested it with the system, the flow rate was really high compared to the 50 mL/min desired. In order to fix this problem, we figured out a new head level that would give the needed flow rate. Controlling the flow rate leaving the entrance tank was rather simple and easy to apply: if we used a tube of the same length and inner diameter and had the same head level, in theory, the flow rates should be exactly the same. Through this deduction, we were able to move around the entrance tank and the constant head tank until we got the right head level for each of the two tubes and as in theory, the water level in the entrance tank was able to stabilize, thereby increasing the precision of the float system.

The next thing on our task list was the Doser Part of the Demo Plant. One of the main improvements was to create a lever arm that would simulate the lever arm of an actual plant. This lever arm is designed to keep the dose rate in a linear relationship to the flow rate of water through the plant. This could be accomplished by creating a bob that not only was light enough to float, but also heavy enough to have a similar mass to balance out the other components on the other side of the lever (a small "free fall" tube with two holes, one for the incoming chemical coagulant entering through a smaller tube, and one for the outgoing chemical coagulant exiting through a larger thicker tube). This was a little challenging at first because our first couple of ideas failed, but after we thought a little outside the box, we figured out that a hollow shell of PVC with enough air inside and enough surface area on the bottom of it would be able to float rather nicely in the small entrance tank that we designed. With this we attached a copper wire that was slightly bent at an angle, so that when the water level would go up and down the bob would be able to push up its side of the lever arm because the copper wire is rigid.The bob would also not be obstructed by the sides of the entrance tank. Everything for this part worked rather nicely except for the fact that the lever arm was not very balanced because the components on the other side of the lever arm were decidedly heavier than the copper wire and the bob. In order to compensate for this imbalance we attached the components on the other side of the lever onto a "slider" at the middle of that half of the lever arm, and then we also added a "slider" weight that we would be able to manually adjust and slide around on the same side of the lever arm as the copper wire and the bob. These additions not only balanced the weight between the two sides of the lever, but it also gave us room to tweak the dose rate and flow rate relationship a little bit if something wasn't working according to plan.

Lastly, our team realized that we still needed to figure out the right concentrations for the raw water stock and the chemical coagulant. Another big change was that we switched our coagulant from Alum to PAC because it gave a lot more leeway than Alum, as flocs would still form pretty nicely even if a person were to overshoot the dosing by a little bit. However, we would rather not run the risk of overshooting or undershooting, and so we wanted to determine the exact amount of PAC we would need to dose the system with in order to get good flocs forming in the flocculator. To do this, we used the formula relating the stock concentration and the concentration of the water flowing through the plant with the dose rate and the flow rate of the overall plant:

$$Q_{plant}C_{plant} = Q_{PACl}C_{PACl} \tag{2}$$

where C_{plant} is the desired concentration of PACl throughout the plant, Q_{PACl} is the flow rate of the influent coagulant, and C_{PACl} is the concentration of the influent coagulant. We set the concentration of the water flowing through the plant, the dose rate and the flow rate of the overall plant and solved for the stock concentration needed. Then we tested to see if this concentration worked well in the plant and at first the flocs were too big and were getting stuck on the bottom of the flocculator, but after we tweaked the concentration a bit it was working really well.

Sedimentation Tank

A sedimentation tank has been constructed, consisting of a vertical 1" PVC tube (the floc blanket section), connected by a 45-degree elbow to a PVC tube of the same diameter (the tube settler section). Water enters the tank through a 3/8" outer inner diameter tubing connection and exits through tubing of the same size. A floc drain has also been constructed, consisting of a hole and fitting in the side of the sedimentation tank, to which a section of 1/4" tubing is connected with a valve that controls flow through a piece of 1/16" peristaltic pump tubing.. An emergency floc drain is located at the bottom of the tank, consisting of a t-connection of valve controlled 3/8" tubing, allowing for partial drainage of the tank in the case of excessive floc build-up. The sedimentation tank has successfully created a floc blanket using flocculated water from the Demo Plant.

The design of the sedimentation tank was based on a required upflow velocity of 1 mm/s. This upflow velocity sets the total flow/total area relationship for the sedimentation tank. The floc blanket's success is also dependent on the energy dissipation rate of the incoming flocculated water. The maximum energy dissipation rate was assumed to be less than 10 mW/kg, a constant whose physical value depends on the diameter of the inlet. With higher energy dissipation rates (as from smaller diameter jets), flocs are broken up into tiny fragments that get carried out of the tank instead of settling on the bottom. Thus, the influent jet diameter must be sized in such a way as to prevent floc break-up. To ensure flocs will not get carried out of the sedimentation tank, the flocs need a sedimentation velocity greater than or equal to upflow velocity (1 mm/s). In addition, the tube settler acts to help capture particles once they have passed through the floc blanket. In order to prevent failure of the sedimentation tank as the floc blanket builds over time, a floc weir and hopper system, in the form of two drains, was implemented, to prevent excess build-up of flocs. Below is a diagram of the constructed sedimentation tank.

Main Tube of Sedimentation Tank Dimensions

The flow rate of the sedimentation tank is equal to that of the stacked rapid sand filters, i.e. $Q_{SedTank} = Q_{SRSF} = 40\frac{mL}{min}$. This flow rate was based on the current capacity of the water tank, as well as the resultant constraints of the velocity on the dimensions of the rapid sand filter. The diameter of the sedimentation tank can be based either on a direct calculation based on its flow rate, or through use of the ratio 1:11 of its velocity to the backwash velocity used to size the SRSF. The two calculations are:

$$D_{SedTank} = D_{Filter} * \sqrt{11} = 0.34 * \sqrt{11} = 1.129in \tag{3}$$

$$D_{SedTank} = \sqrt{\frac{Q_{SedTank} * 4}{\pi * V_{Upflow}}} = 1.147in \tag{4}$$

Both equations give similar values, so a 1" outer diameter PVC pipe was selected to use as the sedimentation tank base. The thickness of the pipe walls meant that the pipe had a slightly smaller inner diameter, but because the 1" pipe has worked historically in the ENGRI 1131 class, it seemed a reasonable starting point. As it worked with the demo plant as well, there is no reason to change to a diameter closer to the calculated ones. Based on the selected pipe, the actual upflow velocity was:

$$V_{Upflow} = \sqrt{\frac{Q_{SedTank} * 4}{\pi * D_{SedTank}^2}} = 1.316\frac{mm}{s} \tag{5}$$

This is well within the range of typical upflow velocities to form floc blankets.

Floc Characteristics

The effectiveness of the sedimentation tank floc blanket is based on its ability to capture flocs. The flocs' sedimentation velocity must be at least equal to the tank's upflow velocity–i.e., the flocs cannot be carried up through the sedimentation tank faster than they can settle. With a 1" diameter sedimentation tank, the upflow velocity is 1.316 mm/s.

The settling velocity of the flocs is based on their diameter. The diameter of the floc is based on the average energy dissipation rate:

$$D_{floc} = \left(\frac{\varepsilon_{avg}}{\frac{W}{kg}}\right)^{\frac{-1}{3}} * .75\mu m = 0.4386mm \tag{6}$$

7

$$V_{sed} = \frac{g * d_0}{18 * \phi * \nu_{H_2O}} * \frac{\rho_{floc} - \rho_{H_2O}}{\rho_{H_2O}} * \left(\frac{d}{d_0}\right)^{D_{fractal}-1} = 1.297\frac{mm}{s} \tag{7}$$

where, with an average energy dissipation rate of $\varepsilon_{avg} = 5 * 10^{-3}\frac{m^2}{s^3}$,$d_0 = 1\mu m$ is the initial diameter of a clay particle of density $\rho_{floc} = 2640\frac{kg}{m^3}$, $\phi = \frac{45}{24}$ is the shape factor for the fluid drag on the flocs, $\rho_{H_2O} = 1000\frac{kg}{m^3}$ is the density of water, $\nu_{H_2O} = 10^{-6}\frac{m^2}{s}$ is the kinematic viscosity of water, and $D_{fractal} = 2.3$ is a number which describes the fractal pattern of floc formation. This settling velocity is very close the the upflow velocity, but is actually somewhat less than it. This was worrisome, because it implied that flocs may in fact be carried out of the floc blanket column too quickly to form a useful floc blanket. However, the closeness of the two velocities, and the historical success of the ENGRI 1131 class implied that the sedimentation tank dimensions were reasonable, and that the floc blanket should work effectively (assuming inlet and tank geometry, as well as other factors were well-designed).

Influent Jet Dimensions

The influent jet diameter determines the energy dissipation rate of the flocculated water entering the sedimentation tank. This energy dissipation rate must be low enough that it will not break up already-formed flocs, but high enough that the jet can act as a re-suspender of flocs at the bottom of the tank. The equation below for the required diameter jet is based on notes from Monroe's 4540 class:

$$D_{SedInlet} = \left(\frac{Q_{Sedtank}}{\varepsilon_{max}^{\frac{1}{3}} * \Pi_{vc}^{\frac{7}{6}}} * \frac{4 * \alpha_{Jet}}{\pi}\right)^{\frac{3}{7}} = 0.152in \tag{8}$$

where $\Pi_{vc} = 0.62$ and $\alpha_{Jet} = 0.34$. This is a minimum diameter, so a 1/4" ID (3/8" OD) push-to-connect fitting served to use as the inlet. It is possible, however, that the fitting diameter was so large as to result in a problematically low energy dissipation rate, affecting the ability of the influent jet to re-suspend settled out flocs .

Tube Settler Dimensions

The tube settler serves to capture smaller flocs once they have progressed out of the floc blanket. A piece of PVC piping of the same diameter as the floc blanket portion of the sedimentation tank was used, connected by a PVC elbow at 45 degrees to that lower portion. The required length of the tube settler is based on the desired capture velocity:

$$L_{settler}(V_{capture}) = \frac{4 * Q}{\pi * D_{Sedtank}} * \frac{1}{V_{capture} * cos(\alpha)} - D_{Sedtank} * tan(\alpha) \quad (9)$$

The capture velocity of the AguaClara plate settlers is 0.12 mm/s. For the demo plant, this would result in a tube settler 31.4 cm long. Because the floc blanket portion of the sedimentation tank is only 40 cm high (as explained in the next section), having such a long tube settler might create an overturning moment on the tank. Therefore, a decision was made to settle for a higher capture velocity (meaning some of the slower moving flocs would pass through the tank). A capture velocity of 0.2 mm/s (only 0.08 mm/s faster than that desired) requires a 17.7 cm length tube settler, which is much less likely to overbalance the sedimentation tank. This was preferable to the solution of packing drinking straws into the larger tube, as their small diameters could make them more prone to failure because floc buildup would occur proportionally more quickly. Further, there is no guarantee that having several short, small-diameter settlers would be equivalent to a single long one of the same diameter.

Thus, a tube settler of length 20 cm was constructed. The tube settler length gives a capture velocity of 0.127 mm/s:

$$V_{capture} = \frac{4 * Q}{\pi * D_{Sedtank} * cos(\alpha)} * \frac{1}{L_{settler} + D_{Sedtank} * tan(\alpha)} \quad (10)$$

Floc Weir and Hopper Dimensions

A floc drain was installed in the form of 27 cm of 1/4" outer diameter piping inserted into a hole in the sedimentation tank wall, and then downsizing to 45 cm of 1/16" peristaltic pump tubing. It was placed about 5 cm from the top of the floc blanket building section, thus setting the height of the floc blanket at about 40 cm. The excess flocs flow into that tubing, which leads to a waste bucket. The flow of flocs through the drain is determined by a valve located between the two types of tubing. During operation, the valve is continuously partially open, resulting in a floc drainage rate of 5 mL/min. This drainage rate was based observationally on what rate would allow for the clearest water in the tube settler (i.e., maximum floc drainage) while still resulting in the required effluent flow rate of 40-50 mL/min out of the sedimentation tank.

An additional floc drain, consisting of 10 cm of 3/8" OD tubing connected to a T-junction and a valve, was installed at the bottom of the sedimentation tank between the influent jet and the effluent from the flocculator. This drain allows for quick, partial drainage of flocs from the bottom of the floc blanket column, as needed when floc build-up in that section becomes too high. It is opened at the operator's discretion.

Stacked Rapid Sand Filter

The general design of the Demo Plant SRSF involves using a clear acrylic pipe as the main filter column. In contrast to the full scale SRSF, we do not have inlet or outlet boxes. In addition, we will add a freefall column before the SRSF and a clearwell column after. We will attach 3 inlet pipes from a freefall column after the sedimentation tank to the filter column using a 3-way connector. The advantage of eliminating open inlet and outlet boxes is to decrease the risk of air bubbles entering the SRSF. We also attached the 2 outlet pipes in the same fashion. They will go from the filter to a clearwell column.

The water will enter the bottom of the clearwell and leave from the middle, so that when the filter is running there will always be clean water in the column to visually demonstrate the filter's effectiveness. From this clearwell, water will leave out the side and go down into an effluent bucket. There are visual and functional advantages of having two free surfaces before and after the SRSF. The location of the clearwell column will be designed so that its water level is just lower than the water level in the freefall column. The height difference, which is easy to see, will be the head required to get the water through the tubes and sand layers. Furthermore, the bottom of the clearwell column will be below the bottom of the freefall column, so the freefall column will never be fully drained. This will ensure that no air bubbles can enter the SRSF.

There will be 6 valves total in the system, including 3 for inlets, 2 for outlets, and 1 for backwash tubing. A tube is installed near the top of the filter column and connected with a valve for backwash. During filtration, 3 inlet valves and 2 outlet valves will be open. During backwash, only the bottom inlet pipe valve and the backwash valve will be open. Due to the scale of the Demo Plant, the bottom inlet tube will be the same size as the two upper inlets. Because the SRSF is pressurized and sealed on the top using a threaded valve, it can be located at any height as long as it is lower than the freefall exit (located at the bottom of the freefall column) and as long as there is sufficient head available for backwashing.

The Demo Plant team is proposing to treat approximately 50 mL/min with four 10 cm deep layers of sand. The sand media will have effective size 0.5mm and uniformity coefficient of 1.6. The target backwash velocity is 7 mm/s. We have defined many of the necessary inputs for the filtration analysis below.

$Q_{Plant} = 50\frac{mL}{min}$
$\rho_{FiSand} = 2650\frac{kg}{m^3}$
$k_{Kozeny} = 5$
$H_{FiLayer} = 10cm$

$\rho_{Water} = 1000\frac{kg}{m^3}$
$Nu_{Water} = 1\frac{mm^2}{s}$
$N_{FiLayer} = 4$
$D_{FiSandES} = 0.5mm$
$UC_{FiSand} = 1.6$
$\epsilon_{FiSand} = 0.4$
$V_{FiBw} = 7\frac{mm}{s}$
To calculate the total sand depth:

$$H_{FiSand} = H_{FiLayer} * N_{FiLayer} = 0.4m \tag{11}$$

To calculate the D.60 for the sand grain size:

$$D_{60} = D_{FiSandES} * UC_{FiSand} = 0.8mm \tag{12}$$

To calculate the minimum velocity of backwash to fluidize sand layers:

$$V_{MinBW} = \frac{\varepsilon^3_{FiSand} * g * D^2_{60}}{36 * k_{Kozeny} * Nu_{Water} * (1 - \epsilon_{FiSand})} * (\frac{\rho_{FiSand}}{\rho_{Water}} - 1) = 6.14\frac{mm}{s} \tag{13}$$

To calculate the expansion ratio of fluidization:
The equation below is from Michael Adelman's empirical data.

$$\varepsilon_{Exp}(V_{FiBW}) = (\frac{V_{FiBW}}{114.33\frac{mm}{s}})^{\frac{1}{3.46}} = (\frac{7\frac{mm}{s}}{114.33\frac{mm}{s}})^{\frac{1}{3.46}} = 0.446 \tag{14}$$

$$\Pi_{Exp}(V_{FiBW}) = \frac{1 - \epsilon_{FiSand}}{1 - \varepsilon_{Exp}(V_{FiBW})} = 1.083 \tag{15}$$

To calculate the height of expanded sand layers:

$$H_{Exp} = \Pi_{Exp}(V_{FiBW}) * H_{FiSand} = 43.327cm \tag{16}$$

To calculate the required filtration velocity:

$$V_{FiLayer} = \frac{V_{FiBW}}{N_{FiLayer}} = 1.75\frac{mm}{s} \tag{17}$$

To calculate the filter bed plan view area:

$$A_{Filter} = \frac{Q_{Plant}}{V_{FiBw}} = 119.048mm^2 \tag{18}$$

To calculate the diameter of the filter :

$$D_{Filter} = 2 * \sqrt{\frac{A_{Filter}}{\pi}} = 0.485in \tag{19}$$

To calculate the filtration velocity:

$$V_{Fi} = \frac{V_{FiBw}}{N_{FiLayer}} = 1.75\frac{mm}{s} \tag{20}$$

To calculate the headloss through the filter at the beginning of the filtration run with a clean filter bed :

$$HL_{FiCleanLayer} = 36 * k_{Kozeny} * \frac{(1-\epsilon_{FiSand})^2}{\epsilon_{FiSand}^3} * \frac{Nu_{Water} * V_{Fi}}{g * D_{60}^2} * H_{FiLayer} = 28.231mm \tag{21}$$

To calculate the headloss across the bed during backwash:

$$HL_{FiBwSS} = \frac{H_{FiSand} * (\rho_{FiSand} - \rho_{Water}) * (1-\epsilon_{FiSand})}{\rho_{Water}} = 0.396m \tag{22}$$

After these initial calculations, decisions on what size materials to use were made and they are shown in 2. A clear acrylic tube, 0.75” OD and 0.5” ID, was used as the main SRSF column. Teflon tape was used to ensure watertight connections between the inlet and outlet tubes and the main filter column.

To fabricate the inlet and outlet slotted pipes on such a small scale presented us with a real challenge. We have researched the possibility of using a Wire Electrical Discharging Machine (Wire EDM) and abrasive wires coated with powdered diamond to fabricate the slots needed. These two methods work similarly by using a thin metal wire to cut through the pipe by rapidly running current discharges along it. We tracked down the Wire EDM in Rhodes Hall and the abrasive wires in Bard Hall, contacting the lab technicians with AutoCAD drawings of the slotted pipes. Based on our research, we concluded that these two methods are too expensive and time-consuming for this application.

We then looked into alternative fabrication methods, realizing that we will have to simulate the slots instead of actually replicating them. Ideas included using wire mesh with appropriately-sized holes, wrapped around piping with epoxy. Some prototypes and experimentation with different wire meshes were done. Paul Charles, the Facilities Coordinator and Equipment Tech V in B56 Hollister Hall, proposed using compressed springs within the inlet and outlet pipes to mimic the slot width of the full-scale slotted pipes. As a result, we used two compressed springs within each brass pipe and pinned them in place. The brass pipes have about 5 holes in 4 directions to maximize flow of water. The springs are compressed so that the gaps within springs are approximately 0.2 mm wide. The inlet and outlet pipes are made of brass, 3/16” OD and 1/8” ID, with 0.2 mm openings from the compressed springs inside. The 3 below shows the uniformly compressed springs.

The 4 below shows the overall filter after initial fabrication.

Demo Plant: Full Configuration

A new frame was constructed out of modular pieces of aluminum from the company 80/20 to house the new processes, replacing the old system of a table

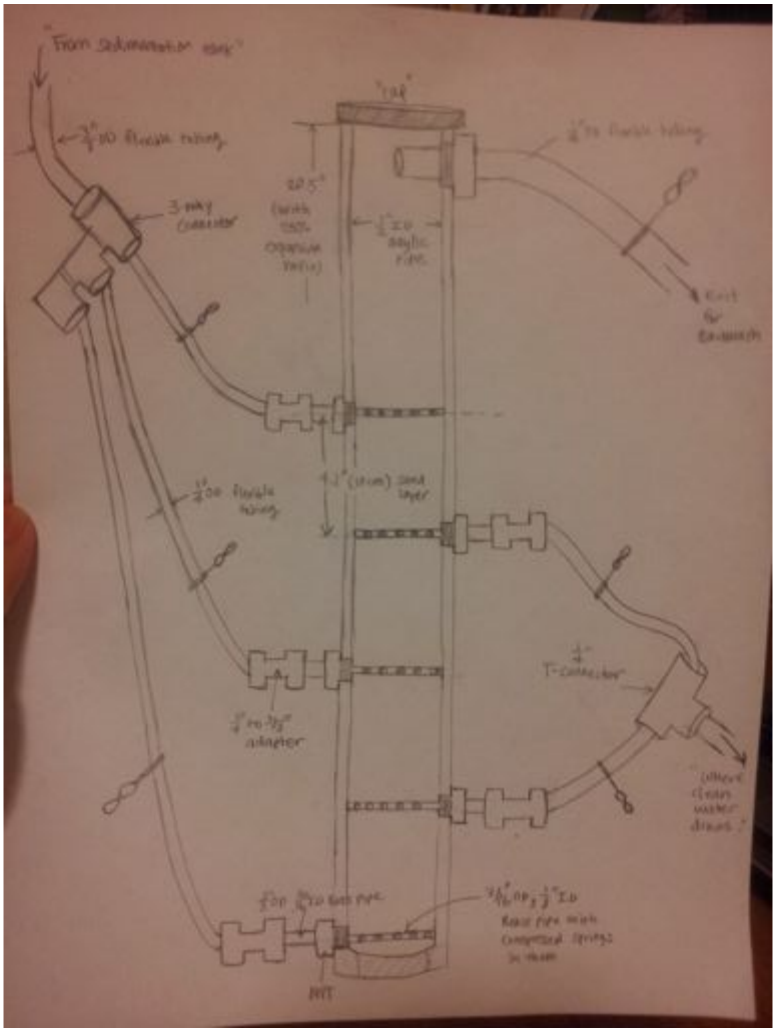

Figure 2: Updated schematic of SRSF (hand-drawn, *not in scale)

Figure 3: Compressed springs in inlet and outlet pipes

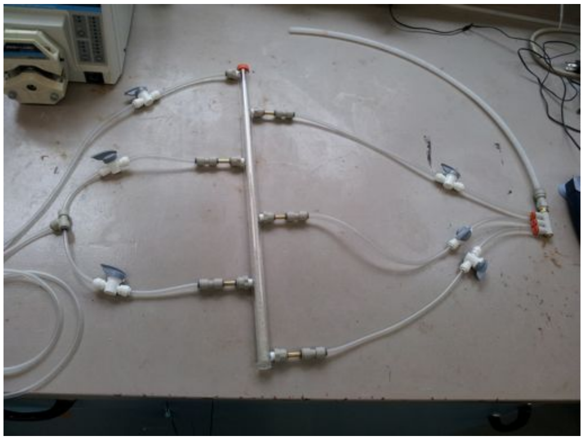

Figure 4: Assembled SRSF

Figure 5: Overall Demo Plant

and PVC piping. This frame is easily deconstructed, is simple to pack for transportation, and is easily modified to accommodate changes in the required relative positions of the unit processes, due to the adjustable nature of the 80/20 pieces. The new frame is shorter, lighter, and more professional looking than the previous frame, while continuing to be simple to operate. The frame is more fully described in the Demo Plant user manual.

The fully assembled Demo Plant is shown below in 5

Head losses

Important hydraulic calculations necessary to the functionality of the overall Demo Plant must include the headlosses incurred from the tubing, connectors, and valves used to connect the unit processes. In the heat of the P3 competition, different parts were fabricated and modified rapidly. We realize that the length and size of tubing used is significant and is something that can be changed in the future to make the Demo Plant more efficient. So we have tabulated all the tubing, lengths, diameters, and headlosses for different sections to make the Demo Plant more modular. See the figure below 6The headlosses were calculated using the AguaClara Fluids Functions MathCAD worksheet. If any tubing is changed, the effective head losses can easily be looked up and modified as needed. Minor loss coefficients used in this analysis are shown in the table below1:

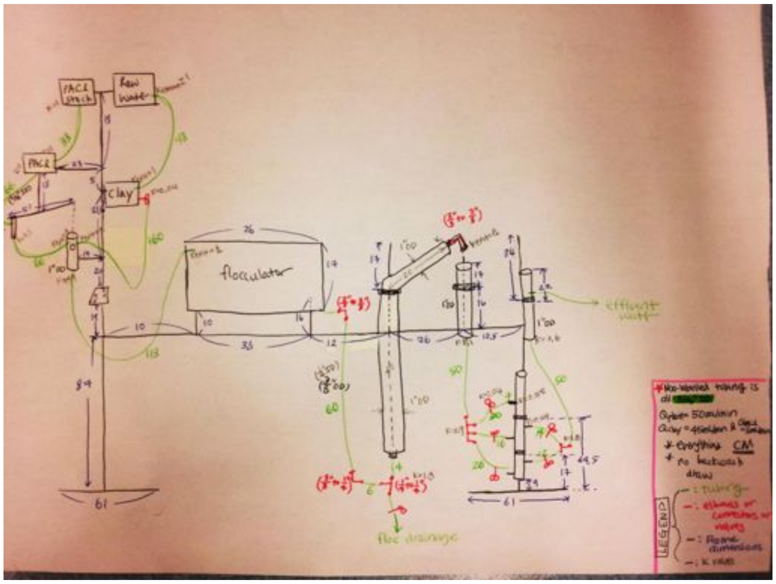

Figure 6: Detailed Demo Plant Diagram

Section	Headloss
PACl stock tank to PACl tank	7.098×10^{-3}cm
PACl tank to lever arm	3.616 cm
Lever arm to entrance tank	0.014 cm
Raw water to clay stock	0.098 cm
Clay stock to entrance tank	0.31 cm
Entrance tank to Flocculator tube	0.246 cm
Through Flocculator	0.5 cm
Flocculator exit to sedimentation tank entrance	0.23cm
Through sedimentation tank	5.276×10^{-4}cm
Free fall to Clear well	1.468 cm

Table 1: Headloss Calculations

Results and Analysis:

Flow Control and Chemical Dosing

After testing the rate of water flow at different points in the plant, the over-all plant flow rate was set at 48 mL/min. This was accomplished by setting the length of tube connecting the raw water constant head tank to the entrance tank (PVC pipe) at 156 cm long. The tube leaving the entrance tank and feeding the flocculator was set to be 113 cm long, which accounts for both the influent raw water and the influent coagulant dose and keeps the plant flow rate in the range of 45 to 55 mL/min.

The coagulant dose of poly aluminum chloride was then chosen based upon the concentration of the chemical, the difference in head level created by the lever, and the time it would take to refill the one liter PACl stock tank. Setting the expected dose rate for the polyaluminum chloride (PACl) to 5 mL/min worked to the specifications of the plant flow rate. Based on this dose rate, the one liter stock tank of PACl would run for a full three hours before needing to be refilled. The stock concentration of influent PACl was chosen to be 150 mg/L. This dose corresponds to coagulating water with 1 g/L clay (i.e. 500 NTU). While the dose rate of PACl into the entrance tank is controlled by the lever, the equations were still used to find the length of 1/8" ID tube that connects the constant head PACl tank to the lever arm. Based on the equations this length was set to approximately 50 cm which corresponds to the correct flow rate that is expected. Another advantage of the lever arm is that increasing the dose of the coagulant is very easy. A second head level was calculated to correspond to an 8 mL/min dose which would account for times that a high dose rate would be needed. This would be accomplished simply by moving the end of the dose tube attached to the lever further away from the pivot, outward to a second marking which reads "8 mL/min".

Sedimentation Tank

The assembled sedimentation tank is shown below 7:

The sedimentation tank results in a floc blanket after about 15-20 min of operation, using a raw water solution of 1 g/L suspended clay, and alum dosing with a stock solution of 150 mg/L. The alum dose flow varies between 5 and 10 mL/min (i.e., 0.625 mg/min to 1.25 mg/min).The flow rate entering the sedimentation tank is close to that exiting: the measured influent flow rate is ˜55 mL/min, and the exit rate is ˜50 mL/min– a difference explained by the ˜5 mL/min floc drainage rate. The observed head loss is cm (as compared to the calculated headloss of cm).

Since the sedimentation tank was able to produce a floc blanket in practice, it seems that the calculated difference in upflow and settling velocities, which implied that flocs would be carried out of the column too quickly to form a floc blanket, is either incorrect or negligible. This is perhaps because of the velocity gradient in the pipe, meaning that enough particles near the walls of the pipe

Figure 7: Sedimentation Tank

Figure 8: Emergency Floc Drain

moved upward more slowly than the calculated settling velocity, and thus were capturable. This may also be because our assumptions about the flocs' initial dimensions were incorrect.

After operating for an hour or so, floc buildup in the entry of the tank becomes so high that an excess of head is required for water to flow through this entrance region. This results in stopping flow through the plant, and backing up in the flocculator. This floc build-up is likely a result of both the geometry of the sedimentation tank bottom - ideally, it would be fully conical, rather than the current, stepped design - and the influent jet dimensions. It is possible that using an influent jet diameter larger than the calculated minimum resulted in a too-low energy dissipation rate, meaning the influent jet is unable to sufficiently re-suspend settled-out flocs. The emergency floc drain (8) was installed at the bottom of the sedimentation tank as a temporary fix, however a permanent solution based on preventing such build-up is preferable.

The current sedimentation tank set-up also results in the tube settler quickly becoming turbid as well as the floc blanket section (although the former is less turbid than the latter). The floc drain at the top of the floc blanket helps to combat this issue; however, opening the floc drain enough to result in the desired turbidity in the tube settler results in stopping flow through the plant. A clearer tube settler would be desirable, as it would indicate cleaner water exiting the sedimentation tank, and its current turbidity implies insufficient floc drainage. Because the water is sufficiently clean both upon exiting the sedimentation tank and filter, however, the turbidity of the tube settler is relatively unimportant, as it is clearly still achieving its purpose.

The head loss calculated from the flocculator to the entrance of the sedimentation tank (tubing and elbows) by MathCAD was about 0.23 cm. However, when we ran the Demo Plant, we observed a headloss of about 0.5 cm, a discrepancy of 0.2 cm which can likely be attributed to some minor losses.

The headloss through the entire flocculator calculated in MathCAD was around 0.5 cm, which very well matched our observation of 0.5 cm when we ran the plant. Therefore, we can infer a headloss of just about 0.3-0.4 cm from the entrance to the exit of the sedimentation tank.

Stacked Rapid Sand Filter

Initial tests of the SRSF were fairly successful. There was a lot of difficulty removing air bubbles after adding sand and filling the column with water. We found it is important to first fill the column entirely with water, then add sand to replace the water. This way, there will be less air trapped in between the dry sand grains.

Also, we had trouble finding a strong airtight seal to pressurize the SRSF. We first used a rubber cap obtained from the Environmental Teaching Lab. This did not provide a tight enough seal and was not very reliable. It fell off several times and did not provide the desired airtight seal. So we threaded the top of the main filter column and installed a manual valve (as shown in 9). This way, we could remove the valve completely when filling the filter with sand, or just open the valve to allow air to escape as needed However, this method is still does not provide as good a seal as we would like it to.

After making these changes, more tests showed that the filter would not fluidize at all if there is any air in the main column. To remove trapped air, gently shaking and tapping the column is very effective but impractical when using the Demo Plant for outreach purposes. To reduce this problem during backwash, we started by only opening the top inlet instead of bottom inlet valve. With gentle shaking and tapping, we got only the top sand layer to fluidize and removed any air bubbles trapped in that layer. We had to closely monitor the sand height during this process and close the backwash valve if the sand height was too high, to avoid losing sand. Then only the middle inlet was opened, fluidizing more sand layers and removing additional air bubbles. Finally, we were able to first open the bottom inlet valve and then close the middle inlet to effectively fluidize the sand bed. We noted the importance of opening the bottom inlet before closing the middle inlet. If this order is not followed, it is not possible to fluidize all layers using only the bottom inlet valve. The additional fluidization provided by water flow through the middle inlet is initially needed to maintain fluidization throughout the backwash process. As

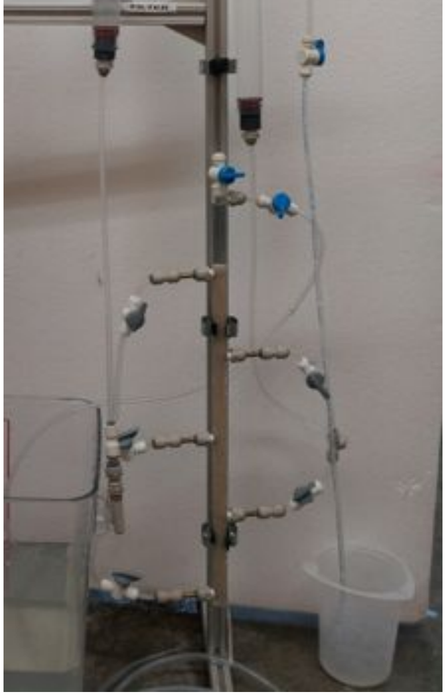

Figure 9: Overall Stacked Rapid Sand Filter

can be seen, operating the SRSF in backwash was tedious and complicated. Often we needed more than one person to do this and lost sand numerous times.

However, adding the freefall column seen in 9 after the sedimentation tank and before the SRSF made things easier. The freefall column eliminated the entrainment of any air bubbles from the sedimentation tank to the SRSF. Running the SRSF in filtration mode for a while and then backwashing also made the process easier. Also, some of the difficulties of fluidization arise from the fact that the sand grains are too big relative to the diameter of the main filter column. This causes the sand to overflow during backwash.

Conclusion:

Sedimentation Tank

The success of the sedimentation tank validates the assumptions made in building it. The difficulty with floc build-up in the tank imply that a maximum influent jet diameter should be calculated in the future, so as to ensure that the energy dissipation rate is within the correct range.

Stacked Rapid Sand Filter

The SRSF has been an important addition this semester as previously there was no filter in the Demo Plant nor any calculations done to design one. Our theoretical calculations proved successful for fabricating the first SRSF on such a small scale. The filter does efficiently remove flocs from the water and illustrates the SRSF process.

There are still issues with backwashing and fluidizing the sand bed. We need a better mechanism to remove air bubbles than tapping the column. The threaded manual valve at the top of the SRSF does not provide a good enough seal and is difficult to work with at times. By using acrylic tubing for the main column, the filter is fragile. The column was more difficult to tap and thread as necessary, and all connections were installed with extra care as to not break the column. Due to its fragility and odd shape, there is currently no way to easily and safely transport the SRSF.

Future Work:

Overall

The Demo Plant frame needs to be optimized; it can be made more compact and collapsible so as to be easier to store and transport. Also, clearer laminated labels must be made, in order to better explain the plant's functioning to a layperson. Smaller, more attractive buckets and appropriately sized bottles need to be ordered, and a consistent, efficient form of packaging the plant must be developed

Flocculator

The flocculator geometry has to be redesigned to prevent floc buildup in the bottom. This is visually distracting as the purpose of flocculation does not include the settling of flocs.

Sedimentation Tank

Investigation into the geometry and influent jet dimensions of the sedimentation tank is necessary in order to prevent excess floc build-up on the sedimentation tank floor. The floc drain design should also be improved. Ideally, the valve could be opened fully, rather than to a marked partial point, as it would be simpler and easier to operate. That design change would likely be a result of changing the diameters and lengths of the tubing used to make the drain. Floc drain modifications could also take into account and affect the turbidity of the tube settler.

Stacked Rapid Sand Filter

The SRSF can be fabricated using clear PVC piping for the main column to make it less fragile. An extra slotted pipe can also be fabricated for display purposes. Work needs to be done to fluidize the entire sand bed efficiently and easily, especially during outreach opportunities so the Demo Plant SRSF can demonstrate how an SRSF works properly. The SRSF needs to be stronger for transportation purposes. We realize that this can be improved upon - the SRSF will still be considerably fragile, so some type of carrying case is necessary. A carrying case needs to be fabricated or modified from some existing case.

Currently, the SRSF is the lowest unit process of the Demo Plant. This was necessary to obtain the appropriate headlosses through the Demo Plant. In the future, if things are rearranged, it will be helpful to have the SRSF higher up so it is more visible and people will not have to crouch down to get a closer look.