Sedimentation Tank Hydraulics

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Abstract

A floc blanket is a dense, fluidized bed of particles that forms in the sedimentation tank. It helps to reduce effluent turbidity by trapping small flocs and reduces clean water waste through less frequent draining of the sedimentation tank. Floc resuspension is necessary for floc blanket formation so that flocs are recirculated through the tank instead of settling on the tank bottom as sludge. Research was conducted to examine the effectiveness of the retrofitted Marcala sedimentation tank. At high influent turbidities, a steady floc blanket was obtained, but performance was slightly compromised when the influent turbidity was lowered to simulate Marcala conditions during the dry season. A floc blanket visibly formed with an influent turbidity of 5 NTU after about 1 week but "seeding" the tank with coagulated flocs will minimize floc blanket formation time. Images were also acquired for hindered sedimentation velocities of 0.6 mm/s, 1.2 mm/s, and 1.6 mm/s and analyzed with a floc-water interface program using a region of interest to better understand hydraulic processes within a floc blanket. Complete settling curves from this data confirmed wall effects significantly affect settling velocity. A floc hopper proved to be effective at controlling the height of the floc blanket when the accumulated flocs were drained at an adequately high flow rate. A lower alum dose of about 39 mg/L for an influent turbidity of 100NTU resulted in a less sticky sludge that could be more easily drained from the hopper.

1 Introduction

A floc blanket is a dense fluidized bed of flocs that forms above the inlet jet and below the plate settlers in the sedimentation tank. Introducing a floc blanket to an AguaClara sedimentation tank has been shown to help reduce effluent turbidity in the sedimentation tank by trapping smaller flocs that would otherwise escape through the plate settlers [**?**, **?**]. A floc blanket will also waste less clean water as a result of less frequent draining of the sedimentation tank because an ideal floc blanket eliminates sludge build up in the tank. In typical vertical flow sedimentation tanks without a floc blanket, it is necessary to drain the sedimentation tank to remove settled solids. Draining is accomplished through the sludge drain, located at the bottom of the sedimentation tank (Figure1). It easier and less time consuming for the plant operator to concentrate waste in a floc hopper and continually waste than to drain and clean the sedimentation tank.

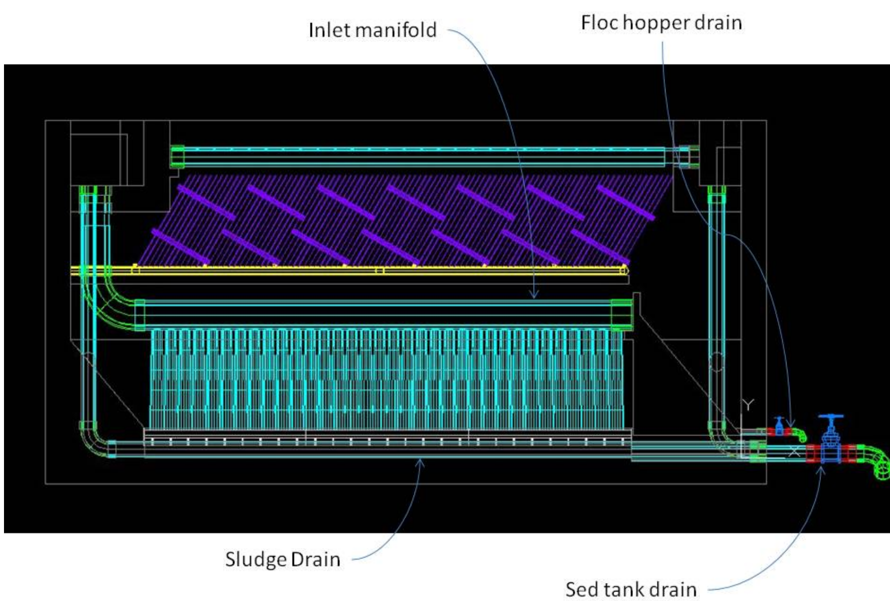

Figure 1: Side view of a typical sedimentation tank

Floc resuspension without floc breakup or sludge buildup is crucial to floc blanket formation in the sedimentation tank because with floc breakup, there will be more smaller flocs to potentially escape lamellar sedimentation. Floc breakup typically occurs with high energy dissipation rates, and sludge build-up occurs in dead-zones in the tank or areas of high hydrostatic pressure. We hypothesize that floc resuspension is directly related to the dynamic pressure of the jet and the hydrostatic pressure of solids built up on the incline. The dynamic pressure of the jet is given by:

$$P = \rho \int \frac{V^2}{R} dn \tag{1}$$

Where: ρ is the density of the fluid, V is the fluid velocity, and R is the local radius of curvature. Equation 1 applied across streamlines determines the dynamic pressure of the jet and shows that holding all else constant, a decrease in the radius of curvature will result in an increase in dynamic pressure. Thus, a narrower rounded trench bottom should result in a greater dynamic pressure and therefore minimal sludge buildup and floc blanket formation. An increase in jet velocity will also increase the dynamic pressure of the jet, and will have a greater impact on the dynamic pressure than a decrease in the radius of curvature.

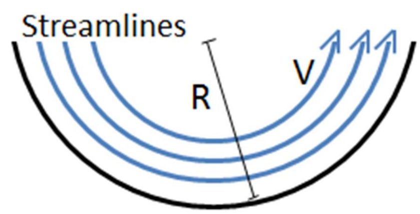

Figure 2: Application of the dynamic pressure equation across streamlines

Without adequate hydrodynamic pressure, insufficient jet velocity will cause flocs from the incline to fall into the path of the jet or become entrained by it. We hypothesize that returning debris with higher hydrostatic pressure will enter the trench, or jet reverser, and divert the path of the jet. Debris built up in the trench will cause the cross-sectional area of the jet stream to decrease and the average velocity of the jet to increase. In addition, there will be a solid surface of sludge where scouring can occur. These two effects will greatly reduce floc resuspension and increase floc break-up, producing more small particles, which cannot be effectively trapped in the floc blanket and could escape lamellar sedimentation. The dynamic pressure is dependent on the jet velocity, which is affected by the bottom geometry of the tank. The purpose of last semester's research has been to find bottom geometries that maximize the dynamic pressure of jet while minimizing energy dissipation rate and floc breakup. Further information regarding minimizing energy dissipation rate can be found in STHT Fall '11 Final Report [Fall '11 Final Report]. Research done by previous sedimentation tank hydraulics teams focused on using data acquisition software and image analysis software to generate, support, and refute hypotheses based on qualitative analysis of data.

2 General Apparatus and Set Up

We used the same experimental apparatus and procedure as with the experiment documented in the Sedimentation Tank Team's Research Report 1 [STHT Summer '11 Final Research Report]. A thin $1.27\,cm$ wide tank was used to model a thin slice of the full scale sedimentation tank. Figure 1 in The Sedimentation Team Final Research Report Summer 11 shows AutoCAD renderings of the side view and front view setups for the one half inch wide sedimentation tank and light panel system. We used a MathCAD file to calculate the appropriate plant flow rate and alum dose according to our desired upflow velocity. Typical parameters for our experiments include a flow of $456\,mL/min$ of aerated raw water containing $45\,mg/L$ of alum. An average influent turbidity of $100\,NTU$ made from a concentrated kaolinite clay stock regulated by Process Controller was run through a tube flocculator before being expelled through a vertical downward-pointing jet suspended about $2\,cm$ above the jet reverser. $100\,NTU$ was chosen for the influent turbidity because it was a well characterized turbidity from previous studies [**?**, **?**]. Upflow velocity above the floc-water interface was $1.2\,mm/s$, which reflects the upflow velocity in an actual plant, constraining the initial jet velocity to $0.011\,m/s$, as it is dependent on flow rate and cross-sectional area of the inlet tube:

$$V_{up} = \frac{Q}{A} \tag{2}$$

where $V_{up}$is the average upflow velocity, Q is the jet flow rate, and A is the cross sectional area of the clarifier [**?**, **?**].

Images of the tank were acquired with a camera and recorded using the LabVIEW data acquisition software in order to evaluate the minute incremental change in floc blanket height with time. The images were compiled using MasterProgram image analysis software to make a video of the experiment (Figure3).

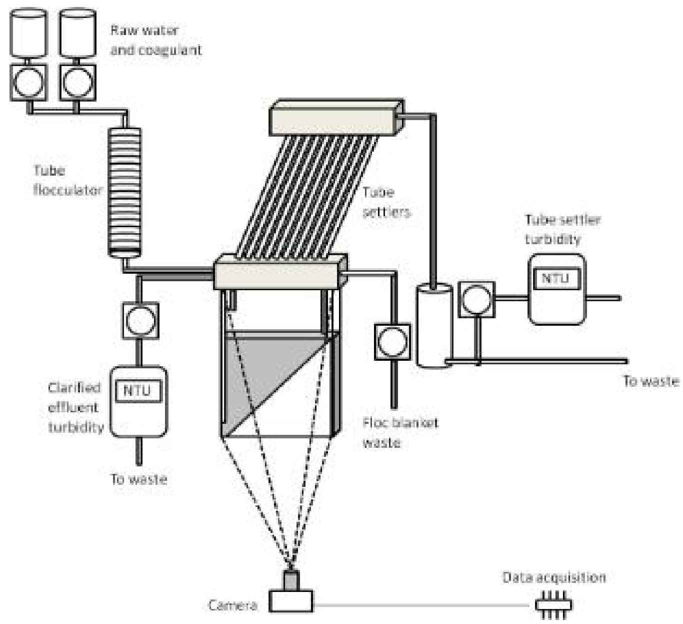

Figure 3: Schematic of turbid water flow through flocculator and sedimentation tank.

Experiments were performed using foam inserts of various geometries made from $1.27\,cm$ wide foam board inserts laminated with tape. Magnets were used to secure the position of the inserts. By making a video from photos of the apparatus taken a high frequency of 1 shot per 0.1 s, we can make qualitative observations about floc blanket formation and growth. This semester, we intend to utilize image analysis to quantify our observations, such as floc blanket height and concentration, with regards to performance and hydraulic conditions in the reactor.

3 Experiments and Results

3.1 Marcala Simulation

Background

The Marcala plant was completed in July 2008 with no inlet manifold diffusers and a flat bottom geometry. The plant was retrofitted in January 2012 so that the diffusers on the manifold would be flattened so that a line source of fluid is created to be divided between the two sides of the sedimentation tank. One inch couplings were attached about every foot and a one inch pipe was cut in half lengthwise and glued within the coupling to simulate a semicircular bottom geometry, which the Fall 2011 team concluded was the optimal bottom geometry to meet several design objectives, including minimal energy dissipation, ease of construction, and tolerance of asymmetry (Figure 4). [Fall '11 Final Report]

Figure 4: Marcala Retrofit Design

Experiment

The bottom geometry for the Marcala Simulation experiment was created by attaching a 1/2 inch ($1.27\,cm$) thick, $2.54\,cm$ diameter semi-circle, which would act as a jet reverser, to the flat bottom of a $10\,cm$ by $10\,cm$ slab of PVC using epoxy glue. The jet reverser rests on top of the PVC slab, while in Marcala the reverser is suspended a few millimeters above the bottom of the tank to allow sludge to reach the sludge drain, but we suspect that this difference will have little to no impact on sedimentation tank performance (Figure5). The experiment was initially run with an influent turbidity of $100\,NTU$ to allow for faster floc blanket formation, and was turned down to $10\,NTU$ 211 minutes into the experiment, after the floc blanket grew to the height of the floc weir, to better represent conditions in Marcala. While the turbidity was decreased, alum dosing was unchanged, but is a operational possibility in the field. Influent NTU was changed by halting the input of clay stock into the CSTR raw water source and therefore the change in influent turbidity was gradual (Figure7). Images were taken at 5 s/shot initially and at 20 s/shot after floc blanket formation. Clarified effluent was sampled from an area near the submerged ends of the tube settlers and the clarified effluent turbidity and tube settler turbidity were recorded on Process Controller. A floc draining tube was used, but did not successfully control floc blanket growth, so flocs may have been lost through the top of the reactor.

Results

Initially flocs entering the tank rolled down the inclines and built up as sludge around the jet reverser. Once the sludge level at the center reached the height of the jet reverser, the jet began to resuspend flocs at the edge of the jet reverser, resulting in floc blanket formation (Figure6). This occurred because hydrodynamic pressure of the jet overcame the hydrostatic pressure of the returning solids. The floc blanket grew at a steady rate, but floc blanket thinning was observed as the influent turbidity was decreased because the coagulant dose to clay ratio produces less dense flocs.

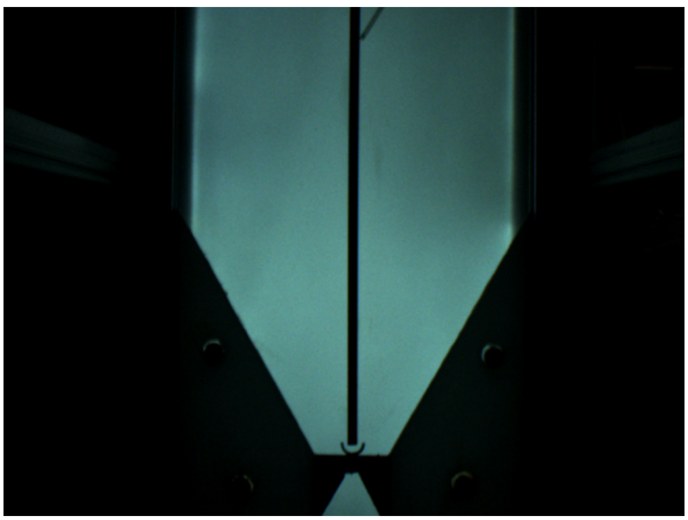

Figure 5: Bottom geometry design for Marcala simulation

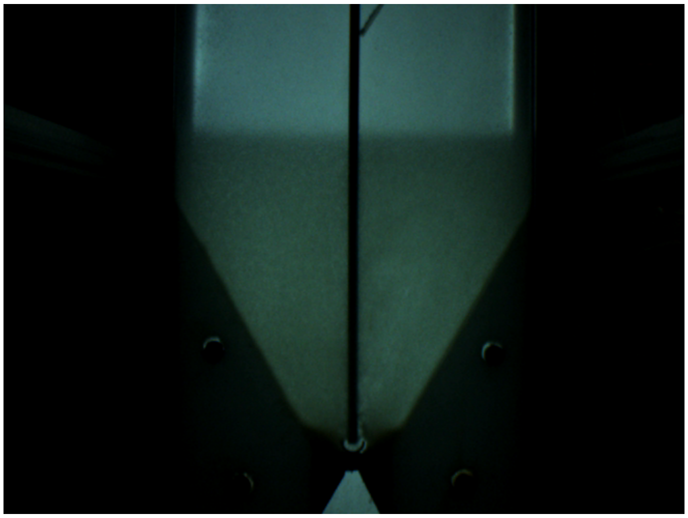

Figure 6: Marcala floc blanket at an influent turbidity of 100 NTU

Tube settler turbidity remains below $2\,NTU$ for the majority of the experiment, which is comparable to previous experiments run with a semi-circular jet reverser at an influent turbidity of $100\,NTU$ (Figure8). The spikes in turbidity may be caused by air bubbles in the tank, because they cause high turbulence and bring flocs from the blanket to the top of the reactor. Bubbles in the tank may also be responsible for the spikes in clarified effluent turbidity stated in the previous section.

The decrease in influent turbidity from $100\,NTU$ to $10\,NTU$ at 211 minutes corresponds to an increase in clarified turbidity. A decrease in floc blanket concentration was observed around 300 minutes, which may be due to the decrease in influent turbidity. The pC* of the influent to clarified effluent, which represents the particle removal efficiency of the floc blanket, becomes negative at the end of the experiment, meaning that the clarified effluent has a higher turbidity than the influent (Figure9). This is due to both the increase in clarified effluent turbidity, probably a result of floc blanket thinning, and the decrease in influent turbidity from 100 to $10\,NTU$. At the lower turbidity, particles entering the tank may have been smaller due to less particle collisions in the flocculator, resulting in a decrease in the floc blanket's ability to capture these particles. Another possible explanation for the increase in clarified effluent turbidity is that the alum to clay ratio was increased, which could have created fluffier flocs that did not settle as easily.

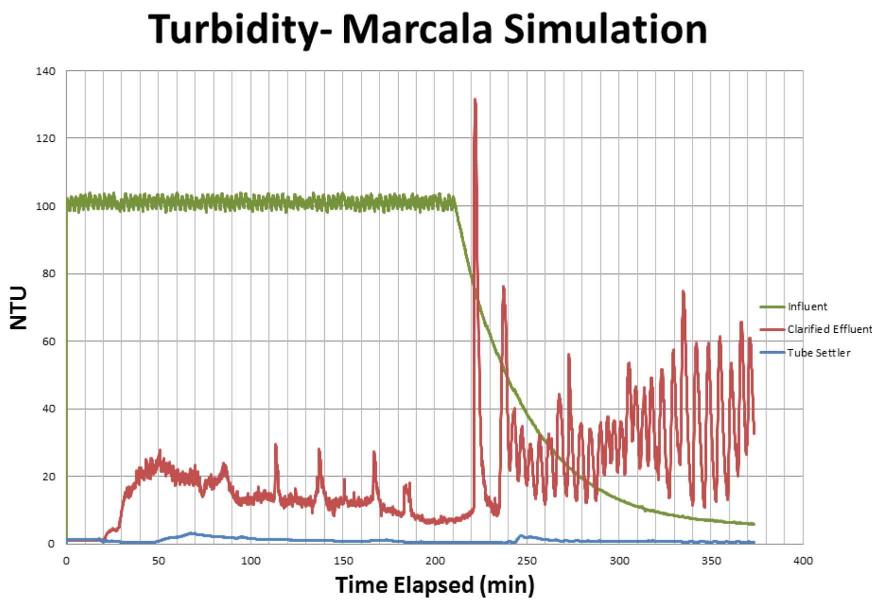

Figure 7: Influent, clarified effluent, and tube settler turbidity

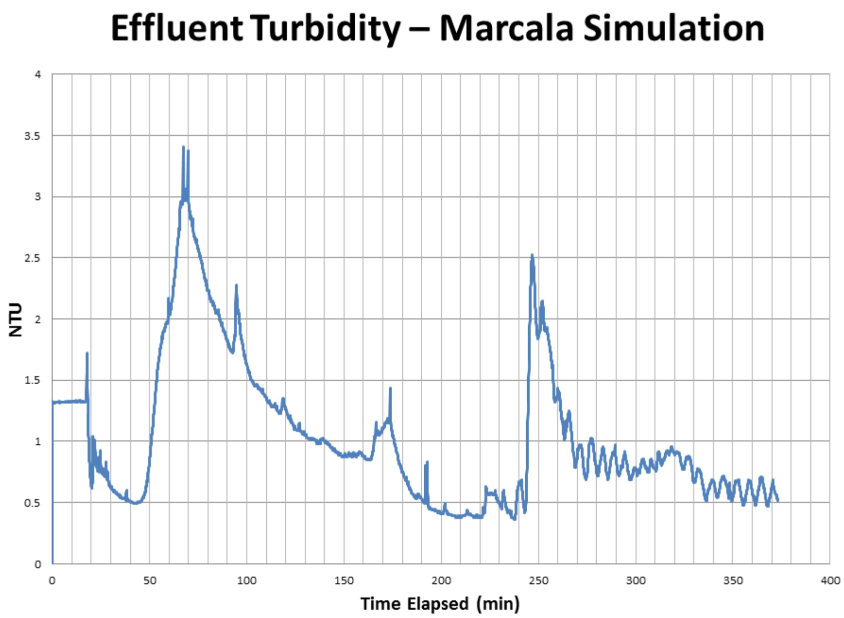

Figure 8: Tube settler turbidity.

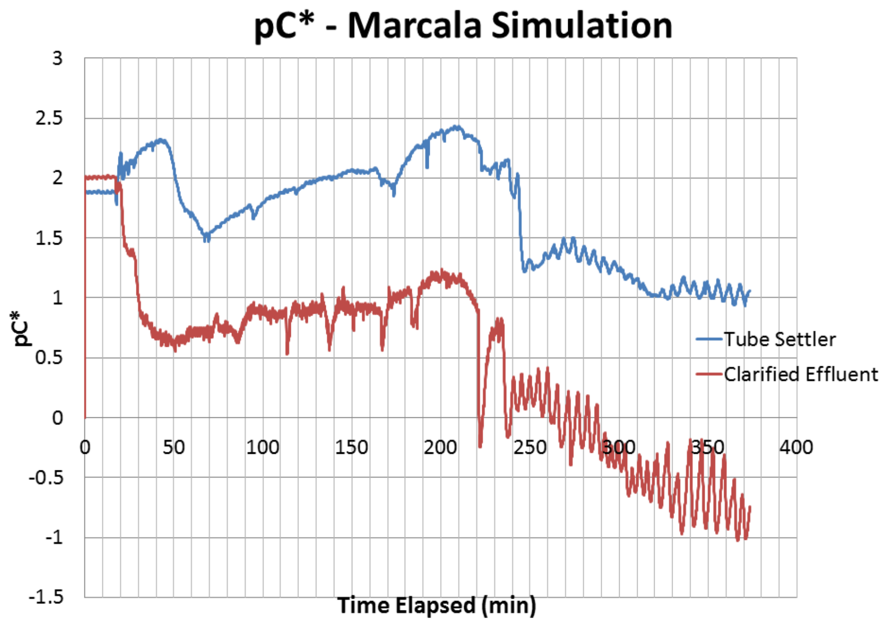

Figure 9: Marcala pC*

Marcala Sedimentation Tank Performance

Marcala plant operators currently clean sedimentation tanks by completely draining them about twice a day, but would like to reduce the cleaning frequency to weekly or biweekly. They also hope to establish a more regulated schedule for cleaning all the sedimentation tanks. On 3/1/2012, Fred Stottlemyer directed the Marcala plant operators to continue to clean sedimentation tanks 1, 2, and 3 but to not clean sedimentation tank 4 for one week. A form was left with the operators to record the turbidity results of all four tanks and the total turbidity from the four tanks a number of times throughout the day. The results of the first three days of this tests show that effluent plate settler turbidity in sedimentation tanks 1, 2, and 3 were consistently below 1 NTU while effluent plate settler turbidity in sedimentation tank 4 was comparable to that of sedimentation tanks 1, 2, and 3 for approximately 30 hours without cleaning but after 30 hours, the turbidity shot up and hit a high of 7.59 NTU, which is about the same as the influent turbidity (Table1).

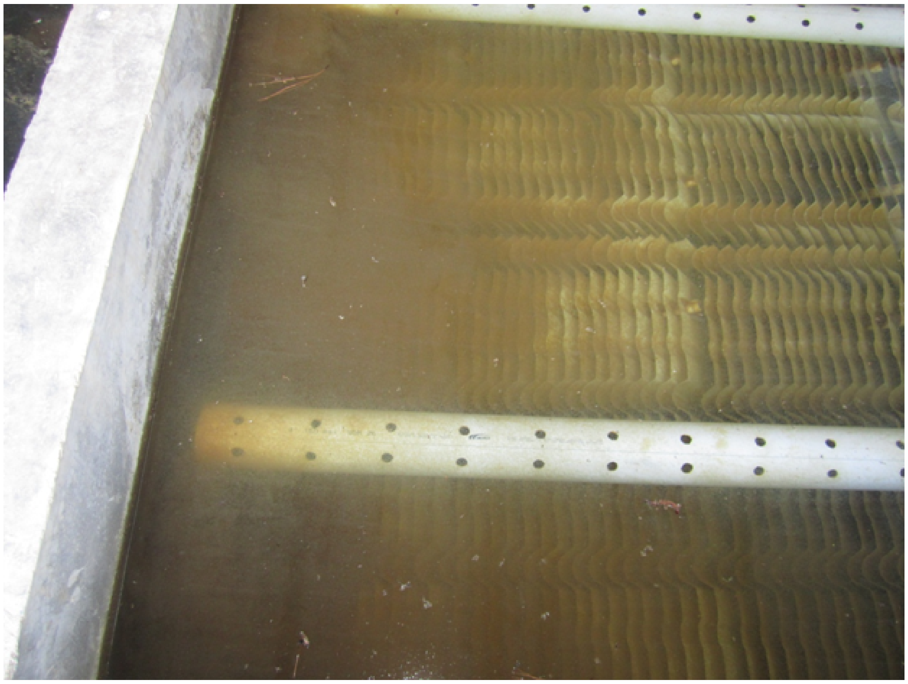

Figure 10: Visible flocs above Marcala's Tank 4's plate settlers

Table 1: Marcala Plate Settler Effluent Turbidity Results

Date	Time (hrs)	Tank #1 NTU	Tank #2 NTU	Tank #3 NTU	Tank #4 NTU	Plant Average NTU
3/1/12	0	0.00	0.00	0.00	0.00	0.00
3/1/12	6	0.09	0.06	0.29	0.20	0.14
3/1/12	10	0.18	0.34	0.45	0.32	0.28
3/2/12	20	0.21	0.24	0.34	0.16	0.14
3/2/12	26	0.39	1.52	0.10	0.35	0.21
3/2/12	30	0.35	0.40	0.10	1.70	0.27
3/2/12	34	0.10	0.12	0.10	1.45	1.90
3/3/12	44	0.09	0.05	0.20	0.95	0.24
3/4/12	74	0.34	0.48	0.3	7.35	2.85

From the above results and photo below, we believe there is a high possibility that a floc blanket formed. However, because there was no floc weir, the height of the floc height grew past the bottom of the plate settlers, blowing through it and causing a sharp increase in plate settler effluent turbidity (Figure10). We hope to better understand this failure mode by replicating it in our apparatus.

3.2 Hindered Settling Velocity

Background

There are two interpretations for the hindered sedimentation velocity of particles in a floc blanket: (1) the hindered sedimentation velocity of the aggregate blanket is equivalent to the fluid upflow velocity immediately above the floc-water interface and (2) the hindered sedimentation velocity for a particle in the floc blanket is equivalent to the upflow fluid velocity the particle experiences in the blanket.

In the first interpretation, the floc blanket is viewed as an aggregate whole. The change in height of the floc blanket over time, $\frac{dH}{dt}$, is a function of the hindered velocity of flocs V_H and the fluid upflow velocity immediately above the floc-water interface, $V_{Up-Interface}$ (Equation 3). This interpretation assumes that a negligible amount of flocs is wasted and that the floc blanket growth rate is very slow.

$$\frac{dH}{dt} = V_{Up-Interface} - V_H \tag{3}$$

$$V_{Up-Interface} = \frac{Q}{A_{Planar}} \tag{4}$$

Where Q is the plant flow rate and A_{Planar} is the plan area of the location of the floc-water interface.

For a relatively stationary floc blanket at steady-state, $\frac{dH}{dt} = 0$, the upflow velocity should balance the hindered settling velocity of the floc blanket (Equation 5). Therefore, a free-settling floc blanket is expected to settle at a velocity equal to the upflow velocity of the fluid.

$$V_{Up-Interface} = V_H \tag{5}$$

In the second interpretation, we consider the individual floc particles in the floc blanket. For flocs to remain relatively stationary in a floc blanket, the average hindered sedimentation velocity of a floc particle should counteract the average fluid velocity that the particle encounters in a floc blanket. The average fluid velocity in the floc blanket is equivalent to the plant flow rate divided by the product of the planar area of the location of the floc-water interface and the porosity of the floc blanket, ϕ (Equation6). It is assumed that nearly all flow passes around floc particles and a negligible portion of the flow actually passes through the particles. If this interpretation accurately reflects the physical processes in the floc blanket, then a free-settling floc blanket is expected to settle at a velocity greater than the upflow velocity of the fluid.

$$V_H = \frac{Q}{A_{Planar}\phi} \tag{6}$$

Experiment

A floc blanket was built under the conditions of $45\,mg/L$ of alum per $100\,NTU$ for three different upflow velocities: $0.6\,mm/s$, $1.2\,mm/s$, and $1.6\,mm/s$. The floc weir was set to a height of about $60\,cm$ above the bottom of the jet reverser and the floc blanket was wasted at a rate of $50\,mL/min$. The tube settlers were set at a capture velocity of about $0.1\,mm/s$.

Once the floc blanket is formed, the influent pump was shut off and the floc blanket was allowed to settle for about $20\,s$ and then the pump was turned on again. The camera recorded images of the settling process at a rate of $0.05\,s$ per shot. After waiting for about $10\,min$ or until the floc blanket grew to its original height, this procedure was repeated two more times to obtain a total of three sets of images, which we refer to as our "quick settling images". Finally, the influent pump was turned off and the floc blanket was allowed to settle completely. Images of the settling process was taken at a rate of $1\,s$ per shot for the first $8\,min$, followed by $30\,s$ per shot for the next $24\,hr$. We refer to these images as our "complete settling images".

We initially analyzed both the quick and complete settling images using the Floc-Water Interface (FWI) LabVIEW program, which determines the height of the FWI in each image. The program first determines the concentration of flocs at each point in the region of interest (ROI) by comparing the light intensity of the image to the light intensity of the background image, and then it determines the height where the second derivative of the concentration is equal to zero, or where there is the greatest change in concentration with respect to height occurs. This point represents the floc-water interface. However, the LabVIEW program was unable to accurately analyze the quick settling images because the change in height of the floc water interface was very small. Instead, we estimated the hindered settling velocity using the complete settling images to plot settling curves for each upflow velocity. We manually recorded the change in height of the floc-water interface over a period of several minutes using the y-coordinates of the floc-water interface on the images acquired. For each image, the y-coordinate of the FWI was obtained by running the ROI program on the image, placing the cursor over the FWI and reading off the corresponding y-coordinate. The change in height for each image was calculated in pixels by taking the difference between the y-coordinate of the FWI in the image and the y-coordinate of the FWI in the image at time zero. The number of pixels per millimeter was determined to be $0.7\,pixels/mm$ by dividing the number of pixels of a segment of the tank in the image by the known distance of the tank segment. The change in FWI height in millimeters was calculated by dividing the change in height in pixels by the number of pixels per millimeter. Settling curves were plotted for each set of images and a settling velocities were calculated from the slope of the settling curves.

Results

For the complete settling trials, images were taken at $1\,s/shot$. The change in floc blanket height was calculated every five images, corresponding to a time interval of $5\,s$. The change in floc blanket height was plotted over time and best-fit lines were determined for each settling curve (11). These curves are linear, indicating that the the hindered settling velocity does not slow significantly during the first few minutes of settling. The slope of the best-fit line represents the hindered settling velocity corresponding to each upflow velocity. The hindered sedimentation velocities for the $0.6\,mm/s$, $1.2\,mm/s$, and $1.6\,mm/s$ upflow velocities are $0.52\,mm/s$, $1.02\,mm/s$, and $1.10\,mm/s$, respectively.

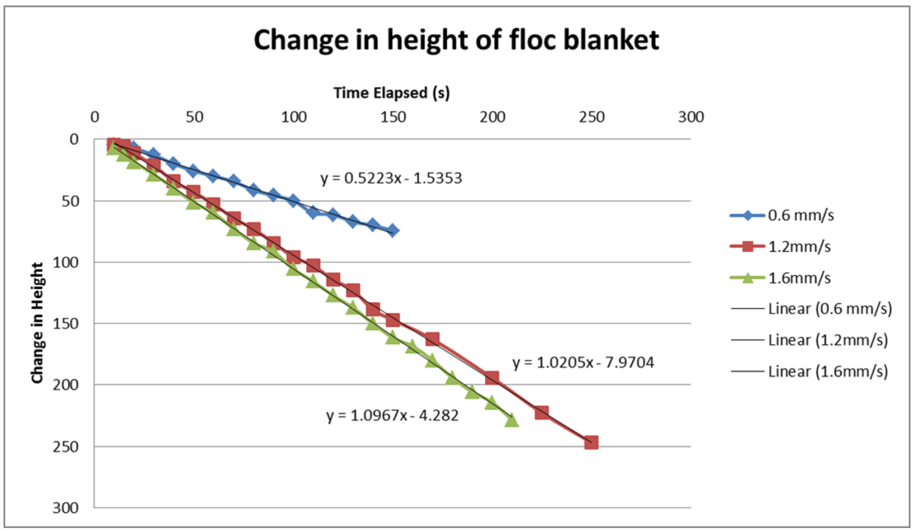

Figure 11: Complete settling curves for upflow velocities of 0.6, 1.2, and 1.6 mm/s

We can determine the expected hindered settling velocity for the two theories without the influence of wall effects by Equation 5 and 6if the porosity of the floc blanket is known. The porosity of the floc blanket is a measure of the empty space in the blanket and is defined as:

$$\phi = \frac{V_{void}}{V_{floc\,blanket}} = \frac{V_{floc\,blanket} - V_{solids}}{V_{floc\,blanket}} \tag{7}$$

where V_{void} is the volume of void space, or fluid, in the floc blanket, $V_{floc\,blanket}$is the volume of the floc blanket before settling begins, and $V_{solids}$is the volume of solids in the floc blanket. V_{solids}can be approximated as the volume of sludge after the floc blanket has settled completely. The measured and calculated hindered settling velocities for each upflow velocity is shown in Table 2.

Table 2: Measured and theoretical hindered settling velocities

Upflow Velocity	$V_{H,\,Theory\,1}$	$V_{H,\,Theory\,2}$	$V_{H,\,Measured}$
$0.6\,mm/s$	$0.600\,mm/s$	$0.626\,mm/s$	$0.522\,mm/s$
$1.2\,mm/s$	$1.200\,mm/s$	$1.33\,mm/s$	$1.02\,mm/s$
$1.6\,mm/s$	$1.600\,mm/s$	$1.68\,mm/s$	$1.10\,mm/s$

The data shows that the measured settling velocities are consistently lower than the theoretical settling velocities. This suggests that wall effects have a significant effect on the hindered settling velocity in our tank, which were not taken into account in either of the hindered settling theories. Wall effects slow down the effective hindered settling velocity due to friction and boundary layer effects at the wall and play a significant role in our reactor due to the high perimeter plan-view area ratio. Wall effects are most significant for the $1.6\,mm/s$ upflow velocity trial, as the measured hindered settling velocity differed from the hindered settling velocity in both theories by the greatest amount. Due to the high porosity of the floc blanket, the difference in hindered settling velocities between the two theories is only about 5%. However, the difference between the theoretical hindered settling velocity and measured hindered settling velocity ranges from 13% to 30% for Theory 1 and from 17% to 34% for Theory 2. The differences between actual and theoretical hindered settling velocities are due primarily to wall effects in the tank. In order to accurately determine the validity of each theory, we will need a method to account for these wall effects. Since we do not know the extent to which wall effects play a role, we cannot say for certain which theory is more plausible.

However, according to Richardson et al., it has been shown that the falling velocity of a suspension relative to a fixed horizontal plane is equal to the upward velocity of liquid (based on the empty tube) required to maintain a suspension at the same concentration [**?**, **?**]. This implies that Theory 1 is correct.

3.3 5 NTU Experiment

Run 1

We ran an experiment at 5 NTU, a turbidity similar to that of Marcala's influent water, to see if and how long it would take to form a floc blanket. Using a MathCAD file, we used an upflow velocity of $1.6\,mm/s$ adjusted pump flow rate to $610\,mL/min$ and alum dose to $3\,mg/L$. During the 2 hours, flocs were not visible in either the tube flocculator or the influent jet stream. After 2 days, there were still no visible flocs in the tube flocculator or the tank so we discontinued the experiment. Process controller data showed that no clay was added to the mixing tank after the experiment began. This suggests that the turbidimeter was dirty and was consistently reading a turbidity higher than $5\,NTU$, although the actual turbidity was much less than this value, so no clay was added to the tank to increase the turbidity.

Run 2

To obtain more accurate observations of floc blanket formation and behavior at an influent turbidity of $5\,NTU$, we cleaned out the turbidimeter reading from the raw water tank to ensure a correct reading of $5\,NTU$. The alum dose was increased to $10\,mg/L$ to more accurately represent conditions in Marcala, where the alum dose is decided by the plant operators based on their observations of the flocs. The upflow velocity was $1.3\,mm/s$ and the tube settler pump was set to $127\,rpm$. The experiment was left to run over several days as measurements were taken.

For the first few days, few flocs were observed in the tank and the concentration of the flocs in the tank remained relatively constant, although the influent turbidity remained at $5\,NTU$ and the effluent turbidity was significantly lower 12. About 25 hours into the experiment, the sampling rate from the clarified effluent tube was increased to $55\,mL/min$ from $15\,mL/min$. This would result in more flocs being removed from the tank through the clarified effluent tube and less water escaping through the overflow weir at the top of the tank. The effluent turbidity through the tube settlers increased as the sampling through the clarifier increased, which may be due to less flocs escaping over the overflow weir12. After about 52 hours, the influent turbidity had decreased to $2\,NTU$ because the clay tube got clogged and thus concentrated clay stock was not being added to the raw water mixing tank. The clay tube was unclogged and the turbidimeter for the raw water tank was cleaned, allowing the turbidity to increase back to $5\,NTU$, resulting in a short spike in influent turbidity 13. During this spike, the effluent turbidity doubled for a short period and returned to about $2\,NTU$ after about an hour. After about 75 hours, the influent turbidity remained at about $2\,NTU$. The tube connecting the clay stock to the raw water tank was unclogged, resulting in the turbidity spiking and returning to a steady value of $5\,NTU$. After about 120 hours, no floc blanket had yet been observed. The effluent turbidity remained around $1\,NTU$ while the influent turbidity remained around $5\,NTU$, a pC* of about 0.7 14.

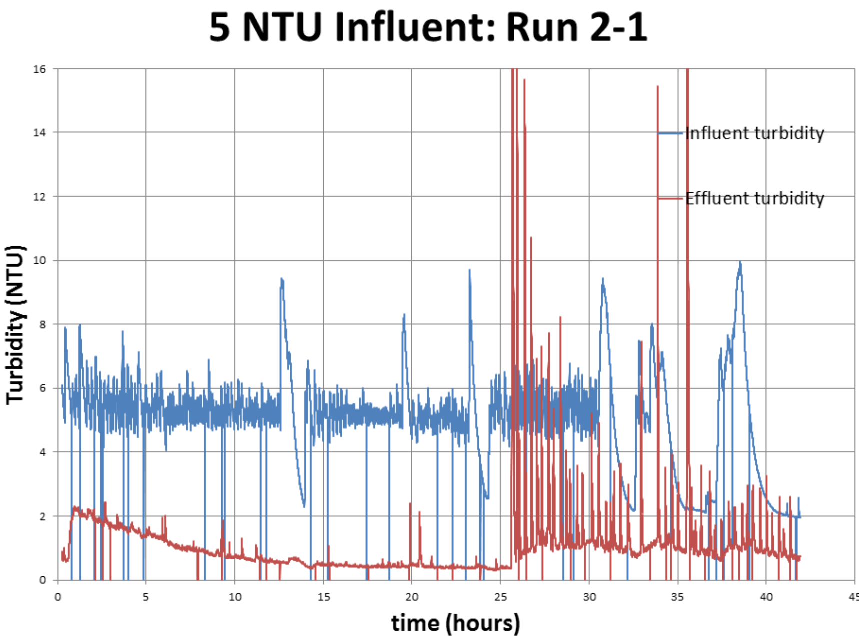

Figure 12: 5 NTU Run 2-1

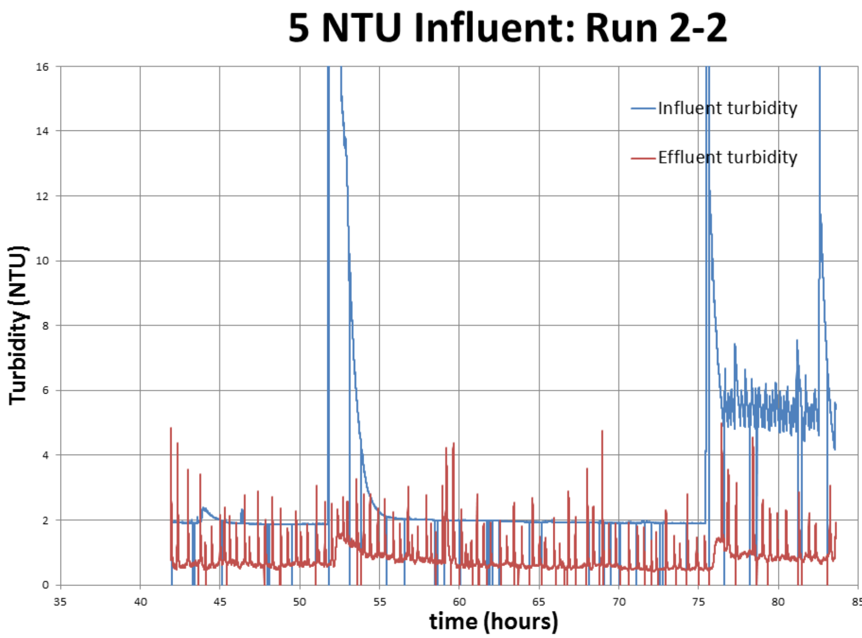

Figure 13: 5 NTU Run 2-2

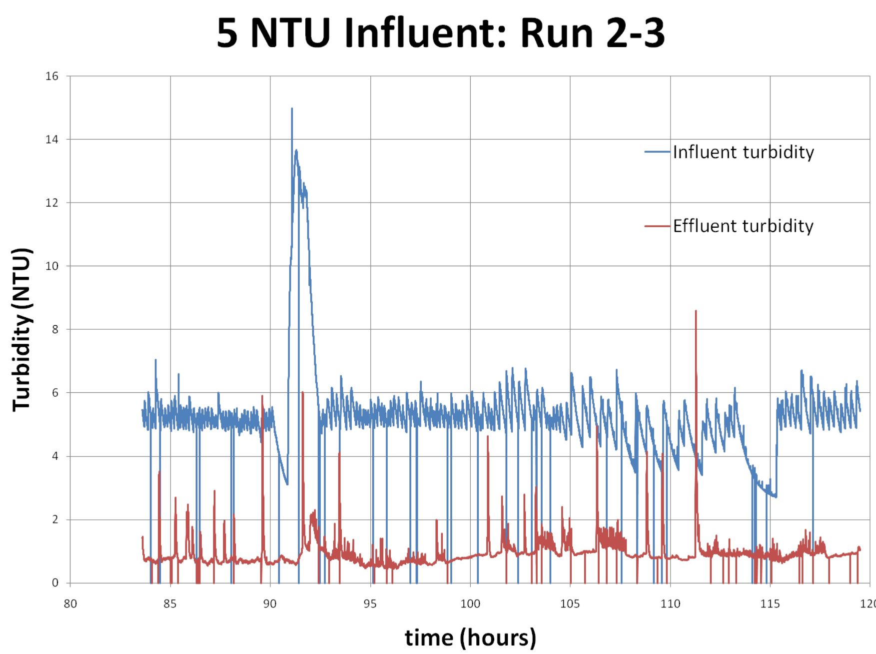

Figure 14: 5 NTU Run 2-3

Run 3

After 120 hours of Run 2, a floc blanket still had not formed. A possible reason was that the alum dose was too high, resulting in larger, fluffier flocs that did not settle easily. The alum dosing was therefore decreased to $5\,mg/L$ to observe the effects on floc blanket formation. The flow through the tube settlers was decreased slightly to $120\,rpm$. No significant changes within the tank were observed and the influent and effluent turbidities remained around $5\,NTU$ and $1\,NTU$, respectively.

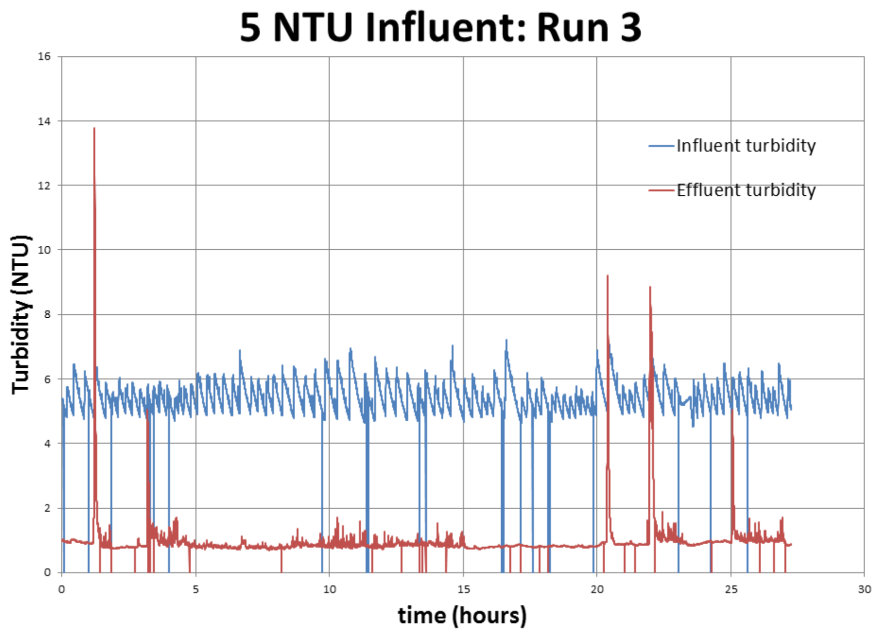

Figure 15: 5 NTU Run 3

Run 4

Because the turbidity of the water leaving the tube settlers was significantly less than the turbidity of the water entering the tank and no flocs were accumulating in the tank, the flocs must have been leaving the tank by some other means–either through the clarified effluent tube or through the overflow weir at the top of the reactor. The upflow velocity in the tank was decreased to $1\,mm/s$ and the clarified effluent sampling tube was removed to reduce the amount of flocs escaping from the tank. The tube settler flow rate was adjusted so that all of the flow from the plant would pass through the tube settlers. This flow rate was found by trial and error and corresponds to a tube settler pump speed of $110\,rpm$ for an upflow velocity of $1\,mm/s$.

When the adjustments were made, huge clumps of flocs started falling down from the tube settlers. These clumps are probably accumulated sludge at the base of the tube settlers from the previous several days of experiment. After the clumps of flocs fell down, a floc blanket quickly formed within 15 minutes. After an hour, the floc blanket had reached the top of the tank. The quick formation of a floc blanket at low influent turbidity by the rapid addition of coagulated particles into the tank suggests a method of 'seeding' the tank with coagulated particles to form a floc blanket.

After about 3 hours, the raw water tank ran out of water and the tube settlers drained empty, resulting in the spike in tube settler turbidity measurements seen in 16. After about 20 hours, the tube settler turbidimeter was cleaned out to produce more accurate measurements, but errors in tube settler turbidity followed. After about 30 hours, the tank remained filled with flocs while the tube settlers contained very little flocs, suggesting that the overflow weir was acting as a floc weir. The effluent turbidity remained around $0.25\,NTU$ while the influent turbidity remained around $2\,NTU$, a pC* of about 1.

Given the correct conditions, a floc blanket can be formed at $5\,NTU$. This is beneficial, as illustrated by low turbidity at the end of run 4. However, due to the length of time taken to form a blanket during the first 3 runs, seeding the tank with coagulated particles may be a more efficient method of forming a floc blanket at low turbidities.

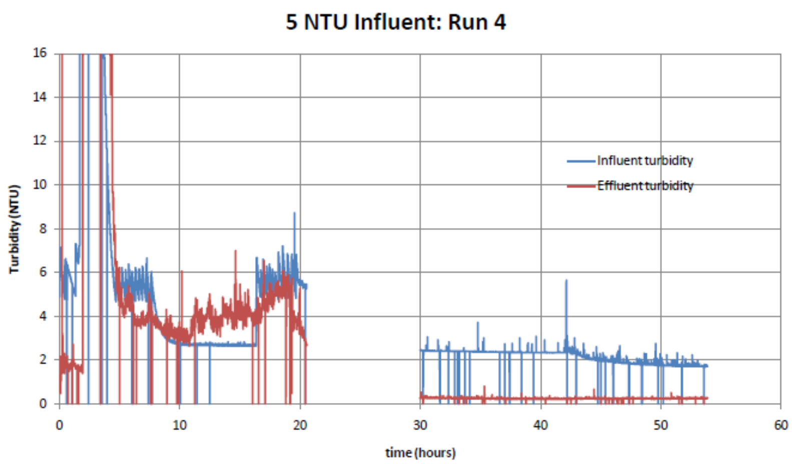

Figure 16: 5 NTU Run 4

3.4 Tube Settler Failure Mode Experiment

In this experiment, we created a floc blanket under the usual conditions of $100\,NTU$ influent turbidity and $45\,mg/L$alum dose with an upflow velocity of $1.2\,mm/s$. We will define tube settler failure mode to have a pC* of less than 1.53, or 97% removal. The floc blanket grew as expected in the absence of a floc weir and floc hopper. After the floc-water interface reached the bottom of the tube settlers, the floc blanket continued to grow at a slower rate within the tube settlers because of the tube settler's capture velocity due to its angle. Pumps were only connected to nine of the ten tube settlers (the placement of the influent jet prevented the fourth tube settler from the right to be placed low enough so that the bottom was below the tank's water height) and the height of concentrated flocs grew at very different rates within each tube settler. Even within each tube settler, the rate varied a lot, creating a pulsating increase (Figure17). After $2.5\,hours$, the raw water tank was found empty due to errors with process controller. Bubbles being drawn into the sedimentation tank were pulling flocs through the tube, causing the spike in turbidity of the clarified and tube settler effluent (Figure18) (Figure19). The tube settlers that were nearer to the middle and right side were cloudy with flocs. After the raw water tank was refilled, the tube settlers visibly returned to their initial state of turbidity, suggesting that the presence of bubbles caused them to be cloudy rather than floc blanket growth. The floc blanket continued growing till it reached the top of the tube settlers.

Figure 17: Tube settlers in failure mode

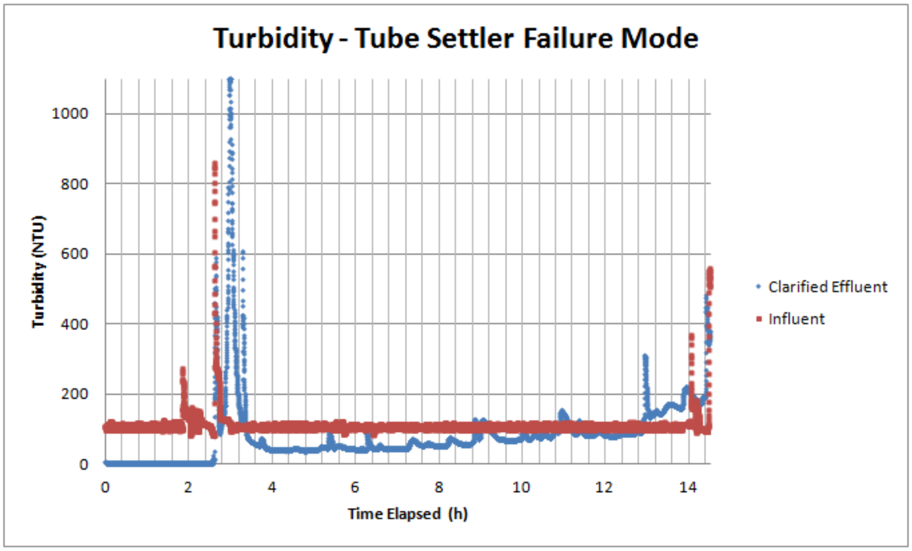

Figure 18: Tube Settler Failure Mode - Influent and clarified effluent turbidity

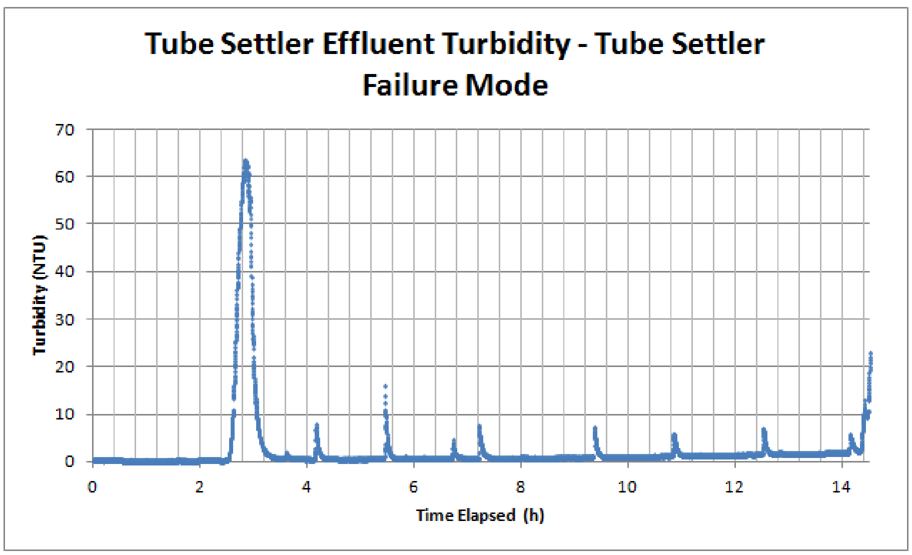

Figure 19: Tube Settler Failure Mode - tube settler turbidity

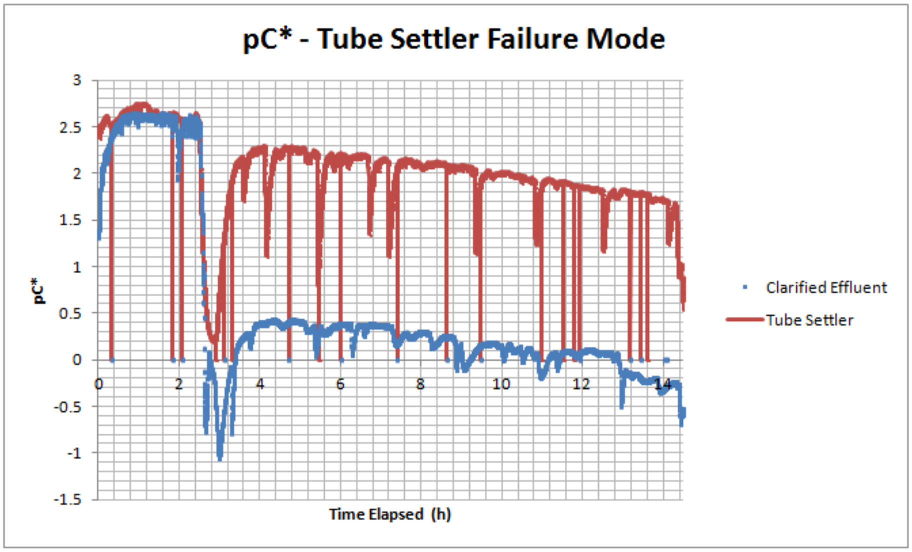

Figure 20: Tube Settler Failure Mode pC*

The pC* of the tube settlers were initially around 2.5, indicating very high removal. After about $2.5\,hours$, pC* of both the clarified effluent and tube settlers decreased dramatically to zero due to the aforementioned spike in influent turbidity. After the influent turbidity was readjusted back to $100\,NTU$, the effluent turbidities returned its normal pattern of decreasing. As time progressed, pC* of the tube settlers slightly decreased but remained above 1.7, indicating about 98% removal. The effluent tube settler turbidity increases a short period after the influent turbidity increases as expected. The negative pC* values for clarified effluent indicate that the turbidity of the floc blanket was higher than the influent, assuming that the floc blanket concentration is approximately uniform. The decreasing positive pC* value of the clarified effluent indicates increasing floc blanket turbidity and thus, thickening. We do not seem to have reached tube settler failure mode until about $14\,hours$ since there is a steep decrease in pC* at this time, but the experiment was stopped soon after. However, examining the trend of decreasing pC*, tube settler failure is expected.

3.5 Floc Hopper Experiment

Mass Balance Model

The purpose of the floc weir and hopper is to maintain the height of the floc blanket in the sedimentation tank by collecting, consolidating, and removing excess flocs. After the floc blanket forms, it grows until it reaches the height of the floc weir. Flocs will then fall over the weir and be collected in the hopper, thereby keeping the floc blanket height constant.

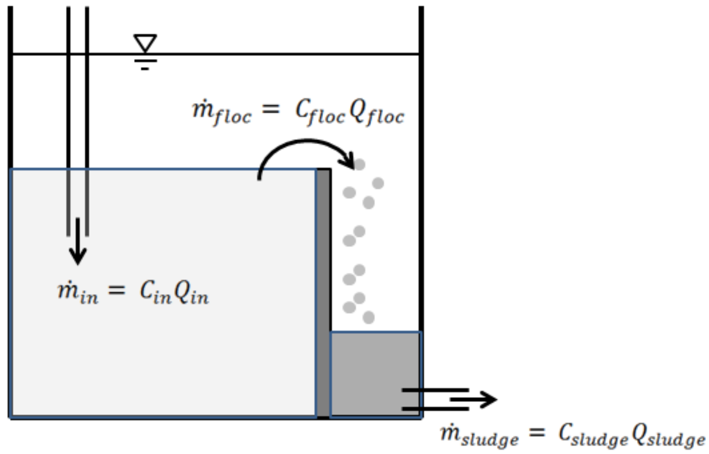

Figure 21: Mass balance of floc hopper

In constructing this model, we assumed that at steady-state, the concentration of the floc blanket remains constant and uniform. The floc blanket also grows at a constant rate. To simplify the model, we will use a rectangular floc hopper, however in the real plant, the actual floc hopper will have an inclined bottom to facilitate the draining of sludge.

From the mass balance in Figure 21, once the floc blanket grows to the height of the floc weir and reaches steady-state, the mass flow into the sed tank, $\dot{m}_{in}$, should be equal to the mass flow over the floc weir, $\dot{m}_{overflow}$. It should be also equal to the rate of removal of sludge mass from the hopper, $\dot{m}_{waste}$. Therefore,

$$C_{in}Q_{in} = C_{FB}Q_{overflow} = C_{sludge}Q_{waste} \tag{8}$$

Here, we consider two cases for sludge wasting: continuous wasting and pulsed wasting.

Continuous Wasting

In continuous wasting, sludge is removed from the hopper at a constant rate. From our initial floc hopper experiment, we have found that due to the relatively short residence time of flocs in the hopper (on the order of seconds), it is more likely that suspended flocs will be removed instead of consolidated sludge, because the flocs are not given sufficient time to compress before they are removed. Therefore, the desired continuous wasting rate should be equal to the rate at which flocs are flowing from the blanket into the hopper, $Q_{overflow}$. The continuous wasting rate is a function of the influent concentration of flocs, C_{in}, and the influent flow rate, Q_{in}, as well as the concentration of the floc blanket, C_{FB}, (Equation 9) which can be determined via image analysis using LabVIEW.

$$Q_{ContWaste} = Q_{overflow} = \frac{C_{in}Q_{in}}{C_{FB}} \quad (9)$$

The following is a sample calculation for continuous wasting: From past experiments using our lab apparatus, we have found that an influent turbidity of $100\,NTU$ and a plant flow rate of $514\,mL/min$ will form a floc blanket with a concentration of approximately $1800\,mg/L$22.

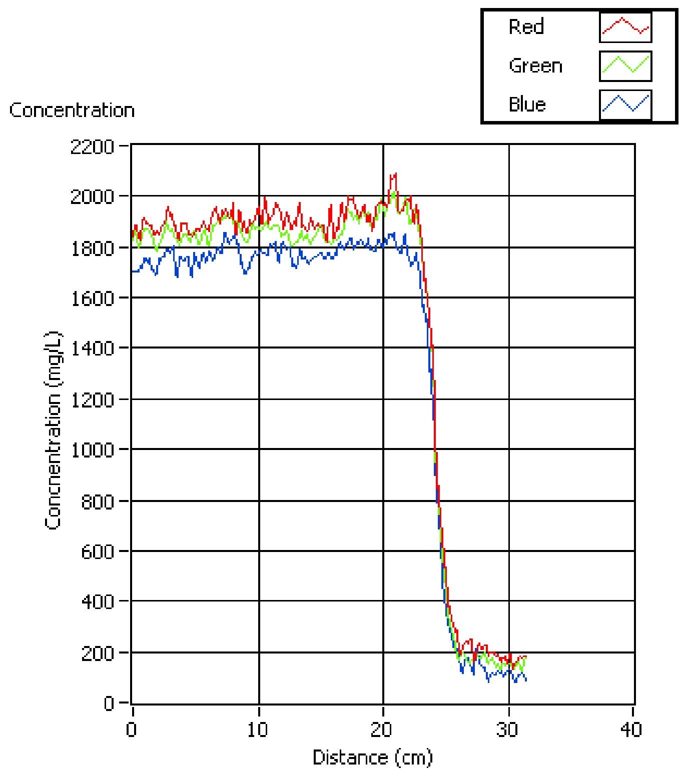

Figure 22: Concentration profile of floc blanket formed with 100 NTU influent. The sharp decline in concentration indicates the location of the floc-water interface.

Using a calibration curve from previous AguaClara research, we can convert turbidity in units of NTU to clay concentration in units of mg/L using Equation 10. A turbidity of $100\,NTU$ corresponds to a clay concentration of $274\,mg/L$.

$$Conc[\frac{mg}{L}] = 2.6817NTU + 5.5884 \quad (10)$$

Substituting these values into Equation 9, the continuous wasting rate of suspended flocs from the hopper in our lab set up is $78\,mL/min$.

In the case where flocs are given sufficient time to consolidate, and sludge is continuously wasted from the hopper, Equation 9 can be modified:

$$Q_{ContWaste} = \frac{C_{in}Q_{in}}{C_{sludge}} \tag{11}$$

From our previous TSS test on sludge that has been left to consolidate for about 24h (from our Complete Settling Test), we found that $C_{sludge} \approx 30g/L$. Substituting this into Equation 11, the continuous wasting rate of consolidated sludge from the hopper in our lab set up is $4.7\,mL/min$.

Since flocs are being removed from the hopper soon after they flow over the floc weir, the volume of the hopper does not have to be very large. The minimum volume required has yet to be determined. While this wasting method can keep the size of the hopper small, the tradeoff is that significantly more water will be wasted than with pulsed wasting. Since the residence time is shorter than $24\,hours$, the sludge concentration will be significantly less than $30\,g/L$ and the wasting rate will be greater than $4.7\,mL/min$. However, designing a floc hopper for longer residence times will allow for a lower wasting rate.

Pulsed Wasting

In pulsed wasting, the floc hopper is drained only after a significant period of time, which is on the order of hours. Because the residence time of flocs in the hopper is long, flocs are able to consolidate and form sludge, which is then removed. At steady-state, the increase in mass of flocs in the tank, $\dot{m_{in}}$, is equal to the accumulation of mass of sludge in the hopper, and the latter can be approximated by $\dot{m}_{waste}$(Equation 12). This equation is only an approximation because the sludge is simultaneously growing from the new mass in and consolidating, hence the concentration of sludge varies with depth in the hopper. We can calculate the volume of sludge, V_{sludge}, that will accumulate over the given period of filling time, t_{fill}, as shown in Equation 13.

$$\dot{m}_{waste} = \dot{V}_{sludge}C_{sludge} = C_{in}Q_{in} \tag{12}$$

$$V_{sludge} = \frac{C_{in}Q_{in}}{C_{sludge}}t_{fill} \tag{13}$$

The concentration of the sludge in the hopper, C_{sludge}, can be estimated by total solids test on a sample of flocs that has been allowed to consolidate in the model sedimentation tank over a fixed period of time, which we found to be about $30\,g/L$ for a $24\,hour$ residence time as mentioned above. Alternatively, we can measure how long a floc hopper of known volume takes to fill up with sludge, and then estimate $C_{sludge}$by manipulating Equation 13. Presently, we do not have a model for compression settling of flocs, but we expect the concentration of sludge in the hopper to be a function of time in the hopper. The longer the hopper is allowed to fill with flocs, the more consolidated the sludge will be because there is a larger load of flocs exerting a downward force, as well as a longer time for water to be squeezed out from the spaces between the flocs.

Based on the most recent sedimentation tank design, the entrance and exit channels are both on the same side of the sedimentation tank and the floc hopper is located underneath 23. For a $70\,L/s$ plant, the volume of the hopper is approximately $V_{hopper} = 0.56\,m^3$.

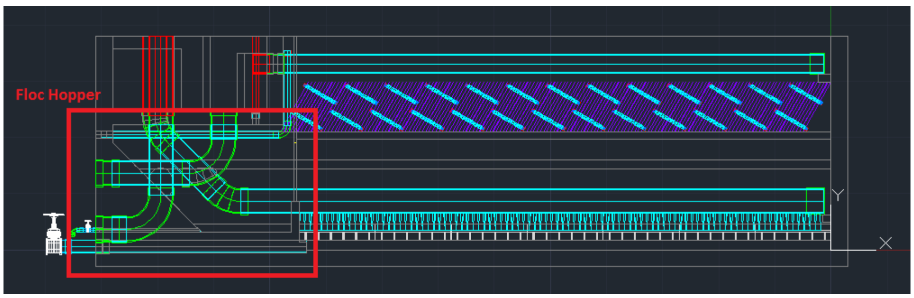

Figure 23: Sedimentation tank with floc hopper (boxed in red) underneath entrance and exit channels

Rearranging Equation 13, we can estimate the time taken for this hopper to fill up with sludge, assuming an influent turbidity of $100\,NTU$.

$$t_{fill} = \frac{V_{hopper}C_{sludge}}{C_{in}Q_{in}} = \frac{0.56(10^6)cm^3 \cdot 30,000\frac{mg}{L}}{274\frac{mg}{L} \cdot 70(10^3)\frac{cm^3}{s}} = 876\,s = 14.6\,min \quad (14)$$

It will be unreasonable to have the operator drain the floc hopper every 15 minutes, hence we will most likely need to design the floc hopper for a continuous draining system instead of a pulsed draining system.

To compare how much water is lost in pulsed wasting versus continuous wasting, assume that the floc hopper will need to be completely drained in order to flush out all the sludge. We will use a floc hopper volume of $0.56(10^6)cm^3$, which was used in the above calculations. The amount of water wasted in a day from pulsed wasting is approximately

$$Q_{PulsedWaste} = \frac{V_{Hopper}}{t_{fill}} = \frac{0.56(10^3)L}{876s} = 55,200\,L/day$$

With continuous wasting of flocs at the concentration in the floc blanket, which would occur if the flocs were wasted before they were allowed to consolidate, the amount of water wasted is

$$Q_{ContFlocWaste} = \frac{C_{in}Q_{in}}{C_{FB}} = \frac{274\frac{mg}{L} \cdot 70\frac{L}{s}}{1800\frac{mg}{L}} = 920,000\,L/day$$

With continuous wasting of consolidated sludge, the amount of water wasted is

$$Q_{ContSludgeWaste} = \frac{C_{in}Q_{in}}{C_{sludge}} = \frac{274\frac{mg}{L} \cdot 70\frac{L}{s}}{30,000\frac{mg}{L}} = 55,200\,L/day$$

Theoretically, pulsed wasting and continuous wasting of consolidated sludge will waste the same amount of water if the concentration of the wasted sludge is the same. However, it is more feasible to waste sludge continuously than at a pulsed rate in the actual tank so as to reduce the workload for the operator. We need to make sure that we are draining sludge and not flocs, because the latter will result in a more than ten-fold increase in the amount of water wasted.

Floc Hopper Trial Experiment

To simulate a realistic floc hopper, a small triangular insert was fabricated and placed in the laboratory's reactor. This design is meant to remove flocs from the sedimentation tanks once they have fallen over a weir and compressed into sludge at the bottom of the hopper. In all previous experiments, we simulated a floc hopper by pulling flocs directly out of the floc blanket with a tube without allowing them to concentrate first. In doing so, we were wasting water that could have otherwise undergone more treatment and eventually stored as potable water.

To begin, the geometry of the floc hopper was created using a 1/2 inch ($1.27\,cm$) thick PVC slab and fabricating the shape in Figure 24. The important variable parameters of the floc hopper design are its width of $5\,cm$, the $60°$ incline and the hole for a magnet. The small width was used because it occupies just 10% of the $50\,cm$ wide reactor and the $60°$ incline is utilized to direct all flocs that enter the floc hopper to a compression zone where the wasting tube was located. The magnet is necessary to secure the hopper at its height of $60\,cm$ from the bottom of the tank and to ensure that the vertical portion of the design is flush with the reactor wall, which prevents flocs from escaping the hopper. Once fabrication was completed and the hopper, as well as the wasting tube, were secured in the reactor, the experiment was run with an influent turbidity of $100\,NTU$. Initially, a wasting rate of $10\,mL/min$ was used in order for the floc blanket to grow quickly without removing a substantial amount of flocs. Once the floc blanket reached the height of the floc weir ($60\,cm$), the wasting rate was continuously adjusted to match the mass flow rate into the tank as to avoid overflowing the hopper with flocs.

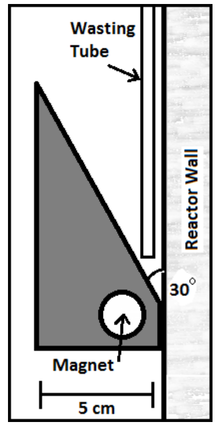

Figure 24: Initial Floc Hopper Design

The experiment was run with a total flow into the reactor of $456\,mL/min$ and a wasting rate of $10\,mL/min$. Under these conditions, the floc blanket's height grew and eventually rose above the floc weir. This led us to define a failure mode of the floc hopper; where the volume of the hopper fills with what seemed to be suspended flocs. The hopper essentially became part of the floc blanket and, if anything, was an obstruction. The fact that the flocs were suspended inside the floc hopper is interesting because the particles technically should not feel an upflow velocity and should settle. In the ideal case, there would be a thin stream of flocs cascading down the incline of the hopper, while the rest of the hopper's volume is either empty, or filled with sludge rather than suspended flocs (Figure 25).

Next, the wasting rate was increased to $40\,mL/min$ 2.5 hours into the experiment to remedy the failure. And after 15 minutes of the increased wasting rate, the floc blanket height dropped to the height of the floc weir. Under these new flow rate conditions the flocs began falling over the weir as one would expect in the ideal case. Unfortunately, the flocs that were removed were not in the form of concentrated sludge, but rather the same concentration of the floc blanket (Figure 25). Although this result was not ideal, the floc hopper waste stream is significantly higher in concentration compared the tank influent and would be very beneficial to the floc recycling process. It was also apparent that the floc hopper was leaking a small amount of flocs because the triangular insert was thinner than the reactor's thickness ($1.27\,cm$). This was due to the fact that the inserts were inaccurately sanded down in that dimension. Though this seemingly had a negligible effect on our analysis, the fabrication of the next floc hopper will be more precise.

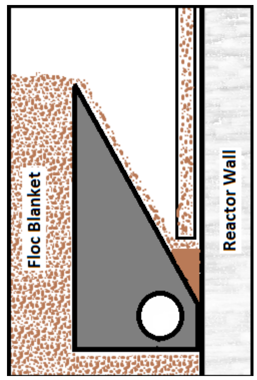

Figure 25: Successful Floc Hopper

Because the data gathered from this experiment was purely observational, there are many aspects of the floc hopper that need further investigation with numerical analysis. Quantitative analysis could be implemented to determine the most sensitive parameters of the design; width, angle of incline, depth or volume of the hopper. More importantly, a model could be formed to calculate the appropriate wasting rate based on draining frequency and mass rate into the reactor. This approach would be preferred to the current method used, where we essentially estimated a wasting rate through trial and error. Though a rate of $40\,mL/min$ avoided the failure mode described previously, it may not be the minimum rate required for its function. It is vital to optimize this wasting rate because wasting too much results in a loss of clean water, a scarcity in many of the communities AguaClara facilities serve.

Sludge Growth in Floc Hopper Experiment

This experiment was conducted to find a relationship between width of the floc hopper and growth rate of sludge in the hopper. If this relationship exists, we could possibly relate the width of floc hopper to the rate of floc consolidation. A floc blanket was built under the conditions of $39\,mg/L$ of alum per $100\,NTU$ and an upflow velocity of $1.2\,mm/s$. Tube settlers or a wasting tube were not used. The floc hopper was designed as a rectangle with a constant height of $70\,cm$. The width was varied to be $5.0\,cm$, $7.5\,cm$, and $10\,cm$. Two PVC strips of width $2.5\,cm$ and length $1.25\,m$ were placed lengthwise into the floc hopper adjacent to the left side of the tank so that the width of the floc hopper would be $5.0\,cm$. The PVC strips were pulled out to increase the width of the floc hopper by $2.5\,cm$ per strip removed.

The change in height of sludge in the floc hopper and time for growth were measured. The growth rate was calculated by dividing the volume of sludge accumulated by the elapsed time. For example, for a floc hopper with width of $5.0\,cm$, $5.0\,cm \cdot 5.5\,cm \cdot 1.27\,cm/49\,min = 0.713\,cm^3/min$.

Table 3: Values for calculation of sludge growth rate

Width of floc hopper (cm)	Change in height of sludge (cm)	Time (min)	Growth rate (cm^3/min)
5.0	5.5	49	0.713
7.5	2.7	62	0.415
10.0	2.3	48	0.609

Our results show that there is no clear relationship between width of floc hopper and growth rate. Due to limitations of our reactor geometry, it was difficult to create perfect controls. For example, when a PVC strip was removed, we allowed the sludge to settle for 15 minutes before measuring the initial height of the sludge for the next growth rate measurement. However, we suspect that this was insufficient time and sludge continued to settle as the growth rate was measured. This would cause an underestimation. We expected a constant growth rate or linear relationship, which would exist if the growth rate for a width of $7.5\,cm$ was inaccurately measured.

3.6 Effect of Alum Dose on Floc Blanket

The objective of this experiment was to form a floc blanket and then gradually lower the alum dose until the floc blanket started to thin out. We expect this to happen because flocs are likely to be smaller in size and less "fluffy" when the alum dose is low, therefore they are more likely to escape through the top of the tube settlers. Upon observing the thinning out of the floc blanket, we would then increase the alum dose to observe if the floc blanket would revert back to its previous thickness. We could then deduce the minimum alum dose required to form and maintain a floc blanket for an influent turbidity of 100 NTU.

A floc blanket was formed with an upflow velocity of $1.2\,mm/s$ and an influent turbidity of $100\,NTU$. A single 60 degree insert with a $10\,cm$ wide floc hopper was placed in the tank, with an additional $75\,degree$ insert within the hopper so that sludge could flow downwards towards the entrance of the sludge-wasting tube. The secondary objective of this experiment was to observe the effectiveness of this $75\,degree$ insert in sludge removal. The influent tube was placed at the far left edge of the tank26.

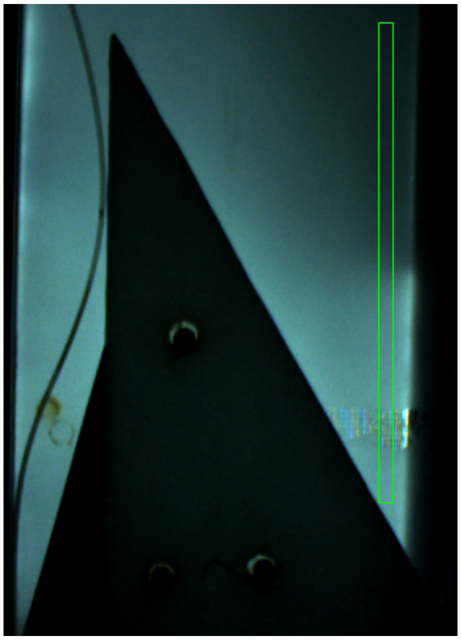

Figure 26: Tank set up with selected ROI in green

Water was flowing out of the tank through10 tube settlers, with an upflow velocity of $1.2\,mm/s$. The alum dose was initially set to $45\,mg/L$. After 4 hours into the experiment $(t = 4h)$, the alum dose was reduced to $40\,mg/L$, and it was subsequently reduced every 2 hours after that to concentrations of $35\,mg/L$ $(t = 6h)$, and finally $27.8\,mg/L$ $(t = 8h)$. The experiment was then left to run for about 12 hours, after which the floc blanket was observed to have become less concentrated, and the alum dose was increased slightly to $33\,mg/L$ $(t = 20h)$ for another 4 hours$(t = 24h)$. The floc blanket concentration was estimated by analyzing selected images with LabVIEW. The program compared the light absorbance of a selected region of interest of the image to a background image, and then estimated the floc blanket concentration from a pre-determined calibration curve.

At $t = 2h$, there was no floc blanket in the tank, but upon turning off the tube settlers, the floc blanket formed within $10\,min$. The tube settlers were turned off because we thought flocs were being sucked up the tube settlers, making it difficult for them to settle and negatively impacting floc blanket formation. The floc blanket then grew steadily to the height of the floc weir and sludge was collected in the hopper. Even though the alum dose was constantly lowered $27.8\,mg/L$, the concentration of the floc blanket steadily increased over the next 18 hours27. (Due to an error with the image acquisition software, we were unable to obtain any images between $t = 9h \text{ and } t = 20h.$) At $t = 20h$, the small flocs were observed in the blanket and the floc water interface was not very clear because there were many flocs in the clarified water above the interface. Because of this observation, the alum dose was increased to $27.8\,mg/L$ at $t = 20h$ in an attempt to create larger flocs and a denser floc blanket. Instead, the concentration of the floc blanket decreased, the flocs appeared to become smaller in size, and the floc water interface became indistinguishable at $t = 25h$. At this time, the floc hopper was about three quarters full of sludge. Although the flocs were smaller at lower alum concentrations, the concentration of the floc blanket appeared to be higher. Increasing the alum dose resulted in fluffier flocs and a more clear floc-water interface, but a less concentrated floc blanket.

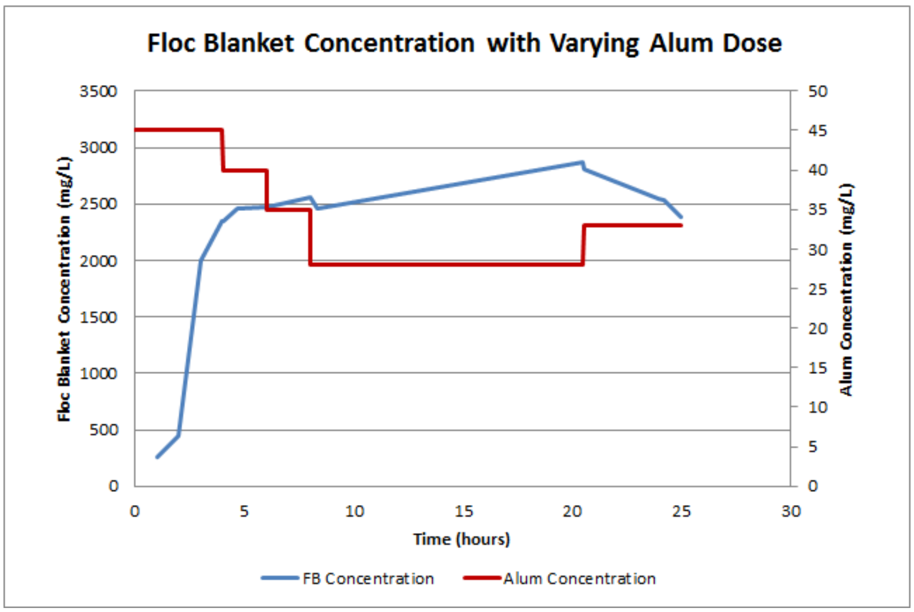

Figure 27: Change in floc blanket concentration with varying alum dose

Based on the data shown in 27, it appears that an alum dose of $27.8\,mg/L$ is sufficient to maintain a floc blanket at an influent turbidity of $100\,NTU$. It is unclear if this alum dose is adequate for building a floc blanket, since the flocs that were already in the tank when the alum dose was lowered to $27.8\,mg/L$ could be large enough because they were mixed with a larger alum dose earlier on. At $t = 8h$, the floc blanket could already be thick enough to trap the smaller flocs that were entering the tank as a result of the lower alum dose, hence the concentration of the floc blanket increased steadily. When the alum dose was increased to $33\,mg/L$ at $t = 20h$, this could have created larger, fluffier flocs that broke up the floc blanket. At present, we are not entirely sure of the reason behind this observation. However, this observation bears resemblance to the initial Marcala simulation experiment where the influent turbidity was reduced from $100\,NTU$ to $10\,NTU$ while alum dose remained constant. In both experiments, when the alum to clay ratio was increased, the floc blanket was observed to become less dense.

We were also unable to determine if the $75\,degree$ insert in the hopper was effective in allowing sludge to flow down the sides of the hopper because we faced some difficulties with sludge removal at low flow rates. The tube diameter was too small and we had to pump the sludge upwards against gravity. In the real plant, it is unlikely that the operator will face such a difficulty because sludge will be drained from the bottom of the tank, with the weight of the water in the tank pushing down on the sludge. Therefore we would expect the $75\,degree$ incline to work more effectively in the real plant in allowing sludge to flow down to the bottom of the hopper.

4 Conclusion

The results above provide a much needed insight into retrofits of sedimentation tanks as well as future strategies for efficient floc blanket formation and maintenance of floc blanket height. We proved that the simple addition of a 1 inch ($2.54\,cm$) diameter half pipe to the end of diffuser tubes can help form a floc blanket. This occurs because the flat portion of the tank is filled with settled flocs that eventually form an angle of repose that returns solids to the resuspension zone of the jet. Unfortunately the data, though valuable for AguaClara retrofits, does not completely represent the Marcala treatment. An overdosing of coagulant when the turbidity was turned down to $10\,NTU$ may have resulted in flocs that have proportionately more water incorporated into their aggregated matrix, decreasing floc density. The lower density of the flocs could indicate that the particles must be significantly larger in size to achieve the same terminal settling velocity in the reactor and that these particles have weaker particle-particle connections. Flocs with this lower fractal dimension have weaker interactions between the particles and are more likely to break up due to shear forces. Therefore, it is necessary to further investigate the Marcala plant's performance with low turbidity, more analogous to dry season conditions. This information could be used to determine relationships between performance and floc blanket concentration, providing further understanding of this intricate system. The 5 NTU experiment showed that forming a floc blanket with an influent turbidity that reflects that of an actual plant is tedious and time consuming but "seeding" the tank with coagulated flocs can minimize floc blanket formation time.

Our initial floc hopper experiment returned promising results that suggested that a floc hopper would be effective in controlling the height of the floc blanket in the sedimentation tank. The method of draining the hopper (either continuously or periodically) is an important consideration that needs to be made when designing the hopper. Decreasing the alum dose to $33\,mg/L$ proved effective at maintaining a floc blanket and may allow more effective draining of consolidated sludge from the hopper due to less sludge clumping. Varying the width of the hopper did not have a significant effect on the volumetric growth rate of sludge in the hopper and therefore would not significantly change the theoretical wasting rate.

5 Future Work

5.1 Floc Hopper Experiments

We would like to test the validity of our mathematical models by running a continuous draining experiment and a pulsed draining experiment in our model sedimentation tank. In the continuous wasting experiment, we can calculate the rate at which we should be draining sludge from the hopper using Equation **??** instead of using the trial and error method we used previously. We can then conduct an experiment to check if this flow rate is high enough to drain flocs from the hopper such that the hopper does not fill up with flocs. We can also take a concentration reading of the wasted flocs and compare this measured value with our theoretical expected value for mass flux out of the hopper.

In the pulsed draining experiment, we can first attempt to measure the concentration of sludge in the hopper by measuring the volume of sludge that accumulates over time, as described previously. We can then calculate the concentration of sludge using Equation 15, and check this against measurements from a TSS test of the sludge.

$$C_{sludge} = \frac{C_{in}Q_{in}}{V_{sludge}} t_{fill} \tag{15}$$

By measuring the volume of sludge over time, we can then start to form a relationship between the time for accumulation, the volume of sludge, and the concentration of sludge. This initial compression settling experiment is likely to give us more insight into the floc consolidation process.

We would also like to test the effects of various parameters on floc hopper wasting rate, including the angle of incline in the hopper, the volume of the hopper, and solids residence time.

The Floc Hopper Width experiment should be run again with an additional vertical strip placed in the hopper to obtain a wider range of data points. Sludge should also be completely wasted from the hopper before removing a strip to avoid errors due to sludge consolidation in the bottom of the hopper, and should be allowed to settle for a longer period of time.

5.2 5 NTU Seeded Tank Experiment

From our observations of re-runs of the 5 NTU experiment, we suspect that "seeding" the tank with coagulated flocs may help to speed up floc blanket formation when influent turbidity is low. We intend to explore this idea by retaining some coagulated sludge from our floc hopper experiment and measuring its concentration. We will then pour a known mass of sludge into the clean sedimentation tank at the start of the experiment when the influent pump is turned off, then run the experiment with a 5 NTU influent turbidity, and measure how long the floc blanket takes to form. The mass of sludge added to the tank should be approximately equal to the mass of flocs already in the tank. We expect the floc blanket to form in a significantly shorter period of time because the large amount of coagulated flocs will quickly be resuspended by the influent jet. If our hypothesis is correct, we will be able to form floc blankets more reliably and quickly, especially when influent turbidity is low.

5.3 Effect of Alum Dose on the Floc Blanket

We would like to run another experiment in which we vary the alum dose and observe the effects on the floc blanket. We should form a floc blankets at various alum doses and compare formation times, size of flocs formed, and floc blanket concentrations. We can also change the alum dose while the floc blanket is formed and observe the effects on floc blanket concentration. We would like to determine a minimum alum dose below which the floc blanket fails.

References

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