EVALUATION OF PARAMETERS AFFECTING STEADY-STATE FLOC BLANKET PERFORMANCE

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ABSTRACT

A laboratory-scale reactor was used to simulate a water treatment process sequence of rapid mix, hydraulic flocculation, upflow clarification with a floc blanket, and lamellar sedimentation to accomplish removal of colloidal particles. This process sequence, followed by chlorination, has been employed to create affordable designs for water treatment in the Global South. This study focused on variables affecting performance of the floc blanket including: condition of hydraulic flocculation, raw water turbidity, coagulant dose, upflow velocity through the floc blanket, floc blanket height, and bulk density and solids concentration of the floc blanket. An upflow clarifier velocity between 90-110 m/day produced the best floc blanket performance for most influent turbidities studied. The results show that particle removal efficiency in lamellar sedimentation improved linearly with respect to floc blanket heights up to 45 cm. Improved performance is also correlated with increased hydraulic flocculator residence time and energy dissipation rate. At floc blanket heights above 45 cm, there is still improvement in performance for most cases, but improved performance and blanket height no longer follow a linear relationship. Lamellar sedimentation with a capture velocity of 10 m/day is a key component in improving clarifier performance when utilizing a floc blanket. Future studies are needed to determine mechanisms of particle removal in a floc blanket.

BIOGRAPHICAL SKETCH

Matt Hurst was born in Tucson, Arizona in 1984. He became really interested in the environmental field after taking an environmental science class his senior year of high school. He graduated magna cum laude with a degree in Civil Engineering and a minor in Environmental Engineering and a degree in Chemistry with a minor in Spanish from Rose-Hulman Institute of Technology in 2007. In college, he was the president of the student group UNITY and worked with the Human Rights Council of Terre Haute. His work experiences in the environmental field include three years of undergraduate research with Dr. Penny Miller as part of WATERCAMPWS and a summer as a student organizer for GreenPeace. In September, 2007, he entered Cornell University and initiated his studies towards the M.S. Degree in Environmental Processes.

Dedicated to

My parents, Bob and Peg

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LIST OF ABBREVIATIONS

AFR – Arbitrary Flow Reactor

ASCE – American Society of Civil Engineers

AWWA – American Water Works Association

CMFR – Constantly Mixed Flow Reactor

NOM – Natural Organic Matter

NTU – Nephelometric Turbidity Unit

PF – Plug flow

WTP- Water Treatment Plant

LIST OF SYMBOLS

$A_{clarifier}$ cross-sectional area of the clarifier (L^2)

A_s normal area of the tube settler (L^2)

C_{in} influent concentration (M/L^3)

C_{out} effluent concentration (M/L^3)

d inner diameter of tubing (L)

D tubular floculator coil diameter (L)

f_{ratio} ratio of the friction factor for curved tubing versus that for straight

G velocity gradient in viscous subrange (1/t)

$G\theta$ dimensionless flocculation parameter, product of G and θ

h_{floc} height of floc blanket (L)

h_l head loss (L)

h_{water} height of water that would produce the same pressure as h_{floc} (L)

L length of tubing (L)

N_{De} Dean number

$pC*$ removal efficiency $\left[-\log\left(\frac{C_{out}}{C_{in}}\right)\right]$

Q flow rate (L^3/t)

V is the average axial velocity of flow (L/t)

V_{up} upflow velocity in the clarifier (L/t)

V_{growth} growth rate of floc blanket (L/t)

V_{ratio} ratio of the upflow velocity to the capture velocity

α angle of tube settler with respect to the horizontal

ε energy dissipation rate (L^2/t^3)

$\theta_{flocculator}$ hydraulic residence time of fluid in the hydraulic flocculator

$\theta_{clarifier}$ hydraulic residence time of fluid in upflow clarifier (t)

$\theta_{floc\ fluid}$ hydraulic residence time of fluid in floc blanket (t)

θ_{solids} residence time for solids in floc blanket (t)

ν kinematic viscosity (L^2/t)

v_c capture velocity of the tube settler (L/t)

ρ_{water} density of water (M/L^3)

$\rho_{bulk\ floc}$ bulk density of floc blanket (M/L^3)

Φ porosity of the floc blanket

CHAPTER 1: INTRODUCTION

1.1. Background Information

Access to clean and affordable water is important for human health, economic productivity, and environmental sustainability. Watershed management is paramount for all communities, especially those utilizing a surface water source for consumption. However, most surface water quality is well below minimum standards for human consumption especially during rainy seasons which increase surface erosion and runoff.

It is estimated that one billion people lack access to improved water sources as defined by the UN (WHO, 2000). This figure does not include another estimated 1 billion people with access to improved water sources (water transported in a pipe network) that are not directly treated. By these estimates, there are two billion people without access to safe drinking water. Thus, there is a need for a cost-effective solution to provide safe drinking water for a large proportion of the world's population currently lacking safe drinking water.

AguaClara is a unique project in the School of Civil and Environmental Engineering at Cornell University that utilizes design, laboratory and field research, as well as extensive community outreach and working partnerships to provide cost-effective community-scale water treatment plants for the Global South. Of the 2 billion people without access to clean drinking water, a quarter could utilize turbid surface waters. A quarter of those utilizing untreated surface waters are estimated to live in communities between 1000 and 50,000 people. Thus, an estimated 125

million people could be potentially served by AguaClara technology. AguaClara water treatment plants utilize a gravity-driven treatment process train of rapid mix, flocculation, sedimentation, and disinfection.

This thesis presents the evaluation and optimization of effluent performance in an upflow sedimentation tank with floc blanket and lamellar sedimentation. Optimization of effluent performance in this system is crucial for achieving low turbidity water for disinfection to be effective.

1.2. Overview of Research

Turbidity is a water quality parameter correlated with the concentration of suspended colloidal particles. Turbidity measurement is based on light scattering caused by suspended or colloidal material present in that liquid. The amount of light scattered by a known standard (typically Formazin) provides the scale for measurement of turbidity in Nephelometric Turbidity Units (NTUs).

Colloidal particles are of particular interest in water treatment because they correlate with the presence of pathogenic organisms, interfere with disinfection, and negatively impact drinking water quality. Colloidal particles (0.001-1.0 μm) are difficult to remove by gravity sedimentation because of their low settling velocities.

Naturally occurring colloids typically have a negative surface charge and electrostatic repulsion acts to hinder particle aggregation. Use of a coagulant such as alum ($Al_2(SO_4)_3$*14(H_20)) is commonly employed in water treatment to neutralize the negative colloid surface charge. Alum

dissolves and forms positively charged species such as Al^{+3}, $Al(OH)^{+2}$ and $Al(OH)_2^{+}$ that could adsorb to the surface of colloids. Precipitation of $Al(OH)_3(s)$ also occurs on colloid surfaces. The solid surface charge of $Al(OH)_3(s)$ is positively charged at circumneutral pH .

Aluminum can also form polymer species in water. In solution, Al_2 to Al_6 polymers can form fairly rapidly, however longer polymers that aid bridging between floc particles can take days to form utilizing alum. Different forms of polyaluminum chloride (PACl) can assist the formation of longer chain polymers facilitating bridging between particles in much shorter time.

A rapid mix reactor is used to blend raw water and coagulant. There are two goals in rapid mix. The first is large scale turbulent mixing that can be accomplished by a flow expansion. The second goal in a rapid mix reactor is to achieve a high energy dissipation rate (~ 0.5 to 1 W/kg) to provide small scale turbulent mixing so that molecular diffusion can finish the mixing process in a few seconds.

Charge neutralization of the colloidal suspension allows particle aggregation and floc formation. A flocculator with controlled energy dissipation rate and residence time is used to promote floc particle growth. Particle size is correlated with the terminal settling velocity of a particle. After flocculation the resulting larger, flocculated, particles can be separated by gravity sedimentation (discussed in greater detail below).

After sedimentation, the clarified low-turbidity effluent is disinfected with an oxidant such as calcium hypochlorite. The goal of disinfection is to kill or inactivate pathogens present in the water. Chlorine disinfection is non-site specific and will act to oxidize any organic with which it comes into contact. Therefore chlorine disinfection is less effective at higher turbidities.

Because there is no filtration in the AguaClara water treatment process sequence, sedimentation is a key unit process for removal of suspended and colloidal particles to minimize their interference with disinfection.

This thesis focuses on use of upflow floc blanket clarification technology as a tool for producing high quality, low turbidity water. Performance is measured as the removal of turbidity (correlating to concentration of colloidal particles). The operational parameters that control floc blanket performance will be characterized and optimized from the point of view of the operator. Optimization of parameters such as coagulant dosing, and energy dissipation rate in the flocculator, and upflow velocity and floc blanket height in the clarifier, can provide better design guidelines to be utilized in the creation of AguaClara sedimentation tanks.

1.2.1 Research objectives

Operational parameters that influence floc blanket performance include: raw water turbidity, coagulant dose, upflow velocity in the floc blanket, height of the floc blanket, and extent of flocculation of the suspension entering the floc blanket. Bulk properties of the floc blanket, including solids concentration and bulk density, are parameters that could be related to performance. Understanding how operational parameters affect floc blanket performance is critical for application at a full-scale clarifier. Without floc blanket observation and operational control of dosing, complete loss of the floc blanket has been observed (AWWA/ASCE, 1990).

The focus of this research was to investigate parameters affecting floc blanket performance given constant raw water turbidity and alum dose. Although conditions of constant dose have been used by other investigators on a pilot and laboratory-scale (Miller & West, 1968; Zhang et al.

2006), this research was unique with respect to the wide range over which parameters were varied and the inclusion of both flocculation and tube settlers in the experimental apparatus. Continuous monitoring of effluent turbidity from both tube settlers (used to mimic lamellar plate settlers) as well as from the floc blanket clarifier, and quantification of the energy dissipation rate and residence time in the flocculator and floc blanket clarifier were also distinguishing features of this research.

The research objectives were to characterize floc blanket performance with respect to each of the variables listed above and to develop an understanding of the underlying mechanisms that affect floc blanket performance. The experiments that were conducted benefited from use of process control software developed by Weber-Shirk (2008) to automate operation of the laboratory-scale plant as well as to monitor and record influent and effluent turbidity readings.

CHAPTER 2: LITERATURE REVIEW

The following sections present a review of conventional sedimentation and floc blanket technology as well as a discussion and review of coagulation, flocculation, and lamellar sedimentation processes.

2.1. A Review of Sedimentation Technology

Horizontal flow sedimentation has been utilized in many water treatment applications including the first AguaClara sedimentation tank design employed in La 34, a rural community in northern Honduras. The tank was designed with a surface loading rate, i.e., the total flow rate (Q) divided by the plan surface area (A_s), equal to the terminal settling velocity of the smallest diameter particle size (V_c) to be completely removed as shown in equation (2-1)

$$V_c = \frac{Q}{A_s} \tag{2-1}$$

A simplistic model of sedimentation is to consider that flocs in the sedimentation undergo discrete settling. Discrete settling assumes that the settling particles will have no interaction with other particles in the system and that the terminal settling velocity of the particle (V_t) can be calculated based upon the particle diameter. The capture velocity of the sedimentation tank (V_C)

can be used to estimate sedimentation tank performance based upon the terminal settling velocity of the particle and the height of the particle in the sedimentation tank.

An estimate of floc terminal velocities, V_t, of a particle of diameter (d) can be calculated based upon Stoke's law for spherical particles shown in equation . In reality a floc particle is not spherical and this is corrected by a shape factor term, Θ given a value of $\frac{45}{24}$ by Tambo & Wantanabe (1979). A drag coefficient, C_d, can be calculated in equation by the Reynolds number (Re) and shape factor. The Reynolds number as shown in equation (2-2), Re, is calculated based upon the diameter of the floc particle, d , and the kinematic viscosity of the fluid, ν.

$$V_t = \sqrt{\frac{4}{3}\frac{gd}{C_d}\frac{(\rho_{floc} - \rho_{water})}{\rho_{water}}} \qquad (2\text{-}2)$$

$$C_d = \left(\frac{24}{\mathrm{Re}}\right)\Theta \qquad (2\text{-}3)$$

$$\mathrm{Re} = \frac{V_t d}{\nu} \qquad (2\text{-}4)$$

Where: g is acceleration due to gravity, ρ_{floc} is the density of a floc particle, and ρ_{water} is the density of the water.

Tambo & Wantanabe's model (1979) for predicting terminal velocity assumes that a floc is a solid object. Wu and Lee (1998) argued that, for a highly porous structure like that present in a floc, water would not just pass around, but through the floc. Because of the highly porous nature

of the flocs, Stokes model which is applicable up to a Reynolds number of 40 should account for flocs up to sizes on the order of 1 mm.

There are several additional considerations in horizontal flow sedimentation tank design:

- The horizontal flow velocity of water in the tank should be low enough that settled particles are not re-suspended. Scouring can occur from the turbulent motion of eddies as well as potentially high energy dissipation rate from jets at the inlet.
- The particle collection system should minimize re-suspension of settled particles.
- The inlet should be designed so that floc breakup is minimized. If significant floc breakup occurs at the inlet, then particle capture efficiency of the tank will be reduced.

These considerations and the design recommendations of Schulz and Okun (1984) guided the design at La 34. Schulz and Okun (1984) specified a capture velocity to be between 20 to 60 m/day and a particle residence time of 1.5 to 2 hours. In reality, the tank at La 34 had a particle capture velocity between 20-30 m/day and a residence time closer to 3 hours. The tank was 3 m deep allowing flocs a greater opportunity to collide via differential sedimentation and Brownian motion compared to shallower tank designs.

A drawback to the horizontal flow design at La 34 was the cost of construction of a sedimentation tank with a volume sufficient to allow a hydraulic residence time of three hours. The 3 m height and the target capture velocity of 20-30 m/day were the critical design constraints. While the 3 m height would act to maintain relatively quiescent flow in the tank, the height of the tank complicated its construction because of the structural stress associated with pressures of 3 m of water height.

Subsequent AguaClara designs beginning with the Ojojona plant utilized vertical flow sedimentation. Compared to horizontal flow sedimentation, vertical flow sedimentation can reduce the required reactor volume while maintaining similar levels of treatment (Tchobanoglous & Schroeder, 1987). In vertical sedimentation, each particle in the reactor has an upflow velocity (V_{up}) counteracting the particle's terminal settling velocity. The upflow velocity is the flow rate divided by the plan area of the tank (A_s) as shown in equation (2-5).

$$V_{up} = \frac{Q}{A_s} \qquad (2\text{-}5)$$

Both horizontal flow and vertical flow sedimentation tanks can utilize plate settler technology. Saleh and Hamoda (1999) showed that plate settler technology could increase removal efficiency in a sedimentation tank while decreasing the required plan area of the sedimentation tank. Plate settler systems are a series of inclined plates situated slightly below the surface of a sedimentation tank. The plates are designed to allow particles to settle on their surface and then slide back down into the sedimentation tank.

Plate settlers decrease the capture velocity in the clarifier. The capture velocity is based upon the size of the particle to be captured and this is, in turn, based upon consideration of the desired effluent turbidity. Schulz and Okun (1984) recommend capture velocities between 10 and 30 m/day. AguaClara facilities are currently designed with a capture velocity of 10 m/day.

At appropriate upflow velocities in a vertical flow sedimentation tank, a fluidized bed of particles called a floc blanket will form. For the fluidized bed of flocs, it is important to consider the extent of fluidization. A fluidized bed expands as upflow velocity increases. The maximum

fluidization velocity is the highest upflow velocity possible before the fluidized bed is washed out. Above the maximum fluidization velocity, all floc particles that enter should theoretically be lost to the effluent. A floc blanket is unique as a fluidized bed because the particles can change composition over time and the size distribution of particles in the floc blanket is variable and depends upon previous flocculation and coagulation processes.

In most sedimentation basins with a floc blanket, a relatively clear effluent layer lies just above the floc-water interface. Floc blankets are thought to facilitate particle removal because of increased particle-particle interactions that lead to flocculation (Tchobanoglous et al, 2003) and filtration (Miller & West, 1968) occurring in the floc blanket. Figure 2-1 illustrates the layers in a floc blanket clarifier including the clarified portion above the floc blanket, the floc-water interface, and the fluidized bed of flocs forming the floc blanket. Particle concentration in a floc blanket is relatively constant throughout except at the bottom of the reactor (Gould, 1969) where concentration dramatically increases and compression settling may occur.

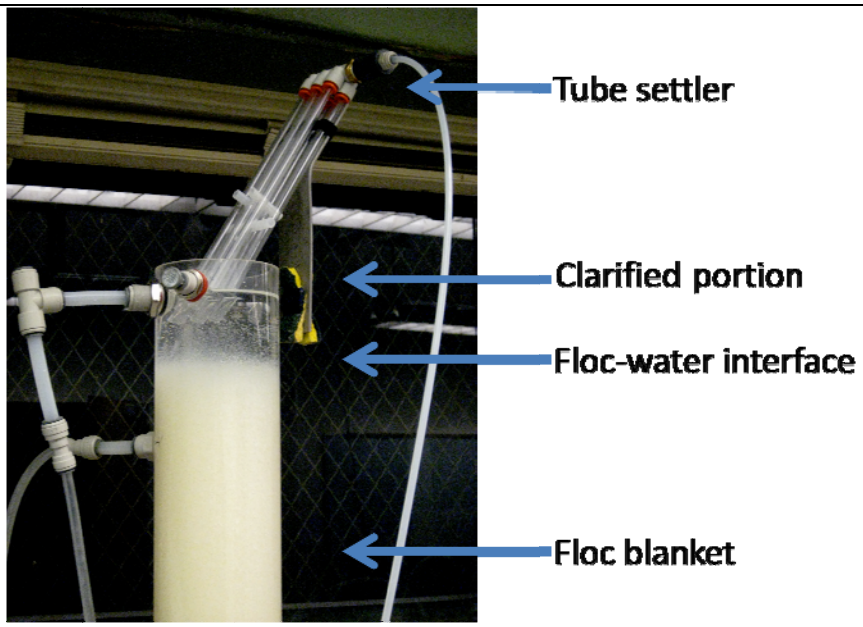

Figure 2-1. Diagram of fully formed floc blanket in experimental reactor.

2.2. Floc blanket technology

While floc blanket technology has been documented since the 1930s, there has been very little published research related to this topic in the past eight decades. Existing literature includes reports of experimental observation of floc blankets, investigations of floc blanket stability, and empirical models that consider mass flux. However, there is still a lack of a fundamental understanding of how floc blankets work.

A central goal of this research was to optimize particle removal in a process train of rapid mix, flocculation, floc blanket clarification, and lamellar sedimentation. Prior research has not studied or optimized the performance of a floc blanket in this complete process train. There is also a lack of understanding of particle removal mechanisms in a floc blanket and no mechanistic models

exist that can predict floc blanket performance. A new focus on colloid removal mechanisms is necessary in understanding the role of floc blankets in particle removal.

Much of the current literature pertains to observational and mass flux studies of floc blankets. In much of the literature, flocculation and coagulation processes used prior to vertical flow sedimentation are poorly characterized. Unlike previous studies, this study utilized laboratory-scale laminar flow flocculation that permitted conditions in the flocculator to be characterized and controlled. Residence time and energy dissipation rate can be varied by changing the length of tubing, flow rate, coil radius or inner tube diameter (see Chapter 3 for more details).

The current study also included continuous monitoring of influent and effluent turbidity from both the clarifier and a subsequent tube settler at a set capture velocity of 10 m/day. Previous studies with floc blankets have not included lamellar sedimentation subsequent to the floc blanket except for those of Galvin (1992). In other laboratory studies by Su et al. (2004), Sung et al. (2005a), Sung et al. (2005b), and Zhang et al. (2006), effluent turbidity was reported for a 30 minute or 2 hour settled grab sample from the top of the clarifier. These studies did not specify the sedimentation column height and thus it is not possible to compare their results with full scale performance or to the results obtained in this study.

It is also reasonable to expect that floc blanket performance and stability are dependent on the preceding coagulation and flocculation processes. However, flocculation was not optimized in prior studies nor was it a variable of consideration, and no prior investigators made an attempt to compare flocculation conditions or make a strong connection between flocculation and floc blanket performance. Instead floc blanket performance comparisons have been made for results

that may have been obtained under different coagulation and flocculation conditions. Most of the available studies involving floc blankets are scant on details surrounding flocculation and coagulation making it impossible to replicate such research.

Frequently, literature studies have studied mass flux and correlated mass flux with floc blanket stability and in many cases performance. Although mass flux is dependent on floc sedimentation velocity, it is not the dependent parameter that matters in assessing effluent performance in a water treatment plant. The dependent parameter for effluent performance emphasized in this study is residual turbidity after sedimentation.

Much of floc blanket research has focused on mass flux in a floc blanket. This focus may result from the notion that floc blankets are unstable and particle carryover can easily occur with changes in coagulant dosing, upflow velocity, or influent turbidity (AWWA/ASCE, 1990, Chen et al., 2004, and Chen et al., 2006). Gregory (1979) reported that floc blanket operation was optimal (operation was not defined and it was not necessarily based on particle capture efficiency) when the mass flux (kg/m^2-day) through a floc blanket was maximum. Letterman et al. (1999) found that a floc blanket gave best clarifier effluent at solid fluxes 60-75% of the maximum solid flux. However, this research offered no mechanistic understanding of why 60-75% of the maximum flux would give optimal clarifier performance. In addition, in a process train that includes plate settlers, optimal turbidity removal measured at the effluent of the floc blanket is not necessarily correlated with turbidity removal measured at the effluent of the plate settlers. Table 2-1 summarizes reported observations of floc blanket performance and studies of mass flux in floc blankets. The table lists the type of study conducted, the scale of the study, the conditions under which particles were flocculated and the nature of results that were obtained.

Table 2-1. Summary of floc blanket research.

Author	Type of study	Rapid mix/ flocculator conditions	Parameters investigated	Sampling and results
Chen (2003)	Continuous observation at full scale	Combined rapid mix/flocculation tank: Q = 380,000 m^3/day ; $\forall$ = 1600 m^3	Influent turbidity and PACl dosage	Grab samples. Measured settleability of sludge, zeta potential, particle size
Chen et al. (2006)	Continuous observation at full scale. Investigation of the role of charge reversal	Combined rapid mix/flocculation tank: Q = 380,000 m^3/day ; $\forall$ = 1600 m^3	Influent turbidity, effluent turbidity from clarifier, effluent turbidity from sand filter, pH and PACl dosage	Hourly grab samples. measured influent and effluent turbidity, pH, zeta potential in samples 4 m from top of clarifier, at top of clarifier and subsequent to a sand filter
Galvin (1992)	Continuous observation of lamellar sedimentation with a floc blanket clarifier at full scale	Unclear	Influent turbidity, effluent turbidity from lamella alum dosage, upflow velocity, natural organic matter (NOM)	Grab samples. Measured turbidity and NOM concentration from effluent of lamella
Head et al. (1996)	Continuous observation at full scale. Performance modeling based upon CMFR model by Gregory (1979)	Unclear	Influent turbidity, effluent turbidity from clarifier alum dosage, and temperature	Hourly grab samples. Measured turbidity from clarifier and solids concentration and compared to model predictions.

Author	Type of study	Rapid mix/ flocculator conditions	Parameters investigated	Sampling and results
Lin et al. (2004)	Semi-continuous observation of full scale and pilot plant. Study of two-stage and one-stage clarification	Pilot Plant: Jar test conditions simulating rapid mix and flocculation for pilot plant: 90 rpm for 1.5 min; 50 rpm for 8.5 min Full Scale: Combined rapid mix/flocculation tank: Q = 380,000 m^3/day ; $\forall$ = 1600 m^3	Influent turbidity, effluent turbidity from clarifier, effluent turbidity after rapid mix, and PACl dosage	Grab samples. Measured from residual turbidity at top of clarifier and after rapid mix. Measured solids concentration and particle size at different reactor heights
Miller & West (1968)	Continuous observation of pilot plant	Flocculation occurred in clarifier: $d_{clarifier}$ = 12" ; V_{up} = 4-20 ft/hr	Influent turbidity, effluent turbidity from sand filter, pH, alum dosage, and upflow velocity	Grab samples. Measured residual turbidity from sand filter. Measured pH, and solids concentration over height in the floc blanket
Purushothaman & Damodara (1986)	Continuous performance study	Flocculator: 600 mm height 12-40 mm pebbles. Coagulation provided by 6-90 degree bends	Alum dosage and fluoride concentration	Fluoride concentration measured in grab samples from floc blanket effluent

Author	Type of study	Rapid mix/ flocculator conditions	Parameters investigated	Sampling and results
Su et al. (2004)	Batch laboratory-scale and full scale study	Pilot Plant: Flocculation/ coagulation: Jar Test: 90 rpm for 1.5 min 50 rpm for 8.5 min Full Scale: Combined rapid mix/flocculation tank: Q = 380,000 m^3/day; $\forall$ = 1600 m^3	Upflow velocity, influent turbidity, PACl dosage, 2 hour settled turbidity and floc blanket height	Measured batch flux, floc blanket height, solids concentration, and 2 hour settling time residual turbidity in samples from the clarifier
Sung (2003)	Laboratory-scale and full scale solid flux study	Flocculation/coagulation: Jar Test: 90 rpm for 1.5 min 50 rpm for 8.5 min	Upflow velocity, PACl dosage, influent turbidity, floc blanket height, natural organic matter (NOM)	Measured solid flux, floc blanket height, solids concentration, particle size
Sung et al. (2005a)	Batch laboratory-scale solid flux and performance study	Flocculation/coagulation: Jar Test: 90 rpm for 1.5 min 50 rpm for 8.5 min	Upflow velocity, PACl dosage, influent turbidity, 2 hour settled turbidity from clarifier, floc blanket height, natural organic matter (NOM)	Measured solid flux, floc blanket height , solids concentration, and 2 hour settling time for residual turbidity from clarifier

Author	Type of study	Rapid mix/ flocculator conditions	Parameters investigated	Sampling and results
Sung et al. (2005b)	Batch laboratory-scale solid flux and performance study	Flocculation/coagulation: Jar Test 90 rpm for 1.5 min 50 rpm for 8.5 min	Upflow velocity, PACl dosage, influent turbidity, 2 hour settled turbidity from clarifier, floc blanket height, natural organic matter (NOM)	Measured floc blanket height, solids concentration, and 2 hour settling time for residual turbidity from clarifier Report 2-D and 3-D solid flux curves (upflow velocity and solids concentration (2-D) and dosage (3-D))
Zhang et al. (2006)	Semi-continuous laboratory-scale study comparing one-stage and two stage clarification	Flocculation/coagulation: $G = 350\ s^{-1}$ for 2 min $G = 27.5\ s^{-1}$ for 10 min	Influent turbidity, 30 minute settled turbidity from clarifier, upflow velocity, PACl dosage	Grab samples from clarifier. Measured residual turbidity after 30 minute settling

Based on Gregory's and Letterman's early work that considered mass flux in floc blankets, more recent mass flux studies were conducted (Chen et al., 2004, Lin et al., 2004, Su et al., 2004, and Sung et al. 2005a) which related solids concentration and upflow velocity and empirical models were developed. Empirical mass flux models in turn relied upon empirical models of hindered settling velocity of floc particles in the floc blanket. Theoretically, if wasting of flocs is neglected, the hindered velocity of flocs (V_H) will be counterbalanced by the fluid upflow velocity (V_{up}). A simplistic relationship given by Gould (1974) for the change in floc blanket height over time ($\frac{dH}{dt}$) that neglects floc wasting and floc input is shown in equation (2-6).

$$\frac{dH}{dt} = V_{up} - V_H \qquad (2\text{-}6)$$

Gregory (1979) and later Letterman (1999), Chen (2003), Su et al. (2004) expanded upon Gould's work. Later empirical models of hindered settling velocity are shown in Table 2-2.

Table 2-2. Empirical models of hindered settling velocities

Author	Model
Barnea & Mizrahi (1973)	$V_H = V_T(1 - qC^*)^n$ Where: C^* is the measured floc blanket concentration based upon a 30 minute settling test, q is a shape factor, V_T is the terminal settling velocity based upon Stoke's Law and n is an empirical exponential constant
Gregory (1979) Letterman (1999)	$V_H = V_T(1 - k_2\Phi^*)$ Where: Φ^* is the porosity of the floc blanket and k_2 is estimated from the ratio of the concentration at the compression point in a batch flux curve to the half-hour settled concentration (typically around 2.5)
Chen et al. (2003)	$V_H = V_T \exp(-5.0C_S)$ Where: C_S is the solids concentration in the floc blanket

Semi-empirical models of mass flux through a floc blanket (some of which employ hindered settling velocity) are listed in Table 2-3.

Table 2-3. Mass flux models for floc blankets

Author	Type	Model
Sung and Lee (2005)	Plug flow reactor for solid flux	$\frac{\partial C}{\partial t}+\frac{\partial C\left(V_{up}-V_H(C)\right)}{\partial z}=0$ Where: $\overline{C}$ is the average concentration of the floc blanket V_{up} is the upflow velocity of the floc blanket
Chen et al. (2003)	Arbitrary flow reactor for solid flux	$\frac{\partial C}{\partial t}=D\frac{\partial^2 C}{\partial z^2}-\frac{\partial C\left(V_{up}-V_T\right)}{\partial z}$ Where: D is the dispersion coefficient
Gregory (1979)	Constantly mixed flow reactor for solid flux	$\frac{dC}{dt}=\frac{Q}{\forall}(C_o-C_{exit})-\left(\frac{k_{fl}C*H}{L}+\frac{V_s A_s}{\forall}\right)C_{exit}$ Where: V_s is settling velocity of primary particles entering the tank k_{fl} is the flocculation factor reflecting the collision efficiency of floc particles H is the height of the floc blanket above the bottom of the tank $\forall$ is the volume of the clarifier C_o and C_{exit} are the concentration of floc particles coming into and exiting the floc blanket L is the height of the tank A_s is plan area of the clarifier.

Head et al. (1997) utilized Gregory's CMFR model (1979) to predict the effluent turbidity of a floc blanket clarifier. Although, Head et al. (1997)'s model showed a good

correlation between Head's experimental data and Gregory's model, this doesn't mean that the model can be generalized. Head et al. (1997) utilized a flocculation factor in fitting Gregory's CMFR model, so the researchers showed a model with performance correlated with bed height that could fit the data for the conditions at their WTP.

A CMFR model is a simplistic way to describe how large solid particles behave in the floc blanket portion of the clarifier. However, colloidal and smaller floc particles that have low settling velocities relative to the upflow velocity are expected to behave more like the fluid moving through the floc blanket. Simply investigating fluid dynamics in a floc blanket does not elucidate mechanisms of particle removal or reveal how floc particles are interacting in the floc blanket. Models incorporating CMFR, AFR or PRF do not capture the complexities of either filtration or flocculation mechanisms that could be occurring in the floc blanket, but could if these mechanisms were incorporated.

2.3. Flocculation

A problem with current design guidelines for floc blanket reactors is that flocculation prior to floc blanket formation has not been well characterized. No study has shown a correlation of particle removal efficiency obtained using floc blanket clarification and flocculation in the process train preceding a floc blanket. It seems reasonable to expect that the size of flocs and the efficiency by which colloid (primary) particles have been removed in flocculation will affect the effluent turbidity of a floc blanket clarifier. Su, et al. (2003) have reported that the changes in floc properties can affect floc blanket stability and performance.

Flocculation parameters including residence time and energy dissipation rate will affect the properties of individual floc particles. While colloidal particles such as clay are crystalline in structure, flocculated particles are porous and have an irregular geometry. As flocs grow, they become more porous and less dense and the geometry of floc aggregates can be approximated by the floc fractal dimension. The fractal dimension accounts for the floc particle porosity and higher fractal dimensions have a more compact floc structure (Jarvis et al. 2005). Flocculated particles created by aluminum hydroxide precipitation are reported to have fractal dimensions between 2.1 to 2.3 (Lambert et al. 2003; Li and Ganczarczyk 1989).

The history of how a floc was formed including energy dissipation rate and flocculator residence time could affect floc strength. Yeung and Pelton (1996) indicated that energy dissipation rates are related to floc breakup which, in turn, is related to strength of a floc particle. Francois (1987) found an increase in floc strength for flocs formed with higher energy dissipation rates as well as stronger flocs for increased residence time in the flocculator. Floc strength also increases as floc compaction increases because the number of bonds holding the floc together increases. Meakin (1988) found that a floc with three contact points (bonding points) had a higher fractal dimension than a floc with two contact points. Higher energy dissipation rates in a flocculator as well as higher residence time are correlated with a higher fractal dimension and stronger floc. Cailleaux et al. (1992) correlated higher performance with longer residence time in a mechanically mixed turbulent flocculator. At a constant energy dissipation rate removal efficiency (determined as the difference between effluent values after a thirty minute settling test

from the flocculator and influent values) increased from 67% after a residence time of 6 minutes to 86% after a residence time of 17 minutes.

While more collisions and longer residence time for collisions intuitively produce larger floc particles, there are not consistent design guidelines in place for flocculation. For mechanical flocculation, recommendations of applicable values of "velocity gradient" (G) as well as residence time (θ) vary depending on the literature source. Use of G is fundamentally appropriate only for laminar flow reactors, but continues to be used in literature for turbulent flow reactors. A G of 75 s^{-1} in turbulent flow conditions and residence time of 12.5 minutes are often recommended for 80% removal of turbidity (Cailleaux et al., 1992) ($G\theta$ = 56,000). For hydraulic flocculation, as is used in AguaClara facilities, Schulz and Okun (1984) recommend a G between 20-100 s^{-1} and residence time between 17 to 25 minutes ($G\theta$ = 20,000-150,000). Thus, the recommendations for hydraulic and mechanical flocculation are of the same order of magnitude for G and $G\theta$.

The goal of this research is to produce water with very low residual turbidity. An understanding of conditions in a flocculator by which floc particles will effectively flocculate will enhance performance in subsequent floc blanket and plate settler processes. Effective flocculation will produce flocs that settle fast enough to be removed by the plate settlers or by the floc blanket. The research described in this thesis includes a comparison of floc blanket performance with and without particle passage through a flocculator.

2.4. Coagulation

Coagulation destabilizes the negative charge of colloids allowing subsequent flocculation. However, charge neutralization cannot be thought of as the singular method involved in forming flocs. Floc formation requires the interaction of both contact with raw water colloidal particles and formation of amorphous aluminum hydroxide precipitate from the coagulant (Letterman et al., 1999). Alum ($Al_2(SO_4)_3$*$14H_20$) was the coagulant used in this research because that is the coagulant utilized in AguaClara plants, but other aluminum based coagulants would also work. Precipitation of alum is most effective in the pH range 6-7.5 as shown by the pC-pH diagram (Figure 2-2).

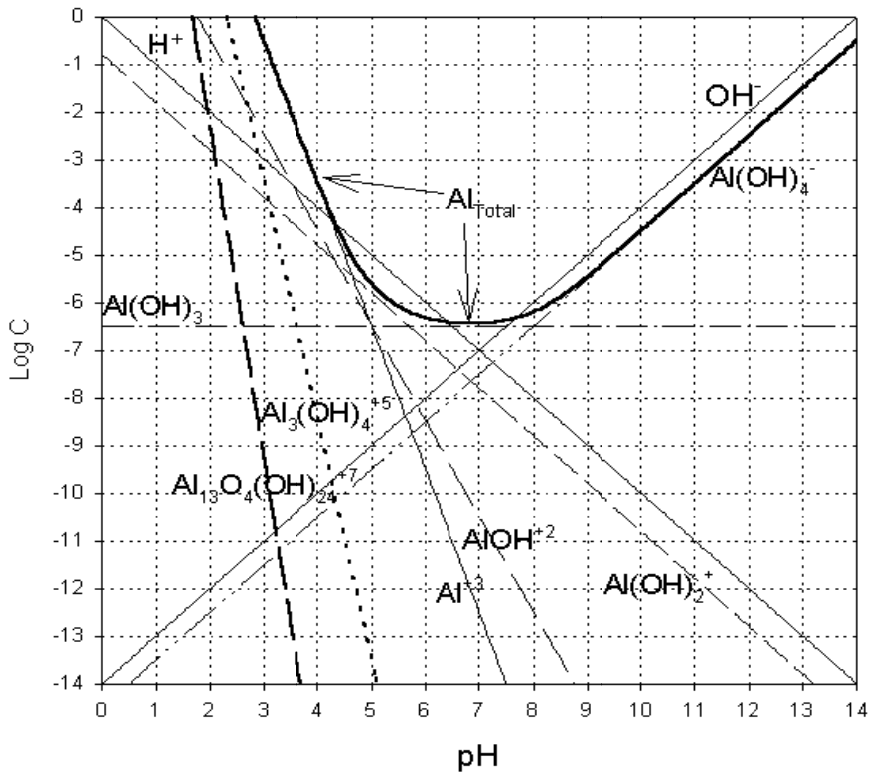

Figure 2-2. Diagram of potential aqueous aluminum species formed from the hydrolysis of alum (Reckhow, 1999).

At high alum dosages, pH can dramatically decrease if the treated water does not have sufficient alkalinity. If the pH drops below the effective range (i.e., below pH $\approx$ 6), then aluminum hydroxide precipitation and the production of flocculated particles will be inhibited.

In coagulation, alum will consume an amount of alkalinity based upon stoichiometric considerations. Each aluminum ion produced by hydrolysis of alum should consume three hydroxides in water to produce aluminum hydroxide as shown in equation (2-7).

$$\left[Al(H_2O)_6\right]^{3+}{}_{(aq)} + 3OH^-{}_{(aq)} \rightarrow \left[Al(OH)_3\right]_{(s)} + 6H_2O \qquad (2\text{-}7)$$

Insufficiently buffered systems would experience a decrease in pH after addition of alum and aluminum speciation would be shifted to favor Al^{+3} and $AlOH^{+2}$. At low pH, aluminum species will not precipitate, so coagulation will be less efficient and flocculation of particles will be suboptimal. Under conditions of low alkalinity, lime ($Ca(OH)_2$) or an alternative base can be used to replace the hydroxide consumed by aluminum hydroxide precipitation to maintain optimal pH conditions for flocculation.

A wide range of applicable alum dosages may be employed to give similar performance as long as the solution is sufficiently buffered (Xiao et al. 2008a) (Figure 2-3).

In decreasing solution temperature to 2 °C, Xiao et al. (2008a) postulated that there are two stages to coagulation: the first stage was characterized by the growth of very small floc particles which is akin to rapid mix of a WTP. The low temperature purportedly slowed the reaction kinetics enough to reveal the first stage is a diffusion driven process. Alternatively, one could think of molecular diffusion as the rate limiting step in rapid mix because sufficient mixing of the raw water and coagulant is required before precipitation and growth of small floc particles. Although not explicitly studied, at higher temperatures, molecular diffusion could still be a rate limiting step depending on the residence time in rapid mix.

Small particles that were observed in the first stage, rapid mix, only had adsorbed aluminum, and thus were very compact with a high fractal dimension. The second phase, rapid floc growth, occurred as very small floc particles begin to collide to form more porous flocs characterized with a smaller fractal dimension. Alternatively, the second phase could be thought of as the flocculation phase of a WTP. Xiao et al. (2008b) speculated that residual turbidity will be higher and alum dose will be ineffective except over narrow ranges unless diffusion occurs in rapid mix allowing rapid floc particle growth.

In Figure 2-3, at 2ºC, the sample was more sensitive to alum dose and performed worse at each alum dose compared to the 22ºC. The sample at 2ºC purportedly slowed the reaction kinetics sufficiently to prevent some molecular diffusion from occurring so that first and second stage rapid floc growth was limited. Limiting floc growth in Xiao et al.'s (2008b) study was correlated with increased residual turbidity in solution.

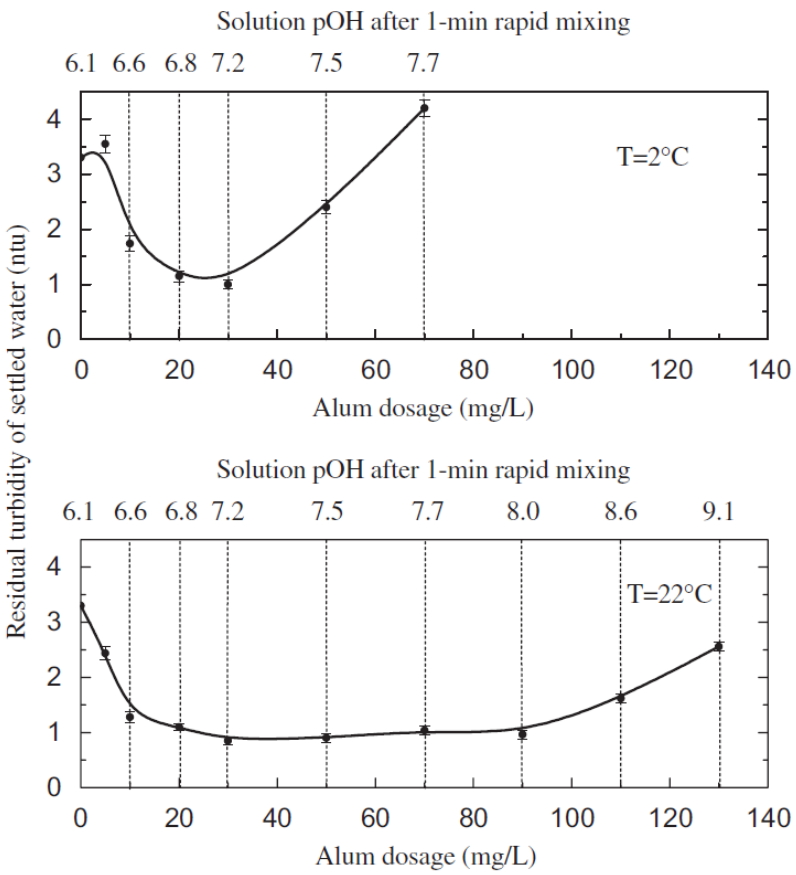

Figure 2-3. Effect of alum dosage on residual turbidity and on solution pOH after 1 min of alum addition (Initial pOH = 6.1, Initial turbidity = 3.3 NTU) (Xiao et al., 2008a).

Van der Waals attractive particle forces between particles can overcome repulsive forces if the particle surface charge is not completely neutral. Slight overdosing or underdosing of alum will produce similar performance. Although a wide range of applicable alum doses exist for waters with sufficient alkalinity, two different dose-based mechanisms for coagulation are commonly described: charge neutralization and sweep floc.

Charge neutralization is reported as a predominant mechanism utilized when the goal of the treatment plant is to form large, settleable floc particles (Letterman et al., 1999). The

idea of charge neutralization is that the coagulant will destabilize the negative surface charge of the colloid sufficiently to allow particle collisions between destabilized colloids to occur. Charge neutralization can be expected to be stoichiometric, if one knows the surface charge of the colloid, then one can add a sufficient amount of coagulant to neutralize that charge. However, there is no evidence from laboratory testing (Figure 3-12) that there is a simple stoichiometric relationship between alum dose and clay concentration, and the lack of a simple stoichiometric relationship suggests something more complicated than charge neutralization is occurring.

AguaClara utilizes alum as a coagulant. Alum will dissolve in water forming positively charged aluminum species and sulfate shown in equation (2-8).

$$Al_2(SO_4)_3 \leftrightarrow 2Al^{3+} + 3SO_4^{2-} \qquad (2\text{-}8)$$

While pH certainly has an enormous effect on solution chemistry as well as surface charge, cations and anions can also bind to the surface of particles competing with aluminum hydrolysis products for these surface sites. Sulfate is a predominant anion in solution when alum is used as the coagulant.

Letterman (1983) utilized a jar test to test the variables of pH and sulfate concentration on flocculation efficiency. Letterman (1983) tested the extent of particle removal when sulfate was present and not present in the system. When the sulfate ion was not present, charge neutralization and charge reversal was only possible in a narrow span of aluminum coagulant dosing and pH. There only existed a narrow window where turbidity

removal could be achieved by charge neutralization before particle repulsion from charge reversal by positive charge dominated the solution.

However, in the presence of sulfate, the electrostatic charge of particles in the solution remained near neutral over more than 4 orders of magnitude change in alum dose. The charge neutralization in this case was explained by the adsorption of sulfate ions on positive surface sites acting to neutralize surface charge over a wider range of coagulant doses. Another interesting note is that turbidity removal improved with coagulant dose and this improvement may have been due to the increased floc volume.

Sulfate and other anions have a high affinity for the aluminum hydroxide surface present on a flocculated particle (Letterman, 1983), thus sulfate adsorption reactions on the aluminum hydroxide surface affect the stoichiometry of charge neutralization. These adsorption reactions suggest that there is not a simple relationship between alum dose and turbidity in the raw water. Hohl et al. (1980) was first to describe the surface reactions between sulfate and aluminum hydroxide described below in equations (2-9) and (2-10) where $\overline{AlOH}$ denotes the aluminum hydroxide surface site.

$$\overline{AlOH} + H^+ + SO_4^{2-} \leftrightarrow \overline{AlOH}_2^+ + SO_4^{2-} \qquad (2\text{-}9)$$

$$\overline{AlOH}_2^+ + SO_4^{2-} + H^+ \leftrightarrow \overline{AlOH}_3SO_4 \qquad (2\text{-}10)$$

Letterman and Iyer (1985) utilized a model to predict the effects of solution and suspension variables of flocculation efficiency when aluminum salt coagulants were utilized. The studies of Letterman (1983) and Letterman and Iyer (1985) determined that

pH as well as sulfate concentration had a direct effect on charge neutralization and ultimately flocculation processes.

There also is competitive interaction of additional adsorbing anions such as bicarbonate and fluoride in charge neutralization processes. Additionally, positively charged species present in the water can interact with the surface. While the chemistry of the actual system can be quite complex, charge neutralization appears to be an important mechanism of coagulation when utilizing an aluminum salt as a coagulant.

Under most conditions, alum dose will be high enough so that precipitation reactions dominate. It is expected sulfate and other anions will adsorb on the surfaces of $Al(OH)_3(s)$ particles, in effect, aiding in further charge neutralization that is relatively insensitive to changes in alum dose at circumneutral pH. The efficiency of flocculation is expected to increase proportionally the amount of metal hydroxide precipitate in solution that acts to enmesh particles in sweep flocculation. Sulfate adsorption keeps the surface charge of all species near neutral and so sulfate adsorption is probably important in forming sweep floc. It appears from available information that precipitation reactions are more likely than charge neutralization to be a determinate factor in determining coagulation and flocculation efficiency.

Xiao et al. (2008b) found that coagulation of particles by charge neutralization to be a slow process unless voluminous hydroxide precipitates are formed in the solution. Counter to previous results, Xiao et al. (2008b) reported that flocs could grow in environments of positive (charge restabilization) and negative (charge neutralization)

electrophoretic mobility, while flocs did not always grow in environments where there was neutral electrophoretic mobility. Further testing is needed to confirm these findings.

Xiao et al.'s (2008b) study reported that enmeshment by floc particles could occur in spite of repulsive surface charges and a predominant factor of floc formation was the pH of the solution. Floc formation is believed to occur between pH ranges of 6.5-7.5 as illustrated in Figure 2-4.

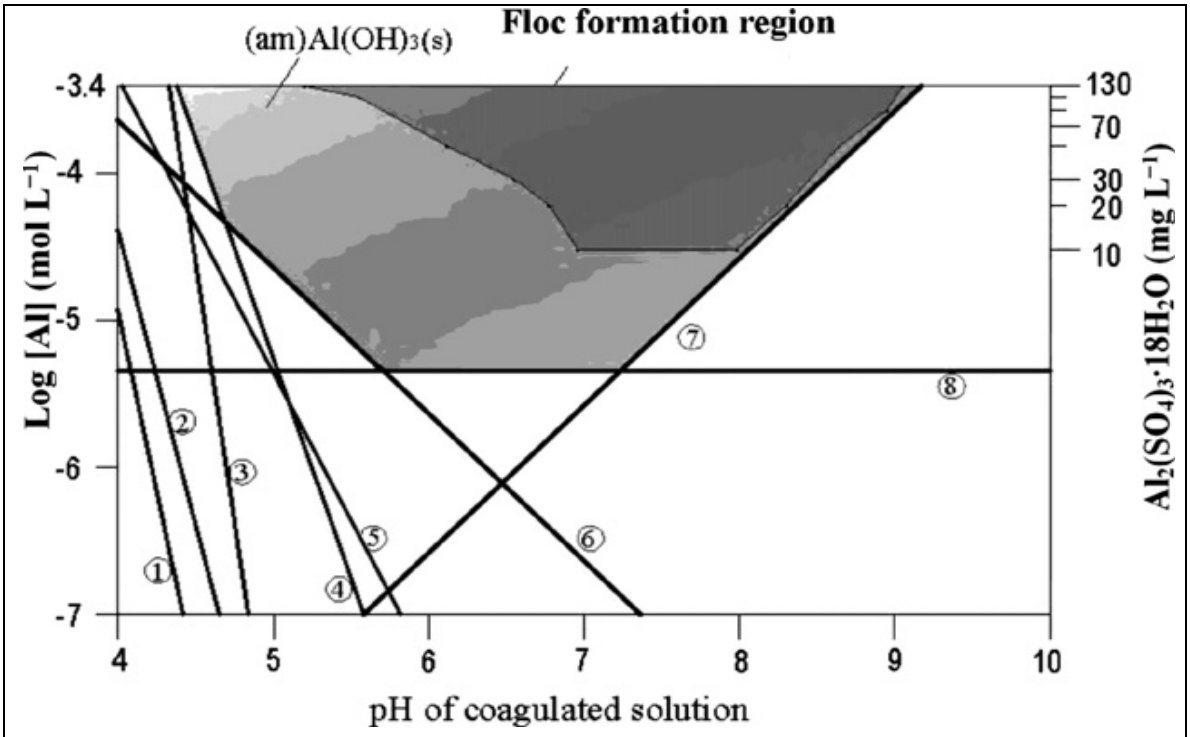

Figure 2-4. Aluminum solubility diagram in equilibrium with amorphous $Al(OH)_{3(s)}$ based on thermodynamic data, and floc formation region based on experimental observations. Lines 1, 2, 3, 4, 5, 6, 7, 8 represent the concentrations of $[Al_3(OH)_4]^{5+}$, $[Al_2(OH)_2]^{4+}$, $[Al_{13}O_4(OH)_{24}]^{7+}$, Al^{3+}, $Al(OH)^{2+}$, $Al(OH)_2^{+}$, $Al(OH)_4^{-}$, $Al(OH)_3(s)$, respectively (Xiao et al., 2008b).

2.5. Lamellar Sedimentation

Plate settlers allow for the operator to significantly decrease the capture velocity, while maintaining the same upflow velocity in the clarifier. At an angle of 40º or greater, particles in tube settlers tend to slide down because of gravity (Degremont, 1985). Galvin (1992) found that sludge that slipped down tube settlers back into the clarifier had good settling properties. The observation seems to indicate that some of the particles captured by tube settlers could grow in size as the flocs slide down the plate settler in an avalanche. The larger particles would then fall into the floc blanket below. Lamellar sedimentation could be important for low turbidity water, because it would return solids that escape the floc blanket back to the floc blanket. Thus plate or tube settlers could make it possible for floc blankets to be stable with lower turbidity waters. Returning solids could increase particle concentration in the floc blanket and could enhance floc blanket performance by increasing particle-particle interactions.

If designed correctly, lamellar sedimentation could significantly improve performance. The current AguaClara design for plate settlers provides a capture velocity of 10 m/day. While the plate settlers can capture all particle sizes, with proper flocculation and subsequent removal of particles through a floc blanket, a very small proportion of particles would end up in the effluent because a large proportion of particles' terminal settling velocity would exceed the capture velocity of the plate settlers. Counterintuitive to the idea that lamellar sedimentation would improve performance, some reviews from literature indicate that lamellar sedimentation does not enhance floc blanket performance.

The 5th edition (1999) Water Quality and Treatment: A Handbook of Community Water Supplies states:

> "Inclined Settling with Floc Blankets. Tube modules with the typical spacing of 50 mm between inclined surfaces are not cost-effective in floc-blanket tanks (Gregory, 1979). With the blanket surface below the tube modules, the settled-water quality is no better than from a stable and efficient tank without modules. With the blanket surface within the modules, the floc concentration in the blanket increases by about 50 percent, but no commensurate improvement in settled-water quality occurs. The failure of closely spaced inclined surfaces to increase hindered settling rates relates to the proximity of the surfaces and a circulatory motion at the blanket surface that counteracts the entrapment mechanism of the blanket (Gregory, 1979). The problem with closely spaced surfaces diminishes with more widely spaced inclined surfaces. An effective spacing is about 0.3 m, but no optimization studies are known to have been published. Large (2.9 m) plates, however, have been shown to be preferable to shorter (1.5 m) plates (Casey, O'Donnel, and Purcell, 1984). The combined action of suppressing currents and inclined settling with widely spaced surfaces can result in about a 50% greater throughput than with a good floc blanket without inclined surfaces. The proprietary Superpulsator tank is the Pulsator design with widely spaced inclined surfaces."

Galvin (1992) conducted a study that compared floc blanket performance with and without lamella. The study found similar removal efficiency when upflow velocity

increased from 75 m/day without lamella to 120 m/day with the addition of lamella. The study treated water with both NOM (25-50 on the color scale) and turbidity (6-30 NTU). Average effluent readings for both cases ranged from 1.6 to 4.0 NTU. After sedimentation, the effluent water was passed through a filter so there was no need for floc blanket performance to be optimized and instead this research focused upon gaining more throughput through the clarifier.

Contrary to the findings of other authors, Saleh and Hamoda (1999) observed that plate settler technology could increase removal efficiency in a sedimentation tank without a floc blanket while decreasing the overall volume of the sedimentation tank. Sarkar, et al. (2006) developed a model to predict plate settler efficiency based upon plant flow rate and plate settler geometry. In their model, efficiency is dependent on particle size as well as the initial concentration of solids.

It seems that performance of the plate settlers would be dependent on floc blanket characteristics such as the size of particles in the effluent from the floc blanket. Plate settler performance could enhance clarification performance, but is also dependent upon properties of the floc blanket. A more robust model will need to be developed to correlate floc blanket properties and particle size distribution with plate settler performance.

CHAPTER 3: PARAMETERS AFFECTING STEADY-STATE FLOC BLANKET PERFOMANCE[1]

3.1. Parameters affecting steady-state floc blanket performance

3.1.1 Abstract

[1] The contents of this chapter have been submitted to *Aqua* for publication with co-authors: Dr. M. Weber-shirk and Prof. L. Lion

A laboratory-scale reactor was used to simulate a water treatment process sequence of rapid mix, hydraulic flocculation, upflow clarification with a floc blanket, and lamellar sedimentation to accomplish removal of colloidal particles. This process sequence, followed by chlorination, has been employed to create affordable designs for water treatment in the Global South. This study focused on variables affecting performance of the floc blanket including: condition of hydraulic flocculation, raw water turbidity, coagulant dose, upflow velocity through the floc blanket, floc blanket height, and bulk density and solids concentration of the floc blanket. An upflow clarifier velocity between 90-110 m/day produced the best floc blanket performance for most influent turbidities studied. The results show that particle removal efficiency in lamellar sedimentation improved linearly with respect to floc blanket heights up to 45 cm. Improved performance is also correlated with increased hydraulic flocculator residence time and energy dissipation rate. At floc blanket heights above 45 cm, there is still improvement in performance for most cases, but improved performance and blanket height no longer follow a linear relationship. Lamellar sedimentation with a capture velocity of 10 m/day is a key component in improving clarifier performance when utilizing a floc blanket. Future studies are needed to determine mechanisms of particle removal in a floc blanket.

Keywords: AguaClara, floc blanket, flocculation, upflow sedimentation

3.1.2 Nomenclature

$A_{clarifier}$ cross-sectional area of the clarifier (L^2)

A_s normal area of the tube settler (L^2)

C_{in} influent concentration (M/L^3)

C_{out} effluent concentration (M/L^3)

C_s concentration of solids (M/L^3)

d inner diameter of tubing (L)

D tubular floculator coil diameter (L)

f_{ratio} ratio of the friction factor for curved tubing versus that for straight

g acceleration due to gravity (L/t^2)

G velocity gradient in viscous subrange (1/t)

$G\theta$ dimensionless flocculation parameter, product of G and θ

h_{floc} height of floc blanket (L)

h_l head loss (L)

h_{water} height of water that would produce the same pressure as h_{floc} (L)

L length of tubing (L)

N_{De} Dean number

$pC*$ removal efficiency $\left[-\log\left(\frac{C_{out}}{C_{in}}\right)\right]$

Q flow rate (L^3/t)

V is the average axial velocity of flow in the tube flocculator

V_{up} upflow velocity in the clarifier (L/t)

V_{growth} growth rate of floc blanket (L/t)

V_{ratio} ratio of the upflow velocity to the capture velocity

α angle of tube settler with respect to the horizontal

ε energy dissipation rate (L^2/t^3)

$\theta_{flocculator}$ hydraulic residence time of fluid in the hydraulic flocculator

$\theta_{clarifier}$ hydraulic residence time of fluid in upflow clarifier (t)

$\theta_{floc\ fluid}$ hydraulic residence time of fluid in floc blanket (t)

θ_{solids} residence time for solids in floc blanket (t)

ν kinematic viscosity (L^2/t)

v_c capture velocity of the tube settler (L/t)

ρ_{water} density of water (M/L^3)

$\rho_{bulk\ floc}$ bulk density of floc blanket (M/L^3)

Φ porosity of the floc blanket

3.1.3 Introduction

Cornell University's AguaClara Project is actively working to improve drinking water quality in the Global South through an automated online design service for gravity-driven municipal water treatment plants. These plants are designed to remove colloidal particles that correlate with the prevalence of pathogenic organisms, interfere with disinfection, and negatively impact drinking water quality. An AguaClara goal is to provide an average effluent turbidity of less than 1 NTU (Nephelometric Turbidity Unit) after sedimentation without subsequent filtration. Thus, a crucial component of design is optimization of the sedimentation tank.

Economic constraints in the Global South mandate cost-effective and efficient designs and a high cost is associated with the construction of large (and deep) horizontal flow sedimentation tanks. Compared to horizontal flow sedimentation, vertical flow sedimentation can reduce reactor volume while maintaining similar levels of treatment (Tchobanoglous & Schroeder, 1987). The use of lamellar (or plate) settlers can potentially allow a reduction in the size of vertical flow sedimentation tanks while maintaining a similar standard of treatment (Saleh & Hamoda, 1999). Plate settlers are designed for capture of particles with a specific terminal settling velocity or their design can be based on a desired effluent turbidity. Schulz and Okun (1984) recommend capture of particles with terminal settling velocities between 10 and 30 m/day with AguaClara facilities currently designed for a capture velocity of 10 m/day.

Flocculation employed in a treatment process train before sedimentation affects sedimentation efficacy. In an upflow sedimentation tank, particles whose settling velocity is greater than the upflow velocity will settle out, while particles with lower settling velocities are either captured by plate settlers or are lost to the effluent. Effective flocculation before sedimentation will produce larger particles with higher sedimentation velocities.

At appropriate upflow velocities, a fluidized bed of concentrated flocs forms in upflow sedimentation basins. A floc blanket is a stable fluidized bed of flocculated particles with a visible floc-water interface between the concentrated flocs and relatively clear effluent layer above. Upflow clarification with a floc blanket is thought to enhance particle removal compared to conventional upflow clarification by providing an increased likelihood of particle-particle interactions that can result in further flocculation of particles and filtration-like removal of small particles (Miller & West, 1968; Reynolds & Richards, 1996; Tchobanoglous, Burton, & Stensel, 2003).

The objective of this research was to characterize and optimize floc blanket performance at steady-state with respect to the following parameters: alum dose at different influent turbidities, upflow velocity in the clarifier, floc blanket height, and the stipulation of hydraulic flocculation proceeding upflow sedimentation. Although constant dosing on a pilot and laboratory-scale has been documented in the literature (Miller & West, 1968; Zhang et. al. 2006), this study is unique with respect to: the range over which each parameter was evaluated, the continuous monitoring of effluent turbidity from both the

floc blanket clarifier as well as subsequent tube settlers, and stringent control of the energy dissipation rate and residence time in the flocculator and floc blanket clarifier.

Performance was measured based upon continuous sampling of turbidity above the floc blanket and tube settler effluent and is reported here as the negative log of the ratio of the treated and influent turbidities (pC*) in equation (3-1).

$$pC^* = -\log\left(\frac{C_{out}}{C_{in}}\right) \tag{3-1}$$

Sung, Lee, and Wu (2005) and Gould (1974) identified upflow velocity as critical in determining floc blanket stability and performance utilizing mass flux theory. If upflow velocity is too high, a large proportion of particles will be washed out making it difficult to establish a floc blanket. If the upflow velocity is too low, sedimentation can irreversibly change the nature of the flocculated particles and the effectiveness of treatement (Arai, Yazaki, & Otsub, 2007). The average upflow velocity (V_{up}) is defined as the flow rate (Q) divided by the cross-sectional area ($A_{clarifier}$) of the clarifier shown in equation (3-2).

$$V_{up} = \frac{Q}{A_{clarifer}} \tag{3-2}$$

Floc blankets are reported to be effective at removing colloidal particles and organic matter for a wide range of influent qualities (Lin, et al., 2004). For high turbidity water, some investigators have recommended that the majority of the turbidity should be removed in a pre-sedimentation tank with a suggested residence time of 90 minutes

(Chen et al. 2002). For high turbidity source waters (>200 NTU), Sung et. al. (2003) reported that treatment was feasible with the addition of a pre-sedimentation tank. In contrast, Sung et al. (2005) reported a stable floc blanket could be formed from 450 NTU source water without the need for a pre-sedimentation tank or two-stage clarifier.

At very low turbidities (<5 NTU) floc blankets have been reported to be easily washed out (Chen et al., 2006). Chen et. al. (2002) observed stable floc blanket formation from raw waters with turbidity between 4-10 NTU in full-scale clarifiers, but during a low turbidity period (2-3 NTU), floc blankets gradually lost solids until no floc blanket remained. Thus, it appears that floc blanket formation may not be feasible in very low turbidity water.

At conditions of low turbidity, flocculation processes are less efficient in creating large flocs and solids loading to a floc blanket clarifier are significantly reduced. Utilizing plate settlers above the floc blanket could extend the range of floc blanket utility because particles that are captured by the plate settler will fall back into the underlying floc blanket, thereby increasing solids concentration and solids residence time in the floc blanket.

Flocculation prior to the upflow clarifier is expected to affect the density and size of entering particles, ultimately affecting floc size distribution and concentration in the floc blanket. The ability of particles to remain suspended in a floc blanket depends upon the settling velocity of the flocculated particles counterbalanced against the upflow velocity in the clarifier (Gregory, Head, & Graham, 1996; Head, Hart, & Graham, 1997). The

density and size of a flocculated particle are functions of how the floc was formed, thus energy dissipation rate and residence time in a flocculator prior to the upflow floc blanket clarifier could be important parameters that influence particle removal.

3.1.4 Materials and Methods

3.1.4.1 Setup and Control of Parameters

Conditions of constant input turbidity were created using a concentrated kaolin clay suspension diluted with temperature controlled, aerated tap water (Figure 3-1) to produce a raw water source for treatment.

Figure 3-1. Schematic showing how influent turbidity is controlled using process control software written by Weber-Shirk (2008).

Raw water source turbidity was continuously sampled using a turbidimeter, and computer controlled to maintain a target turbidity. When the turbidity reading dropped below the

target level, process control software sent a signal to an output control box to open a solenoid valve allowing release of a small amount of concentrated clay stock solution into the raw water source. The result was relatively constant input turbidity with a coefficient of variation of ± 3%.

Other controlled influent parameters included: water temperature and water level in the raw water source tank. Temperature and water level in the raw water source tank were controlled using process control software that monitored pressure and temperature sensors, and controlled solenoid valves connecting cold and hot tap water to the system. The pH of the source water did not vary significantly and was not controlled. A summary of raw water characteristics is provided in Table 3-1.

Table 3-1. Raw water characteristics

Parameter	Average Value
Temperature	22.5 ± 0.5 ºC
pH	7.5 ± 0.3
Aluminum concentration prior to addition of alum	90 ± 70 μg/L
Turbidity	Experimentally varied between 10-500 NTU
Total Hardness*	150 mg/L as $CaCO_3$(s)
Total Alkalinity*	111 mg/L as $CaCO_3$(s)
Total Organic Carbon*	2.0 mg/L

*Denotes value obtained from 2008 consumer water quality report for Cornell University Water System

Raw water was combined with a desired amount of alum, and rapid mix was achieved by directing the flow through a tube 0.48 cm-I.D (inner diameter) and 1 m in length resulting in turbulent flow for all flow rates tested with varying energy dissipation rates (0.05

W/kg - 1.10 W/kg) (Figure 3-2). The alum coagulant was prepared daily to avoid ageing (Rossini, Garcia, & Galluzo, 1999) and to improve reproducibility.

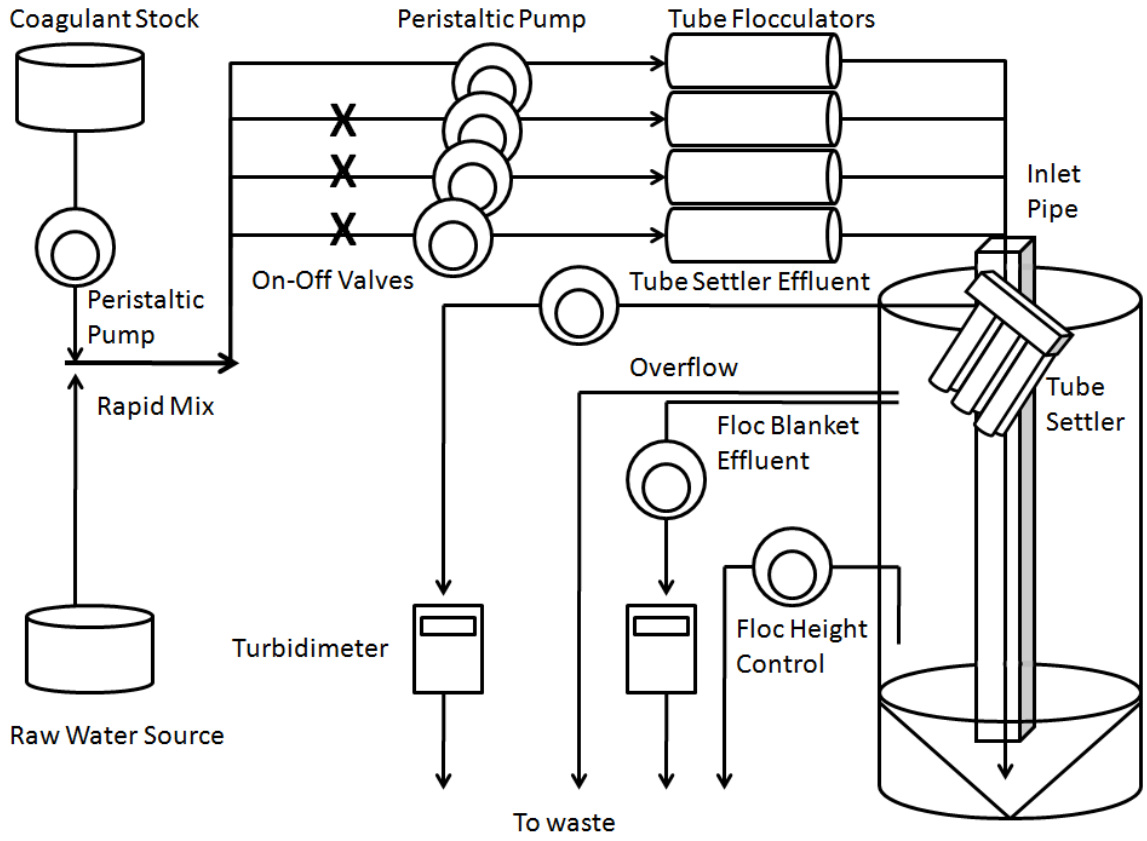

Figure 3-2. Schematic of flow through laboratory scale plant.

In this research one to four coiled tube flocculators in parallel were used to vary the energy dissipation rates without changing the overall plant flow. Laminar flow in a straight tube provides a predictable velocity gradient as shown in equation) (Ito, 1969).

$$G = \frac{64Q}{3\pi(d)^3} \qquad (3\text{-}3)$$

Where: G (s^{-1}) is the velocity gradient for laminar tube flow, Q is flow rate, and d is the tubing diameter.

Coiled tubes develop secondary flow circulation (Zhou & Shah, 2006) that causes additional mechanical energy loss and increased velocity gradients. Liu and Masliyah's model (1993) for Dean numbers less than 5000 compared the ratio of the friction factor of curved versus straight tubing $\left(f_{ratio}\right)$ based upon the calculated Dean number (N_{De}) equations) and).

$$N_{De} = \frac{Vd}{\nu}\left(\frac{d}{2D}\right)^{\frac{1}{2}} \tag{3-4}$$

$$f_{ratio} = \frac{1 + \left[0.0908 + 0.0233\left(\frac{d}{D}\right)^{\frac{1}{2}}\right] N_{De}{}^{\frac{1}{2}} - 0.132\left(\frac{d}{D}\right)^{\frac{1}{2}} + 0.37\left(\frac{d}{D}\right) - 0.2}{1 + \frac{49}{N_{De}}} \tag{3-5}$$

where: D is the coil diameter, V is the average axial velocity of flow in pipe, and ν is kinematic viscosity. Friction factors determined by equations) and) were used to predict head loss (and the related energy dissipation rates) for the flocculation process used in this research.

Flow from the rapid mix entered coiled tube flocculators (inner diameter, d = 0.95 cm). For constant volumetric flow rate (Q) the residence time (θ) in the flocculator was controlled by the length of the tube flocculator (L) equation (3-6). The energy dissipation rate (ε) is the energy loss per unit time and can be calculated from the product of head

loss through the flocculator (h_l) and acceleration due to gravity (g) per unit residence time in equation (3-7). The velocity gradient in the viscous subrange (G (s^{-1})) is related to the energy dissipation rate and fluid viscosity (ν) (Tambo & Hozumi, 1979) in equation (3-8). The average energy dissipation rate in flocculation was controlled by the number of tube flocculators utilized (between 1 and 4) and the flow rate through each tube flocculator.

$$\theta = \frac{L}{Q}\frac{\pi d^2}{4} \tag{3-6}$$

$$\varepsilon = \frac{g h_l}{\theta} \tag{3-7}$$

$$G = \sqrt{\frac{\varepsilon}{\nu}} \tag{3-8}$$

After tube flocculation, the flow was released 8 cm from the bottom of the floc blanket reactor. The upflow floc blanket reactor was 11.4 cm- I.D. and 90 cm high. A cone 15 cm high inclined at 67 degrees was placed in the bottom to reduce the volume of the reactor where flocs could settle out. The floc blanket elevation was controlled by continuously removing fluid at a desired height in the upflow column using a flow equal to one sixth the total flow rate in the reactor. Other effluent was removed from the reactor using a combination of controlled flow through a tube settler consisting of a cluster of 6 tubes (used to mimic lamellar sedimentation) and an overflow weir 2 cm from the top of the reactor. The tube settler was located 5 cm from the top of the reactor and was utilized

to create particle capture velocities that would be comparable to the plate settler capture velocities in full-scale water treatment plants.

A peristaltic pump pulled water from the top of the tube settlers at a flow rate set to control the capture velocity (V_c) of the tube settler at 10 m/day through the relationships shown in equations (3-9), and (3-10) (Schulz & Okun, 1984).

$$\frac{V_\alpha}{V_c} = \frac{L\cos(\alpha) + d\sin(\alpha)}{d} \tag{3-9}$$

$$Q = \frac{L\cos(\alpha) + d\sin(\alpha)}{d}\left(\pi\left(\frac{d}{2}\right)^2 n\right)V_c \tag{3-10}$$

Where: Q is the pump flow rate, d is the inner diameter of the tube (d = 0.95 cm), n is the number of tubes utilized (n = 6), L is the length of the tube (L = 19 cm), α is the angle of orientation (α = 60°), A_s is the normal area of the tube settler, and V_α is the average fluid velocity in the tube settler.

3.1.4.2 Data Acquisition and Sampling

Turbidity readings were obtained for continuous sampling of both the clarified fluid above the floc blanket and for the effluent from the tube settler using Micro TOL Turbidimeters (HF Scientific Model 20053, Ft Myers, Fl). The clarified water above the floc blanket was continuously sampled 5 cm below the overflow weir. Raw water turbidity was also logged and compared to the effluent data to determine particle removal efficiencies. Exemplary results for steady-state performance are presented in Figure 3-3.

These results indicate that an effluent turbidity below 1 NTU is quite feasible for the process sequence of flocculation, floc blanket clarification and lamellar sedimentation.

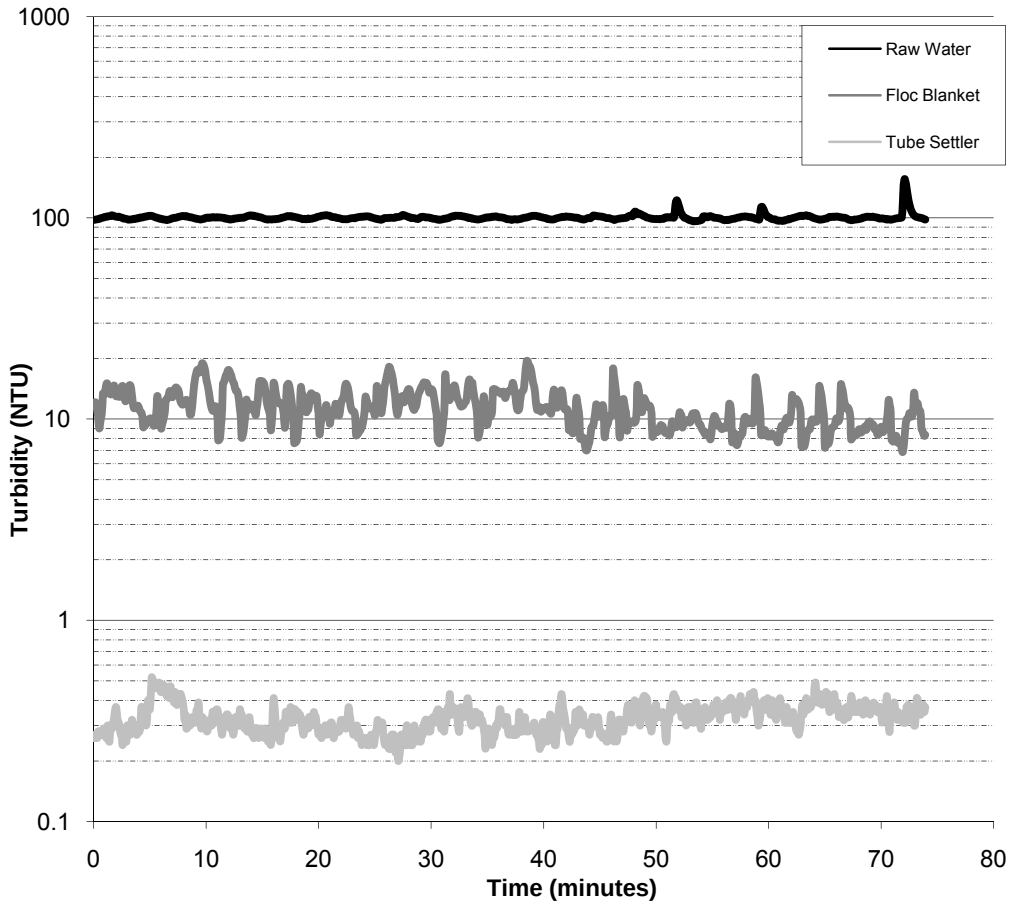

Figure 3-3. Continuously sampled turbidity readings for raw water influent, clarified water above the floc blanket and the tube settler effluent. The upflow velocity in the floc blanket was 100 m/day and the capture velocity in the tube settler was 10 m/day.

Data presented in this paper are for conditions of floc blanket steady-state. Steady-state was assumed to be reached when the floc blanket obtained its full height and performance of the floc blanket did not change as measured over three theoretical maximum fluid

residence times where residence time (θ_{fluid}) is defined as the total volume of the clarifier ($\forall_{clarifier}$) divided by the total flow rate (Q_{total}). For an upflow velocity of 100 m/day, the theoretical maximum hydraulic residence time was 13.3 minutes. A distinction was made between theoretical maximum hydraulic residence time and that of the hydraulic residence time in the floc blanket ($\theta_{floc\ fluid}$) that was based upon floc blanket height and floc blanket porosity in equation (3-14).

Data collected at steady-state were the average over three maximum theoretical hydraulic residence times where measured performance remained relatively consistent for the tube settler and floc blanket effluent as shown in Figure 3-3. Bulk density of the floc blanket was measured using a pycnometer and solids concentrations were obtained as described in Standard Methods (Clesceri, Greenberg, & Eaton, 1998). A linear relationship between solids concentration (C_s), and bulk density ($\rho_{bulk\ floc}$) in the floc blanket was observed in equation (3-11) over a wide range of floc formation conditions (Figure 3-4).

$$\rho_{bulk\ floc} = 0.687\,Cs + \rho_{water} \qquad (3\text{-}11)$$

Where: ρ_{water} is the density of water.

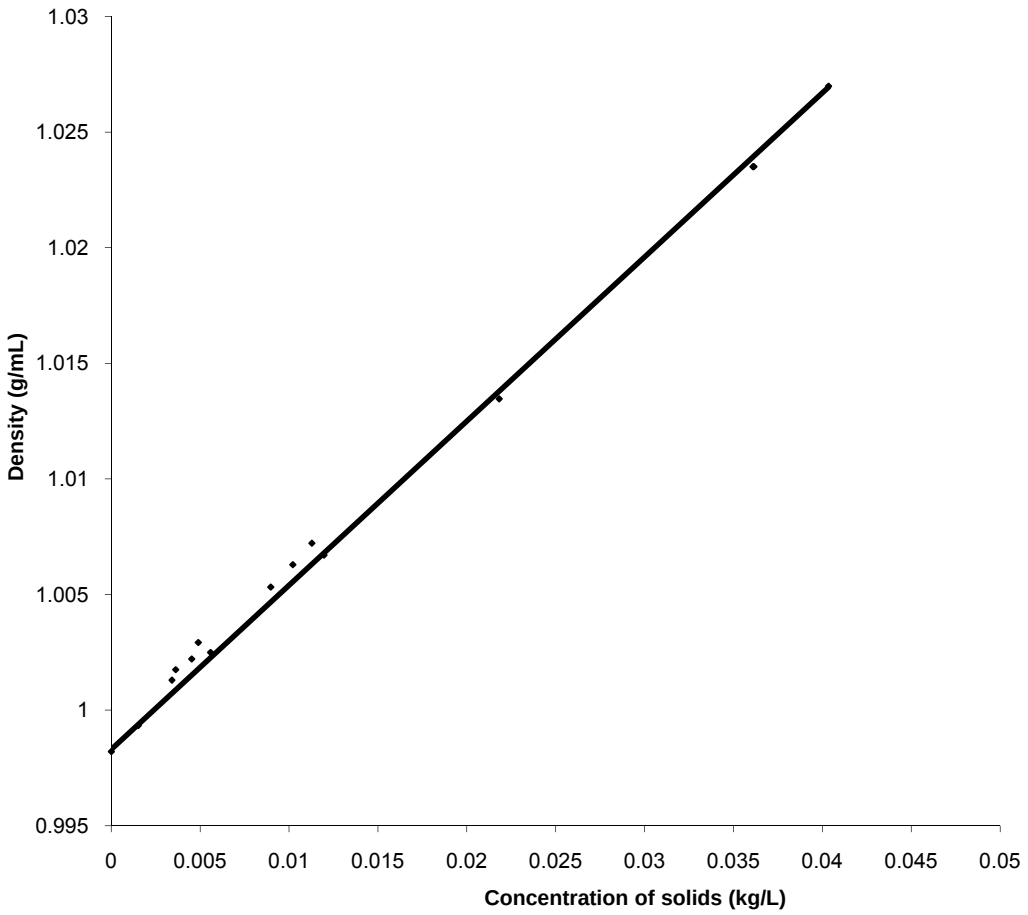

Figure 3-4. Relationship between floc blanket density and solids concentration (r^2 = 0.98).

3.1.5 Results and Discussion

3.1.5.1 Change in solids concentration in floc blanket with upflow velocity

Solids concentration in the floc blanket were measured at heights of 72, 51, 40, 33, 26, and 15 cm for a fully built floc blanket of 75 cm. Results are shown in Figure 3-5.

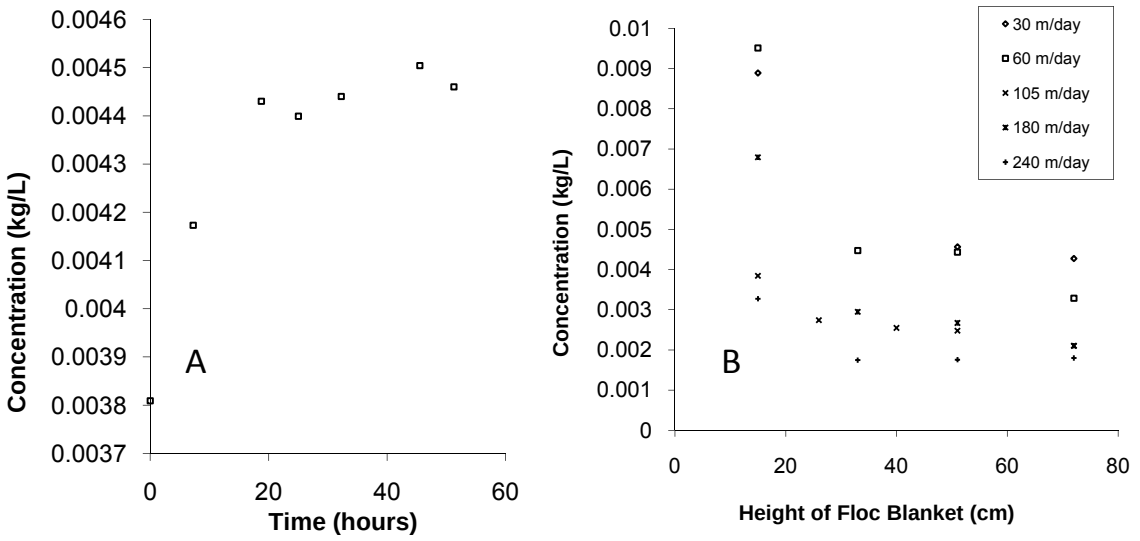

Figure 3-5. A. Solids concentration sampled at a height of 51 cm from the bottom, starting at time zero when the floc blanket reached a target height of 75 cm, with an upflow velocity of 120 m/day.

B. The change in the solids concentration with respect to height of the floc blanket in the reactor for several upflow velocities. Influent turbidity was 100 NTU and the alum dose was 55 mg/L for both A and B.

Solids concentration tended to increase as upflow velocity decreased. The floc blanket solids concentration measured at a height of 51 cm that did not change significantly over a large time period 6 hours after the floc blanket formed. Small changes could be attributed to statistical differences in samples as well as small changes in mass flux at different periods of time in a floc blanket. Once a floc blanket reached the target height there was little evidence of additional changes in solids concentration over a very long

time period (Figure 3-5A). Consistent with the observations of Gould (1969), the solids concentration throughout the floc blanket was fairly uniform.

3.1.5.2 Energy dissipation in the floc blanket

A force balance requires the head loss through a fluidized bed to be proportional to the difference between the bulk density of the fluidized bed ($\rho_{bulk\ floc}$) and the density of water (ρ_{water}). Head loss, h_l , through the floc blanket with height (h_{floc}) is given by

$$h_l = h_{floc} \frac{\rho_{bulk\ floc} - \rho_{water}}{\rho_{water}} \qquad (3\text{-}12)$$

Combining equations (3-12) and (3-11) gives:

$$h_l = h_{floc} \frac{0.687 Cs}{\rho_{water}} \qquad (3\text{-}13)$$

The hydraulic residence time in the floc blanket ($\theta_{floc\ fluid}$) can be defined in terms of the height of the floc blanket (h_{floc}), the upflow velocity of the fluid (V_{up}) and the porosity of the floc blanket (Φ).

$$\theta_{floc\ fluid} = (\Phi) \frac{h_{floc}}{V_{up}} \qquad (3\text{-}14)$$

The porosity of the floc blanket was determined to be approximately 85% based upon a 30 minute settling test. Substituting head loss, h_l , and hydraulic residence time, $\theta_{floc\ fluid}$, into the energy dissipation rate relationship in equation (3-7) allows floc blanket energy

dissipation rate to be expressed in terms of upflow velocity and solids concentration in equation (3-15).

$$\varepsilon = \frac{gV_{up}}{(\Phi)} \frac{0.687Cs}{\rho_{water}} \tag{3-15}$$

From equation (3-15) the energy dissipation rate in a floc blanket can be compared at different upflow velocities based upon the average solids concentrations found in Figure 3-5. The values of G and $G\theta_{floc\ fluid}$ for the floc blanket could then be estimated for a floc blanket based upon the hydraulic residence time in the floc blanket and the value of G in equation (3-8) calculated based upon the energy dissipation rate in equation (3-15).

One can estimate the minimum size of a floc particle that will experience turbulent flow in the flow blanket ($\eta_{Kolmogorov}$) utilizing equation (3-16) and estimating energy dissipation rate using equation (3-15).

$$\eta_{Kolmogorov} = \left(\frac{\nu^3}{\varepsilon} \right)^{\frac{1}{4}} \tag{3-16}$$

For a floc blanket formed with an upflow velocity of 100 m/day with a solids concentation of 0.004 kg/L, the Kolmogorov scale is 0.4 mm. This result suggests that the flow in the pores of the floc blanket is turbulent since most flocs in the floc blanket have been visually observed to be at least one millimeter in size. Although collisions between colloidal sized particles can still be considered as occuring in a laminar fluid, collisions between larger flocs separated by distances exceeding 0.4 mm will be influenced by

turbulence. A flocculation analysis in a floc blanket utilizing $G\theta$ for colloids is appropriate.

Predicted variation of G and $G\theta$ with V_{up} in the floc blanket is shown in Figure 3-6A and B.

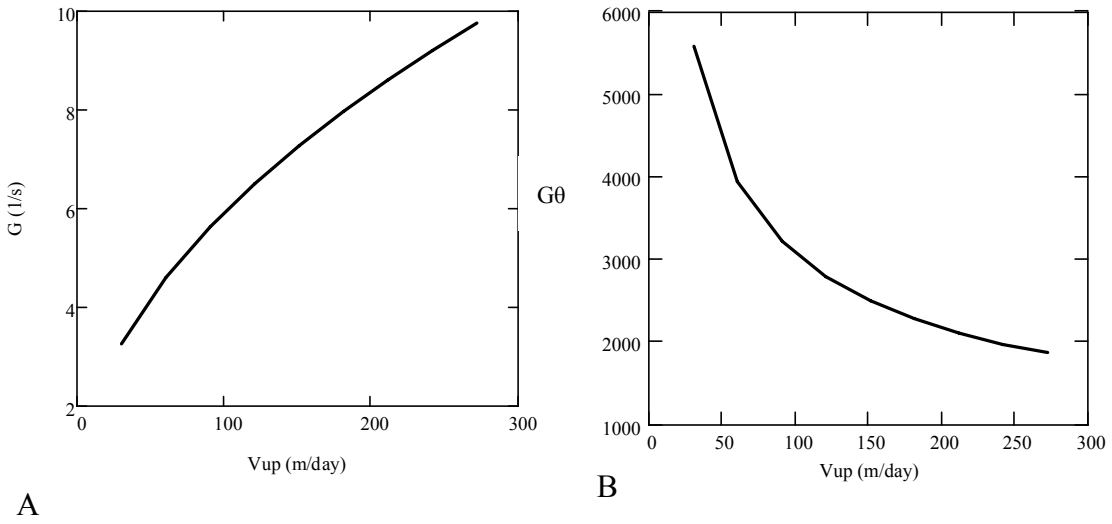

Figure 3-6. A. G as a function of upflow velocity (right). B. $G\theta_{floc\ fluid}$ as a function of upflow velocity for a floc blanket height of 75 cm (left).

3.1.5.3 Energy dissipation in tube flocculators

Head loss across the tube flocculators was measured for flows ranging from 100 mL/min to 900 mL/min (Figure 3-7) with a diameter of coil (D) of 12.5 cm, and an inner tube diameter (d) of 0.95 cm. The total length of tubing was 16 m of which 12.5 m was coiled. All flow was laminar with a maximum Reynolds number of 2200.

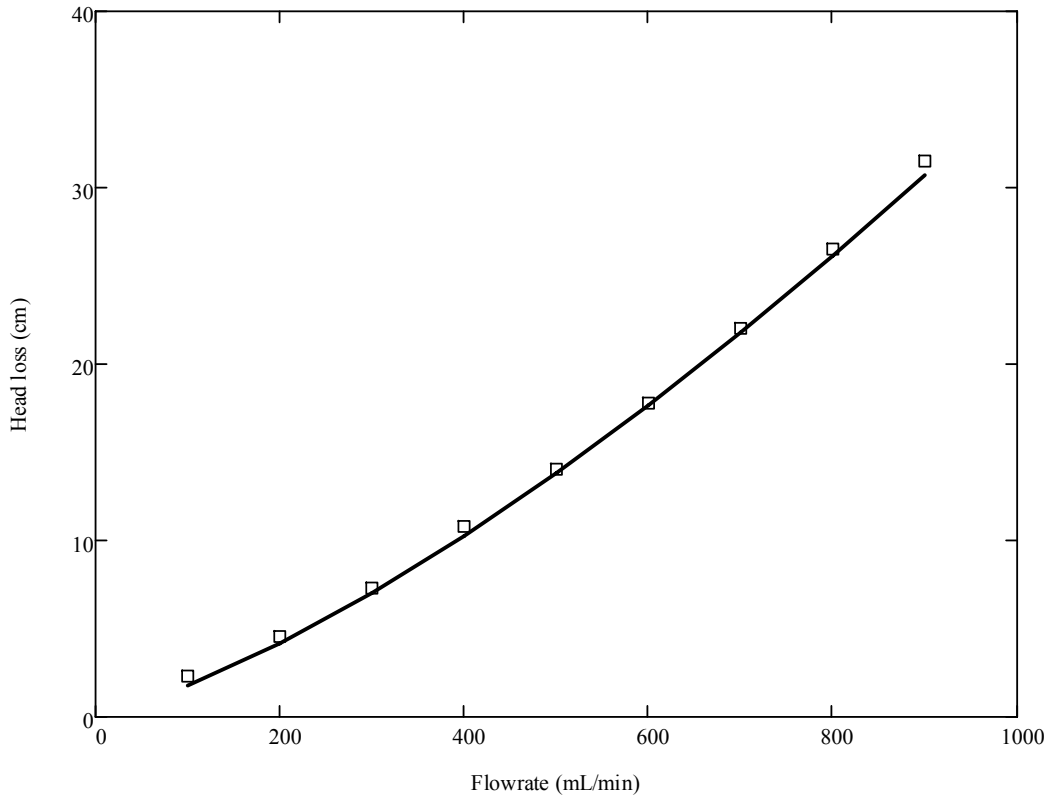

Figure 3-7. Measured head loss (boxes) across the tube flocculator compared to theoretical predictions (curve) of Lui & Masliyah for laminar flow through coiled tubes.

The measured head loss data fit very well to the Liu & Masliyah correlation in equation). Energy dissipation (ε) in equation (3-7) and the velocity gradients for the viscous subrange (G) in equation (3-8) were calculated and compared to the measured G values based upon measured head loss (Figure 3-8A). The resulting value of $G\theta$ was calculated multiplying G by the hydraulic residence time in the flocculator (θ) (Figure 3-8B). The values of $G\theta$ and G presented in Figure 3-8 are representative for the range of flow rates through one tube flocculator utilized this in this experiment. Gθ would be independent of

flow rate for laminar flow through a straight tube flocculator, but the nonlinear effect of tube curvature on energy dissipation causes Gθ to increase with flow rate.

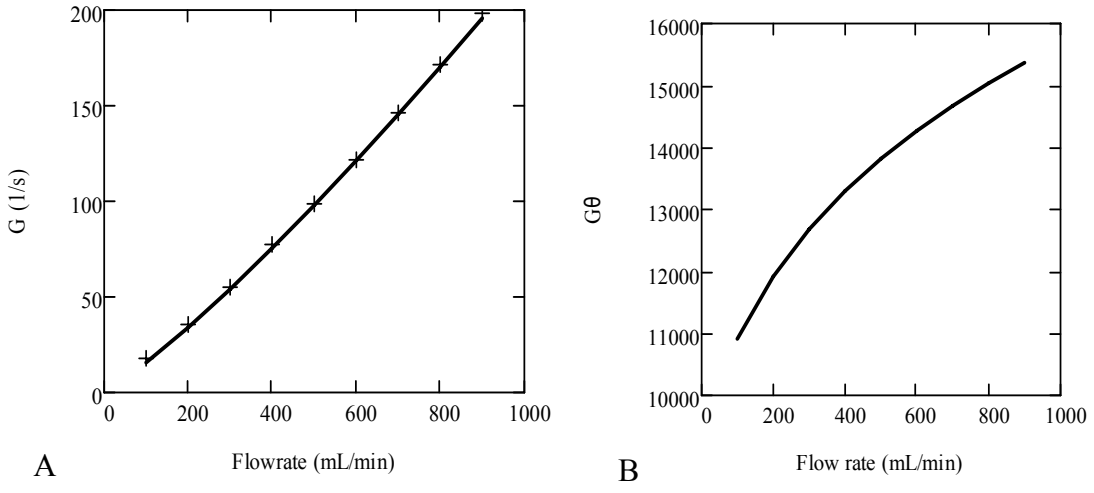

Figure 3-8. A. Measured G (crosses) compared to theoretical predictions (line) based upon Lui & Masliyah for laminar flow through coiled tubes (right). B. Theoretical $G\theta$ versus flow rate (left).

Energy dissipation rates in the flocculator were orders of magnitude higher than energy dissipation rate in the floc blanket (Figure 3-8A and Figure 3-8B). Removal of colloid particles inside the floc blanket could still potentially occur even with lower energy dissipation rates because of relatively long floc blanket hydraulic residence times (Figure 3-6B) and the much higher floc volume fraction that reduces the time required for particle-particle collisions.

3.1.6 Characterizing floc blanket effluent performance at steady-state

3.1.6.1 Effect of upflow velocity on floc blanket effluent performance

The upflow velocity in the sedimentation column was varied while alum dosage, turbidity, and floc blanket height (75 cm) were held constant. Figure 3-9A and B shows the steady-state turbidity in the fluid above the floc blanket and in the effluent from the tube settler for influent turbidities of 100 and 500 NTU.

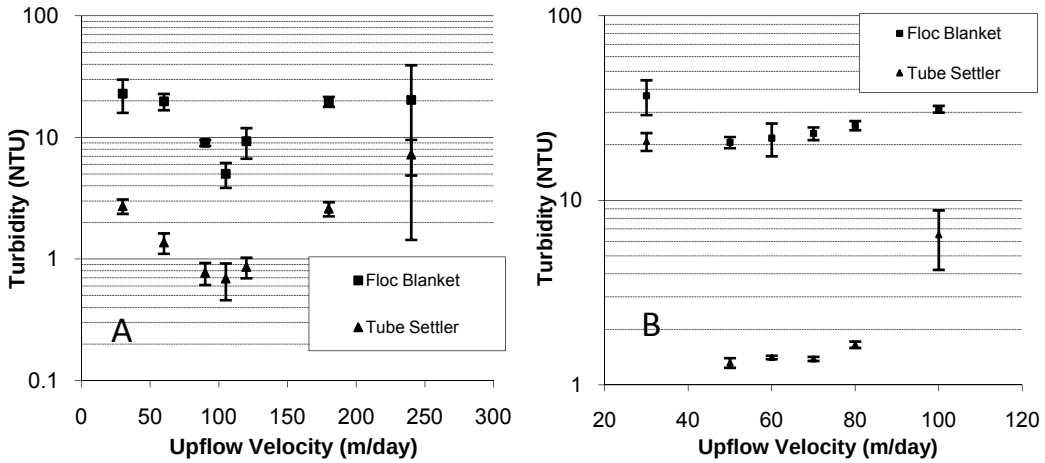

Figure 3-9. A. Effluent turbidity of tube settlers and floc blanket at 100 NTU and 55 mg/L alum dosage. B. Effluent turbidity of tube settlers and floc blanket at 500 NTU and 95 mg/L alum dosage.

As seen in Figure 3-9 for 100 and 500 NTU water, an optimal range of upflow velocities produced a floc blanket with a relatively clear effluent above. The optimum upflow velocities were approximately 100 m/day and 70 m/day for influent turbidities of 100

NTU and 500 NTU, respectively. Upflow velocities outside the optimal range increased turbidity and performance variability.

In extreme cases of low upflow velocity, the flow was not sufficient to counteract the terminal settling velocity of the flocculated particles. The bottom 25 cm of the upflow clarifier was no longer fluidized and instead small flow channels formed in the settled sludge. The small flow channels with their associated high velocities likely caused floc breakup and the production of small floc particles that could not be captured by the tube settlers. Increased variability in the effluent turbidity could be attributed to variability in channeling through the settled sludge over time. For very high upflow velocities, the upflow velocity was greater than the settling velocities of most of the flocculated particles so that the floc-water interface became blurred and the suspension more dilute.

The effects of variable alum dose were tested at 100 NTU and 200 NTU influent turbidities (Figure 3-10). Upflow velocity and floc blanket height (75 cm) were held constant while alum dose was varied. Each floc blanket was reformed to a height of 75 cm.

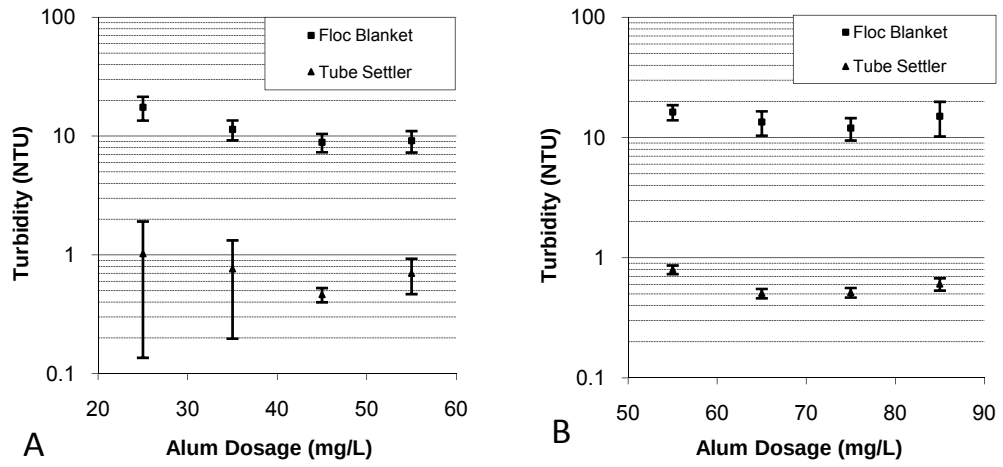

Figure 3-10. A. Effect of alum dosage on 100 NTU water. B. Effect of alum dosage on 200 NTU water.

The optimum alum doses for 100 NTU and 200 NTU water were approximately 45 mg/L and 65 mg/L, respectively (Figure 3-10). However, performance did not significantly deteriorate at higher dosages of alum in either case. Optimization of alum dose was also tested for a higher influent turbidity (500 NTU) and a lower influent turbidity (10 NTU). For optimal alum dosage at 500 NTU, the optimal upflow velocity occurred at approximately at 70 m/day (Figure 3-11) and it was 100 m/day for 10 NTU water (data not shown). At the influent turbidity of 500 NTU, the tube settler effluent did not fall below 1 NTU, however, a pC^* removal efficiency of 2.5 was achieved.

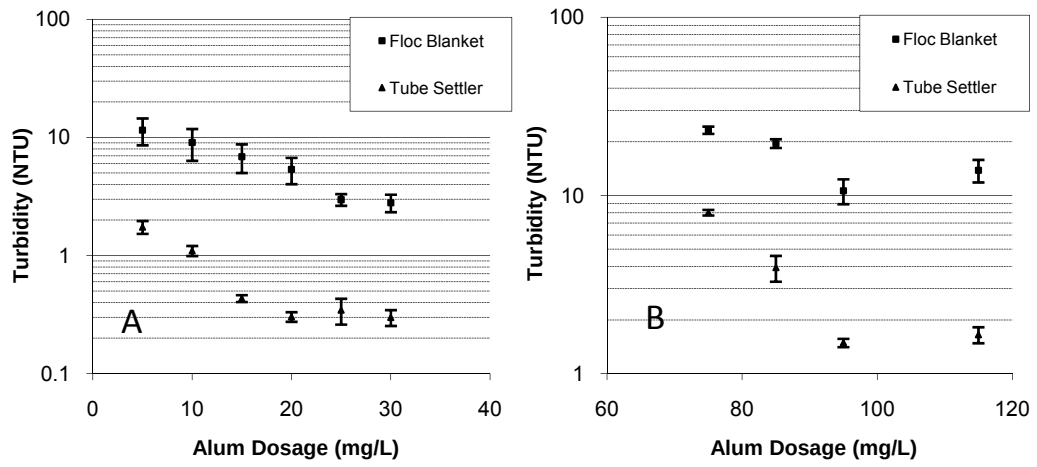

Figure 3-11. A. Effect of alum dosage on 10 NTU water. B. Effect of alum dosage on 500 NTU water.

Underdosing of alum could decrease the size and the amount of flocculated particles entering the floc blanket. Thus, a higher proportion of particles would not be captured by tube settlers or the clarifier. Overdosing showed little effect on floc blanket performance for the range of dosages tested. Based upon optimal performance of the entire treatment train, a dosing model for the specific conditions of the raw water was developed (Figure 3-12).

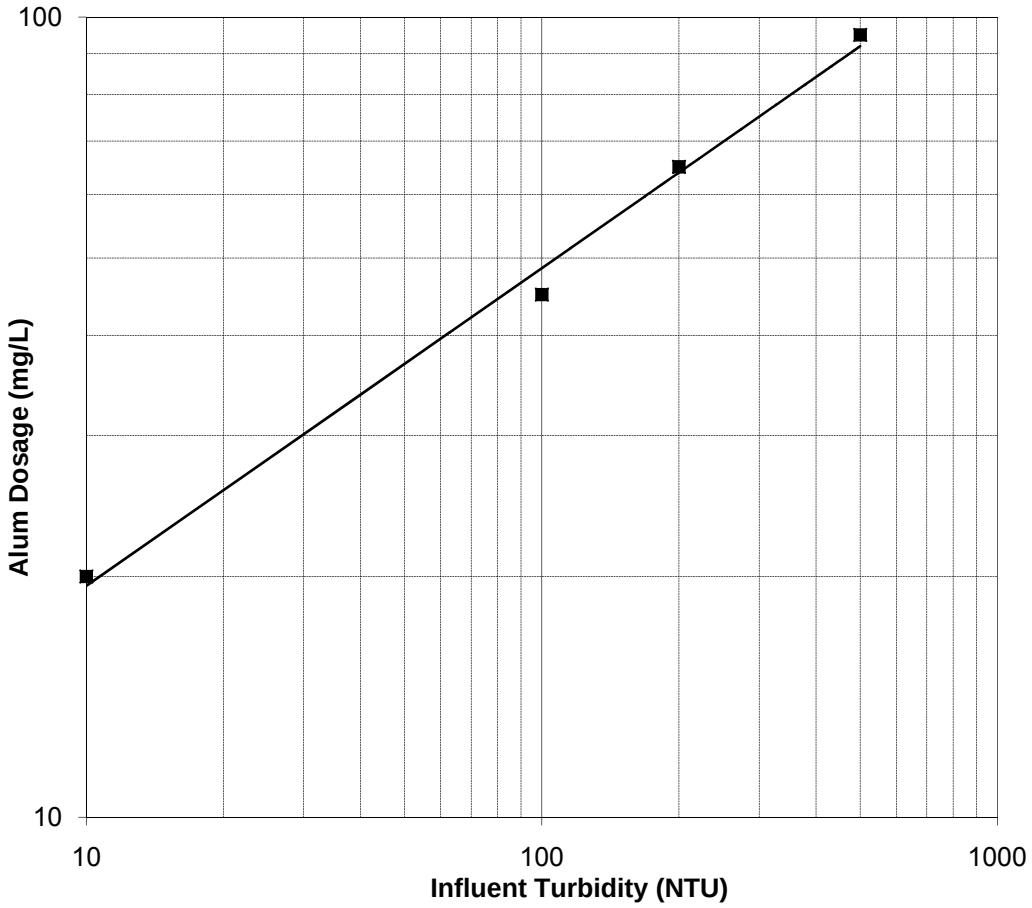

Figure 3-12. Empirical dosing model for the system studied.

While the model is empirical, the data fits well to a power law function in equation ((3-17).

$$Alum\ Dosage\,(mg/L) = 7.8\,(Turbidity)^{0.4} \qquad (3\text{-}17)$$

3.1.6.2 Effect of floc blanket height on floc blanket effluent performance

Effluent turbidity was monitored over a range of floc blanket heights. Conditions for these experiments were: alum dosage 45 mg/L, influent turbidity 100 NTU, and an

upflow velocity of 100 m/day. Miller and West (1968) observed increased removal efficiency with increasing blanket height. These observations were confirmed in this study (Figure 3-13).

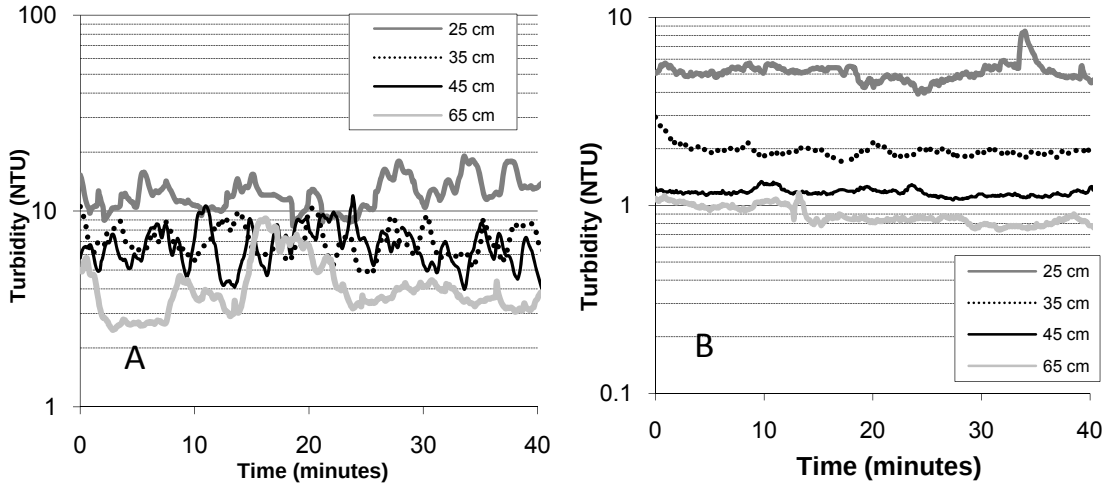

Figure 3-13. A. Effect of floc blanket height on floc blanket effluent performance. B. Effect of floc blanket height on tube settler effluent performance.

Contrary to the findings of Casey et al. (1984) and Gregory (1979), the laboratory scale data obtained in this study suggest effective implementation of lamellar settlers above a floc blanket can significantly improve effluent performance. The tube settlers were vital in achieving effluent turbidities below 1 NTU (**Error! Reference source not found.**B) at loc blanket heights above 65 cm. Based upon these results, a small water treatment plant (6.3 L/s) equipped to produce a floc blanket beneath plate settlers has been built by Agua Para el Pueblo for a rural community in Honduras, and will be tested soon.

3.1.6.3 Effect of flocculator and floc blanket energy dissipation rate on floc blanket effluent performance (turbidity removal)

The effect of varying energy dissipation rates in the flocculator on floc blanket effluent performance was evaluated while maintaining a relatively constant parameter $G\theta$ in each flocculator. For example, splitting the flow from one tube to two in parallel that were the same length would double the hydraulic residence time (θ), but would decrease the velocity gradient (G) by a factor of approximately two (Figure 3-8B).

The experimental conditions included an alum dosage of 45 mg/L, influent turbidity of 100 NTU, and upflow velocity of 100 m/day while varying the number of tube flocculators (Figure 3-14). A control (no tube flocculation) experiment was also performed in which coagulated particles were introduced directly into the upflow reactor without flocculation.

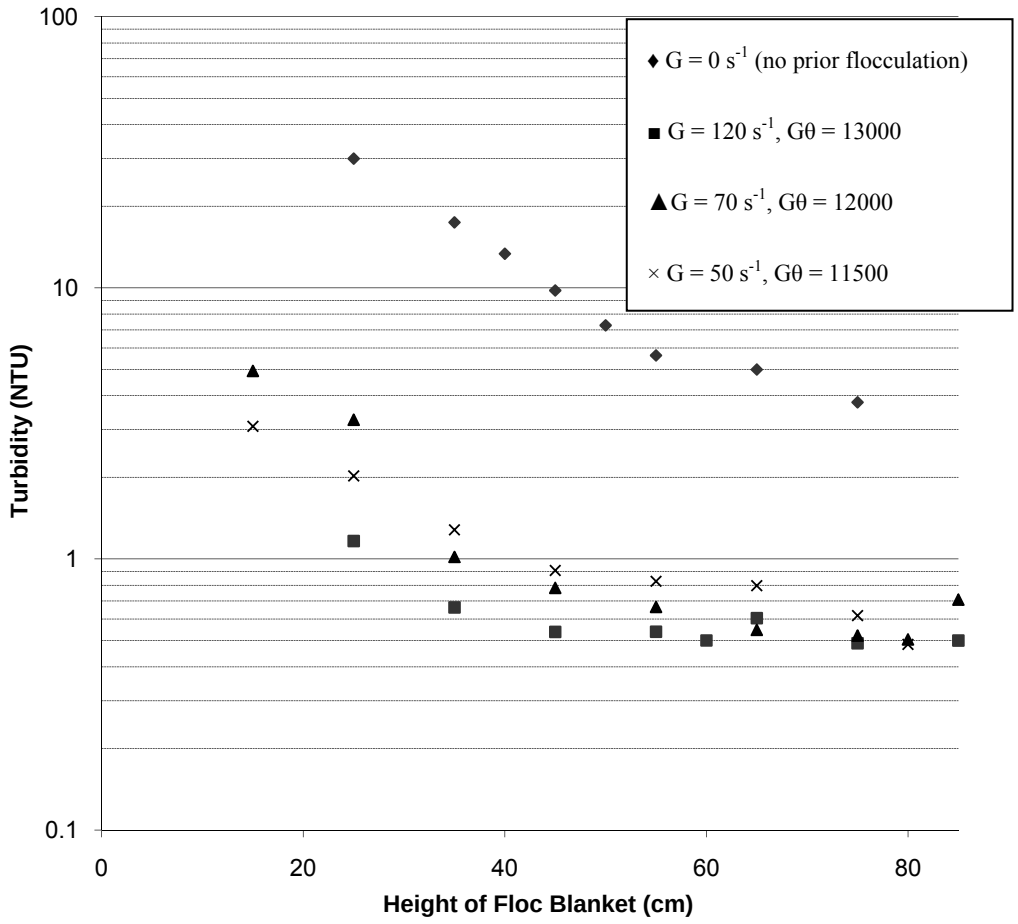

Figure 3-14. Effect of floc blanket height and flocculation in the flocculator on tube settler effluent turbidity.

Floc blanket performance increased with increasing energy dissipation in the flocculator especially between a floc blanket height of 20 and 60 cm (Figure 3-14). Floc blanket performance did not improve appreciably for heights above 45 cm for the cases where there was a tube flocculator present and the rate of improvement decreased above 55 cm for the case with no prior flocculation.

Energy dissipation rate in the flocculator influences floc strength. Francois (1987) found an increase in floc strength for flocs formed with higher energy dissipation rates as well as stronger flocs for increased residence time in the flocculator. If the particles formed in the flocculator at higher energy dissipation rates were stronger they would be less prone to breakup in the floc blanket and they would have a higher density. Given the long solids residence times in the floc blanket, floc breakup could be an important contributor to effluent turbidity at blanket heights greater than 45 cm. The higher density of the flocs also could increase the solids concentration in the floc bed. The velocity gradients in the floc blanket (predicted from equations (3-15) and (3-8) shown in Figure 3-8A) were less than 10/s. Thus, floc breakup due to fluid-particle interactions would not be expected to be significant in the floc blanket. However, it is possible that particle-particle interactions are a significant source of high local stresses that result in floc breakup.

The removal efficiency of particles, as expressed by pC^* for floc blanket effluent and for tube settler effluent for the control (no hydraulic flocculation) case are shown in Figure 3-15.

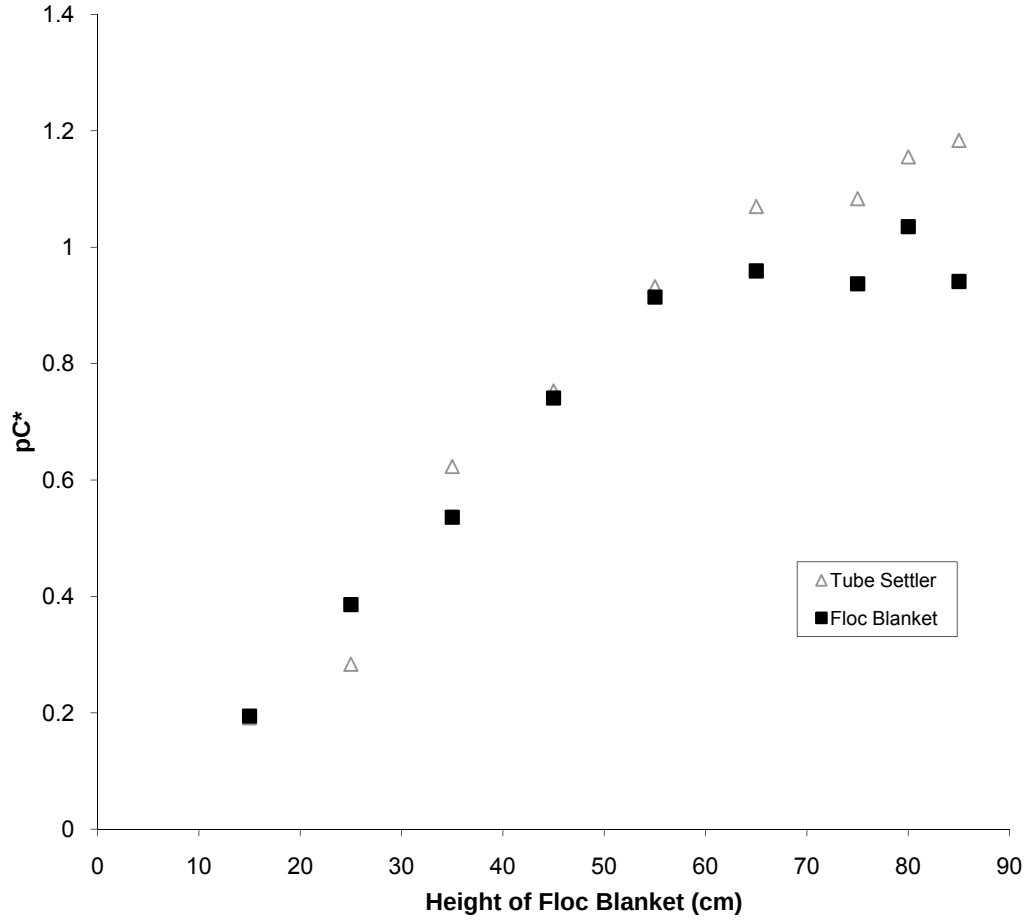

Figure 3-15. Effect of floc blanket height on particle removal efficiency from both tube settler and floc blanket effluent for the case where floc blanket influent was not passed through a flocculator

Without the benefit of a tube flocculator, particles entering the floc blanket were coagulated with alum but not flocculated. Nevertheless, the floc blanket formed in the upflow clarifier and effluent turbidity decreased as the floc blanket increased in height. Particle removal expressed as pC^* was linear with blanket height up to a height of 55 cm. A linear association of pC^* with increasing height is consistent with the

expectation of first order removal of particles with height in porous media filtration (Iwasaki, T. 1937).

In the absence of flocculation, the tube settler did not improve particle removal until the floc blanket height exceeded 55 cm (Figure 3-15). Since the energy dissipation rates in the floc blanket were sufficient to flocculate particles, the extent of flocculation would increase with residence time in the floc blanket, which increased as a function of blanket height. The data in Figure 3-15 indicate a floc blanket height greater than 55 cm was required to create flocs large enough to have a terminal velocity that allowed them to be removed by the tube settler.

In pre-flocculated water increasing particle removal in tube settler effluent was observed with increasing floc blanket height up to a height of 45 cm. However, particle removal within the floc blanket clarifier was relatively constant (Figure 3-16).

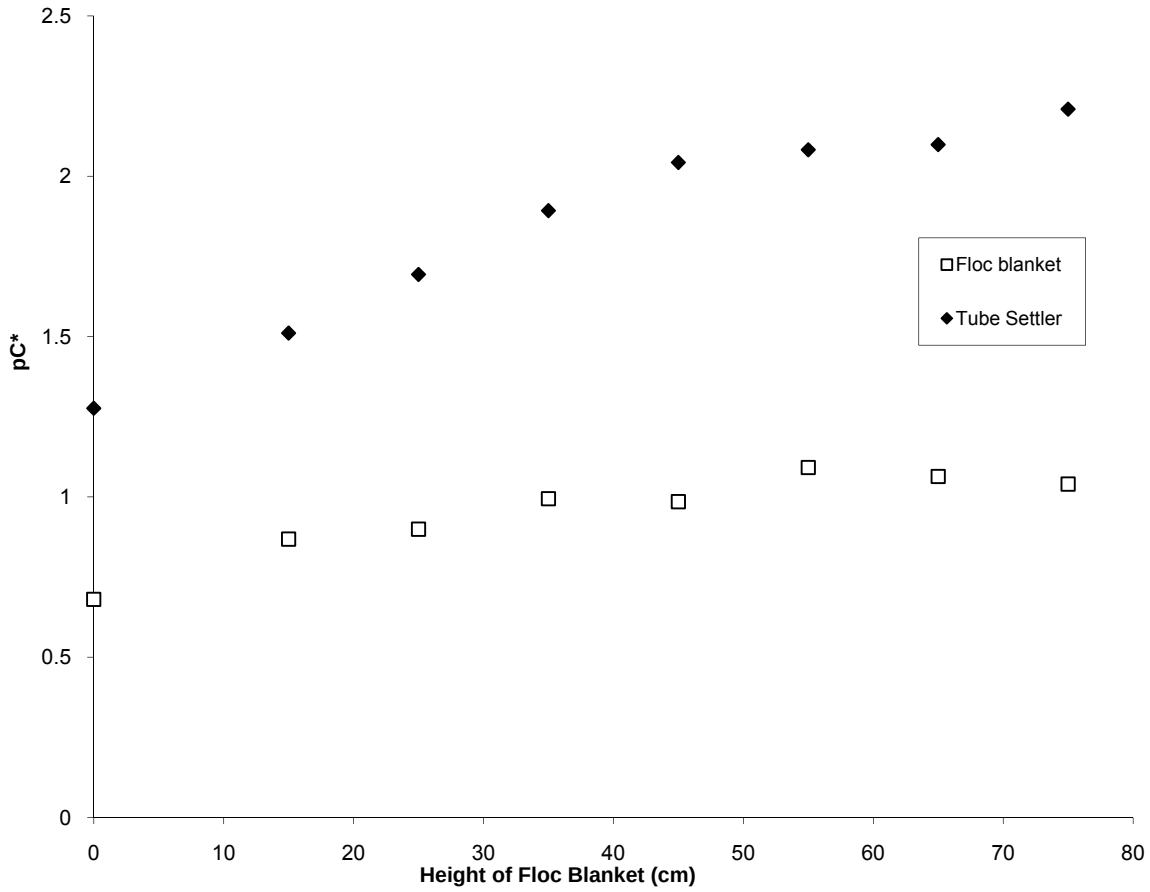

Figure 3-16. Effect of floc blanket height on removal efficiency from both tube settler and floc blanket effluents for flocculation conditions in the flocculator of $G = 50\ s^{-1}$ and $G\theta = 11500$.

Letterman (1999) stated that tube settlers do not improve performance in a floc blanket clarifier. Contrary to that finding, the results shown in Figure 3-16 indicate that tube settlers have the ability to provide removal efficiencies far beyond that of a typical upflow clarifier when coupled with a floc blanket.

The high efficiency flocculation utilized in this study produced a pC* removal of approximately 0.7 or 80% (at 0 cm height) in the absence of a floc blanket. At 0 cm

height, the tube settler had a pC* of 1.3, indicating that the tube settler was essential in improving performance. As floc blanket height increased, it appears that particle removal mechanisms in the floc blanket were aiding in removing small particles (less than 10 m/day terminal settling velocity) because tube settler performance continued to improve linearly with floc blanket height up to a height of 45 cm while floc blanket performance (i.e. particle removal by the floc blanket) remained relatively constant.

3.1.7 Conclusions

Optimal particle removal was obtained at an upflow velocity of 100 m/day for all turbidities tested except for the case of very high influent turbidity (500 NTU) that had an optimal upflow velocity of approximately 70 m/day (Figure 3-9). Control of upflow velocity was important to keep the bed of particles suspended in a floc blanket. At higher than optimal upflow velocities particle removal declined consistent with expectations that the decreased hydraulic residence time in the floc blanket would result in poorer filtration and flocculation. At lower than optimal upflow velocities, some particles settled and created channeling of the influent flow through the settled sludge. This channeling acted to decrease particle removal. At a very low upflow velocity (30 m/day) there was no fluidized bed.

Flocculation before floc blanket formation significantly enhanced performance of the floc blanket in removing particles. Increasing $G\theta$ in the flocculator also improved floc blanket performance (Figure 3-14). Increasing alum dose improved performance up to a point and then had no additional beneficial effect (Figure 3-10). Performance improved

markedly in all cases with increasing floc blanket height up to 45 cm (Figure 3-14). At floc blanket heights greater than 45 cm, it is hypothesized that floc breakup contributed significantly to effluent turbidity. In the absence of flocculation prior to the upflow column (Figure 3-15), the tube settlers did not improve particle removal until the floc blanket was sufficiently deep that raw water colloids grew to have a terminal velocity that exceeded the tube settler capture velocity.

The results obtained in this research show that effluent turbidities less than 1 NTU can be obtained at lab-scale (Figure 3-3), in the absence of sand filtration, using a process sequence of coagulation, upflow floc blanket filtration, and lamellar sedimentation. The results also show that lamellar settlers installed above a floc blanket can significantly improve particle removal efficiency (Figure 3-16).

3.2. Acknowledgements

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CHAPTER 4: FUTURE STUDIES

4.1. Mechanisms of particle removal in a floc blanket

Most recent literature on floc blanket clarification has focused upon modeling solids flux in the floc blanket to predict floc blanket performance (Chen et al., 2003; Sung & Lee, 2005; Zhang et al., 2006). Such an empirical approach cannot generally predict steady-state floc blanket response with respect to changes in coagulant dosing and turbidity just as mass flux cannot be utilized to predict residual turbidity in the effluent from a floc blanket clarifier. In order to predict performance, we need a greater understanding of the mechanisms of particle removal in a floc blanket. Understanding mechanisms of particle removal in a floc blanket may allow for the optimization of design and operation of a floc blanket clarifier with lamellar sedimentation. To achieve a fundamental understanding of particle removal in upflow sedimentation with a floc blanket, future research is needed to evaluate different mechanisms of particle removal.

The mechanisms of particle removal to be investigated should include flocculation, filtration and sedimentation. It is likely that if a particle has a terminal settling velocity close to the upflow velocity, that the solids residence time of that particle in the floc blanket will be controlled through physical wasting. However, for smaller sized particles that disproportionally impact effluent quality it appears that flocculation and filtration are both mechanisms that could potentially affect particle removal in the floc blanket. An experimental study is needed to explore both of these removal mechanisms and the

resulting information is expected to serve as a basis for modeling of floc blanket performance.

4.2. Effect of NOM and particle type on floc blanket effluent performance

An alum dosing relationship for a floc blanket was derived in this thesis for ranges of kaolin turbidity between 10-500 NTU (Figure 3-12). The generality of this dosing relationship to other raw water compositions and other types of colloidal particles is uncertain. It is established that natural organic matter will adsorb to the surface of colloidal particles effectively increasing the negative surface charge of these particles. If charge neutralization were the predominant mechanism by which flocs formed in floc blanket clarification, then the surface charge of NOM would be an important consideration as higher NOM content would require more coagulant dose.

However, it seems that the predominant mechanism of floc formation in a floc blanket is sweep floc, so understanding how NOM changes the nature of floc particles in sweep flocculation will be critical in designing effective strategies for dealing with surface waters with high NOM content.

Bacteria and algae have a negative surface charge but a much lower density than clay particles. It is unclear whether the upflow velocities applicable to flocs containing clay will be applicable to other particle types. Research appears warranted on the effect natural organic matter and suspended microorganisms on removal of turbidity and NOM.

CHAPTER 5: APPENDICES

5.1. Appendix A. AguaClara and the Global Water Crisis

Access to clean and affordable water is important for human health, economic productivity, and environmental sustainability. Watershed management is paramount for all communities, especially those utilizing a surface water source for consumption. However, most surface water quality is well below minimum standards for human consumption especially during rainy seasons which increase surface erosion and runoff.

The Global North possesses the technological capability to treat surface waters in the Global North and South, but, in general, utilizes technology that requires complex infrastructure for unit processes that can be cost prohibitive and unsustainable for smaller-scale systems and countries lacking such infrastructure. Thus, there is a need for low cost, sustainable surface water treatment technologies. Design of a surface water treatment plant or point of use system for the Global South could consider the following constraints:

- Power outages are the norm in developing countries; thus sustainable unit processes for reliable production of safe drinking water must be designed to operate without external sources of energy input.

- The capital and operational and maintenance costs should be as low as possible so that it is affordable to the population utilizing the water source.
- The plant and every unit process in that plant should be understandable and easy to operate from the point of view of the plant operator. Each unit process should be designed so that problems that arise can be easily fixed with the materials and knowledge available in the community. Maintenance that requires specialized components that are not available within the country may not be sustainable.
- The plant should be robust enough to produce drinking water that is safe for consumption over the range of influent conditions that occur during the rainy and dry periods of the year.
- Both the size of the community population and the availability of a piped distribution system will influence whether point of use or municipal scale water treatment will be utilized.

As discussed in the introduction to this thesis an estimated 125 million people reside in communities between 1000 to 50000 people that do not have access to treated drinking water. AguaClara treatment plants provide an affordable and sustainable solution for this sector of the world's population.

The AguaClara project is at the forefront in the exploration, design, and dissemination of low cost, high performing municipal water treatment plants. AguaClara utilizes design, laboratory and field research, as well as extensive community outreach and working partnerships to provide cost-effective community-scale water treatment plants for the

Global South. AguaClara water treatment plants utilize a gravity-driven treatment process train of rapid mix, flocculation, sedimentation, and disinfection. To date, AguaClara has designed five water treatment plants that have been constructed in Honduras. AguaClara's water treatment goal is to deliver water below 1 Nephelometric Turbidity Unit (NTU) without the use of a filtration unit process. AguaClara has created a web-based automated design tool with the expressed goal of helping AguaClara designed technology spread from country to country. Access to the design tool allows interested communities to eliminate the reactor design costs from the expense associated with providing safe drinking water.

5.2. Appendix B. Measurement of floc blanket porosity

Background

The floc blanket is a highly porous media, but there are no standardized tests for determining the porosity of the floc blanket. Gregory (1979) proposed measuring the solids concentration after 30 minutes of quiescent settling as an important parameter in determining floc blanket flux. The height of the settling column is an important parameter in this test because it can correlate with the velocity of the settling particles and the final height of the floc bed that will be slowly releasing water.

The thirty minute settling test is a way to estimate hindered settling in a floc blanket. At the end of the 30 minute settling test, the height of the suspension in a settling column should roughly approximate the settled volume of flocs in the floc blanket. In the 30

minute settling test, it is assumed that all particles have settled out, but that the particles have not fully undergone compression settling, so that the settled floc can be used to gather a rough estimate of floc blanket porosity.

The porosity test described below was adapted from the settled sludge volume test from Standard Methods (1998). In Standard Methods, a 30 minute settling test is used to determine the sludge volume index for both dilute and concentrated suspended solids.

Apparatus

a. *Settling column:* 5-100 mL cylinders filled with floc blanket samples taken from a floc generated in an upflow clarifier

b. Stopwatch

c. Thermometer

Procedure

Samples are taken 45 cm from the bottom of a fully built 75 cm floc blanket through the use of a peristaltic pump to fill a 100 mL volumetric cylinder. When the volumetric cylinder is full, cover the top of the cylinder and invert and mix the suspension three times. Record the height of the suspension in the cylinder at an elapsed time of 30 minutes. Utilizing equation (5-1) will yield an estimated porosity of the floc blanket.

$$\varepsilon = \frac{\forall_{cylinder} - \forall_{settled}}{\forall_{cylinder}} \qquad (5\text{-}1)$$

Where: ε is the porosity of the floc blanket, $\forall_{cylinder}$ is the volume of the cylinder (measured in mLs) at the 100 mL mark, and $\forall_{settled}$ is the volume of the settled suspension in the cylinder (measured in mLs) after 30 minutes have passed.

5.3. Appendix C. Measurement of floc blanket solids concentration

Background

The solids concentrations analysis is adapted from Standard Methods' (1998) total solids dried at 103-105 ºC test. The results are representative of the mass of solids in the sample per total mass.

Apparatus

a. *Drying Oven* set at 105 ºC

b. Dessicator

c. *Gooch crucible*: 25 mL capacity

Procedure

A Gooch crucible that has been oven dried at 105 ºC is desiccated for at least 30 minutes. The dry mass is taken and then a sample of at least 25 mL taken from the floc blanket with a peristaltic pump at a specified floc blanket height is carefully poured into the Gooch crucible and the mass is taken again. The Gooch crucible is carefully loaded into a

drying oven at 105 ºC. After the sample is evaporated and dried, the sample is put into a dessicator to cool and then weighed. The sample is then put back into the oven and dried. The procedure is repeated until the dried sample is a constant mass. The solids concentrations can then be ascertained from this procedure utilizing equations (5-2) and (5-3).

$$m_{sample=crucible} = m_{liquid+crucible} - m_{crucible} \quad (5\text{-}2)$$

$$C_s = \frac{m_{drymass}}{m_{liquidmass}} \quad (5\text{-}3)$$

Where: $m_{crucible}$ is the dry mass of the crucible, $m_{liquid+crucible}$ is the total mass of the crucible and liquid, $m_{sample=crucible}$ is the mass of the sample in the crucible, $m_{drymass}$ is the dry mass of the crucible, and C_s is solids concentration of the sample taken.

5.4. Appendix D. Calibration of a pycnometer

Background

A calibrated pycnometer is required for the analysis of floc blanket bulk density (described below).

Apparatus

a. Pycnometer

b. Thermometer

Procedure

A dried pycnometer is placed in a desiccator for at least thirty minutes. The pycnometer is then weighed utilizing an electronic balance and the dry weight of the pycnometer is recorded. The temperature of a sample of distilled water is taken and then put into the pycnometer at a marked height and weighed. The volume of the pycnometer can then be calculated utilizing equations (5-4) and (5-5). The measurements should be repeated at least three times for reproducibility and accuracy and the average of these measurements should be used as the calibrated value.

$$m_{water} = \overline{m}_{sample} - \overline{m}_{dry} \tag{5-4}$$

$$\forall_{measured} = \frac{m_{water}}{\rho_{calibrated}} \tag{5-5}$$

Where: $\overline{m}_{sample}$ is the average mass of the pycnometer filled with water, $\overline{m}_{dry}$ is the average mass of the dried pycnometer, m_{water} is the calculated mass of water in the pycnometer, $\forall_{measured}$ is the measured volume of the pycnometer, and $\rho_{calibrated}$ is the density of the water at the temperature of the distilled water in the test.

5.5. Appendix E. Bulk density analysis for a floc blanket

Background

The bulk density is an aggregate measure of the concentration of flocculated particles in the floc blanket. The bulk density of the floc blanket is slightly higher than that of water. The highly porosity of a floc blanket makes it difficult to measure head loss in the floc blanket with sensitive pressure probes even at heights of 75 cm. Bulk density is a useful alternative tool for estimating the head loss and ultimately the energy dissipation rate through a floc blanket. Bulk density also can provide insight into the changing properties of floc particles in a floc blanket based upon changes in upflow velocity, influent turbidity, extent of flocculation in a flocculator, and alum dose. The test for bulk density has been adapted from the specific gravity test listed in Standard Methods (1998).

Apparatus

a. Calibrated pycnometer

b. Thermometer

Procedure

A 1000 mL sample is taken 45 cm from the bottom of a fully built 75 cm floc blanket through the use of a peristaltic pump. The temperature of the sample is measured as a reference for future temperature correction in density calculations. A calibrated pycnometer taken from a desiccator is weighed utilizing an electronic balance to confirm no significant mass changes have taken place.

A known amount of liquid is transferred to a calibrated pycnometer and the pycnometer is carefully dried and weighed on the electronic balance again. The test is repeated taking

different samples from the 1000 mL sample a minimum of three times. The bulk density is then calculated in equations (5-6) and (5-7).

$$m_{liquid} = \overline{m}_{measured} - \overline{m}_{dry} \tag{5-6}$$

$$\rho_{bulk} = \frac{m_{liqiuid}}{\forall_{measured}} \frac{\rho_{calibrated}}{\rho_{measured}} \tag{5-7}$$

Where: m_{liquid} is the mass of the liquid in the calibrated pycnometer, $\overline{m}_{measured}$ the total average mass of replicate pycnometer tests, ρ_{bulk} is the bulk measured density of the floc blanket, and $\rho_{measured}$ is the density of the water at the temperature of the liquid in the test.

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