PARTICLE REMOVAL IN FLOC BLANKET CLARIFIERS VIA INTERNAL FLOW THROUGH POROUS FRACTAL AGGREGATES

A Thesis

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Master of Science

by

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ABSTRACT

The current gap in global access to safe and reliable drinking water, especially in rural communities, calls for a reevaluation of the design bases of treatment technologies. Robust and cost-effective design requires optimization of the various unit processes in a water treatment train. The mechanism of primary particle removal in floc blanket clarifiers was characterized via size-based performance curves obtained from light blocking particle counters that measured the effluent of a laboratory-scale floc blanket clarifier treating synthetic raw water. Particle capture was first order with respect to depth up to a depth of 30 cm, after which diminishing removal of non-settleable particles was observed as depth increased. Observed particle removal is best described by finite particle capture via internal flow through flocs, as set by floc properties such as porosity. This mechanism is consistent with the observed changes in performance with floc blanket depth and time.

BIOGRAPHICAL SKETCH

Kevin Sarmiento was born in Queens, New York and was the son of Colombian immigrants. He graduated high school in 2012 and attended the University at Buffalo in upstate New York immediately after that. He struggled to connect to any of the courses he was taking and quickly lost motivation to continue, resulting in his eventual academic dismissal from the university in 2013. He returned to Queens and began working in retail stores in order to stay busy and generate an income. However, in his free time he began to curiously comb through publicly available OpenCourseWare videos on YouTube, particularly the introductory biology and chemistry ones. That newfound desire to learn about science led him to enroll at LaGuardia Community College in New York City where in 2017 he obtained his Associate's of Science in Environmental Science with Honors.

In 2015, Kevin, along with 15 other LaGuardia students, took part in the Intercollegiate Partnership Program at Barnard College of Columbia University. As a result of his success in the summer program he got the opportunity to take additional courses at Barnard College and Columbia University during the fall of 2015 through the spring 2016 and also conduct research during the summer of 2016. His research experiences at both Barnard College and LaGuardia Community College nurtured his interest in water science and gave him a greater appreciation for the seemingly invisible and yet critical infrastructures, such as wastewater and drinking water treatment, that make 21st century life possible.

Kevin transferred to Cornell University in 2017 with the goal of joining the AguaClara project team. The mission of making safe water on tap accessible to more communities globally resonated deeply with both his personal experiences and his academic interests. He graduated cum laude with a Bachelor's of Science in Environmental and Sustainability Sciences in 2019. His ever growing passion for impact engineering led him to continue his education as an engineer with a Master's of Science in Environmental Engineering in the school of Civil and Environmental Engineering at Cornell University.

I dedicate this thesis to the past, current, and future members of AguaClara. The work completed here was made possible by the efforts and dedication of hundreds of individuals before me. My hope is that this work will be continued by other curious and passionate engineers, bringing us just a bit closer to providing safe and reliable drinking water on tap for the many people around the globe who need it.

ACKNOWLEDGMENTS

I would like to thank the U.S. National Science Foundation for funding this research.

A special thanks to Dr. Monroe Weber-Shirk for inspiring me to become the scholar and engineer I’ve become. Through your compassionate humanity and never-ending quest for fundamental truth and understanding, you have shown me, and countless others, that engineering is love. Your commitment to the AguaClara mission and your guidance has been instrumental in this work.

Thanks to Prof. Ruth Richardson and Prof. Len Lion for their personal and academic support throughout the entire MS degree program. Your insight, feedback, and discussions have made me a better researcher and writer.

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I am very grateful for all the professors, mentors, and teachers at LaGuardia Community College, Barnard College, and Cornell University that have contributed to my development as a scientist and person.

I could not have accomplished this without the unwavering support of my family, friends, and colleagues. Thank you all. This is for you. Para toda mi familia, los quiero mucho. Este logro es gracias al esfuerzo de cada uno de ustedes.

Lastly, thank you mom, for being my star.

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LIST OF ABBREVIATIONS

CCA – Cluster-Cluster Aggregation

CPA – Cluster-Particle Aggregation

EDR – Energy Dissipation Rate

HA – Humic Acid

NOM – Natural Organic Matter

NTU – Nephelometric Turbidity Unit

PACl – Poly-Aluminum Chloride

PC – Particle counter

RO – Reverse Osmosis

SDG – Sustainable Development Goals

LIST OF SYMBOLS

C_{Clay}	Clay concentration in a sample suspension (M/L^3)
$C_{Clay_{Floc}}$	Clay concentration of floc (M/L^3)
D_{Clay}	Diameter of clay particle (L)
D_{Floc}	Diameter of a floc (L)
$D_{Fractal}$	Fractal dimension of an aggregate
M_{Clay}	Mass of clay particle (M)
$M_{Clay_{Floc}}$	Total mass of clay in a fractal aggregate (M)
n_{Clay}	Number of clay particles in a fractal aggregate
pC^*	Removal performance
V_{Floc}	Volume of a floc (L^3)
$\Delta\, pC^*$	Additional removal performance from floc blanket
ρ_{Clay}	Density of clay particle (M/L^3)

CHAPTER 1: INTRODUCTION

Background

Worldwide, 47% of people in rural communities and 15% of those in urban areas lack adequate access to safely managed drinking water, totaling over 2.2 billion people (United Nations, 2017). Large gaps exist, especially for rural communities, in meeting the United Nations Sustainable Development Goal (SDG) 6.1 of achieving universal and equitable access to safe and affordable drinking water for all by 2030. González Rivas et al. (2014) identified three main challenges needing to be accounted for in the successful provision of water solutions to rural communities: technology/infrastructure, management, and governance. However, many implemented drinking water solutions overlook one or more of those challenges and as a result 30-40% of rural water systems in developing countries are dysfunctional at any given moment, resulting in no changes to the community's water and hundreds of millions of dollars of lost investments (Lockwood & Smits, 2011). As a result, there is a need for sustainable drinking water solutions that address the particular challenges faced in rural communities.

The AguaClara program at Cornell University was founded in 2005 with the goal of providing households in rural Honduras with safe drinking water on tap. Since then, AguaClara has conducted primary research in various areas of drinking water treatment, such as flocculation and floc blanket sedimentation, and designed low-cost, low-maintenance, electricity-free water treatment solutions for rural communities throughout the world. To date, there are 20 AguaClara treatment plants in Central America and 5 plants in India, collectively serving over 80,000 people (*AguaClara Cornell*, n.d.). The design and implementation of AguaClara technologies aims to address each of the three challenges outlined by González Rivas et al. (2014), the first being technology.

Unlike many modern water treatment solutions that are highly mechanized, require electricity, and require highly trained individuals to operate, AguaClara plants use no mechanical moving components, are gravity powered, and can be operated by members of a community with little training. This simplicity in design reduces the managerial and governmental burden rural water projects have when compared to conventional technologies. AguaClara plants are also entirely constructed and overseen by local implementation partners in the region, such as Agua Para el Pueblo in Honduras. These partners provide the individual communities with the technical expertise to construct, operate, and maintain the system, providing long lasting local support.

Introduction to Drinking Water Treatment and Floc Blanket Clarification

Natural waters, from sources such as rivers, creeks, lakes, and groundwater, contain organic particles, such as natural organic matter (NOM) and microorganisms (including pathogens), and inorganic particles, such as clay minerals, that make them unsafe for human consumption. While solid inorganic particles are not directly harmful, they are vectors for microorganisms and their presence strongly correlates with that of potentially harmful protozoa (U.S. Environmental Protection Agency, 1999). The goal of drinking water treatment is to reduce the concentration of both particle types to safe levels before water is distributed for consumption. To accomplish this, conventional water treatment techniques utilize gravity separation, where particles settle from raw water and clarified water is produced. However, most particles in the raw water matrix are colloidal in nature and do not readily settle. Coagulation, the process of dosing chemical coagulants, such as poly-aluminum chloride (PACl), Aluminum sulfate (Alum), ferric chloride, among others, allows for particle-particle bridging which facilitates particle aggregation. Shear is then applied to coagulated waters to promote particle-particle and floc-floc collisions which form larger floc structures with settling velocities large enough to be captured in a clarifier.

Clarification then removed over 90% of the solids from the suspension via gravity in the form of settling flocs. The remaining particles not removed in sedimentation are then removed in porous media filtration before distribution to the consumers.

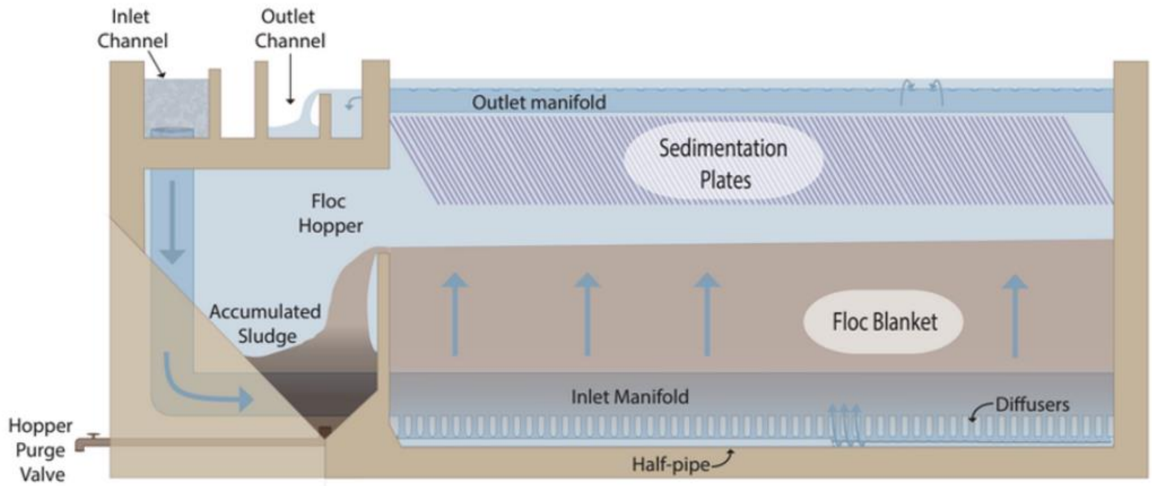

Figure 1. Schematic side view of an AguaClara clarifier. From *The Physics of Water Treatment Design—AguaClara Textbook.* n.d. (https://aguaclara.github.io/Textbook/Sedimentation/Sed_Design.html)

AguaClara has made significant contributions to the design of conventional coagulation-flocculation-sedimentation-filtration systems, improving their performance, and bringing down their overall project costs. One such example is the design of a self-sustaining upflow floc blanket clarifier (see figure 1). Floc blankets are a concentrated fluidized bed of aggregated particles (flocs) in upflow clarifiers. Particles with terminal velocities lower than the upflow velocity in the clarifier flow up and out of the floc blanket without being captured in the floc blanket directly whereas flocs with setting velocity greater than the upflow velocity are retained in the clarifier. As flocs enter the clarifier from flocculation and accumulate, a distinct floc-water interface begins to form, after which point a floc blanket can be said to exist. The high solids concentration in the floc blanket (1000 to 5000 mg solids/L) increases the probability of floc-particle interaction that leads to the removal of small colloidal particles, thereby improving effluent water quality.

To date, the physical process of particle removal in floc blankets remains unknown. The objective of this research was to determine the mechanism of particle removal in floc blanket clarifiers. Chapter 2 discusses how light blocking particle counters were used to examine the effluent stream of a lab-scale floc blanket water treatment train to gain insight into the various dynamic stages of the floc blanket. Four methods for removing flocs from the floc blanket were also tested, top weir and bottom weir removal via gravity and top layer and bottom layer removal using peristaltic pumps. Evaluation of the collected data in conjunction with review of peer-reviewed literature is presented. A thorough understanding of the mechanism of particle removal in floc blankets provides an opportunity to build physics-based models for the floc blanket clarification unit process. More broadly, it allows for integration of other unit processes models already created, such as the flocculation modeling developed by previous researchers (Pennock et al., 2018; Du et al., 2019), to build robust models capable of predicting overall performance of a fully assembled AguaClara plant, a feat not yet accomplished for conventional water treatment processes. Lastly, chapter 3 summarizes the main findings of this research and outlines the suggested next steps for floc blanket research.

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CHAPTER 2: PARTICLE REMOVAL IN FLOC BLANKET CLARIFIERS VIA INTERNAL FLOW IN POROUS FRACTAL AGGREGATES[1]

Abstract:

Floc blankets are a concentrated fluidized bed of aggregated particles (flocs) in upflow clarifiers that significantly improve colloidal (primary) particle removal in drinking water treatment plants. However, the mechanisms of primary particle removal in floc blankets have remained elusive. This work investigated the floc blanket particle removal mechanism for particle diameters in the 2 - 65 µm range. Effluent water quality was evaluated using light blocking particle counters to enumerate and size particles escaping capture by a floc blanket. Experiments were conducted with synthetic raw water in a laboratory-scale treatment apparatus designed for observing and analyzing floc blanket formation and performance. Particle capture was observed to be first order with respect to depth only for the first 30 cm, after which diminishing removal of non-settleable particles was observed as depth continued to increase. It is hypothesized that streamlines carrying particles can penetrate the body of the flocs in floc blanket, depositing primary particles in the interior of the floc rather than by behaving as individual non-porous collectors as previously suggested. Incoming flocs from the flocculator are expected to have near-equal capacity to capture particles but as pores in the flocs fill with primary particles their capacity for additional capture falls. The dynamic equilibrium between newly introduced flocs from the flocculator, wasting of flocs to maintain a constant blanket height, and the filling of floc pore space with particles are hypothesized to determine the overall steady state performance of the floc blanket system.

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[1] The contents of this chapter will be submitted to *AWWA Water Science* for publication with co-authors M. L. Weber-Shirk, L.W. Lion, and R. Richardson

Introduction

Worldwide, 47% of people in rural communities and 15% of those in urban areas lack adequate access to safely managed drinking water, totaling over 2.2 billion people (United Nations, 2017). Large gaps exist in meeting the United Nations' Sustainable Development Goal (SDG) 6.1 of achieving universal and equitable access to safe and affordable drinking water for all by 2030. Improved water treatment technologies with reduced capital, operating, and maintenance costs are needed to achieve SDG 6.1.

Floc blanket clarification has been widely employed over the last 80 years for drinking water treatment throughout Europe and Asia (Gregory, 1996). High-rate floc blanket clarifiers, or fluidized floc beds, have been a research focus of the AguaClara Cornell program since 2008 and are a key component of AguaClara treatment plants, successfully implemented in 20 AguaClara plants in Central America (*AguaClara Cornell*, n.d). The clarifiers have a residence time of less than 30 minutes, are cleaned with no moving parts, and use the asymmetric jet reverser system invented by the AguaClara Cornell team (Garland et al., 2016).

The high solids concentration in floc blankets (1000 to 5000 mg solids/L) promotes floc-floc and floc-particle interactions that lead to increased capture and removal of particles that are not removable using gravity-based sedimentation alone. Additionally, the high loading rates obtained from floc blanket clarifiers allow them to occupy less footprint than conventional horizontal flow sedimentation systems. Floc blanket clarifiers can also be less than 2 m deep in part because the floc blankets efficiently dissipate energy from the incoming flow and helps produce uniform flow into the plate settlers. Increased performance and reduced cost have made treatment systems with floc blanket clarifiers an appropriate and sustainable solution in communities with limited resources, particularly rural communities in the majority world (González Rivas et al., 2014). However, our understanding of the mechanism by which colloidal particles are captured in floc blanket sedimentation remains incomplete and thus there may be opportunities for substantial design improvements.

Flocculation, entrapment, and sedimentation are hypothesized to be the three main mechanisms of particle removal in floc blanket clarifiers according to Gregory et al., (1996). Flocculation within a floc blanket can play a role in particle capture by allowing particle-particle collision, leading to the formation of larger flocs with settling velocities equal to or greater than the upflow velocity in the clarifier. Floc blanket reactors described by Gregory et al. (1996) served as both flocculators and floc blankets as the influent stream was only dosed with coagulant and not flocculated before entering the clarifier. However, floc blanket experiments conducted by Garland (2017) separated the flocculation and sedimentation process by injecting flocculated waters into an upflow clarifier and demonstrated that the observed overall particle removal could not be predicted solely by modeling the floc blanket as an extension of the flocculator. On the other hand, the particle removal contribution by sedimentation is limited only to aggregates with settling velocities greater than the upward velocities in the clarifier. This suggests that the mechanism of most probable importance in particle removal, according to Gregory et al. (1996), is entrapment, which they defined as the external interception of particles on the surface of flocs, akin to granular media filtration.

However, that hypothesis is not supported by analysis of floc blanket performance carried out by Gregory (1979), Hurst et al. (2014), and Garland (2017) which demonstrated that performance, as measured by pC* ($pC^* = -log\ (\frac{C_{out}}{C_{in}})$ where C_{out} is the instantaneous effluent solids concentration and C_{in} the initial), did not increase linearly with depth as depth increased. A linear relationship between the particle removal performance and the depth of a floc blanket is expected if external interception of particles was the primary mechanism of capture. Performance can be predicted using the simple Yao et al. (1971) clean bed granular media filtration model where instead of the collectors describing granular media in a filter, they describe flocs in a floc blanket clarifier. Therefore, every additional layer of media added, flocs in this case, to the floc blanket should produce a proportional increase in the particle removal performance (pC*) of the system. The deviation from linearity is unexplained by the mechanism of particle capture suggested by Gregory et al. (1996).

The aforementioned experiments used turbidity, which is a measure of a sample's scattered light intensity (O'Dell, 1996), as the parameter to evaluate the performance of the floc blanket. Measurement of turbidity, in Nephelometric Turbidity Units (NTU), is a standard method for determining the overall particle load in raw and treated waters due to its ability to measure the presence of a broad range of particle sizes quickly and simply. However, turbidity is an aggregate measure of the degree of light all particles above 0.5 μm will scatter in a sample volume and therefore does not provide information on the relative abundance of particles of different sizes. Prior to this research we hypothesized that a divergence in performance based on particle size was likely occurring in the floc blanket that was not detectable by turbidimeters alone. Specifically, linearity in performance with respect to depth was expected for all depths for the smallest size of primary particle present whereas larger particles and small aggregates were expected to exhibit diminishing returns similar to the overall turbidity trends. That hypothesis assumed that external interception of particles on the surface of a floc was the dominant capture mechanism and therefore larger particles would experience significantly more shear after attachment to the surface of the floc when compared to the attachment of primary particles, leading to a higher degree of particle detachment. Thus, light blocking ChemTrac particle counters were used to size and count the particles in the effluent of a laboratory-scale floc blanket clarifier treating synthetic raw water to obtain particle removal performance curves for six particle size bins spanning from 2 to 65 µm.

An understanding of the particle removal mechanism in floc blankets has the potential to guide the operation and design of drinking water treatment systems for enhanced particle removal. Filtration theory suggests that larger particles and flocs are removed most effectively in depth filtration and particles smaller than 10 µm are captured least effectively (Tufenkji & Elimelech, 2004). Maximum removal of primary particles and small flocs in floc blankets before filtration would improve the quality of filtered water and increase the interval between backwash by reducing the influent solids load. The AguaClara floc blankets are designed empirically based on laboratory research. The goal is to discover the particle capture mechanism and use that understanding to provide a theoretical basis for floc blanket design and operation.

Materials and Methods

Floc blanket experiments were conducted with the apparatus described in Garland et al. (2015) with several modifications as shown in figure 2. Briefly, a concentrated stock suspension of reverse osmosis (RO) treated water, kaolin clay (R.T Vanderbilt Co., Inc., Norwalk, CT) and humic acid (HA) (Sigma-Aldrich: H16752) was metered into aerated and temperature-controlled Cornell University tap water to produce a constant synthetic raw water turbidity of 100 Nephelometric Turbidity Units (NTU) and 2 mg/L HA. Turbidity was measured with an in-line MicroTol 4 IR HF scientific turbidimeter and relayed to Process Control and Data Acquisition (ProCoDA) software developed by Weber-Shirk (2020) for monitoring. Reported Cornell University tap water characteristics are: Total Hardness = 150 mgL^{-1} as $CaCO_3$, total alkalinity = 133 mgL^{-1} as $CaCO_3$, and dissolved organic carbon = 2.18 mgL^{-1} (Cornell University

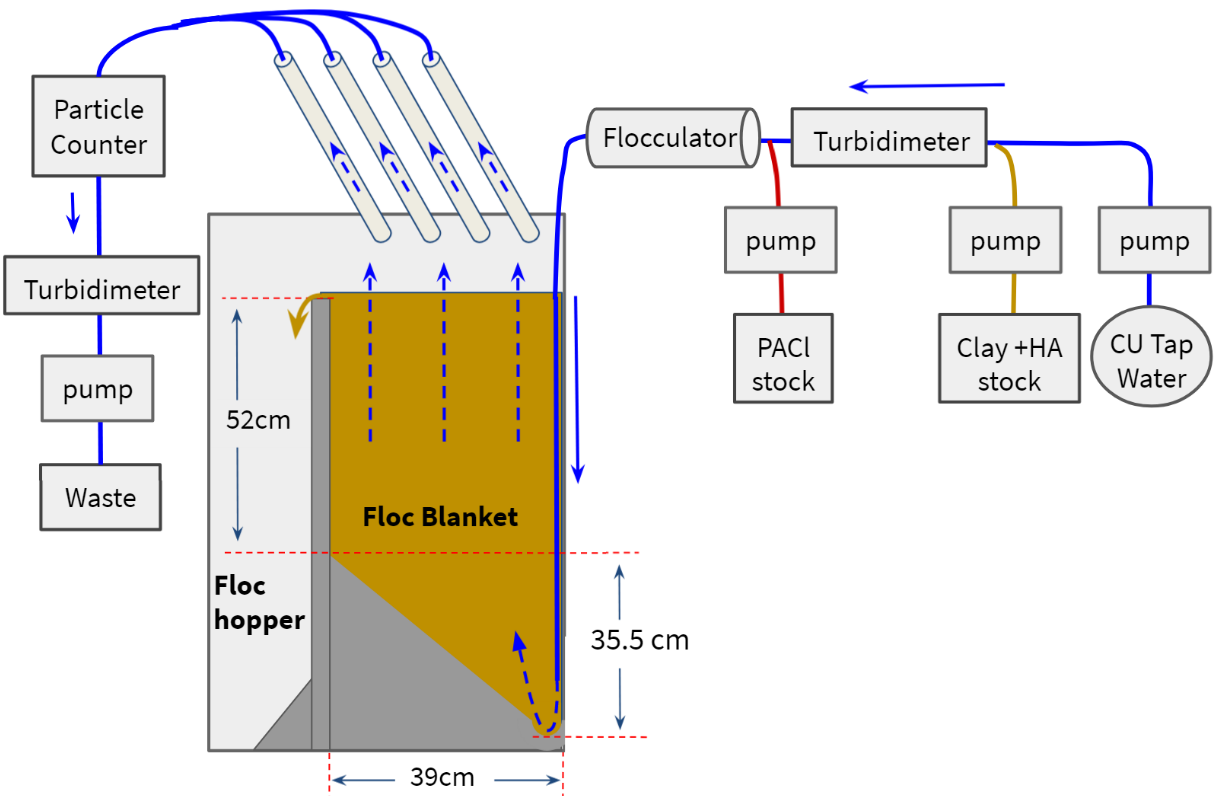

Figure 2. Experimental apparatus for studying floc blanket performance with a 50 degree sloped bottom. 100 NTU Synthetic raw water was flocculated and injected into the jet reverser at the bottom of the clarifier.

Drinking Water Quality Report, 2020). Poly aluminum chloride (PACl) coagulant (Holland Company, Adams, MA) was dosed into synthetic raw water to obtain the desired coagulant dose, 3.1 mgL^{-1} Al, for all experiments shown unless otherwise stated. PACl and stock clay + HA suspension were dosed with peristaltic pumps controlled with ProCoDA software.

Coagulated synthetic water was flocculated in a laminar flow, coiled-tube flocculator with the following characteristics: inner diameter = 0.95 cm, coil diameter = 15 cm, length = 25 m. The high Peclet number of coiled tube flocculators make them an idealized lab scale analog of the baffled hydraulic flocculators used by AguaClara plants (Weber-Shirk, 2010). Flocculated water was then injected into the lab scale clarifier 5 cm from the bottom of the apparatus from a 5 mm diameter tube and directed in the downward direction towards the 8 cm diameter jet reverser (see figure 2). The jet reverser redirected the flow upwards while also resuspending settled flocs as they slid down the sloped bottom region, 50 degrees from horizontal, of the clarifier. The experimental apparatus has the same geometry as AguaClara's municipal clarifier design allowing for lab-scale simulation of floc blanket growth. Upflow velocity in the clarifier was 1 mm/s for all experiments. The experimental apparatus had a thickness of 1.3 cm, full blanket width of 39 cm, and total blanket depth of 87.5 cm as measured from the bottom of the jet reverser and the top of the floc weir. During operation the tank had a maximum water depth of 105 cm.

Supernatant from the clarifier flowed through four laminar tube settlers with the following dimension: 88 cm long, 2.6 cm in diameter, and an angle of 60 degrees from horizontal. The tube settler capture velocity was calculated to be 0.13 mm/s based on capture velocity equations presented by Hurst et al. (2014). The resulting effluent after sedimentation was sampled with light blocking particle counters (Chemtrac Inc, GA USA) capable of sizing and counting particles in the 2 to 127 μm range. Settled water turbidity was then measured with a MicroTol 4 IR HF Scientific turbidimeter.

Controlling Blanket Height:

To maintain the floc blanket at a constant height, an internal blanket overflow weir was used as previously described by Garland et al. (2015). Briefly, the weir was submerged in the clarifier which separated the active settling zone from the floc hopper zone. Flocs accumulating above the weir flowed over the weir and consolidate in the floc hopper, preventing additional blanket growth past the height of the weir. The weir was preset to a height of 52 cm from the top of the sloped bottom, the point at which the full-width blanket began (see figure 2).

Data Collection and Analysis:

In-line particle count and turbidity data was collected from the influent turbidimeter, effluent turbidimeter, and the particle counter every five seconds using ProCoDA. Data cleaning was done to remove read errors reported by ProCoDA. Data was then smoothed by averaging 100 data points into one, spanning 500 seconds (8.3 minutes). Cleaning and processing of data was done in Python 3.7.10.

Results:

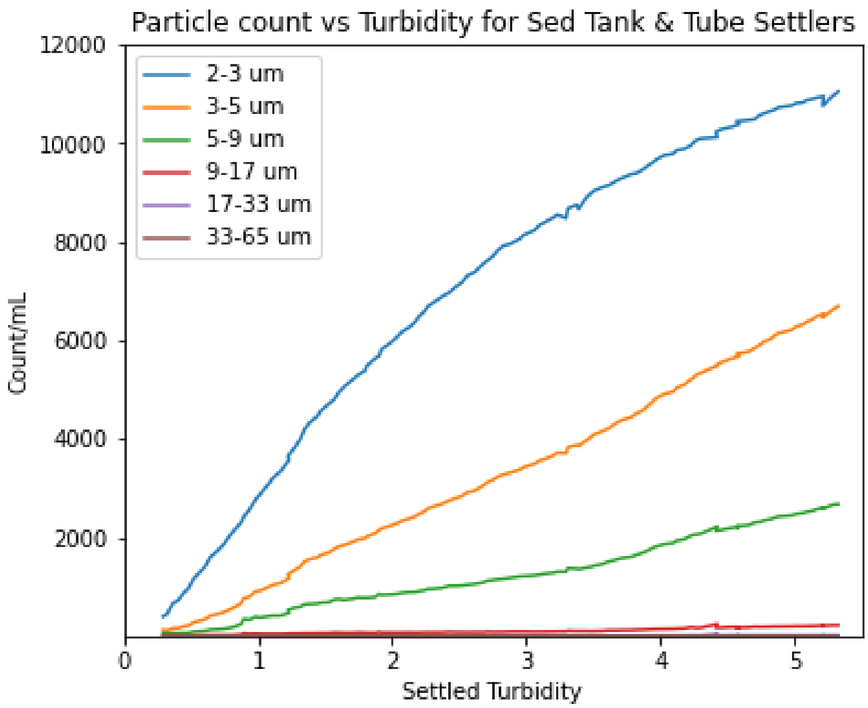

Figure 3. Relationship between turbidity and particle counts.

Synthetic raw water, with no added coagulant, was run through the experimental apparatus to measure the relationship between turbidity and particle counts for the six predetermined size classifications: 2-3 µm, 3-5 µm, 5-9, µm, 9-17 µm, 17-33 µm, and 33- 65 µm. Laminar tube settlers used in these experiments removed most particles larger than 65 µm and as a result the maximum sizing was limited to 65 µm. A linear relationship between settled turbidity and counts is expected for turbidity below 40 NTU (U.S. Environmental Protection Agency, 1999). This was observed for turbidities below 1.5 NTU as shown in figure 3 but for turbidities above that the relationship deviates from linear. As turbidity increases, the probability of having more than one particle within the path of the laser in the quartz cell increases, underestimating the counts of small particles and overestimating counts for larger particles. To avoid these coincidence errors, all particle count data was interpreted only after turbidity dropped below 1 NTU. Floc blanket effluent reached 1 NTU or lower by the time the floc blanket reached full-width at the top of the sloped bottom, 35.5 cm from the bottom of the jet reverser, for each experiment shown hereinafter.

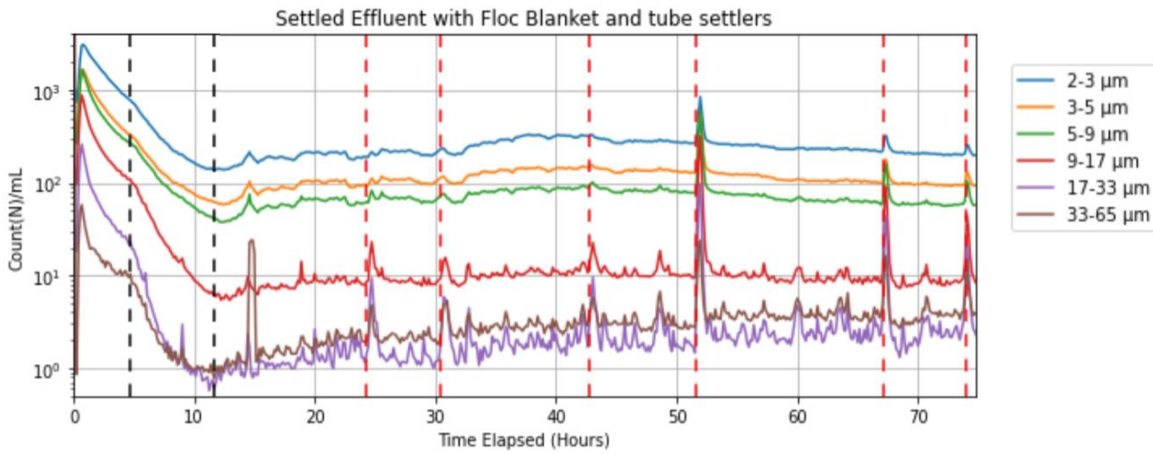

Figure 4: Particle counts for six bin sizes, ranging from 2 to 65 µm, during floc blanket formation and during constant blanket depth. First black dashed vertical line at hour 4 marks when the blanket reached a depth of 35 .5 cm from the bottom of the jet reverser (the location where the full width blanket begins) and second black dashed line marks when blanket reached its maximum depth of 87.5 cm. Red dashed vertical lines mark times when the floc hopper was emptied, which caused vibrations and temporary spikes in particle counts.

Particle counters were used to size and count particles escaping capture during the formation and steady depth phases of experimental tests with floc blankets and laminar tube settlers (figure 2). Floc blanket particle capture performance was measured as $\Delta pC^* = -log\ (\frac{C_{out}}{C_{in}})$, where C_{in} for each bin size was the particle count after floc blanket first reached the full width depth of 35.5 cm from the bottom of the jet reverser during startup of the experiment, as seen in figure 5a. C_{out} was the instantaneous effluent count obtained. Particle counter accuracy was compromised when testing turbidities above 1.5 NTU due to the increased coincidence error from having multiple particles in the flow cell at once, resulting in multiple particles being sized as a much larger one (figure 3). Additionally, particle count data revealed a performance shift after the floc blanket grew past the sloped bottom and transitioned into the full-width section, at a height of 35.5 cm, due to changes to the upflow velocity in that region. A clear shift in the slope of the particle count curves can be observed after hour 4, marked by the first black vertical dashed line in figure 4. As a result, C_{in} was measured after both conditions previously mentioned were satisfied, which for the experiment shown occurred at a blanket depth of 35.5 cm.

The raw water influent turbidity of 100 NTU was reduced to 1.0 NTU by the time the floc blanket reached the top of the sloped region in the clarifier as shown in figure 5(a) at hour 0 and Table 1, an overall turbidity performance pC* of 2.0. ΔpC* for the particle counts is defined as increased performance with time or depth beyond that which occurred when the blanket reached full-width. figure 5 shows the particle removal performance of the six particle size ranges from the time the floc blanket reached full-width (hour 0) to when the blanket reaches the maximum full-width depth of 52 cm (hour 7). Particle counts for turbidity greater than 1 NTU are not considered as discussed above. From hour 0 to 3, shown in figure 5, a linear relationship between performance as measured by ΔpC* can be observed for each size range measured. Total mass of solids entering the clarifier throughout the experiment was held constant by keeping influent turbidity at 100 NTU, resulting in a uniform linear increase in blanket depth between hours 0 and 7 (heights shown in figure 5 a-c). After hour 3, the linear relationship between time (also blanket depth) and removal performance for each particle size range broke down and performance began to level off well before the blanket reached the terminal blanket depth shown in figure 5c.

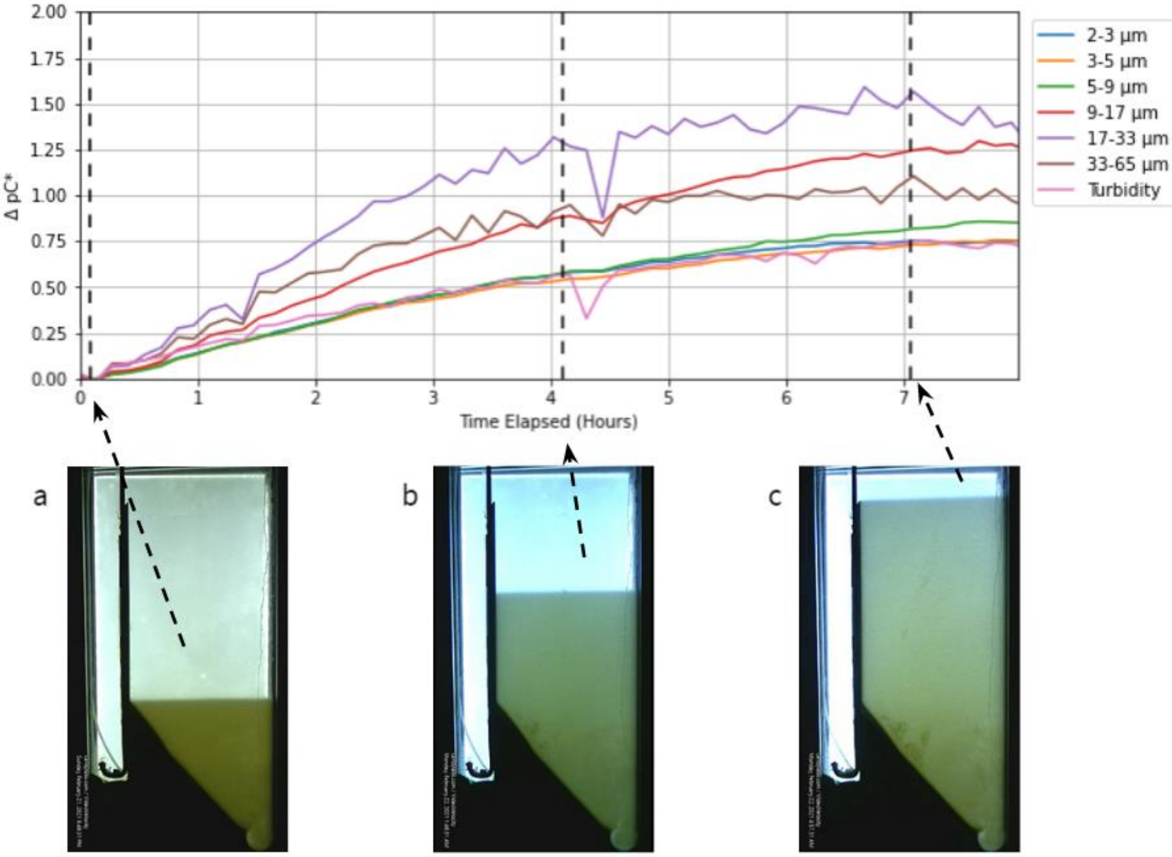

Figure 5: Removal performance for six particle ranges and overall turbidity during the growth stage of a floc blanket experiment. Floc blanket height during the first 8 hours of the experiment is shown in a-c.

Table 1. Measured particle counts and effluent turbidity at hour 0, 4, and 7 for floc blanket experiment shown in figure 5. Hour 0 marks when floc blanket reached full width depth.

	Counts per mL for six bin sizes (mL^{-1})						
Time Elapsed (hours)	2-3 µm	3-5 µm	5-9 µm	9-17 µm	17-33 µm	33-65 µm	Turbidity (NTU)
0	778	332	271	108	22	10	1.0
4	208	97	72	14	1.2	1.2	0.28
7	138	61	41	6	0.6	0.8	0.18

Particles between 17-33 µm had the highest degree of additional removal in the floc blanket, 9-17 µm the second highest and 2-3, 3-5, and 5-9 µm the lowest. The three smallest groups measured had nearly identical performance curves, only diverging slightly after hour six. The largest particle sizes measured, 33- 65 µm, had a Δ pC* of approximately 1 at hour seven, greater than particles smaller than 9 µm but less than particles of size 9-17 µm.

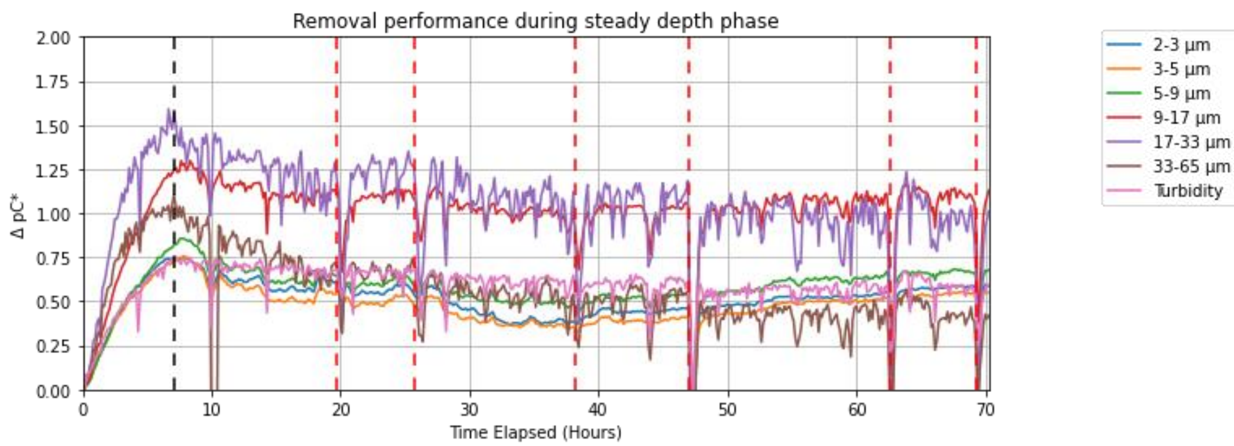

Figure 6. Floc blanket performance during the growth phase is shown from hour 0 to 7 and during constant blanket height from hour 7 to 70. Maximum blanket height was reached on hour 7 as shown by the black dashed vertical line. Red dashed vertical lines show tim show times when the floc hopper was emptied, causing vibrations and temporary performance changes.

Maximum particle removal performance for all sizes measured occurred at hour seven when full width blanket height reached the maximum depth of 32 cm as shown in figure 5 & 6 and table 1. Figure 6 shows the ΔpC* during the blanket growth stage, hours 0-7, and the constant blanket depth stage, hours 7 to 70. After reaching maximum blanket depth, performance began to deteriorate for turbidity and for all particle sizes measured despite blanket height remaining unchanged. After 50 hours, performance for particles in the 9-17, 17-33, and 33-65 µm ranges reached a stable steady state lower than the peak performance observed at hour 7. For particle sizes 2-3, 3-5, and 5-9 µm, performance deteriorated from hour 7 to hour 38 and saw slight improvement from hour 38 to 70, reaching similar performance observed between hours 15-25.

Discussion

Mechanism of Particle Removal in Floc Blankets

Size based performance curves for all size ranges measured showed a linear relationship between particle removal performance (as measured by pC*) and time (or blanket depth) during the first three hours of the start-up period of the floc blanket experiments. Diminishing returns in performance for all size ranges measured were observed as blanket depth approached maximum height between hours 3 and 7 as shown in figure 5. This result is consistent with what has been observed previously by Gregory et al. (1979), Hurst et al. (2014), and Garland (2017) where a diminishing return in performance was observed with increased blanket depth. A linear relationship between a wide range of blanket depths and performance is expected if primary particles and small flos are captured on the exterior surfaces of the flocs in the floc blanket. Additionally, a gradual decrease in the overall capture capacity of all particles, as seen from hour 7 to 70 in figure A6, became evident after the full-width floc blanket depth steadied at a height of 52 cm, indicating either a shift in the collectors' capacity to capture particles or a different particle capture mechanism altogether.

Two plausible dominant particle capture mechanisms exist. The first assumes particles are only captured by attaching to the exterior surface of a floc. Particle capture in a floc blanket has historically been attributed to surface attachment of particles on flocs, analogous to that in clean bed granular media filters, and flocculation of unsettleable particles into larger particles that can be captured in floc blanket or laminar plate settlers (Gregory et al., 1996 ; Binnie & Kimber, 2013). However, this assumption ignores the fractal and porous nature of flocs produced in drinking water treatment (Adler, 1981; Meakin, 1988; Veerapaneni & Wiesner, 1996; Wu &

Lee, 1998; Gorczyca & Ganczarczyk, 2002; Xiao et al,. 2013). Therefore, a second mechanism of particle removal through floc filtration, which accounts for flow through the body of a porous floc, is also discussed.

Exterior Interception of Particles on Floc Blanket Flocs

Exterior interception of particles onto the surface of flocs would predictably lead floc size to increase over time. As floc diameter increases, the ratio of hydrodynamic forces on the floc to cohesive forces within the floc increases while the critical breaking ratio between the two forces decreases (Adler & Mills, 1979), leading to floc breakup. Permeable flocs, like those in drinking water treatment, in uniform flow fields, break up along the equatorial plane (Adler & Mills, 1979), producing floc units with approximately half the volume of the original floc. Broken flocs will continue to capture particles in the floc blanket if their terminal velocity is greater than the capture velocity of the tube settlers, allowing them to settle and return to the blanket to continue growing. Thus, particle capture on exterior floc surfaces is not thought to cause irreversible changes to the flocs in the blanket that would diminish their ability to capture additional particles.

Floc blanket experiments with injectors of various velocity gradients in the same research apparatus used in this study showed no performance changes for jet velocity gradients less than 560 Hertz (Garland et al., 2016). That is because velocity gradients less than 560 Hz do not produce enough shear force to break flocs into pieces smaller than the capture capacity of the tube settlers. The velocity gradients experienced within the bulk of the floc blanket, away from the jet reverser, range from 4-6 Hz, as measured by Hurst et al. (2014), and 360 Hz in the free plane jet exiting the jet reverser in this experiment. This result suggests that flocs in this floc blanket experiment are not broken into fragments smaller than the minimum capture size of the plate settlers, 35 µm, and therefore are not responsible for the observed performance shift with time.

McCurdy et al. (2004) hypothesized that floc breakup may affect performance by changing the surface coverage of the coagulant on the floc by exposing previously hidden floc surfaces that were not destabilized or coated by the coagulant to the same magnitude as that on the floc surface. Given that the floc subunits in this investigation were all previously coagulated and passed through the flocculation process, it is not likely that floc breakup prevents the attachment of new particles, especially given that the incoming primary particles themselves are coated with coagulant nanoparticles. Therefore, it is unlikely that the breaking of flocs in the floc blanket and jet reverser is responsible for the deterioration of performance, and instead suggests an alternative mechanism that results in a finite capacity to capture flocs.

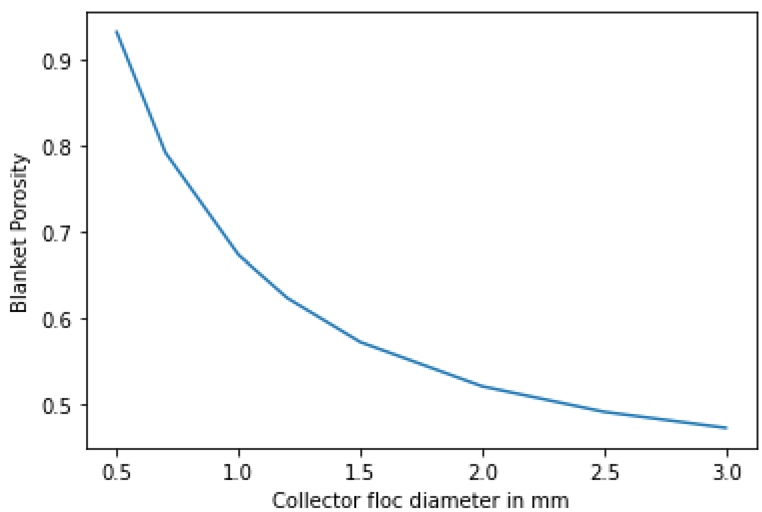

Figure 7: Relationship between collector floc equilibrium size and blanket porosity at an upflow velocity of 1 mm/s and static bed porosity of 0.4.

Particle transport mechanisms used in single spherical collector models, such as those presented by Yao et al. (1971), Rajagopalan and Tien (1976), and Tufenkji and Elimelech (2004), include Brownian motion, sedimentation, and interception to describe the rate of particle attachment on the surface of a collector. A modified Yao model, which only accounts for particle removal by interception and Brownian motion as mechanisms of particle transport, is shown in figure 8. The model accounts for the decrease in the porosity of the floc blanket as floc diameter increases as shown in figure 7. It predicts that as the average floc (collector) size increases, removal performance of the largest particle sizes, greater than 10 µm, diminishes while that of particles between 1 and 10 µm remain approximately unchanged. However, results from this study demonstrate performance reductions for all particle sizes measured over the course of the steady-

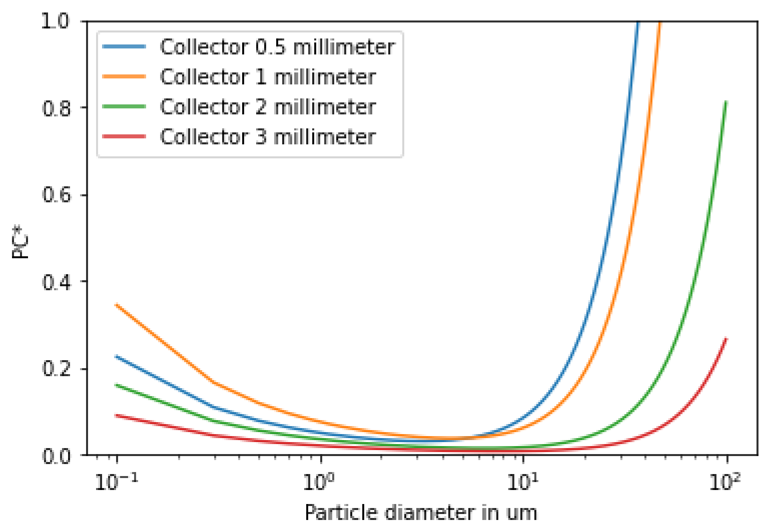

Figure 8:Predicted performance of floc blanket under modified Yao et al. (1971) model with increasing collector sizes, analogous to the diameter of flocs in a fluidized bed.

height floc blanket phase. The disagreement between the predicted performance and the observed further discounts an increase in floc size as a reason for the observed performance decline. Exterior interception as a mechanism of particle removal in floc blankets alone is unable explain the diminishing performance as a function of depth and time during blanket growth observed in this and previous studies.

Interior Interception of Particles in Floc Blanket Flocs (Floc Filtration)

Nearly a third of the streamlines within the cross-sectional area of a falling floc produced in most water treatment systems pass through the body of the floc (Xiao et al., 2013). Two significant assumptions come from this: 1) particle transport into the body of a floc takes place in floc blankets and 2) the boundary layer on the exterior surface of porous flocs is reduced or eliminated. This leads us to hypothesize that the probability of successful collisions between flocs suspended in the fluidized bed and unsettleable particles is enhanced by allowing streamlines closer to the floc. Furthermore, particle deposition within a floc is finite and limited by the available pore spaces, revealing a natural maximum physical capture capacity set by the floc porosity. After the deposition limit is reached, the floc provides no additional internal particle removal opportunities as resistance to fluid flow through the floc is observed to increase with increasing fractal dimension (Veerapaneni & Weisner, 1996). The filling up of available pore space in the body of the floc may be one of the primary mechanisms for the diminishing removal of particles in the floc blanket over time. Additionally, the filling of pore spaces with particles is expected to increase the fractal dimension of the floc and its density, causing irreversible changes to the floc properties and directly influencing floc blanket performance.

The characteristics of the flocs entering the floc blanket from the flocculator are determined by the transport mechanism responsible for their formation. For example, flocs formed through collisions of like-sized clusters, known as cluster-cluster aggregation (CCA), are scale-invariant, meaning the fractal dimension of the floc is equal to that of the aggregates from which it formed, and have low fractal dimensions, while flocs formed by collisions of primary particles onto flocs, cluster-particle aggregation (CPA), are not scale-invariant and have higher fractal dimensions than those formed through CCA (Gmachowski, 2006 and Meakin, 1988). Plug flow hydraulic flocculators such as those used in these experiments produce flocs of relatively low fractal dimension as particle aggregation is more CCA like than CPA (Gmachowski, 2006; Pennock et al., 2018). Hydraulic flocculation models by Pennock et al. (2018) and Du et al. (2019) showed that observed experimental data fit the flocculation model when collision and growth of flocs was described by CCA. This is supported by Li & Logan (1997) who showed that the high shear environment of the flocculator is not ideal for capturing small particles with porous flocs as particle capture efficiency decreased with increase to both shear rate and floc size. Although a particle approaching the surface of a porous floc should experience considerably reduced hydrodynamic resistance (Veerapaneni & Wiesner, 1996), any potential increases in particle collision frequencies caused by higher fluid velocities between approaching particles will be partially offset by less contact time between these particles (Li & Logan, 1997). Therefore, hydraulic flocculators are ideal environments to produce low fractal dimension flocs useful in particle capture in the floc blanket.

While measuring changes to the fractal dimension of flocs in the floc blanket throughout the course of a blanket run was not done in this study, data collected by Hurst et al. (2014) suggests that floc properties such as floc size or density increased during the its development. Hurst et al. (2014) conducted floc blanket experiments in the same research apparatus used for this study and observed a simultaneous asymptotic increase in both floc blanket concentration and performance that leveled out before blanket depth reached the final depth. Additionally, a gradual increase in blanket solids concentration during blanket steady depth was observed. The increase in blanket concentration is attributable to both an increase in floc size and fractal dimension but only changes to floc fractal dimension are expected to cause the observed simultaneous plateau in performance and blanket concentration shown in Hurst et al. (2014). These results are in agreement with a hypothesis of internal interception of particles in flocs. Unlike particle capture on the exterior surface of a floc that would result in consistent first order removal with respect to floc blanket depth, internal capture explains both the deviation from first order removal and the increase in floc blanket concentration.

Summary

Particle removal performance gathered in this research suggests flocs in floc blankets behave as permeable porous filter-like units with a finite capture capacity determined by the fractal properties of the aggregate structure. This mechanism of particle capture is analogous to porous media filtration in that particles and smaller aggregates within the floc act as the collectors while the individual flocs act as an individual filtration unit. Like in porous media filtration, floc filtration also experiences breakthrough, where the pores within the filter unit fill to the point where no additional particles can attach. In fact, the shift in the size distribution of particles escaping capture in a floc blanket and granular media filter over the course of a floc blanket and filter run respectively are very similar.

Figure 9 illustrates the shift in the size distribution of particles escaping capture in the floc blanket at four distinct times. Hour zero corresponds to when effluent turbidity was 1.0 NTU and the floc blanket first reached its full width, hour 4.0 at a full width blanket depth of 30 cm, hour 7.0 at maximum full width depth of 52 cm, and hour 60.0 after 53 hours at constant full width blanket depth of 52 cm. A decrease in the normalized counts for all particle sizes is observed as the blanket grew taller. However, the largest change in counts for all bin sizes occurred between hour 0.0 and 4.0 and little reduction was seen from hour 4.0 to 7.0. Once full width blanket depth was obtained normalized counts for particles smaller than approximately 15 μm began to increase to levels similar to hour 4.0 while normalized counts for those larger than 15 μm increased even further. This trend in particle size distribution is also observed during the various stages of a granular media filter run; maturation, pseudo steady-state, and breakthrough (Moran et al., 1993)

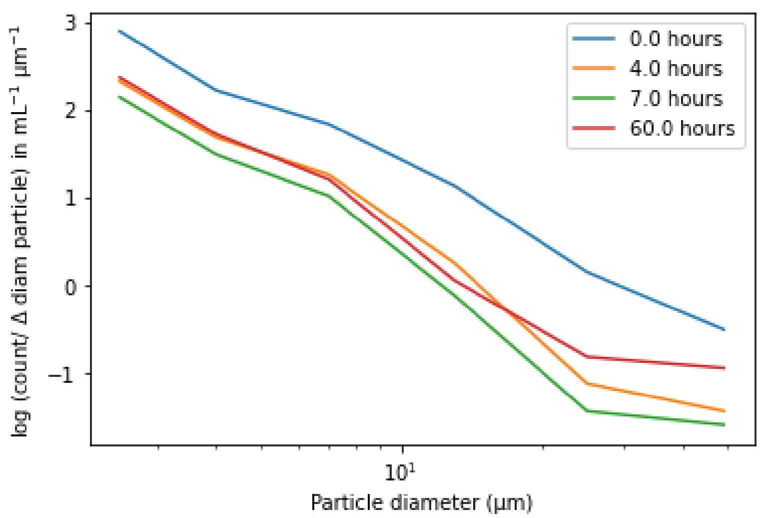

Figure 9: Particle size distribution of effluent after floc blanket sedimentation at hours 0, 4, 7, and 60.

Unlike a sand filter, a floc blanket is constantly receiving new filter units (new flocs) from both the upstream flocculator and downstream tube settlers which ensures that there are always flocs that have not reached their maximum particle capture capacity in the clarifier. As a result, breakthrough in floc blanket clarifiers does not result in performance decreases of the same magnitude as in porous media filters. In fact, steady state floc blanket operation occurs during the breakthrough phase of a developed floc blanket. Given that floc blankets are relatively well mixed and homogeneous, the dynamic equilibrium between high fractal dimension flocs and low fractal dimension flocs is a function of the solids retention time of the tank, the rate at which new particles are introduced into the tank, and the rate at which flocs reach their maximum capture capacity within the blanket.

We hypothesize that overall particle removal performance is determined by the total flow passing through the pores of low fractal dimension flocs. Early in the formation of a floc blanket, hours 0 to 3 as shown in figure 5, the blanket is composed entirely of active flocs as every additional centimeter of blanket added increases the performance at a constant rate. After hour 3 there is a clear decrease in the added performance for every added centimeter of blanket depth suggesting a fraction of the flocs in the blanket have reached their maximum capture capacity and no longer aid in particle removal. Therefore, the development of models to predict blanket performance should focus on predicting the fraction of low fractal dimension flocs in the blanket.

Based on the data collected in this and previous studies of floc blanket dynamics, the proposed sequence of events during the formation and steady state of a floc blanket is presented below.

1. At start-up flocs from the flocculator accumulate in the clarifier
    - Some flocs grow in size by being captured in the plate or tube settlers and then aggregating as they cascade back into the clarifier
2. As more flocs enter the clarifier, a visible floc-water interface forms, a hindered settling regime dominates, and the blanket solids concentration increases
    - Floc permeability decreases as particles are captured in the porous structure
3. The flocs with the longest time in the floc blanket approach maximum particle capacity and have significantly reduced capture efficiency because of reduced porosity

- performance continues to increase with increasing blanket depth but with diminishing returns as more flocs reach their maximum capacity

4. Performance peaks as the blanket reaches maximum blanket depth (in this study, 52 cm)
    - flocs at the top of the blanket are removed as they fall over the floc weir and into the floc hopper
5. Performance diminishes slightly before reaching a steady state
    - The floc porosity distribution reaches a dynamic equilibrium and performance is stabilized

Design Considerations and Future Work:

Current floc blanket sedimentation design leads to the unintended accumulation of high fractal dimension flocs within the clarifier which do not provide particle removal benefits. An optimized clarifier design would minimize the proportion of high fractal dimension flocs in the clarifier by preferentially removing them from the reactor. The relative location of these flocs within the clarifier may be determined by calculating the terminal velocity of both the low and high fractal dimension flocs. However, estimating floc settling velocity requires both a model for describing the changes in fractal dimension of the floc and the changes that fractal dimension has on the overall drag coefficient of the floc. High fractal dimension flocs are denser, which increases terminal velocity, but experience greater drag forces as the floc becomes less porous (Wu & Lee, 1998), which decreases terminal velocity. Accurate modeling of the floc settling velocity based on fractal dimension would allow us to selectively remove the high fractal dimension flocs using gravity separation if mixing in the floc blanket is reduced. If successful, this would allow for optimization of the clarifier depth based on the desired clarifier performance.

Another proposed way of optimizing the floc blanket clarifier would be to increase the rate at which low fractal dimension flocs enter the floc blanket. If the floc blanket is well mixed and gravity separation of high and low fractal dimension flocs is not feasible then an alternative is to increase the ratio of low to high fractal dimension flocs by increasing the rate of introduction of low fractal flocs. Both the flocculator and the tube settlers are sources of low fractal dimension flocs and can be optimized. In fact, no research, to the authors' knowledge, has explicitly studied the role returning flocs from tube settlers have on the performance of a floc blanket. Experiments where the floc blanket depth was controlled by sipping flocs with a peristaltic pump at the top of the floc-water interface (see figure A4) showed a pC* below 0.25 for particles smaller than 9 µm for all depths tested. Removal of the topmost layer of flocs via sipping was the only distinction between this experiment and others that showed a pC* of 0.75 for particles smaller than 9 µm, suggesting that the topmost layer of blanket plays an important role in particle removal. Another method for introducing a new stream of low fractal dimension flocs is through recycling of flocs from the floc hopper by vigorously breaking, flocculating, and then reintroducing them into the floc blanket. The high concentration of solids in the floc hopper makes it so that flocculation of that stream produces a much more favorable ratio of low fractal dimension flocs to primary particles. That ratio is important because if too many primary particles are added then that can increase the rate at which low fractal dimension flocs convert to high fractal dimension ones within the clarifier.

Conclusion

The research presented here demonstrates the added value obtained by measuring particle removal performance with light blocking particle counter compared to turbidity alone. While direct observations of flocs in the floc blanket were not obtained from this work, several conclusions about the mechanism of particle capture in floc blankets are supported by the collected data and current understanding of fractal aggregates. These conclusions include:

- Floc blanket particle removal efficiency increases but with diminishing returns as depth increases for particles ranging from 2-65 µm (limit of detection).
- Flocs in floc blankets behave as permeable porous filter-like units with a finite capture capacity. The capture capacity of each floc is determined by the fractal properties of the aggregate structure. Particle capture by a floc diminishes as the floc fractal dimension increases.
- Flocs in a floc blanket are no longer able to capture particles when the available pore space inside the floc is filled and flow through the floc approaches zero.
- The dynamic equilibrium between newly introduced flocs from the flocculator and returning flocs from the tube settlers along with the filling of floc pore space with particles determines the overall performance of the floc blanket system. Under the experimental conditions this occurred a few hours after reaching maximum blanket depth. The time required to reach dynamic equilibrium is expected to vary with the flocculation suspension concentration and the particle size distribution entering the floc blanket.
- A steady state effluent turbidity of 0.25 NTU is accomplished with flocculation (residence time = 5.7 minutes), floc blanket filtration (residence time = 13.0 minutes), and laminar tube settling (residence time 6.0 minutes) of influent synthetic raw water of 100 NTU, overall pC* of 2.6.

- Particle removal efficiency for 2-9 micrometer particles was very similar to the removal efficiency measured using turbidity.

Appendix:

Clay and Humic Acid Stock Solution Preparation:

20 L of 15 g/L clay stock was made in deionized water with kaolinite clay and stirred at 1550 RPM with a Dayton 115V, 4W motor. Initial observations of clay stock showed clay settling in minutes if stirring stopped. Additionally, settling was observed in the microbore tubing (0.042-inch inner diameter Cole Parmer Masterflex Transfer Tubing) used to pump clay stock into the bulk flow of the experimental apparatus. To prevent this, humic acid (HA) was added to the clay stock to stabilize the clay and make it more colloidal like. HA is known to adsorb onto clay and act as a stabilizing agent.

shows the effect HA has on the turbidity of a 1 g/L sample in a turbidimeter cuvette. Each

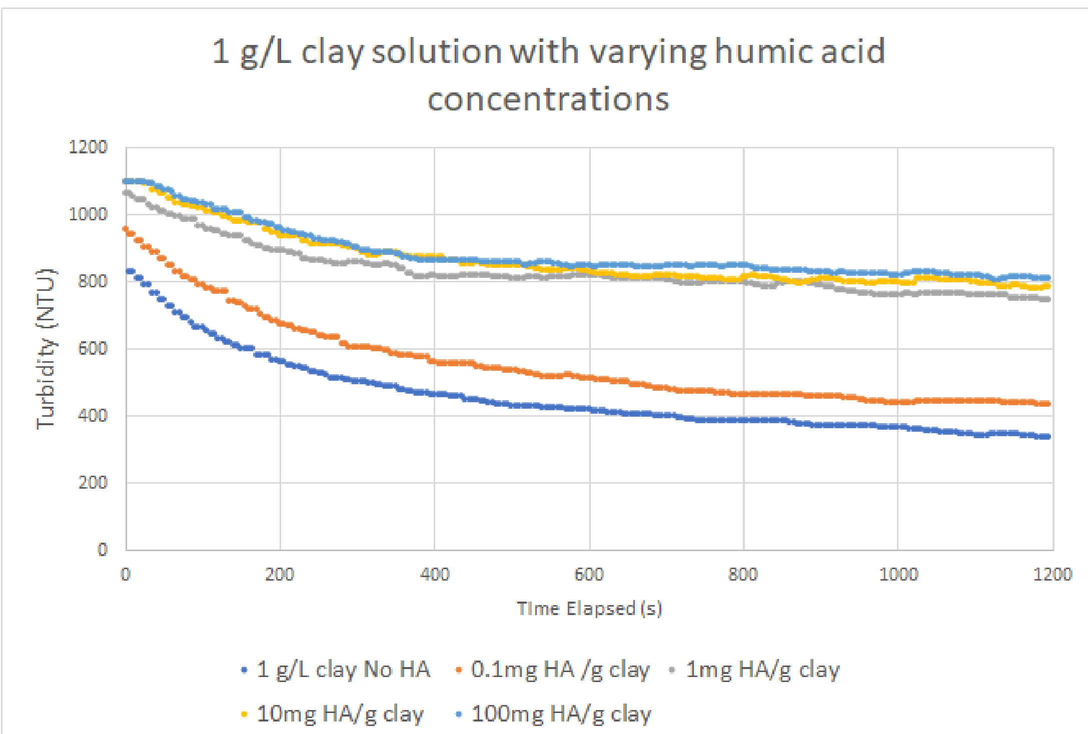

Figure A1: Settling test for 1 g/L kaolinite clay solution with varying humic acid concentrations. 25 mL sample cuvette placed in MicroTol 4 IR HF scientific turbidimeter and left undisturbed.

sample was prepared and poured into a 25 mL turbidimeter cuvette and immediately placed in the turbidimeter for analysis. Without the addition of HA, the clay sample showed a significant amount of settling, as reflected by the large decrease in turbidity within 20 minutes. A minimum of 1 mg HA/g clay was observed to be necessary for preventing excessive settling of the clay stock solution. Clay stock for all experiments had 6.6 mg HA/g clay.

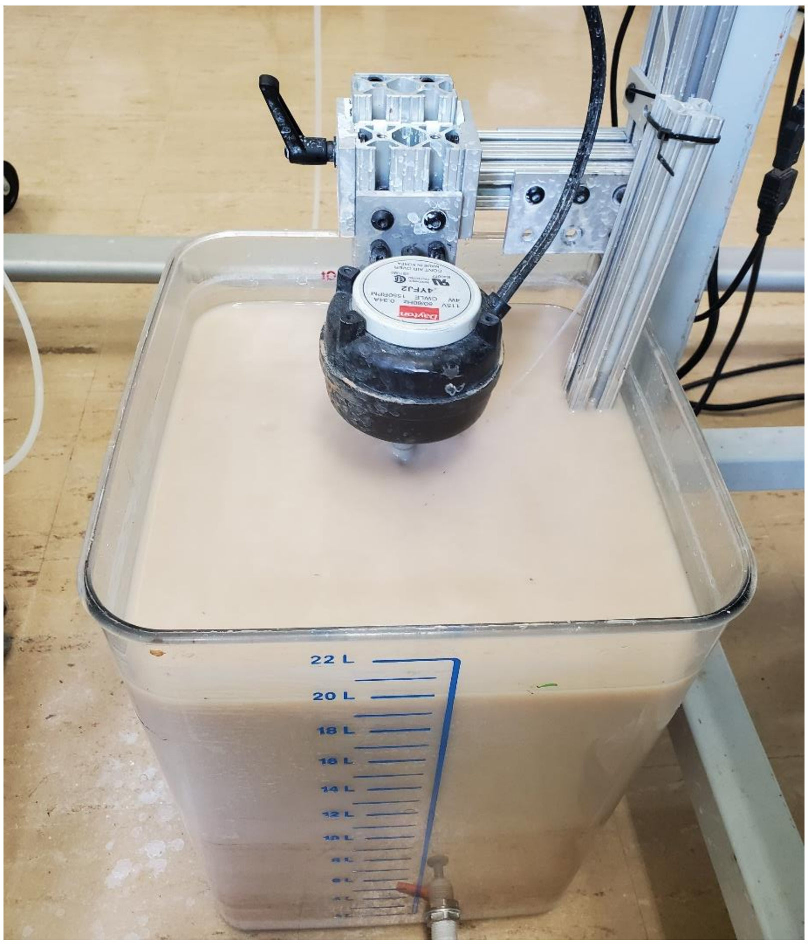

Figure A2: Clay and humic acid stock.

Clay Mass Fraction

Mass contributions per particle bin size were calculated by assuming that the size of the influent clay was uniformly distributed and particles larger than the clay diameter were fractal aggregates. Total clay concentration per particle bin size required calculating the mass of clay per floc and was calculated as follows:

The mass of a clay particle, M_{clay}, of diameter D_{clay} was found by calculating

$$M_{clay} = \rho_{clay} \frac{\pi}{6} D_{clay}^3$$

where the ρ_{clay} is the density of the clay primary particle.

The number of clay particles in a fractal floc of diameter D_{floc} can be expressed as

$$n_{clay} = \left(\frac{D_{floc}}{D_{clay}}\right)^{D_{fractal}}$$ (Weber-Shirk & Lion, 2015)

where $D_{fractal}$ is the fractal dimension of the floc. Total mass of clay in a floc is the mass of a single clay particle times the number of clay particles in the floc

$$M_{clay_{floc}} = n_{clay} M_{clay} = \left(\frac{D_{floc}}{D_{clay}}\right)^{D_{fractal}} \rho_{clay} \frac{\pi}{6} D_{clay}^3$$

Clay concentration in a floc is equivalent to the ratio of the mass of clay in a floc over the floc volume, $V_{floc} = \frac{\pi}{6} D_{floc}^3$

$$C_{clay_{floc}} = \frac{M_{clay_{floc}}}{V_{floc}} = \rho_{clay} \left(\frac{D_{clay}}{D_{floc}}\right)^{3-D_{fractal}}$$

The clay concentration passing through the particle counters in each particle counter bin size was then calculated using the clay concentration in a floc of diameter D_{floc}, its volume and the total counts per milliliter.

$$C_{clay} = C_{clay_{floc}} V_{floc} \frac{N_{counts}}{mL}$$

The average floc size for each bin (2.5, 4, 7, 13, 20, and 44 µm) was used to calculate $C_{clay\text{-}floc}$ and V_{floc} for each respective bin. Measured counts for each bin, N_{counts}, were experimentally determined.

The effluent clay concentration after floc blanket sedimentation and tube settlers for each particle counter bin size is shown in figure A3. According to Sun et al. (2015), the average particle diameter of kaolin clay is 7.7 µm and an NTU is equivalent to a clay concentration of 1.73 mg/L. However, particles of size 2-3 µm are 7.5 times more abundant than 5-9 µm and 3.75 times more abundant

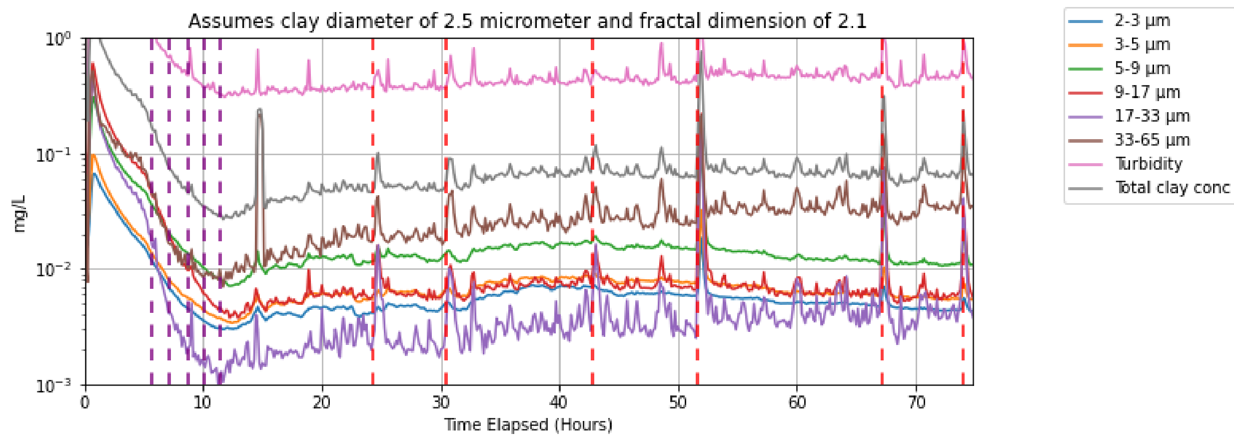

Figure A3: Estimated mass contribution from each bin assuming a primary particle size of 2.5 µm and fractal dimension of 2.1. Red dashed vertical lines show times when the floc hopper was emptied, causing vibrations and temporary spikes in particle counts.

than 3-5 µm at 1 NTU without addition of coagulant (see figure 3), suggesting that in this experiment primary particles are an average of 2.5 µm in diameter. A fractal dimension of 2.1 for flocs is used in this analysis (Meakin, 1988). Total clay concentration based on the sum of all bins underestimated the clay concentration based on turbidity, 0.5 mg/L, by 86 %. The significant difference between turbidity based clay concentration and particle count based concentration alludes to sizing errors by particle counters. Light blocking particle counters, like the ChemTrac PC6 used in this research, use projected area diameters, $D_{floc} = \sqrt{\frac{A}{\pi}}$, to estimate floc size and are calibrated using Thermo 4K Series PSL Spheres of 2, 5, and 10 µm according to the manufacturer. However, the particles measured in these experiments are porous fractal aggregates made from small 2.5 µm kaolinite clay particles. Floc size estimates obtained from light blocking particles counters assume particles are solid spheres, severely underestimating floc size in the sample as a result of light passing through the body and perimeter of the floc. This effect is magnified as flocs increase in size.

The largest bin size, 33-65 µm, made up the bulk of the total effluent mass measured and bin 5-9 the second largest mass contribution. While the total count for particle sizes between 33-65 µm was low, the large floc contributes a majority of the total mass. In contrast, particle diameters of 5-9 µm are made up entirely of one or a few individual clay particles but have a large count. Given that the average clay particle is 2.5 µm, all bins larger than that were assumed to be fractal aggregates. Bins 2-3 µm and 17-33 µm respectively had the lowest estimated effluent clay concentrations.

Stepwise Blanket Growth Experiments

In experiments where floc blanket depth was varied, a peristaltic pump and solenoid valves were used to sip flocs from one of five 2 mm diameter flexible tubes spaced at 10 cm intervals in the clarifier which allowed for five steady state blanket heights to be tested. Stepwise blanket growth and stepwise blanket shrinking was tested with this method. The rate of sipping was 5% of the system flow rate and solenoid valves were actuated via the ProCoDA controller.

Stepwise blanket growth experiments were conducted to study the steady state particle removal efficiency at five constant blanket depths. figure A4 shows the removal performance for two experiments, one started on 12/19/2020, (a), and the other started on 1/18/2021, (b).

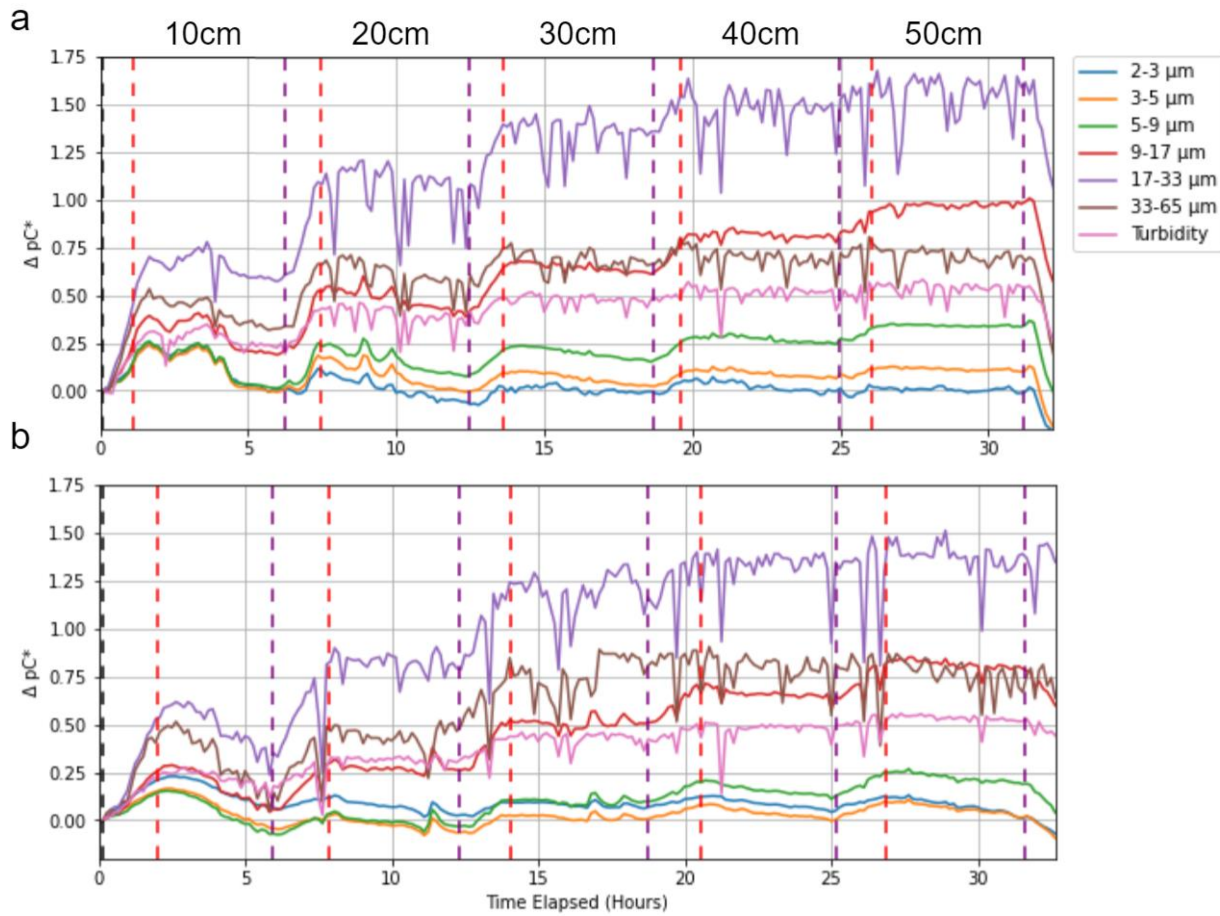

Figure A4: Particle removal performance during stepwise floc blanket formation. Red vertical dashed lines indicate the time when blanket depth reaches the steady depth indicated above. Purple vertical dashed line indicates the time when the blanket began to grow to grow to the next depth. 12/19/2020 experiment is shown in (a) and 1/18/2021 shown in (b).

The initial particle counts used for calculating pC* were determined to be those after blanket depth reached the top of the sloped bottom. Experiment shown in figure 4(a) had a turbidity of 1.01 NTU, turbidity pC* of 2.0, at hour zero while; the experiment shown in figure 4(b) had a turbidity of 0.85 NTU at hour zero, turbidity pC* of 2.1.

Each red vertical dashed line in figure 4c indicates the arrival of the blanket to the new blanket depth, either 10, 20, 30, 40, or 50 cm above the sloped bottom. The purple vertical dashed lines indicate the time when the blanket began to grow again. During the first growth period, from hour zero to the time the blanket reached the 10 cm mark, removal performance for all particle sizes improved significantly. After reaching the first steady depth of 10 cm, performance began to steadily deteriorate for all particle sizes measured in both experiments. Over the course of the four hours where the blanket remained at the 10 cm mark, ΔpC* for particles in the 3-5 and 5-9 µm range dropped to zero, as shown in figure A4(a) and (b), while in (a) ΔpC* for particles in the 2-3 µm bin decreased below 0. The additional 10 cm of blanket depth provided no additional removal of particles in the 2-9 µm range after four hours of operation and minimal improvement for particles larger than 9 µm. After four hours of steady depth, the blanket was stepped up to a height of 20cm above the sloped region and performance increased during the growth phase and then steadily decreased after reaching steady depth, like that at 10cm. At greater blanket depths there was no observed overall increase in the removal of the smallest range of particles measured (2-9 µm). However, for particles between 9 and 65 µm there was an increase in removal as depth increased that tapered off as the blanket became deeper. This trend continued as the blanket grew to new steady depths.

For particles ranging from 9-65 µm the observed performance trends as blanket depth increased were consistent with what was observed during previous experiments. Similarly, during periods of constant blanket height performance diminished steadily as observed previously. However, divergence in the performance between large (9-65 µm) and small (2-9 µm) particles was unlike that observed during uniform blanket growth experiments. One hypothesis for that observation is that the sipping port removed flocs from the top of the blanket and caused enough of a fluid disturbance to prevent returning flocs formed in the tube settlers from penetrating into the bulk of the blanket before they were removed. Flocs formed in the tube settlers are hypothesized to have low fractal dimension and therefore may make excellent flocs for capturing small particles in the floc blanket. If those flocs are being removed at the top of the blanket from the sipping then it suggests that the flocs returning from tube or plate settlers play a key role in floc blanket particle capture.

Future work on the role of tube settlers in determining the performance of floc blankets is suggested. To distinguish between the performance contributions from the incoming flocs from the flocculator and those from the tube settlers it would be necessary to isolate one from the other. One way of doing this would be to build a floc blanket where flocs from the tube settlers are diverted away from the floc blanket and wasted.

Stepwise Floc Blanket Formation and Drawdown Experiment:

After stepwise formation of the full width floc blanket to a depth of 50 cm, it was then drawn down incrementally by sipping 10 cm below the blanket surface. This is shown in figure A5 after hour 32. Clear performance deterioration was observed as blanket depth decreased. Interestingly, Δ pC* was negative for both the smallest bin sizes (2-9 µm), after blanket depth reached 40 cm at hour 33, and for the larger bin sizes (9-65 µm), after reaching 20 cm depth at hour 45. Negative performance indicates particle counts for the respective bins were higher than that measured at hour 0. In other words, at hour 33, the 40 cm of full width floc blanket provided no additional removal of particles smaller than 9 µm. During the stepwise removal of 10 cm of floc blanket, a reduction in performance equal to the gain in performance attributed to the addition of a 10 cm layer of floc blanket would be expected if floc properties remain constant.

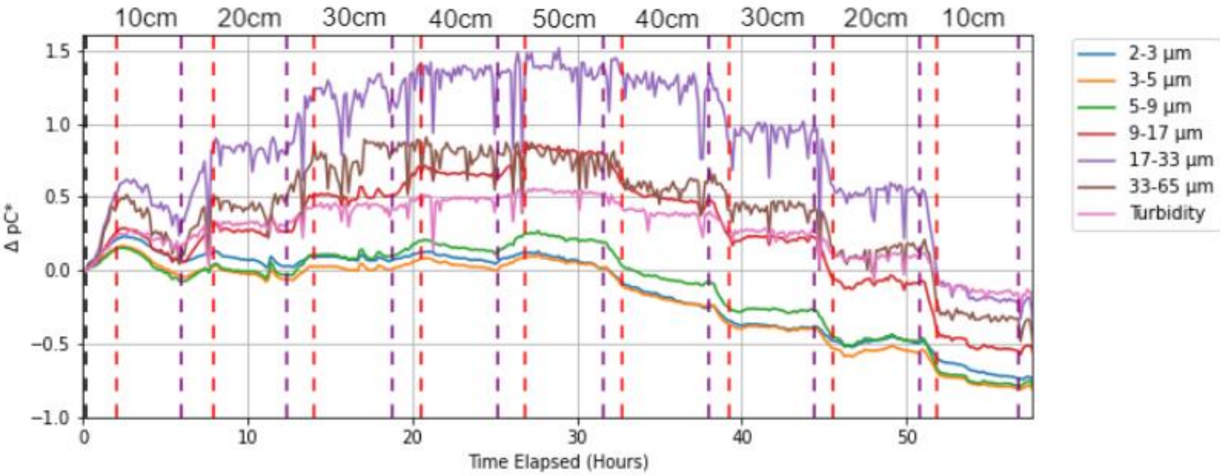

Figure A5: Particle removal performance during stepwise floc blanket formation and drawdown. Blanket growth phase is shown from hour 0 to 32 and shrink phase from hour 32 to 59. Red vertical dashed lines indicate the time when blanket depth reaches the steady dep depth indicated above. Purple vertical dashed line indicates the time when the blanket began to grow or shrink to the next depth.

The poor performance observed when removing the top 10 cm of the floc blanket suggests that flocs entering the floc blanket from the tube settlers may be playing a key role in particle removal. This data also supports the hypothesis that floc properties change as they spend more time in the floc blanket and their pores become filled. This is highlighted by the distinct performances observed at equal floc blanket depths but hours apart. Finally, these results suggest that removing flocs at the floc-water interface of the floc blanket with a sipping mechanism influences the performance of the system, especially for the smallest particle sizes measured.

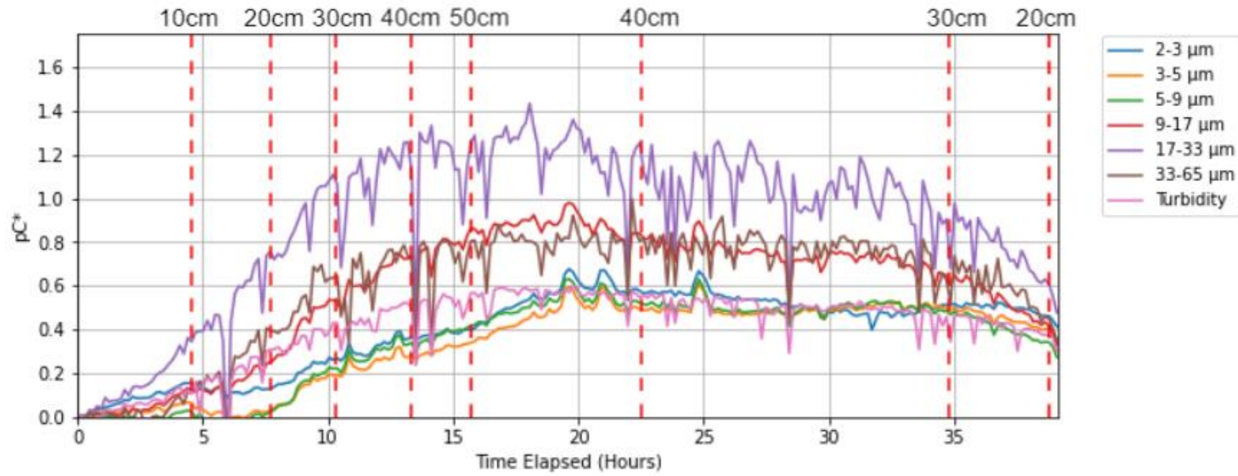

Figure A6: Particle removal performance of floc blanket that was wasted from the bottom of the tank (above). Blanket growth phase is shown from hour 0 to 16 and shrink phase from hour 16 to 38. Red vertical dashed lines indicate the time when blanket depth reaches the depth indicated above.

Figure A7: Location of sipping port when wasted from bottom of floc blanket.

An additional experiment was conducted where the floc blanket height was controlled by removing flocs as they settled and slid on the sloped bottom of the tank towards the jet reverser, figure A6 &A7. This eliminated any potential effects from removing flocs from the top of the blanket surface. Control of the floc blanket was more challenging, particularly during the drawdown phase of the experiment. Inconsistencies in the rate of floc removal caused some drawdown periods to take longer than others, such as between 40 and 30 cm at hours 22.5 and 35. Unlike the experiments where drawdown was done by removing the top 10 cm of the floc blanket, as shown in figure A5, removing flocs from the bottom of the tank resulted in constant removal performance for particles of 2-9 µm, even when blanket depth was decreasing. This provides additional evidence to suggest that the top layer of the floc blanket is playing an outsized role in particle capture.

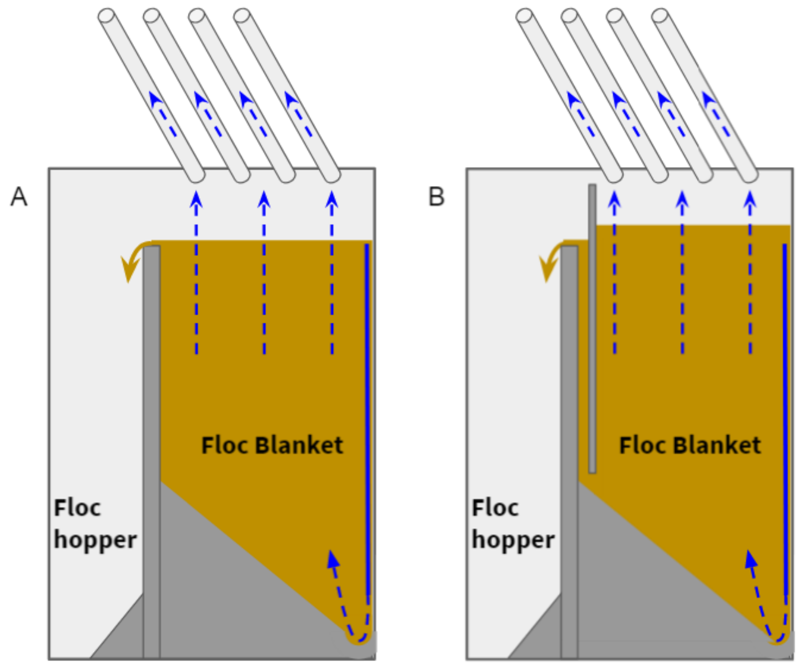

Figure A8: Diagram of the top weir (A) experiment and bottom weir (B) experiment. In the top weir configuration flocs near the top of the floc blanket flow over the top of the weir whereas in the bottom weir configuration only flocs 50 cm below the top can be pushed up and over the weir.

To eliminate the influence that pump sipping had on the performance of the floc blanket an experiment was done to measure performance of a floc blanket where height was controlled by hydraulically removing flocs 50 cm below the floc-water interface. Hydraulic removal of flocs from the bottom of the floc blanket was accomplished by inserting a watertight divider between the floc blanket and the floc weir that extended 10 cm above the level of the weir and 50 cm below the level of the weir. The goal was to force flocs out of the floc blanket from 50 cm below the floc-water interface (figure A8 B) by creating a small pressure difference between the floc blanket region and the spacing between the weir and divider, which was done by allowing the blanket to grow a few centimeters taller. This caused flocs to rise through the spacing and over the weir but not exit the tank from the top of the blanket. Results from this experiment (figure A9) show similar trends to standard weir experiments, such as a gradual decrease in performance after reaching constant depth.

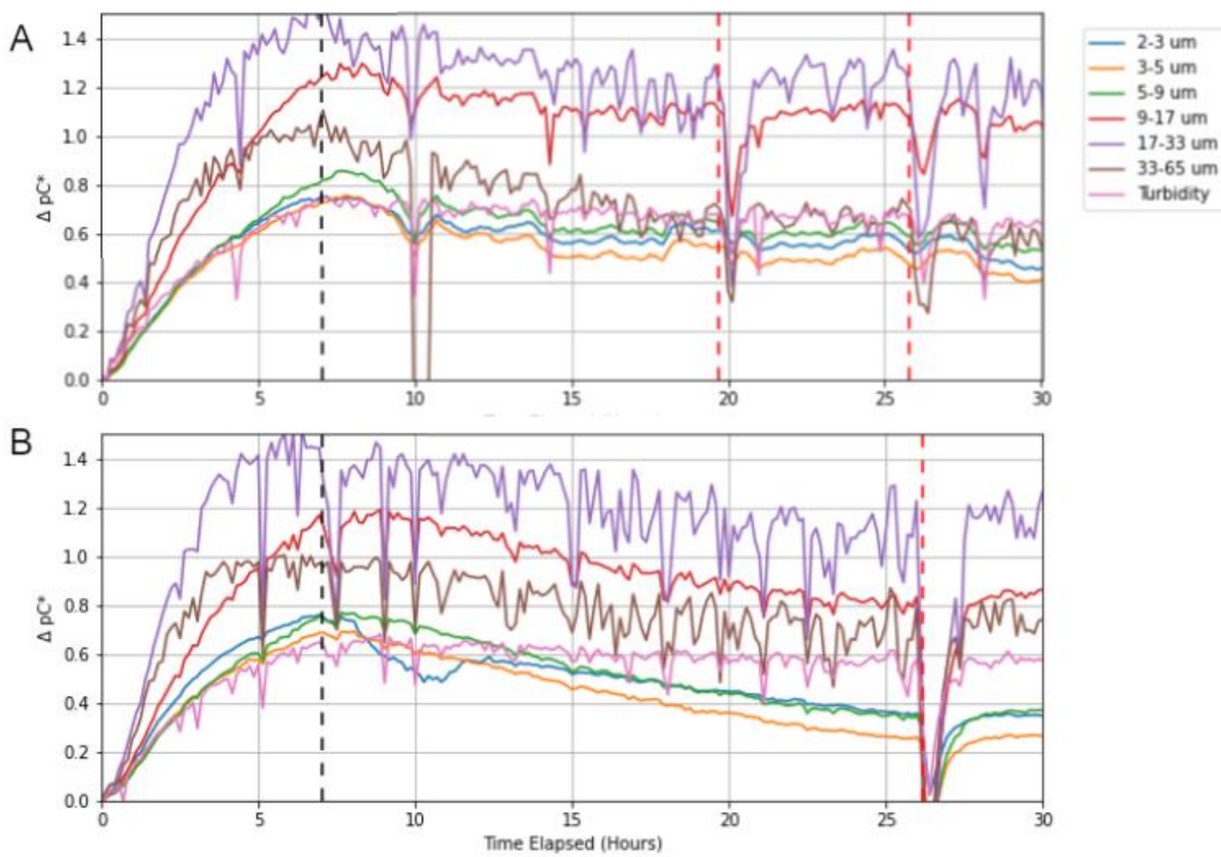

Figure A9: Performance for the first 30 hours of a floc blanket experiment where flocs exited the floc blanket from the top is shown in (A) and from 50 cm below the top of the blanket is shown in (B). Black dashed vertical line marks the time when the floc blanket reached the maximum height of 52 cm from the top of the sloped bottom. Red dashed vertical lines show times when the floc hopper was emptied, causing vibrations and temporary performance changes.

Counts for all bins in both experiments were remarkably similar at hour 7 when the blanket reached the top of the weir. However, particle removal for all sizes measured at hour 25 was slightly higher in the experiment where flocs were removed from the top of the weir as opposed to 50 cm below the weir. Removal of flocs from the top layer of the floc blanket with an overflow weir has minimal effects on the performance of the floc blanket in comparison to top layer removal by sipping with a pump. This could be due to a few things: 1) if the blanket is well mixed then a separation of low and high fractal dimension flocs is unlikely to occur in the floc blanket and 2) settling of high fractal dimension flocs in the spacing may prevent them from escaping if they have a terminal velocity greater than that of the upflow velocity in the spacing. Additional experiments are suggested to compliment these observation.

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CHAPTER 3: CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

Conclusions

Particle count analysis of synthetic raw water treated using a lab scale coagulation-flocculation-floc blanket clarification-tube settler system provided insight into the mechanism of particle removal in floc blanket clarifiers. Experiments showed that floc blanket particle removal efficiency increased but with diminishing returns as depth increased for particles ranging from 2-65 µm (limit of detection). This result is consistent with performance trends observed by other researchers (Gregory et al.,1979 ; Hurst et al., 2014; Garland, 2017) despite those experiments measuring performance based on effluent turbidity instead of particle counts. Furthermore, overall particle removal performance diminished consistently after the floc blanket reached and maintained steady depth, suggesting changes to floc blanket properties with time. This research proposes that flocs in floc blankets behave as permeable porous filter-like units, capturing particles through internal interception instead of through exterior interception as previously hypothesized. The particle capture capacity of each floc is determined by the fractal properties of the aggregate structure and diminishes as the fractal dimension increases.

Furthermore, the mechanism and location of floc removal from the floc blanket plays a role in the performance of the system. Experiments where flocs exited over a weir performed better than when flocs were sipped off the top layer of the floc blanket with a pump. Removal of flocs with a pump was shown to improve performance when sipping occurred below the sloped bottom region of the clarifier. Additional work to determine how different rates of sipping and locations affect performance are suggested.

Future work:

Stepwise floc blanket formation and drawdown along with bottom weir and top weir blanket control provokes questions regarding the role that flocs formed and returned via tube settlers have on floc blanket performance. Future work on the role of tube settlers in determining the performance of floc blankets is suggested. To distinguish between the performance contributions from the incoming flocs from the flocculator and those from the tube settlers it would be necessary to isolate one from the other. One way of doing this would be to build a floc blanket where flocs from the tube settlers are diverted away from the floc blanket and wasted. Additionally, experiments where the influent energy dissipation rate (EDR) from the diffuser jet are varied may provide more insight with particle counters than with turbidity alone as done by Garland et al. (2016). Higher influent jet EDR causes larger flocs to break, producing flocs that are too small for capture in the floc blanket clarifier but too big to escape capture in tube or plate settlers. In this case, flocs returning from the tube settlers may play a more important role in particle removal than incoming flocs from the flocculator. Additional work is needed to determine the relationship between tube settlers and floc blanket performance.

Lastly, this work allows for the creation of a simple particle removal model in floc blankets based on internal interception of particles in flocs. When coupled with models from other unit processes such as flocculation, it can be used to optimize the design of water treatment processes utilizing floc blanket clarification. Low fractal dimension flocs are highlighted as the most important contributors to particle removal. A model predicting the abundance of low fractal dimension flocs in a floc blanket over time given input parameters such as raw water quality, upflow velocity, rate at which low fractal flocs transform to high fractal flocs, and rate at which flocs are wasted is likely capable of predicting overall blanket performance. Such a model also has significant implications for downstream processes such as granular media filtration, where the input particle size distribution determines the rate at which head loss through the filter increases and time before breakthrough occurs. Optimization of the entire treatment train requires an understanding of the influent and effluent particle size distribution of each unit process in the train.