

Tools for drinking water reuse and treatment:

Aluminum Sulfate coagulation optimization for ultrafiltration membrane
pre-treatment using raw surface water blended with ultrafiltration permeate

By:

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Submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the Degree of
Master of Environmental Assessment

Raleigh, NC

2021

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August 2, 2021

ABSTRACT

COBLER, DALE. MASTER OF ENVIRONMENTAL ASSESSMENT. TOOLS FOR DRINKING WATER REUSE AND TREATMENT: ALUMINUM SULFATE COAGULATION OPTIMIZATION FOR ULTRAFILTRATION MEMBRANE PRE-TREATMENT USING RAW SURFACE WATER BLENDED WITH ULTRAFILTRATION PERMEATE.

The primary objective of this study was to identify an optimum aluminum sulfate (alum) coagulation dosing range for pre-treatment of supply water going to an ultrafiltration (UF) membrane system. The supply water assessed consisted of raw surface water (80-90%) blended with ultrafiltration permeate (10-20%). The ultrafiltration permeate used for blending was provided from a secondary ultrafiltration membrane system which recycles Spent Filter Backwash Water (SFBW) generated from conventional granular media filters and the primary ultrafiltration membrane system. Jar testing was completed using blended samples coagulated with alum and settled for a total time of two hours to simulate regulated detention time. The water quality parameter of key interest was the removal of organics as indirectly determined via ultraviolet wavelength absorbance spectrophotometric measurements at 254 nanometers (UVA_{254}). The alum coagulation optimization was selected as a critical method for removal of disinfection by-product (DBP) pre-cursors present in Natural Organic Matter (NOM) which are introduced to the system in the raw surface water. Alum coagulation optimized dosage ranges were between 7-8.5 mg/L for all blended samples. Jar Testing results indicated that introduction of alum coagulation pre-treatment to the primary UF membrane system, achieved organics removal that would be comparable to the conventional treatment system.

Keywords: Aluminum sulfate coagulation optimization, drinking water treatment, ultrafiltration permeate, disinfection by-products, Spent Filter Backwash Water (SFBW)

BIOGRAPHY

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ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to the NCSU Environmental Assessment program faculty, especially Dr. Pandolfo and Mrs. Taylor, for their direction and tireless support which aided in the culmination of this project. I want to thank the staff of Two Rivers Utilities for their collaboration in data collection and analysis. Their dedication to providing safe drinking water to their customers is paramount. I would like to thank Mr. Chris High for his guidance and support for this project. I would especially like to thank Mr. Ed Cross for his professional/technical assistance throughout this study. This research would not have been possible without his support. Lastly, I would like to express the utmost appreciation to my wife, Alicia, for her patience and support of my completing this degree during the last 4 years.

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Introduction

Two Rivers Utilities (TRU) is a joint public utility owned by the City of Gastonia and the town of Cramerton, North Carolina (NC). The utility provides drinking water to approximately 100,000 customers in 7 different municipalities within Gaston county, NC and York county, SC. Mountain Island Lake (MIL) is a man-made lake within the Catawba River Basin of North Carolina. It is the primary raw surface water source used by TRU for drinking water treatment. MIL provides a consistent, reliable quantity of raw water supply with low turbidity to the TRU Water Treatment Plant (WTP). The TRU WTP uses a combination of conventional and ultrafiltration (UF) membrane treatment technologies. The TRU WTP operates both conventional granular media filters and ultrafiltration membrane systems. There are two conventional plants that each have 4 granular media filters.

Conventional drinking water treatment consists of pumping raw water from a designated source to the WTP where it undergoes a series of processes before being distributed to consumers which includes, but is not limited to: screening, disinfection, aeration/oxidation, coagulation, flocculation, sedimentation, filtration, disinfection, and post-chemical treatment ([Spellman, 2015](#)). The coagulation process involves the application of a metal salt coagulant or organic polymer into the raw water which targets suspended, colloidal, and dissolved matter which will then be removed via flocculation. Aluminum Sulfate (Alum) is a commonly used cationic metal salt coagulant for conventional drinking water treatment. Alum hydrolyzes quickly in the water, forming insoluble precipitates that destabilize the particle via adsorption and charge neutralization ([Howe et al., 2012](#)). The next step in the conventional treatment process is sedimentation where the flocculant (floc) that has been formed will settle to the bottom of the basin and be removed prior to the filtration process. The water that enters the conventional filter following sedimentation is known, colloquially among water treatment professionals, as settled water. This water is then filtered, dosed with post-filtration chemicals, and distributed. Conventional granular media filters commonly contain anthracite, sand, and varying sizes of gravel/cobbles to aid in the filtration process. The primary mechanisms of particle/particulate removal in conventional granular media filters following coagulation are sedimentation, interception, diffusion, and straining ([AWWA, 2010](#)). This pre-treatment process is necessary for optimum filtration using conventional granular media filters. However, in recent years other technologies such as membrane systems have been used increasingly for drinking water treatment and can be operated in different configurations which may or may not include coagulant pretreatment.

Membrane technology has an extensive development history with the first example dating back to 1748 and experienced significant innovations during the 1900s. Membranes have an increasing presence in commercial applications since the 1960s. They are used for purification purposes in a variety of applications today including water treatment, water desalination, wastewater, food production, clinical, laboratory and many others. ([Singh, 2015](#)) There are many different types of membranes: reverse osmosis, nanofiltration, ultrafiltration, microfiltration, gas separation, pervaporation, electrodialysis, distillation, dialysis, and others. Membranes are fundamentally organized based on configuration (i.e., flat sheet, tubes, hollow fiber, capillary) and structure (i.e., films, asymmetric, symmetric). Then there is a driving force acting on the membrane (i.e., pressure, temperature, concentration-gradient, electrical-potential) which results in varying degrees of physical separation ([Wang et al., 2008](#)). Membranes remove particulate matter via mechanical sieving as any

matter which is larger than the pore size of the fiber cannot pass through and will be excluded. The TRU WTP has two ultrafiltration membrane systems; one is used to produce permeate for distribution and the other is used to recycle Spent Filter Backwash Water (SFBW). The SFBW is waste that is generated from cleaning both the conventional and first stage membrane filters.

The Filter Backwash Recycling Rule (FBRR) was established in 2001 and provides regulations for recycling waste streams generated from conventional and direct processes in WTPs ([EPA, 2002](#)). SFBW is one classification of waste stream characterized under the FBRR for recycling at drinking WTPs. The conventional and membrane treatment systems both undergo a backwash process which produces SFBW. UF membrane treatment is a proven method for recycling of SFBW ([Reismann & Uhl, 2006](#)). The TRU WTP uses SFBW as defined in the FBRR which is treated by a secondary UF membrane treatment system ([Suez ZeeWeed™ 500d](#)) and then blended with raw surface water from MIL. The ratio of raw surface water to second stage permeate is typically 6:1. This blended water is then used as supply water for the first stage ultrafiltration membrane system ([Suez ZeeWeed™ 1000](#)). A documented challenge with recycling SFBW is the propensity of this waste stream to contribute to formation of Disinfection-By-Products (DBP). UF membranes have been shown to effectively remove DBP precursors when recycling 10% SFBW blended with raw source water and that it could improve the alum coagulation efficiency if the raw source water was low turbidity ([Gora & Walsh, 2011](#)). The conventional filtration treatment and ultrafiltration membrane treatment systems are primarily independent of one another prior to the filtration step. The conventional & UF membrane filtered water, known as permeate for the ultrafiltration membranes, is blended to provide finished water for distribution. This is a key consideration for how the efficiency to remove unwanted matter in one system can influence the other. The primary source of the compounds needed to form DBPs is Natural Organic Matter (NOM).

NOM compounds in natural waters are generally grouped into two categories: (1.) Autochthonous which are formed in the body of water and (2.) Allochthonous which form in the soil or are formed in upstream bodies of water. NOM can further be characterized generically as humic or non-humic. Humic substances include humic acids, fulvic acids, and humins which typically have a high molecular weight. Non-humic substances such as carbohydrates, proteins, and peptides are typically low molecular weight and found in low concentrations of most natural waters. DBPs are compounds that are formed when a disinfectant containing chlorine is used and reacts with NOM during the disinfection treatment process. DBP formation is influenced by NOM, bromide concentration, chlorine dosing, pH, temperature, and detention time ([Karanfil et al., 2008](#)). Humic substances absorb UV light at 254 nm and have been positively correlated with DBP formation ([Korshin et al., 2009](#)). Therefore, the humic portion of the NOM can be reasonably identified using UV Absorbance testing at 254 nm (UVA_{254}). Specific UV-Absorbance (SUVA) is the measure of Dissolved Organic Carbon (DOC) aromatic content that is calculated by measuring the DOC and the UVA_{254} of a 0.45- μ m filtered water sample ([EPA, 2005](#)). SUVA values greater than 4 generally represent a sample composition of hydrophobic, aromatic compounds (humic) whereas a SUVA value less than 3 typically identifies a sample containing more hydrophilic (non-humic) compounds ([Edzwald & Tobiason, 1999](#)). Historical DOC data for the TRU WTP (2014) is often below a SUVA value of 3 which suggests more non-humic NOM in the source water ([Appendix E](#)). UVA_{254} has been shown to be positively correlated (R^2 between 0.71-0.82) with DBP formation potential ([Golea et al., 2017](#)).

The analytical results for TRU indicated that the DBPs, although within regulated limits, were elevated compared to historical values in the distribution system for the TRU WTP in January 2021. There was no pre-filtration chlorination for the membrane treatment system. Two primary contributors that influence DBP formation in the TRU WTP: (1) DBP precursors in source water and (2) chlorine dosing and reaction/contact time. DBP concentrations have regulated limits established by the EPA for drinking water. The TRU WTP kept DBP concentrations within regulated limits but had observed an uncharacteristic increase in the distribution system samples. One of the potential contributors to DBP formation was NOM reactions during the disinfection process. UVA₂₅₄ data needed to be collected throughout the WTP to better understand the efficiency of NOM removal and where opportunities existed to improve coagulation. The hypothesis was that the organics in the first stage ultrafiltration membrane system supply water could be reduced by introducing optimized aluminum sulfate coagulation as pre-treatment. Alum coagulation pre-treatment for first stage membrane supply water could reduce NOM that contributes to DBP formation. Three objectives were established to address the experimental goals of the case study: (1) Establish sampling points in the TRU WTP for process control data collection, (2) Collect treatment process control analytical data and compare these results with historical and present conventional plant values, (3) Determine optimum dose of Aluminum Sulfate (Alum) coagulant for membrane plant pre-treatment targeting removal of DBP precursors using UVA₂₅₄ and turbidity analysis.

Methods

UVA₂₅₄ Sampling

It was necessary to establish sampling sites in the TRU WTP for UVA₂₅₄ sampling which would represent organics removal at varying stages of treatment (Figure 1; Table 1). The conventional and UF membrane combination at the TRU WTP has locations where these systems function independently and where they are combined. Special care was taken to identify similar locations for each system where the samples could be comparable in treatment terms. Samples 1 and A are the same for conventional and first stage membranes. Samples C1 & C2 on the conventional filters are comparable to sample 5 on the first stage membrane system. Both of these samples are essentially filtered water from each system. Samples D1 and D2 represent the conventional filtered samples (C1 & C2) combined with the first stage membrane permeate (sample 5) that has been treated with post-filtration chemicals and sent for storage in the clearwells before being pumped into the distribution system. TRU has two clearwells that are operated in series with D1 being first and D2 being second before the water is pumped out into the distribution system. The selected sampling sites permitted a good overall determination of UVA₂₅₄ throughout the treatment process from raw water to distribution water. UVA₂₅₄ samples were collected at the designated sites from January through June of 2021. A separate field study, independent of this project, was completed to assess DBPs in the distribution.

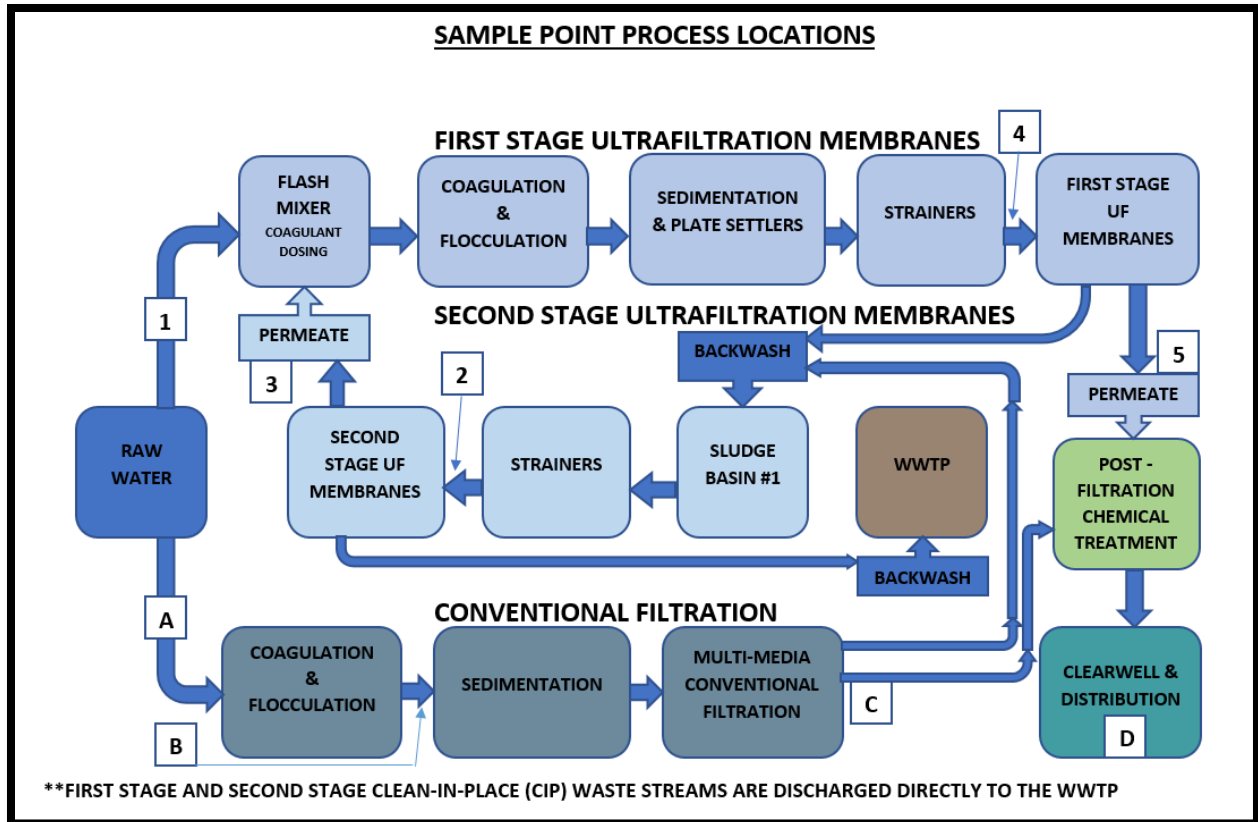


Figure 1. TRU WTP Conventional & Treatment Flow Diagram

Table 1. TRU WTP Conventional & Membrane UVA_{254} Sampling Locations

TRU WTP UVA_{254} Sample Locations 2021	
ID	Description
1	Raw Source Water entering facility
2	Second Stage UF Supply Water (primarily SFBW)
3	Second Stage UF Permeate Water
4	First Stage UF Supply Water (Raw Source + Second Stage Permeate)
5	First Stage UF Permeate Water
A	Raw Source Water entering facility
C1	Filter #6 (North Plant) conventional post-filtration
C2	Filter #7 (South Plant) conventional post-filtration
D1	Conventional filtered & Permeate water combined finished water exiting first clearwell (South Plant) in series
D2	Conventional filtered & Permeate water combined finished water exiting second clearwell (West Plant) in series prior to distribution

Samples points “1” and “A” are a common raw source water sample for the conventional plants and the first stage membrane plant. Both of these systems eventually go to the distribution system. The second stage membrane plant recycles Spent Filter Backwash Water (SFBW) and the filtered water (permeate; sample “3”) is blended with the raw water (sample “1”) to supply the first stage membranes with water to treat. This first stage supply water ratio often consists of 80-90% raw water with 10-20% second stage permeate. There is no coagulation pre-treatment at present time for the first stage membranes so any removal of organics would likely occur from unaided settling during the detention time (minimum of 2 hours) prior to the blended water reaching the membranes. Sample “B” should represent the coagulation effects on the raw water (sample “A”) as coagulation occurs almost instantly. Sample “C” and “5” represent similar process control points for the conventional treatment plants and the first stage membrane plant. These would be the last two samples points that are independent between the membrane plants and the conventional plants. The filtered conventional water and first stage membrane permeate are blended and chemically treated post-filtration. Sample “D” is representative of this blended and treated drinking water.

Logistical and staffing constraints dictated that only nine samples could be collected total for analysis. Sample point “B” was omitted from the sampling to reduce two sampling sites (North and South conventional plants) which reduced the total number of sites to nine. This sample location was also removed as it did not have a comparable location in the membrane system for comparison. Sample point “C” would still indicate the removal efficiency of the coagulation and flocculation process while also identifying the organics removal following conventional filtration. Each sample represents the process control location for each conventional treatment plant. There are two conventional plants that are identified as the North and the South plant, respectively. Each conventional plant has four conventional multi-media filters. The North plant filter #6 was the sample location C1 and the South Plant filter #7 is sample location C2. Additionally, the sample “D” was also split into two samples. There are two clearwells at the WTP and the current treated water is directed in series first through the South Clearwell (D1) and then through the West Clearwell. When the treated water exits the West Clearwell then it is pumped out of the WTP into the distribution system. Sample location “D2” is tapped into a distribution line leaving the distribution pumps and would represent the treated water that has had its full detention time in both of the clearwells.

Jar Testing for Alum coagulation Optimization

One liter of a 1% stock solution of alum was prepared in preparation for the jar testing. Making a one percent alum stock solution simplifies the dosing portion of the jar testing procedure. Three ratios of raw surface water blended with second stage permeate were selected to best represent the potential range for the TRU WTP operational conditions; 90% raw water with 10% permeate, 85% raw water with 15% permeate, and 80% raw water with 20% permeate. The six 2-Liter square beakers were filled with the designated ratio of raw source water and second stage permeate by volume. A separate blended sample was collected simultaneously which was measured for turbidity and pH. The jars were placed in the jar tester and the paddles were secured inside of each jar. The dosages corresponding to 4, 5, 6, 7, 8, and 9 mg/L of alum stock solution were pipetted into hexagonal weighing boats. The jar tester was turned on to paddle speeds of 300 rpm and allowed to mix for 60 seconds prior to dosing the alum to ensure adequate mixing of raw source water and

second stage permeate. A timer was prepared and started once all six jars were dosed with alum. The jars were mixed at 300 rpm for one minute. The jars paddles were then reduced to the following speeds for the specified durations: 70 rpm for 5 minutes, 50 rpm for 5 minutes, and 30 rpm for 10 minutes. The jar paddles were then turned off and settling was allowed to continue for 1 hour 39 minutes for a total test time of two hours. Two hours was selected to mimic the minimum allowable detention time for the first stage membrane system. 200 mL of sample were collected from each jar following the end of settling time. Each sample was collected in a clean 250 mL Glass Beaker which was labeled with alum dosage using time tape. 100 mL from each sample was used to measure pH and turbidity. All samples were then filtered using a 0.45 μm membrane filter using magnetic filter funnel and Erlenmeyer flask prior to UVA₂₅₄ testing. A single 100 mL sample from each jar test (7 mg/L) was taken and filtered additionally through a 0.02 μm membrane filter via filter funnel, vacuum pump, and Erlenmeyer flask prior to UVA₂₅₄ testing. This is used to imitate the blended sample, post-coagulation, being filtered by the first stage ultrafiltration membranes. UVA₂₅₄ was analyzed on both 7 mg/L samples; one had only coagulation and the other had both coagulation and additional filtration with the membrane. This was used to identify any differences in the UVA₂₅₄ results between the samples.

The 0.02 μm filters were 47 mm in diameter and used on a magnetic filter funnel assembly. The PVDF material was hydrophobic so initially surface tension forces repelled water from the pores of the membrane. A modified procedure was followed, per manufacturer specifications, to complete the filtration; A petri dish was filled half-way with 91% isopropyl alcohol. A 47 mm, 0.02 μm PVDF membrane was submerged into the alcohol-filled petri dish using tweezers and allowed to sit for five minutes. A 2 L glass beaker was filled with ultrapure deionized water. The membrane filter was extracted from the petri dish and inserted into the 2 L glass beaker using tweezers. The contents of the beaker were gently stirred with a glass stirring rod for one minute and the membrane continued to soak for a total time of five minutes. The membrane filter was then removed and placed directly on the magnetic filter funnel and a sample was filtered immediately following. The isopropyl alcohol has low surface tension and makes it possible for the dry membrane pores to spontaneously fill via capillary action. The five minutes of time that the membrane spent in the 2 L beaker of ultrapure deionized water was completed to sufficiently dilute the alcohol to avoid interference in the UVA₂₅₄ testing. This test was originally going to be completed on all samples for all three jar tests. However, the membrane filters used had a low liquid flow rate. The limited surface area of the filter ($\sim 10\text{ cm}^2$) combined with the sample clogging some pores resulted in it taking ~ 90 minutes to filter 100 mL of sample. Therefore, the test was only completed once for each jar test on the 7 mg/L jar.

Results & Discussion

UVA₂₅₄ Sampling

An initial series of jar tests (Figure 2) were completed by TRU WTP laboratory staff to establish organics removal at alum dosages between 0-9 mg/L in 0.25 mg/L increments. The sample used was a first stage membrane supply sample (sample “4” in Figure 1 & Table 1) which is variable based on daily demand. The daily mean, determined from treated volume data for the two dates of sample collection, was $\sim 16\%$ second stage permeate blended with $\sim 84\%$ raw source water. An observable

removal plateau for UVA_{254} occurred at $\sim 7\text{-}8.5$ mg/L dosage of Alum. These results were used to establish a Jar Testing range between 4-9 mg/L for membrane pre-treatment optimization. The Jar Testing in the laboratory permitted the use of controlled concentrations of second stage membrane permeate and raw source water.

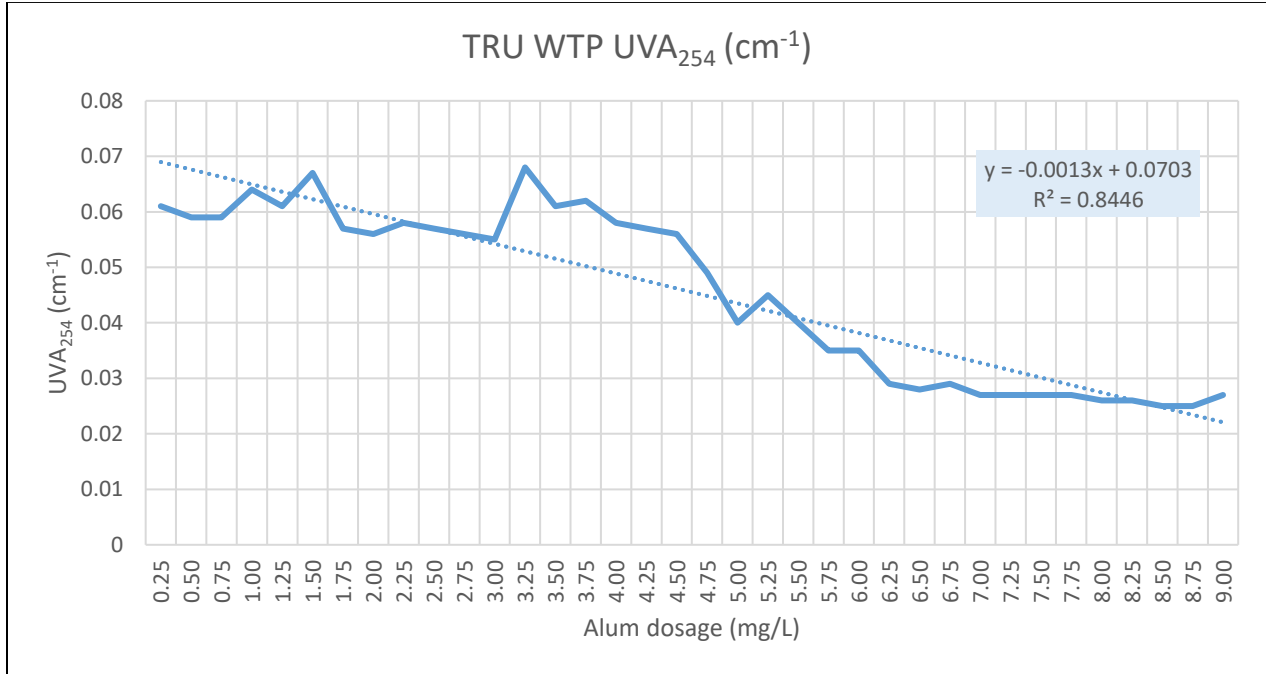


Figure 2. UVA_{254} to Establish Experimental Alum Dosage Range

Figure 3 is showing five weeks of initial UVA_{254} sampling where the stage 1 ultrafiltration supply or feed water sample (sample 4) was collected. This sample was not collected beyond the first five weeks as it did not have an easily comparable sample in the conventional treatment process and for staff sampling limitations. Sample 1 is the raw water source and is the supply water to the conventional filtration system. Samples C1 & C2 were both located in the conventional system and reflect post-coagulation and filtration. The conventional treatment plant demonstrated consistent removal of organics from the raw water. The C1 & C2 samples are comparable to sample 4 in the first stage UF membrane plant. However, the supply water to the first stage UF membrane system is a blend of $\sim 85\%$ of sample 1 with $\sim 15\%$ of sample 3. Sample 4 should be influenced by the organics located in samples 1 & 3. Lastly, the UVA_{254} distribution values reflect the blending of the conventional samples with the first stage UF membrane permeate. The distribution values are higher than the conventional filtration while the first stage permeate was higher than the distribution. It can be deduced that lowering the UVA_{254} values of the first stage permeate would result in a lower distribution organics concentration.

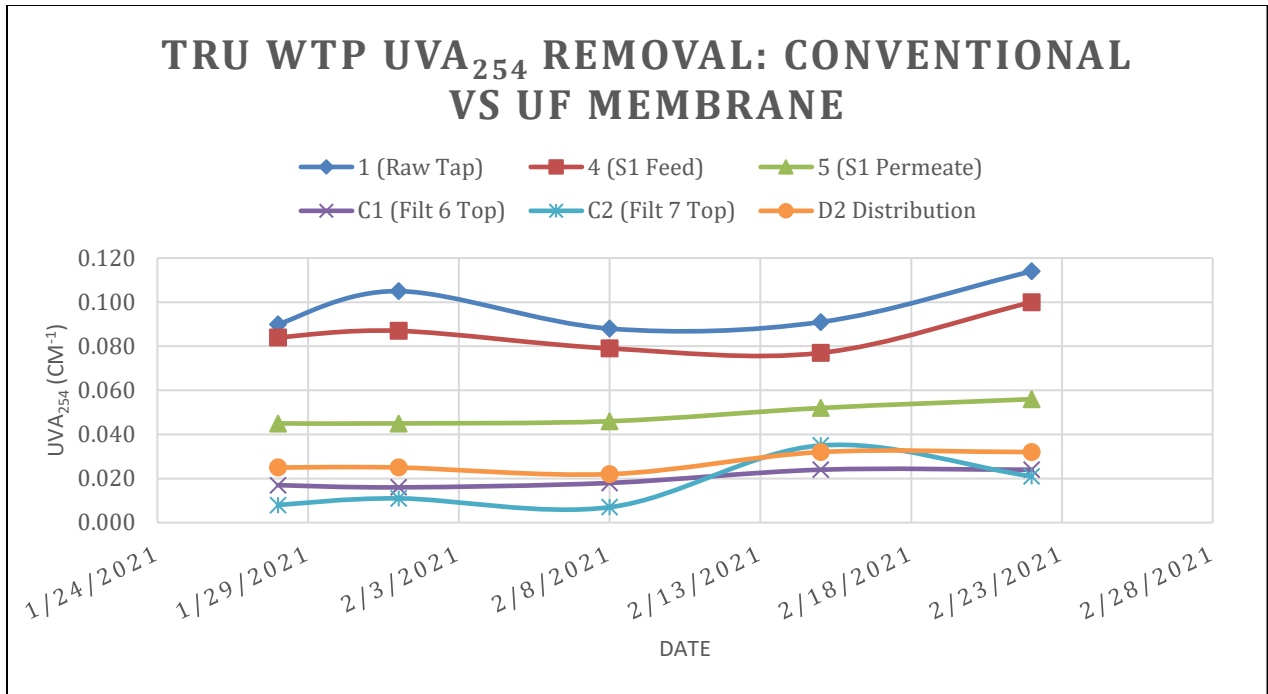


Figure 3. TRU WTP UVA₂₅₄ Removal: Comparison between conventional filtration and membrane filtration

Figure 4 is a visualization of the organic matter removal achieved by the TRU WTP conventional filters. Samples C1 and C2 best represent the two independent conventional treatment systems. Samples D1 and D2 are higher which consists of conventional filtered and permeate water blended.

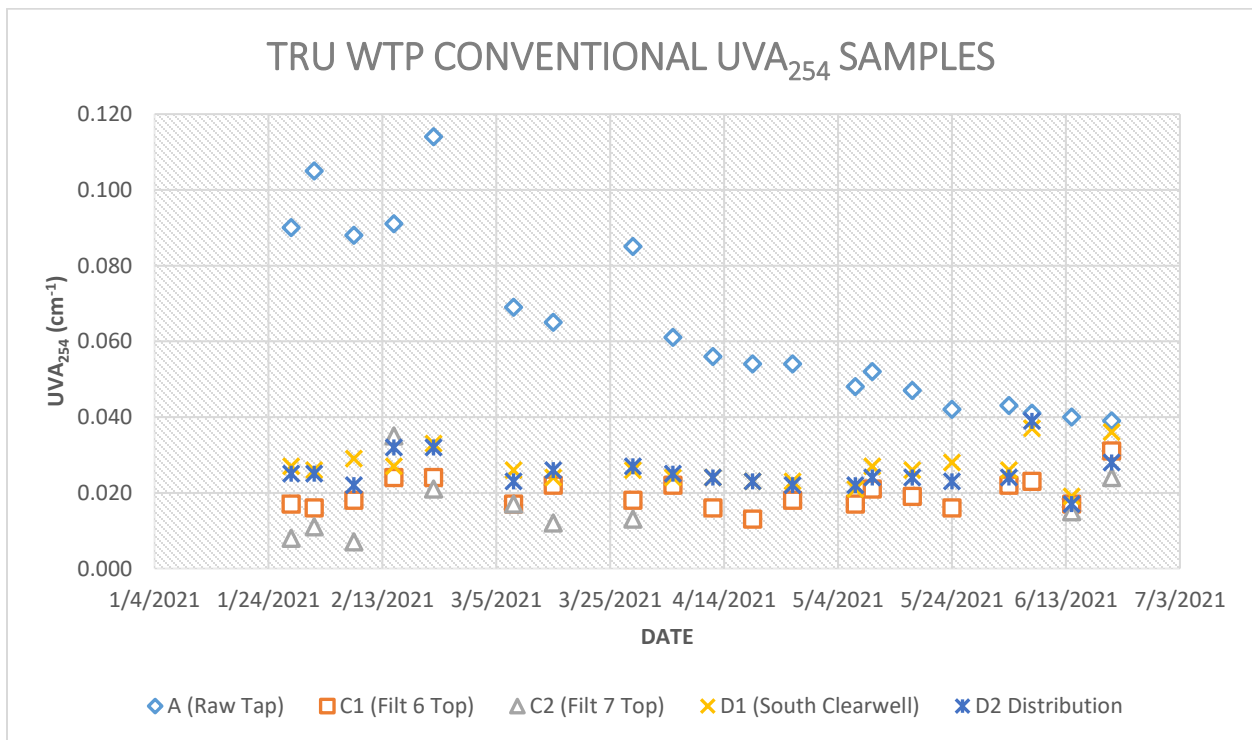


Figure 4. TRU WTP Conventional Process Control UVA₂₅₄ Data

The UVA_{254} samples were collected between January and June of 2021. Figure 5 specifically looks at the membrane treatment system over a 6 month duration as opposed to a 5 week sampling (Figure 3). We can see that the second stage UF permeate (sample 3) consistently demonstrated the most removal of UVA_{254} . This sample is then blended with the Raw Tap (sample 1) to provide supply water (sample 4) to the first stage UF membranes. Both UF membrane systems demonstrated consistent removal of organics despite variability in the feed water as is evidenced by the permeate samples for both (samples 3 & 5). However, it is noted that the removal was still less than that of the conventional filtration treatment as displayed in Figure 4.

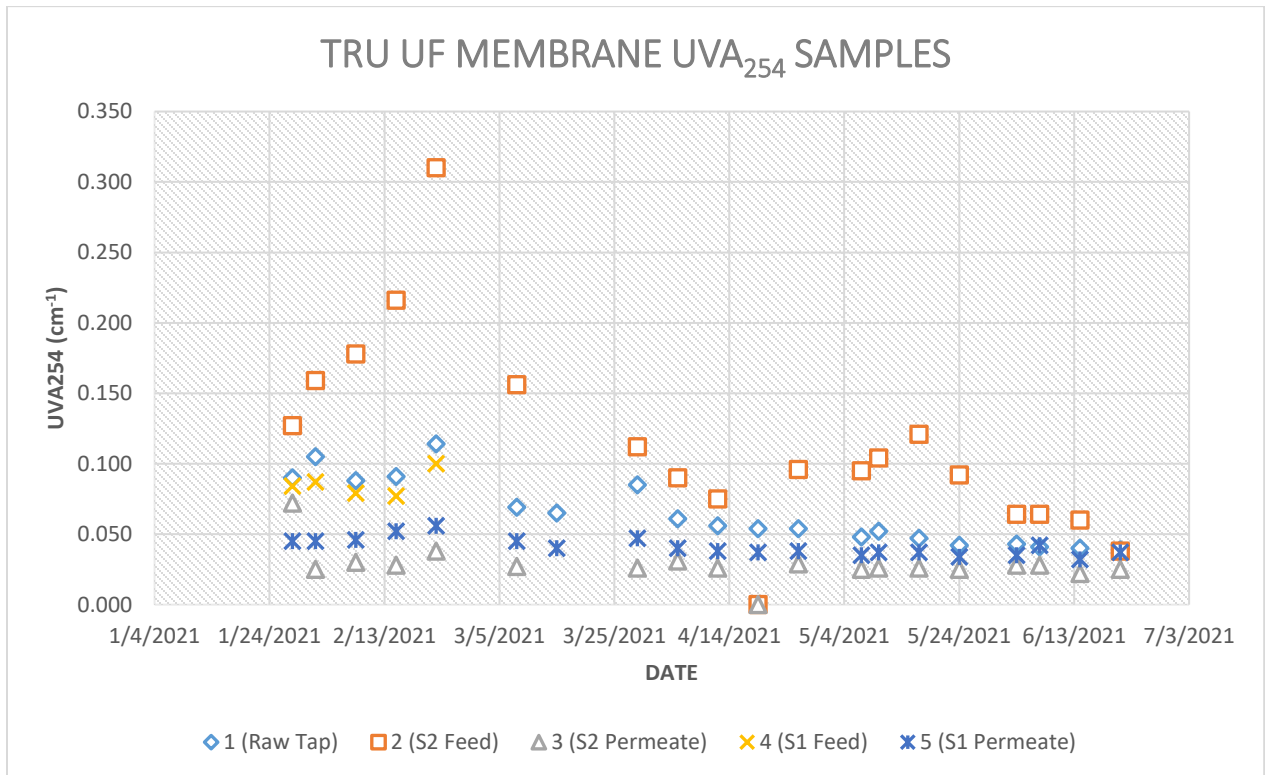


Figure 5. TRU WTP Membrane Plant Process Control UVA_{254} Data

The second stage membranes are supplied by SFBW water which recycles what would otherwise be sent to the wastewater treatment plant. The mean value of organics (sample “2”) is noticeably higher. However, the second stage membranes demonstrate consistent removal of organics, as evidenced by sample “3”, but does not achieve the full removal of the conventional plant (“C1” and “C2”). That second stage permeate (“3”) is then blended with the raw water (“1”) to produce sample second stage supply water which has no coagulation, flocculation, or sedimentation at present time. This combination is represented by sample “4”. Sample “4” was only collected on five dates of the sampling period and may not be as well correlated with the other sample data. The preliminary data collected and sampled represented a significant reduction in UVA_{254} values in the second stage permeate (“3”) when compared to the second stage supply (“2”). Then the blending of the second stage permeate with the raw source water resulted in an elevated UVA_{254} sample for the first stage membrane supply water. The first stage membranes still demonstrated removal of organics in the permeate (“5”) but was not able to achieve the same removal efficiency as the second stage, despite

the fiber pore size specification of 0.02 μm compared to the second stage 0.04 μm . The first stage permeate blends with the conventional filtered water which likely accounts for the increase in UVA_{254} found in samples “D1” and “D2”.

There are established guidelines for expected removal by percentage of DOC using Alum based on SUVA values: (<2, <25%); (2-4, 25-50%); and (>4, >50%) (AWWA, 2010). The mean UVA_{254} values (Figure 6) represent trends on both the membrane and conventional treatment plants in terms of organics removal. Samples “1” and “A” are identical raw water samples. Samples 1-5 are located in the membrane plants and samples A-D2 are located in the conventional plants (see Figure 1). Samples “C1” and “C2” are taken after coagulation, flocculation, and sedimentation on the conventional plant but before the sample is filtrated. Therefore, these samples represent the coagulation removal of organics with a combined mean of 0.018 UV_{254} value. This constitutes a ~72% removal efficiency from the Raw water (sample “A”) mean.

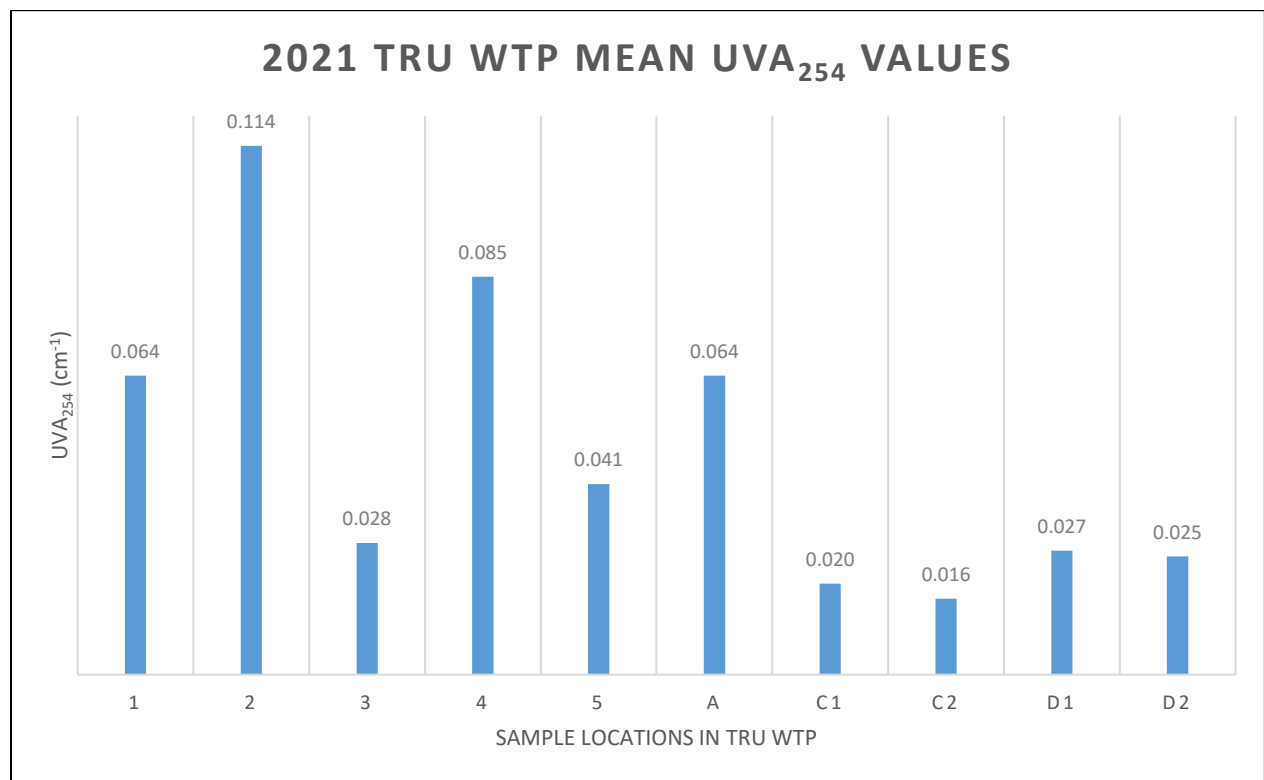


Figure 6. TRU WTP Conventional & Membrane Process Control UVA_{254} Mean Values

Jar Testing for Alum coagulation Optimization

Figure 7 displays the turbidity and UVA₂₅₄ results for the 3 jar tests. Initial turbidity was higher, as expected, in the blended samples that contained a greater percentage of raw water. The lowest turbidity values for the specified ranges were as follows: 7 mg/L for 10% permeate blend, 9 mg/L for 15% permeate blend, and 8 mg/L for 20% permeate blend. The lowest turbidity values were directly correlated with the lowest UVA₂₅₄ readings.

The pH range of the water is important to the efficiency of the coagulation. Alum is most efficient at removing different compounds at different pH ranges. Aluminum coagulants achieve greatest removal efficiency of NOM, algal cells, and inorganic particles in pH ranges of 5-8 with the specific pH depending upon the composition of the water ([Naceradska et al., 2019](#)). Historical particle charge neutralization for the TRU WTP, determined via particle charge analyzer, has indicated that Alum optimum coagulation is achieved between 6.4-6.7 on the pH scale.

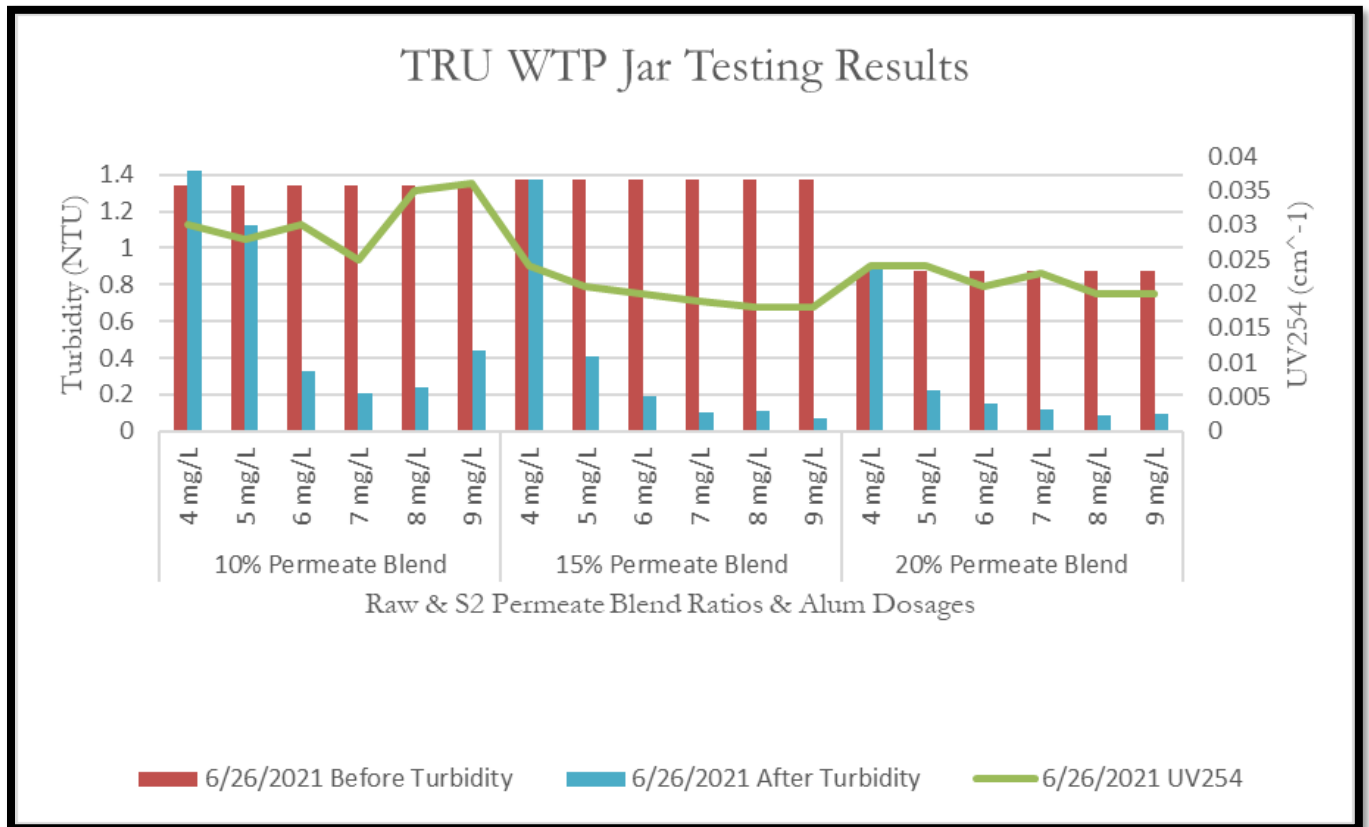


Figure 7. TRU WTP Conventional & Membrane Blended Water Jar Test Experiment Results for Turbidity & UVA₂₅₄

Figure 8 displays pH data for each of the jar tests. The beginning pH was nearly identical for all 3 samples, 7.28 and 7.27, respectively. The higher concentration of permeate to raw source water resulted in a slight increase in buffering capacity or resistance to change. The stage two membrane permeate and raw source water have similar pH values between 7.0-7.3, so blending them should not result in a significant change. Alum is acidic with a pH of ~3.5. Alum reduces alkalinity in the water via hydrolysis which subsequently reduces the pH. It is expected that as the Alum dosage is increased then the pH will decrease. The significance is to maintain a pH range for optimum removal of potentially harmful compounds.

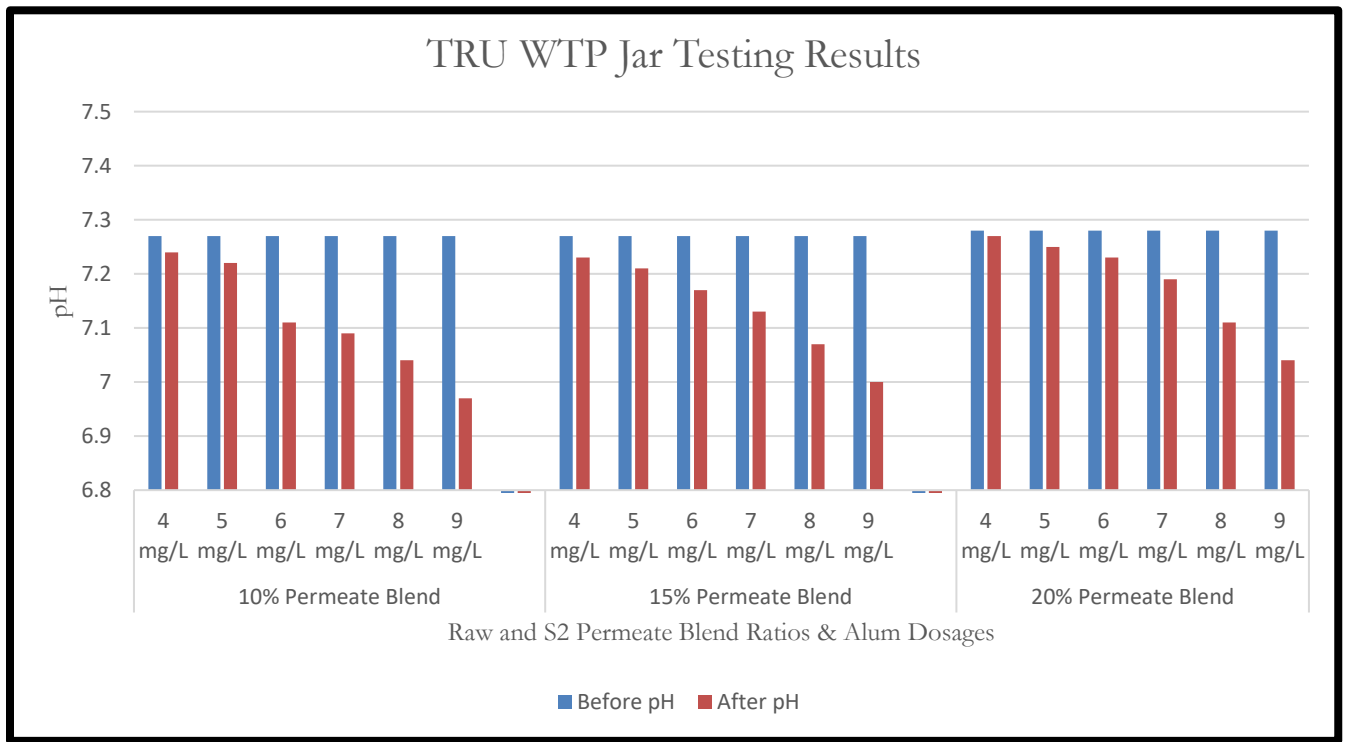


Figure 8. TRU WTP Conventional & Membrane Blended Water Experiment Jar Test Results for pH

Conclusions

Alum coagulation can be used to effectively remove NOM concentrations which contribute to DBP formation for first stage UF membrane permeate as evidenced by removal of UVA₂₅₄. The low turbidity and DOC concentrations of the TRU WTP MIL raw water supply allow for effective removal of organics via alum coagulation without the use of a pH adjusting chemical. Additional study could examine the combination of water quality and economic considerations for coagulation pretreatment with pH adjustment for optimization purposes. The UVA₂₅₄ sampling and analysis identified a consistent trend where the conventional treatment with alum coagulation removed more organics than the ultrafiltration membranes do without alum coagulation. There is an opportunity to introduce alum coagulation pre-treatment to the first stage ultrafiltration membrane system with the goal of achieving similar organics removal to that of the conventional treatment. An additional

benefit is that this could be accomplished with less alum dosing than the conventional treatment process and includes recycling of SFBW. The TRU WTP jar testing results indicate that SFBW treated with ultrafiltration membranes can produce permeate that, when blended with raw source water between 10-20% concentration, can be optimally coagulated with an alum dosage between 7-9 mg/L. The TRU WTP could continue to optimize the alum coagulation process by collecting and analyzing more relevant data. This could result in additional organic matter removal and potential cost savings. Dissolved Organic Carbon, turbidity, alkalinity, UVA_{254} , and SUVA values are critical variables for coagulation optimization. These variables have recently been analyzed by a UNCC researcher using deep neural network modeling to estimate coagulation optimization more effectively with greater success than has been demonstrated previously ([Alansari, 2021](#)). Increased data collection and analysis can only stand to improve the alum coagulation efficiency at the TRU WTP. Additional study is needed within the industry to identify water reuse strategies which can also meet more stringent environmental regulations.

Limitations of study

Several factors could influence the results that other WTPs might experience when operating dual treatment systems with respect to coagulation optimization: seasonal variations in water quality, ratio of permeate to raw surface water used, organics concentrations in other source water locations, water quality/chemistry (i.e., low turbidity, pH adjustment, temperature etc.). The sample size was limited for the final jar tests. Individual WTPs will need to assess their own water quality characteristics and process control systems to optimize coagulation for SFBW recycling.

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Appendices

Appendix A: Alum Stock Solution Preparation

A one percent stock solution of Alum was prepared using the following method:

$$(\% \text{ Alum Strength})(\text{Specific Gravity 1})(\text{Volume 1}) = (\% \text{ Alum Strength})(\text{Specific Gravity 2})(\text{Volume 2})$$

The calculation to solve for Volume 1:

$$(48.57\%)(1.3303)(\text{Volume 1}) = (1\%)(1.0000)(1000 \text{ mL})$$

$$\text{Volume 1} = \frac{(1\%)(1.000)(1000 \text{ mL})}{(48.57\%)(1.3303)} = 15.477 \text{ mL/L}$$

15.477 mL of 48.57% Alum was mixed with deionized water to prepare 1 Liter of 1% stock solution. This preparation allows for dosing of 1 mL Alum stock solution to represent 10 mg per 1 Liter in the jar test. The jars used were each 2 Liters in volume so the dosing value needed to be doubled to account for twice the volume.

Example: 5 mg/L dose needed in jar: $0.5 \text{ mL/L} * 2 \text{ Liters} = 1.0 \text{ mL}$ of 1% Alum stock solution

Appendix B: Experiment Materials List

Novavem™ 0.02 µm Polyvinylidene Fluoride (PVDF20) Membrane filters 47 mm diameter

250 mL glass beakers (Pyrex™)

Phipps & Bird™ Jar Tester

2 L Square Beakers (Hach™)

1000 mL Erlenmeyer Flask

Pipet Bulb

Magnetic Stirrer

Magnetic Stir Bar

Magnetic Filter Funnel (Pall™ 47 mm)

Laboratory Dual Input, Multi-Parameter Meter (Hach™ HQ440D) (resolution 0.01)

Laboratory Laser Turbidimeter (Hach™ TU5200)

Vacuum Pump (Emerson™)

UV-Vis Spectrophotometer (Hach™ DR5000)

Aluminum Sulfate (1%) stock solution of 48% concentration

2000 mL Class “A” Glass Beaker (Pyrex™)

100 mL Glass Graduated Cylinder

Delicate Task Disposable Wipes (Kimtech™ Kimwipe™)

1000 mL Class “A” Glass Beaker (Pyrex™)

Hexagonal Weighing Boat (Spectrum™)

5 mL Glass Class “A” Pipet

Laboratory Time Tape

Isopropyl Alcohol (91%)

Glass Petri Dish

Ultrapure Deionized Water

70 mm diameter, 0.7 µm Glass microfiber filter (Hach™)

70 mm Glass microfiber filtration funnel (Whatman®)

Appendix C: Analytical Method References

Parameter	Instrument	Resolution	Method	Calibration
pH	Hach HQ440d	0.02	USEPA Electrode Method 8156	Daily; 4, 7, and 10 pH
Turbidity	Hach TU5200	0.0001 NTU	Hach Method 10258	Daily; Stablcal standards 10, 20, and 600 NTU
UV ₂₅₄	Hach DR5000		Hach Method 10054 Hach Method Note UVT/UVA EPA Method 415.3	

Appendix D: Historical Plant Data Analysis

UVA₂₅₄ data was compiled and reviewed from membrane pilot testing at the TRU WTP in 2014. This data provided a baseline of conventional treatment removal of organics in the facility at this time. DOC data was compared from the same dates to calculate SUVA values. The filter 6 SUVA value for 2/18/2014 is likely erroneous and may be the result of sampling or data entry errors. The SUVA values were primarily below 3 which suggests a NOM composition of hydrophilic, organic compounds with low molecular mass and charge density.

TRU UF MEMBRANE PILOT DATA (2014)									
UVA₂₅₄				DOC			SUVA		
Date	Raw UV₂₅₄	Basin #6 UV₂₅₄	Filter #6 Effluent UV₂₅₄	Raw DOC	Basin #6 DOC	Filter #6 Effluent DOC	Raw	Basin 6	Filter 6
1/30/2014	0.045	0.022	0.017	1.700	1.150	1.110	2.647	1.913	1.532
2/4/2014	0.045	0.025	0.021	1.740	1.290	1.300	2.586	1.938	1.615
2/11/2014	0.047	0.030	0.037	1.560	1.150	1.050	3.013	2.609	3.524
2/18/2014	0.043	0.022	0.180	1.630	1.440	1.360	2.638	1.528	13.235

The sample locations were identified differently but represent similar sampling sites for the North conventional plant. Therefore, they were compared as follows: “Raw UV₂₅₄” with sample “A”, “Basin #6 UV₂₅₄” with “C1”, and “Filter #6 Effluent UV₂₅₄” with “D1”. The samples were collected during a similar time of the year approximately seven years apart. This was used as a proxy for which to compare historical conventional treatment UVA₂₅₄ values to present.

TRU 2014 Pilot Study UV254 Sample Data Descriptive Statistics						
Variable	Raw UV₂₅₄	A	Basin #6 UV₂₅₄	C1	Filter #6 Effluent UV₂₅₄	D1
Mean	0.047	0.064	0.026	0.020	0.030	0.027
Standard Error	0.002	0.005	0.002	0.001	0.007	0.001
Median	0.047	0.055	0.025	0.018	0.021	0.026
Mode	0.045	0.054	0.025	0.017	0.020	0.026
Standard Deviation	0.008	0.023	0.009	0.004	0.034	0.004
Sample Variance	0.000	0.001	0.000	0.000	0.001	0.000
Kurtosis	4.492	-0.539	2.853	1.842	19.603	1.090
Skewness	-1.065	0.810	-0.004	1.092	4.318	0.952
Range	0.039	0.075	0.044	0.018	0.178	0.018
Minimum	0.022	0.039	0.001	0.013	0.002	0.019
Maximum	0.061	0.114	0.045	0.031	0.18	0.037
Sum	1.039	1.284	0.57	0.391	0.657	0.532
Count	22	20	22	20	22	20

UVA₂₅₄ and DOC data were collected during the TRU WTP UF Pilot testing in 2014. These data were used to calculate SUVA and UVT₂₅₄ values. The 2/14/2014 filter #6 Effluent UVA₂₅₄ data is an order of magnitude higher than previous values collected which altered the SUVA and UVT₂₅₄ data for this date and sample location. It is suspected that it may have been a data entry error. This, along with other historical DOC data, was used as a baseline for which to compare raw water historical values to the present.

TRU UF MEMBRANE PILOT DATA (2014)												
UV ₂₅₄				DOC			SUVA			%UVT		
Date	Raw UV ₂₅₄	Basin #6 UV ₂₅₄	Filter #6 Effluent UV ₂₅₄	Raw DOC	Basin #6 DOC	Filter #6 Effluent DOC	Raw	Basin 6	Filter 6	Raw	Basin 6	Filter 6
1/30/2014	0.0450	0.0220	0.0170	1.7000	1.1500	1.1100	2.647059	1.913043	1.531532	90.15711	95.06048	96.16123
1/31/2014	0.0420	0.0200	0.0200									
2/1/2014	0.0570	0.0450	0.0360									
2/2/2014	0.0610	0.0450	0.0380									
2/3/2014	0.0440	0.0230	0.0200									
2/4/2014	0.0450	0.0250	0.0210	1.7400	1.2900	1.3000	2.586207	1.937984	1.615385	90.15711	94.40609	95.27962
2/5/2014	0.0430	0.0210	0.0210									
2/6/2014	0.0490	0.0240	0.0220									
2/7/2014	0.0510	0.0250	0.0230									
2/8/2014	0.0580	0.0370	0.0310									
2/9/2014	0.0480	0.0230	0.0210									
2/10/2014	0.0590	0.0350	0.0200									
2/11/2014	0.0470	0.0300	0.0370	1.5600	1.1500	1.0500	3.012821	2.608696	3.52381	89.74288	93.32543	91.83326
2/12/2014	0.0450	0.0250	0.0220									
2/13/2014	0.0220	0.0010	0.0020									
2/14/2014	0.0440	0.0260	0.0200									
2/15/2014	0.0450	0.0270	0.0200									
2/16/2014	0.0470	0.0210	0.0180									
2/17/2014	0.0470	0.0210	0.0180									
2/18/2014	0.0430	0.0220	0.1800	1.6300	1.4400	1.3600	2.638037	1.527778	13.23529	90.57326	95.06048	66.06934
2/19/2014	0.0460	0.0230	0.0230									
2/20/2014	0.0500	0.0250	0.0240									
2/21/2014	0.0460	0.0260	0.0200									