Low Flow Stacked Rapid Sand Filtration Fall 2012 Final Report

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Abstract

The use of filtration units for the treatment of drinking water is a common practice in engineering design. However these units are generally used for the treatment of large volumes of water. To improve upon this limitation, a stacked rapid sand filter was designed for low flow rates. Work for the semester began with an existing filtration unit which did not contain sand, due to predicted failure from large head losses in filtration and backwash. The existing design was modeled in AutoCAD 2013 to provide an illustration of the system. Updates to this drawing were completed and will continue to be as fabrication phases occur. One of the primary tasks was to develop a mathematical model in MathCAD to calculate the flows and head losses throughout the system. The model was completed for filtration and backwash, and includes calculations for both cycles with and without sand present. Hydraulic testing was completed to determine the head losses in filtration and backwash, risk of sand transport through the backwash pipe, and flow rates. These measurements and observations were compared with the mathematical model to determine its validity. According to head loss values obtained from the mathematical model, several changes were made to the filter prototype. Such fabrications included complete reconstruction of the backwash pipe, changing of valve types, and installation of NPT fittings and ball valves. Finally performance testing was completed to determine the effectiveness of the prototype in regards to decreasing effluent turbidity. Overall, it was determined that the filter prototype is highly effective at decreasing turbidity for several influent concentrations at the designed flow rate.

Introduction

One of the essential components of human life is accessibility to clean drinking water; however, much of the world suffers a deficiency of this vital resource. In the mean time, the remainder of the countries are able to utilize modern technology to treat raw water and enjoy the benefits of pathogen free and low turbidity drinking water. The primary constraints for the LFSRSF (Low Flow Stacked Rapid Sand Filter) are to provide an economical and electric-free system that can be implemented almost anywhere in the world. The United States is able to utilize its wealth and availability of electrical power to treat raw water; however not all countries are fortunate enough to have these resources. Therefore, the goal was set to develop a drinking water treatment system which is feasible for regions with economic hardships and power shortages. This goal was accomplished through the development of the AguaClara treatment facility, which is currently being utilized in several locations in Honduras. To further optimize this treatment facility, the filtration process was investigated to determine the aspects of the process which could be improved. The goal of this research project is to modify the current design of the LFSRSF so that it may be implemented by Agua Para el Pueblo and used in any subsequent water treatment facilities. Previously, a stacked rapid sand filtration system was designed to remove the particles remaining after sedimentation in an efficient manner prior to chlorination and distribution. However, this method is inappropriate for flows less than 6 liters per second. Smaller communities, who have water treatment plants with less flow, are unable to use this system. Thus, a design and prototype low flow filter was created within the last year. However, the design is not fully complete, and testing and modification of the system is necessary before it can be implemented in a plant. Also, an accurate mathematical model of the design will be created to assist in scaling the filter for multiple flows. The first LFSRSF is projected to be installed by January 2013.

1 Literature Review

1.1 Monroe's Filtration Theory notes from 2011

The material provided by Professor Weber-Shirk illustrates current practices and to-date comprehension of sand filtration systems. These techniques include the slow sand, rough gravel, dynamic gravel, rapid, and stacked rapid filtration. These filtration methods have their relative range of applicability, which is primarily based on the constraints of the water treatment facility. From the previously listed techniques for sand filtration systems, a subset of systems based on sand depth can be observed; including slow, rapid and stacked rapid. Slow sand filtration is a method which utilizes low flow rates to remove particulates and colloids from the raw water. However drawbacks of this system include high head losses and periodic cleaning of the sand. Rapid sand filtration is another filtration method which permits approach velocities of 0.7-2.8 mm/s. The filtration process uses layered media including anthracite, sand, and gravel progressing from top to bottom, respectively. A difference between the rapid and slow sand filtration systems is that rapid sand filtration utilizes a backwash process which fluidizes the sand layer effectively cleaning it. An additional depth based filtration system called stacked rapid sand filtration (SRSF) is a technique which uses a similar approach to the rapid sand filter to treat raw water. Modifications of the SRSF include stacking multiple sand layers as opposed to having several rapid sand filtration units in parallel. The greatest

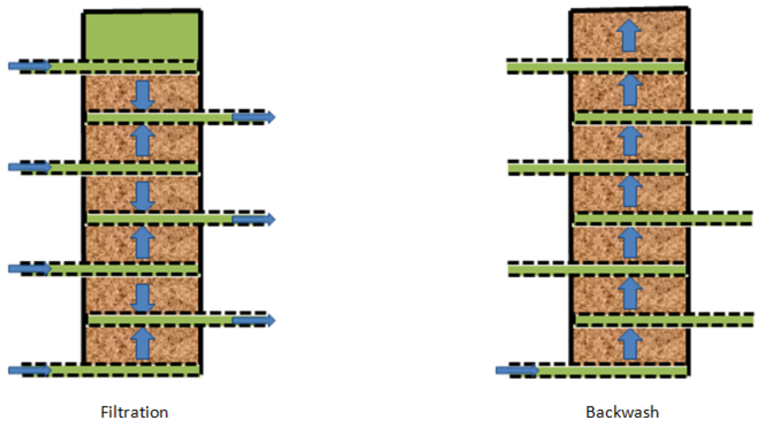

Figure 1: Flow through Filtration and Backwash Modes

benefit from this geometric alteration is the reduction in water required for the backwash process.

As shown in Figure 1 below, the paths that the water travels in a SRSF and LFSRSF are shown by the blue arrows. For filtration, the water flows through parallel paths (equal head loss through each path, with flows summing up to the total flow rate through the system). Water in each path flows through an inlet pipe, travels up or down through one sand bed layer, and leaves through the corresponding outlet pipe. During backwash, all the flow is directed through the bottom inlet pipe and up through all sand bed layers. The flow through backwash is six times that of filtration to provide adequate flow for fluidizing and cleaning the sand bed.

1.2 Fundamentals of Fluid Mechanics 3rd Edition by Munson, Young, and Okiish

Fundamentals of Fluid Mechanics provides background theory and knowledge on water flow through pipes, including head loss equations and minor loss coefficients. For example, when calculating minor head loss of an expansion or contraction, the velocity in the equation is the velocity through the smaller diameter pipe (or the larger given velocity). Information from this book will be referenced when determining head losses through the manifolds and orifices.

2 MathCAD Model

2.1 MathCAD Model

The MathCAD Model was created in order to determine the head loss through the system in filtration and backwash modes before adding sand. This precaution was necessary to ascertain whether the system would be able to handle the filtration and backwash flows without backing-up water causing it to spill out of the first hydraulic disconnect. If sand were placed in the filter while the head loss values were too high, then fabricating the prototype could be more difficult. Also, if the filter column needed modification, all of the sand would have to be removed before fabrication could occur.

In creating the MathCAD model, the filtration and backwash systems were first evaluated without sand so that the model could be verified with actual results taken from the system during operation. Later, sand was accounted for in the model. The calculated head loss with sand was compared to the allowable head loss in the system to determine if the system would be able to support the necessary flows. Once deemed acceptable, sand was placed in the filter column.

Lastly, the MathCAD model provides a basis for other LFSRSFs. The model can be modified with changes in the system to ensure that new designs would still provide adequate head loss levels.

2.1.1 Without Sand

The head loss through filtration and backwash was calculated in MathCAD by determining both the minor and major head losses through one parallel flow. It was assumed that the flow through each of the six parallel paths is equal (1/6 of the total flow through the system), which simplifies the head loss calculations. However, this may be the cause for some error in calculations.

Originally, spring valves were placed on the outlet branches of the prototype and the minor loss coefficients for the tee's were not calculated accurately. With these constraints, the head loss without sand was determined to be 46 inches. This was higher than the actual head loss (35 inches) in the system, which included the head loss through the spring valves. Thus, the MathCAD model was incorrect. These errors were fixed by using accurate minor loss coefficient tee values, swapping spring valves for swing valves, and correcting other minor errors in the MathCAD model.

After fixing the errors and updating the model to include the new spring valves, a head loss of 16.1 inches without sand was calculated. This was very accurate to the actual head loss through the system, which was determined by the height difference between the two hydraulic disconnects. This difference is approximately 18 inches, only 2 inches below the actual system. This error was likely due to the clogging of manifold orifices in the filter tank as the stagnant water had produced organic growth. The corresponding head loss calculation with sand resulted in a value of 18.7 inches, which was well below the allowed value of approximately 25 inches.

The backwash calculations were calculated from the piping starting at the first hydraulic disconnect (where the pitot tube was located), through the bottom most inlet pipe, up through the filter, and out through backwash pipe (the water level in the tank determines outlet head level). The actual head loss through the backwash system was determined to be approximately 2 meters. The MathCAD model calculated a head loss value of only 1 meter. The discrepancy between the MathCAD model and the system was mainly due to captured air in the backwash pipe. Methods of how this problem was fixed can be found in Section 2.5.

The head losses through the 1 inch backwash pipe were determined to be between 20 and 23 inches. This is an unnecessarily large amount of head loss. Thus, the 1 inch pipe was exchanged for a 1.5 inch pipe, and the head loss was reduced to approximately 17 inches. The resulting predicted head loss with sand was still too large for the system. However, it was determined that less flow would yield a smaller head loss while still providing the sand bed fluidization that is necessary during backwash.

As mentioned above, all calculations assume that the flow through each parallel path is equal. Steps to calculate the actual flow through each path have begun by implementing the Hardy-Cross method. In this method, the total head loss in a loop has to sum up to zero. To initialize the functions, the flow rates through each pipe were assumed to be equal. On applying these flow rates to the functions, it was seen that the losses in the loops were in the range of a few centimeters. To get a higher degree of accuracy, an iterative model should be developed to find an exact value for these flow rates.

2.1.2 With Sand

Upon adding sand to the filter, the range that the head loss through the system was calculated changed because the pitot tube that was originally at the first hydraulic disconnect was relocated to the bottom inlet pipe. Therefore, the head losses before the bottom inlet pipe cannot be compared to the actual system. So, the MathCAD model was modified to calculate the head losses between the bottom of the filter bed to the second hydraulic disconnect for filtration and between the bottom of the filter bed to the water level of the tub containing the backwash pipe for backwash.

The filtration head loss in the system at maximum flow (0.85 L/s) was approximately 21 inches. The calculated head loss from the bottom inlet manifold to the second hydraulic jump was calculated as approximately 18 inches. Our model results are slightly lower than the readings from the system. This is intuitive because the mathematical model is a ideal system, but in reality, many other factors or unknown variables could be affecting the system.

The maximum head loss that was attained with the prototype, in the laboratory setting, was approximately 80 inches at a maximum flow rate of 0.8 L/s. For comparison, the flow rate used in the MathCAD backwash model was reduced correspondingly. This provided a calculated value of 73 inches. Similarly to the head loss comparisons for filtration, the calculated value is slightly less

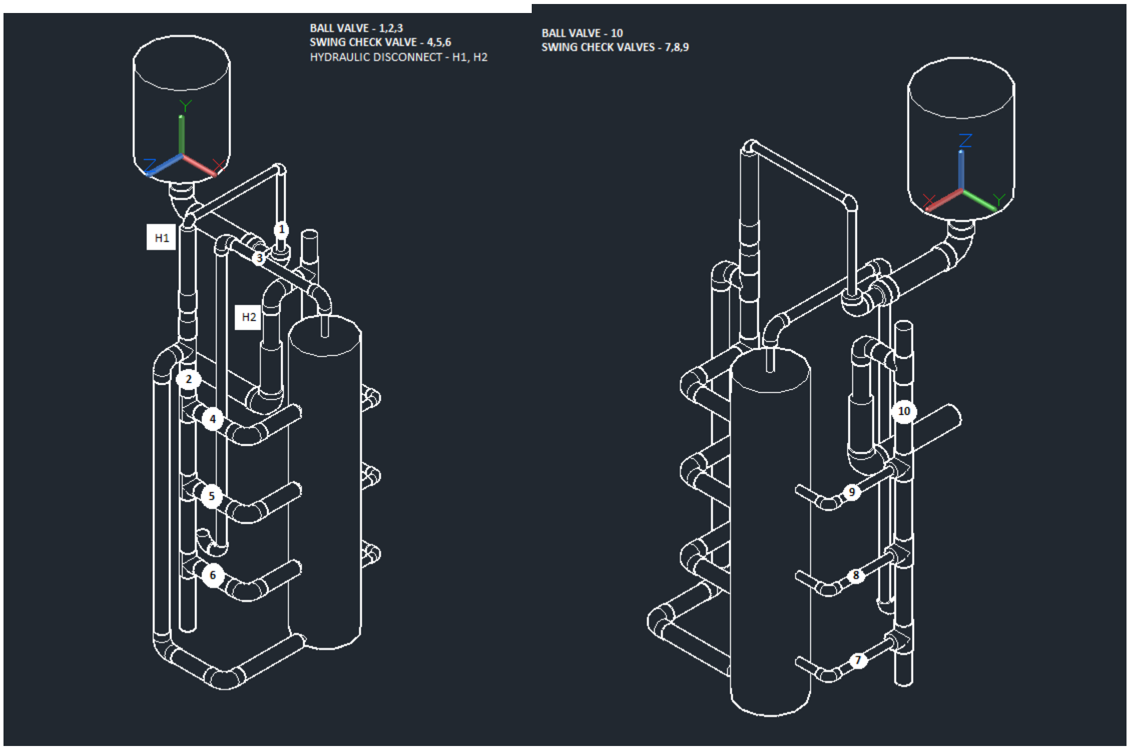

Figure 2: Southeast (left) and Northeast (right) isometric view of the existing LFSRSF

than the values from the prototype. A possible source of error could be due to the unknown amount of flow through each parallel path in the system.

3 AutoCAD 3D Drawing

A visual illustration of the current low flow rapid sand filter is currently being created in AutoCAD 2013. In order for the drawing to be correct, it was necessary create a hand drawn sketch of the existing LFSRSF and acquire all pipe lengths and diameters, as well as the height at various locations. The hand sketch with appropriate dimensions is currently being utilized as a template for creating an existing AutoCAD drawing of the filtration unit. The current progress on the AutoCAD model can be seen below in figure 2.

4 Fabrication

Phase one of fabrication included the reconstruction of the outlet manifolds exiting the filter. For the initial filter prototype, these manifolds were designed with spring check valves. According to results from the MathCAD model, it was determined that these valves were causing considerable head loss. As a result, the outlet manifolds were reconstructed with the swing check valves in place of the spring valves (See Figure 2).

The second phase of fabrication primarily dealt with mitigating head losses to allow the backwash process to function properly. After analysis of the MathCAD model, it was determined that the backwash pipe exiting the top of the filter generated significant head loss. Consequently, the backwash pipe was reconstructed with a 1.5 inch PVC pipe, rather than the existing 1 inch pipe. This pipe was oriented in the same manner, with the same pipe lengths and types of valves, however the diameter of all components increased. An additional source of head loss in the system during backwash was due to air entrapped in the backwash pipe and filter. To resolve this issue, it was necessary to verify the adequacy of the pipe connections and seals. This was done by changing the o-ring located below the cap of the filter. The modified o-ring had an increased diameter and thickness, with holes cut out to ensure a tight fit over the protruding bolts. Additionally it was necessary to tap the backwash pipe and use an NPT fitting with a flexible tube attached. This fitting and associated valve were needed to allow air to flow out of the backwash pipe after it was filled with water.

An additional aspect of the overall fabrication was to have a method which would consistently illustrate whether or not sand bed fluidization was achieved during backwash. The solution to this problem was to insert a long (~5 ft) PVC pipe of small diameter into the filter. The pipe was measured to be long enough to reach the bottom of the filter but also protrude from the top. It was necessary to attached the PVC pipe to the filter in a way which was water and air tight. Ultimately, the pipe was fitted with a cap which was then tightly attached (with fasteners) to a rubber connector. This way, the operator is able to move the PVC pipe if the sand bed is successfully fluidized.

Once it was estimated that the filter would work effectively with sand it, sand was introduced into the filter in the presence of water to prevent damage to the manifolds. The system was then run in backwash mode to fluidize the bed, clean the sand, and allow the sand to settle naturally in the filter.

5 Data Collection

5.1 Flow Measurement

To get an estimate of the head losses prevalent in the system, an accurate flow measurement system needs to be set up. This is to be accomplished by setting up a process controller, which will measure all the variables in the system and record them on a computer. However, as a prelude to this, to get an estimate of the current flow through the system for the given pump, the fluid flowing out of the LFOM was redirected to a tank where the volume was measured for a given interval of time. This process was repeated 10 times to obtain a consistent result and to avoid any manual or runtime errors. The average of these values were taken and a flow rate of 0.85 L/s was obtained.

5.2 Hydraulic Testing

To determine the permissible flow rate, system head loss, and overall effectiveness of the LFSRSF prototype, it was necessary to complete hydraulic testing. This testing was completed for the system during both filtration and backwash to determine the parameters previously mentioned. The results and operations completed during hydraulic testing will have a significant influence on the level of responsibility for the operator. Thus it was important to attempt to mitigate the number of steps required for conducting filtration and backwash, as well as alternating between the two.

5.2.1 Filtration Testing

Filtration testing was completed for the LFSRSF prototype with and without sand in the filter column. In order for the system to operate in filtration, the operator is required to open valves 1, 2, and 10 (See Figure2). While the system is functioning in filtration, the head loss is measured by the height of water in a pitot tube which is connected to the bottom of the filter column. The head loss for the system corresponds to the difference in water height between the height in the pitot tube and second hydraulic disconnect (See Figure 2). Additionally there is a hydraulic disconnect on the inlet side of the filter column; therefore the head loss cannot exceed the elevation of this or water will pour out of the system. During preliminary testing of the system in filtration, it was very important to monitor the height of water in the pitot tube, because it was unknown at the time whether or not head loss was significant. The system head losses during filtration with and without sand are less than the height between the bottom of the filter column and the hydraulic disconnect; thus it functions properly. The flow rate at which this system operates effectively is 0.85 L/s.

5.2.2 Backwash Testing

Testing during the backwash process was completed for the filter prototype with and without the presence of sand in the filter column. To operate the system in backwash, the operator is required to open valve 3 and close valves 2 and 10 (See Figure 2). The pitot tube connected to the bottom of the filter column is also utilized to determine the head loss in the system during backwash. The head loss in the system during backwash is measured as the difference between the height of water in the pitot tube and the height of the water exiting the backwash pipe. The system was first tested without the presence of sand in the filter column. At full flow the head losses were larger than those measured during filtration, but less than the height of the hydraulic disconnect; therefore it functions properly. However, based on preliminary testing, it was found that backwash water was entering the slotted manifolds in the filter column and exiting through the outlets. This is not how the system is intended to function; therefore a ball valve (See Figure 2) was added to the prototype. During backwash, the operator is required to close this valve to avoid backwash water exiting the filter outlets.

The system was then tested with the presence of sand in the filter column. Based on testing of the system in backwash, it was determined that air bubbles were becoming entrapped within the backwash pipe (exiting the top of the filter) as well as the inlet manifolds. It was proposed that these air bubbles were the cause for the significantly high head losses during backwash. In order to solve this problem, several operation alterations and fabrications were made. The first being that the seals at various connections were replaced. This will reduce the risk of air entering the filter during backwash. The second alteration required the blocking of the backwash pipe the moment it fills with water. The third change was to tap an NPT fitting into the top of the backwash pipe. When the system is in backwash, and the backwash pipe is filling with water, this NPT fitting (with attached flexible tube) will provide an additional path for air to exit the system. Once the backwash pipe is filled with water, it is blocked and then any remaining air in the pipe will exit through the NPT fitting. The moment water begins flowing out the NPT fitting, the valve on the fitting is closed, the backwash pipe is unblocked, and the system is air tight. Preliminary testing utilizing the previously mentioned procedure, has proven to significantly reduce the head loss through the system. Utilizing the previously described process, the maximum flow rate obtained during backwash was found to be 0.8 L/s.

Due to the increased velocities during the backwash cycle, there is a risk that sand within the filter column could be transported up through the backwash pipe. This is an additional parameter which was closely monitored during the backwash cycle. In order to test the risk of this transport occurring, the backwash process was operated at various flow rates. Initially the flow would be low, but to monitor sand transport, the operator will gradually increase the flow rate by opening the valve. As the flow rate through the filter column increases (with velocity), the risk of sand transport into the backwash pipe increases. Preliminary results indicated that at the maximum permissible flow rate for backwash (0.8 L/s), the transportation of sand through the backwash pipe is not a major issue. After completing several backwash cycles, there was a small accumulation of sand at the bottom of the tank for backwash water; however it is a relatively insignificant amount compared to the volume in the filter column.

5.3 Performance Testing

To complete the performance analysis of the filter prototype, it was necessary to set up the process controller, control box, turbidimeters, and coagulant/clay peristaltic pumps. The two turbidimeters measure the influent and effluent turbidity of the water from the filter. The water for the influent turbidimeter was obtained from a flexible tube connected to an outlet at the base of the filter column, and then discharged back into the backwash tank. The water for the effluent turbidimeter was obtained by tapping an NPT fitting below the second hydraulic disconnect, and then discharged back into the backwash tank. Both turbidimeter set-ups are gravity driven processes instead of using pumps to convey water to and from the turbidimeters. During preliminary testing, it was determined that the location at which the water for the turbidimeters is collected is vital to the effectiveness of the filter. The location needs to have a constant flow of water; thus mitigating the risk of air bubbles. The presence of air bubbles in a turbidimeter measurement vial will cause a falsely high measurement of turbidity. When functioning properly, no air bubbles are present in the turbidimeter vial; therefore a constant stream of water flows through the devices.

To simulate the available raw water in Honduras, it was necessary to add a concentration of clay particles to the influent water. In order for the clay particles to disperse uniformly through the influent water, it was necessary to connect a flexible tube from the clay source to an existing NPT fitting, which was located before valve 1 (See Figure 2). The flexible tubing was connected with the peristaltic pump to generate a constant flow rate into the filter. It was proposed to add the clay particles to the constant head tank; however it was later surmised that the water recycling which occurs in the tank would cause the concentration of clay particles entering the filter prototype to be highly variable. The clay concentrations input to the filter were calculated to provide three different influent raw water turbidities of 5 NTU, 10 NTU, and 20 NTU. Based on the current operating Atima plant data, the low turbidity level is around 5 NTU; therefore the formula,$Q_{system} * C_{target} = Q_{pump} * C_{stock}$, where Q_{system} = 0.85 L/s, C_{target} = from data from Atima plant and Q_{pump} = 0.1 L/min, was used to determine the clay stock concentration. The resulting stock concentration is 2550 NTU, which is approximately 3.8 g/L (utilizing a conversion factor of 1 NTU = 1.5 mg/L). In order to increase the stock concentration to higher turbidities, the concentration of clay (g/L) was scaled accordingly. Consequently, if the desired NTU increased by a factor of 2, then the required clay concentration would increase by a factor of 2.

In order for the effectiveness of the filter prototype to be further improved, the coagulant Polyaluminum chloride (PACl) was added to the influent water. This coagulant will mix with the clay particles to form flocs which have a larger volume than the individual colloids; thus increasing the probability of particle interception in the filter column. The PACl was input into the system through a flexible tube which was fed into hydraulic disconnect. After the hydraulic disconnect there are various bends and pipe expansions, which all provide an excellent means for mixing the coagulant and clay particles. In order for the PACl to work effectively, it needs to be well mixed and uniformly dispersed amongst the clay particles. This will aid in more particle collisions between the coagulant and colloid particles; thus increasing the number of flocs created.

Figure 3: Prototype and Testing Set-up

Based on current operating data from the Atima plant, a coagulant dose of 2 mg/L is used for an influent raw water turbidity of 5 NTU. Using the previously mentioned formula and flow rates, the PACl stock concentration for 5 NTU water was found to be 1.02 g/L. This coagulant stock concentration was maintained constant for testing with higher influent turbidities.

5.3.1 Results

The Filtration Unit was run under varying loads for varying lengths of time, and the data obtained was tabulated and plotted on a semi-log graph as shown below:

Load: 5 NTU, Time: 30 minutes The initial increase in concentration of the influent and effluent streams can be accounted for by the start-up time for the filtration unit. As the initial influent concentration varies, there is a slight lag in the concentration of the effluent stream, which is due to the time taken by the water to run through the filter. After the first 10 minutes of operation, the percentage removal increases to 85%, which keeps increasing to a value of 97.5% at the 30 minute mark. There is a general decreasing trend in the effluent concentration (or increasing trend in the percentage removal) which is limited by the fact that the filter was only operated for half an hour. Running the filter for a longer time promises better removal of suspended particles. The sudden spike

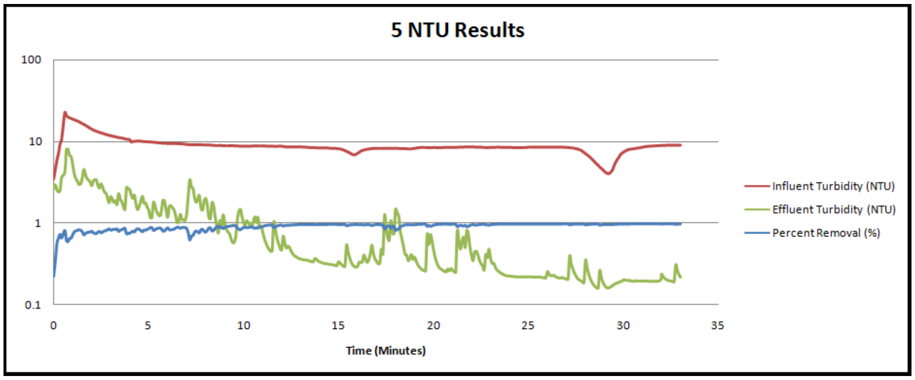

Figure 4: 5 NTU Results

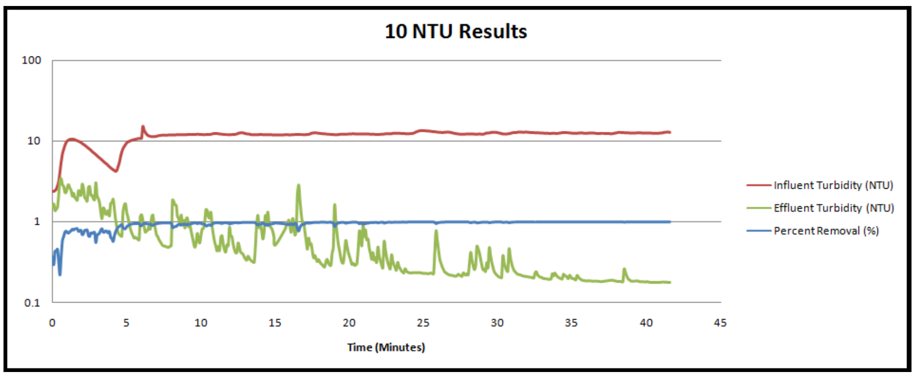

Figure 5: 10 NTU Results

in effluent turbidity at the 17th minute was due to the fact that the coagulant had been used up and needed to be restocked. The drop in concentration of the influent turbidity at the 28th minute was due to the improper mixing of the clay suspension.

The variability of the turbidity of the effluent stream is not known, but is believed to be due to either or both of the following problems: Presence of air bubbles in the turbidity meter and/or errors in the turbidity meter.

Load: 10 NTU, Time: 40 minutes The start-up time for the filter is again seen to be about 5 minutes. The initial variablity of the influent load was due to errors in the turbidity meter, possibly caused by the presence of air bubbles. After 10 minutes, the percentage removal is approximately 94%, which increases to 98.3% at the 30 minute mark. At 40 minutes, the efficiency is 98.5%. Again, more time is needed to find out the ultimate removal efficiency.

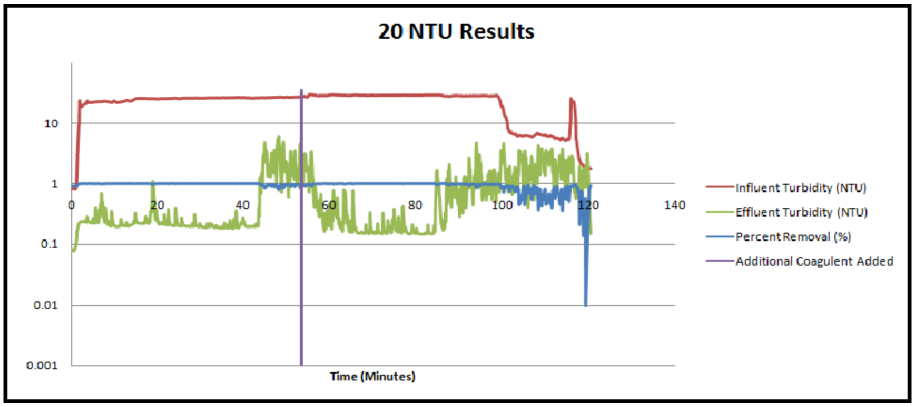

Figure 6: 20 NTU Results

Load: 20 NTU, Time: 120 minutes Running the filter with a higher NTU, illustrated that the unit could operate with improved performance under increased loads. After 10 minutes of operation, the percentage efficiency was 99.15%, which remained constant until the 40th minute. At the 40th minute, a sudden spike in effluent turbidity is seen. This is because the coagulant had been used up and again needed to be restocked. This error was rectified at about the 55th minute mark. This illustrates the importance of the coagulant. The data depicts that without the presence of PACl the effluent turbidity increases; thus the removal efficiency decreases. Subsequent efficiencies reflected the percentage removal as obtained before the error. Again, at the 85th minute, the coagulant stock had emptied and at the 100th minute, the influent clay suspension had emptied as well.

The start-up time for this experiment was relatively quick. The filter was not shut down after collecting the 10 NTU experiment data. It continued to operate for approximately 15 minutes (without the addition of clay particles and coagulant) before increasing the turbidity and again adding the coagulant. It is possible that running the filter (while disposing of the water) for a few minutes before adding the coagulant could achieve the same start-up times without wasting coagulant.

Another test performed during operation of the filter, was the pH test. It was estimated that the pH of the water would decrease due to the addition of the coagulant (PACl) which is acidic, with a pH of 3.5 - 5. However, after running the filter with sink water (pH = 8) for about half an hour it was seen that the pH had increased by a value of 0.1. This could be due to human or calibration errors and is not a good representation of the actual scenario. The filter needs to be run for a longer time to determine the actual variation in pH.

6 Conclusions

Over the course of the semester, a great deal of modeling, testing, and fabrication was completed in order to prepare the LFSRSF prototype for field testing in Honduras. The objectives completed for the semester include extensive MathCAD modeling, hydraulic testing, and performance testing. A MathCAD model was developed to calculate the head losses through the system during backwash and filtration. Initially the model was developed to determine head losses without the presence of sand in the filter column, but after this model was optimized it was modified to include sand. The hydraulic testing of the LFSRSF included head loss measurements during filtration and backwash, sand transport during backwash, and flow measurements. The results from hydraulic testing were used to either confirm or nullify the MathCAD model. Once filtration and backwash were functioning properly in the presence of sand, performance testing was completed to determine the removal efficiency and overall effectiveness of the filter prototype. Results from this testing illustrated a substantial decrease in turbidity of the effluent water; thus validating the prototype as an effective drinking water treatment system.

7 Future Work

7.1 MathCAD Model

The next step in the modeling is to set-up an iterative program, to determine the the flow rate that each parallel flow path receives. These flows will be inputted into the head loss equations for backwash and filtration to calculate more accurate results. This data can be compared to experimental flow data to ensure that the model is correct.

Also, the MathCAD filtration and backwash models can be modified as alternative LFSRSF designs are created. Thus, the hydraulic abilities of the systems can be easily estimated before fabrication begins.

7.2 Data Collection

Some of the LFSRSF testing is more feasible/accurate if conducted in the field. This is because the filter recycles the water in the lab rather than wasting clean sink water. This is not a good measure of real life situations as coagulant in the water may also be recycled (increasing pH levels and flocs). Once the LFSRSF design is introduced in Honduras, additional filters can be built and their hydraulic and performance abilities documented without recycling or wasting water. This will provide viable feedback as to the benefits and disadvantages of the design and stimulate new design ideas.

7.2.1 Hydraulic Testing

As mentioned in Section 3.2, the amount of sand lost during backwash is unknown. Too much sand loss would cause the filter to perform less efficiently. Additional testing could provide information about the amount of sand loss seen at various flows. This would allow operators to know approximately how often they must add sand to the filter column. Ultimately, the best solution would be to keep the sand in the filter column by using bar screens at the backwash outlet or other method. However, additional testing and mathematical modeling must occur to make certain that the additional head losses do not interfere with the performance of the filter.

The estimated maximum backwash flow is 0.8 L/s, which is calculated from the bottom inlet to the height of water in the tub containing the backwash pipe outlet. In a community, the backwash pipe will unlikely be in a bucket as large as the laboratory's (uses the bucket to capture and recycle water). Thus, the available head loss may be larger as the height of water exiting the backwash pipe is lower than the height of water in the tub during testing. This would allow slightly larger flow rates to be reached.

The LFSRSF was designed for a maximum flow of approximately 0.85 L/s. Many communities need to treat flows that are above this flow rate but below the minimum flow rate that a SRSF can accommodate. A method of connecting multiple LFSRSF in parallel or enlarging the filter should be analyzed.

7.2.2 Performance Testing

Some of the questions that may be researched further include:

1. How long can the filter run before backwash is necessary (based on various influent turbidity)?
2. How long after backwash does the filter water need to be thrown out before sufficient efficiencies are obtained?
3. What is the maximum influent turbidity that the filter can sufficiently clean?
4. How do pH levels affect filtration in the LFSRSF?
5. What is the optimal coagulant dosage for the influent turbidity?

Additional performance testing partly relies on on-site operation testing due to limitations in the laboratory. For example, questions 1 and 2 would be difficult to measure in the lab as filtration for SRSFs can often operate for a week without needing to be backwashed. This is unfeasible in the lab. Alternatively, questions 3-5 can be tested in a lab setting.

One of the possibilities for implementing the LFSRSF is to use it as a stand-alone filtration system. This question relies heavily on the third question. If influent water is extremely turbid, the LFSRSF as a stand-alone system may be infeasible. Additionally, as mentioned in Section 3.3, coagulant is necessary in obtaining high filtration efficiencies. In a stand-alone system, when should the coagulant be added to the water (how far before entering the sand bed)? The laboratory testing recirculates the water and thus some of the clay and coagulant particles. The coagulant remaining in the water may create additional flocs that a system in real life may not have the opportunity to create.

7.3 Fabrication

This January, the LFSRSF prototype will be shipped to and assembled in Honduras. This will allow operators to see the design and provide their expertise on the system's ease of operation and construction. This feedback and will be the basis for designing and building a newer model at Cornell University that can be tested in the next semesters.

One known modification of the LFSRSF will include improving ease of switching between filtration and backwash and vice versa. Currently, the design has several ball valves which need to be opened and closed in the proper order depending on whether backwash or filtration is occurring. It is impractical to have a single operator manage this type of system; therefore to guarantee the success of the filter more simplistic operations need to be implemented.

Another future modification will be to shorten the thin PVC pipe that extends out of the top of the filter column. The purpose of the pipe is to check if the sand bed is fluidized during backwash. When the operator is able to move the PVC pipe, the bed is fluidized. Shortening the pipe so that it extends just above the top manifold would allow the operator to check if the filter column has a sufficient amount of sand (the operator cannot see into the column). Since the sand height in the filter column should be a little above the top manifold, the operator should not be able to move the PVC pipe during filtration when the sand bed is not fluidized. Thus, the PVC pipe solve two questions about the unseen sand in the filter bed column.

Additionally, some of the filter parts may be likely to fail due to fatigue. Long term testing (likely on-site) could provide insights into the failure modes and what should be modified.