Floc Modeling

Developing a mathematical model that describes flocculation and clarification.

https://github.com/AguaClara/floc_modeling

Table of Contents

Background & Introduction

Methodology

Future Work

Clarification Mechanisms

Initial Results

Background & Introduction
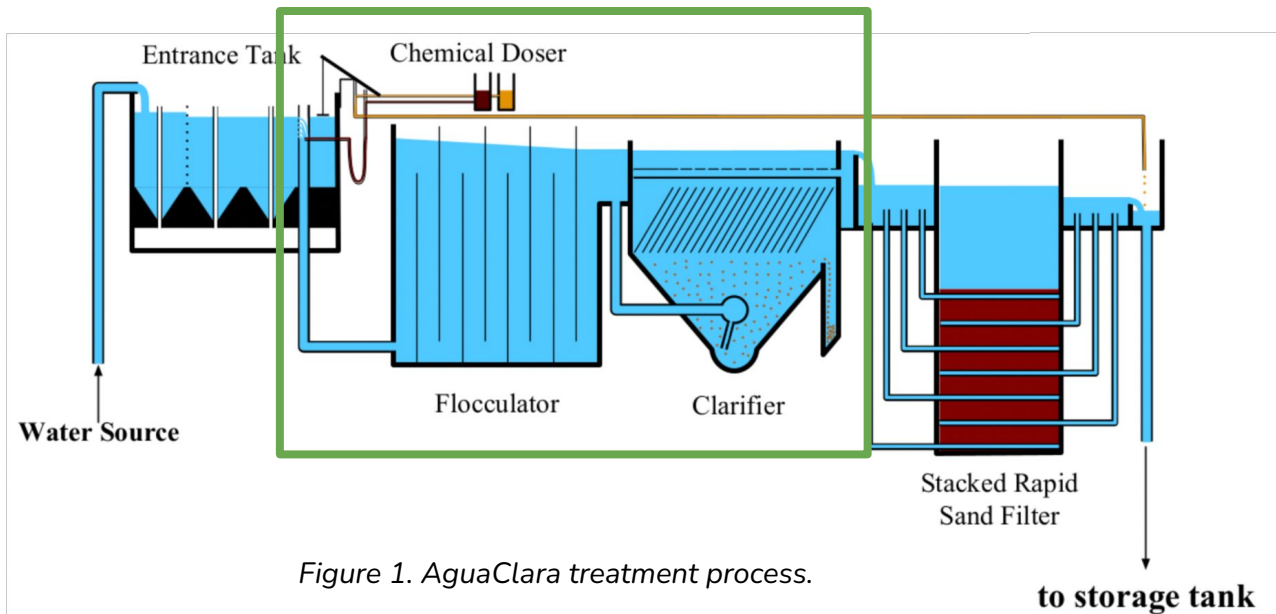
AguaClara Water Treatment Process

Figure 1. AguaClara treatment process.

The physical mechanisms underlying flocculation and clarification remain unclear.

Why develop a mathematical model of flocculation and clarification?

Motivation

Automated Coagulant Dosing (ACDC!)

- Improve performance and reduce costs

Clarifier Design

- Optimize floc wasting by strategically placing the waste tube

Flocculator Design

- Optimize floc formation and particle removal

Fundamental Understanding

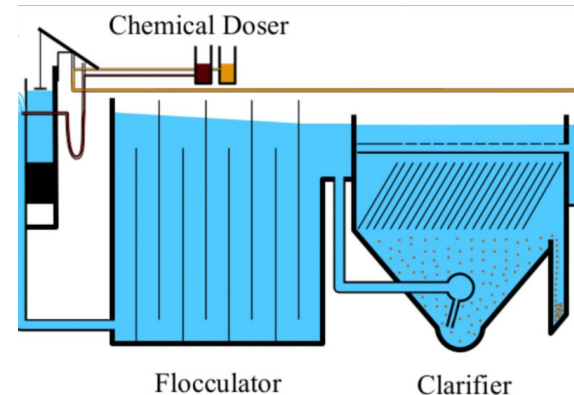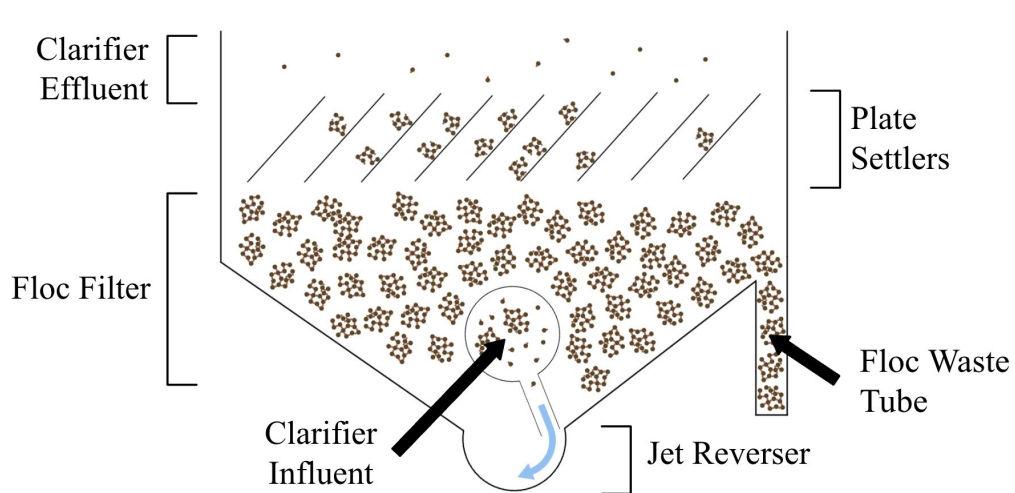- Speed up future discovery and innovation in water treatment, beyond AguaClara

Figure 2. Chemical doser, flocculator, and clarifier in an AguaClara plant.

Clarification Modeling

Clarification Mechanisms
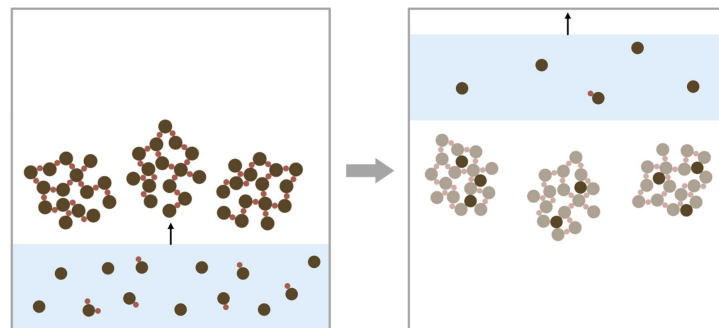

Floc Sweeping

Figure 3. Clarifier diagram and primary particle removal mechanism within the clarifier.

Labels on diagram:
- Clarifier Effluent
- Plate Settlers
- Floc Filter
- Floc Waste Tube
- Clarifier Influent
- Jet Reverser

Floc Saturation

Floc Saturation = $\dfrac{\text{primary particles captured by a floc}}{\text{maximum number of particles the floc can capture}}$

- Increases as a floc captures primary particles and its pores fill
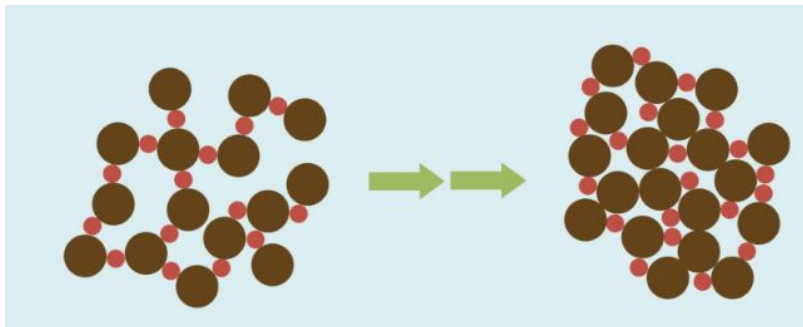- Saturated flocs have reduced capture efficiency

Figure 4. An unsaturated floc vs. a saturated floc.

Previous Clarification Models

- Pennock et al. (2018), Sarmiento (2021), and Pennock et al. (2024):
  - **Settleable vs. non-settleable particle distribution** post-flocculation
  - **Coagulant dosage** impact on clarification performance

- However, experimental results indicated a **decrease in clarification performance** over time contrary to model predictions
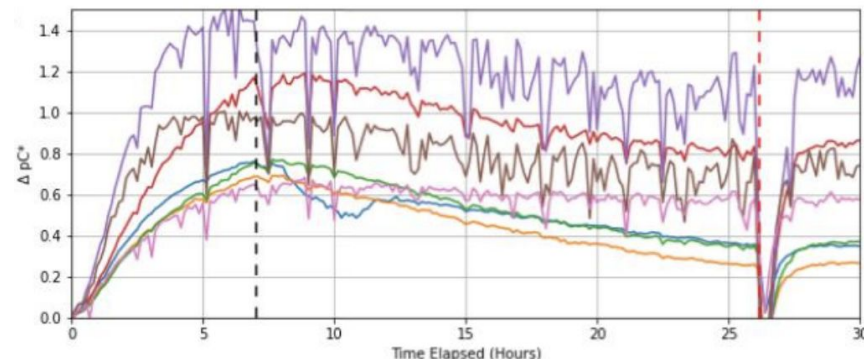 - Possibly due to **floc saturation**

Figure 5. Particle removal performance decreases over time (Sarmiento, 2021).

Current Clarification Model

Drawbacks of these models:

- No incorporation of **floc sweeping** or **floc saturation**: significant mechanisms in floc filter-based clarifiers

To address this:

- Summer 2024 ACC team accounted for floc sweeping and floc saturation

$$C_{clarified} = C_{flocculated} e^{-k_c \frac{C_{coagulant}}{C_{influent}}(1-P_{floc\ saturated})^{2/3}h_{floc\ blanket}} \quad where\ k_C = k'\beta \frac{\pi r^2_{floc} C_{floc\ blanket}}{m_{floc}}$$

$$C_{flocculated} = (\frac{C_{coagulant}}{k_{pf}C_{influent}} + C_{influent}^{-2/3})^{-3/2} \quad where\ k_{pf} = \frac{3}{2\pi kk'G\theta}(\rho\frac{\pi}{6})^{2/3}$$

$$P_{floc\ saturated} = \frac{C_{flocculated}-C_{clarified}}{q(C_{influent}-C_{clarified})}$$

$$C_{coagulant} = C_{coagulant\ added} - \lambda C_{DOM}$$

Figure 6. Clarification model equations from SU24.

Our Clarification Model Assumptions

Despite these enhancements, discrepancies exist between experimental and theoretical parameter values (k_c)

Must reevaluate model assumptions:

- ❏ Flocs in floc filter are at their **steady-state saturation level**
- ❏ Floc filter is **well-mixed**

Need better understanding the dynamics of floc saturation within the clarifier to evaluate assumptions → **Experimentation!**
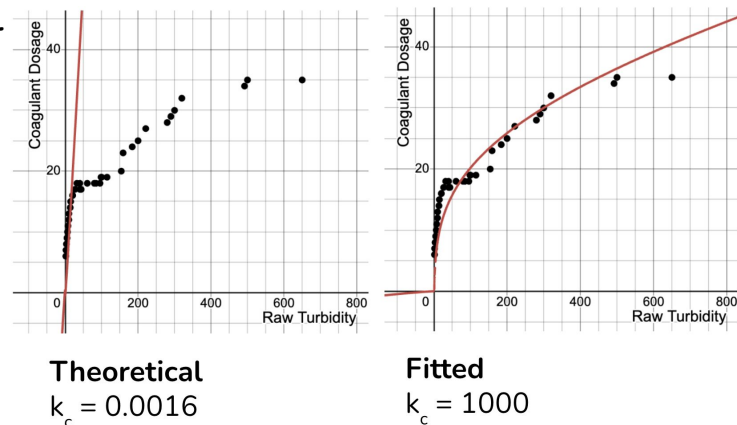

Theoretical
k_c = 0.0016

Fitted
k_c = 1000

Figure 7. Theoretical model predictions vs. model fit to AguaClara data from Nicaragua plants.

Experimental Objectives

❏ Visually determine the **spatial distribution** of **floc saturation** in the floc filter

❏ Correlate floc filter saturation state with **particle removal performance**

❏ Analyze how the above variables depend on **influent turbidity** and **coagulant dose**

Methodology

How can we measure floc saturation in the floc filter?

Methods

Idea: Use colored primary particles to visualize distribution of floc saturation

- Flocs that have captured more colored particles are more saturated

- More colorful regions ⇒ higher saturation

- *Hurst et al., 2013*: Visualize floc filter concentration and growth rate
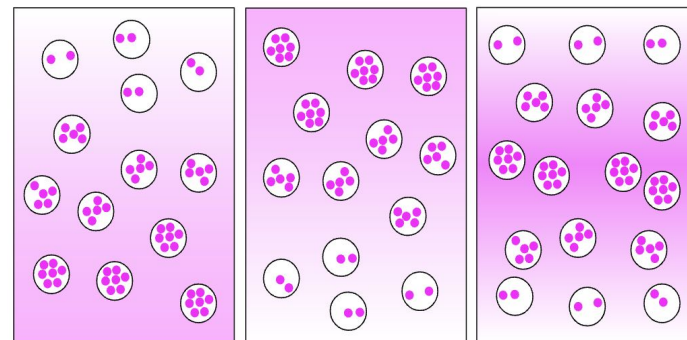

Figure 8. Examples of floc saturation spatial distributions.

Setup Overview

1. Form uncolored flocs with white clay and coagulant

2. Add colored particles into clarifier using red clay

3. Image floc filter to see what regions contain the most saturated flocs
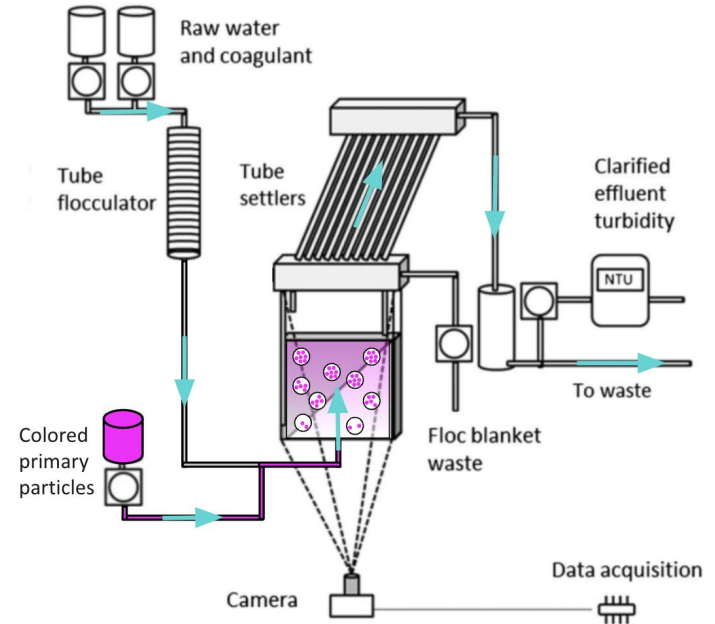

Figure 9. Experimental setup for measuring floc saturation.

Clarifier Design & Fabrication

Design Parameters

- ❏ Ability to visualize floc filter
- ❏ Suspends floc filter
- ❏ Lab-bench scale
- ❏ Easy to clean
- ❏ Easy to modify
- ❏ Reflective of actual AguaClara plants
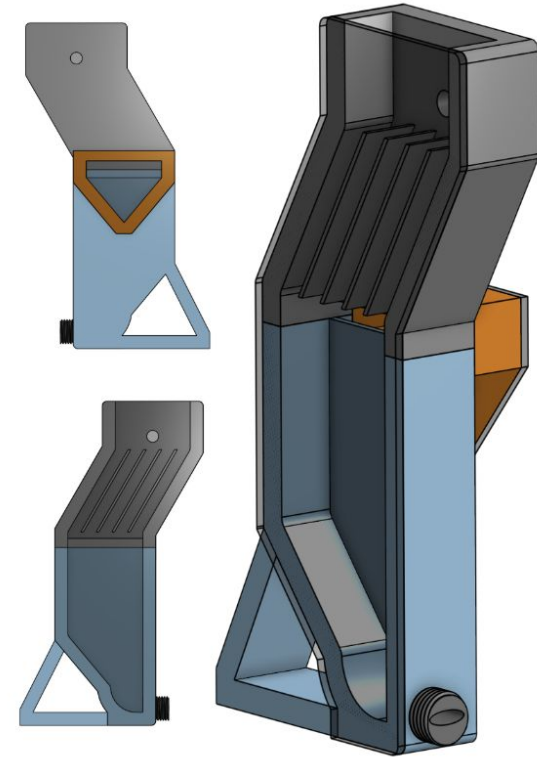- ❏ Watertight

Figure 10. Miniature clarifier design.
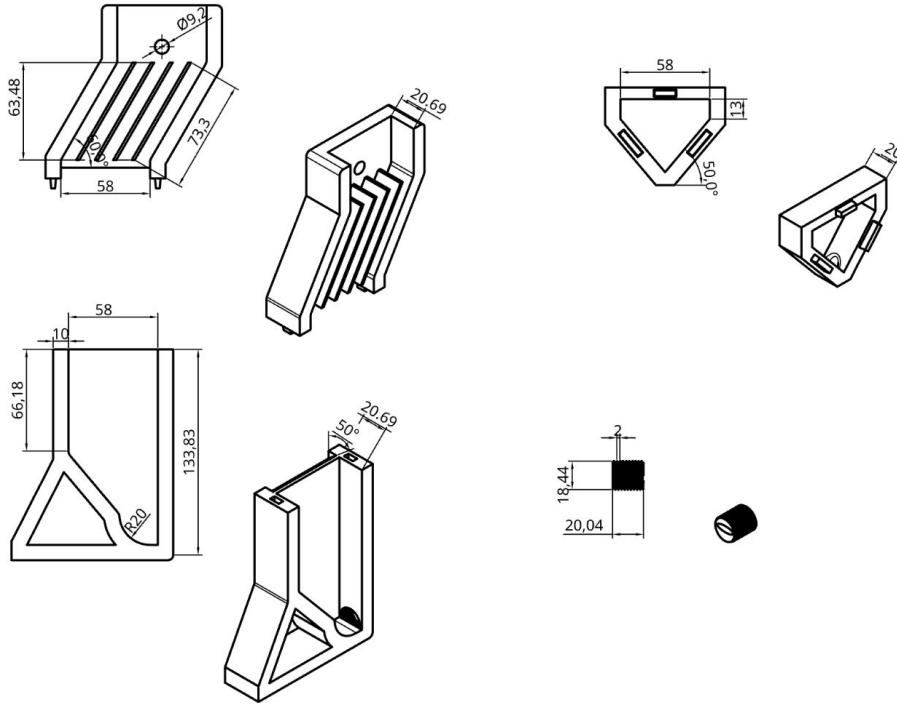
Clarifier Design & Fabrication

Figure 11. Miniature clarifier schematics and model dimensions.

Figure 12. Resin-printed miniature clarifier.

Experimental Setup

Experiment 0: Verify that red clay can be used to model primary particle capture

Table 1. Clarifier influent concentrations of red clay, white clay, coagulant.

		Red clay (mg/L)	White clay (mg/L)	Coagulant (mg/L)
STEP 1	White floc filter growth	0	100	30
STEP 2	Red flocs (Trial 1)	100	0	30
	Red primary particles (Trial 2)	50	0	0
	Red primary particles (Trial 3)	25	0	0

Mass Balance Calculator

Figure 13. Process flow diagram of experimental setup and mass balance calculator spreadsheet.

Trial 0.1		
Information		
	Total clarifier influent flow rate (mL/s)	**1.2**
	Total flocculator influent flow rate (mL/s)	1.197763635
	Clarifier influent concentration (mg/L)	**10**
	Flocculation influent concentration (mg/L)	10.01867117
Clay stock	**Stock Concentration (mg/L)**	**1300**
	Flow rate (mL/s)	0.009230769231
	Pump RPM (rev/s)	4.907112451
	Clarifier influent concentration (mg/L)	**14.25**
	Flocculation influent concentration (mg/L)	14.27660642
Coagulant	**Stock Concentration (mg/L)**	**200**
	Flow rate (mL/s)	0.0855
	Pump RPM (rev/s)	43.61391905
Water	Flow rate (mL/s)	1.103032866
	Pump RPM (rev/s)	24.84989203
	Clarifier influent concentration (mg/L)	**1**
	Stock Concentration (mg/L)	**536.585**
Rose stock	Flow rate (mL/s)	0.002236365161
	Pump RPM (rev/s)	5.167520706
Waste	**Flow rate (mL/s)**	**0.02**
	Pump RPM (rev/s)	1.412073701
	Flow rate (mL/s)	1.2
	Pump RPM (rev/s)	0.4308797127
	Flow rate during wasting (mL/s)	1.18
Effluent	Pump RPM during wasting (rev/s)	0.4236983842
Results/Observations		

Initial Results

White flocs

Figure 14. White floc filter and floc hopper.

Red flocs

Figure 15. Red floc filter.
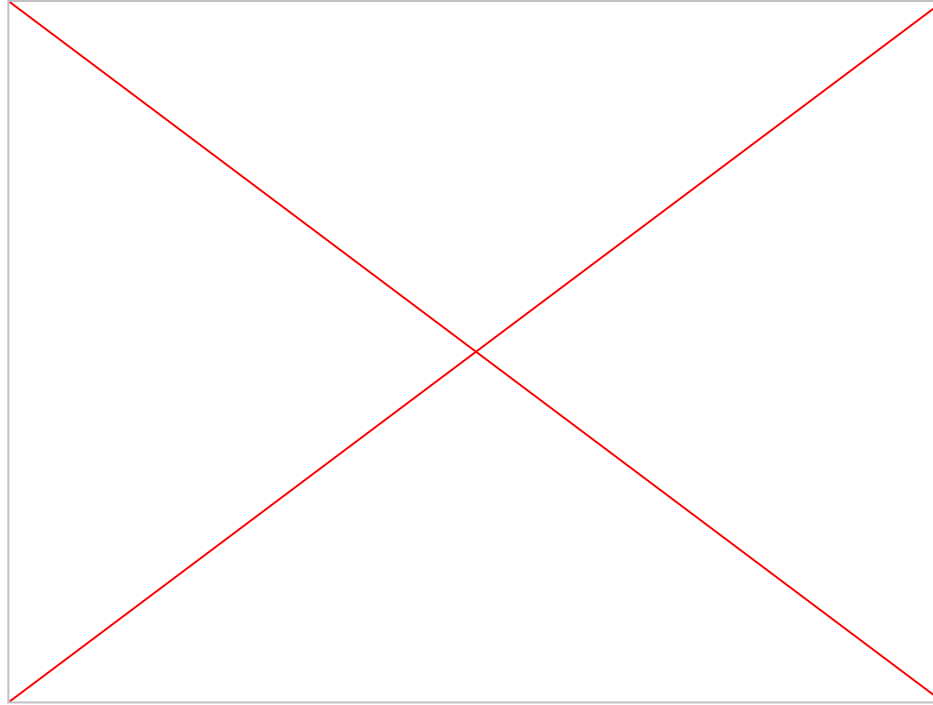
Initial Results

Figure 16. White floc filter video.

Observations

The transition from a white floc filter to a red floc filter appears to occur mostly uniformly, with the middle section of the clarifier remaining white for longest.

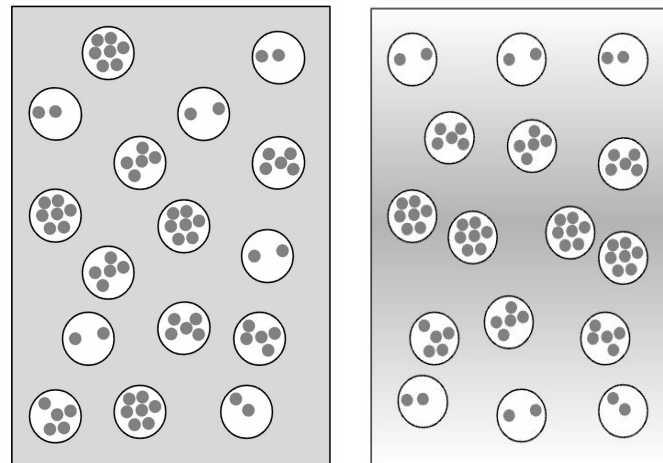- Suggests flocs are well mixed → minimal spatial gradient of saturated flocs

Figure 17. Current conclusions for floc saturation distribution in the clarifier.

Future Work

Short Term:

- ❏ Determine whether we can visualize red clay primary particle capture in the floc filter (spatial distribution of saturated flocs)
  - ❏ Run experiment with several different colors (determine average floc residence time in the floc filter)
- ❏ Effects of floc filter saturation on effluent turbidity
- ❏ Effects of influent turbidity, coagulant dose on floc filter dynamics (floc size)
- ❏ Improve imaging and lighting techniques (eg. front vs. back lighting, floc app camera)
- ❏ Test different lighting conditions

Long Term:

- ❏ Video processing and analysis - particle tracking
  - ❏ Flocs created in the plate settlers vs. in the flocculator
- ❏ Visualization of flocs in the tube flocculator
- ❏ Flocculation modeling
  - ❏ Coagulant collisions with each other and flocculator walls (diffusion, shear, turbulent mixing)

References

Du, Y., Pennock, W. H., Weber-Shirk, M. L., & Lion, L. W. (2019). Observations and a geometric explanation of effects of humic acid on flocculation. *Environmental Engineering Science*, *36*(5), 614–622. https://doi.org/10.1089/ees.2018.0405

Hurst, M., Weber-Shirk, M., & Lion, L. W. (2014). Image analysis of floc blanket dynamics: Investigation of floc blanket thickening, growth, and Steady State. *Journal of Environmental Engineering*, *140*(4). https://doi.org/10.1061/(asce)ee.1943-7870.0000817.

Hurst, M., Weber-Shirk, M., Charles P., & Lion, L. W. (2013). Apparatus for Observation and Analysis of Floc Blanket Formation and Performance. *Journal of Environmental Engineering*, *140*(1). https://doi.org/10.1061/(ASCE)EE.1943-7870.0000773.

Pennock, W. H., Weber-Shirk, M. L., & Lion, L. W. (2018). A hydrodynamic and surface coverage model capable of predicting settled effluent turbidity subsequent to hydraulic flocculation. *Environmental Engineering Science*, *35*(12), 1273–1285. https://doi.org/10.1089/ees.2017.0332

Sarmiento, K. (2021). Particle Removal in Floc Blanket Clarifiers Via Internal Flow Through Porous Fractal Aggregates. *Cornell University*.

Weber-Shirk, M. (n.d.). Clarification Introduction. *The Physics Of Water Treatment Design*. https://aguaclara.github.io/Textbook/Clarification/Clarifier_Intro.html

Thanks for Listening! Questions?

Anjali Asthagiri
aa2549@cornell.edu

Alex Gardocki
rag325@cornell.edu

Lauren Hsu
lkh58@cornell.edu

Isabel Crovella
isc25@cornell.edu

Max Zheng
hz687@cornell.edu

Appendix

Clarifier Design & Fabrication

Key Design Considerations

- Floc filter suspension while minimizing floc breakage
  - Diffuser velocity, length, geometry
  - Jet reverser size, slope angle (50º)
- Plate settler performance
  - Length, angle (60º), spacing, thickness
- Particle removal in the floc filter
  - Floc filter height
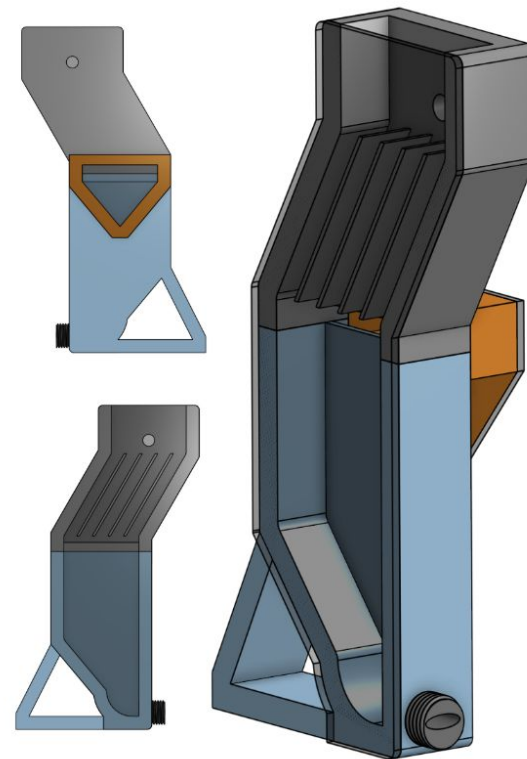- Visualization of the floc filter and floc hopper
  - Acrylic/glass
- Resin printer size

Figure A1. Miniature clarifier design.