AguaClara Cornell Floc Modeling

Summer 2025: Final Report

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Abstract

This summer, the main focus of the Floc Modeling subteam was revising the existing experimental setup by improving the model clarifier and gathering data to be analyzed in the upcoming semester. The data will be used to validate the existing flocculation and clarification models as well as to test a previously proposed method for measuring floc saturation within the clarifier based on the capture of colored particles by the floc filter. If viable, this measurement technique for floc saturation may improve current understanding of floc filters and allow for further improvements to the clarification model.

Introduction

The purpose of the Floc Modeling subteam is to develop a mathematical model of the flocculation and clarification processes used in AguaClara water treatment plants in order to optimize plant design and operation. With an accurate physical model of these processes, plant operators can more accurately adjust coagulant dosages in response to influent conditions, leading to improved performance and reduced cost by minimizing excess coagulant. Furthermore, by integrating electronic sensing and dosing systems, these models can partially automate plant operation, further reducing costs from operator expenses.

The current focus of the Floc Modeling subteam is to investigate the physical properties and interactions between flocs and primary particles in the floc filter during clarification through the use of a lab-scale model vertical clarifier. This model clarifier allows for observation of the floc filter in order to monitor spatial variations in floc filter concentration and floc saturation as well as effluent turbidity under different coagulant dosages and influent conditions. This prototype model clarifier, shown in Figure 1, was developed and assembled by the Spring 2025 team, and it successfully demonstrated the ability to form a floc filter. The clarifier's small volume and low hydraulic residence time (~90 seconds) allows for faster experimentation and less time spent to grow the initial floc filter than in previous experimental setups.

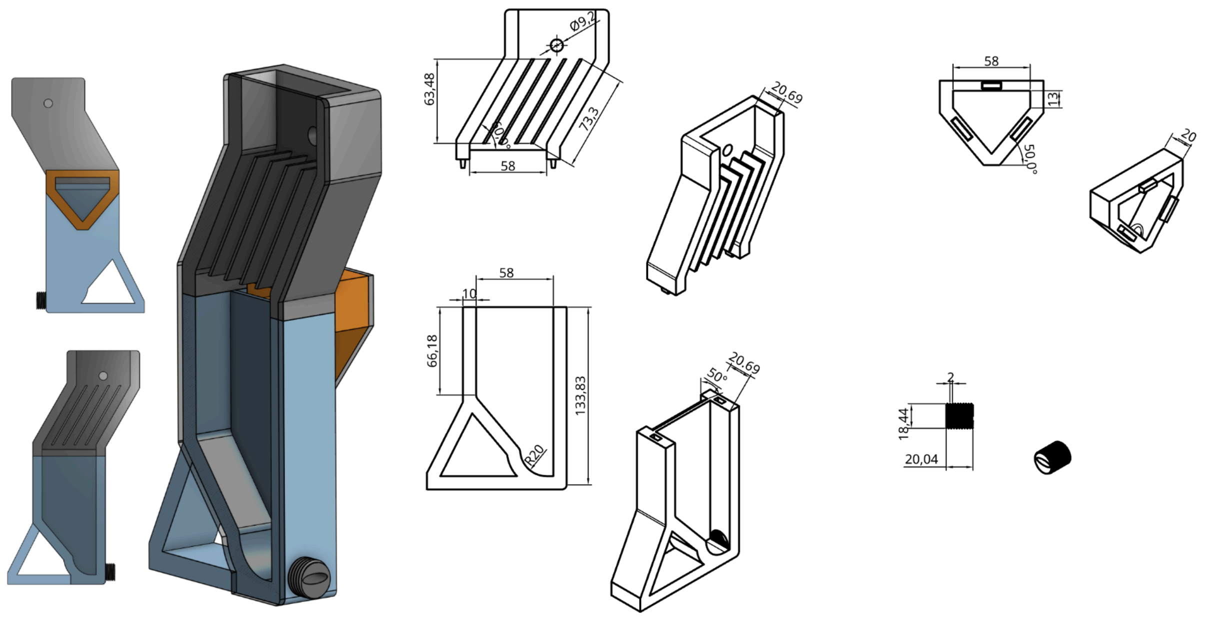


Figure 1. Schematic of prototype model clarifier. Dimensions are given in millimeters.

Despite its success, testing revealed opportunities for improvement of the model clarifier design. One of the main uses for the clarifier was to test a proposed method for detecting spatial variations in floc saturation, shown in Figure 2. For the proposed method, the clarifier would first be populated with a floc filter formed from white kaolin clay and coagulant run through a coiled tube flocculator. Once the floc filter was fully grown, colored primary particles in the form of dyed clay would be added directly to the clarifier without passing through the flocculator. These smaller primary particles would then be captured by the flocs in the floc filter. Over time, the more saturated areas of the floc filter which had captured more primary particles would become more strongly pigmented than the rest of the floc filter, allowing us to determine the spatial distribution of floc saturation within the floc filter. Unfortunately, the grey resin back of the initial clarifier made it difficult to distinguish color variations within the clarifier. It also prevented us from backlighting the floc filter, which would allow us to use the method described by Hurst et al. (2014b) to determine the spatial distribution of floc concentration within the floc filter. The summer team developed and assembled a new design to remedy these issues and to evaluate the proposed method for detecting floc saturation.

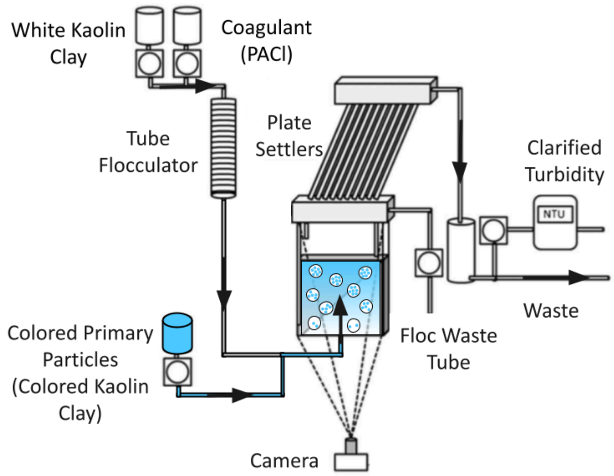


Figure 2. A diagram of the proposed experimental apparatus for detecting variations in floc saturation within the floc filter. Adapted from Hurst et al., 2014a.

Literature Review & Previous Work

Previous Clarifier Design

The clarifier design created by the Spring 2025 Floc Modeling team was the basis for the revised design. The clarifier was composed of four resin-printed parts and two laser-cut acrylic panels glued together using J-B Weld epoxy resin. This ensured the container was water-tight. Inlets and outlets used threaded push-to-connect fittings to allow for easy reconfiguration of the system. A threaded resin-printed insert was used to form the jet profile, which could be replaced with other inserts to test jet profiles of different shapes and sizes. Dimensions were chosen to mimic those in actual AguaClara plants as closely as possible. For example, the diffuser angle was 50º, the same as in AguaClara plants (Weber-Shirk, n.d.). In order to ensure an upflow velocity of 1 mm/s through the clarifier like in AguaClara plants, the cross-sectional area of the clarifier was designed to be 1200 mm^2 so that a target flow rate of 1.2 mm/s would reach the desired velocity (Weber-Shirk, n.d.). The 60º angle of the plate settlers was also consistent with actual AguaClara plants (Weber-Shirk, n.d.).

Floc Filter Imaging

The method for quantifying floc saturation was based on the work done by Hurst et al. (2014b) to quantify floc concentration using imaging. Hurst et al. took images of a vertical clarifier that was lit from the back during the growth of a floc filter. As the floc filter grew denser, more of the transmitted light was obscured by the flocs, allowing the concentration of the floc filter to be calculated based on the expected composition of the flocs and Beer's Law, which relates the light absorbance of a solution to the solution's concentration and the path length through the solution. Since each image could capture the entire floc filter, this allowed for the comparison of the concentration of flocs within different regions of the floc filter.

The Fall 2024 Floc Modeling team (formerly the Coagulant Dosing team) adapted this idea by considering the use of reflected light instead of transmitted light, which would allow the images to demonstrate variations in coloration. Combined with the addition of colored particles that could be captured by the flocs, this provides a method for detecting variations in floc saturation. With further post-processing and analysis of the coloration in these images, it is possible that quantitative measurements of floc saturation could also be recovered.

To this end, Houle et al. (2024) provides a comprehensive method for quantifying coloration in digital photographs. A color chart with known reflectance values is included in each picture so that the true color values can be recovered regardless of variations in lighting. Images are then formed in RAW format to avoid compression. Since cameras often record reflectance on a curve, a set of sample images representing all lighting conditions in the dataset is used to linearize the reflectance values based on the grey reflectance values in the color chart. This linearization is then applied to all the images in the dataset before analysis, making color measurements standardized and repeatable.

Methods

Experimental Apparatus

Figure 3 shows the revised clarifier design. The main difference from the original design was the use of an acrylic plate for both the front and the back of the clarifier. This allowed the background of the floc filter to be changed, providing more flexibility when imaging. The clarifier could also be backlit through the acrylic backplate, meaning we could also measure floc concentration (Hurst et al. 2014b). Additionally, sampling ports were added at different heights within the floc filter. The sampling ports can be used to take samples from the floc filter or to run experiments which require wasting from somewhere other than the top of the floc filter. One of the potential applications for measuring floc saturation is to detect the most saturated region of the floc filter. Flocs can then be wasted from this saturated region instead of from the top of the floc filter in order to improve performance.

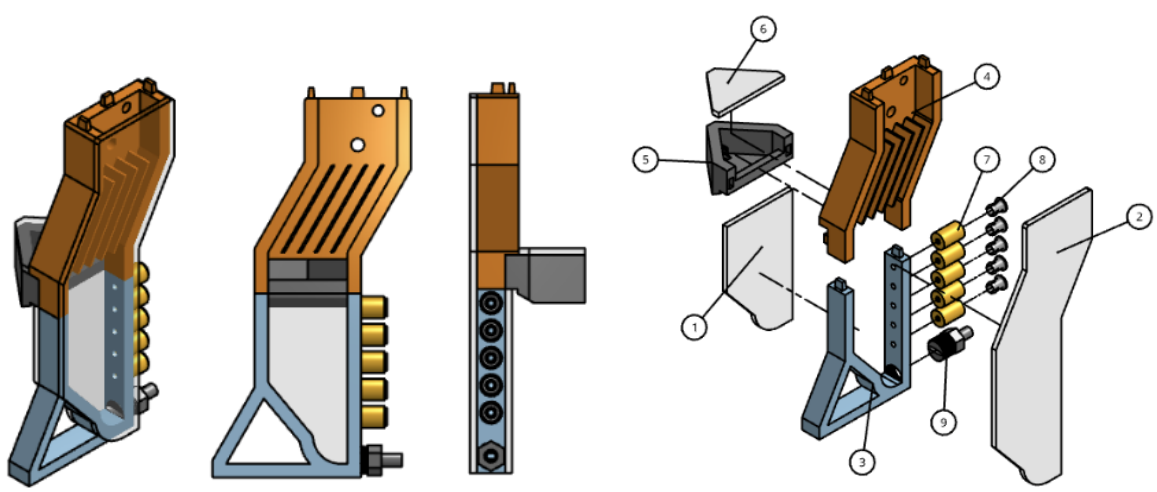


Figure 3. CAD and exploded view of revised model clarifier.

Further minor modifications were also made to the clarifier design. The size of the passage leading into the floc hopper was expanded since, in the previous design, flocs had trouble entering the floc hopper. The shape of the jet profile was also modified to be slightly wider to prevent flocs from becoming stuck in the corners next to the inlet. To reduce printing time, rather than resin printing the parts, the clarifier was printed using PETG filament. PETG is highly water resistant, but can suffer from poorer layer adhesion than resin printing due to the inherent limitations of fused deposition modeling (FDM). For this reason, the infill and outer layer thickness were increased to ensure the clarifier was still watertight. The fully assembled clarifier with an active floc filter can be seen in Figure 4.

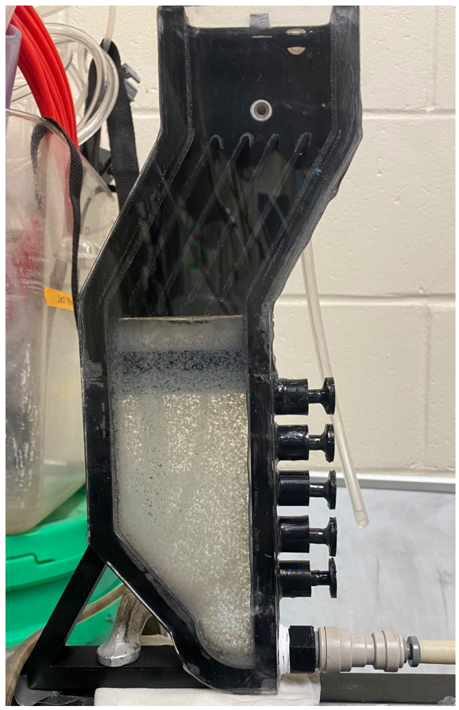


Figure 4. The assembled clarifier with an active floc filter.

Floc Saturation Experiment

As we did not have access to a digital camera and a color chart to follow the procedure proposed by Houle et al. (2024), we performed a proof of concept test using a phone camera and a variety of lighting conditions. First, a floc filter was formed by running a solution containing 50 NTU of white kaolin clay and 20 mg/L of Poly-Aluminum Chloride (PACl) coagulant through a tube flocculator and into the clarifier. Due to a bleeder valve (used to remove trapped air bubbles) placed between the tube flocculator and the clarifier, a flow rate of 1.5 mL/s into the tube flocculator was chosen so that the flow rate into the clarifier would be approximately 1.2 mL/s. The tube flocculator had a radius of curvature of 42 mm and an inner diameter of 4.381 mm, which, based on calculations performed by Tse et al. (2011), gave a velocity gradient of 193 Hz. The kaolin clay was added from a 1300 mg/L stock solution, with the dosage controlled using a PID controller and a turbidimeter. The coagulant was added from a 648 mg/L stock solution. The floc filter was grown for approximately 75 minutes.

Once the top of the floc filter interface reached the entrance to the floc hopper, we stopped growing the floc filter and began adding colored particles. The experiment was performed using both rose kaolin clay and black kaolin clay as the source of colored particles. Colored clay from a stock solution of 750 mg/L was added after the tube flocculator but before the clarifier so that the concentration of colored clay entering the clarifier would be 50 mg/L. Additionally, coagulant was added so that the concentration of coagulant entering the clarifier would be 5 mg/L. The addition of coagulant was meant to facilitate particle capture of colored clay by the flocs. Colored clay was added for approximately 75 minutes.

Following the addition of colored clay, pictures of the floc filter were taken using a phone camera under 3 separate lighting conditions: phone flash, LED flashlight, and ambient light. For each lighting condition, a picture was taken using both a white background and a black background. Pictures were also taken with backlighting from the LED flashlight. Following these initial pictures, the clarifier was flushed with water until the effluent turbidity reached 1 NTU to remove any remaining colored particles that had not been captured by the floc filter. Then, more pictures of the floc filter were taken under each of the lighting and background conditions.

Results and Analysis

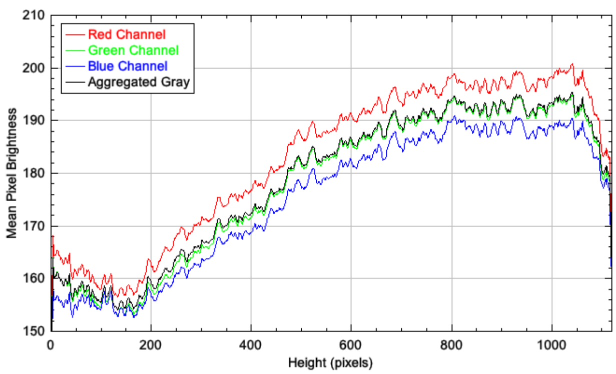
Each image of the floc filter was analyzed and processed using ImageJ, an image processing software. The red, green, and blue color channels for each image were separated, and the images were cropped to include only the floc filter. Then, the average pixel brightness for each row of pixels was calculated and graphed to show the trend in pixel brightness as the height within the floc filter increased. All graphs and processed images can be found in Supplement 1.

The images of the floc filter when photographed using reflected light show a general trend of increasing pixel brightness across all three (red, green, and blue) color channels as the height within the floc filter increases. The graphs showed little difference between the flushed and unflushed images. Some images also show a large initial spike in pixel brightness, which appears to be a result of the lower density of flocs in the region directly above the jet. The graphs also tend to level out as they approach the top of the floc filter. While some graphs show little to no increasing trend, none appear to show a consistent decrease in pixel brightness with height. This suggests that floc saturation is higher towards the bottom of the floc filter where primary particles are entering the clarifier and are first able to be captured. However, further analysis reveals a number of possible confounding factors.

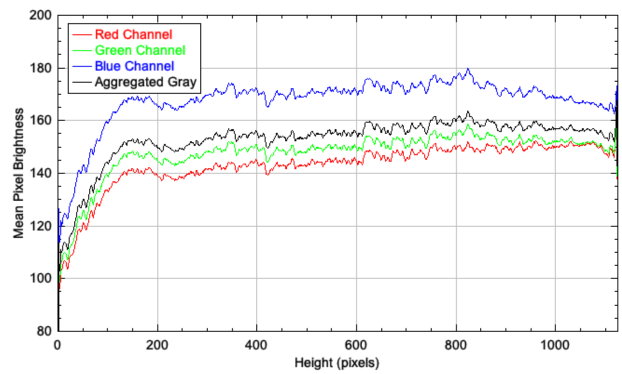
Firstly, since the pictures were taken using a phone camera without a color chart, the reflectance could not be linearized or adjusted for the lighting conditions. Furthermore, the RAW image files could not be recovered from the camera, so the images are subject to JPEG compression, which reduces the range of color values that can be recorded in the image. However, because the coloration of each image is only being analyzed qualitatively in comparison to other regions within the same image, this should have minimal effect on the shape of the observed trends.

A more serious sign of error is that for the images using rose clay, the trends in the red channel do not appear to differ significantly from the trends in the green or blue channels. If the rose clay were actually being captured towards the bottom of the floc filter and causing the change in pixel brightness, we would expect the brightness of the red channel to be higher at the bottom relative to the green and blue channel, while at the top, the variation between the channels would be smaller. However, as seen in Figure 5, the variation between the red channel and the blue and green channels does not change significantly as height within the floc filter increases. This suggests that the trends in pixel brightness are the result of other factors.

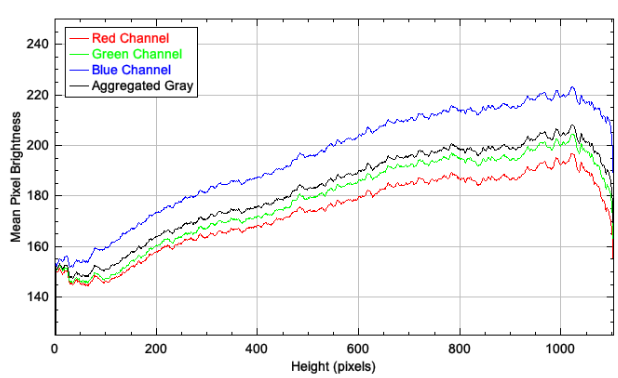
a)



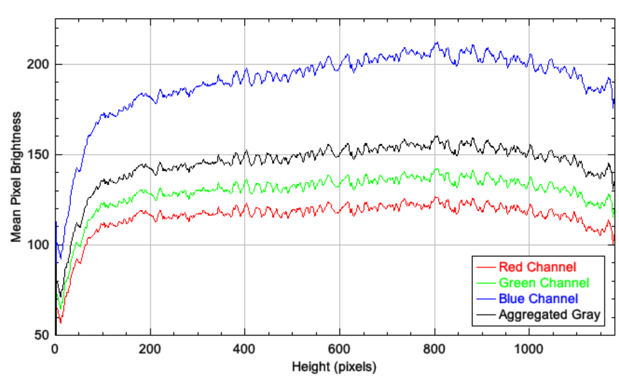
b)



c)



d)



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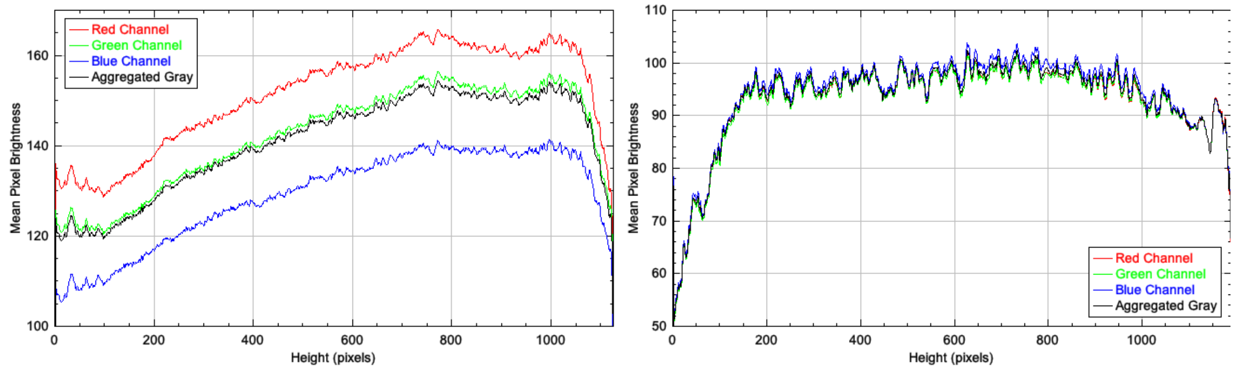

Figure 5. The graphs show the mean intensity of the red, green, blue, and aggregated grey channels at varying heights within the floc filter using rose clay in the images taken under the following conditions: a) white background and flash, b) black background and flash, c) white background and LED light, d) black background and LED light, e) white background and ambient light, f) black background and ambient light. The trend of each red channel is almost identical to the corresponding green and blue channels other than a constant offset in brightness.

One possible alternative source for the trends in brightness was the lighting used to take the photos. If the lighting was not sufficiently diffuse, then the images could have been capturing the variation in the intensity of the lighting rather than the intensity of the coloration of the floc filter itself. Figure 6 shows images of the individual red, green, and blue channels for the picture of the floc filter using rose clay with a white background and LED light (corresponding to Figure 5(c)). The images appear to show a central region towards the top middle of the clarifier that exhibits the greatest pixel brightness, with brightness decreasing radially outwards. This is likely the area at which the LED flashlight was aimed. The effect is most apparent in the blue channel, possibly because the LED light was slightly blue rather than a neutral white light. This can also be seen in the prominence of the blue channel in the images taken with the LED light (Figures 5(c) and 5(d)) compared to the images with different lighting.

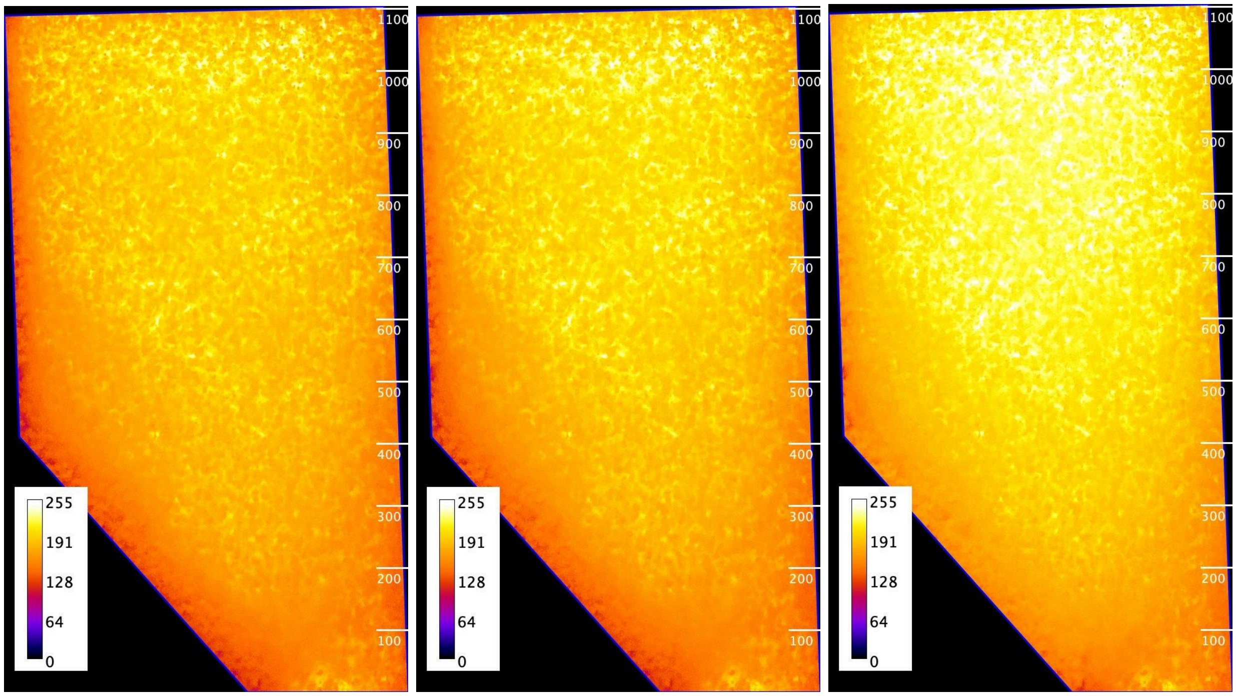

Figure 6. The red, green, and blue channels (left to right) for the image of the floc filter using rose clay with a white background and LED light. A lookup table was applied to make variations in pixel brightness more distinct.

Another possible source for the trends in brightness was the spatial distribution of flocs. The floc filter was sparse enough that the unobscured background could be seen in the gaps between flocs. For the images with a white background, the gaps between flocs tended to be brighter than the flocs themselves, as seen in Figure 6. It is possible that the average distance between flocs increases as height within the floc filter increases, causing more gaps and hence greater pixel brightness. This would not explain the trends for the images with black backgrounds as the gaps in these images were darker than the flocs. However, the images with white backgrounds tended to show a greater increase in pixel brightness, suggesting that this effect at least contributed to the observed trends.

Discussion

The effectiveness of the floc filter imaging method for detecting variations in floc saturation remains unclear. The image data gathered did not consistently indicate a clear variation in coloration. It is possible that the floc filters that develop within the current clarifier do not have the capacity to capture enough colored particles to change color significantly. This could also be a result of the amount of coagulant being added to the clarifier rather than an intrinsic property of the floc filter itself; more or less free coagulant may be needed in order to effectively facilitate primary particle capture. A different, more vibrant source of colored particles such as Red-40 or fluorescent particles may be able to remedy this issue.

It is also possible that floc saturation is distributed uniformly within the floc filters formed by our clarifier. If this is true in general for all floc filters, it would have significant implications for clarification modeling as it would validate a useful simplifying assumption. Unfortunately, because our proposed method for detecting floc saturation relies largely on spatial variation, this would make it difficult to validate our method. However, it is possible that instead of looking at spatial variation, we could focus instead on temporal variation by comparing the average color of the floc filter across time as more colored particles are added. This could also provide insight into how quickly the floc filter becomes saturated.

Future Work

Floc Saturation

New sources of colored particles such as Red-40 need to be evaluated. If another dye can be captured in a floc filter and demonstrate greater visibility, then this method for evaluating the spatial distribution of floc saturation may still be viable. The method should also be tested with multiple images taken over time as colored particles are added to see if it can detect temporal variations in saturation.

Clarifier Design

While the new clarifier offered improvements when it came to imaging, there are still further problems that need to be addressed. There are some leaks at the interface between the acrylic and the printed body. This may be due to the ridges introduced by using PETG instead of resin-printing. Additionally, the design of the floc hopper needs to be revised to prevent sludge from getting stuck. These problems will need to be resolved in future iterations of the clarifier design.

References

Houle, C., Turcotte, A., Paterson, J. E., Blouin-Demers, G., & Garant, D. (2024). A step-by-step method to quantify coloration with digital photography. *MethodsX*, *12*, 102648. https://doi.org/10.1016/j.mex.2024.102648

Hurst, M., Weber-Shirk, M., Charles, P., & Lion, L. W. (2014a). Apparatus for observation and analysis of Floc Blanket Formation and performance. *Journal of Environmental Engineering*, *140*(1), 11–20. https://doi.org/10.1061/(asce)ee.1943-7870.0000773

Hurst, M., Weber-Shirk, M., & Lion, L. W. (2014b). 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

Tse, I. C., Swetland, K., Weber-Shirk, M. L., & Lion, L. W. (2011). Method for quantitative analysis of flocculation performance. *Water Research*, *45*(10), 3075–3084. https://doi.org/10.1016/j.watres.2011.03.021

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