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Energy Research and Development Division

FINAL PROJECT REPORT

Improving Membrane Treatment Energy Efficiency Through Monitoring the Removal of Colloidal Particle Foulants

Gavin Newsom, Governor

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PREPARED BY:

Primary Authors:
Ganesh Rajagopalan, PhD, PE, BCEE
Helia Safaee
Ryan Holloway, PhD, PE

Kennedy/Jenks Consultants
3200 El Camino Real, #200
Irvine, CA 92602
Phone: 949-567-2162
www.kennedyjenks.com

Orange County Water Dist.
18700 Ward St.
Fountain Valley, CA 92708
www.ocwd.com

West Basin Municipal Water Dist.
17140 S. Avalon Blvd.
Carson, CA 90746
www.westbasin.org

Contract Number: EPC-15-012

PREPARED FOR:
California Energy Commission

Rajesh Kapoor
Project Manager

Virginia Lew
Office Manager
ENERGY EFFICIENCY RESEARCH OFFICE

Laurie ten Hope
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Drew Bohan
Executive Director

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Improving Membrane Treatment Energy Efficiency Through Monitoring the Removal of Colloidal Particle Foulants is the final report for the Improving Membrane Treatment Energy Efficiency Through Monitoring the Removal of Colloidal Particle Foulants project (Contract Number EPC-15-012) conducted by Kennedy/Jenks Consultants. The information from this project contributes to Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at 916-327-1551.

ABSTRACT

There is an increased emphasis on indirect and direct potable reuse of water in recent years to meet future water demand and increase water security. Low-pressure membranes, consisting of microfiltration and ultrafiltration, are integral components of most indirect and direct potable reuse processes and provide reliable water quality for reuse applications. However, fouling of these membranes increases the need for membrane cleaning and replacements as well as energy. Studies attribute fouling to deposits of feed water colloidal particles smaller than 200 nanomicrons inside the membrane pores.

No online techniques are available to directly measure colloidal particles in feed water, a process that would aid in appropriate pretreatment and real-time control to remove colloidal particles and prevent deposition in the membrane pores. In this study, the research team implemented a real-time monitoring technology to track colloidal particle concentration and size distribution in feed water to assist targeted removal by coagulation. This new strategy used nanoparticles tracking analysis (NanoSight NS500 by Malvern Instruments) and was tested at Orange County Water District and West Basin Municipal Water District. Although the team conducted similar demonstration tests at both sites, there were differences in type of coagulants tested, membrane type, feed water quality, and the absence of reverse osmosis testing at West Basin.

Results showed that targeted polyaluminum chloride coagulation mitigated fouling potential for the microfiltration membranes tested at Orange County, with transmembrane pressure values reduced by 60 percent after six weeks compared to not adding coagulant. For reverse osmosis operations, researchers observed no negative impact related to coagulation of the microfiltration feed water but do recommend longer testing. Energy and economic evaluation at the Orange County Advanced Water Purification Facility indicated that the proposed approach can reduce energy consumption from microfiltration by 28-35 percent with potential savings of 2,940 megawatt-hours (MWh) per year and $610,000 per year in membrane cleaning, replacement, and operating costs for a 100-million gallon per day (GPD) plant.

Ultrafiltration membrane testing at the West Basin demonstration site indicated that targeted polyaluminum chloride coagulation can improve membrane filtration performance and energy efficiency compared to no coagulant. However, coagulant choice is important to the success of the targeted pretreatment strategy. Targeted coagulation with polyaluminum chloride slowed the rate of transmembrane pressure increase by 43 percent compared to the control and reduced energy consumption by 63 percent. Based on West Basin's 14.4-million GPD ultrafiltration facility, these results could provide savings of more than 600 MWhs/year and $110,000 per year in overall operating and maintenance costs.

Keywords: Online monitoring, colloidal particles, membrane fouling, ultrafiltration, microfiltration, targeted coagulation, Nanoparticle Tracking Analysis, NanoSight

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EXECUTIVE SUMMARY

Introduction

There has been an increased emphasis on indirect and direct potable reuse in recent years to meet future water demands and increase water security. Microfiltration and ultrafiltration membranes are integral components of most indirect and direct potable reuse processes. However, fouling of these membranes results in increased energy demand, cleaning, and frequency of membrane replacement. Studies have identified colloidal nanoparticles smaller than 200 nanomicrons (nm) found in feed water as a major contributor to microfiltration and ultrafiltration membrane fouling.

Currently, no techniques are available to directly monitor colloidal particles in the feed water, which would facilitate appropriate pretreatment to remove these particles and prevent their deposition into membrane pores. Surrogate techniques, such as measurement of turbidity or organic content (through oxygen demand) are sometimes used for monitoring the feed water fouling potential. However, these techniques do not correlate well with the levels of colloidal particles and hence, lead to ineffective fouling control. In part because of these limitations, many utilities do not pretreat the feed water to remove fouling particles prior to microfiltration/ultrafiltration membrane treatment.

Project Purpose

This project provides field demonstration of nanoparticle tracking analysis using Malvern Instruments' NanoSight NS500, coupled with pretreatment via coagulation, as a fouling mitigation strategy for microfiltration/ultrafiltration membrane filtration. The NS500 uses light scattering technology to measure colloidal particle foulants directly. The primary goal of this project is to demonstrate the capability of the online particle counter to monitor the concentration and size of incoming colloidal particles in real-time and accordingly optimize (tailor) coagulant dosing for pretreatment of microfiltration/ultrafiltration membrane filtration systems. Field demonstration of the online monitoring system provides other water reclamation agencies with the data needed to confidently implement the proposed technology to mitigate membrane fouling and save energy at their facilities. Water reclamation is a major component of water resources in California and the practice is only likely to increase as utilities work to meet the state's recycled water goals. Reducing microfiltration/ultrafiltration membrane fouling, as demonstrated in this study, improves water reclamation by reducing membrane cleaning, replacement frequency, and energy costs, or by producing reliably higher yields and water quality, which will help ensure California's water security during droughts and increasing water demand.

Project Approach

The targeted pretreatment strategy using nanoparticle tracking analysis was implemented at two demonstration sites: Orange County Water District and West Basin Municipal Water District. Each site offered distinct operating conditions that tested the versatility of the proposed technology. At Orange County Water District, two microfiltration pilot units were fitted with polypropylene membrane elements (typical pore size ~200 nm), one operating as control (no coagulant) and another receiving targeted coagulation (commercial polyaluminum chloride). The two units were operated in parallel to demonstrate the efficiency of the proposed technology in reducing membrane fouling when challenged by secondary-treated wastewater. At West Basin, a single ultrafiltration pilot unit was fitted with a polyvinylidene membrane (typical pore size ~100 nm) and operated sequentially with varying pretreatment conditions (control – no coagulant, constant polyaluminum chloride concentration dosing, targeted polyaluminum chloride dosing, and targeted ferric chloride dosing). The ultrafiltration pilot at West Basin received more challenging secondary-treated wastewater than that observed at Orange County Water District and required frequent chemical cleanings. These varying operating conditions, membrane material, and source water quality helped to define the relevant parameters for implementing this technology at other facilities in the future.

The project work at each demonstration site consisted of:

- Feed water monitoring and measurement of colloidal particle concentrations and size distribution using nanoparticle tracking analysis.
- Bench-scale studies to determine the relationship between colloidal particle concentration, size distribution, and optimum coagulant dose to reduce membrane fouling.
- Integration of the feed-forward loop-based chemical feed system to deliver a targeted coagulant dose based on the real-time feed water colloidal particle concentration.
- Field demonstration of the targeted coagulation system using microfiltration membranes at Orange County Water District and ultrafiltration membranes at West Basin.
- Cost-benefit analyses for implementation of this technology.

Project Results

The Orange County Water District microfiltration pilot demonstration indicated that monitoring and removing colloidal particles using nanoparticle tracking analysis technology can be very effective in minimizing microfiltration membrane fouling and improving energy efficiency. Results from the pilot demonstration include:

- Nanoparticle tracking analysis technology was successful in measuring colloidal particle concentrations in real-time. The diurnal trend of colloidal particles showed that peak (noon to 5 p.m.) particle levels were 4 to 5 times higher than during nonpeak periods. The diurnal fluctuations in colloidal particles supported the need to adjust coagulant dosing in real-time, which in this study is referred to as “targeted” coagulation. Otherwise, constant dosing would result in significant under- or overdosing at certain times of day, impacting fouling control and potentially increasing chemical costs.
- The algorithm developed through bench-scale studies was effective in optimizing coagulant dosing. By implementing the developed algorithm to the pilot’s feed-forward control strategy, the fouling potential for the coagulant-dosed pilot was mitigated. Transmembrane pressure values, which indicate the degree of fouling, were approximately 60 percent lower than the control pilot after six weeks.
- An increase in aluminum concentration due to polyaluminum chloride coagulation was a potential concern related to reverse osmosis scaling. Results showed that no significant increase of aluminum was detected in the microfiltration effluent following polyaluminum chloride pretreatment. Reverse osmosis operation was also monitored but was inconclusive in showing that there is no significant impact due to pretreatment.

Additional testing is recommended to further assess the operating advantages of this strategy for reverse osmosis and manage assessed risks.

- The pump energy consumption data from Orange County Water District's full-scale (100 million gallons per day [MGD]) plant was used along-side the transmembrane pressure profiles developed from the pilot demonstration tests to perform a preliminary energy and economic evaluation. This data indicated that the proposed approach can reduce energy consumption by 28 percent to 35 percent, resulting in 2,940 megawatt-hours per year (MWh/year) of projected energy savings and $610,000/year of potential savings in membrane cleaning, replacement and operating costs for a 100-MGD plant.

The pilot demonstration at West Basin also indicated that targeted polyaluminum chloride coagulation can improve membrane filtration performance and energy efficiency compared to the control. However, coagulant choice plays a critical role in the success of the targeted pretreatment strategy, as targeted ferric chloride dosing was not equally successful in reducing energy use and transmembrane pressure during filtration. Overall results from the project pilot demonstration include.

- Targeted coagulation with polyaluminum chloride slowed the rate of transmembrane pressure increase by 43 percent compared to control. This effect was less pronounced with constant polyaluminum chloride dosing, and non-existent with targeted ferric chloride dosing. Targeted polyaluminum chloride dosing also showed reduced membrane fouling after consecutive chemically-enhanced membrane cleanings.
- Pretreatment with constant polyaluminum chloride, targeted polyaluminum chloride, and targeted ferric chloride coagulation improved ultrafiltration effluent quality compared to the control, as observed in reduced COD levels and colloidal particle concentrations.
- Energy consumption of the pilot filtration pump showed higher degree of efficiency when the ultrafiltration was operated at transmembrane pressures below 7 pounds per square inch. This was achieved by targeted polyaluminum chloride dosing which resulted in a 63 percent reduction in energy consumption. Assuming the pump energy performance observed during the pilot demonstration translated directly for full-scale operation, this could result in more than 600 MWh/year of energy savings for a 14.4-MGD ultrafiltration facility and potential savings of more than $110,000/year in membrane cleaning, replacement and operating costs. Unlike the demonstration at Orange County Water District, however, full-scale energy performance data was not available at West Basin and only full-scale pump efficiency was tracked and used in the economic evaluation. Therefore, this evaluation will need further testing for full-scale verification.

Comparison of the demonstration sites indicates that the performance of this pretreatment control strategy will vary depending on source water quality, type of membranes installed, and the operating procedures implemented at the treatment facilities. However, results from the pilot studies indicate that the proposed technology can lower the overall cost of water reclamation due to improvement in energy efficiency and reduction in membrane fouling, including savings in membrane cleaning and replacement costs resulting from the reduced fouling.

Technology/Knowledge Transfer/Market Adoption (Advancing the Research to Market)

In the wastewater treatment and water recycling industry, technology transfer for an emerging technology typically starts with presentations at conference attended by water and wastewater treatment staff to learn about new products. Staff requests for testing of new products and technologies in their treatment plants is typically followed by on-site presentations and site visits by interested utilities. Permitting issues are also assessed, and in some select situations, an on-site demonstration/piloting study is commissioned.

The findings from this study have already been shared with a variety of audiences through a comprehensive presentation aimed at industry professionals to share project findings and outcomes. The researchers have presented findings from this study at four conferences:

- California Annual Water Reuse Conference, San Diego, CA. 19 – 21 March, 2017.
- California Annual Water Reuse Conference, San Diego, CA. 17 – 19 March, 2019.
- American Membrane Technology Association Conference, New Orleans, LA. 26 – 28 February, 2019.
- California-Nevada Section American Water Works Association Annual Fall Conference, San Diego, CA. 21 – 24 October, 2019.
- Kennedy Jenks has held multiple discussions with the technology vendors (Malvern, Particle Metrix and Hyperion Analytical) to optimize the technology and expand its capability. These efforts include improving the ability of the instrument to measure smaller size particles (less than 40 nm) and more dilute samples (for example, particle concentration less than 106/ml) in order to expand the market to address different types of membranes and different water qualities used by various utilities. Malvern has recently commercialized a newer model that has these capabilities.
- Kennedy Jenks is in the final stages of submitting a manuscript to journal Water Research for peer review publication.
- Based on the test results, Orange County Water District, one of the test sites under this grant agreement, is now pilot testing this technology for additional applications related to direct and indirect potable reuse.
- Kennedy Jenks has reached out to large utilities using low pressure membranes to market this technology. The utilities are interested in this technology. However, they would like to obtain additional field data specific to their water quality and membrane types prior to installation of this technology.

Benefits to California

A survey by the American Membrane Technologies Association indicates that there are approximately 100 microfiltration/ultrafiltration treatment plants with a total design capacity of approximately 400 MGD in California. Nearly half of these facilities (on flow basis) treat drinking water and the remaining treat wastewater for recycling. Industrial membrane treatment facilities are not included in this list. Based on the survey performed by the California State Water Resources Control Board, it is estimated that nearly 33 percent of the total recycled water producers are in the Pacific Gas and Electric Company service area, 53 percent in the Southern California Edison service area, and 5 percent in the San Diego Gas & Electric Company service area.

Estimated Reduction in Energy Consumption

Energy requirements for microfiltration membrane filtration can vary depending on the water quality characteristics. Taking Orange County Water District as an example, an energy consumption rate of 0.22 kilowatt-hours (kWh)/1,000 gallons of water is assumed. Based on the findings from this study, a conservative assumption of 32 percent improvement in microfiltration membrane energy due to the proposed technology, and a 50 percent market penetration would yield a potential energy reduction of 5.8 GWh/year. This estimate does not include energy conservation in industrial membrane processes or membrane bioreactors used in wastewater treatment or possible energy savings due to improved backwashing performance. Table ES-1 shows the estimated energy savings for treating 400 MGD of water (or 200 MGD at 50 percent market penetration) via microfiltration due to the implementation of the proposed technology, and how this value can vary with changing electricity prices.

Table ES-1: Annual Savings from Reduced Electricity Consumption for Varying Electricity Prices

Savings	0.095 $/kWh	0.12 $/kWh	0.15 $/kWh
Annual savings with 100% market penetration (400MGD)	$2,444,000	$3,087,000	$3,859,000
Annual savings with 50% market penetration (200 MGD)	$1,222,000	$1,544,000	$1,929,000

Source: Kennedy/Jenks Consultants

Estimated Reduction in Use of Membrane Cleaning Chemicals

The proposed technology minimizes the number of colloidal particles plugging the membrane pores. This, in turn, extends the time interval between membrane cleaning and hence, lowers the amount of chemicals needed for membrane cleaning. Typical chemical requirement estimates range from $0.15 to $0.25/1,000 gallons of water treated during microfiltration treatment. Results from this study indicate that chemical cleaning frequency can be reduced 50 percent to 89 percent depending on the type of pretreatment and cleaning procedure used. Based on these findings, the proposed technology has the potential to lower the chemical cost by up to $1.36 million/year for California rate payers, assuming a market penetration of 50 percent for the proposed technology.

Estimated Reduction in Membrane Replacement Cost

During microfiltration/ultrafiltration membrane treatment, the membranes are periodically replaced due to loss of capacity caused by irreversible fouling and wear-and-tear due to continuous operation. Since the proposed technology lowers the potential for irreversible fouling, the frequency of cleanings and therefore membrane replacement will be reduced. Results from this study indicate that membrane replacement can be reduced by 67 percent.

This could result in potential savings of approximately $3.52 million/year assuming a 50 percent market penetration.

Market Segment and Penetration

There are more than 100 microfiltration/ultrafiltration and reverse osmosis membrane installations in California. Two of the major facilities representing more than 25 percent of the total flow have participated in this study. A preliminary economic evaluation performed using estimated benefits indicated that membrane plants with greater than 12 MGD of microfiltration or 10 MGD of ultrafiltration will have a return on investment of less than two years for the implementation of the proposed technology (Nanosight instrumentation). Nearly 75 percent of the membrane installations in California have treatment capacity of more than 10 MGD treating approximately 300 MGD of flow. Based on flow volume, it is conservatively assumed that the proposed technology can be implemented to treat 50 percent of the flow in California. This would require installation of the proposed technology in the 5 largest reclamation facilities in California.

Qualitative Benefits to Ratepayers

Through supporting deployment and eventual adoption of the proposed technology through the Electric Program Investment Charge program, California investor-owned utility ratepayers will experience other qualitative benefits, including: 1) improved environmental sustainability of water reclamation through reduced energy demand and associated carbon footprint; and 2) greater availability of a locally available water resource through water recycling.

CHAPTER 1: Introduction

This chapter provides background on low pressure membrane fouling and summarizes the objectives and goals of project, the report scope, and the report organization.

1.1 Background

Population growth, climate change, and droughts have reduced availability of clean water sources. Wastewater reclamation and reuse has become an acceptable solution to augment water supplies and is a vital part of California's water supply portfolio. It provides a local, reliable, and secure water source that can be used for landscape and crop irrigation, industrial cooling water, groundwater supply, and surface water augmentation. Although water reuse provides many benefits, the water must be treated appropriately to protect public health and the environment. California regulations require reclaimed water to be filtered and have a filter effluent turbidity less than 2 NTU for all indirect potable reuse projects and for non-potable applications including irrigation of parks, playgrounds, school yards, and residential landscaping (CCR Title 22, 2014). Conventional media filtration can be used to meet California's filter effluent turbidity requirements; however, low-pressure membrane filtration (LPMF) technologies such as microfiltration (MF) and ultrafiltration (UF) have become a preferred option for many water reuse providers because of the superior and consistent effluent quality they produce (Title 22 effluent turbidity requirement of less than 0.2 NTU). Although LPMF has advantages over conventional media filtration, the membranes are susceptible to fouling; which, increases the operating costs and reduces the water productivity and energy efficiency of the filtration system.

Membrane fouling is characterized by a reduction of filtrate flux through the MF membrane matrix as result of increased flow resistance due to pore blocking, pore plugging, concentration polarization, and cake formation (Bai & Leow, 2002). The extent of fouling on flux decline depends on membrane pore size, solute loading and distribution, membrane polymer material, source water quality, and operating conditions. Fouling causes a reduction in filtration flux; the long-term effects of fouling may be irreversible, resulting in the reduction of membrane performance and membrane lifetime. Previous studies (Safarik & Phipps, 2005; Huang & Morrisey, 1998) demonstrated that there are two mechanisms of MF fouling: 1) the classical MF cake formation, which may result in reduction of hydraulic conductivity, and 2) deposition of microbial detritus (protein, carbohydrates, phospholipids and colloidal particles) which are responsible for the majority of the observed fouling. Membrane fouling contributes to shortened membrane lifespans and increased energy demands during operation. The colloidal particles can also be problematic for downstream treatment processes like reverse osmosis (RO).

Pretreatment of the LPMF feed water via coagulation is an effective method of mitigating the fouling potential of colloidal particles. However, providing proper coagulant dosage is critical. Coagulant overdosing can lead to scaling on downstream RO membranes, while under-dosing risks getting suboptimal particle removal and membrane pore plugging during LPMF.

Although colloidal particles have been shown to be a significant contributor to membrane fouling, no techniques are currently available to monitor colloidal particles directly in the feed water, which would facilitate appropriate pretreatment (for example, coagulation and oxidation) to remove these particles and minimize their deposition on the membrane surface and within the membrane pores. This project provides field demonstration of a light scattering technology that will directly measures colloidal particle concentration and size distribution in the feed water, and hence, facilitates pretreatment for targeted removal of these particles. This technology (Nanoparticles Tracking Analysis [NTA] by Malvern Instruments) is currently commercialized for applications in other industries (for example, medical, polymer) (Malvern Panalytical, 2019). Extending its application to water treatment offers a potential new tool for mitigating membrane fouling and reducing energy consumption.

1.2 Goals and Objectives

This report presents a field demonstration of an online particle counter with the capability to directly measure the colloidal particles composition (concentration and size distribution) in the feed water. The online particle counter was used to optimize LPMF pretreatment for targeted removal of colloidal particles. The primary goal of this project was to demonstrate the capability of online particle counter to mitigate membrane fouling, save energy, and to provide other water reclamation agencies with the data needed to confidently implement NTA technology at their facilities. The specific goals of the project were to demonstrate:

- Colloidal particles of various size and concentration in the feed water can be reliably detected and quantified by the particle counter.
- The particle counter can be successfully integrated into the water treatment system and function effectively as an on-line monitoring device.
- The amount of coagulant dosed for LPMF pretreatment can be targeted and optimized using the online NTA technology.
- The transmembrane pressure (TMP) of a LPMF system filtering pre-treated feed water is lower than the TMP of a LPMF system filtering untreated feed water.
- The microfilter filtrate using pre-treated feed water does not unduly foul the downstream reverse osmosis membranes.
- Energy consumption can be reduced at water reclamation facilities by optimizing coagulant addition using the NTA particle counter.

Specific project objectives established to achieve these goals include:

- Identification of optimal settings for pretreatment control systems to ensure proper integration of the light scattering technology for colloidal particle monitoring.
- Demonstration of the instrument's ability to measure colloidal particles and to determine the particle size range effectively under dynamic flow conditions.
- Refinement of pre-treatment requirements and collection of performance data under different field conditions (for example, flow rates, effluents from multiple locations, different membranes, etc.) to improve facility confidence for successful commercialization of the technology.

- Collection of reliable capital and operations and maintenance (O&M) cost data, including energy efficiency and resulting cost savings, to determine the return on investment (ROI) and to demonstrate economic viability of the proposed technology.

Southern California Edison (Irwindale, California) performed measurement and verification (M&V) of energy consuming components using standard protocols. The project team used the resulting data to perform economic analyses and demonstrate achievement of project goals.

1.3 Report Scope

The intent of this report is to clearly present data that demonstrates the benefits of the NTA technology to other water reuse agencies and encourage them to implement colloidal particle monitoring to minimize LPMF membrane fouling, increase membrane life, reduce chemical cleaning frequency and usage, and save energy at their facilities.

1.4 Report Organization

The remainder of the report is divided into the following chapters:

- Chapter 2 provides a technology review summarizing impact of colloidal particles on membrane fouling, the benefits and drawbacks as a pretreatment to membrane filtration, and the current state-of-the-art of online particle counting technology.
- Chapter 3 provides a discussion of the project approach, description of the demonstration facilities, and the methods used to obtain data to document process results.
- Chapter 4 presents the results of pilot testing at Orange County Water District.
- Chapter 5 presents the results of pilot testing at West Basin Municipal Water District.
- Chapter 6 summarizes measurement verification of the results.
- Chapter 7 provides a summary of the projected benefits and economic evaluation of the project.
- Chapter 8 presents the production readiness plan.
- Chapter 9 discusses the technology transfer activities for this project, and
- Chapter 10 summarizes the conclusions and recommendations for the project.

CHAPTER 2:
Technology Review

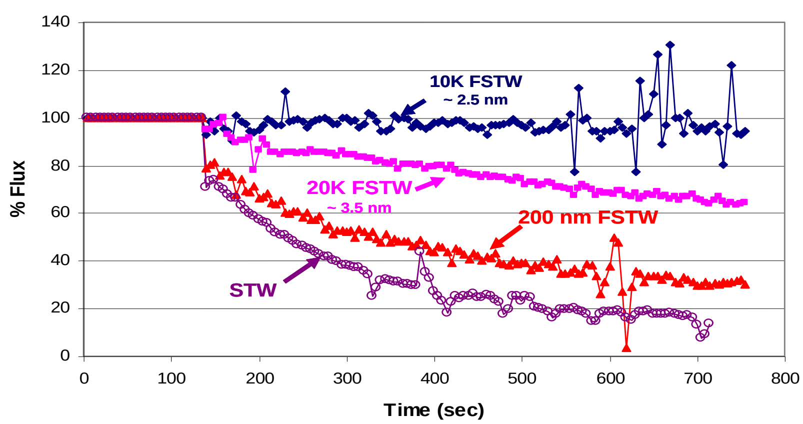
The concepts of LPMF fouling by colloidal particles, on-line monitoring of colloidal particles, and colloidal particle removal by coagulation are introduced in this chapter.

2.1 Role of Colloidal Particles in Membrane Fouling

Colloidal particles, which range in size from 1 nm to 1 µm, are present in raw wastewater and can be formed during biological (Song, Wang, Chiu, & Westerhoff, 2010) and chemical treatment (Tang, Chong, & Fane, 2011). These particles can be organic (NOM, polysaccharides, and proteins) or inorganic (aluminum silicate, silica, and iron oxides) and have been shown to be major contributors to MF and UF membrane fouling; which, results in lower membrane permeability, higher TMPs needed to maintain water flux, and increased energy demand for operation ((Huang, Schwab, & Jacangelo, 2009; Wang & Tarabara, 2008). Additionally, colloidal particles easily adsorb to the membrane and are very difficult to remove due their small size.

Researchers at Orange County Water District (OCWD) and others investigated the impact of colloidal particles on MF membrane fouling. Safarik and Phipps (2009) found that 80 percent of the observed fouling was due to colloidal particles between 2.5 nm and 200 nm, with 45 percent of the observed fouling due to colloids between 2.5 nm and 3.5 nm (Figure 1). Similarly, Howe and Clark (2002) found that particulate matter larger than 450 nm played a relatively minor role in membrane fouling, while colloids smaller than 14 nm accounted for 65 percent of the observed fouling on MF membranes treating raw surface water. This study also demonstrated that colloids smaller than 3 nm were responsible for 15 percent of the observed fouling. Other studies (Roorda, Poele, & van Graaf, 2004; Wiesner & Chellam, 1999) have also shown that colloidal particles smaller than the membrane pores are responsible for most of the fouling.

Figure 1: Comparison of Flux Reduction of Unfiltered and Microfiltered Microfiltration Feed



Source: Data from Orange County Sanitary District secondary treated wastewater [STW] or filtered secondary treated wastewater [FSTW]).

In addition to quantifying the concentration and size distribution of colloidal particles, the inherent day-to-day variation in secondary treated effluent necessitates a monitoring system that can track their presence over time (Citulski, Farahbakhsh, Kent, & Zhou, 2008). Therefore, to design a successful fouling mitigation strategy, it is necessary to have an online monitoring technology that can accurately assess feed water colloidal particle concentration of particles <200nm (typical pore size of MF membranes) and detect varying trends in real-time.

2.2 Low Pressure Membrane Pretreatment: Coagulation

There are multiple pretreatment techniques, including oxidation, pre-filtration, and coagulation, that have been used to reduce fouling of LPMF membranes in full-scale water and wastewater treatment. Of these pretreatment options, coagulation has been shown to be the most successful for LPMF fouling control (Huang et al., 2009). Chen et al. (2007) evaluated the extent and reversibility of LPMF fouling using raw river water, coagulated river water, and coagulated and settled river water. Observations from this study demonstrated that coagulation of the river water resulted in less flux decline and more recoverable flux. Additionally, the best membrane performance (lowest flux decline and highest recoverability) was measured for tests conducted with river water that was coagulated, but not settled. Chen et al. (2007) attributed this improvement over the untreated river water and coagulated-and-settled river water tests to the deposition of coagulated flocs on the membrane surface capable of absorbing neutral hydrophilic compounds. These low MW neutral NOM compounds would have otherwise remained in suspension, even after sedimentation, and contributed to the observed membrane fouling. These studies demonstrate how coagulation contributes to mitigating fouling in low pressure membrane filtration processes, but also highlight the importance of process set-up and the mechanistic advantage of in-line coagulation.

Lee et al. (2009) evaluated the effect of coagulant type and dosage on ultrafiltration membrane fouling in a system treating wastewater from a textile factory. The results from the coagulation and filtration experiments showed varying trends. For example, water flux increased linearly by 20, 60, and 80 percent at ferric chloride ($FeCl_3$) dosages of 0.05, 0.179, and 0.5 mM Fe^{3+}, respectively, and no improvement in water flux was observed at lower $FeCl_3$ doses. However, for polyaluminum chloride (PACl), a substantial improvement in water flux was noted at a dosage of 0.0186 mM Al^{3+} but water flux decreased at higher PACl dosages of 0.0925 and 0.185 mM Al^{3+}. Scanning electron microscopy (SEM) images of the membranes exposed to higher PACl dosages showed the membrane surface to be covered with a thick cake layer of coagulant that caused increased resistance to water permeation, signifying that larger coagulant dosing doesn't guarantee better performance.

Fan et al. (2009) studied the variation in pretreatment performance between MF and UF membranes. In MF experiments treating secondary effluent with alum and ferric chloride doses of 2 mg/L (0.036 mM Fe^{3+}, 0.074 mM Al^{3+}) and 5 mg/L (0.090 mM Fe^{3+}, 0.185 mM Al^{3}), flux recoveries of 88 to 94 percent were observed, compared with 61 percent for the untreated water. The same doses however only achieved flux recoveries ranging from 70 to 80 percent with UF, compared with 58 percent for the untreated water. For UF pretreatment, the flux recovery at 5 mg/L of alum was 10 percent higher than the flux recovery at 2 mg/L. However, changing ferric chloride doses did not improve flux recovery. These results show that the optimal coagulant pretreatment for reducing membrane fouling not only relies on finding the right coagulant and dose, but also on considering the physiochemical properties of the specific membrane.

While the aforementioned studies evaluated improvements in membrane flux using coagulation, the role of colloidal particle concentration and their size relative to the membrane pore size was not investigated.

2.3 Reverse Osmosis Membrane Fouling

RO membranes separate virtually all suspended organic and inorganic particles, and most dissolved organic matter and inorganic ions from the feed water. The high rejection of contaminants by RO membranes make them well suited to water reuse applications with stringent water quality requirements. However, because RO membranes indiscriminately reject almost all contaminants, they are susceptible to inorganic membrane scaling, and biological, organic, and colloidal fouling (Raffin et al., 2011), which increases operational costs and system downtime. Membrane scaling can be managed to a certain extent with chemical addition (for example, acids and antiscalants) and is typically more prevalent in RO systems designed for high water recovery (Shenvi, Isloor, & Ismail, 2015). Biological, organic, and colloidal fouling however are very common in RO systems treating wastewater because of the water's higher carbon, nutrient, and colloidal content (Xu et al. 2010, Ashhab et al., 2014, Tang et al. 2010). Additionally, dissolved organic and colloidal foulants can have synergistic effects that can worsen RO membrane fouling, thus increasing the need to remove these foulants before RO treatment (Li et al. 2008).

LPMF has been shown to be one of the most effective pretreatment technologies to reduce organic and colloidal RO fouling and improve RO system performance (Jamaly, 2014). For example, Herzberg et al. (2009) demonstrated MF pretreatment of secondary effluent reduced RO permeate flux decline by two- to three-fold and increased salt rejection from 94 percent-97 percent to 98.2-98.8 percent. Without prefiltration, particles and colloids accumulate on the membrane surface and are primarily responsible for cake enhanced osmotic pressure, which has been shown to be a major mechanism in salt rejection as well as permeate flux decline (Hoek & Elimelech, 2003). RO performance may be further improved, and treatment costs reduced by optimizing LPMF. For example, Pearce (Pearce et al., 2008) demonstrated that the improved water quality provided by MF pretreatment compared to conventional pretreatment (combination of chemical treatment and media filtration) reduced RO system energy demand by 0.8 kWh/m^3 and operations and maintenance (O&M) costs by 10 cents/m^3. This equates to annual O&M savings of $135,000 (38 percent reduction) for a 1 MGD facility.

Providing the proper coagulant dosage for low pressure membrane treatment can also help reduce RO membrane fouling. For example, overdosing of coagulants can allow excess coagulant to permeate through the low-pressure membrane and lead to subsequent scaling of downstream RO membranes. Alternatively, under-dosing the LPMF feed risks getting suboptimal contaminant removal. Because RO membrane treatment is significantly more energy intensive (three to four times) than low pressure membranes, any scaling of RO membranes that lowers their capacity can significantly increase the energy demand to maintain the design flow rate (OCWD, 2010). Because of these limitations and the lack of an available technology for accurate and real-time pre-treatment optimization, many utilities do not coagulate the feed water prior to membrane treatment.

2.4 Online Monitoring of Colloidal Particles

Currently, there are no reliable techniques in place to directly measure the levels of colloidal particle concentration in secondary-treated waste water. A combination of light scattering and ultramicroscopy techniques have shown to be capable of accurately measuring colloidal particle size distribution, but this technology is not well-established in the water reuse industry. Instead, most agencies use surrogate methods to assess their water quality.

2.4.1 Surrogate Techniques for Membrane Foulant Monitoring

Surrogate techniques such as total organic carbon (TOC), UV absorbance, turbidity, total suspended solids (TSS), and zeta potential have been used to monitor feed water quality (Ratnaweera & Fettig, 2015; AWWA, 2011). However, surrogate measurements typically do not correlate well with colloidal particles concentrations. For example, turbidity measurements do not distinguish particles by size or concentration and are not sensitive to particles smaller than 0.5 μm (500 nm) and hence, cannot effectively measure the smaller (<500 nm) colloidal particles in the feed water (Hergesheimer & Lewis, 1995).

Online TOC analyzers are used to measure dissolved organic, colloidal, and larger (micron size) particles. This measurement is too broad for targeted foulant prevention because much of the LPMF membrane fouling is caused by colloidal sized particles. Additionally, TOC analyzers do not detect inorganic colloidal particles that are also responsible for LPMF membrane fouling. UV absorbance and specific UV absorbance at 254 nm (SUVA) has been used as an online surrogate measurement for dissolved organic matter (DOM) and coagulation dosing control for water treatment (AWWA, 2011). However, UV absorbance and SUVA primarily measure aromatic DOM and give no indication of the colloidal content of the water (Weishaar, 2003). As a result, control of foulants using these surrogates is often ineffective.

2.4.2 Direct Detection of Colloidal Particles

There are many techniques used to measure the size, structure, and number of colloidal particles in solution (Babick, 2016; Tropea, 2011; Gregory, 2009). Of these, only light scattering and ultramicroscopy techniques will be discussed here because they are the most relevant to the instrument used in this study. In light scattering, a laser beam (incident beam) is directed through a solution containing particles, light from the beam is refracted by particles in the solution, and the refracted light intensity is measured by one or several detectors placed at specific angles from the incident beam. There are two typical light scattering methods used to measure particle size in solution: static light scattering (SLS) and dynamic light scattering (DLS).

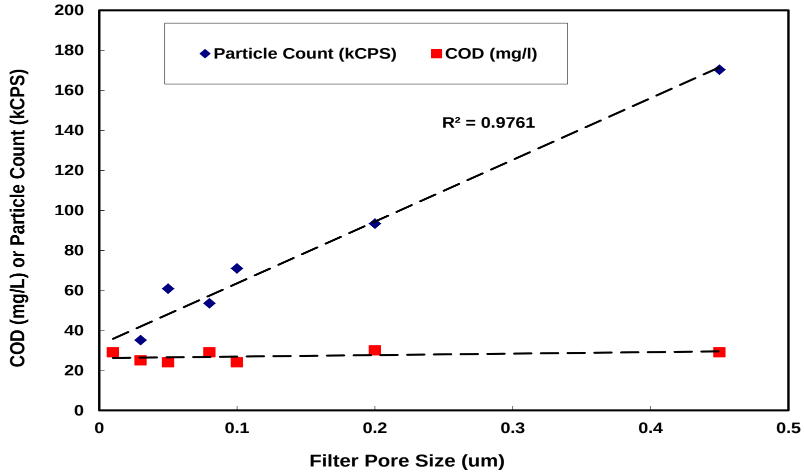
In SLS, the intensity of the refracted light is measured and the molecular weight and size of the particles is quantified. SLS is well suited for measuring particle size but is not as well suited for determining particle size distribution or concentration of heterogeneous colloidal solutions. DLS techniques measure the fluctuations in the intensity of refracted light caused by motion or vibration of the particles in solution. The size, molecular weight, and particle size distribution can be determined from analysis of the measured fluctuations. DLS has been shown to provide highly reproducible measurements of mean particle size and can be used to analyze heterogeneous colloidal solutions (Babick, 2014). The main limitation of DLS for analysis of feed water colloidal constituents is the presence of a lower size limit for what can be reasonably detected. This minimum detectable size is dependent on the particle's refractive index. For biological and polymer nanoparticles, the smallest reliably detectable size is approximately 40 nm, whereas for metal and semiconductor nanoparticles it is 10 – 15 nm. Smaller nanoparticles with weaker scattering properties can still be detected and counted, but with more difficulty (Shang & Gao, 2014). One option to overcome some of these limitations is to combine DLS measurements with optical measuring techniques having complimentary benefits.

Ultramicroscopy is an optical measurement technique that allows for a more direct measurement of colloidal particle concentration, size, and size distribution. Using ultramicroscopy, colloidal particles can be directly visualized by illuminating the particles laterally against a dark background (dark field microscopy) (Carr & Wright, 2013; Babick, 2016). The particle size is determined by measuring the movement (Brownian motion) of the projected particles over time. This method has not been practical for real-time particle size analysis in the past because it took time to develop images and measure particle movement. However, advances in digital imaging and image analysis software have allowed for rapid real-time analysis and have been implemented in new measurement techniques. One such technique is nanoparticle tracking analysis (NTA); in which, a laser is directed through a particle suspension producing a light scatter that can be captured with a x20 magnification microscope connected to a high-sensitivity camera. The camera captures a video of the particle movement, a video imaging software is used to determine the average distance moved by each captured particle, and the size is calculated with Stokes-Einstein equation for diffusion coefficients. The ability to measure the size of individual particles using NTA allows for the particle size distribution to be closely determined (Mehn, et al., 2017). Thus, combining NTA and DLS analysis provides a method to precisely and accurately measure the colloidal particle size distribution and mean particle size. This technology is selected for colloidal particle monitoring and removal in this study.

2.4.3 Comparison of Conventional Parameters with Colloidal Particle Counts

There are limited studies that compare colloidal particle counts and conventional parameters, such as soluble chemical oxygen demand (sCOD), as a function of particle size. Rosso and Rajagopalan (2013) measured sCOD levels and nanoscale particle counts in OCSD secondary effluent pre-filtered with filters ranging in size from 2.5 nm to 450 nm (0.0025 μm to 0.45 μm). As shown in Figure 2, the sCOD remained relatively constant (~30 mg/L) for all filter sizes while the particle count (measured with a Zetasizer-Nano) decreased as the pore size of the pre-filters decreased. The relatively constant sCOD level suggests that dissolved constituents primarily contribute to the sCOD and therefore sCOD concentration does not correlate well with colloidal particle concentration.

Figure 2: Chemical Oxygen Demand and Colloidal Particle Count for Pre-Filtered Secondary Effluent



Source: Kennedy/Jenks Consultants

Schulz et al (2011) compared colloidal particle counts measured using NTA with several conventional surrogates including dissolved organic carbon (DOC), ultraviolet light absorption at 254 nm (UV_{254}), and suspended solids in secondary effluent at a German wastewater treatment plant. Table 1 summarizes correlation coefficients for colloidal particles of various size fractions (< 200 nm, 200 nm to 300 nm, 300 nm to 400 nm, and > 400 nm) with these surrogates. The data show poor correlation (low R^2) for any of these parameters with colloidal particles.

Table 1: Correlation Between Colloidal Particles and Conventional Parameters in Secondary Wastewater Effluent as Indicated by Correlation Coefficients (R^2)

Colloidal Concentration	DOC	UVA_{254}	Suspended Solids	Turbidity
Total	0.082 (25)	0.174 (25)	-0.315 (25)	-0.29 (11)
<200 nm	0.095 (25)	0.12 (25)	-0.244 (25)	-0.311 (11)
200 to 300 nm	-0.105 (25)	0.185 (25)	-0.337 (25)	-0.302 (11)
300 to 400 nm	0.126 (25)	0.322 (25)	-0.428 (25)	-0.302 (11)
> 400 nm	-0.091 (25)	-0.016 (25)	-0.108 (25)	-0.489 (11)

Note: Values in parenthesis show number of samples; DOC = dissolved organic carbon; UV_{254} = absorbance at 254 nm

Source: Schulz, 2011

Schulz et al (2011) simultaneously monitored the turbidity and colloidal particle profiles in the influent and effluent of a WWTP. The turbidity and colloidal particles followed a similar profile in the influent; however, there was a difference in the lag-time (time entering and exiting system) between the two measurements. Turbidity had a much shorter lag time (~2 hours) than colloidal particles (~18 to 20 hours). The shorter lag time for turbidity, which includes measurement of larger suspended particles (> 450 nm), suggests poor flow characteristics of the secondary settling tank resulting in lower retention time and quicker exit for some larger particles due to poor settling. The colloidal particles remained as part of the liquid stream and exited in the effluent after a period equivalent to the hydraulic retention time. The difference between the turbidity and colloidal particle profiles indicate that the turbidity levels in wastewater samples are not an ideal surrogate for colloidal particles.

2.5 Online Monitoring of Colloidal Particles to Control Membrane Fouling

Schulz et al (2011, 2012) used NTA via an online NanoSight NS500 instrument to investigate the role of colloidal particle (< 200 nm) loading of UF membranes. The UF colloidal particle loading was adjusted with pre-ozonation and various levels of coagulation. During the study, continuous samples of feed water and pre-treated waters were collected over several days. The extent of particle removal and filtration performance was directly proportional to the initial concentration of nanoparticles smaller than 200 nm. Schulz used NTA to demonstrate that coagulation pretreatment resulted in a decrease of colloidal particle concentration and improved UF membrane performance. These results helped to establish the NanoSight NS500 as a reliable instrument for direct monitoring of colloidal particle concentrations in real-time. This capability can be leveraged to further reduce membrane fouling and enhance membrane performance by allowing for coagulant pretreatments to directly target the removal of colloidal particles present in the incoming feed. NTA's capacity for real-time monitoring also allows the system to respond to any fluctuation in colloidal particle size and concentration. This would ensure an optimal coagulant dose is used, not overdosing and risking downstream RO coagulant fouling or under-dosing and causing fouling of the LPMF membranes.

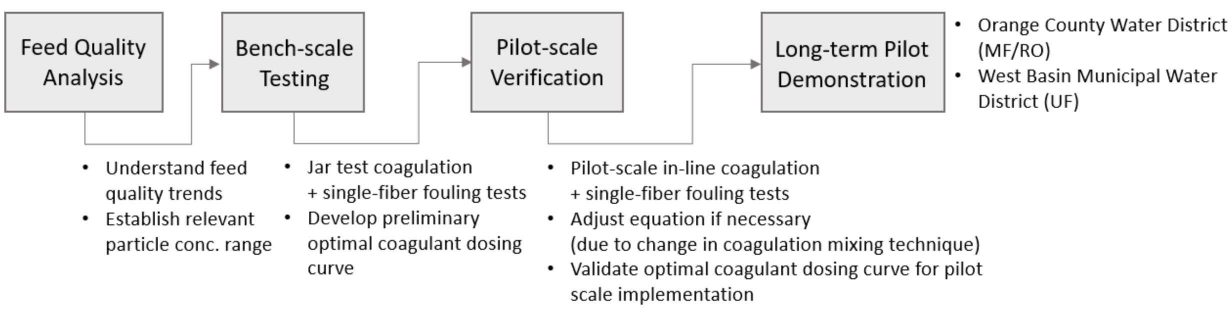
CHAPTER 3: Methodology

The study approach, the test facilities, and the methods of data and sample collection and analyses are described in this chapter.

3.1 Study Approach

The objective of the study was to demonstrate the ability of the NTA technology to monitor colloidal particles concentration in the membrane feed water and thus facilitate their removal via calibrated release of coagulants. The demonstration studies were performed at Orange County Water District (OCWD) and West Basin Municipal Water District (West Basin). Figure 3 shows the steps undertaken for this demonstration at each facility. Each of these steps are discussed in the sub-sections below.

Figure 3: Workflow Schematic for Obtaining an Optimal Coagulant Dose



Optimal coagulant dosing curves were determined for different coagulant types, and for pretreatment of different low-pressure membranes.

Source: Kennedy/Jenks Consultants

3.1.1 Assessment of Membrane Feed Water Quality

The first step in the demonstration study was to measure the levels of colloidal particles and determine the diurnal fluctuations in the membrane feed water. The colloidal particles concentration and characteristics are dictated by various factors including nature of wastewater discharges and source water treatment. Initially, grab and continuous samples of the feed water from OCWD and West Basin were analyzed using the NTA system. A range of colloidal particle concentrations in the feed water were thus established for both facilities.

3.1.2 Bench-Scale Testing to Develop Relationship Between Colloidal Particles Concentration in the Feed Water and Optimum Coagulant Dose

The following three-step process was used to establish the relationship between the feed water colloidal particles characteristics and optimum coagulant dose to lower membrane fouling and enhance membrane flux.

- Jar testing was used on feed water from each site (containing three different concentrations of colloidal particles) to study colloidal particles removal at different coagulant doses.

- Bench scale, single-element membrane fouling tests were then performed using coagulated and settled supernatant from the jar test. Optimum coagulant dosing corresponding to the initial colloidal particles concentration feed water was determined using the flux rate.
- Subsequently, regression analyses were performed to develop a relationship between the colloidal particle concentration in the feed water and the optimum coagulant dosing.

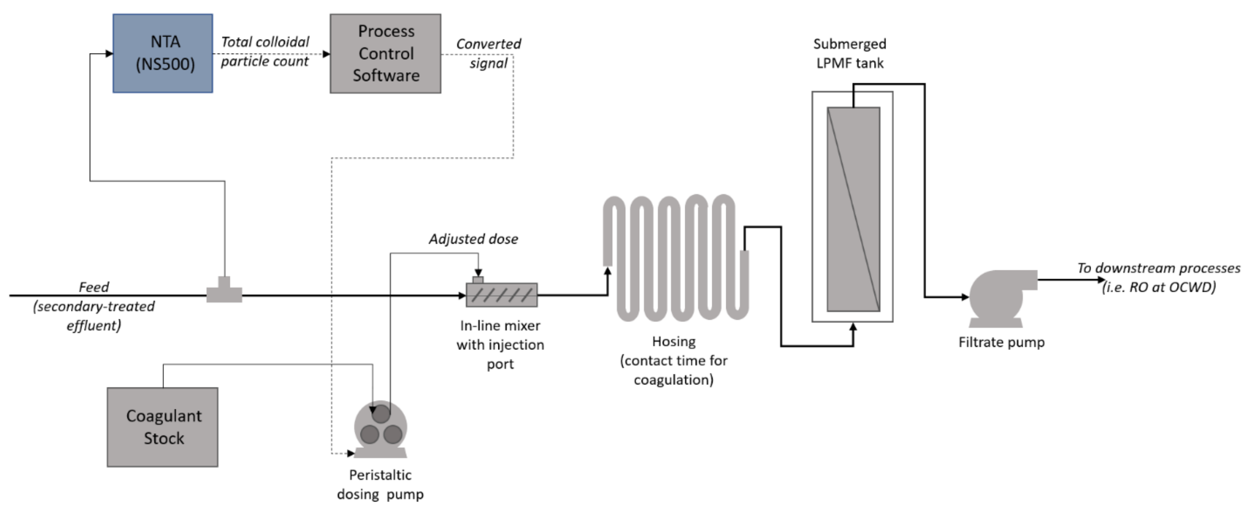
3.1.3 Validating Bench-Scale Optimum Coagulant Dosing Curve at Pilot-Scale

The equation developed from the bench scale study was then verified for possible adjustment in the pilot study set up. This helped to account for the differences in mixing techniques used at the pilot and at the bench-scale. In the bench-scale setup, the coagulant was mixed with the feed water in a jar (that is, continuously stirred tank reactor [CSTR], details in section 3.2.1). In the pilot unit, the mixing was provided by a 1.5 in diameter tube with appropriate length to yield a mixing time of 10 minutes (details in section 3.6). Hence, tests were performed to verify and adjust the optimum coagulant equation.

3.1.4 Long Term Pilot Demonstration

Finally, long term pilot demonstration studies were performed on a pilot system at two different water treatment facilities. The approach used in this study revolved around a feed-forward control loop that utilized the direct monitoring capabilities of the NTA technology. By monitoring the colloidal particle concentration of the incoming feed (secondary-treated effluent) at the two pilot facilities, the pretreatment coagulant dose to the LPMF system was continuously adjusted. This strategy aimed to improve targeted colloidal particle removal and provide membrane fouling protection to improve energy efficiency. Figure 4 gives an overview of the experimental setup used in the field demonstrations of this project.

Figure 4: General Schematic of Proposed Pilot Treatment System



Source: Kennedy/Jenks Consultants

In this pilot testing setup, a slip stream of the membrane feed water was analyzed by NTA (NS500) to obtain colloidal particle concentrations and size distribution. Based on the NS500 data, the process control software signaled the release of the appropriate coagulant dose. This pretreatment dose was adjusted and optimized based on developed dosing curves and real-time particle distribution data provided by the online particle counter (see Section 3.6.1 for more detail). Control tests with no coagulant feed were also run for comparison.

3.1.5 Benefits Evaluation

The benefits evaluation consisted of measurements and verifications performed by SCE (Irwindale, CA) of the energy consuming components (connected to the pilot systems filtration pumps) at both field demonstration sites. The collected data was used to perform an economic analysis that accounted for the savings in energy consumption, membrane replacement, and membrane chemical cleaning costs.

3.2 Bench-Scale Studies

Bench-scale studies were performed to establish the relationship between the feed water colloidal particles characteristics and optimum coagulant dose at each demonstration site.

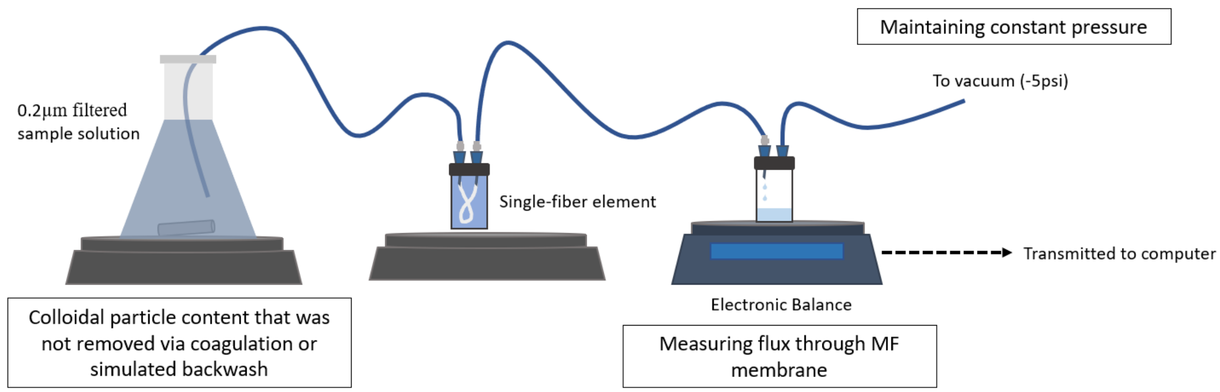
3.2.1 Bench-Scale Jar Testing

Bench-scale jar tests were performed using a six-paddle jar tester (Phillips and Bird, Richmond, VA). Based on initial screening tests, PACl coagulant (CalChem2060, CalChem Inc., Modesto, CA) was selected for use at OCWD, and both PACl and $FeCl_3$ were selected for use at West Basin. A range of concentrations of each coagulant (PACl 5 to 20 mg/L, ferric chloride 5 to 20 mg/L) were added independently to a 1-L beaker containing MF feed water. To obtain feed water with a representative range of colloidal particle concentrations, nanoparticle concentration of the collected feed was first counted by the NS500. This concentration was then adjusted by adding either MF/UF filtrate for reducing the colloidal concentration, or by adding backwash water to increase the colloidal concentration. Adjustments were made until the target concentration for low, medium, and high particle count was obtained. Upon adding coagulant, the samples were rapidly mixed at 120 rpm for 1 minute and slowly mixed at 30 rpm for 10 minutes, then allowed to settle for 10 minutes. Supernatants were collected, filtered through a 0.22 μm filter (Cellulose acetate low binding - sterile 500 mL filter system, Corning), and analyzed for nanoscale particle size distribution, turbidity, and used in bench-scale membrane fouling tests.

3.2.2 Bench-Scale Membrane Fouling Tests

Samples treated through the bench-scale jar tests were collected and used to conduct bench-scale membrane fouling tests and determine the effect of feed particle concentration and coagulant dose on membrane fouling. The fouling tests were conducted with an apparatus comprised of a sample container, a sealed membrane cell containing a single MF or UF hollow fiber membrane sample, and a sealed filtrate collection bottle placed on an electronic balance (Sartorius) and connected to a vacuum pump. A schematic drawing of the apparatus is provided in Figure 5.

Figure 5: Experimental Arrangement Used for Microfiltration Flux Rate Evaluation Studies



Source: Kennedy/Jenks Consultants

The vacuum pressure was held at 5 psi during the test to maintain a constant driving force for water flux. As water was drawn through the single fiber element, the filtrate water weight was measured over time with the electronic balance. The balance was connected to a computer running a software program (WinWedge, Tal Technologies, Philadelphia, PA) programmed to automatically record and store the filter water mass at constant time intervals. The change in mass over time and membrane area were used to calculate water flux.

3.2.3 Bench-Scale Optimum Coagulant Dosing Curve

Coagulant dosing curves were developed to determine the optimum coagulant needed to minimize membrane fouling based on the feed water particle concentration. The curves were constructed by selecting the coagulant dose that resulted in the least amount of membrane fouling (that is, highest flux rate) during the single fiber fouling tests conducted with feed waters containing low, medium and high particle concentrations. The criteria used to evaluate the amount of fouling was the percentage of pure water flux maintained after 5 minutes of testing. During a single-fiber fouling test, the particle concentration increases over time as water is filtered through the membrane while colloidal particles in the feed water stock are retained. Thus, the percentage of pure water flux after 5 minutes, as opposed to the flux at the end of the 10-minute test, was used to develop the curve to limit the impact increasing feed water colloidal particle concentration would have on the results. The selection also considered cost-effectiveness by favoring lower coagulant doses that can achieve similar performance to those at higher doses.

3.3 Validating Bench-Scale Optimum Coagulant Dosing Curve during Pilot-Scale Testing

The pilot-scale coagulant dosing system resembles a plug-flow reactor more than the completely stirred-tank reactor (CSTR) used in the bench-scale testing. Because the bench- and pilot-scale dosing and mixing systems were configured differently, coagulant dosing curves were also developed using the pilot-system to account for differences in mixing and reaction times. Pilot tests for verifying the dosing curve were conducted at OCWD, with five different coagulant doses. PACl was dosed at rates of 12.3, 18.4, 21.4, 24.5, and 36.7 mg/L using the pilot-system chemical dosing pump. Approximately 1000-feet of hose was added between the dosing point and the MF unit to allow for adequate coagulant contact time before the feed water was filtered through the MF unit.

For each dosing condition, the coagulated feed water was collected at the end of the 1000-feet MF feed hose, filtered through a 0.2 μm membrane, and a flux test performed using the bench-scale fouling test unit. The coagulation and fouling tests were completed over a period of approximately 3 hours to limit any changes in the feed water colloidal particles concentration. In fact, the concentration of feed water colloidal particles remained at approximately 5.7×10^8 particle/mL throughout the tests. The optimal coagulant dose determined from these tests was compared to those obtained through the bench-scale coagulant dosing tests.

3.4 Demonstration Sites

Two field demonstration sites, OCWD, Fountain Valley, CA and West Basin, El Segundo, CA, were used to test the efficacy of optimized coagulant dosing on the LPMF systems. Although the demonstration tests conducted at OCWD and West Basin sites were similar, there were a few key distinctions between the two, including the type of coagulants tested, the membrane type (MF and UF), feed water quality, and the absence of RO testing at the West Basin demonstration site. The notable differences between these two sites helped to define the capabilities and limitations of the online nanoparticle counting system over a range of operating conditions (Table 2).

3.4.1 Overview of Orange County Water District Full-Scale Operation

The Orange County Water District (OCWD) Advanced Water Purification Facility (AWPF) in Fountain Valley, CA utilizes microfiltration (MF), 3-stage reverse osmosis (RO) and an ultraviolet/hydrogen peroxide advanced oxidation process (UV/H_2O_2 AOP) to recycle secondary-treated municipal wastewater as a supplement to the local drinking water supply. The OCWD treatment train is considered a model facility for potable reuse of wastewater and is representative of other facilities around the world. The secondary wastewater effluent (source water) contains membrane fouling materials, including colloidal particles, microorganisms, microbial detritus and dissolved organic matter. Deposition of these materials results in membrane biofouling and chemical and organic fouling that impairs the performance of the MF and RO systems by decreasing water production and increasing operational costs. The MF and RO unit processes make up 90 percent of the energy demand needed for treatment. The specific energy consumption of the MF and RO systems are approximately 0.9 kWh/1000 gal and 1.7 kWh/1000 gal, respectively, much higher compared to the 0.26 kWh/1000 gallons needed for UV-AOP treatment (Holloway, Miller-Robbie, Patel, & Cath, 2016). As such, improving energy efficiency of these membrane treatment systems is a high priority to OCWD.

Table 2: Operating Parameters at the Two Pilot Demonstration Sites

Site	Filtration units	Filtrate flow rate	Membrane pore-size	Membrane material	Feed source and water quality	Standard cleaning protocol
OCWD	MF (then RO)	18 GPM (12 GPM)	0.2 µm	MF – Polypropylene (PP) hollow fibers (Evoqua) RO – polyamide membranes (Hydranautics)	Secondary treated wastewater from OCSD[1] (trickling filters) Avg. daily turbidity: 2.6 NTU	MF: backwash every 22 min, CIP initiated at terminal TMP (12.5 psi)
West Basin	UF	5 GPM	0.1 µm	UF – Polyvinylidene fluoride hollow fibers (Scinor)	Ozonated secondary effluent from Hyperion WRP[2] (Suspected growth activated sludge process using high purity oxygen) Avg. daily turbidity: 4.5 NTU	UF: backwash every 20 min, EFM[3] every 24 h, CIP[4] initiated by operator after reaching terminal TMP (approx. 12.5 psi, every month)

[1] OCSD – Orange County Sanitation District.

[2] Hyperion WRP – Hyperion Water Reclamation Plant.

[3] EFM – Extended flux maintenance. During the span of the pilot study at West Basin, automatic daily EFM cleaning was shut off. Instead, EFM was manually initiated every other day.

[4] CIP – clean-in-place (CIP) is a chemical cleaning process, similar to EFM but with additional acid and caustic soak cycles. CIP was performed before the start of each new phase in the study.

Source: Kennedy/Jenks Consultants

3.4.2 Overview of West Basin Municipal Water District Full-Scale Operation

The City of Los Angeles' Hyperion Water Reclamation Plant (HWRP) high purity oxygen (96 percent) activated sludge secondary treatment followed by secondary clarifiers to produce secondary effluent which is pumped to West Basin's Edward C. Little Water Recycling Facility (ECLWRF) for further treatment and distribution. ECLWRF treats, on average, approximately 40 million gallons per day (MGD) of secondary effluent to produce recycled water of various qualities and meet the specific needs of its industrial and municipal customers. In the past five years, ECLWRF produced approximately 14 MGD of advance treated water for indirect potable reuse via groundwater replenishment (~10 MGD, O_3 → MF (UF)[1]→ RO→ AOP (UV/H_2O_2) → Cl_2) and industrial uses (~4 MGD, MF followed by single- or double-pass RO, depending on product water quality requirements). Additionally, it produces an average of 16 MGD of Title 22 recycled water for irrigation use (~4 MGD) and for industrial use after treatment at other satellite facilities (~12 MGD).

A major portion of West Basin's recycled water sales are for ground water recharge and to local refineries requiring process water with low levels of total dissolved solids or ammonia (nitrified recycled water). Reducing the energy demand and chemical consumption in the UF and RO treatment process through fouling management and prevention could lower the recycled water operational and maintenance costs and increase financial efficiency.

3.5 Colloidal Particle Monitoring System and Pilot Equipment

A combined MF-RO pilot and an UF pilot system was used at the OCWD and West Basin demonstration sites, respectively. The schematic drawing in Figure 4 shows the pilot system configurations used to evaluate the effect of targeted coagulant dosing and particle removal on membrane performance. Secondary effluent from OCSD and HWRP were used to feed the membrane filtration units at OCWD and West Basin, respectively. A slip stream of the feed water was analyzed by the NTA nanoparticle counter. Based on the nanoparticle measurement, the process control software (LabView, National Instruments) adjusted the coagulant dose by varying the peristaltic dosing pump speed (Grundfos, DDA Digital Smart Dosing Pump, Downers Grove, IL). Mixing was provided in the feed pipe by an in-line PVC mixer (Koflow, Cary, IL) followed by enough hosing to provide approximately 10-minutes of contact time calculated based on the feed flow rate and volume of any downstream holding tanks. The coagulated water was then treated by the MF/UF membrane units in a constant flux operating mode. The TMP of the MF/UF membranes was continuously measured with online pressure transducers and was used to evaluate the system performance over the testing period.

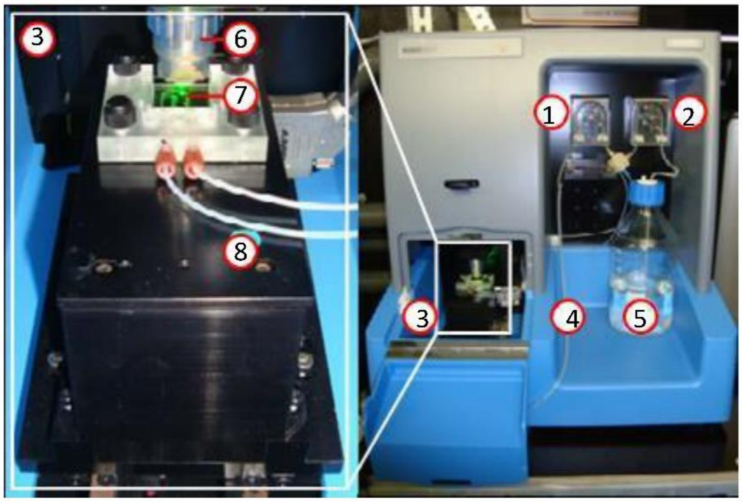
Detailed descriptions of the various pilot unit systems at the OCWD and West Basin demonstration sites are provided in the following sections.

3.5.1 Online Colloidal Particle Monitoring System

The online particle counter used in this study was a NanoSight NS500, developed by Malvern Instruments (Westborough, MA) and designed to directly measure colloidal particles in aqueous samples. The instrument uses DLS and NTA technology to measure colloidal particles in aqueous streams. The DLS instrument uses a laser to measure the rate of fluctuation in light intensity caused by Brownian motion of the particles in suspension. Analysis of the fluctuations in intensity yields the velocity of the particle due to Brownian motion and hence, the particle size. A captioned photo of the NS500 is shown in Figure 6.

[1] Part of the flow was treated using UF membranes at the time of this study.

Figure 6: Nanosight NS500 Online Nanoscale Particle Counting System



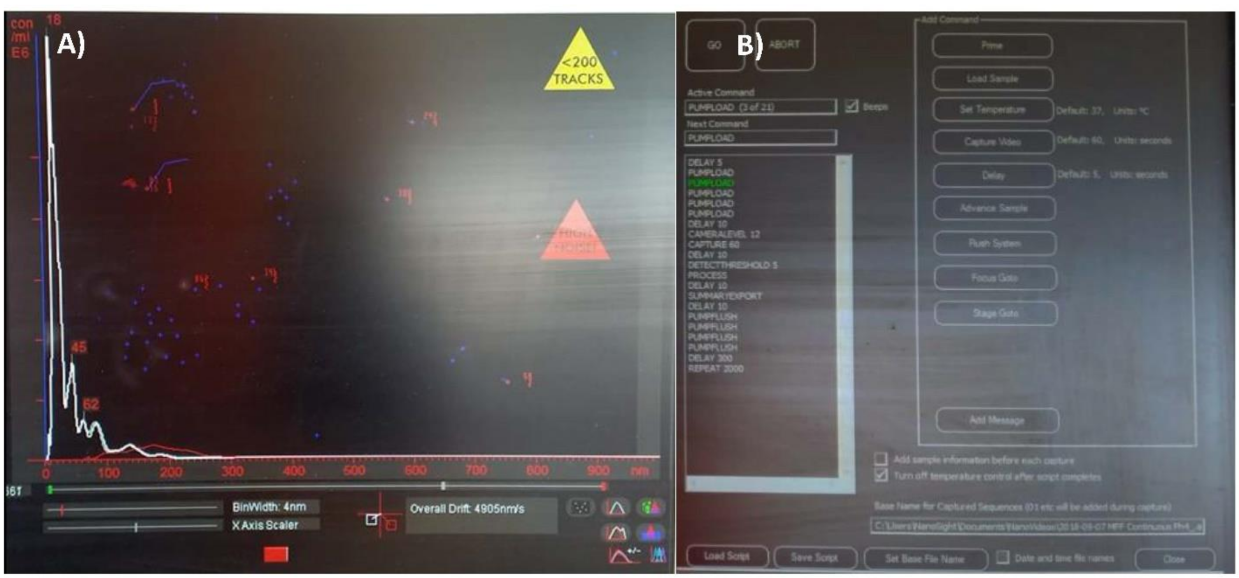
1. Sample Pump
2. Dilution/Flush Pump
3. Viewing Unit
4. Sample Pipe
5. Rinse Solution
6. Microscope
7. Sample Chamber
8. Laser Light Source

Source: Kennedy/Jenks Consultants

As depicted in the above figure, the Nanosight NS500 consisted of automated components that allowed for single and continuous testing of samples. For on-line implementation, a peristaltic pump (Watson-Marlow 102R, Wilmington, MA) (depicted in the Figure 6 as [1]) drew raw feed water samples to the NS500 unit at a rate of 30 ml/min. The sample was pushed through a sample pipe [4] into the viewing unit [3] and through a microfluidic sample chamber [7]. Here, the NTA instrument captures the motion of the particles using a camera equipped with a 20x microscope objective [6].

Figure 7A depicts an example of the NTA program as it is processing the particle size distribution within the sample.

Figure 7: Field Shot of The Nanosight NS500 A) During Video Capture and Particle Counting, and B) the Command Script Window



Source: Kennedy/Jenks Consultants

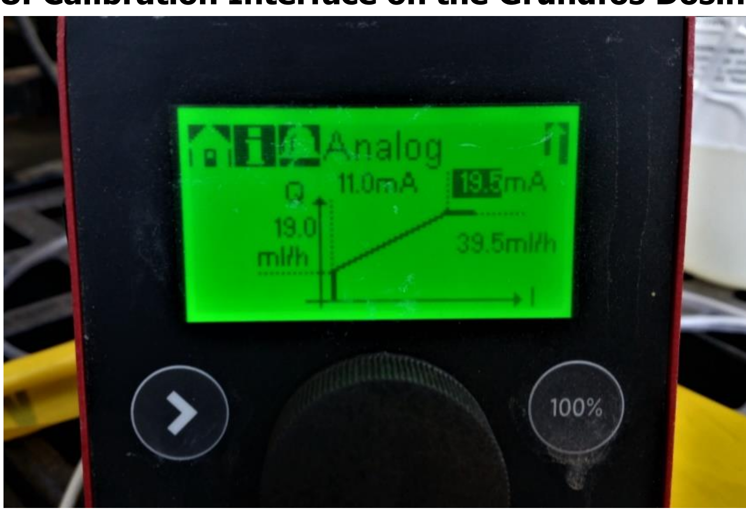
The average distance traveled by each captured particle is automatically calculated by image analysis software and the hydrodynamic diameter is obtained. The results are displayed as a frequency size distribution graph and output to a spreadsheet as concentration of detected particles (10^6 particles/mL). Video files are also recorded and archived. Depending on the composition of the water sample, particles in the size range of 1 nm to 1000 nm (1 μm) can be measured. To continuously read feed samples from the pilot skid, a repeating command script was written for the NanoSight NS500 to perform (

Figure 7B). The script consisted of several pumping steps to draw in a new sample volume, followed by video capture, image processing steps, and file storage. Every sampling cycle was followed by a rinse with DI water to dislodge any bubbles in the sample chamber and to prevent buildup of contaminants that could block the pipe. The sampling frequency of the NS500 was adjusted using a 'delay' step added to the script. Samples were read every 15 minutes at OCWD and every 10 minutes are West Basin. A higher sampling frequency was used at West Basin due to the prevalence of water quality fluctuations observed at the site.

3.5.2 Signal Transmittance to Chemical Dosing Pump

Pretreatment dosage was determined based on the raw water colloidal particles concentration measured by NTA. As previously explained, the NS500 monitoring system generated a spreadsheet containing the number of colloidal particles ranging from 1 nm to 1000 nm in diameter. To convert this information to coagulant dosage, the values recorded in the spreadsheet were first summed up. This value for 'total particle count' was then mapped on a scale ranging from 0 particles/mL=0 V to 1000 * 10^6 particles/mL = 5 V. This scaling covered the range of total particle concentrations observed at each site – typically within 100 to 900 * 10^6 particles/mL. The output generation software used for reading the spreadsheets was written in LabView (National Instruments). An interface box, designed by the team at Malvern, contained a USB device with a 0-5V output converter that additionally scaled this output as 4 – 20 mA. This value was used as the analog input signal to the chemical feed pump (Grundfos, DDA Digital Smart Dosing Pump, Downers Grove, IL). Figure 8 shows the calibration interface for the pump's automatic dosing program.

Figure 8: Calibration Interface on the Grundfos Dosing Pump



Source: Kennedy/Jenks Consultants

The analog signal input was scaled to the maximum and minimum pump output that best matched the optimal coagulant dosing relationship previously developed. The dosing pump calibration was able to achieve a good correspondence to the optimal dosing curve because both the conversion of feed particle count to mA (pump input), as well as the optimal dosing curve (pump output) were linearly correlations. For trial periods that used constant dosing, the Grundfos linear dosing pump was switched to manual mode.

3.5.3 Microfiltration/ Ultrafiltration Units

3.5.3.1 OCWD Pilot Microfiltration Unit

Two direct filtration Evoqua 4S10V CS submerged MF pilot units (Evoqua Water Technologies, Pittsburgh, PA) were used in this demonstration. One unit received feedwater without pre-coagulation and the other unit received feedwater which was precoagulated with CalChem 2060. The MF membranes were operated in direct filtration, with a filtrate flow rate of 18 gpm. To accommodate this capacity, membrane modules were isolated in a submerged tank in groups of four. The polypropylene hollow-fiber MF membranes had a nominal pore size of 0.2 μm. The skid was equipped with a feed and filtrate pump (Goulds Pump, Bluffton Motor Works, and Emerson); feed, filtrate, and backwash magnetic flow meters; feed and filtrate turbidimeters, air compressor; and an automated cleaning skid.

The cleaning protocol for the MF membrane units consisted of an automated backwash cleaning and air scouring every 22 minutes. The TMP for these units were logged automatically using feed and filtrate pressure transducers (Deltabar PMD235 Endress+Hauser). Upon reaching terminal TMP (set to approximately 12.5 psi), the pilot was shut down for chemical (clean-in-place [CIP]) cleaning. Membrane cleaning, clean in place (CIP), procedure was performed according to OCWD's MF cleaning protocol. The pilot tests were carried out at the OCWD Engineering Research Center (ERC). Activated sludge/trickling filter from the Orange County Sanitation District (OCSD), also OCWD's Groundwater Replenishment System feedwater, was used as the feed to both pilot units. Chlorine (sodium hypochlorite) was added to both pilot feedwater and the residual combined chlorine levels were maintained at 5 mg/L.

3.5.3.2 West Basin Pilot Ultrafiltration Unit

A single module pilot system with a SMT600-S26 PVDF UF submerged membrane (Scinor Water America, LLC, New York, NY) was used at the West Basin demonstration site. The UF membrane was operated in direct filtration, with a filtrate flow rate of 5 gpm. The polyvinylidene fluoride (PVDF) hollow-fiber UF membrane had a nominal pore size of 0.1 μm.

The skid was equipped with a feed and filtrate pump (Bluffton Motor Works), feed, filtrate, and backwash field mounted magnetic flow meters and transmitters (Rosemount 8732E), feed and filtrate turbidimeters (FilterTrek 660SC Laser Nephelometer, Hach, and 1720E Turbidimeter Low range, Hach), air compressor (Husky), and an automated cleaning skid. The TMP for the membrane unit was logged automatically using feed and filtrate pressure transducers (Cerabar M PMP51-9RA8/0 Endress+Hauser).

The cleaning protocol for the UF membrane unit at West Basin consisted of an automated backwash cleaning and air scouring every 20 minutes. During normal operation, an automated enhanced flux maintenance (EFM) clean is typically performed every 24 hours, while a CIP (cleaning-in-place) is performed approximately every one-and-a-half month or when the TMP reaches 12.5 psi. The EFM cleaning protocol consisted of a 45-minute acid soak, while a CIP consisted of a 3 – 6 hour-cycle of caustic/acid/caustic soaking. For the duration of the pilot study, the EFMs were switched to manual mode and initiated every other day or based on operator's discretion. The reduction in EFM frequency was done to allow more membrane foulants to buildup, such that variations between the test conditions would be more distinguishable within the shorter testing periods. During pilot operation, CIPs were initiated at the end of each testing phase to reset the membrane TMP.

3.5.4 Reverse Osmosis Unit

A RO unit was not assembled or tested as post-treatment of UF at the West Basin demonstration site. At OCWD however, a self-contained, skid-mounted RO unit (Hydranautics model ESPA2-LD) was installed downstream of the MF filtration tanks to study the impact of targeted coagulation pretreatment on RO performance.

The RO pilot system was designed to simulate operations of the AWPF 5-mgd RO units with respect to operational flux and recovery. Compared to the three-stage full scale facility, the pilot is configured as a two-stage process, in which concentrate from the first stage is fed to the second stage. The system was operated at 85 percent recovery to match the recovery of the three-stage full scale RO system; hence the membranes in each stage were operated at a higher recovery (more production) compared to the full-scale system. As with the 7M (membrane) vessels in the AWPF RO system, each stage was configured as a 7M stage (for example, 4M followed by 3M, 2M, and 1M). Manual and digital flowmeters allowed for flux and permeability to be monitored across the pilot system. RO system performance in terms of flux and electrical conductivity (EC) was monitored over the course of the trial.

Membrane cleanings were conducted with 2 percent sodium triphosphate (STP) and 0.2 percent of Sodium dodecylbenzenesulfonate (SDBS) to achieve a target pH of 10.5 ± 0.5. The cleaning chemicals were recirculated through the first stage for 1-hour, then soaked for another hour, before this process was repeated for the second stage of vessels. Following membrane cleaning, the RO unit was operated with 3.5 mg/L of AWC A-110 anti-scalant and sulfuric acid was used to maintain the pH at 6.9. Feed water pH was controlled through an in-line sensor which was coupled to a proportional-integral-derivative controller (PID) and connected to a digital dosing pump. High-precision digital dosing pumps were also employed to deliver (neat) antiscalant – avoiding the need for product dilution and injection at higher delivery rates.

3.6 Analytical Methods

Various analytical methods were used in the bench- and pilot-scale testing to evaluate the effectiveness of coagulant dosing on particle removal and membrane fouling. These analytical methods are described in the following sections.

3.6.1 Colloidal Particle Counting

The NanoSight NS500 particle counter used in pilot scale testing was also used to measure the particle size distribution in the supernatant from the jar tests. The viewing unit and all tubes of the instrument were flushed with distilled water before analyzing the supernatant. Following the distilled water flush, the flow through chamber was rinsed and filled with the sample, which was pre-filtered through a 1-µm filter. The instrument settings were adjusted depending on the anticipated concentration, polydispersity, and sizes of the colloids in the sample before the measurement was taken. The detection range for the NanoSight NS500 was 0 to 2 µm, with a higher accuracy for particles ranging in 30 nm to 1 µm in size.

3.6.2 Turbidity

Turbidity of grab samples from the pilot studies were measured using the Hach 2100Q portable turbidimeter (Hach, Loveland, CO).

3.6.3 UV Absorbance

Ultraviolet absorbance (UV) was measured at a wave length of 254 nm (UV_{254}) with a benchtop spectrophotometer. The Hach DR 5000 and Hach DR 6000 (Hach, Loveland, CO) spectrophotometer was used for UV absorbance at West Basin and OCWD, respectively.

3.6.4 Chemical Oxygen Demand

The supernatant for jar testing, filtrate from bench-scale fouling tests, and MF/UF and RO pilot test feed and filtrate were sampled and measured for chemical oxygen demand (COD) concentrations. The COD analysis was conducted using Hach low-range COD (3-150 mg/L) reagents and measured with the Hach DR 5000.

3.6.5 Electricity Demand

Southern California Edison personnel monitored electricity demand for the pilot units. Dataloggers were strategically placed on the filtrate pump at OCWD, and filtrate pump and backwash pump at West Basin. The significance of these pumps stems from the fact that their energy load is directly related to the extent of membrane fouling as they try to maintain a fixed flux during filtration as well as backwash. ELITEpro SP power meters (DENT Instruments, S/N SP1211003) were used to quantify energy use. This device measured, stored, and analyzed electrical consumption data derived from the voltage and current inputs. The DENT meters were used to log average voltage [V], average amps [A], average kW [kW], and the average power factor [PF]. Date and time stamps were also recorded in correlation to the fields above. These data loggers collected information on pump energy consumption every 15 minutes over several weeks of operation. TMP was collected simultaneously by pressure transmitters (Deltabar PMD235 Endress+Hauser) for each membrane filtration unit. Corresponding values were used to develop a correlation between the energy consumption and TMP. The developed relationship for each pump was extrapolated to calculate the overall energy use, based on the membranes' TMP performance which was measured throughout the study.

3.6.6 Metals, Trace Elements and Total Organic Carbon

Feed and MF/UF/RO filtrate samples were preserved with nitric (1:4) or phosphoric acid (1:1) and sent to an independent laboratory for metals and trace elements (silica oxide (SiO_2), aluminum, calcium, magnesium, and fluoride) and total organic carbon analysis. Metals and trace element analyses were performed using an inductive coupled plasma (ICP) spectrophotometer and in accordance with EPA method 200.7 revision 4.4. TOC was measured using Standard Method 5310C.

3.6.7 Aluminum

Aluminum analyses were performed on OCWD and West Basin pilot grab samples for the untreated feed, coagulated feed, MF filtrate with and without coagulation pretreatment, and RO permeates following coagulation pretreatment. The Hach Alumion method 8012 was used to quantify the aluminum analysis.

3.6.8 Iron Analysis

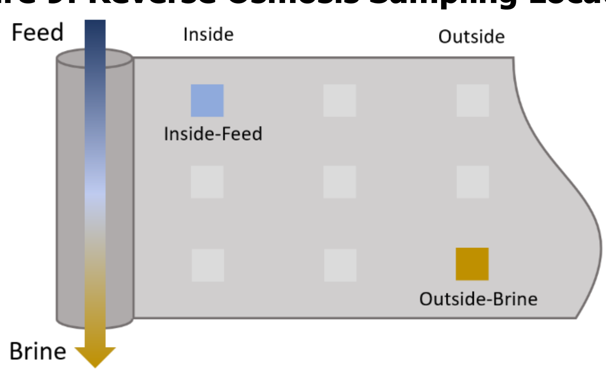
Iron analysis were performed on West Basin pilot grab samples for the untreated feed, coagulated feed, and MF filtrate when ferric chloride was being administered as the pretreatment coagulant. The Hach method 8008 (IRON-FerroVer pocket calorimeter II alongside Permachem reagents (cat. 2105769)) was used to quantify the presence of total soluble ferrous and ferric iron. Complexed iron compounds and other insoluble iron forms are also included in the measurement.

3.6.9 Membrane Autopsy

After each test phase, autopsies were performed on membranes to help understand the extent of fouling that had taken place. Samples were collected from the polypropylene MF fibers at OCWD at the end of the study period. At West Basin, samples were extracted from the PVDF membrane at the end of each testing phase, prior to CIP being performed. To be able to reuse the filtration unit for the remaining duration of the study, membrane barrier and module integrity had to be restored for the PVDF membrane. This was achieved by performing a bubble test after each extraction, identifying the leaking fibers, and permanently plugging them with pins. For each phase of the project, fiber samples were collected from the top, middle, and bottom of the filtration unit.

For autopsies performed on the RO membrane, samples were extracted from the tail and lead elements of the treated and untreated units. Samples were extracted following the end of Phase 1 pilot testing (no coagulation) and analyzed with the Tescan GAIA-3 GMH FIB-SEM. Samples extracted following Phase 2 pilot testing (with targeted coagulation) were examined with the Philips XL-30 FEG-SEM. The membranes and spacer samples were collected from either the inner-most RO layer from the feed side, or from the outer-most RO layer closer to where the feed concentrate was being discharged (refer to Figure 9). These two sample locations represented the areas of the RO module where fouling was least likely (inside-feed) or most likely (outside-brine) to be observed.

Figure 9: Reverse Osmosis Sampling Locations



Source: Kennedy/Jenks Consultants

3.6.9.1 Scanning Electron Microscopy and Energy Dispersive X-Ray Spectroscopy

The composition of the fouling layer on the membrane surface and the extent of fouling penetration into the membrane was visualized and quantified by Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) (Philips XL-30 FEG-SEM and the Tescan GAIA-3 GMH FIB-SEM) at the Materials Research Institute in the University of California, Irvine (UC Irvine). To allow imaging of the hollow fiber's cross-section, membrane samples were fractured after being flash frozen using liquid nitrogen. All samples were sputter coated with gold of Pd/Pt (4 nm) before analysis.

CHAPTER 4: Orange County Water District Demonstration

This chapter describes the pilot testing of the colloidal particle monitoring system performance at OCWD's pilot testing facilities.

4.1 Testing Program

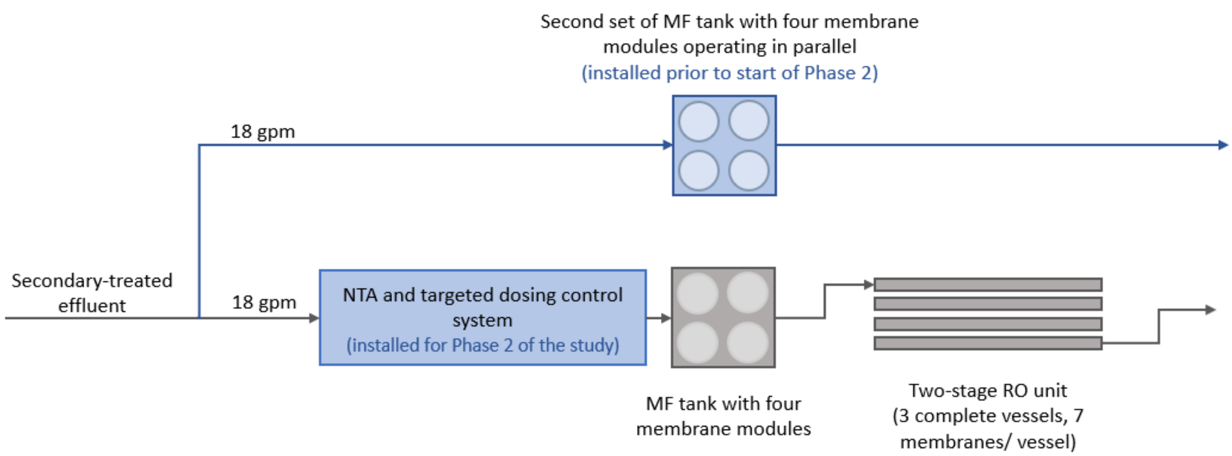
The Orange County Water District demonstration consisted of two phases:

- Phase 1: Establishing baseline performance (3 cycles of testing)
- Phase 2: Testing targeted coagulant dosage (3 cycles of testing) – using side-by-side testing of two pilot units, with and without the proposed system

The pilot skid used to conduct the study at OCWD initially consisted of a set of four-module MF membranes, and a two-stage RO unit. During Phase 1, the 18-gpm MF pilot unit was operated without coagulant addition to establish the baseline MF system performance. The pilot tests were conducted for three operational cycles with a clean-in-place (CIP) performed at the end of each cycle. An operational cycle was considered complete when the MF transmembrane pressure was between 9 and 12.5 psi. Additionally, Phase 1 tests were used to understand the diurnal patterns of colloidal particle concentration in the incoming feed water, which was later used to define the operating range for the optimal coagulant dosing curve.

After Phase 1, the OCWD facility expanded their pilot skid to include another MF unit operated in parallel to the existing MF unit. Although baseline values had been established from Phase 1, this parallel system helped to reduce experimental variation by allowing two test conditions to run simultaneously, receiving the same feed water. In Phase 2, two 18-gpm MF pilot units were operated in parallel – one operated with targeted coagulant dosing and one operated without treatment (control). Figure 10 depicts the Phase 2 set-up.

Figure 10: Pilot Skid Setup During Phase 2 at Orange County Water District, after Installation of Parallel Microfiltration Unit



Phase 1 setup is depicted in grey. Phase 2 additions are depicted in blue.

Source: Kennedy/Jenks Consultants

The membrane performance results from Phase 2, instead of Phase 1, were used to evaluate the effectiveness of each treatment compared to baseline operation because uncertainty related to changing feed water quality was reduced by using the parallel systems. Phase 1 results were used for the preliminary dosing study and to characterize the feed water quality (see Appendix A more detail).

4.2 Results

The OCWD demonstration results are summarized and discussed in this section. Results outline the feed water quality, how the optimal coagulation dosing curve was developed, and how MF membrane performance was impacted by targeted coagulant dosing.

4.2.1 Feed Water Quality

The MF feed water was sampled weekly and measured for general water quality parameters over the full testing period. The results from the feed water quality analyses are provided in Table 3.

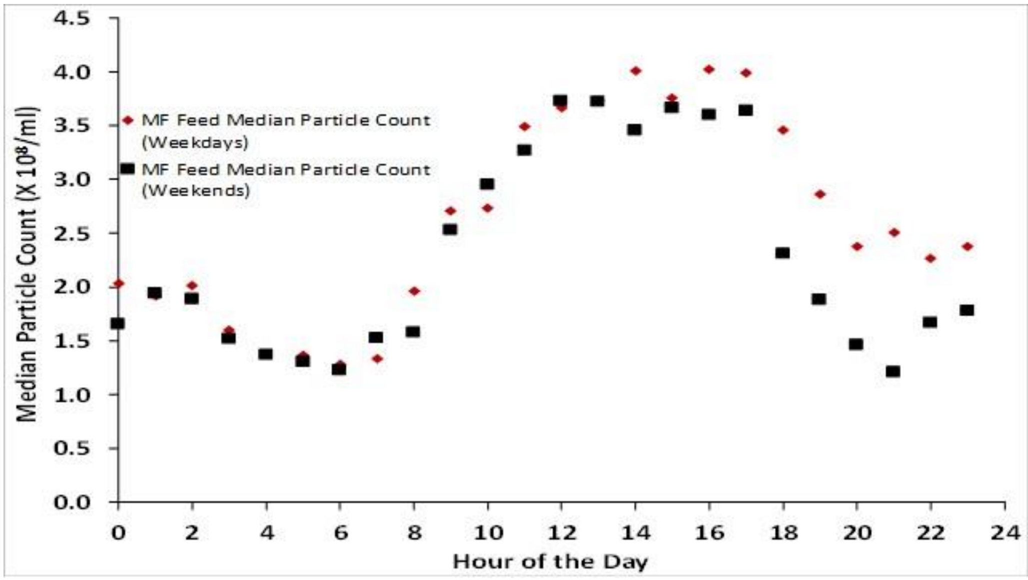
Table 3: Range of Orange County Water District Microfiltration Feed Water Quality Measured during Phase 1 and Phase 2 Pilot Tests

Feed water quality parameters	Measured Range
Total Hardness (mg $CaCO_3$/L)	250 - 320
pH	6.90 - 7.95
TDS (mg/L)	780 - 1000
Temperature (°C)	20 – 30
COD (mg/L)	30 – 55
Turbidity (NTU)	0.7 – 6.2
UVA	0.32 – 0.35

Source: Kennedy/Jenks Consultants

The feed water quality measured during pilot testing is typical of OCSD’s secondary effluent quality (Orange County Sanitation District - Resource Protection Division, 2017). The quality and consistency of the feed water is particularly important for coagulation chemistry because changes in pH and solids content can impact floc formation and stability (Borchate, Kulkarni, Kore, & Kore, 2014), and performance of downstream filtration processes. In addition to the general feed water quality measurements provided in Table 3, the feed water particle count was continuously measured and recorded using the NTA counting system. Feed water particle counts measured over a 24-hour weekday and weekend period are illustrated in Figure 11.

Figure 11: Weekday and Weekend Hourly Median Particle Count of Orange County Water District Microfiltration Feed Water Measured during Phase 1



Source: Kennedy/Jenks Consultants

The feed water particle concentration shown in Figure 11 followed a cyclical pattern – reaching a peak value near 4 PM and a minimum value near 6 AM. The cyclical pattern is offset but very similar to the cyclical diurnal flow pattern observed at most WWTPs, where the flow peaks between 9 AM and 10 AM and is lowest between 3 AM and 4 AM. The reason the peak particle concentration is offset from the diurnal flow pattern is likely due to the time it takes for the wastewater flow to move through the OCSD WWTP's multiple unit processes. It is very possible that higher flow rates through the WWTP's primary and secondary clarifiers result in higher effluent particle concentrations. Although there is variation in particle count over the day, the minimum and peak particle counts appear to be consistent in magnitude and timing. This is an important result because the range of necessary coagulant dosing based on particle concentration can be more reliably determined and a dosing strategy implemented.

4.2.2 Development and Validation of Optimal Coagulant Dosing

As previously explained in Section 3.3, bench-scale jar and membrane fouling tests were conducted to determine the relationship between changing feed water quality and the optimal coagulant dose necessary for reducing MF membrane fouling. This relationship was validated at pilot-scale using the pilot dosing and in-line mixing systems to determine if any modifications to the equation were needed.

4.2.2.1 Bench-Scale Jar Testing

The jar tests were conducted using OCWD MF feed water at low (1.4 x 10^8 particles/mL), medium (3.0 x 10^8 particles/mL), and high (6.0 x 10^8 particles/mL) nanoparticle concentrations. These nanoparticle concentrations were used because they covered the range of feed water concentrations observed during the Phase 1 tests (see 24-hour diurnal pattern of concentration in Figure 11). In these tests, 1-L aliquots of feed water were added with various doses of coagulant, rapidly mixed at 120 rpm for 1 minute and then slowly mixed at 30 rpm for 10 minutes (refer to section 3.3.1). To conduct the jar test, the range of nanoparticle concentrations was simulated by first counting the particle concentration of the collected feed using the NS500. This concentration was then adjusted by adding either MF filtrate (for dilution of colloidal concentration) or backwash (for increasing colloidal concentration). A range of PACl doses (5 mg/L to 20 mg/L) was used for each water quality. After performing the jar tests, the supernatants were collected from each sample and filtered through a 0.2 μm filter before the single-fiber membrane fouling test was performed.

4.2.2.2 Bench-Scale Single-Fiber Membrane Fouling Tests and Developing Optimal Coagulant Dosing Curve

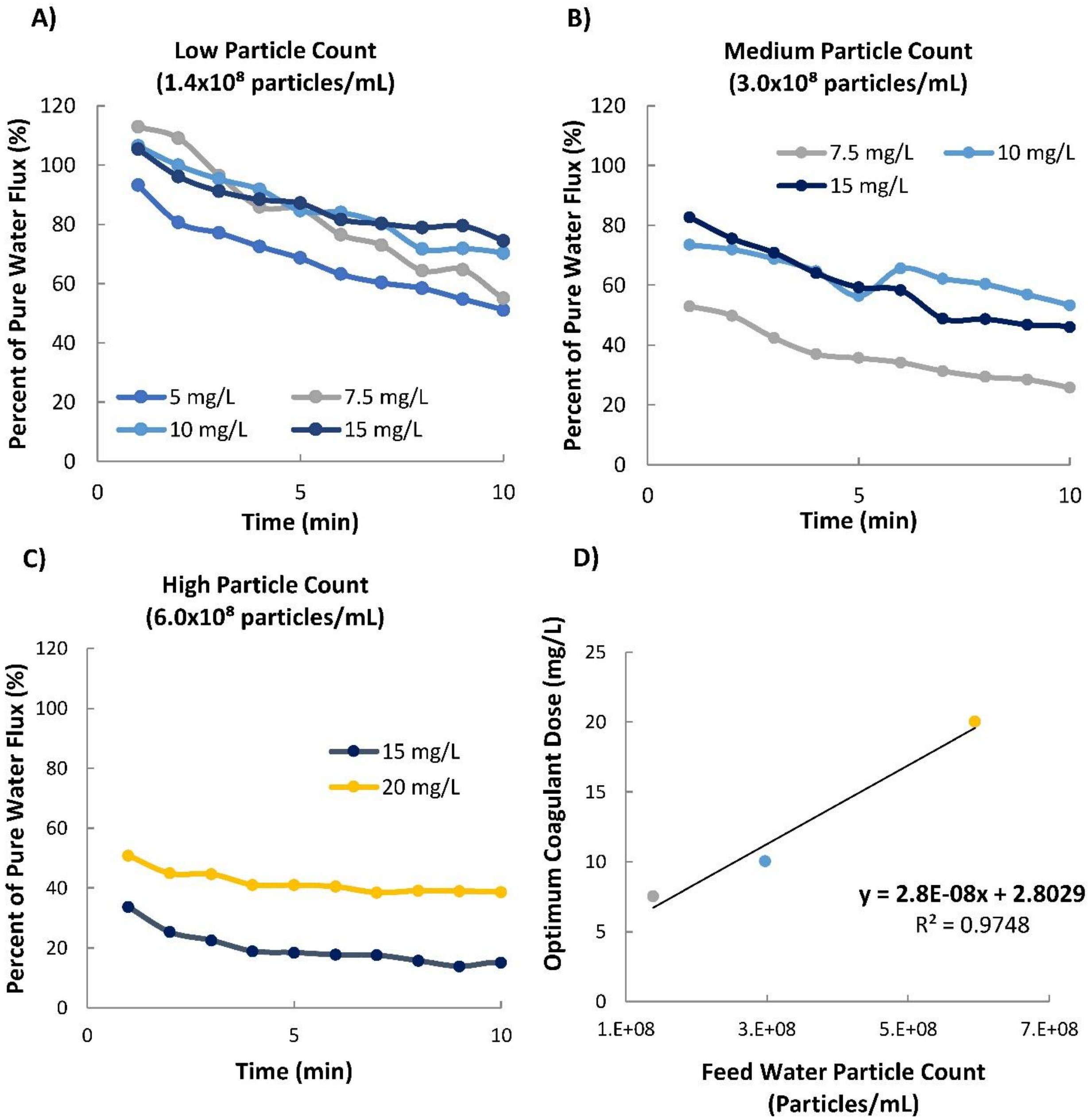
The optimum coagulant dose was determined for each water quality (low, medium, or high particle concentration) based on the percentage of pure water flux maintained after 5 minutes of testing. Under constant pressure, the filtrate flux decreased as membrane pores became blocked by retained particles and the resistance to filtration increased. This reduction in permeability and decrease in flux rate over time was used as an indicator for the extent of membrane fouling. Results from the single-fiber MF fouling tests as well as the developed optimal coagulant dosing curve are presented in Figure 12.

Because the bench-scale tests were operated in a batch mode, the particle concentration and fouling potential of the water increased over time as particles were retained by and water was filtered through test fibers. Therefore, the flux decline observed earlier in the test (after 5 minutes) was more representative of the fouling in the flow-through pilot system than the flux decline observed at the end of test, after 10 minutes.

Tests conducted with a feed water containing a low particle count (Figure 12A) and coagulant doses of 7.5, 10, and 15 mg/L had a similar flux after 5 minutes of testing. Towards the end of the experiment, tests performed with 10 and 15 mg/L doses exhibited less flux decline. As discussed above, the optimal coagulant dose was selected based on the water flux results after 5 minutes of testing. Based on this consideration, 7.5 mg/L was selected as the optimal coagulation dose for the low particle count feed water because it conserves coagulant usage and achieves comparable results.

Tests conducted with a feed water containing a medium particle concentration (Figure 12B) performed poorly with 7.5 mg/L of coagulant and achieved only 35 percent of the initial flux after 5 minutes, while the flux was maintained at 56 percent and 59 percent of the initial flux at coagulant doses of 10 and 15 mg/L , respectively. A dose of 10 mg/L was selected as the optimal dose, as flux was not significantly improved at a dose of 15 mg/L. For feed water with higher concentrations of particles (Figure 12C), larger doses of coagulants were tested due to the higher fouling potential of the concentrated feed. A dose of 20 mg/L was able to achieve a significantly better performance (41 percent of initial flux after 5 minutes) and was selected as the optimal coagulant dose.

Figure 12: Microfiltration Water Flux Measured during Bench-Scale Single-Fiber Fouling Tests



Tests performed at various coagulant dosing for feed water containing (a) low, (b) medium, and (c) high particle counts. The optimal coagulant dose as a function of feed water particle count (d) was developed from these tests. Water flux is shown as the percentage of the flux measured during pure water flux experiments.

Source: Kennedy/Jenks Consultants

Table 4 summarizes the optimal doses selected for varying colloidal particle loads.

Table 4: Optimal Coagulant Dose with PACl for Various Colloidal Particle Loadings in MF Source Water

Colloidal Particle Loading in Feed Water	Total Particle Concentration ($x10^8$/mL)	Optimal PACl Dose (mg/L)
Low	1.39	7.5
Medium	2.98	10
High	5.95	20

Source: Kennedy/Jenks Consultants

The optimum coagulant dose determined from the membrane fouling tests was plotted for feed water with different particle concentrations. Figure 12D shows the coagulant dosing curve developed in this way, expressed by the following relationship:

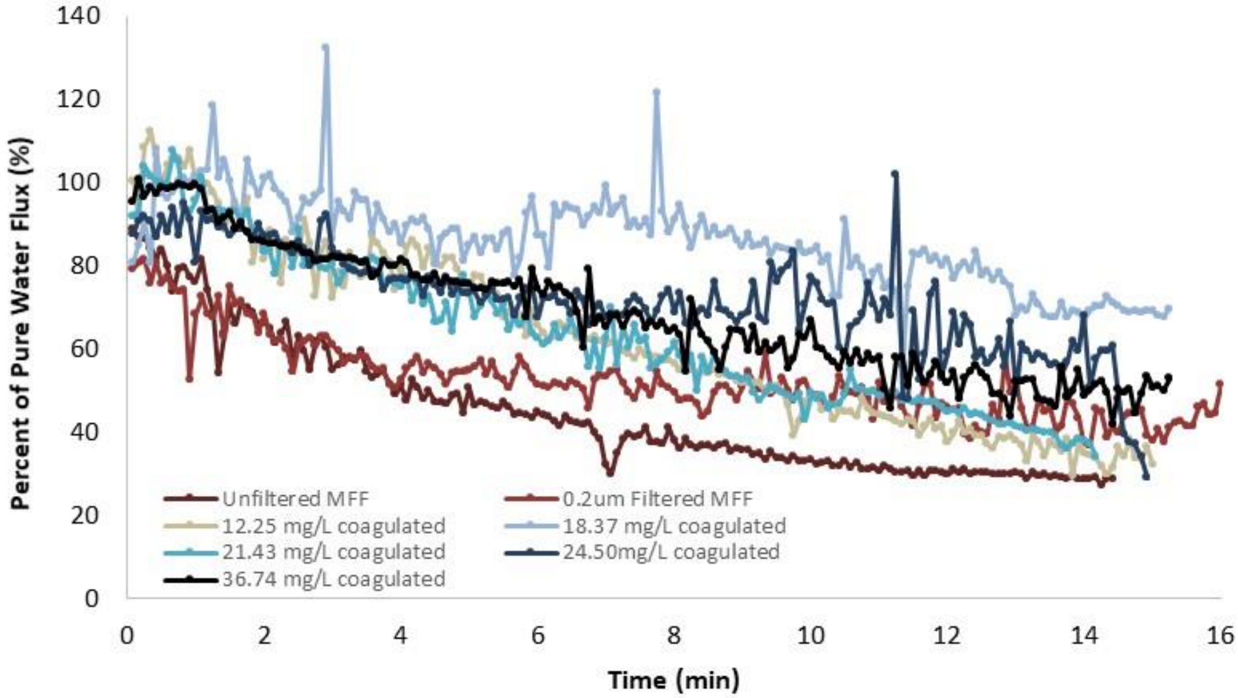
$$Optimal\ PACl\ Coagulant\ Dose\ \left(\frac{mg}{L}\right) = 2.8 \times 10^{-8}\left(\frac{Particles\ in\ Feed\ Water}{mL}\right) + 2.8029$$

It is illustrated from the dosing curve that there is a positive linear relationship between the optimum coagulant dose and the feed water particle concentration over the range of particle concentrations tested at OCWD.

4.2.2.3 Validating Optimal Coagulant Dosing Curve at Pilot-scale: Single-Fiber Membrane Fouling Test

The bench-scale dosing curve was developed with the intention of controlling the coagulant dosing in the pilot system based on the feed water particle concentration. The supposition was that if the in-line mixing provided by the pilot-scale testing system was as effective as that provided by the jar test unit, then the coagulant dose that yields the optimum flux in the single fiber element setup would be similar for both the pilot system and jar tests. This hypothesis was tested by conducting single-fiber bench-scale fouling tests on feed waters that were dosed over a range of coagulant concentrations using the MF pilot coagulant dosing and mixing system. Samples were collected upstream of the MF modules after they had been completely mixed and coagulated through the pilot skid's in-line mixing and hosing tube. Samples were filtered through a 0.2 μm filter before the single fiber bench-scale fouling tests were performed. The results from these tests are presented in Figure 13.

Figure 13: Measurement of Fiber Fouling due to Varying Coagulant Dosage, as a Percentage of Initial Flux

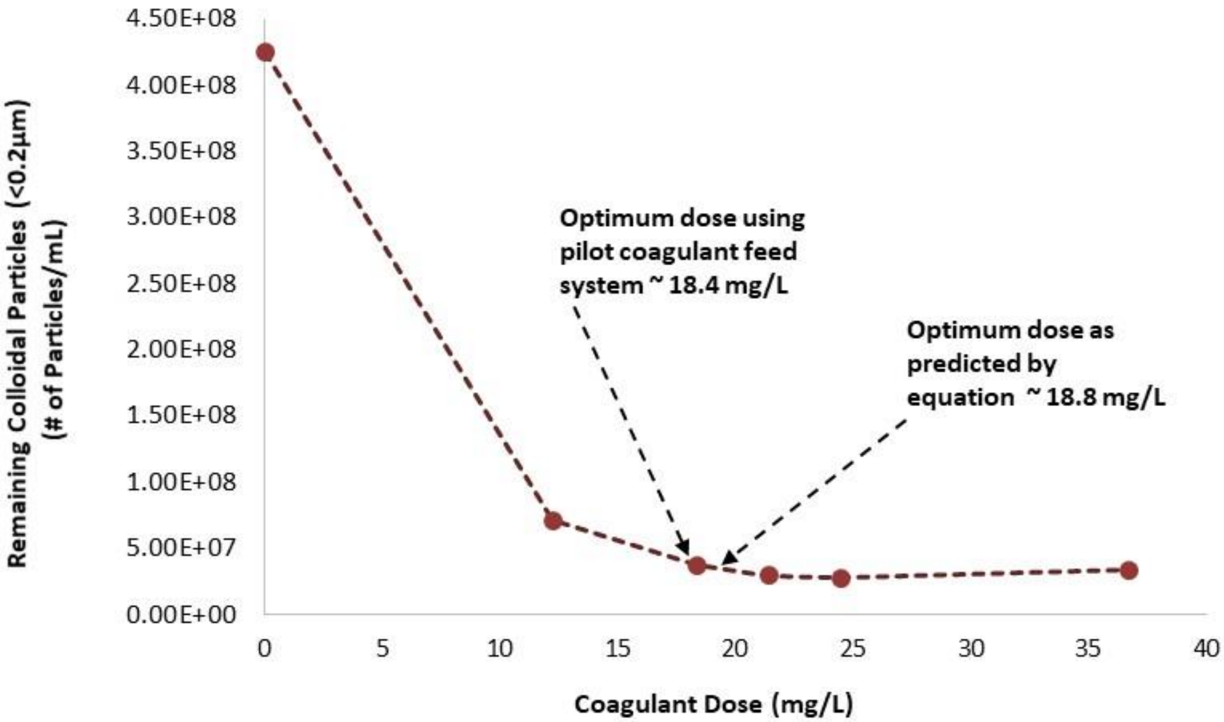


Source: Kennedy/Jenks Consultants

Figure 13 shows the declining flux for unfiltered MF feed water, 0.2 μm filtered MF feed water, and coagulated MF feed water (12.25 – 36.7 mg/L of PACl). Results indicate that feed water that was not pretreated with coagulation exhibited the steepest initial decline in water flux. This flux decline is an indication of the inherent fouling potential of the untreated MF feed water. The similarity between the unfiltered and 0.2 μm filtered feed illustrates that the remaining small colloidal particles (those smaller enough to pass through the 0.2 μm filter) are responsible for a substantial portion of the observed fouling. In general, higher water flux was measured for samples that were pretreated with coagulation. The highest water flux was maintained at a dosing rate of 18.4 mg/L, and thus was identified as the optimal coagulant dose under these experimental conditions. This dosing rate is close to the dosing rate predicted (18.8 mg/L) by the relationship developed in Figure 12D for a feed water with a particle concentration of 5.7 x 10^8 particle/mL. The similarity between the pilot-scale result and the predicted value suggests that the correlation developed from the jar tests is applicable to the in-line mixing system of the pilot skid.

Smaller colloidal particles can pose a risk to low-pressure membrane filtration by either increasing the extent of hydraulically irreversible membrane fouling or passing through LPMF to reduce filtrate quality and put downstream treatment systems like RO at risk. Therefore, another way to determine optimal coagulation dose is to evaluate which dosing regimen can optimize the removal of small colloidal particles (< 0.2 μm). The number of colloidal particles that remained after coagulation with varying doses on the pilot system and filtration with the 0.2 μm filter was measured. These results are depicted in Figure 14.

Figure 14: Remaining Colloidal Particles Following Coagulation



Source: Kennedy/Jenks Consultants

The experiment conducted without coagulation (0 mg/L dose) had the highest number of colloidal particles remaining after 0.2 μm filtration. With the addition of 10 mg/L and 18.5 mg/L of coagulant, the small colloidal particle count was reduced from 4.25 x 10^8 to 7.1 x 10^7 and 3.7 x 10^7 particles/mL, respectively. At higher coagulant doses, the reduction of colloidal particle count by increasing coagulant doses was less discernible. This indicated that an effective coagulant dose, without overdosing, was approximately 18.4 mg/L. This result supports the previous optimal dose findings obtained through the bench-scale fouling tests and is similar to the optimal dose predicted by the dosing curve developed in Figure 12. This shows that the mixing system used in the pilot system can produce a mixing efficiency similar to that obtained in the bench-scale tests. Thus, it was determined that the relationship derived from Figure 12 was applicable for use on the pilot control system.

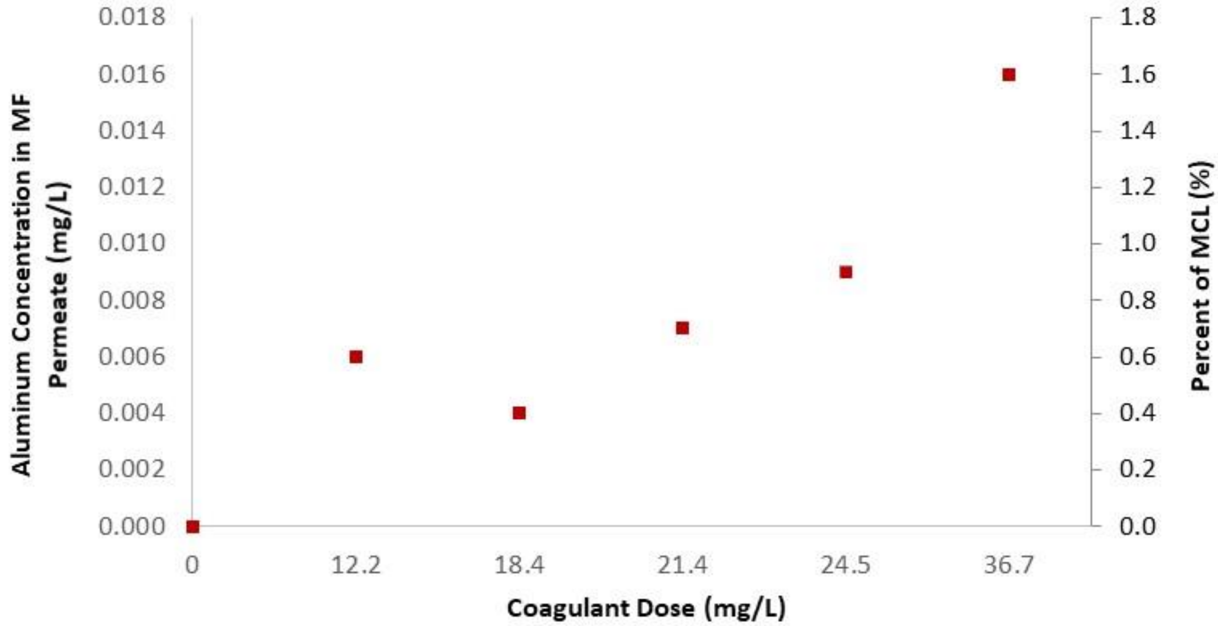
4.2.3 Evaluating Coagulant Breakthrough

As soluble aluminum reacts with silica and anti-scalant compounds, it can form colloidal foulants that have a costly and detrimental impact on RO membranes. It is important to ensure that the pretreatment with an aluminum-based coagulant will not interfere with the downstream RO treatment process.

4.2.3.1 Presence of Aluminum due to Coagulant Dosing

To understand whether aluminum can penetrate the MF membrane, filtrate from the single-fiber flux tests was examined with increasing doses of PACl. Results from these experiments are summarized in Figure 15.

Figure 15: Aluminum Concentration in Filtrates from the Single-Fiber Flux Tests



Source: Kennedy/Jenks Consultants

Figure 15 shows that less than 0.2 percent of the of the added aluminum, over the range tested, breaks through the MF membrane. This means that at the highest coagulant dosing on the pilot (15 mg/L), or beyond (36.7 mg/L), the aluminum concentration in the MF filtrate would be less than 2 percent of the enforced MCL standard (limited to 1 mg/L of aluminum in drinking water). Therefore, pretreatment with PACl in its applicable range of dosing will not significantly increase aluminum levels in the filtrate. Aluminum breakthrough on the MF filtration unit was further investigated during Phase 2 pilot testing.

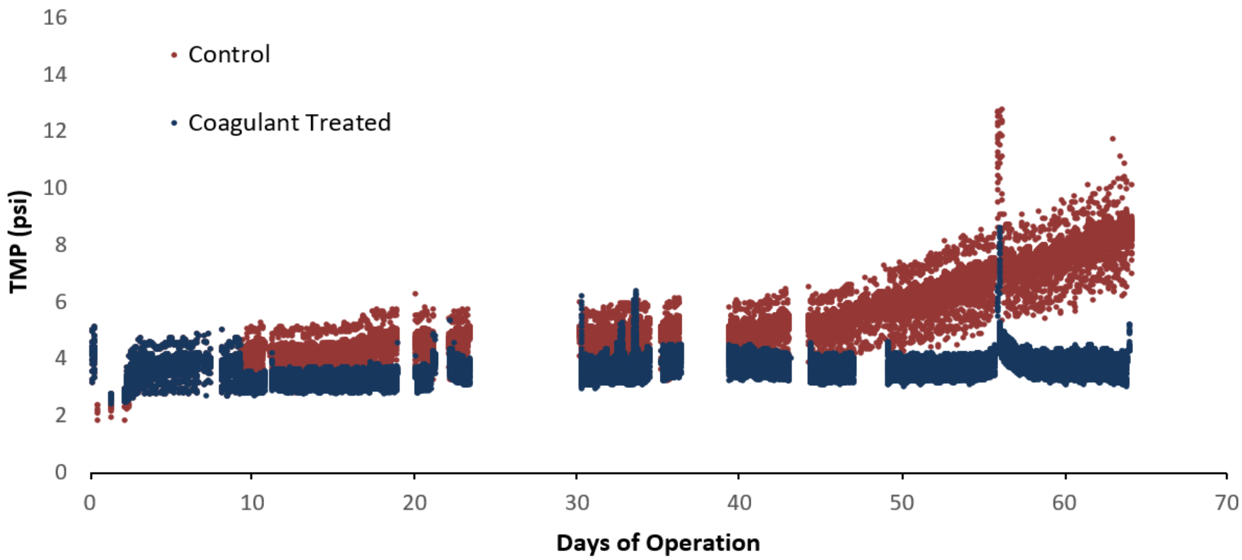
4.2.4 Microfiltration Pilot Testing

During Phase 1 of the study, three long-term pilot tests were conducted to establish the baseline response of the MF pilot unit to secondary-treated effluent feed water from OCSD. The results from these tests are provided in Appendix A. After the installation of a second set of MF units in Phase 2, MF pilot performance was evaluated by testing coagulated and untreated feed water in parallel. The results from these tests are presented in the following sections.

4.2.4.1 TMP Performance

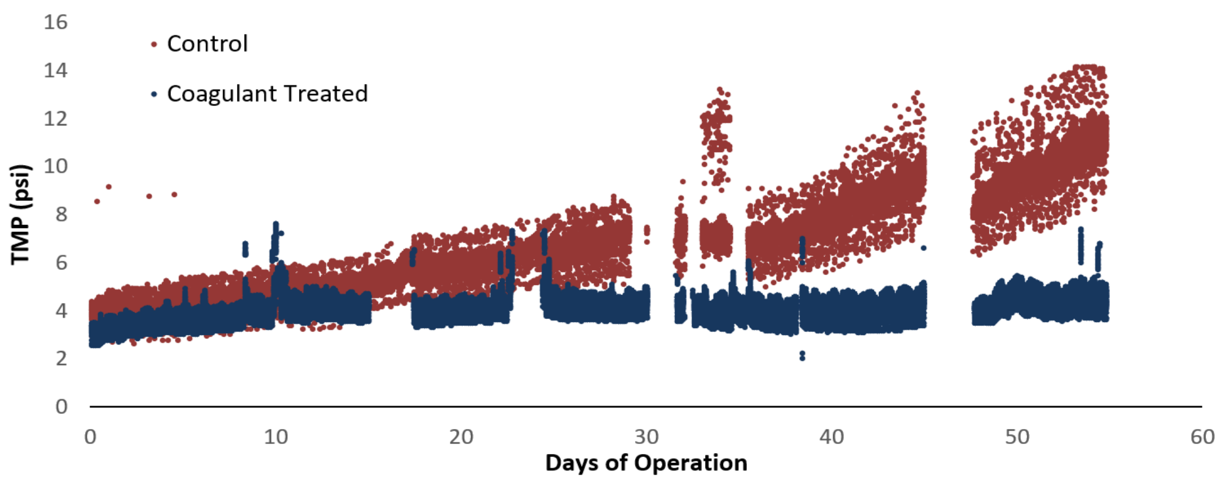
The MF pilot systems were operated in dead-end filtration at a constant flux of 18 gpm. This side-by-side pilot comparison was performed three times, however, the TMP data for the untreated MF unit was lost during the data recovery process for the initial test (refer to Appendix B for recorded results). TMP recordings for the remaining tests are shown in Figure 16 and Figure 17.

Figure 16: Transmembrane Pressure Performance of Control and Coagulant Treated Microfiltration Pilot (Phase 2, Test 2 - Dec. 2017 To Feb. 2018)



Source: Kennedy/Jenks Consultants

Figure 17: Transmembrane Pressure Performance of Control and Coagulant Treated Microfiltration Pilot (Phase 2, Test 3 - Feb. 2018 To Apr. 2018)

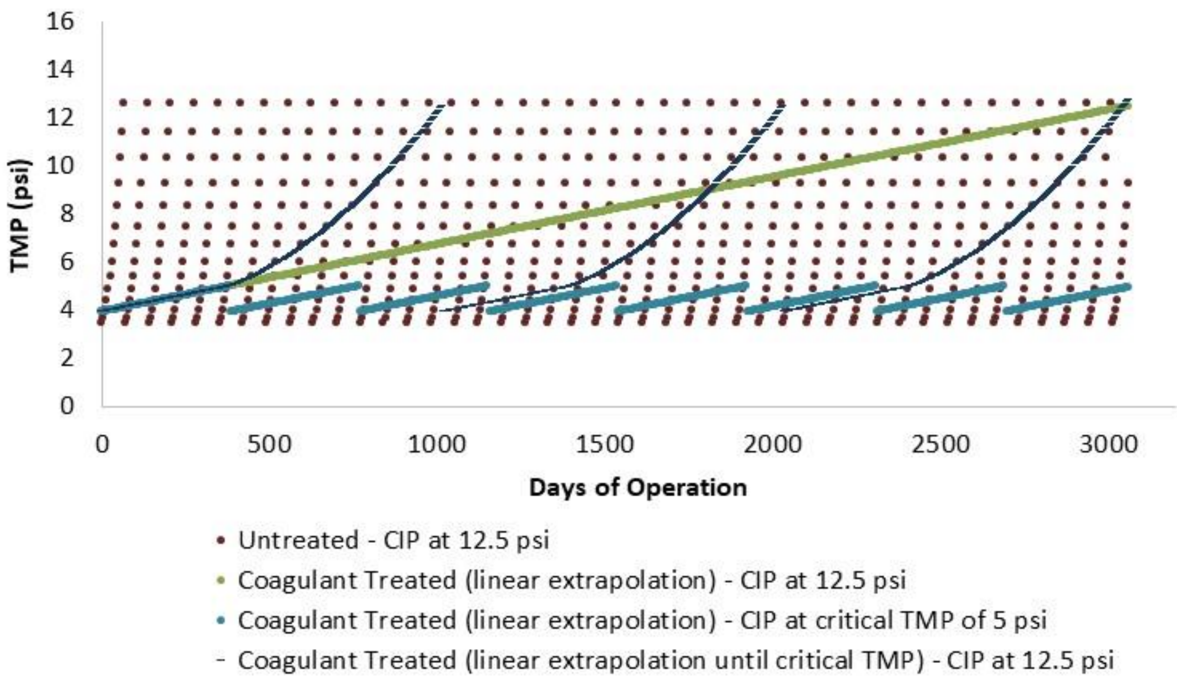


Source: Kennedy/Jenks Consultants

The initial TMP of the two pilot systems was approximately 2.8 psi. Comparison of the MF pilot performance between coagulant treated feed water and control (no coagulant) during the second test shows that the coagulant treated pilot TMP remained below 4 psi for 65 days (Figure 16). However, in the parallel control pilot that received the same feed water but without coagulant, the TMP increased continuously and reached a maximum of 10 psi. The same improvement in TMP with coagulant addition was observed in the third test (Figure 17). The TMP of the coagulant treated MF pilot remained below 5 psi; whereas, the control MF pilot reached a terminal TPM of 12.5 psi after 55 days. These results are consistent with Phase 1 findings in Appendix A.

Based on these results, the untreated MF units would be expected to have a TMP increase of approximately 6 psi after 50 days, while coagulant treated MF units would experience only an increase of approximately 1 psi over the same duration. This reduction in rate of TMP increase would allow the MF units to be operated for a longer duration before needing a CIP. The possibility for controlled coagulant dosing to extend the duration between CIPs is illustrated in Figure 18.

Figure 18: Projected Transmembrane Pressure Profiles and Clean In Place Requirements for Prolonged Microfiltration Operation Using Targeted Coagulation for Colloid Removal



Source: Kennedy/Jenks Consultants

Although over the study period the treated MF unit exhibited a linear increase in TMP, it is likely that a critical TMP would eventually be reached and the TMP would begin to increase exponentially. A conservative estimate for the critical TMP would be 5 psi based on the observed TMP profile of the untreated MF. Assuming a critical TMP was reached at 5 psi, it was projected that it would take approximately 3 years for the TMP to reach 12.5 psi. Conducting CIPs every 3 years is likely unrealistic but conducting a CIP every 6 to 12 months is not unreasonable and would result in substantially less CIPs being performed compared to treating uncoagulated feed water.

In addition to a significant reduction in TMP, the coagulant treatment resulted in a MF membrane that was visually cleaner than the control (Figure 19, see Appendix C for more images). This illustrates how targeted coagulation can reduce membrane fouling, increase the time between CIPs, and potentially provide for energy and cost savings and prolonged membrane life.

Figure 19: Discoloration due to Additional Fouling of the Untreated Microfiltration Membrane

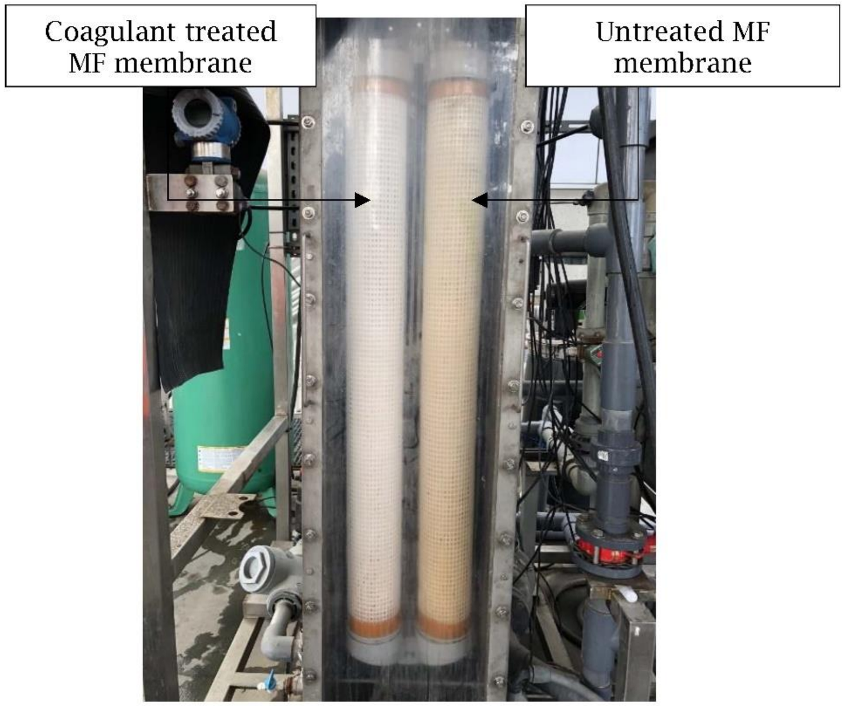


Photo taken after reaching terminal TMP.

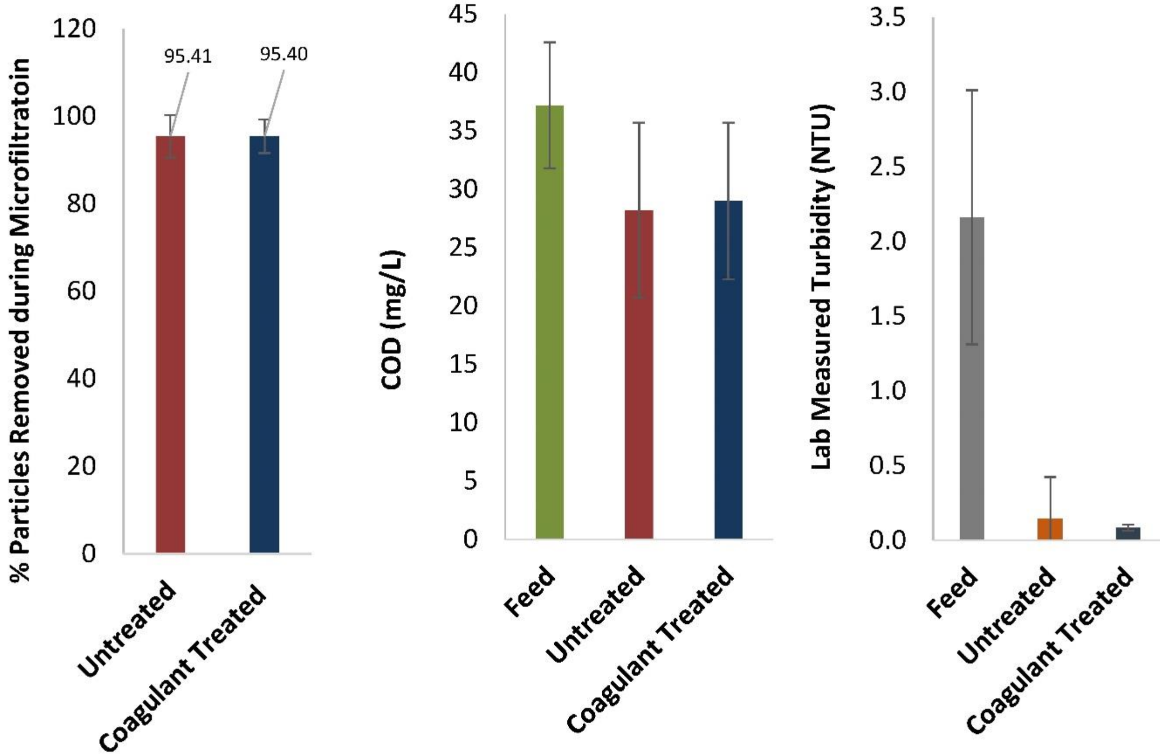
Source: Kennedy/Jenks Consultants

4.2.4.2 Untreated and Coagulant Treated MF Particle Count, COD, and Turbidity

Particle count, COD, and turbidity measurements of the MF feed water and filtrate were completed to compare the MF filtrate quality between tests conducted with untreated and coagulant treated feed water. Results from these analyses are shown in Figure 20.

Figure 20 shows that the percentage of colloidal particles removed, and the COD and turbidity content of the MF filtrate were not significantly affected by coagulant addition. This is an interesting result considering the substantial improvement in TMP and reduction in membrane fouling observed during long-term testing (Figure 16 and Figure 17). Both MF membrane modules received the same number of particles, COD, and turbidity load and exhibited the same pollutant removal, yet there was a much greater build-up of foulants on the untreated MF membrane. This suggests that, although particle and pollutant removal does not change, coagulated particles interact differently with the MF membrane compared to uncoagulated particles. In the untreated case, the removed particles contribute to the membrane fouling; while in the coagulant-treated case, coagulated colloidal particles are more easily removed during the backwash/air scour procedure.

Figure 20: Percent Particle Removal, Chemical Oxygen Demand and Turbidity Before and After Microfiltration



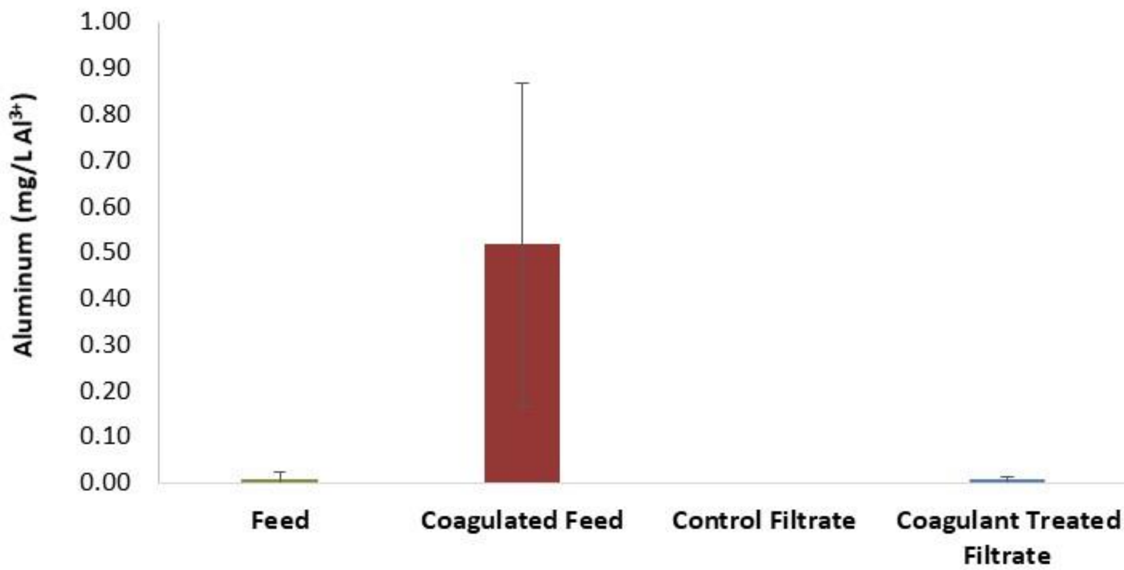
Source: Kennedy/Jenks Consultants

4.2.4.3 Aluminum and Other Water Quality Parameters

The addition of an aluminum-based coagulant may pose a risk of aluminum leakage through the MF membrane that could negatively impact the downstream RO process. Aluminum leakage through the MF membrane was evaluated by collecting grab samples from the untreated feed water, coagulant treated feed water, control filtrate, and coagulant treated filtrate and measuring the samples for aluminum. The results of these analyses are presented in Figure 21.

Results from the aluminum sampling analysis demonstrated that although the addition of the polyaluminum coagulant increased the aluminum concentration in the feed water to 0.52 mg/L, it did not affect the filtrate quality. The control and coagulant treated filtrates show similar aluminum levels, indicating that excess aluminum is primarily retained by the MF membrane and less likely to break through.

Figure 21: Measured Aluminum Levels of Grab Samples from the Pilot Skid



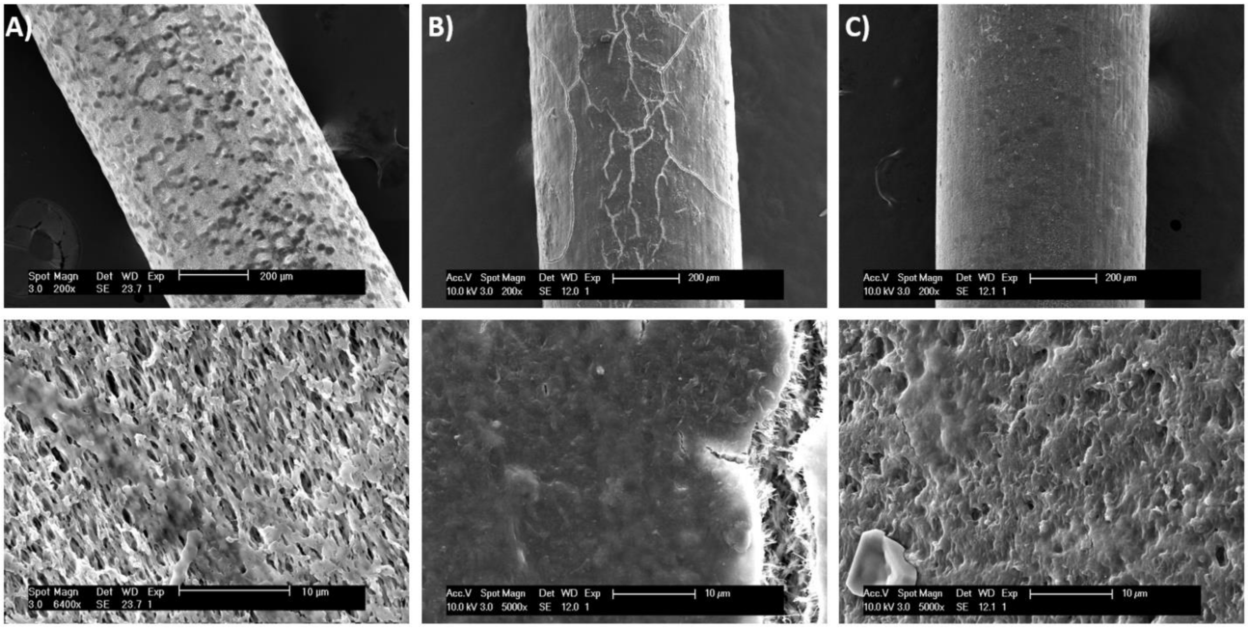
Source: Kennedy/Jenks Consultants

4.2.4.4 Microfiltration Membrane Autopsy

Following the completion of Phase 2 pilot tests, fiber samples were collected from the MF unit receiving untreated feed water and the MF unit receiving targeted coagulant pretreatment. SEM images of the membrane samples (top, middle, and bottom of the fiber) are presented in Figure 22 and Figure 23. The inorganic fraction of foulant on the membrane was also analyzed by performing EDS.

Comparing the virgin fiber (Figure 22A) to the control (Figure 22B) and coagulant treated fiber (Figure 22C), it appears that both the control and coagulant treated membranes had accumulated fouling on their surfaces. However, the control membrane had a heavier fouling layer. Additionally, the pores of the coagulant treated membrane surface can still be observed, whereas the surface of the control membrane is entirely covered, and the pores are not visible. This indicates that cake fouling was more prevalent in the untreated condition.

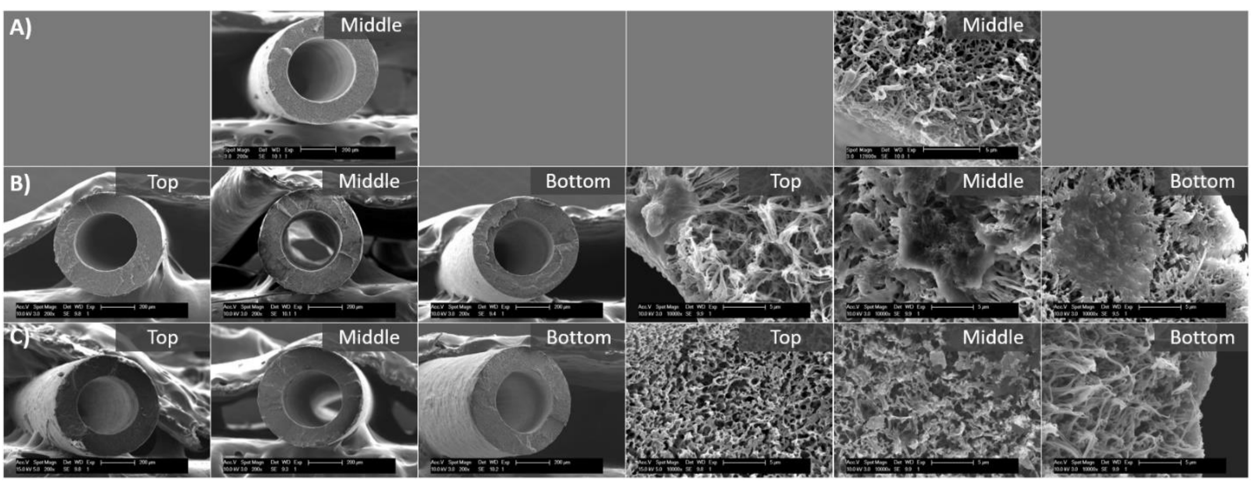
Figure 22: Scanning Electron Microscopy Images of PEG Microfiltration Fiber Surfaces



Images taken following completion of pilot studies. The surface of A) the virgin fiber, B) the untreated MF fiber and C) the coagulant treated MF fiber are shown at 200X (top row) and 500X (bottom row) magnification.

Source: Kennedy/Jenks Consultants

Figure 23: Scanning Electron Microscopy Images Taken from Cross-Section of Microfiltration Fibers



Entire MF fiber as well as a higher magnification image are provided for the top, middle, and bottom of the A) virgin fiber, B) control fibers and C) coagulant treated fibers.

Source: Kennedy/Jenks Consultants

Figure 23 shows the cross-sectional images for the virgin, control, and coagulant treated MF fibers. These images show that both control and treated membranes had visible foulant inside the membrane matrix. The control membrane pore fouling (row B) appeared to be more aggregated, forming large solid masses. In contrast, the coagulant treated membrane (row C) had more open voids and smaller aggregates of nanoparticle deposition. An EDS analysis was performed to better understand the nature of the observed depositions, both on the surface of the MF fibers as well as those that had penetrated the membrane matrix. Table 5 lists the identified elements.

Table 5: Elements Identified to be Present on MF Membrane Sample Specimen, using Energy Dispersive Spectroscopy (EDS)

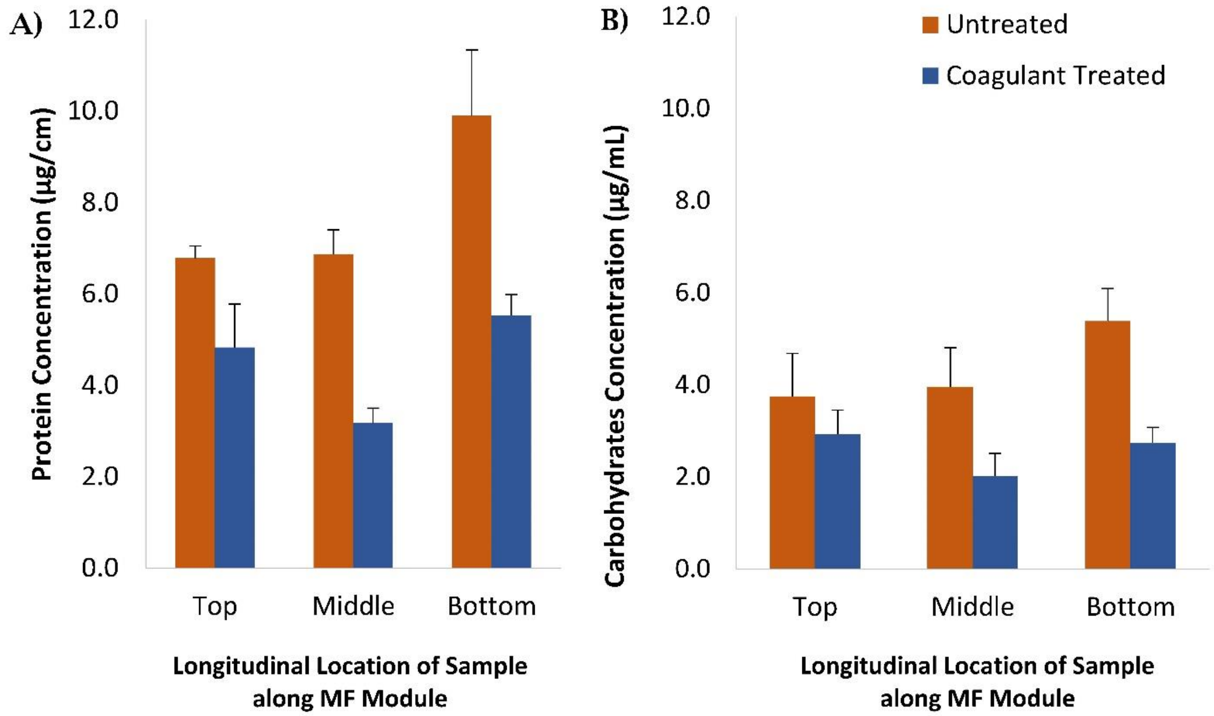
	Surface	Cross-section
Untreated MF Membrane	Na, Mg, Si, S, Cl, Ca, Fe, Zr, P, K, Al	S, Ca, Fe, Zr, Na, Cl, F, Si
Coagulant Treated MF Membrane	F, Na, Mg, Si, S, Cl, Ca, Fe, Zr, Al	S, Ca, Zr

Source: Kennedy/Jenks Consultants

Table 5 shows that both control and coagulant treated membrane surfaces were fouled with similar elements. Aluminum was identified on both membrane surfaces, but not within either membrane matrices. This supports the previous findings that aluminum is less likely to break through the MF membrane at the concentrations used in the coagulant pretreatment system. However, looking at the list of elements identified on the cross-sectional samples, fewer elements were identified inside the coagulant treated membrane matrices. The control membrane elemental composition was more diverse. Therefore, targeted coagulant pretreatment appeared to keep foulant elements from entering and depositing inside the membrane matrix. The protein and carbohydrate content of the MF membranes was also quantified to further characterize the type of fouling taking place. The results of this analysis are provided in Figure 24.

Figure 24A shows that the extent of protein deposition was significantly higher when the MF unit received untreated feed water rather than feed water treated with targeted coagulation. The reduction in protein deposition due to coagulation was especially effective for the middle and bottom segments of the MF fibers (53 percent and 44 percent reduction). Figure 24B shows a similar trend for the presence of carbohydrates, where carbohydrate concentration is reduced significantly when the feed is treated with targeted coagulation (50 percent reduction for middle and bottom fiber segments). The water being treated by the MF units possesses high nutrient loading and biological activity, increasing the risk of biofouling and cake formation. This analysis indicates that coagulation pretreatment was able to reduce the extent of biofouling and reduce the deposition of organic matter (that is, microbial cell residue) on the MF membrane. These results can also help to explain the improved performance observed during MF filtration of coagulated feed water.

Figure 24: Protein (A) and Carbohydrate (B) Data for the Untreated and Coagulant Treated Microfiltration Membrane



Samples collected from three locations of the MF membrane fiber: Top (at suction end of the module), Middle (center of module), and Bottom (opposite from suction side).

Source: Kennedy/Jenks Consultants

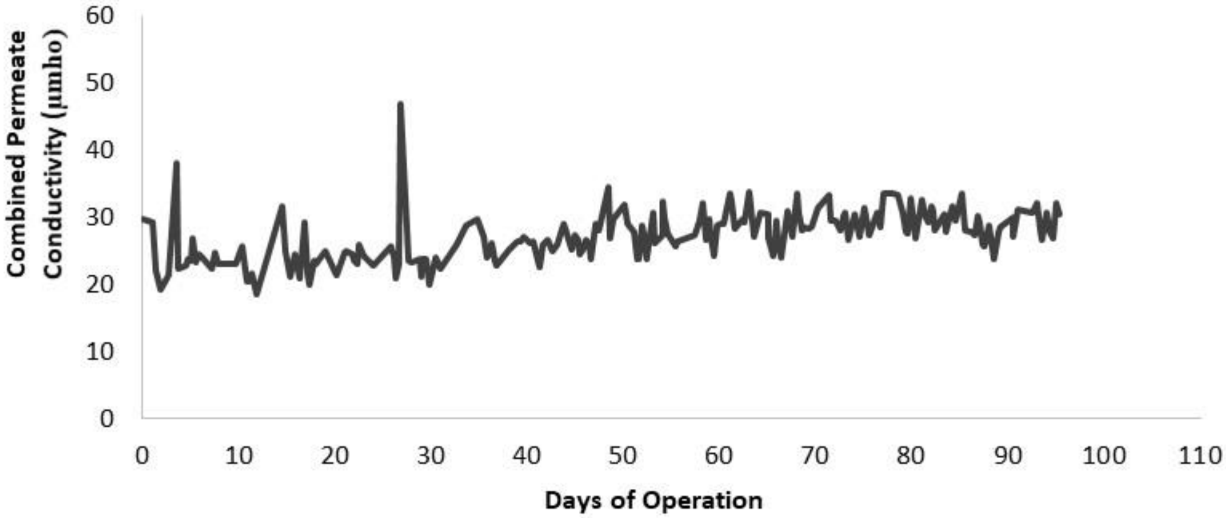
4.2.5 Reverse Osmosis Pilot Testing

A pilot RO system was operated downstream of the MF pilot unit throughout Phase 1 and Phase 2 testing to evaluate the impact of MF pretreatment on RO membrane performance. In addition to monitoring RO pilot performance, additional pilot- and bench-scale tests were performed to study the effect of coagulant overdosing on RO membrane performance.

4.2.5.1 Reverse Osmosis Performance

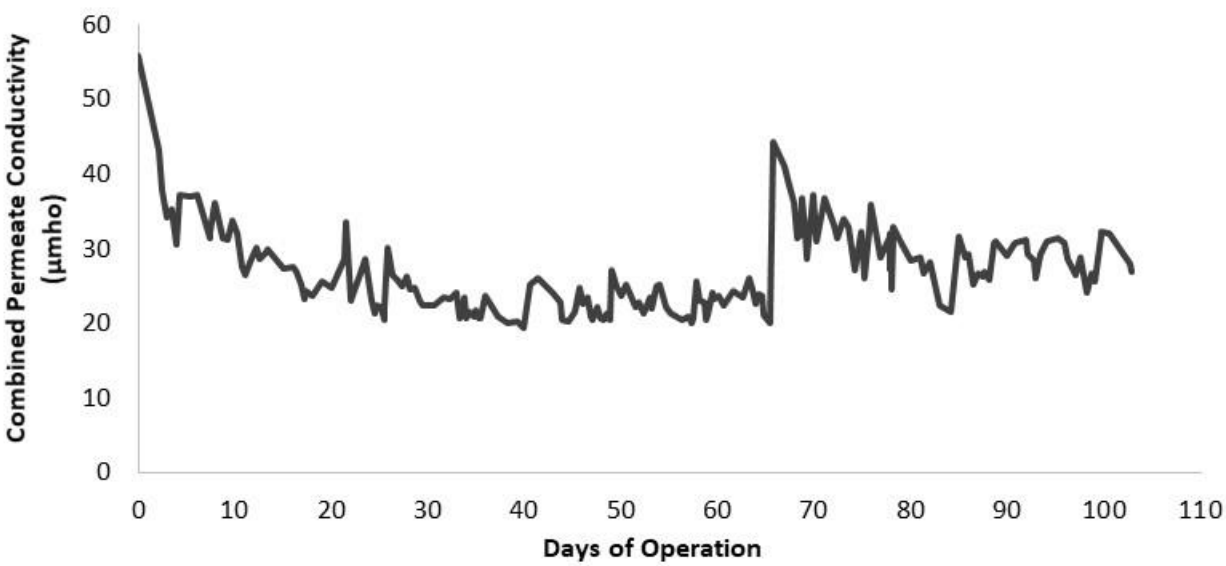
RO combined permeate conductivity and specific flux were continuously measured during pilot testing to monitor RO system performance. Permeate conductivity is a surrogate measurement for dissolved ion concentrations and is used to track the RO permeate water. Specific flux (gfd/psi) is the product water flow rate divided by the hydraulic driving force and is used to describe membrane permeability. Conductivity was measured for each RO vessel permeate and combined based on respective flowrates. Results from Phase 1 and Phase 2 testing is shown in Figure 25 and Figure 26, respectively. RO system specific flux measured during Phase 1 and Phase 2 testing is provided in Figure 27 and Figure 28, respectively.

Figure 25: Combined Conductivity of Reverse Osmosis Permeate During Phase 1 Testing, Receiving Untreated Microfiltration Permeate



Source: Kennedy/Jenks Consultants

Figure 26: Combined Conductivity of Reverse Osmosis Permeate During Phase 2 Testing, Receiving Microfiltration Permeate Pretreated with Targeted Coagulation



Source: Kennedy/Jenks Consultants

The conductivity of the combined RO permeates during Phase 1 testing was relatively steady but did gradually increase over the testing period, from approximately 25 µmho/cm to 31 µmho/cm (Figure 25). It is normal for the permeate conductivity to increase over long RO operating periods due to membrane degradation and fouling. The TFC RO membrane material has good chemical and physical resistance but the membrane can lose integrity from damage occurring during normal operation such as physical abrasions from rough inorganic particles passing across the membrane and chemical oxidation from regular cleaning activities.

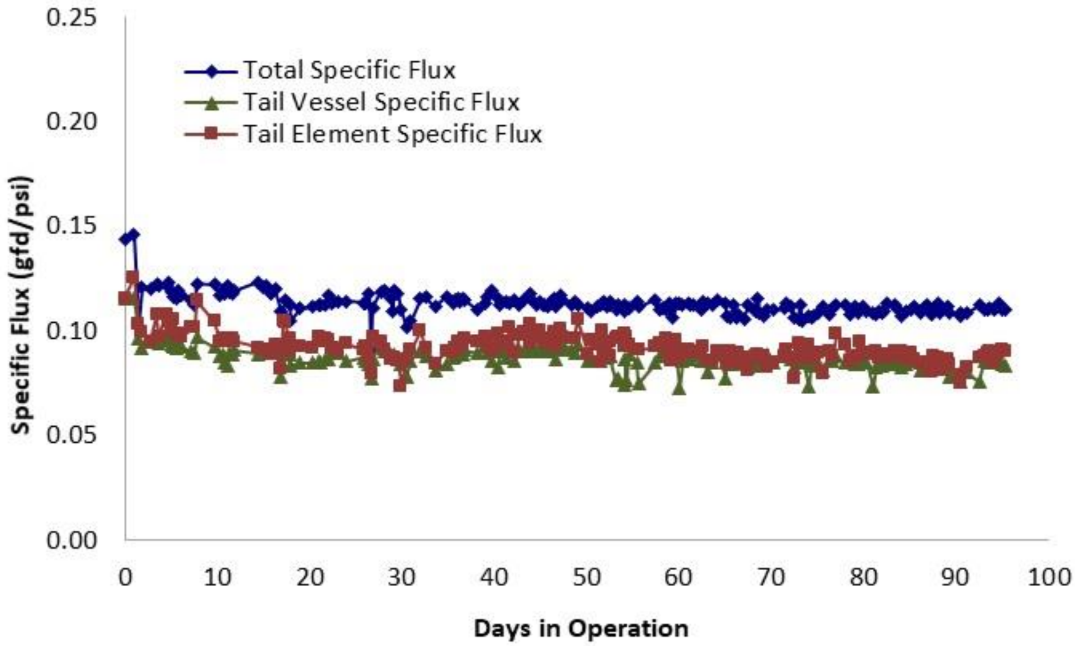
Although the permeate conductivity increased during Phase 1, it is important to note that the RO membrane was still providing > 99.9 percent salt rejection, indicating good performance.

During Phase 2, the combined RO permeate conductivity spiked to 66 µmho/cm at startup and peaked again on day 65 of Phase 2 testing to 44 µmho/cm (Figure 26). These events correlate to CIPs performed on the RO membrane. Caustic and acidic chemical membrane cleaning have previously been reported to result in RO membrane pore expansion and increased solute permeability. Al-Amoudi (2013) reported a nominal pore size increase of more than 12 percent in a nanofiltration membrane soaked in caustic SDS solution for 18 hours. Simon et al. (2012), in a similar study, suggested the strongly acidic and caustic conditions caused internal charge repulsion effects between charged groups in the membrane polymer matrix, leading to expansion of the membrane structure. Figure 26 shows that although CIP resulted in an immediate spike in permeate conductivity, the effect was not permanent. The conductivity decreased after 10 to 20 days of operation, reaching a steady-state conductivity of 20 µmho/cm after the first CIP, and 27 µmho/cm after the second CIP. These conductivity values were lower than the RO permeate conductivity produced during Phase 1. Salt rejection was also maintained above 99.9 percent during Phase 2. Therefore, MF pretreatment with targeted coagulation was able to achieve similar, if not higher, RO permeate quality than the untreated feed.

To evaluate how targeted coagulation affected the RO operating parameters, the specific flux rate of the total RO permeate was monitored. This metric was used to assess the fouling propensity of the system and to identify whether there was any localized fouling in the tail vessel and tail element. The results from this evaluation are shown in Figure 27 and Figure 28.

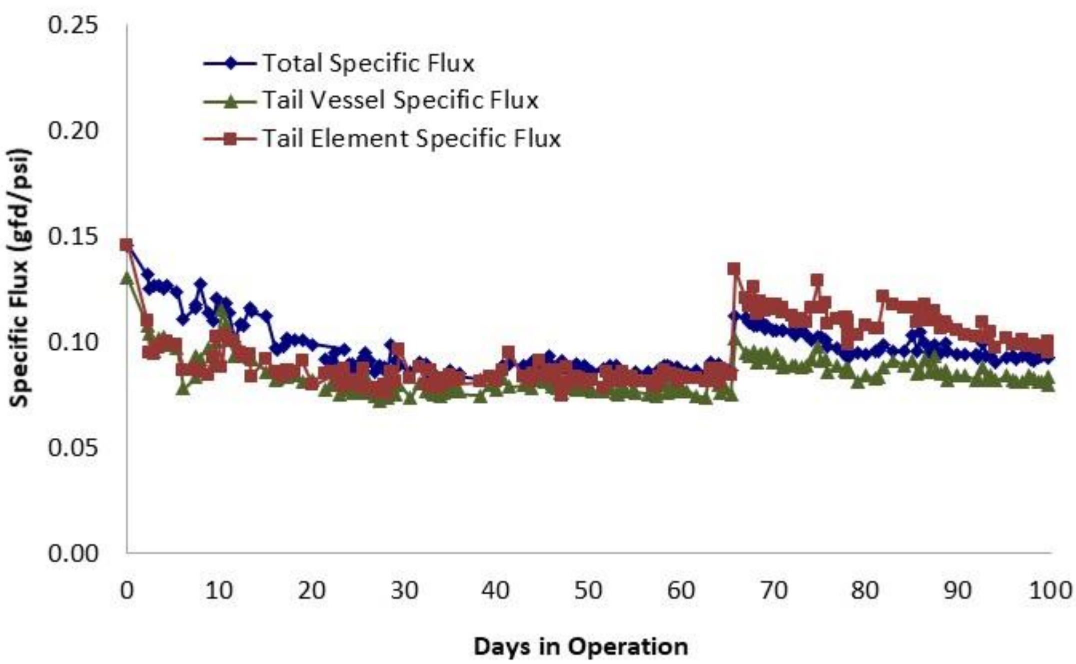
The total specific flux gradually declined from 0.15 gfd/psi to 0.11 gfd/psi (a 24 percent reduction) after 96 days of Phase 1 testing (Figure 27). This is typical of normal RO membrane operation. The permeability of the RO membrane gradually decreases as organic foulants and inorganic scalants accumulate on the membrane surface over time. The specific flux in the tail vessel and element had similar values but were lower than the total system flux, declining from 0.12 gfd/psi to 0.09 gfd/ps during Phase 1 testing. It is typical for the specific flux in the tail elements to decline during RO operation and be lower than the total system's specific flux. This is because the salt concentration is typically highest in these tail elements and they are the most likely place for mineral precipitation and scaling to occur. RO specific flux during Phase 2 testing (Figure 28) declined rapidly from 0.15 gfd/psi to 0.10 gfd/psi over the first day of testing. The steep decline in flux continued for 20 days before reaching a steady-state specific flux of approximately 0.08 gfd/psi (a total reduction of 42 percent). After the second CIP on day 65, the specific flux decreased from 0.11 gfd/psi and to 0.095 gfd/psi over the first 35 days of operation (a 15 percent reduction). The decline in specific flux observed during Phase 2 testing was much greater than the decline observed during Phase 1. This may be attributed to the variation in cleaning protocols between the two testing periods, where CIPs were performed on the RO membranes in Phase 2, but not during Phase 1. Performing CIPs has been shown to change RO behavior initially, before the system equilibrates.

Figure 27: Specific Flux of Reverse Osmosis Permeate During Phase 1 Testing, Receiving Untreated Microfiltration Filtrate



Source: Kennedy/Jenks Consultants

Figure 28: Specific Flux of Reverse Osmosis Permeate During Phase 2 Testing, Receiving Microfiltration Filtrate Pretreated with Targeted Coagulation



Source: Kennedy/Jenks Consultants

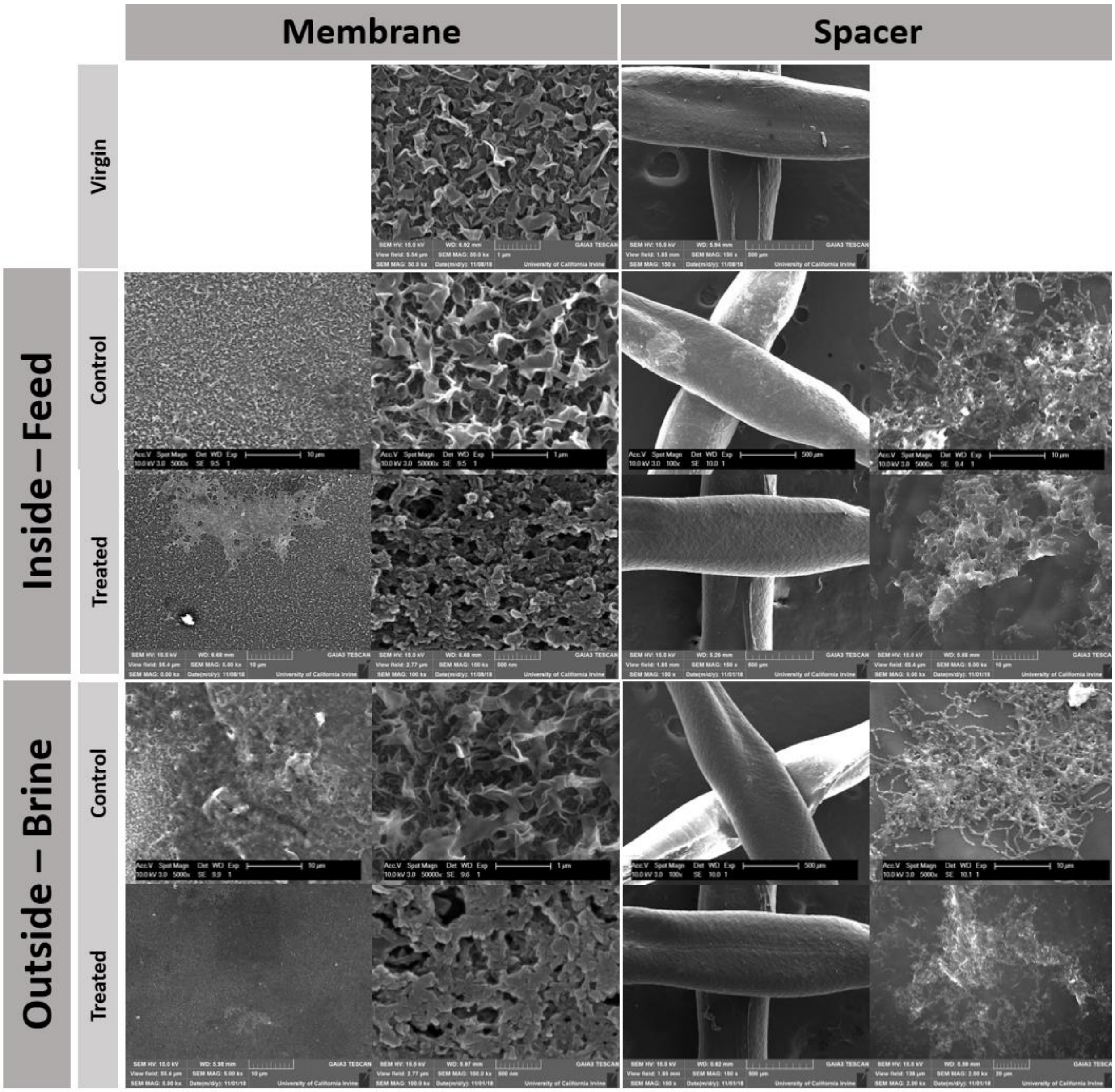
The RO system at OCWD's AWPF (Appendix D) receives a similar water quality as the pilot during Phase 1 (MF filtrate with no pretreatment) and receives regular CIP cleanings. The RO membranes in this full-scale system exhibited a rapid decline in specific flux for several weeks after each CIP, followed by a much slower decline that continued until the next cleaning. The initial rapid decline in specific flux is due to the increased fouling rates of the recently cleaned membranes and is mainly attributed to cake layer formation, while the slower decline in specific flux is attributed to scale formation and biofilm growth (Roehl Jr., et al., 2018). Each cleaning also yielded varying rates of specific flux decline. Therefore, CIPs can have a drastic impact on RO specific flux performance. To assess whether the rapid decline in specific flux observed during Phase 2 was directly related to upstream coagulation and not a symptom of the varying cleaning protocol, further testing with longer operating periods are needed.

4.2.5.2 RO Membrane and Spacer Autopsy

The composition of the RO fouling layer was investigated via SEM and EDS analysis. SEM images of the RO membrane surface and the spacer for the head and tail elements are shown in Figure 29 and Figure 30, respectively.

The SEM image of the virgin membrane in Figure 29 indicates a pristine polyamide active layer that is free of foulants, as well as a clean spacer. Representative SEM images of membrane samples taken from the head element (Figure 29) show that the head element membrane was relatively clean as the porous surface of the active layer can be easily observed for all samples (treated and control). The spacers in the head element, however, showed signs of light biofouling and deposition for both treated and control samples. Samples extracted from the tail element of the RO (Figure 30) exhibited heavier fouling than that observed for untreated and control samples from the head element. Both the membranes' active layer and spacers showed almost a complete coverage by deposited foulants. Comparing between the head and tail samples, it appears that the tail element had a heavier layer of foulant covering its membrane surface and spacers. This is typical of RO train fouling propensity. It is also typical that much of the contaminants localize to the spacers, which is the case for both the head and tail elements of the RO. It was more difficult to conclusively compare the extent of fouling between the different treatments (untreated feed during Phase 1 and coagulated feed during Phase 2). In general, the SEM analysis did not show noticeably heavier fouling on the Phase 2 samples that could account for the dramatic change in total specific flux observed in Figure 28. An EDS analysis was performed to better evaluate the observed depositions.

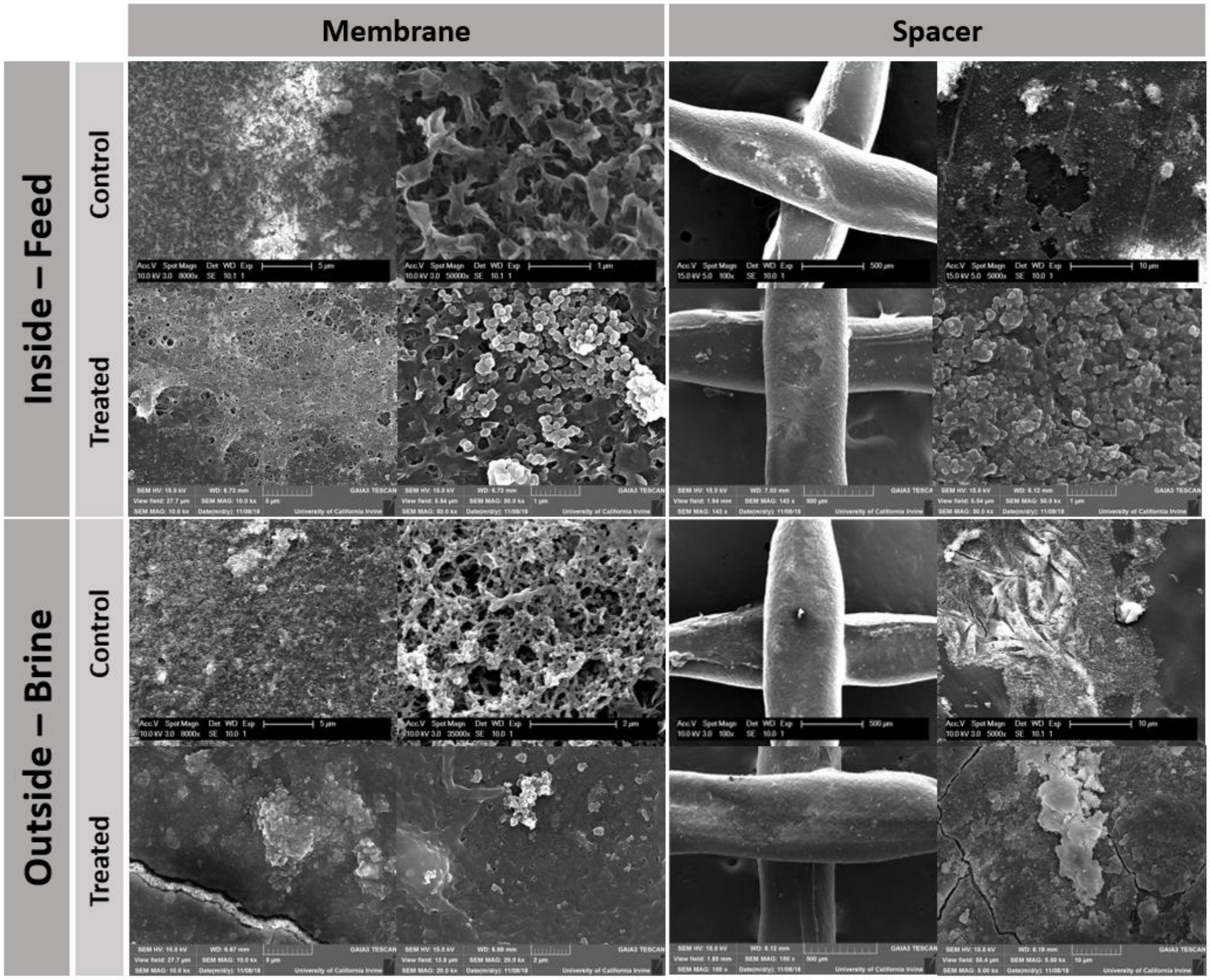
Figure 29: Scanning Electron Microscopy Images Taken from Membrane and Spacer of Lead Reverse Osmosis Element



SEM images taken from the membrane and spacer of the lead RO element, from Phase 1 (control), Phase 2 (treated), and unused (virgin) samples. Inside-feed and outside-brine indicate autopsy sampling locations. SEM images were captured at low and high magnifications (100x to 50kx).

Source: Kennedy/Jenks Consultants

Figure 30: Scanning Electron Microscopy Images Taken from Membrane and Spacer of Tail Reverse Osmosis Element



SEM images taken from Phase 1 (control), and Phase 2 (treated) samples. Inside-feed and outside-brine indicate autopsy sampling locations. SEM images were captured at low and high magnifications (100x to 50kx).

Source: Kennedy/Jenks Consultants

Table 6 lists the identified elements.

Table 6: Elements Identified to be Present on the RO Membrane and Spacer Sample Specimen, Using Energy Dispersive Spectroscopy (EDS)

Sampling Location		Treatment	RO Membrane	Spacer
Lead	Inside - Feed	Control	Cl, Si, Al, Ca	Cl, Si, Al, Ca
		Treated	Cl, Si, Al, Ca	Cl, Si, Al
	Outside - Brine	Control	Cl, Si, Al, Ca, P, Fe	O, Cl
		Treated	Cl, Si, Al, Mg	Cl, Si
Tail	Inside - Feed	Control	Cl, Si, Al, Ca, Fe	O, Cl, Si, Al
		Treated	Cl, Si, Ca, Mg, Na, F	Cl, Si, Al, Ca, Mg, Na, F, K
	Outside - Brine	Control	Cl, Si, Al, Ca, Fe	O, Cl, Si, Al
		Treated	Cl, Si, Al, Ca, Na	Cl, Si, Al, Ca, Mg, Na, K

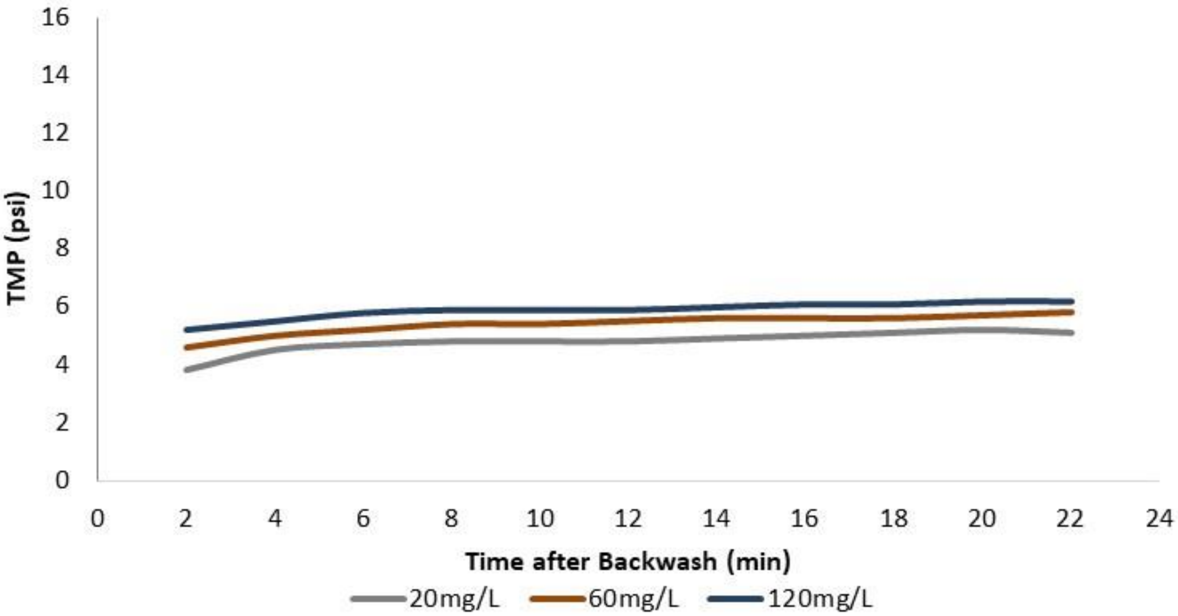
Source: Kennedy/Jenks Consultants

Table 6 shows that both control and coagulant treated feed resulted in similar elemental deposits on the RO membrane. The RO spacer however showed a higher variety of deposited elements during Phase 2 (coagulant treatment). The EDS also showed that chlorine, silica, and aluminum are prevalent in most of the RO membrane and spacer samples, regardless of treatment or sample location. Although it is difficult to quantify the effect of these components, aluminum and silica are both known to cause RO fouling. Aluminum-based coagulants (such as PACl) can react with silica, forming aluminum silicates and colloidal aluminum silicates. Furthermore, reaction with negatively charged anti-scalants can cause a precipitate to form if pH is not well controlled. However, it is difficult to conclusively know if there was excessive fouling occurring on the RO membrane due to coagulation and by what mechanism. Therefore, additional experiments with coagulant overdosing were performed to better understand if PACl had a direct or indirect effect on RO performance.

4.2.5.3 Impact of Coagulant Overdosing

The short testing period used to evaluate the RO performance, and the lack of clear evidence for the presence of significant fouling on the RO membranes necessitated further investigation into the role of PACl. This was achieved by increasing the applied coagulant dosage in the system after Phase 2 tests had been concluded. The response of both the MF and the RO unit to this increased dosing was monitored. The range of optimal coagulation used during the Phase 2 pilot tests was 0 to 15 mg/L of PACl. During the overdosing tests, coagulant doses ranging between 20 to 120 mg/L were applied. TMP performance of the MF unit was recorded after 1 hour of continuous operation (Figure 31). To evaluate how much aluminum could break through, Al^{3+} concentrations in the MF effluent were also measured and compared to permissible MCLs (Figure 32Figure 32). Finally, the RO permeates' specific flux was monitored on the pilot system in order to more directly evaluate the membrane's response to the presence of PACl and coagulant overdosing.

Figure 31: Microfiltration Performance During a Single Filtration Cycle for Overdosing Pilot Experiments

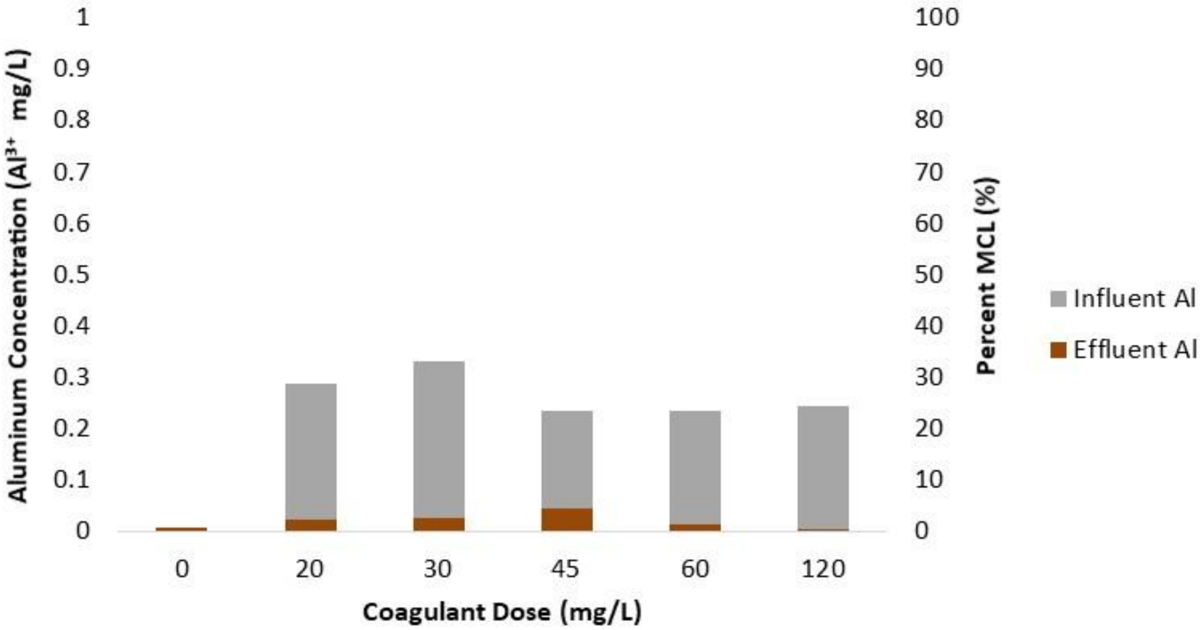


Results depict MF performance during a single filtration cycle (22 minutes) for overdosing pilot experiments. TMP was recorded at every minute following a hydraulic backwash and air-scrub cycle, 1 hour after dosing change.

Source: Kennedy/Jenks Consultants

One hour after injecting either 20, 60, or 120 mg/L of PACl, TMP readings on the MF unit were recorded for a single filtration cycle. Figure 31 shows that at a PACl dosing rate of 20 mg/L (slightly above optimal dosing range), TMP readings were similar to those collected during targeted coagulation. TMP readings reached a maximum of 5.1 psi at the end of the 22-minute filtration cycle. However, the TMP performance of the MF showed an immediate response to elevated dosing. At PACl injection rates of 60 mg/L and 120 mg/L and after only 1 hour of operation, maximum TMP readings (at the end of a filtration cycle) reached 5.8 psi and 6.2 psi, respectively. This effect of increased TMP was compounded if the MF unit was operated longer. For example, after 5 hours of operating with 120 mg/L of PACl, TMP levels reached 9.8 psi at the end of the 22-minute filtration cycle. This is drastically higher than the rate of increase observed during Phase 2 pilot testing with targeted coagulation. Therefore, it can be concluded that overdosing of the PACl coagulant will impede MF performance. Aluminum leakage through the MF was tested to understand whether the negative impact of too much coagulation could extend to other downstream processes. Figure 32 shows the concentration of Al^{3+} in MF effluent after adding varying coagulant doses (0 to 120 mg/L of PACl).

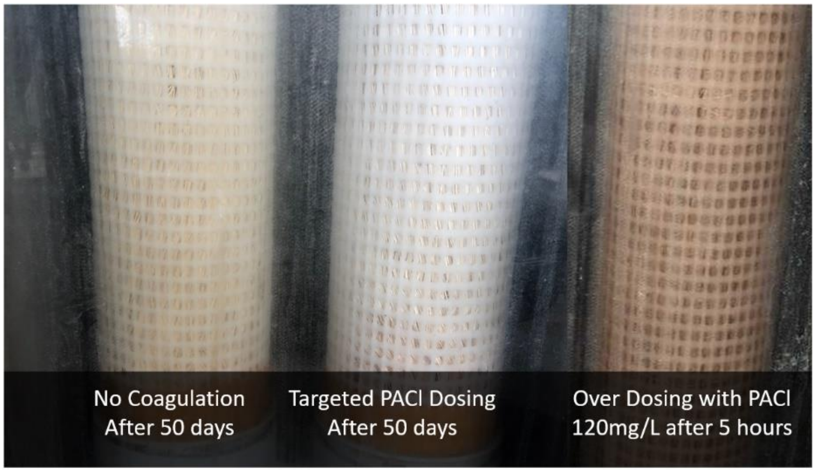
Figure 32: Aluminum Concentrations of Microfiltration Influent and Effluent with PACl Overdosing



Source: Kennedy/Jenks Consultants

Figure 32 shows that adding excess coagulant to the MF feed results in approximately 0.25 to 0.35 mg/L of Al^{3+} in the MF influent after coagulation. The remaining aluminum concentration in the MF effluent following filtration is significantly lower than what is injected. MF effluent concentrated did not exceed 0.045 mg/L of Al^{3+}. The recommended concentration of aluminum in the RO feed water in order to limit silica scaling is 0.05 mg/L (The Dow Chemical Company). For all coagulant dosing rates, Al^{3+} concentrations in the MF effluent were not only below the recommended limits for preventing scaling, but also less than the permitted MCL values (5 percent of the 1 mg/L limit). Therefore, results indicated that excess aluminum from the PACl coagulant did not have a significant breakthrough during MF. Instead, a high percentage of the excess coagulant was likely captured by the MF membranes. Figure 33 depicts the evident discoloration observed on the MF membrane after overdosing with PACl (at 120 mg/L) for only 5 hours of continuous operation.

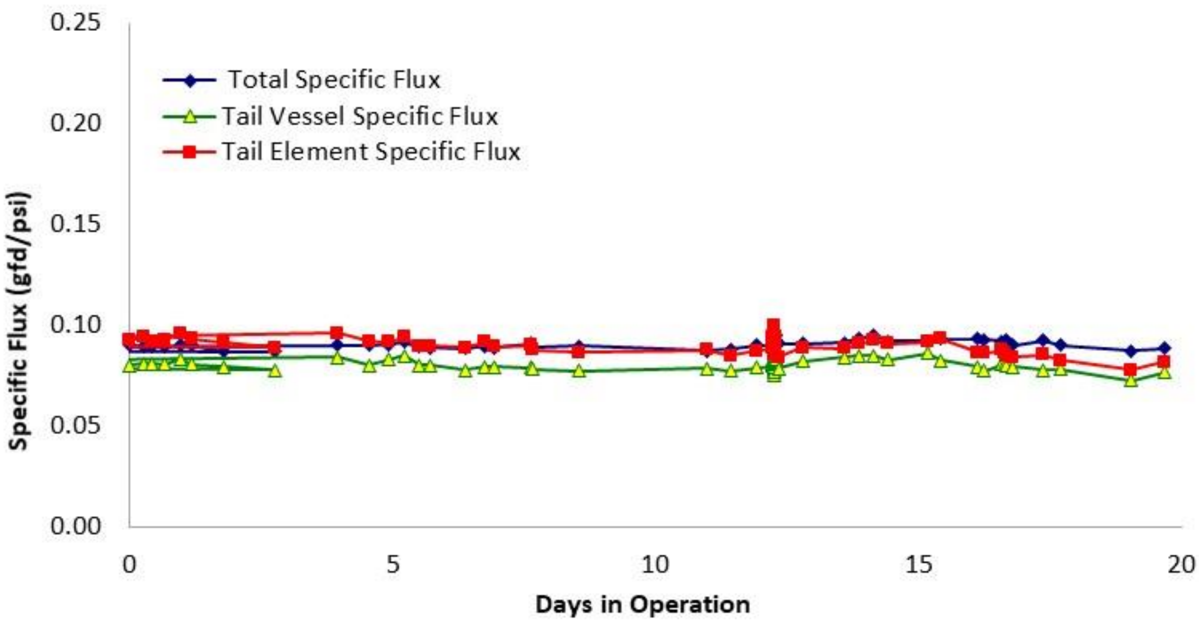
Figure 33: Discoloration of Microfiltration Membrane due to PACl Overdosing



Source: Kennedy/Jenks Consultants

RO performance was also monitored to assess whether the leaking Al^{3+} was inducing a negative impact downstream of the MF. Figure 34 shows the specific flux for the total RO permeate and tail vessel permeate of the RO, during overdosing experiments.

Figure 34: Specific Flux Through the Reverse Osmosis Membrane During Coagulation Overdosing Tests



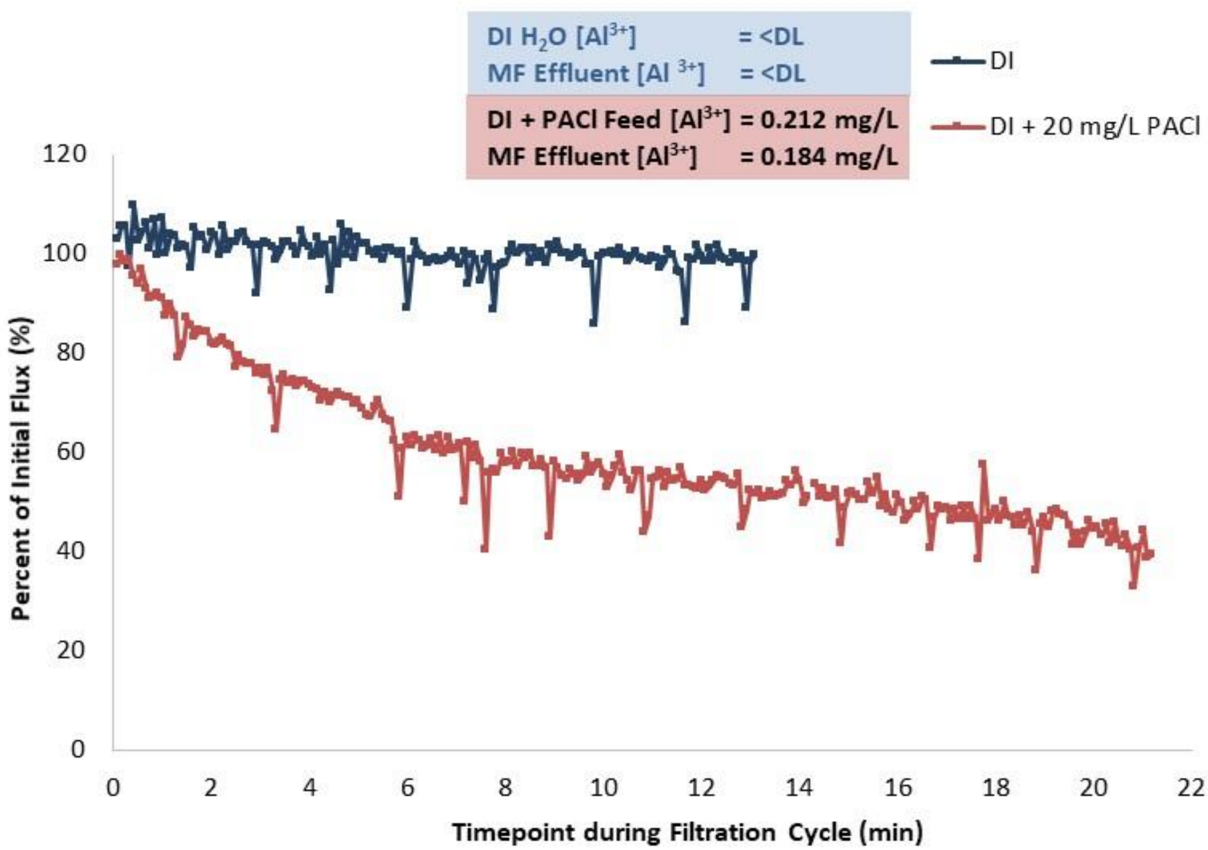
Source: Kennedy/Jenks Consultants

The total specific flux of the RO permeate was 0.092 gfd/psi at the beginning of the overdosing experiments, where 20 mg/L of PACl was being administered to the MF feed. This dose was maintained for 15 days, at which point the RO permeate specific flux was still at 0.092 gfd/psi. No detectable change was observed in RO performance during this time, therefore, coagulant overdosing was increased to 120 mg/L (on day 17) and 200 mg/L (on day 19). This led to a small decrease in total specific flux from 0.093 gfd/psi to 0.089 gfd/psi within 3 days. This is a substantially smaller change than the rapid decline observed during the startup of Phase 2 testing. Therefore, the role of PACl coagulation in directly or indirectly affecting RO performance has yet to be elucidated and requires further investigation in future studies.

4.2.5.4 Mechanism of Aluminum Filtration

Based on the discoloration observed on the MF fibers after overdosing experiments (Figure 33), it became apparent that excess coagulant is likely being captured by the MF membrane. This was further investigated by bench-scale experiments that studied the mechanism of aluminum coagulant removal. Figure 35 and Figure 36 show two single fiber flux experiments that tested the aluminum breakthrough and fiber flux response after adding PACl to DI water or MF feed water (secondary-treated OCSD effluent), respectively.

Figure 35: Single Fiber Flux Experiment with DI Water and Coagulated DI Water (with PACl)

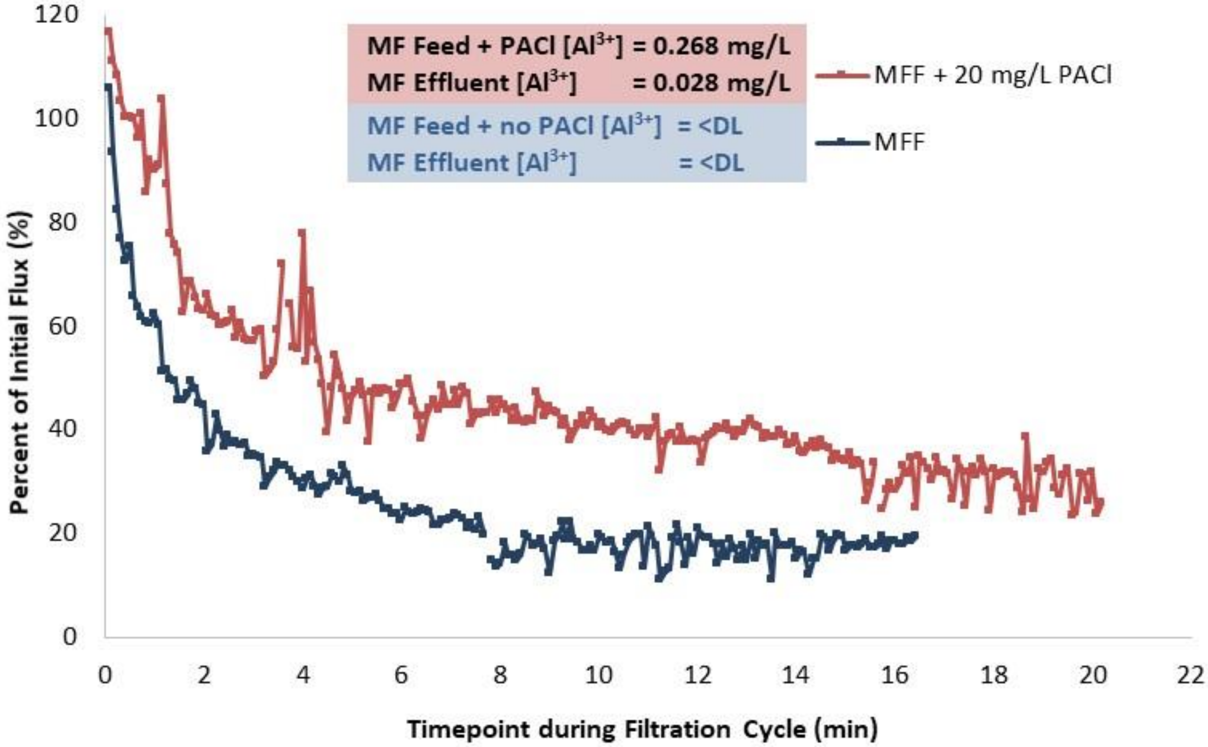


Rate of flux is shown as a percentage of average DI water flux. Aluminum concentration (AL^{3+}) was also measured before and after filtration.

Source: Kennedy/Jenks Consultants

Figure 35 shows that when DI water is filtered through an MF fiber it does not induce fouling. When PACl coagulant (at 20 mg/L) is added to the DI water, flux through the membrane slowly drops, reaching approximately 40 percent of its initial flux rate after 22 minutes of filtration. Measurements of the aluminum concentration before and after filtration indicated that almost all the added aluminum leaked through the fiber. At 20 mg/L of PACl dosing, there was 0.212 mg/L of Al^{3+} in the feed, and 0.184 mg/L Al^{3+} after filtration. This means that the unreacted coagulant gets caught by the membrane and induces fouling, but it can also leak through and increase the risk of fouling for downstream RO processes. Figure 36 shows a similar single-fiber flux experiment but performed with MF feed water (OCSD effluent).

Figure 36: Single Fiber Flux Experiment with Untreated Microfiltration Feed Water (OCSD Effluent) and PACl Treated Microfiltration Feed Water (OCSD Effluent)



Rate of flux is shown as a percentage of average DI water flux. Aluminum concentration (AL $^{3+}$) was also measured before and after filtration.

Source: Kennedy/Jenks Consultants

Figure 36 shows that the untreated MF feed water induced a reduction in flux as filtration proceeded. It reached 16 percent of its initial flux capacity after 17 minutes of filtration. When 20 mg/L of PACl coagulant was added to this feed water, flux reduction was ameliorated, reaching approximately 25 percent of initial flux after 20 minutes of filtration. Additionally, only 0.028 mg/L of Al^{3+} was detected in the permeate water, following filtration. This provides an interesting insight into the mechanism of coagulant removal. If PACl is not able to form a complex, then the aluminum can more freely pass through the membrane into the effluent. However, in the presence of contaminants, it forms flocs that remove particulates in the water, improves filtration, and reduces the flow of free aluminum past the membrane. Therefore, if coagulant dosing with PACl ever exceeds the programmed range, the bulk of adverse consequences are limited to MF performance and not downstream processes like RO. However, based on the experimental limitations during Phase 2 testing, more focused research on RO performance and sensitivity to pretreatment with PACl is warranted. Specific recommendations for future work include monitoring RO performance for longer durations (up to a year).

CHAPTER 5: West Basin Municipal Water District Demonstration

This chapter describes the pilot testing of the particle counting system at the West Basin Municipal Water District's water reclamation plant.

5.1 Testing Program

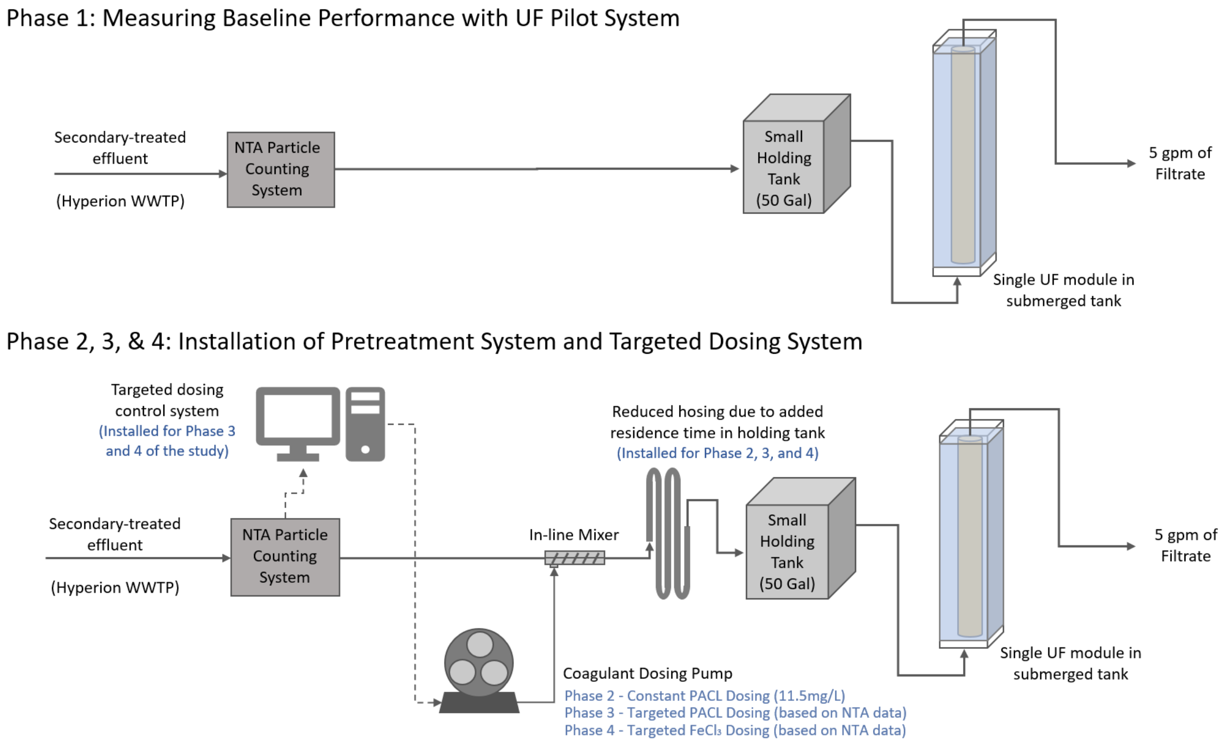
The West Basin Municipal Water District pilot demonstration consisted of four phases:

- Phase 1: Baseline performance
- Phase 2: Constant coagulant dosage (using PACl)
- Phase 3: Targeted coagulant dosage (using PACl) based on colloidal particle count in the feed water
- Phase 4: Targeted coagulant dosage (using $FeCl_3$) based on colloidal particle count in the feed water

Feed water (secondary effluent from Hyperion WWTP) grab samples were collected and analyzed prior to commencing the West Basin field demonstration study. These preliminary analyses were used to establish the feed water quality and range of particle concentrations that would be encountered during pilot testing. Bench-scale PACl and $FeCl_3$ jar tests and single fiber membrane fouling studies were performed before starting the pilot studies at West Basin to determine the relationship between incoming particle concentration and the required optimal coagulant dose. The relationship developed for the OCWD demonstration study could not be used for the West Basin study due to differences in feed water quality and membrane chemistry and structure (polymer material and nominal pore-size).

The pilot skid used to conduct the study at West Basin consisted of a single UF module and a small feed water storage tank (50 gallons). The NS500 particle analyzer was added to the pilot skid setup to track the particle concentration of the feed water. Membrane performance data was collected to establish the baseline performance of the UF module for Phase 1, without pretreatment. This setup was further modified to include additional hosing, an in-line mixer, and a coagulant dosing pump to facilitate the pretreatment process for consequent phases. During Phase 2, a constant dose of 11.5 mg/L of PACl was injected into the feed, irrespective of feed particle concentration. For Phase 3, the particle count provided by the NS500 counting system was utilized to calculate the optimal PACl dose for targeted removal of colloidal particles. In Phase 4, the coagulant was changed to $FeCl_3$ and was dispensed based on the targeted dosing system. A schematic drawing of the pilot skid and the added modifications used for the West Basin demonstration study is depicted in Figure 37.

Figure 37: Process Flow Diagram of the Ultrafiltration Pilot Skid at West Basin



Source: Kennedy/Jenks Consultants

Unlike Phase 2 pilot tests performed at OCWD where two operating conditions could be tested side-by-side, different treatments had to be tested sequentially at West Basin. Each phase of testing lasted for a duration equivalent to approximately two weeks of operation. Fibers were then collected from the UF module, and a CIP was performed before the start of the next phase. The pilot testing operating procedure consisted of regular backwash cycles and air-scrubbing every 20 minutes. Due to the higher fouling propensity of the UF membrane, in addition to the backwashing, an EFM was initiated by the operators when needed.

5.2 Results

The results of the West Basin Municipal Water District demonstration are summarized and discussed in this section. Results presented in this section include a summary of feed water quality at West Basin, optimal coagulation dosing curves developed for PACl and $FeCl_3$, and the UF membrane performance based on different pretreatments.

5.2.1 Feed Water Quality

The feed water was sampled weekly and analyzed for general water quality parameters over the pilot testing period. Samples were collected immediately prior to membrane filtration and after receiving ozonation. The results from the feed water quality analyses are provided in Table 7.

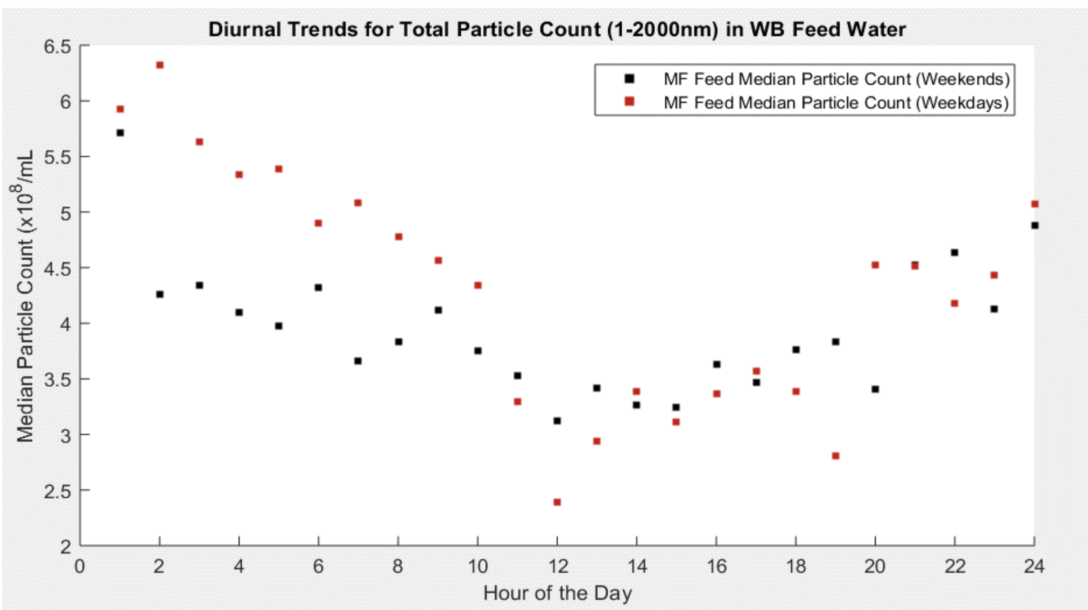
Table 7: WB UF Feed Water Quality Measured During Phase 1 Through Phase 3 Pilot Tests

Feed water quality parameters	Measured Range
Total Hardness (mg $CaCO_3$/L)	219 – 262
pH	7.3 – 7.8
TDS (mg/L)	700 – 740
Temperature (°C)	18 – 31
COD (mg/L)	52 – 94
Turbidity (NTU)	3.45 – 50.1
UVA	0.290 - 0.357

Source: Kennedy/Jenks Consultants

Table 7 shows that the feed water quality at West Basin was generally more turbid and more variable as compared to the feed water at OCWD. In addition to the general feed water quality measurements provided in Table 7, the feed water particle count was continuously measured and recorded using the online colloidal particle analyzer and the turbidity was measured via an online laser nephelometer. Average feed water particle counts measured over a 24-hour weekday and weekend period are illustrated in Figure 38. Average turbidity readings for the same testing period are depicted in Figure 39.

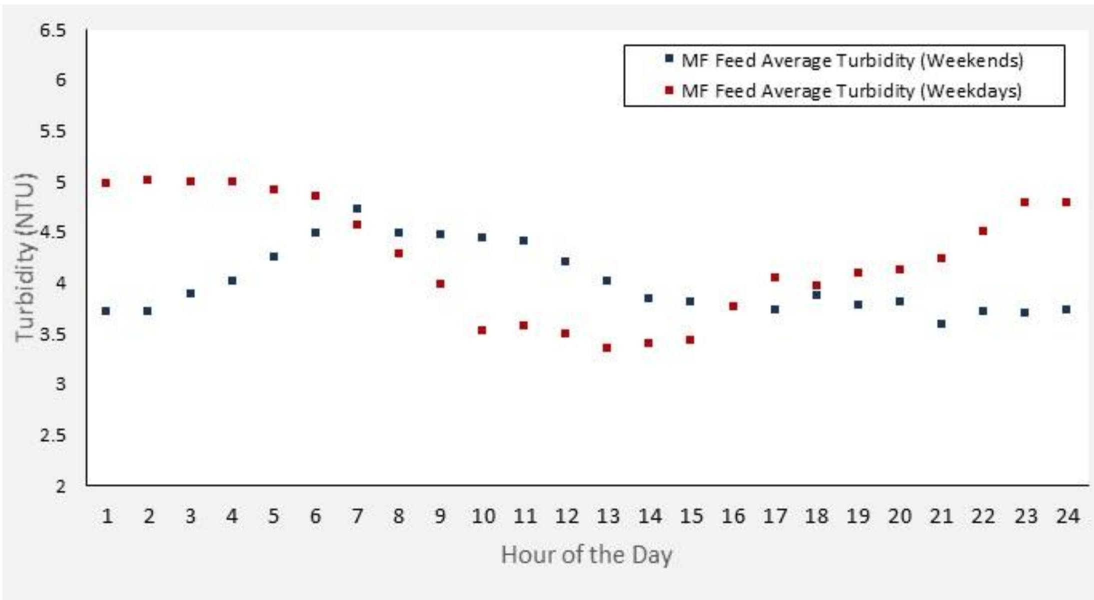
Figure 38: Weekday and Weekend Hourly Median Particle Count of West Basin Microfiltration Feed Water



Source: Kennedy/Jenks Consultants

The feed water particle concentration shown in Figure 38 was also more erratic than those observed at OCWD, but still followed a cyclical pattern. For weekdays, the particle concentration reached a peak value around the early hours of the day (1:00 AM) and a minimum value around mid-day (12:00 PM). On weekends, this trend was less pronounced but still present. This differs from the daily particle concentration trends observed at OCWD, where weekends and weekdays showed almost identical diurnal trends, and both peaked in the afternoons rather than reaching their minimum concentration. Based on Figure 38, it is also clear that West Basin experiences a higher concentration of incoming particles in its feed water than the OCWD plant. On average, West Basin particle concentration ranged from 2.5 x 10^8 to 6.4 x 10^8 particles/mL while OCWD particle count was between 1.2 x 10^8 and 4.0 x 10^8 particles/mL. This is an important distinction as this difference in water quality and less predictable diurnal trend will test the versatility of the dosing strategy being evaluated in this study.

Figure 39: Weekday and Weekend Hourly Average Turbidity of West Basin Microfiltration Feed Water



Source: Kennedy/Jenks Consultants

The turbidity readings depicted in Figure 39 are the average values recorded at the same time as the particle count readings (Figure 38). Although the turbidity trend is similar to the particle count trend during weekdays, the larger variations and unpredictable fluctuations measured by the particle counter are not represented in the turbidity readings. In general, a comparison between Figure 38 and Figure 39 shows that there is not a strong relationship between turbidity and colloidal particle count at West Basin, and variations in particle count cannot be accounted for using the online turbidity readings.

5.2.2 Development of Optimal Coagulant Dosing

A new optimal coagulant dosing curve was developed for PACl to account for the differences between the water quality and membrane material being tested at West Basin and OCWD. The bench-scale jar tests and the single-fiber fouling tests described in Section 3.3 were repeated at West Basin using Hyperion WWTP effluent and PVDF UF fibers. In addition to testing coagulation with PACl, ferric chloride ($FeCl_3$) was tested. Because the effectiveness of the different mixing techniques (jar tests versus in-line coagulation) was previously tested, the pilot-scale validation of the developed equations was not repeated.

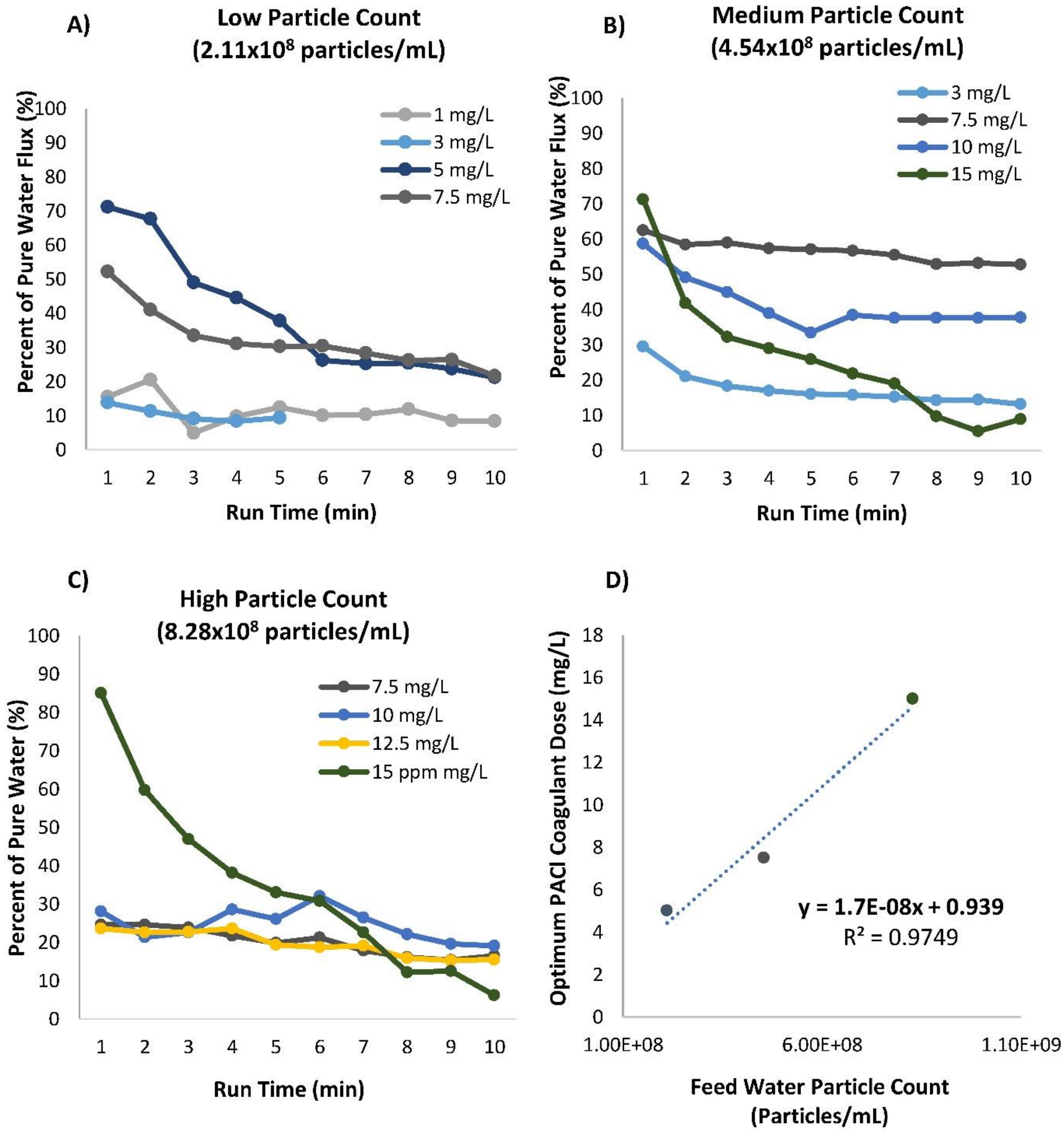
5.2.2.1 Bench-Scale Jar Testing, Membrane Fouling Tests, and Developing Optimal Coagulant Dosing Curve for PACl

Bench-scale jar and membrane fouling tests were conducted using West Basin MF feed water at low (2.11×10^8 particles/mL), medium (4.54×10^8 particles/mL), and high (8.28×10^8 particles/mL) colloidal particle concentrations. These colloidal particle concentrations were used to cover the range of possible water qualities observed during the 24-hour cycle (Figure 38). The optimum coagulant dose was determined for each fouling experiment based on the percentage of pure water flux maintained after 5 minutes of testing. During the constant-pressure membrane fouling tests, the filtrate flux decreased as membrane pores became blocked by retained particles. This decrease in water flux over time was used as an indicator for the extent of membrane fouling. Results from single-fiber UF fouling tests and the corresponding optimal coagulant dosing curve are presented in Figure 40.

Figure 40A-C show that water flux decline during the membrane fouling tests (for low, medium, and high particle count) was generally more substantial than that observed in the flux tests conducted at OCWD (Figure 12A-C). There are two key differences between the tests that can offer a possible explanation for this. First, West Basin feed water had higher particle loading, and hence, a higher fouling potential. Second, the UF membrane fiber used in the West Basin flux test was made of a different material (PVDF at West Basin, Polypropylene at OCWD) and has a smaller pore size than the MF fibers used at OCWD (100 nm at West Basin, 200 nm at OCWD). Previous studies have shown that hollow fiber membranes with smaller pores have greater fouling propensity than those with larger pores (Jeon, et al., 2016).

The optimum coagulant dose was determined for each fouling experiment based on the percentage of DI water flux measured after 5 minutes of testing, see Section 4.2.2 for explanation. Feed water containing a low particle count (Figure 40A) had a similar water flux with coagulant doses of 5, and 7.5 mg/L (38 and 30 percent of the initial flux, respectively) after 5 minutes of testing. A coagulant dose of 5 mg/L was selected as the optimal coagulation dose for the low particle count because it conserves coagulant usage while achieving similar results. Feed water with a medium particle concentration (Figure 40B) performed much better with a coagulant dose of 7.5 mg/L, achieving 57 percent of the initial flux after 5 minutes. Thus, 7.5 mg/L was selected as the optimal dose. For feed water with higher concentrations of particles (Figure 40C), larger doses of coagulants were tested due to the higher fouling potential of the concentrated feed. A dose of 15 mg/L was able to achieve a significantly better performance (33 percent of initial flux after 5 minutes) and was selected as the optimal coagulant dose.

Figure 40: Ultrafiltration Water Flux Measured During Bench-Scale Single-Fiber Fouling Tests with PACl



Single-fiber flux tests performed for feed water containing (a) low, (b) medium, and (c) high particle counts. The y-axis is shown as the percentage of flux measured during DI water flux experiments conducted on the same membrane fiber used during fouling tests. The optimal coagulant dose of PACl (d) is expressed as a function of feed water particle count.

Source: Kennedy/Jenks Consultants

Table 8 summarizes the optimal doses selected for varying colloidal particle loads.

Table 8: Optimal Coagulant Dose with PACl for Various Colloidal Particle Loadings in UF Source Water

Colloidal Particle Loading in Feed Water	Total Particle Concentration ($x10^8$/mL)	Optimal PACl Dose (mg/L)
Low	2.11	5
Medium	4.54	7.5
High	8.28	15

Source: Kennedy/Jenks Consultants

Based on these results, an optimal coagulant dosing curve, tailored for West Basin's feed water and UF membrane was developed (Figure 40D):

$$Optimal\ PACl\ Coagulant\ Dose\ \left(\frac{mg}{L}\right) = 1.7 \times 10^{-8}\left(\frac{Particles\ in\ Feed\ Water}{mL}\right) + 0.939$$

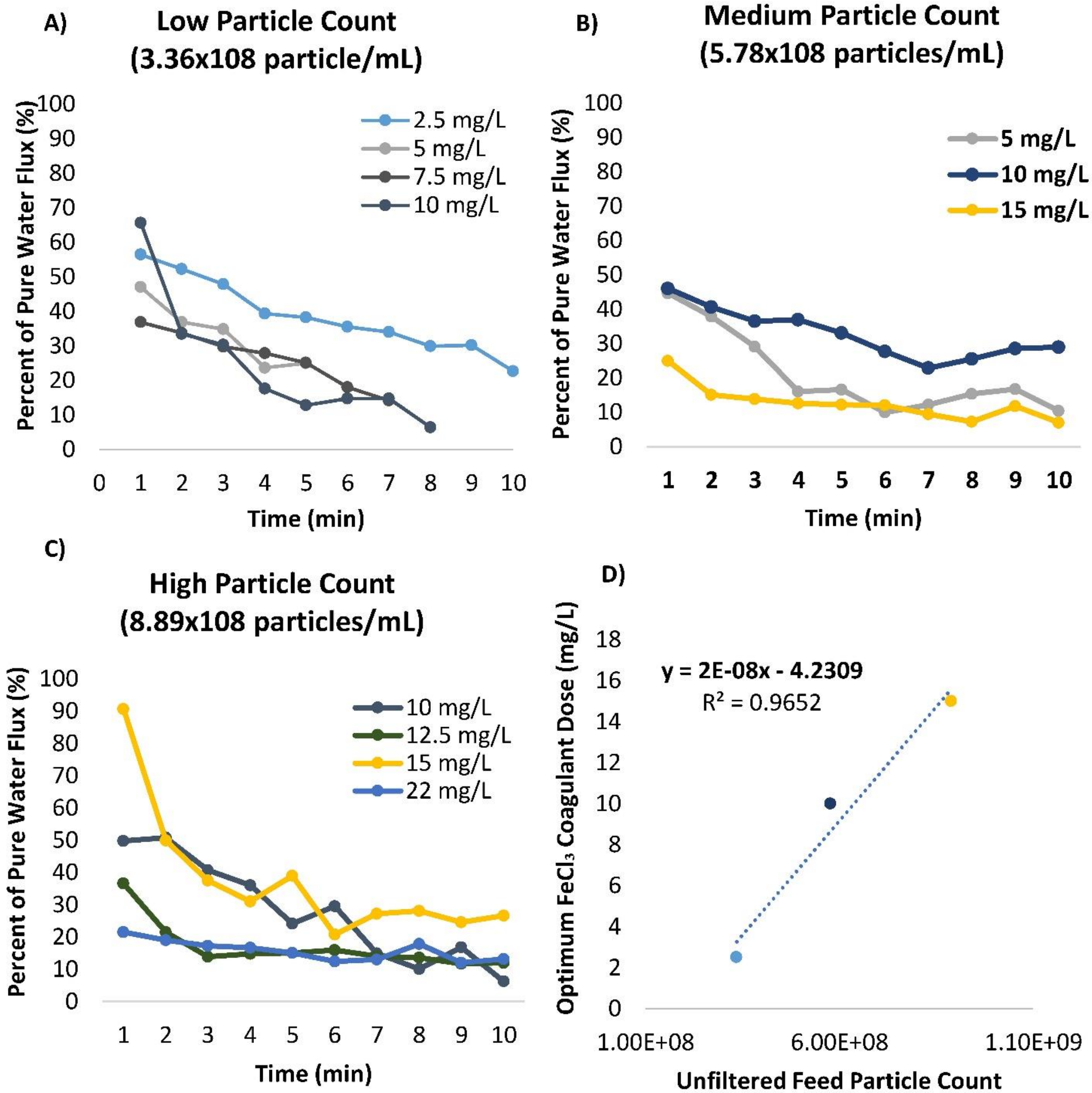
Compared to previous results from OCWD (Figure 12D), the optimal coagulant dose needed at West Basin was almost half of what was needed at OCWD for the same feed particle load.

5.2.2.2 Bench-scale Membrane Fouling Tests and Developing Optimal Coagulant Dosing Curve for $FeCl_3$

In addition to PACl, $FeCl_3$ was tested at West Basin. After performing the necessary jar tests with varying doses of $FeCl_3$ on feed water containing low, medium, and high particle concentrations, a bench-scale flux test was performed. The optimal coagulant dosing curve for $FeCl_3$ was then developed. The results from the single-fiber UF flux tests and the corresponding optimal coagulant curve for $FeCl_3$ are presented in Figure 41.

For feed water containing a low particle count (Figure 41A), the higher coagulant doses of 5, 7.5, and 10 mg/L achieved a flux rate of 25 percent, 25 percent and 13 percent of the initial flux after 5 minutes, respectively. In fact, the lowest dose of 2.5 mg/L was able to maintain the highest flux rate (38 percent at 5 minutes) and was selected as the optimal dose for low particle count water. Feed water with a medium particle concentration (Figure 41B) performed much better with 10 mg/L of coagulant and achieved 33 percent of the initial flux after 5 minutes, while doses of 5 and 15 mg/L maintained the flux at 16 percent and 12 percent, respectively. Here, 10 mg/L was selected as the optimal dose. For feed water with higher concentrations of particles (Figure 41C), larger doses of coagulants were tested due to the higher fouling potential of the concentrated feed. A dose of 15 mg/L was able to achieve a significantly better performance (39 percent of initial flux after 5 minutes) than the other tested doses (10, 12.5, and 22 mg/L) and was selected as the optimal coagulant dose.

Figure 41: Ultrafiltration Water Flux Measured During Bench-Scale Single-Fiber Fouling Tests with Fecl₃



Single-fiber flux tests performed for feed water containing (a) low, (b) medium, and (c) high particle counts. And (d) the optimal coagulant dose of $FeCl_3$ as a function of feed water particle count. Water flux is shown as the percentage of the flux measured during pure water flux experiments conducted on the same membrane fiber used during fouling tests.

Source: Kennedy/Jenks Consultants

Table 9 summarizes the optimal doses selected for varying colloidal particle loads.

Table 9: Optimal Coagulant Dose with $FeCl_3$ for Various Colloidal Particle Loadings in UF Source Water

Colloidal Particle Loading in Feed Water	Total Particle Concentration (x10^8/mL)	Optimal $FeCl_3$ Dose (mg/L)
Low	3.36	2.5
Medium	5.78	10
High	8.89	15

Source: Kennedy/Jenks Consultants

These values were used to construct an optimal dosing curve (Figure 41D) for the use of $FeCl_3$ on the PVDF UF membranes at West Basin.

$$Optimal\ FeCl_3\ Coagulant\ Dose\ \left(\frac{mg}{L}\right) = 2 \times 10^{-8}\left(\frac{Particles\ in\ Feed\ Water}{mL}\right) - 4.23$$

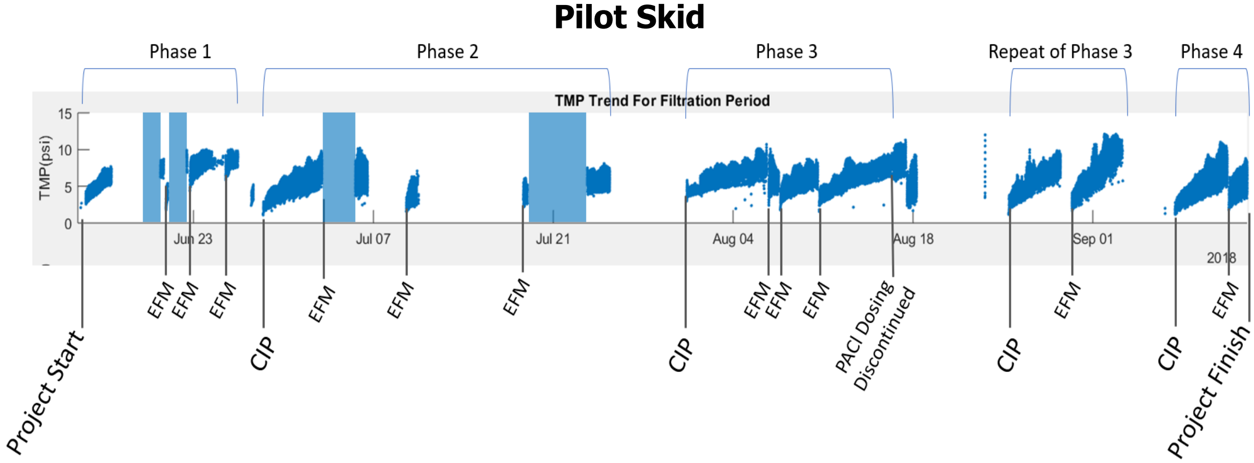
5.2.3 Ultrafiltration Pilot Testing

Four pilot tests were performed at West Basin. During each test, the colloidal particle concentration of the incoming feed was measured by the NS500. Automatic TMP recordings were made every minute. The findings related to UF performance under varying pretreatments are discussed in the following sections.

5.2.3.1 Timeline of Events

Figure 42 shows the TMP recordings made at West Basin and can be used to depict the sequence of events throughout the pilot study. Each CIP signals the beginning of a new testing phase. EFMs were done routinely throughout each phase at the operator's discretion.

Figure 42: Transmembrane Pressure Recordings Collected from the West Basin Pilot Skid

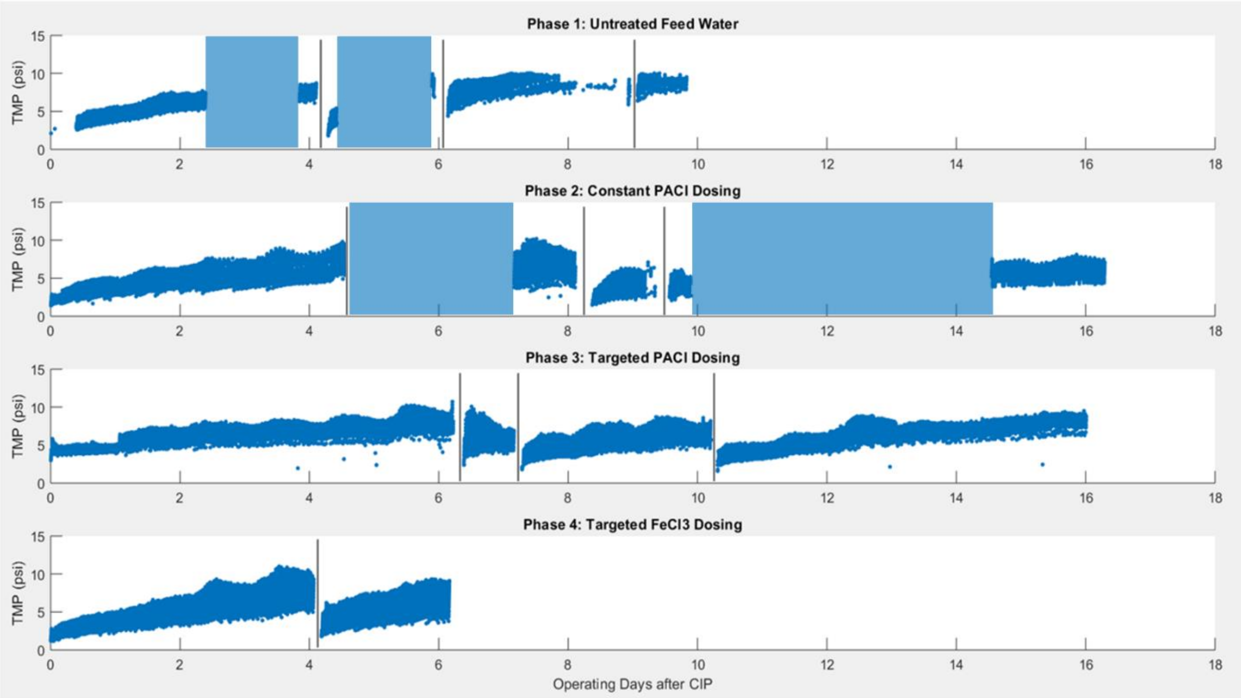


Blue shading indicates that the pilot was running, but TMP recordings were not transmitted. No recordings otherwise mean the pilot skid was shut down or undergoing maintenance.

Source: Kennedy/Jenks Consultants

The UF unit was initially operated at 5 gpm for two weeks without any pretreatment of the feed water to establish the baseline performance. The TMP for the baseline tests was recorded and can be seen under 'Phase 1' in Figure 42. Following baseline testing, a CIP was performed and marks the beginning of Phase 2 (constant PACl dosing). Another CIP was conducted before starting Phase 3 (targeted PACl dosing), however, this CIP did not adequately clean the UF fibers (as seen by the higher initial TMP). A repeat of Phase 3 testing was performed but was excluded from analysis due to a system upset in the main plant (see Appendix E). Phase 4 (targeted coagulation with $FeCl_3$) was the final test performed. Occasionally, pilot testing was interrupted by maintenance needs and the filtration unit had to be shut down. These dates were removed from the TMP datasets and only data from the days the pilot was operational are provided. The TMP data from all four phases is provided in Figure 43.

Figure 43: Transmembrane Pressure Data Collected for Each Testing Phase



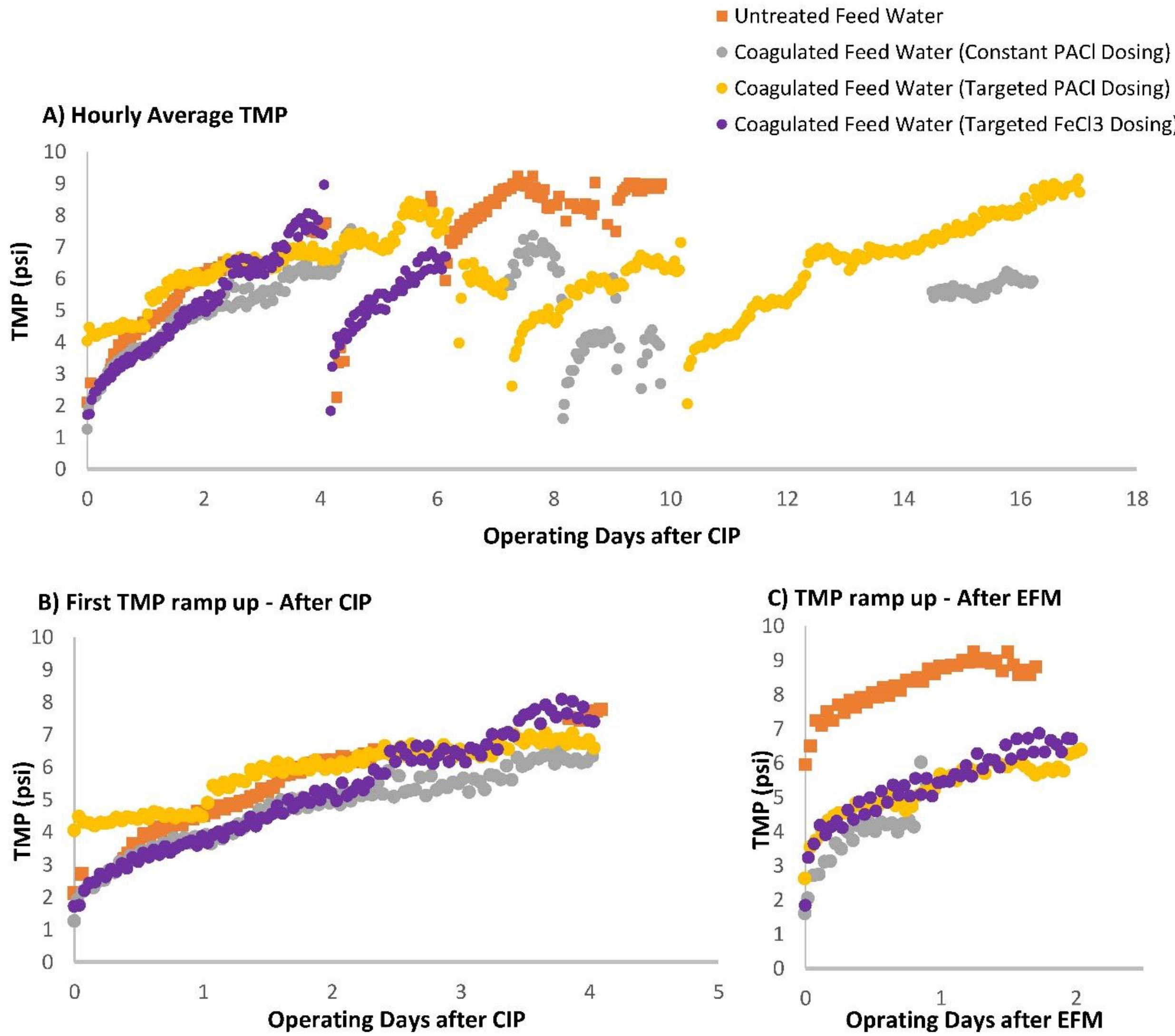
Days of pilot shutdown were removed. Grey lines indicate EFM washing of the UF unit.

Source: Kennedy/Jenks Consultants

5.2.3.2 TMP Performance

The irregularity and varying time intervals between the EMFs for each testing phase make a direct comparison for TMP performance difficult. The sequential nature of the pilot testing setup and the highly variable trends in West Basin source water also made it challenging to ensure that each test condition was receiving a comparable quality of UF feed water. Therefore, conclusions from the TMP dataset serve as a preliminary evaluation and further testing using parallel filtration units (such as those used at OCWD) are recommended for future studies. For easier comparison of the TMP dataset, Figure 44 shows the hourly average of the recorded TMP for all four treatments, graphed based on days of pilot operation. Figure 44B shows the TMP trend of the UF unit during the first four days of operation after a CIP, and Figure 44C shows the TMP trend after an EFM chemical wash.

Figure 44: Hourly Average of Transmembrane Pressure Recordings from Ultrafiltration Unit

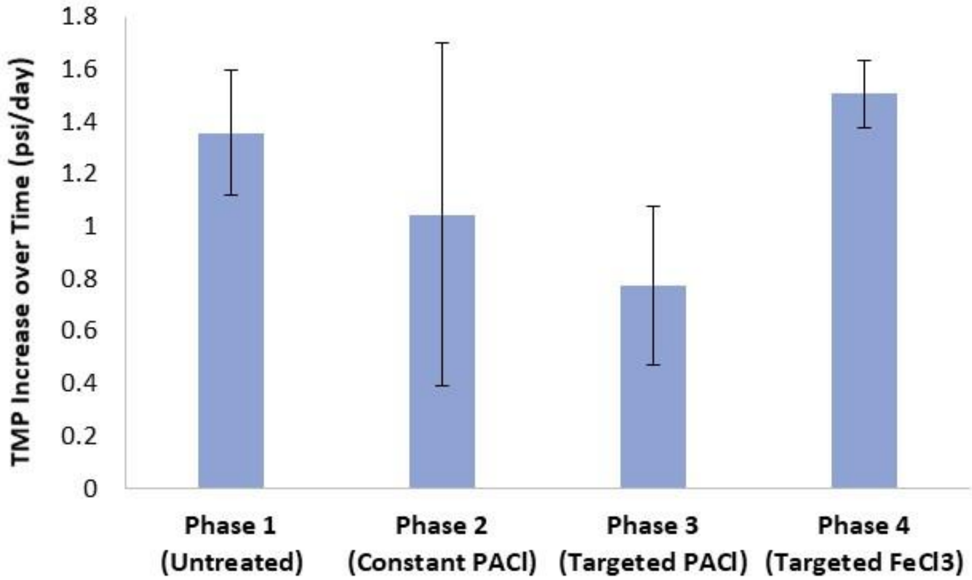


A) all TMP average recordings, B) TMP average for the first four days of the study following a CIP, C) TMP average for the first two days after an EFM.

Source: Kennedy/Jenks Consultants

Based on these results, the TMP increased from 1.7 psi to 7.7 psi after four days on continuous operation with untreated feed water. Constant PACl dosing resulted in an increase from 1.2 to 6.5 psi, while targeted PACl dosing increased TMP from 4 to 6.5 psi. Targeted $FeCl_3$ resulted in a change from 1.7 to 7.4 psi. Interestingly, although the UF cleaning for the targeted PACl treatment was not as efficient as in other phases (initial TMP readings were approximately 2 psi higher compared to other treatments), the final TMP reading was still comparably low. Following an EFM wash (Figure 44C), the TMP reached 8 psi for the control (starting at 5.9 psi) after 1 day of operation. Starting TMPs of other treatment were approximately at 2 psi, and reached 6.0 psi with constant PACl dosing, 5.6 psi with targeted PACl dosing, and 5.5 psi with targeted $FeCl_3$ dosing for operating one day after an EFM. The rate of TMP increase was calculated to allow for better comparison between these results and to account for any variation in starting TMP. Figure 45 uses the slope of each TMP reading following either a CIP or EFM chemical cleaning to define the average rate at which TMP increases per day in response to the different pretreatments.

Figure 45: Average Slope of Transmembrane Pressure Increase for Different Phases of the Pilot Demonstration at West Basin



Average is based on all TMP slopes following a CIP or EFM cleaning.

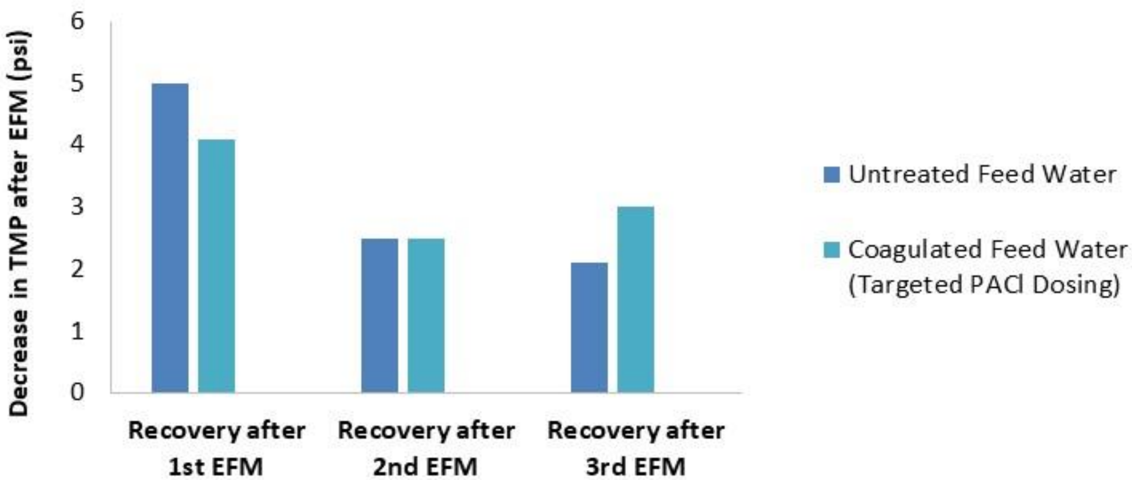
Source: Kennedy/Jenks Consultants

Untreated feed water and targeted dosing with $FeCl_3$ experienced similar rates of average TMP increase (1.36 psi/day and 1.5 psi/day, respectively). Feed receiving constant dosing with PACl experienced an increase of 1.0 psi/day, while targeted dosing with PACl showed an increase of 0.77 psi/day. Compared to feed water receiving no pretreatment, constant PACl dosing reduced the rate of TMP increase by 23 percent on average, while targeted coagulation with PACl reduced the rate of TMP increase by 43 percent. Based on these results, it appears that $FeCl_3$ targeted dosing does not significantly improve overall TMP performance. In addition, although constant dosing with PACl can offer a reasonable improvement in limiting the overall rate of TMP increase compared to untreated feed water, it is still susceptible to system fluctuations. It can yield significantly variable results (as seen by the large error bar for Phase 2, in Figure 45) because it cannot respond to incoming changes. In contrast, the targeted dosing with PACl showed consistently lower rates of TMP increase despite initially receiving a less effective CIP.

In general, TMP increased much more rapidly during the West Basin pilot conducted with UF membranes than during the OCWD pilot conducted with MF membranes. MF membranes took roughly over 30 days to reach TMP values of 7 psi or higher (for untreated feed water), while the same TMP ramp-up occurred within a few days for UF membranes (when no EFMs were performed). Also, the TMP observed in the MF membrane tests gradually increased until a critical TMP was reached, after which the TMP increased more rapidly (see Figure 16 and Figure 17). In contrast, the highest TMP jump observed in the UF membrane tests occurred throughout the first day after a chemical cleaning, after which the TMP increased more gradually. This fouling pattern can help inform operators on how frequently to implement an

EFM, and how to optimize trade-offs between costs of chemicals, down time, waste disposal, and the chemical resistance of the membrane. The following figures offer more information on how the pretreatment conditions tested in this study can impact TMP recovery after chemical cleaning, and the extent to which membrane fouling can be reduced each time.

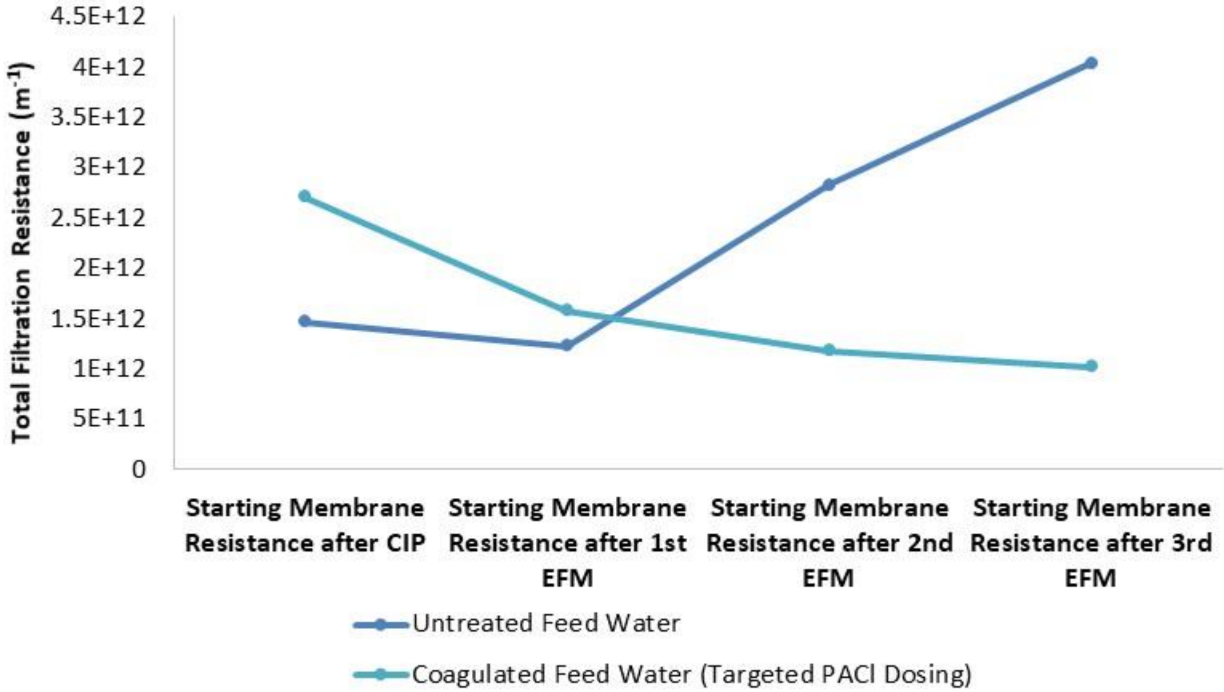
Figure 46: Reduction in Physically Irreversible Transmembrane Pressure after Sequential Extended Flux Maintenance Cleaning



Source: Kennedy/Jenks Consultants

Figure 46 shows the effect of chemically enhanced cleaning (EFM) on decreasing the TMP minima (TMP after a hydraulic backwash and air scrubbing, signifying physically irreversible fouling). For tests using untreated feed water (control), the first EFM achieved a TMP recovery of 4.99 psi, reducing TMP levels from 6.8 to 1.8 psi. Subsequent EFMs for the control recovered 2.50 psi (TMP reduced from 6.9 to 4.4 psi), and 2.10 psi (TMP reduced from 8 to 5.9psi). Feed water treated with targeted PACl dosing achieved an initial TMP recovery of 4.10 psi, reducing TMP levels from 6.5 to 2.4 psi. Later EFMs recovered 2.50 psi (TMP of 4.2 to 1.8 psi), and 3.00 psi (TMP of 4.6 to 1.6 psi). Based on these results, targeted coagulation appears to perform similarly to untreated feed water. However, Figure 47 shows that although the TMP recoveries are similar, the overall impact on the membrane resistance varied for each treatment.

Figure 47: Initial Membrane Resistance Following Clean In Place Cleaning, and Subsequent Filtration Resistance Immediately Following Extended Flux Maintenance Cleaning



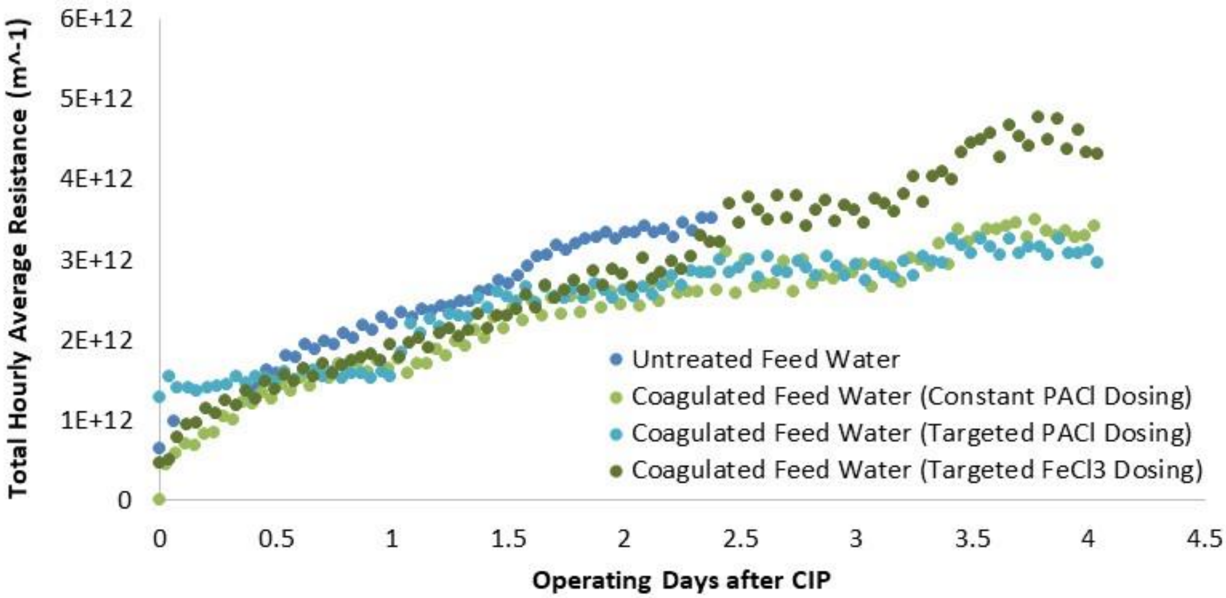
These values represent how effective an EFM was at ameliorating the buildup of physically irreversible fouling on the UF membrane.

Source: Kennedy/Jenks Consultants

As previously mentioned, the CIP cleaning prior to the start of Phase 3 testing was less successful than those performed for other phases, resulting in a higher TMP for that test and indicating that a larger portion of fouling remained on the membrane from previous runs. This higher initial resistance can be observed in Figure 47 where the initial membrane resistance for Phase 1 was 1.46 x 10^{12} m^{-1}, while Phase 3 membrane resistance started off at 2.7 x 10^{12} m^{-1}. As the test progressed, chemical EFM cleanings were performed to remove physically irreversible fouling that could not be removed by hydraulic backwashing or air-scrubbing. Total membrane resistance (which here is defined as the combined cake layer and membrane resistance) for untreated feed water continued to increase, eventually reaching 4.04 x 10^{12} m^{-1} after its third EFM cleaning. Membrane resistance for targeted coagulation decreased and reached 1.02 x 10^{12} m^{-1} despite starting at a higher resistance. The mechanism for why the physically irreversible fouling declines after consecutive EFMs during targeted PACl tests has not been investigated. However, the declining resistance is a positive trend that can be leveraged to improve the filtration process and possibly reduce the frequency of chemical cleanings.

Figure 48 shows the progression of the membrane resistance due to fouling for the first four days following a CIP. To calculate these values, the initial membrane resistance achieved via CIP cleaning prior to the start of the test was subtracted from the overall resistance experienced by the flow through the UF unit.

Figure 48: Total Resistance Experienced by Ultrafiltration Unit After Subtracting Any Membrane Resistance Remaining After Clean In Place



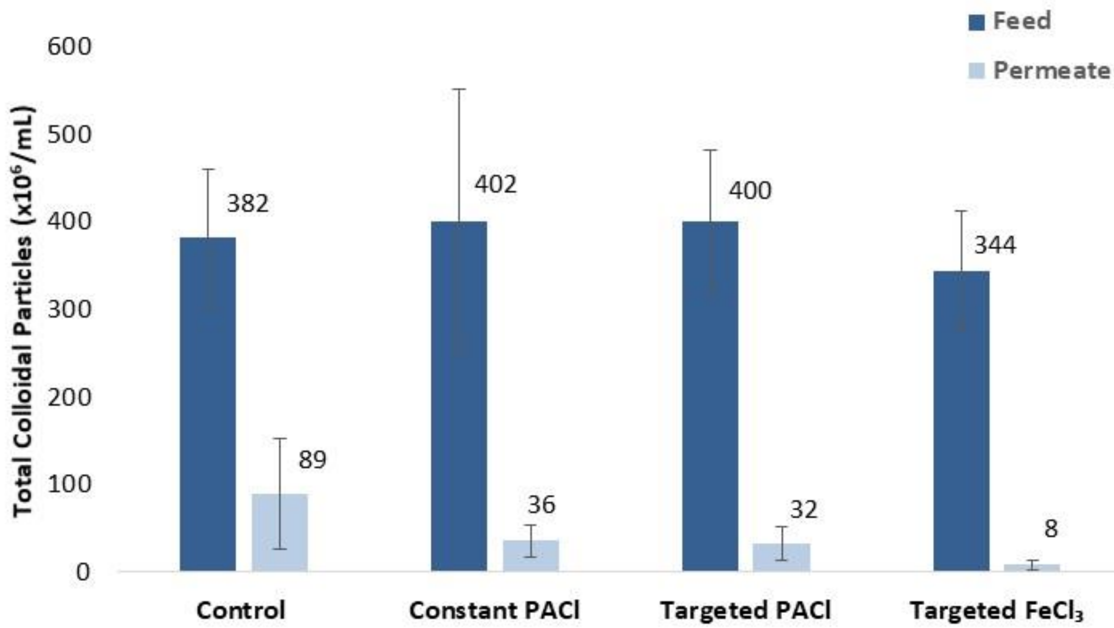
Source: Kennedy/Jenks Consultants

When variation in CIP effectiveness (that is, initial starting resistance) is accounted for and subtracted, the constant and targeted PACl dosing were most effective at reducing the build-up of fouling resistance.

5.2.3.3 Control and Coagulant Treated MF Particle Count, COD, and Turbidity

Particle count, COD, and turbidity measurements of the UF feed water and filtrate were completed to compare the UF filtrate quality between tests conducted with control, constant coagulant treated (PACl), and targeted coagulant treated (with either PACl or $FeCl_3$) feed water. Results from these analyses are shown in Figure 49, Figure 50, and Figure 51.

Figure 49: Colloidal Particle Loading (x10^6 Particles/mL) of the Incoming Feed to the Ultrafiltration and Number of Particles Remaining in the Effluent After Filtration

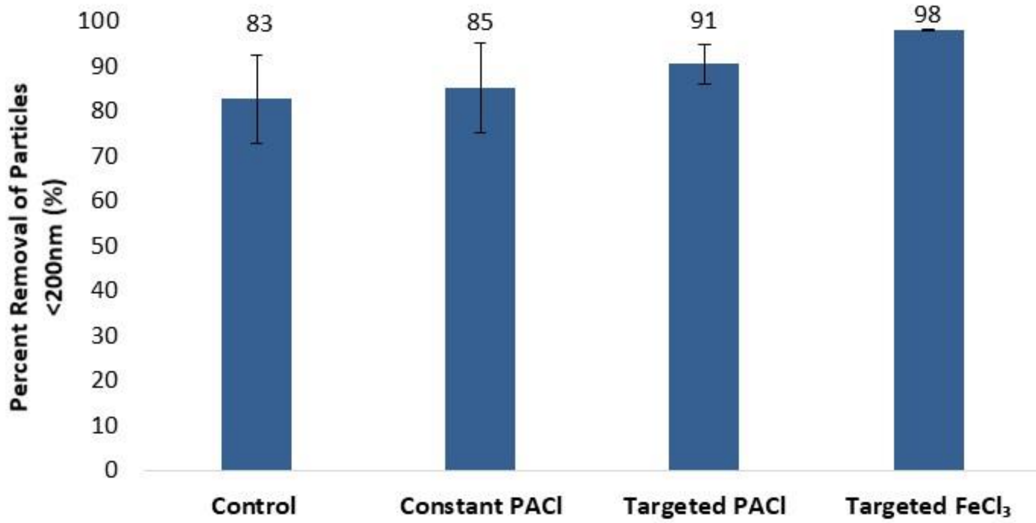


Source: Kennedy/Jenks Consultants

Grab samples taken from the UF influent and effluent during each phase was measured by the NS500. Figure 49 shows the colloidal particle concentration found in these samples. The control feed showed the ultrafiltration process removed more than half of the total colloidal particles in the control feed water without any pretreatments. Samples taken from the pilot during the control phase showed that particle loading of the UF feed was 382 x10^6 particles/ mL, while the effluent had 149 x10^6 particles/ mL on average. Implementing a constant dose of PACl as a pretreatment to the UF process reduced the concentration of particles in the UF effluent to 36 x10^6 particles/ mL, while targeted PACl dosing which responded to incoming feed water quality reduced UF effluent particle concentration slightly more, to 32 x10^6 particles/ mL. Targeted $FeCl_3$ dosing improved UF effluent particle concentration the most, to 8 x10^6 particles/ mL. The percentage of particle removal during each treatment phase was calculated and is summarized in Figure 50.

Figure 50 shows the percent removal of the incoming colloidal particles by the UF system. Filtration without pretreatment (control) was able to remove 83 percent of colloidal particles, on average. This was less than the 95 percent removal observed during OCWD pilot demonstration, by the MF system. The lower percentage of removal by the UF system, despite its smaller pore size, can be attributed to the larger particle loading which it receives in its source water. Constant PACl dosing was able to improve colloidal particle removal to 85 percent. The targeted coagulation systems responding to incoming feed water improved colloidal removal the most, achieving 91 percent removal by targeted PACl dosing and up to 98 percent removal by targeted $FeCl_3$ dosing.

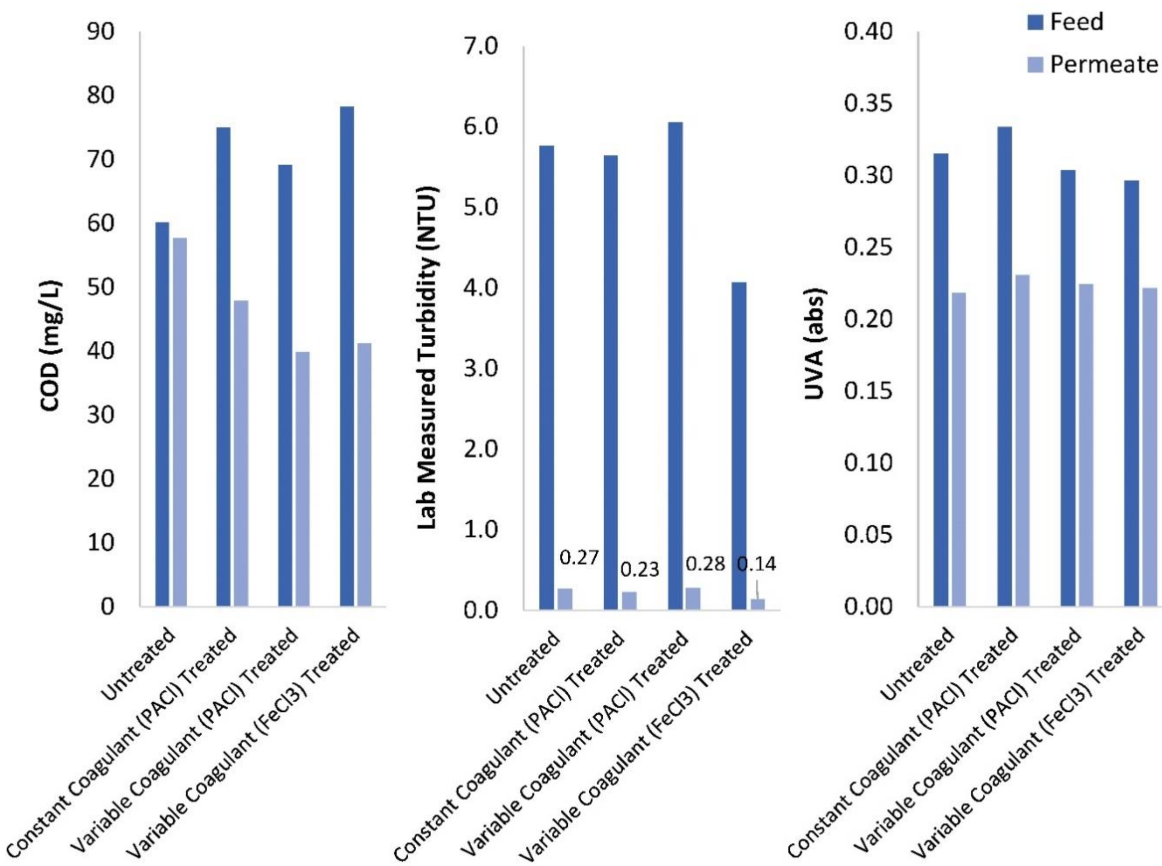
Figure 50: Percentage of Feed Water Colloidal Particles (<200nm) Removed Via Ultrafiltration



Source: Kennedy/Jenks Consultants

Figure 51 depicts how other water quality parameters were affected by the coagulation pretreatment systems.

Figure 51: Chemical Oxygen Demand, Turbidity, and UVA Values Before and After Ultrafiltration



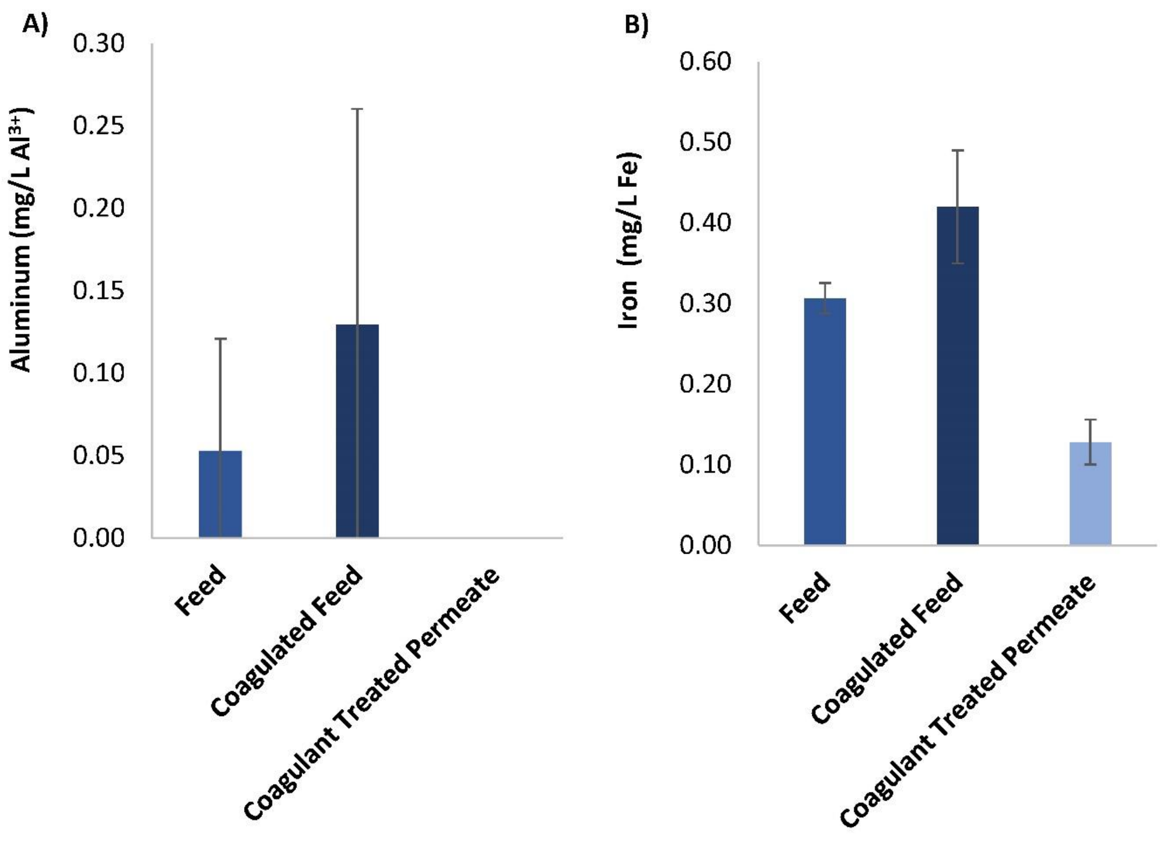
Source: Kennedy/Jenks Consultants

The turbidity and UVA of the UF filtrate were similar for untreated and coagulation pretreatment tests (Figure 51). However, COD values for filtrates of coagulated feed water were lower, despite generally receiving a larger COD load. Untreated feed had COD values of approximately 60 mg/L before and after filtration. With constant PACl dosing however, the influent COD was reduced from 75 mg/L in the feed to 48 mg/L in the filtrate. Targeted PACl dosing resulted in a reduction of 69 mg/L in the feed water to 40 mg/L in the filtrate, and targeted dosing with $FeCl_3$ reduced COD levels from 78 mg/L to 41 mg/L after filtration. These results indicate that the targeted dosing regimen is more successful at removing organic material from the treated water, improving filtrate water quality and reducing the potential risk of organic fouling for other downstream processes.

5.2.3.4 Aluminum and Other Water Quality Parameters

The impacts of aluminum or iron-based coagulant addition on filtrate water quality and other downstream processes was assessed by measuring aluminum and iron concentrations in feed, coagulated feed, and filtrate water samples collected during the pilot study.

Figure 52: Aluminum (A) and Iron (B) Levels of Grab Samples from West Basin Pilot Skid



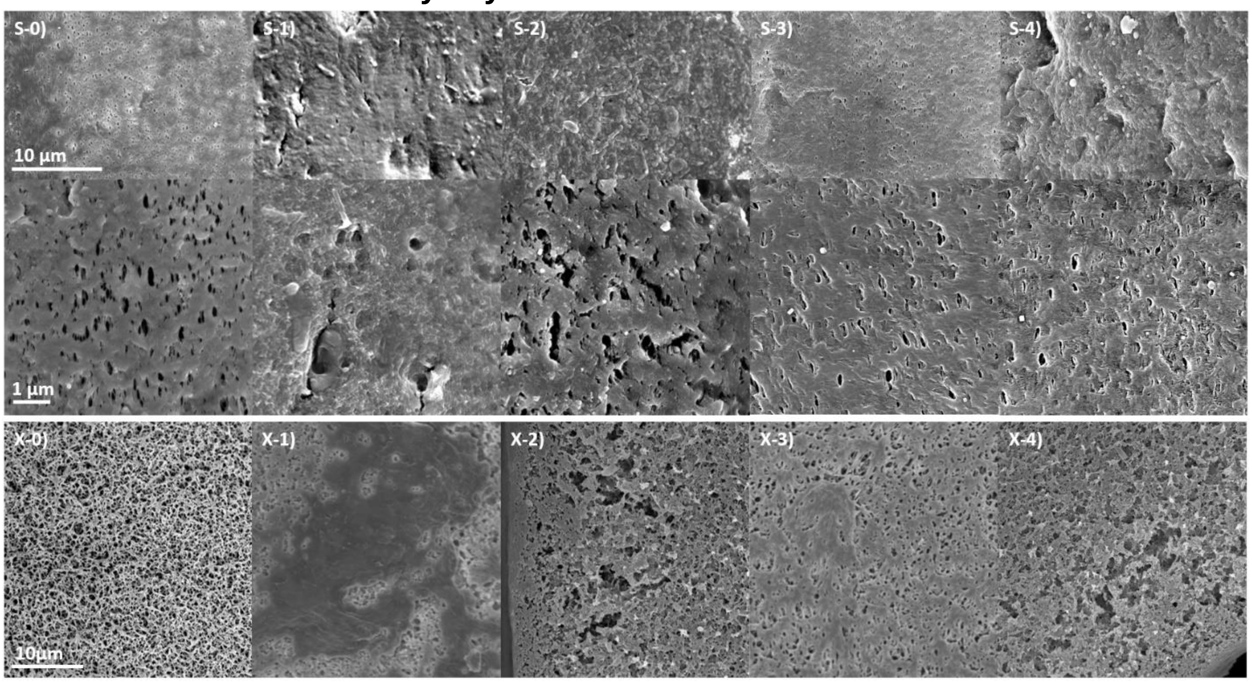
Source: Kennedy/Jenks Consultants

Results from Figure 52 show that the addition of PACl increases the aluminum concentration in the UF feed from 0.05 mg/L Al^{3+} to 0.13 mg/L Al^{3+}, on average. The aluminum sampling analysis demonstrated that there were negligible levels of aluminum breakthrough into the filtrate. These findings indicate that PACl dosing upstream of the UF membrane does not increase aluminum loading to downstream processes and is similar to negligible aluminum concentrations observed in the MF effluent during OCWD pilot testing (Figure 21). The addition of $FeCl_3$ to the pilot UF system increased iron concentrations in the coagulated feed samples, from 0.31 mg/L-Fe to approximately 0.42 mg/L-Fe. UF treatment reduced the iron concentrations, reaching an average value of 0.13 mg/L-Fe. According to West Basin operators, acceptable levels of iron in the UF filtrate is 0.15 mg/L. This qualifies the $FeCl_3$ dosing treatment to be within acceptable operating limits but highlights the need for preventing overdosing for successful $FeCl_3$ pretreatment implementation.

5.2.3.5 Ultrafiltration Membrane Autopsy

SEM images of membrane specimen taken at the end of each phase of pilot testing are presented in Figure 53. The fraction of inorganic material in the fouling layer on the membrane was analyzed by EDS. Membrane samples were taken from the outer edges of the module to perform SEM observations of the membrane surface and cross-section (Figure 53). Results were compared to virgin PVDF fiber samples.

Figure 53: Scanning Elecron Microscopy Images of Surface and Cross-Section of Polyvinylidene Membrane Fibers



SEM images of the surface (S) and cross-section (X) of PVDF membrane fibers 0) prior to filtration and 1-4) after filtration. Fiber samples were taken from the UF module at the end of each phase of the pilot study. 1) Phase 1 with untreated feed water 2) Phase 2 with constant PACl dosing, 3) Phase 3 with targeted PACl dosing, and 4) Phase 4 with targeted $FeCl_3$ dosing.

Source: Kennedy/Jenks Consultants

While it is difficult to make a definitive determination for the extent of fouling for each treatment, SEM images in Figure 53 provide some visual indication. Compared to the surface of a virgin PVDF fiber (S-0), the surface of the untreated (S-1) membrane was completely obscured by a cake layer. Membranes treated with constant PACl dosing (S-2) and targeted PACl dosing (S-3) still had visible surface pores. Larger floc formations were visible on these membrane surfaces which may have altered the cake layer configuration, resulting in a looser and more porous cake (Dong, Chen, Gao, & Fan, 2007). Membranes treated with targeted

$FeCl_3$ dosing (S-4) showed a heavy cake layer formation and some pore blockage. The wide range of TMP observed throughout each filtration cycle during Phase 4 pilot tests can be explained by the formation of the observed cake layer. The formation of this cake layer could also have been a contributing factor to increased colloidal particles removal (Figure 50) and improved effluent quality (Figure 51) observed under this treatment (Dong, Chen, Gao, & Fan, 2007).

Based on the SEM results, the cross-section of the untreated membrane (X-1) showed more extensive fouling compared to the other membrane samples (X-2, X-3, X-4). A large solid mass of nanoparticles can be observed within the pore structure of the untreated membrane, causing hydraulically irreversible fouling. The buildup of fouling observed in the untreated membrane matrix helps to explain why subsequent EFM washes were not successful in reducing the TMP during the Phase 1 pilot tests (Figure 43 and Figure 47). This can also account for the rapid TMP incline observed during Phase 1 pilot testing. Much less fouling was observed within the pore structure of the membranes receiving a feed water with constant PACl dosing (X-2) and targeted PACl dosing (X-3). Targeted $FeCl_3$ dosing (X-4) also showed very light fouling inside the membrane matrix. This can explain why Phase 4 pilot tests had relatively high TMP recovery and effective backwash (hydraulic cleaning) and EFMs (chemically enhanced cleaning). The lack of matrix fouling meant that only the membrane surface depositions needed to be removed to improve TMP. This highlights the impact that fouling mechanisms have on routine plant operations and how different coagulation techniques can result in different membrane performance in the long-run. The elemental composition of surface and matrix fouling on the PVDF UF fibers was further studied with EDS and summarized in Table 10.

Table 10: Elements Identified on UF PVDF Membrane Sample Specimen, Using Energy Dispersive Spectroscopy (EDS)

	Surface	Cross-section
Virgin PVDF Fiber	C, O, F	C, O, F
Phase 1: Untreated Feed Water	C, O, F, Na, Si, Mg, Cl	C, O, F, Na, Al, Si, Cl
Phase 2: Constant PACl Dosing	C, O, F, Na, Al, Si	C, O, F, S, Cl, Ca
Phase 3: Targeted PACl Dosing	C, O, F, Na, Al, Si	C, O, F, Na
Phase 4: Targeted $FeCl_3$ Dosing	C, N, O, F, Na, Mg, S, Cl, Ca, Fe	C, O, F, Ca, S, Cl

Source: Kennedy/Jenks Consultants

The predominance of detected fluoride and carbon are primarily an indication of the PVDF membrane material. The presence of Al and Fe ions are likely due to the addition of PACl and $FeCl_3$. However, Al and Fe were not identified on their respective cross-sectional samples. This supports the findings in Figure 52 that added coagulants are eventually removed via backwashing and are less likely to penetrate the membrane matrix.

CHAPTER 6: Measurement Verification

This chapter describes the findings of the measurement verification system at OCWD's and West Basin's water reclamation plants.

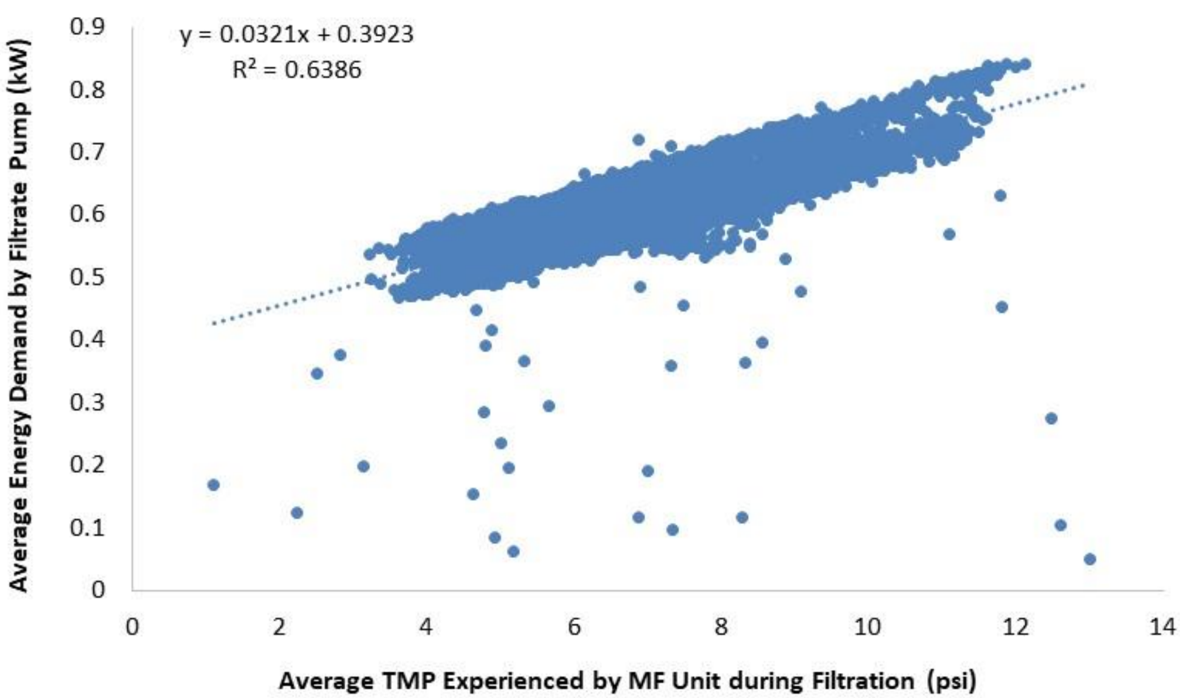
6.1 Energy Consumption at Orange County Water District

The energy consumption of the MF pilot was determined by measuring the energy demand of the MF filtrate pump during Phase 1 and Phase 2 testing. The amount of energy used by the filtrate pump is primarily a function of the filtrate flow rate and TMP. Because the flowrate was held constant during the test, a correlation could be made between TMP and pumping energy. The importance of this correlation is that it could be used to estimate the energy usage of the full-scale system based on TMP.

6.1.1 Correlation between Transmembrane Pressure and Energy Consumption

Energy and TMP data were collected during Phase 2 testing. The data from the control condition in Phase 2 was used to develop the correlation between power (kW) and TMP because the control TMP reached higher values allowing for the correlation to be developed over a wider range of pump operating conditions. The relationship between the filtrate pump power and TMP for two consecutive control pilot tests is provided in Figure 54.

Figure 54: Transmembrane Pressure and Energy Consumption Correlation for Pilot Test Phase 2



Source: Kennedy/Jenks Consultants

The relationship observed between TMP and filtrate pump energy demand (Figure 54) verifies that energy consumption for the MF is directly related to membrane performance and extent of fouling. This positive linear correlation can be described by the following equation:

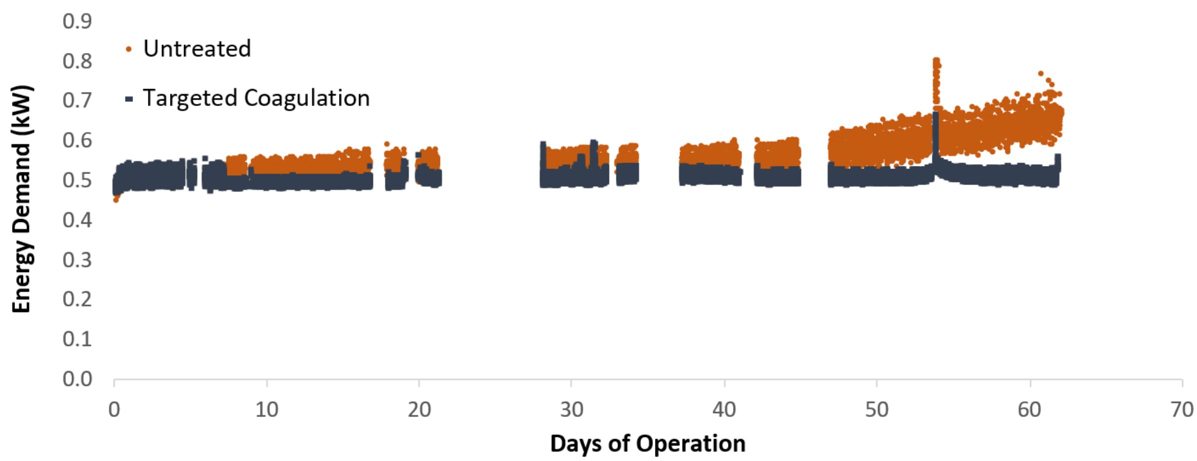
$$Energy\ Demand\ (kW) = 0.0325\ \times TMP\ (psi) + 0.3896$$

This correlation was used to calculate MF energy demand based on online TMP readings.

6.1.2 Energy Consumption during Pilot Study

The recorded TMP and power correlation for OCWD's MF system was used to estimate the energy demand during the Phase 2 testing period. The results from this analysis are provided in Figure 55 and Figure 56.

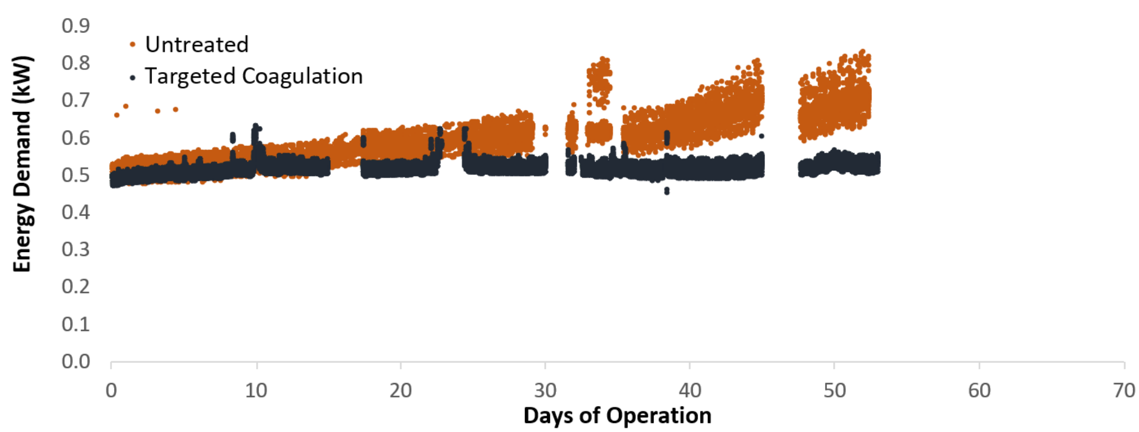
Figure 55: Energy Demand Curve for Microfiltration Filtrate Pumps, Based on Transmembrane Pressure Performance of Control and Coagulant Treated Microfiltration Pilot



Phase 2, test 2 - Dec. 2017 to Feb. 2018.

Source: Kennedy/Jenks Consultants

Figure 56: Energy Demand Curve for Microfiltration Filtrate Pumps, Based on Transmembrane Pressure Performance of Control and Coagulant Treated Microfiltration Pilot



Phase 2, test 3 - Feb. 2018 to Apr. 2018.

Source: Kennedy/Jenks Consultants

Figure 55 and Figure 56 show that under the targeted coagulation treatment, the energy demand of the filtrate pumps can be maintained at a consistently low level. In contrast, the energy demand continuously increased in the control tests. The difference in energy demand between the untreated and coagulant treated feed water tests is further illustrated by the results provided in Table 11, which summarizes the daily energy consumption (kWh) for the first day after chemical cleaning and on the last day of testing.

Table 11: Changes in Daily Energy Consumption at Orange County Water District Pilot Demonstration

	Pilot Test 2		Pilot Test 3	
	Control	Targeted Coagulant Dosing	Control	Targeted Coagulant Dosing
Day 1 (kWh)	10.70	10.64	10.98	10.12
Last day (kWh)	14.01	10.51	15.94	10.57
Percent increase due to fouling (%)	30.9	~ 0	45.2	4.4

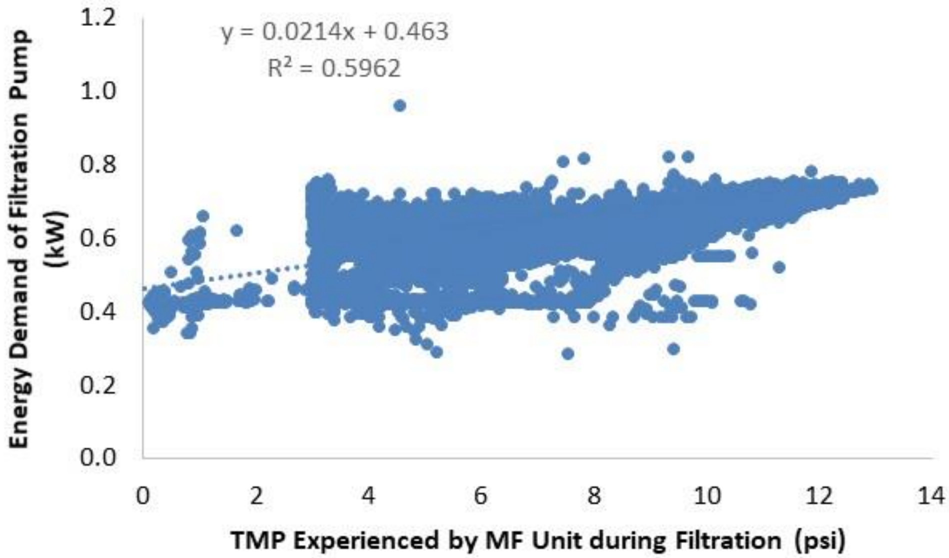
Source: Kennedy/Jenks Consultants

The absolute values for energy consumption can vary depending on the equipment and operating conditions. Therefore, the percent increase in energy consumption was calculated based on the difference in the energy consumption of the filtrate pump on the first day and last day of a test. This value represents how much more energy is required for filtration due to the additional resistance or head losses from fouling. Based on this analysis, the energy consumption of the MF pilot filtrate pump increased by 30.9 percent and 45.2 percent during the control test and in contrast, targeted coagulation resulted in no change or 4.4 percent increase in energy consumption.

6.1.3 Full-Scale Projections for Energy Consumption

The filtrate pumps used on the OCWD pilot skid treated 18 gpm of feed water while full-scale pumps at OCWD were set to treat approximately 3000 gpm of feed water. The pilot filtrate pump was calculated to have an average energy consumption rate of 0.57 kWh/ 1000 gallons, while the full-scale filtration pump had a consumption rate of approximately 0.22 kWh/ 1000 gallons of water treated. The disparity in size and energy efficiency between the pilot and full-scale filtration pumps prevented a direct translation of the pilot’s energy savings to the full-scale plant. Therefore, an energy analysis was performed on the full-scale MF operation at OCWD. The electricity consumption of filtrate pumps used at the main plant were monitored and a new relationship for electricity demand and filtration TMP was determined. Datasets were extracted for filtrate pumps used on both newly installed membranes and 7-year old membranes in order to gauge the full-range effect of TMP variation on filtrate pump performance. Figure 57 shows the developed relationship between energy demand (kW) and TMP (psi) for the full-scale filtration pumps.

Figure 57: Transmembrane Pressure and Energy Consumption Correlation for Full-Scale Filtration Pump at Orange County Water District



Source: Kennedy/Jenks Consultants

Based on the extracted energy datasets of the full-scale filtration pumps, newly installed membranes with no pretreatment (control) consumed electricity at a rate of 0.21 kWh/1000 gallons while 7-year old membranes consumed 0.23 kWh/ 1000 gallons. This translated to approximately 8 GWh to 8.8 GWh of electricity use per year for the current filtration process at the 100-MGD plant, not including backwash and air-scrubbing energy usage.

TMP trends observed during Phase 2 pilot demonstrations were used to develop the expected TMP profile of the full-scale MF units when operated with targeted coagulation. This TMP profile was applied to the correlation developed in Figure 57. Based on this relationship, the rate of energy consumption for MF operation with targeted coagulation was estimated to be 0.15 kWh/ 1000 gallons. This translated to energy savings of 28 percent to 35 percent depending on the age of the MF units being compared to as the control. Therefore, the expected improvement in TMP profile due to the targeted coagulation translates to approximately 3 GWh/ year of energy savings for OCWD's 100-MGD plant. plant operators will also have the choice to change operating and maintenance procedures of the MF units, due to the anticipated improvement in TMP performance. Optimizing trade-offs between chemical cleaning frequency or backwashing and air-scrubbing cycles offers the potential to further increase the energy savings. Additional cost savings related to reduced chemical washing, waste disposal, and membrane preservation are discussed in Chapter 7.

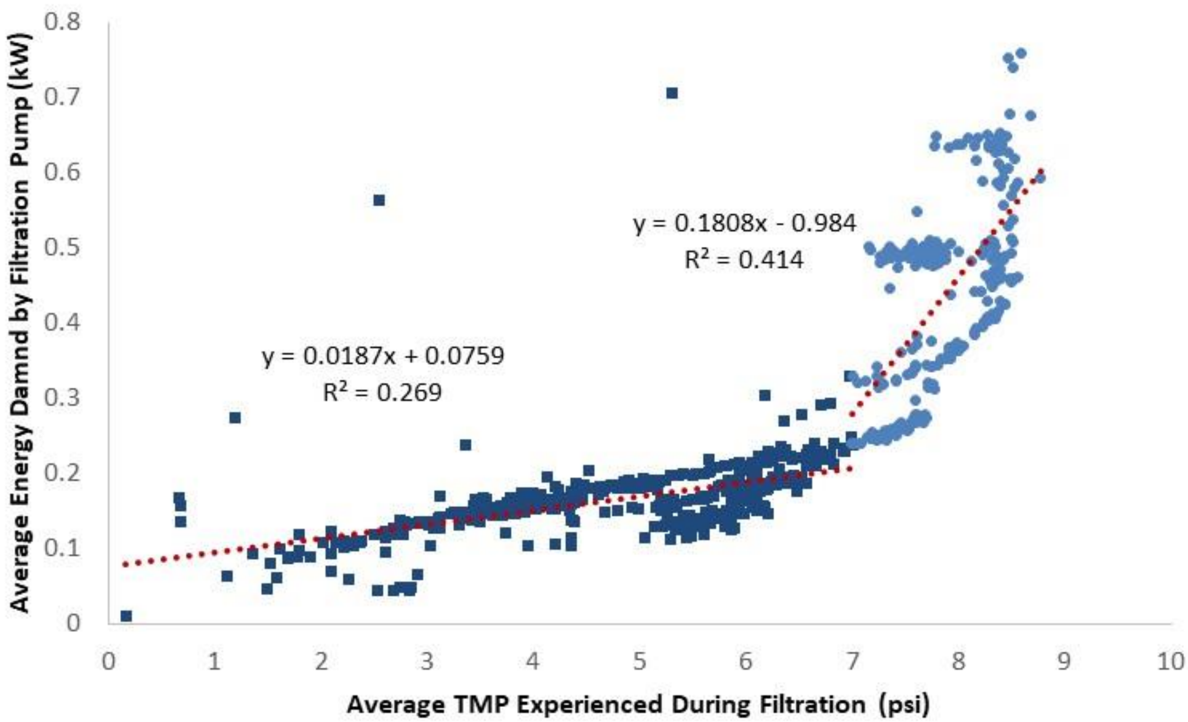
6.2 Energy Consumption at West Basin

Data loggers were placed on the filtrate and backwash pumps at West Basin's pilot UF demonstration system to monitor electricity demand for two weeks. TMP data was collected simultaneously and used to develop a correlation between energy demand and TMP. The overall electricity use of each pump was calculated based on the TMP performance, which was measured throughout the study.

6.2.1 Correlation between Transmembrane Pressure and Energy Consumption

The TMP and energy data collected during demonstration testing at West Basin were analyzed to develop a relationship that could be used to estimate energy demand (kW) based on operating TMP. The following figure depicts the relationship between energy demand and TMP during filtration (Figure 58). The energy demand of the backwash pump was also recorded (Appendix F) but was considered insignificant compared to the energy demand during filtration.

Figure 58: Energy Demand of Filtrate Pump as a Function of Transmembrane Pressure



Source: Kennedy/Jenks Consultants

The energy demand of the filtrate pump at West Basin (Figure 58) was not linearly correlated with TMP, as was observed during the OCWD demonstration tests. The non-linear relationship indicates that more energy is consumed when UF membranes are operated at higher pressures or beyond a threshold fouling level. This phenomenon is represented in Figure 58 by two separate linear relationships that describe the energy demand of the pilot system before and after reaching an inflection point at 7 psi:

$$TMP < 7\,psi: \qquad Energy\ Demand\ (kW) = 0.0187\ \times TMP\ (psi) + 0.0759$$

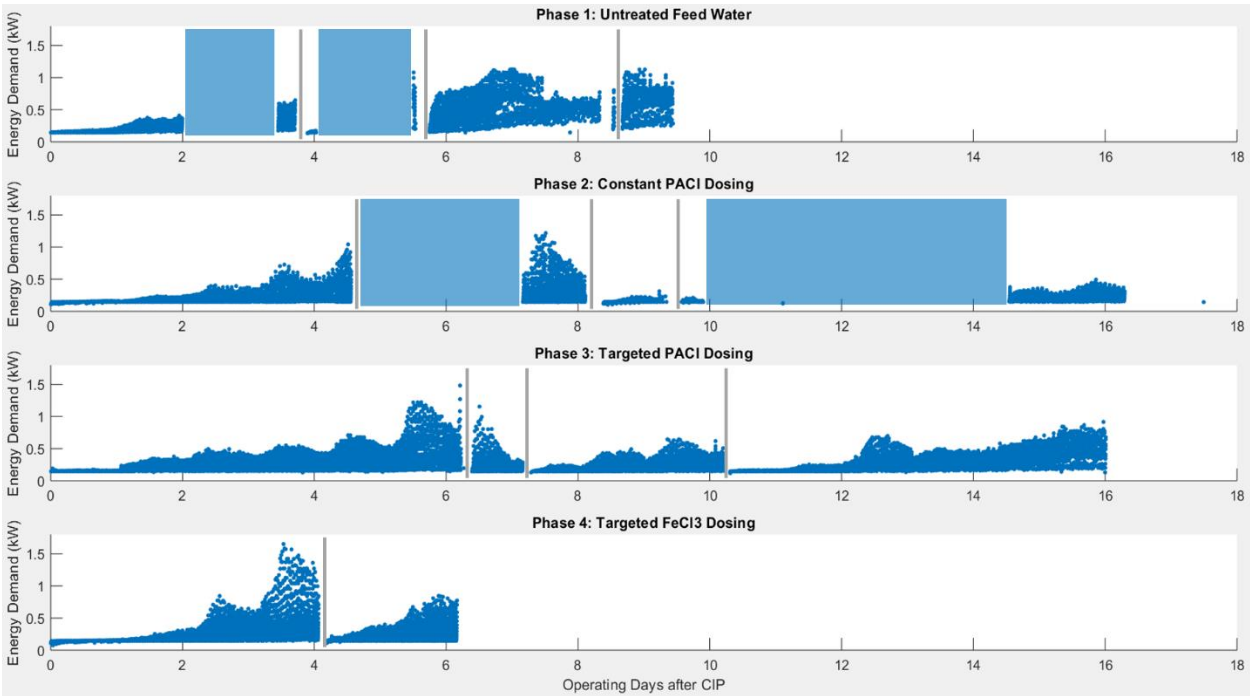
$$TMP > 7\,psi: \qquad Energy\ Demand\ (kW) = 0.1808\ \times TMP\ (psi) - 0.984$$

Based on these results, energy demand of the pilot filtrate pump increases more rapidly beyond 7 psi. Therefore, operating conditions that maintain the TMP below 7 psi could offer significant energy savings.

6.2.2 Energy Consumption during Pilot Study

The daily energy demand of the filtrate pump at West Basin during pilot testing is shown in Figure 59. These results were derived from the TMP performance data provided in Figure 43 and the energy to TMP correlation shown in Figure 58.

Figure 59: Energy Demand Curve for Ultrafiltration Filtrate Pumps



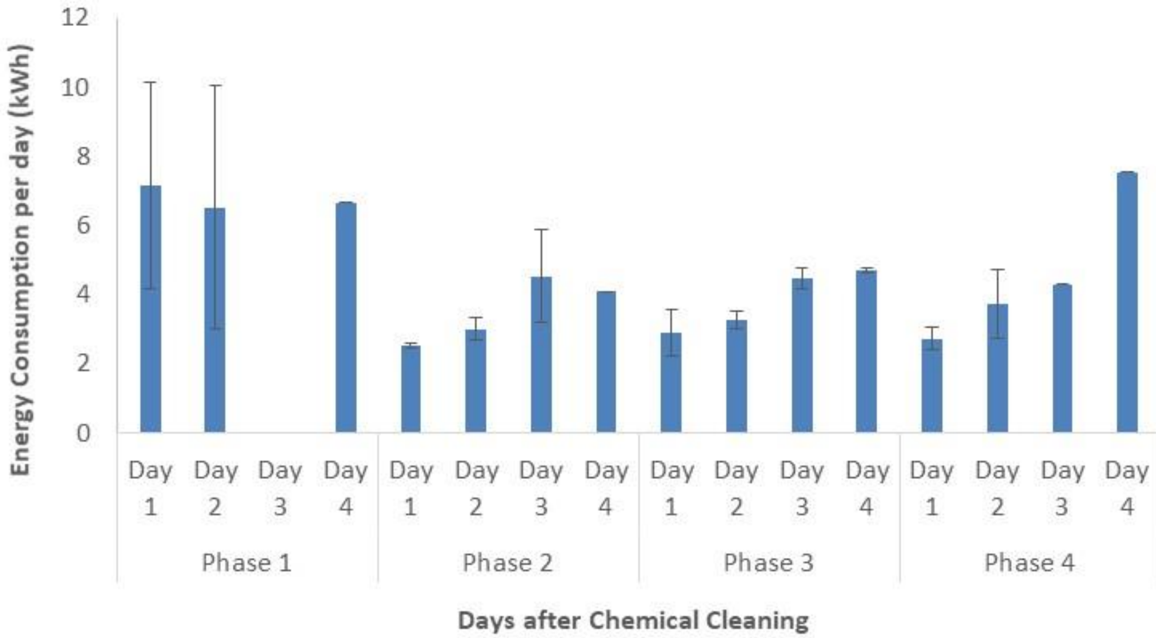
Based on the TMP performance of UF unit during Phase 1, 2, 3, and 4 of pilot testing at West Basin. Grey lines indicate time of EFM cleaning. Blue shading indicates that the pilot was running, but TMP recordings were not transmitted.

Source: Kennedy/Jenks Consultants

Figure 59 shows that in most instances, immediately following each CIP (at day 0) or an EFM (indicated by grey lines), energy demand of the filtrate pump changed dramatically. After a chemical cleaning, energy demands typically fell to 0.1 kW and remained low for several days before gradually increasing. Phase 2 and 3 were able to sustain lower energy demands for longer periods, while Phase 4 showed an increase in energy demand after two days of operation. For Phase 1, consecutive EFMs were not successful in reducing the energy demand, which remained higher over time. These energy profiles were derived from TMP performance during each phase and show that a very low energy demand can be sustained if the TMP is maintained below 7 psi.

Based on the TMP trends and the calculated energy demand throughout the study, the daily energy consumption of the filtrate pump was calculated during the first, second, third, and fourth day of operation following a chemical cleaning. Figure 60 and Table 12 summarize the energy consumption for each day following a chemical cleaning.

Figure 60: Energy Consumption of Filtrate Pump During Each Day Following a Chemical Cleaning (Clean In Place or Enhanced Flux Maintenance) at the West Basin Demonstration Site



Phase 1 (untreated feed water), Phase 2 (constant PACl dosing), Phase 3 (targeted PACl dosing), Phase 4 (targeted $FeCl_3$ dosing).

Source: Kennedy/Jenks Consultants

Table 12: Changes in Daily Energy Consumption at West Basin Pilot Demonstration

	Phase 1 Control	Phase 2 Constant PACl Dosing	Phase 3 Targeted PACl Dosing	Phase 4 Targeted $FeCl_3$ Dosing
Energy consumption per day based on initial membrane cleaning (kWh)	1.67	1.83	2.24	1.86
Average increase in energy consumption 1 day after cleaning (kWh)	5.49	0.68	0.26	0.88
Percent increase due to fouling (%)	328	37	12	47

Source: Kennedy/Jenks Consultants

During Phase 1 when the UF system filtered control feed water, the filtrate pump had an average energy consumption of 7.16 kWh during the first day after an EFM or CIP. When receiving a feed water with a constant or targeted coagulant dose (Phase 2 to 4) the MF system had a much lower energy demand of 2.51 to 2.74 kWh the first day after a chemical cleaning. The constant (Phase 2) and targeted (Phase 3) dosing of PACl were also able to sustain a lower energy consumption four days after a chemical cleaning.

Filtration with the control feed water resulted in 5.49 kWh of additional energy consumption, a 328 percent increase compared to baseline. Constant dosing with PACl resulted in 0.68 kWh of additional energy consumption, a 37 percent increase from membrane baseline. Targeted dosing with PACl had 0.26 kWh increased consumption, a 12 percent increase, while targeted $FeCl_3$ dosing resulted in 0.88 kWh of additional usage, a 47 percent increase from baseline. These results indicate that targeted PACl pretreatment is a viable option for decreasing the energy consumption of the pilot UF system for continuous operation requiring consecutive EFM washing. This reduction in energy consumption can be leveraged to reduce the frequency of EFMs performed, from every 24 hours to every 48 hours. Therefore, PACl pretreatment could result in an annual energy consumption of 1050 kWh/year for the pilot and an energy savings of 63 percent compared to the control. In addition, it has the added benefit reducing the need for cleaning chemicals, waste, and downtime for maintenance.

6.2.3 Full-Scale Projections for Energy Consumption

The energy savings observed during pilot demonstration can be translated to the full-scale operation at West Basin, which produces 14.4 MGD of barrier water. While rate of energy consumption was not monitored continuously on full-scale filtration pumps at West Basin, the energy efficiencies of the pumps were regularly tested by the facility. Based on this information, the average rate of energy consumption for operating the UF system at West Basin was determined to be 0.18 kWh/ 1000 gallons. Based on these values, a baseline energy consumption of 1.1 GWh per year was estimated for the barrier water production at West Basin. By implementing the targeted PACl coagulation system to the UF process, it is anticipated that TMP levels can be maintained below 7 psi, reducing energy consumption without hurting the TMP recovery of subsequent EFM washes. If full-scale verification shows similar results to the pilot findings, the anticipated 63 percent savings would translate to approximately 600 MWh/year in energy savings. Additional cost savings due to reduced washing, waste disposal, and membrane preservation are discussed in Chapter 7.

CHAPTER 7: Projected Benefits and Economic Evaluation

This chapter presents the benefits and economic implications of the targeted coagulant pretreatment system.

7.1 Approach

The cost of full-scale MF or UF operation with and without the targeted coagulation system was estimated. The cost analysis considered the savings in energy consumption, membrane replacement, and membrane chemical cleaning costs using predictive tools developed during pilot demonstration. The economic evaluation of the in-line coagulant pretreatment system included various factors such as size of the plant (flow rates being treated), types of membranes used (membrane replacement frequency and cost), cleaning procedures, and waste disposal. Cost savings from electricity use and other operating and maintenance expenses are counted against additional operating costs due to coagulant pretreatment to yield the overall projected annual savings for each plant. Many of the operating costs and savings used in this analysis are generated based on the performance of the membranes during pilot testing, which is then scaled up based on performance metrics monitored on the full-scale plant units. A sensitivity analysis was performed to account for the potential variation in coagulant polymer and electricity prices, as well as different outcomes for the anticipated improvement in membrane lifetime.

The capital cost for installing the targeted coagulation pretreatment includes the NanoSight NS500 tracking system, as well as the piping and instrumentation required for injecting the coagulant and facilitating contact time. The NanoSight instrument is priced at $75,000-$100,000, but other construction and instrumentation costs are dependent on the specific site layout and design of each plant and are not evaluated in this economic analysis. These estimates must be refined through site-specific analyses prior to installation of the system.

7.2 Orange County Water District Economic Analysis

The economic analysis for implementing the targeted coagulation dosing system includes the annual costs and savings associated with operating MF units with PACl pretreatment.

7.2.1 Orange County Water District System Assumptions

The economic analysis for OCWD considered the full-scale MF facility. The assumptions listed in Table 13 highlight the normal operating and maintenance procedures and costs associated with running the 100-MGD facility, as well as the coagulant and electricity pricing used for baseline cost estimation. Table 14 lists the changes in operating parameters due to implementing the targeted coagulation system, such as filtration TMP, energy usage, membrane cleaning frequency, and membrane replacement frequency.

Table 13: Assumptions About Full-Scale Microfiltration Operation at Orange County Water District

System Assumptions used for Economic Evaluation	
Flowrate	100 MGD
Average energy consumption for MF filtration	0.22 kWh/1000 gallons
Average energy consumption of MF backwash	15% of MF filtration[1]
Energy cost	0.095 $/kWh
Number of MF membrane modules	24, 627 modules
Price of MF modules	750 $/module
Baseline CIP frequency	Every 21 days or upon reaching 12.5 psi
Baseline MF membrane lifetime	7 years
Polymer chemical cost	0.30 $/lb[2]
Required chemical dose	9.5 mg/L of active polymer

[1]Based on Municipal Water Treatment Plant Energy Baseline Study (SBW Consulting Inc., 2006).

[2] CalChem Enterprises Inc., Modesto, CA.

Source: Kennedy/Jenks Consultants

Table 14: Projected Changes to the Operating and Maintenance Procedures of the Full-Scale Microfiltration System at Orange County Water District Based on Pilot and Full-Scale Investigation

Operating Changes due to Coagulant Pretreatment
32% reduction in electricity use 87% reduction in CIP frequency (CIP every 6 months) 67% reduction in membrane replacement (membrane lifetime of 21 years) Addition of coagulant polymer based on MF feed quality

Source: Kennedy/Jenks Consultants

The electricity costs for MF operation were calculated using the average rate of energy consumption for the full-scale filtrate pumps and the current OCWD contract price for energy (0.095 $/kWh). The energy consumption rate for the filtration pumps varies based on the age (or fouling-induced TMP increase) of the membranes and can range between 0.21 to 0.23 kWh/1000 gallons. For the purposes of this analysis, an average rate of 0.22 kWh/1000 gallons was assumed. OCWD currently owns 24, 627 MF modules, costing $750 each and lasting approximately 7 years before replacement. CIPs are performed every 21 days, or when terminal TMP is reached (12.5 psi). It is not atypical for older membranes to reach terminal TMP before the 21-day setpoint. Backwash and CIP waste from MF operation is diverted back to OCSD for treatment. For this analysis, costs associated with conveying the CIP and backwash waste were not considered.

Operating changes brought on by the implementation of the NTA coagulation system includes a reduction in operating TMP by 60 percent over approximately a 50-days period. This translated to 28 to 35 percent energy savings based of the age of the control membrane, or 32 percent savings on average. The reduction in physically irreversible membrane fouling due to targeted coagulation allows for an eight-time reduction in CIP frequency, from every 21 days to every 6 months. Based on pilot data and TMP profile projections, there is the potential for further reducing the CIP frequency to every 12 months. Prolonged on-site testing must be performed to obtain more insight into the feasibility of this plan. The build-up of irreversible fouling which gradually degrades operating performance (volume and quality), coupled with the loss of membrane integrity due to chemical and hydraulic aging (frequent chemical cleaning procedures and operating TMP) are the primary factors in the decision to replace MF membranes. The targeted coagulation system enhances filtrate flux performance due to reduced fouling build-up, operates at lower TMPs for longer durations (60 percent reduction), and reduces chemical exposure due to less frequent chemical cleanings (six times fewer). It is assumed that the synergistic effect of these improvements can extend the membrane lifetime by three times, to 21 years. Long-term studies will help to better define how these operating improvements translate to membrane lifetime projections. However, due to the difficulty in accurately estimating the prolonged membrane lifetime, a sensitivity analysis is used to consider improvements which achieve 25, 50, or 75 percent of this predicted lifetime as well. Finally, the targeted coagulation system requires the addition of PACl polymers. This incurred cost is estimated by a vendor to be $0.30/lb (CalChem Enterprise Inc., Modesto, CA). Based on the average particle load of source water at OCWD, and the optimal coagulant dosing curve developed for the MF membrane, the system will require 9.5 mg/L of active polymer on average. No benefits were considered for the operation of the RO system, as MF filtrate quality for the treated and untreated pilot conditions were similar.

7.2.2 Orange County Water District Economic Feasibility Analysis

Table 15 summarizes the estimated savings and additional costs due to the targeted coagulation pretreatment step.

Table 15: Economic Analysis for Full-Scale Plant Operation At Orange County Water District

Savings in Electricity, O&M Costs, and Chemical Costs	Control	Targeted Coagulation System
Energy Use for MF (kWh/yr)	8,019,300	5,465,100
Energy Use for MF Backwash (kWh/yr)	1,202,900	819,800
Total Energy Use for MF Filtration and Backwash (kWh/yr)	9,222,200	6,284,900
Total Energy Cost ($/yr)	876,100	597,100
Energy Savings in MF due to the Installation of Proposed System (kWh/yr)		2,937,300
Savings in Electricity Cost ($/yr)		$279,000
Chemical Cost for Cleaning ($/yr)	764,000	84,000
Savings in Chemical Cost ($/yr)		$680,000
Membrane Replacement Cost ($/7 yrs)	18,470,250	6,156,750
Savings in Membrane Replacement Cost ($/yr)		$1,759,100
Waste Disposal Costs ($/yr)	-	-
Total Savings ($/yr)		$2,718,000
Chemical Cost for Pre-treatment Chemical Demand (g/yr)	-	2,621,400,000
Chemical Cost for Pre-treatment Chemical Demand (lb/yr)	-	7,023,400
Chemical Cost for Pre-treatment Total Spending ($/yr)		$2,107,000
Total Annual Savings		$611,000

Source: Kennedy/Jenks Consultants

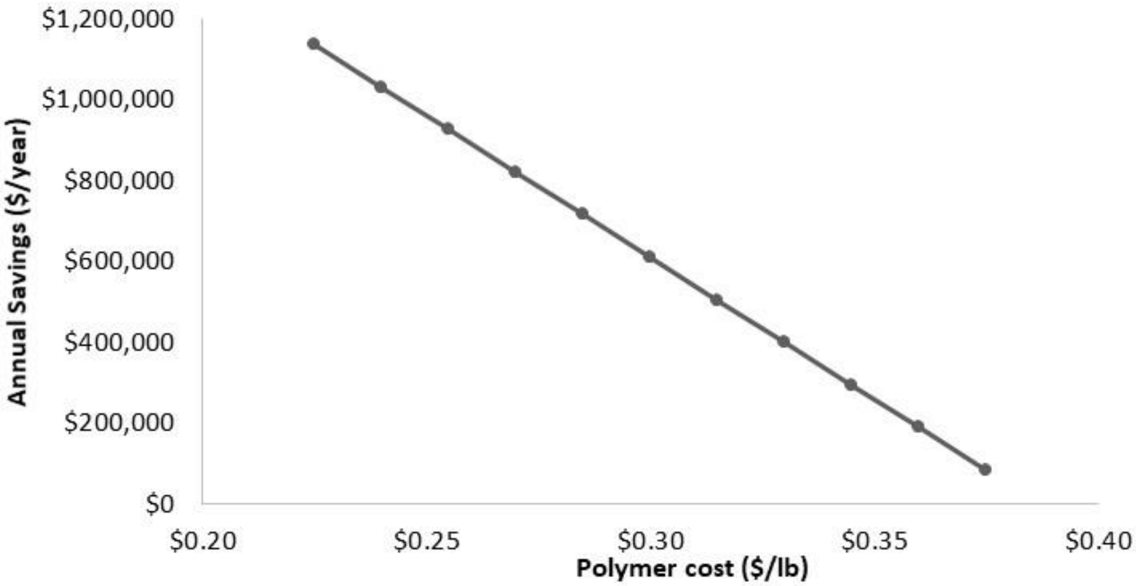
The reduction in physically irreversible membrane fouling due to targeted coagulation allows for a 89 percent reduction in CIP frequency, resulting in a savings of $680,000 per year for chemical cleaning costs. The targeted PACl pretreatment could result in energy savings of 2,900 MWh per year for the 100-MGD plant, or $279,000 of savings at the current electricity price of $0.095/kWh. This does not include possible energy savings from air scouring, which has the potential to offer additional savings if operators conclude that backwashing can also be implemented less frequently without detriment. The most significant savings however come from membrane replacement costs, which can typically amount to $2.6 million/year to replace the OCWD fleet of MF modules every 7 years. It is estimated that the increased membrane longevity can result in savings of $1.76 million a year. This yields a total of $2,718,000 in savings for energy and other operating and maintenance costs.

The additional incurred costs from purchasing and injecting PACl depends on the particle concentration of secondary treated feed water entering the plant, as well as the chemical cost of the polymer. At the current average daily particle concentration and vendor estimated polymer cost, the total chemical cost is estimated to be $2,107,000 per year. Therefore, the overall annual savings will be $611,000.

7.2.3 Orange County Water District Sensitivity Analysis

Sensitivity analyses were performed to account for the variability in electricity and polymer prices, as well as the anticipated membrane lifetime improvement that could greatly impact the overall feasibility of the project. Figure 61 shows how a ±25 percent fluctuation in polymer costs can impact annual savings, and Figure 62 shows annual savings based on increasing energy prices. Figure 63 shows the effect of membrane lifetime on annual savings, if membrane lifetime was improved by varying degrees.

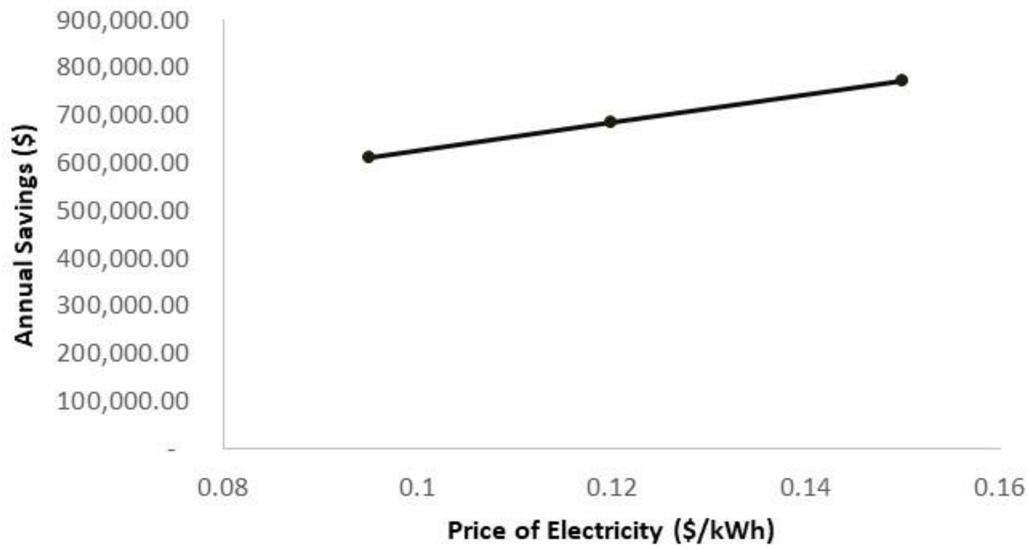
Figure 61: Effect of Polymer Price Change (±25 percent) on Orange County Water District Annual Savings



Source: Kennedy/Jenks Consultants

At the current estimated polymer price ($0.30/lb), a 5 percent change in polymer price (± $0.015/lb) could result in an increase or decrease in annual savings of $106,000, which demonstrates that the process savings are susceptible to changes in the market price. Therefore, a concerted effort should be made to maintain polymer costs below the breakeven price of $0.39/lb and to limit any waste by capping the amount of polymer injection during high particle loadings in the incoming feed.

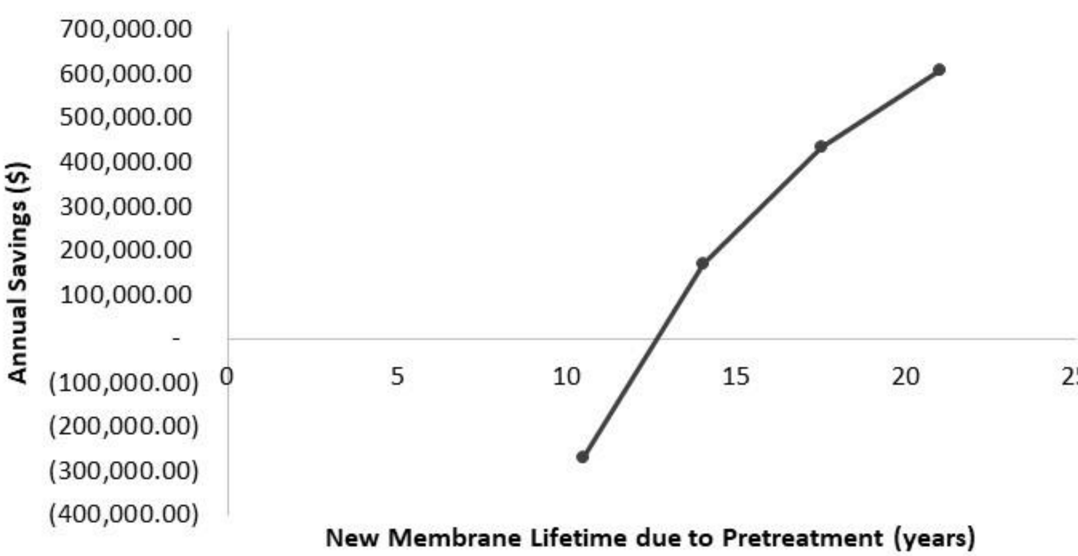
Figure 62: Effect of Electricity Price Change on Orange County Water District Annual Savings



Source: Kennedy/Jenks Consultants

Electricity is currently purchased by OCWD at a rate of $0.095/kWh. However, with rising energy demands, increasing electricity prices are an important factor to account for. Figure 62 shows how increasing electricity prices could results in higher potential annual savings. Potential annual savings rise from $611,000 for electricity prices at $0.095/kWh, to $684,500 and $772,600 for electricity prices of $0.12/kWh and $0.15/kWh, respectively. Therefore, a forecasted rise in electricity prices could further incentivize improvements in energy efficiency.

Figure 63: Effect of Membrane Lifetime on Orange County Water District Annual Savings



Source: Kennedy/Jenks Consultants

The average membrane lifetime (or membrane replacement frequency) for the MF modules currently installed at OCWD is 7 years. Figure 63 shows how the annual savings for OCWD can change if membrane lifetime was extended due to the proposed technology, by 3.5 to 14 years (achieving 25 percent to 100 percent of the predicted improvement). Results from the sensitivity analysis showed that if the membrane lifetime extended to 14 years (50 percent of the anticipated lifetime improvement), then annual savings could be $170,000 per year. If membrane lifetime reaches 17.5 years (75 percent of the anticipated lifetime improvement), the annual savings could be $435,000/year. For this analysis, a membrane lifetime of 12.5 years (40 percent of the anticipated improved lifetime) was determined as the breakeven point for annual costs versus savings. Therefore, while membrane lifetime is difficult to accurately predict, the drastic improvements observed in membrane TMP can offer large savings by lowering membrane replacement costs by varying degrees.

7.3 West Basin Economic Analysis

The economic analysis for implementing the targeted coagulation dosing system includes the annual costs and savings associated with operating UF units with PACl pretreatment.

7.3.1 West Basin System Assumptions

The economic analysis for West Basin considered the UF operating costs for 14.4 MGD of flow used to produce barrier water.

Table 16 lists the assumptions used to perform an economic analysis for operating and maintenance procedures at West Basin's full-scale UF facilities.

Table 16: Assumptions About Full-Scale UF Operation (Barrier Water Production) at West Basin

System Assumption	Value
Flowrate	14.4 MGD
Average energy consumption for UF filtration	0.18 kWh/1000 gallons
Average energy consumption of UF backwash	15% of MF filtration[1]
Energy cost	0.090 $/kWh
Number of UF membrane modules	2,496 modules
Price of UF modules	950 $/module
Baseline CIP frequency	Every 30 days or upon reaching 12.5 psi
Baseline EFM frequency	Every 24 hours
Baseline UF membrane lifetime	6 years
Polymer chemical cost	0.30 $/lb
Required chemical dose	7.7 mg/L of active polymer

Source: Kennedy/Jenks Consultants

Table 17 lists the changes in operating parameters due to implementing the targeted coagulation system, such as filtration TMP, energy usage, membrane cleaning frequency, and membrane replacement frequency.

Table 17: Projected Changes to the Operating and Maintenance Procedures of the Full-Scale UF System (Barrier Water Production) at West Basin, Based on Pilot Investigation

Operating Changes due to Coagulant Pretreatment
63% reduction in electricity use
50% reduction in EFM frequency (every 48 hours)
50% reduction in membrane replacement (membrane lifetime of 12 years)
Addition of coagulant polymer based on MF feed quality

Source: Kennedy/Jenks Consultants

The electricity costs for UF operation used the average rate of energy consumption for the full-scale filtrate pumps (0.18 kWh/1000 gallons of flow) and the current electricity price (0.09 $/kWh). West Basin currently owns 2,496 UF modules in its Phase IV barrier water treatment system, each commercially priced at $950 by Scinor Water America LLC. Membrane lifetime can vary greatly based on site-specific source water quality and cleaning procedures. Previous membranes installed at West Basin had an average lifespan of 3 years. PVDF membranes are estimated to last 5 to 7 years with the challenging source water at West Basin, and for the purposes of this economic analysis, the new PVDF membranes are conservatively assumed to last 6 years before replacement. CIPs are performed when terminal TMP is reached (12.5 psi) approximately every 30 days, and EFMs are performed daily. Backwash and high pH CIP waste from UF operation is returned to pretreatment clarifiers in the Title-22 treatment train, and low pH CIP waste is neutralized before being discharged to the sewer. For the purposes of this economic evaluation, savings of waste water disposal is not considered.

In the case of implementing the targeted coagulation system (with PACl) for the UF facilities at West Basin, it is assumed that the pump energy savings observed during pilot studies translate directly to the full-scale, providing a 63 percent reduction in electricity use. This assumption requires full-scale validation and should be tested in future studies. The EFM frequency was assumed to be reduced from every 24 hours to every 48 hours, due to the improvements in TMP and EFM cleaning performance observed during pilot demonstration. A 50 percent reduction in membrane replacement was assumed for the improved performance in operating TMP (43 percent decrease in TMP rate of increase) and reduced EFMs (50 percent fewer chlorine exposure events). The targeted coagulation system requires the addition of PACl polymers, which will incur a cost at a rate of $0.30/lb of polymer. Based on the average particle load of source water at West Basin, and the optimal coagulant dosing curve developed for the UF membrane, the system will require 7.7 mg/L of active polymer on average

7.3.2 West Basin Economic Feasibility Analysis

A preliminary economic analysis was performed to evaluate the feasibility of applying the in-line targeted coagulation as a pre-treatment step. Table 18 summarizes the current annual costs at West Basin for producing barrier water (14.4 MGD). The estimated savings are calculated based on data collected from the pilot system. In this economic analysis, no benefits were considered for the operation of the RO system.

Table 18: Economic Analysis for Full-Scale Plant Operation at West Basin

Savings in Electricity and other O&M Costs	Control	Targeted Coagulation System
Energy Use for UF (kWh/yr)	951,700	352,100
Energy Use for UF Backwash (kWh/yr)	142,700	52,800
Total Energy Use for UF Filtration and Backwash (kWh/yr)	1,094,400	404,900
Total Energy Cost ($/yr)	98,500	36,400
Energy Savings in UF due to the Installation of Proposed System (kWh/yr)		689,500
Savings in Electricity Cost ($/yr)		$62,000
Chemical Cost for Cleaning ($/yr)	200,000	100,000
Savings in Chemical Cost ($/yr)		$100,000
Membrane Replacement Cost ($/ 8 yrs)	2,371,200	1,185,600
Savings in Membrane Replacement Cost ($/yr)		$197,600
Waste Disposal Costs ($/yr)	-	
Total Savings in Membrane Treatment ($/yr)		$359,600
Chemical Cost for Pre-treatment Chemical Demand (g/yr)	-	305,962,300
Chemical Cost for Pre-treatment Chemical Demand (lb/yr)	-	819,700
Total Chemical Spending ($/yr)		$245,900
Total Annual Savings		$113,700

Source: Kennedy/Jenks Consultants

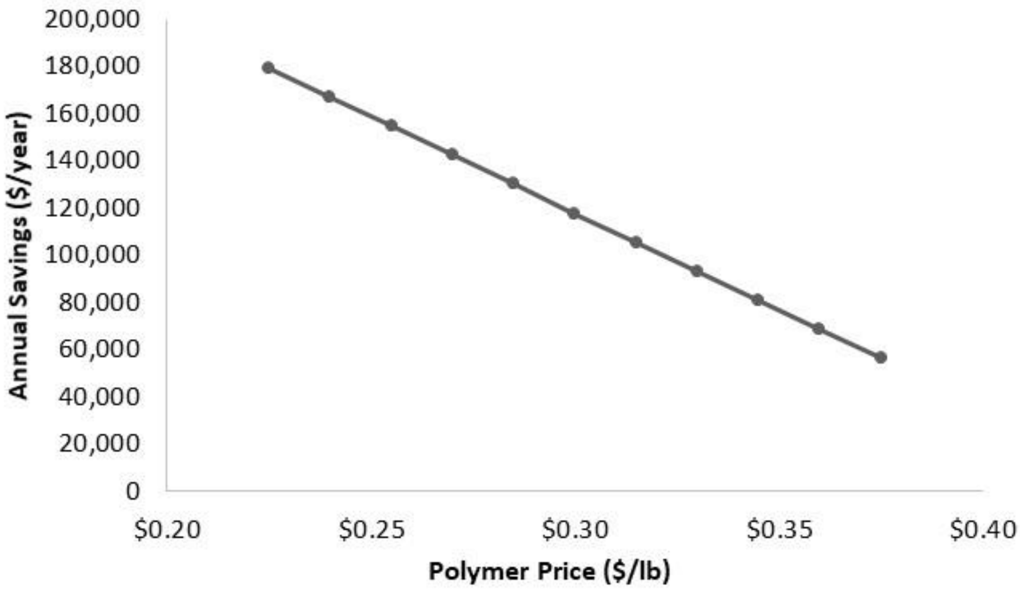
The 63 percent in energy savings translates to $62,000 and 689 MWh of projected energy savings per year for 14.4 MGD of UF operation. Reducing chemical cleaning by extending the time between EFMs is estimated to save $100,000 in chemical costs and $197,000 due to reduced membrane replacement. This yields a total of $359,600 per year in potential savings for energy and other operating and maintenance costs.

The additional incurred costs from purchasing and injecting PACl depends on the particle concentration of secondary treated feed water entering the plant, as well as the chemical cost of the polymer. At the current average daily particle concentration and vendor estimated polymer cost, the total chemical cost is estimated to be $245,900 per year. Therefore, the overall annual savings will be $113,700 for the 14.4 MGD UF facility.

7.3.3 West Basin Sensitivity Analysis

A sensitivity analysis was performed to account for the variability in polymer and electricity prices, as well as the anticipated membrane lifetime improvement that could impact the overall feasibility of the project for West Basin. Figure 64 shows how a ±25 percent fluctuation in polymer costs can impact annual savings, and Figure 65 shows annual savings based on increasing energy prices. Figure 66 shows the effect of membrane lifetime on annual savings, if membrane lifetime was improved by varying degrees.

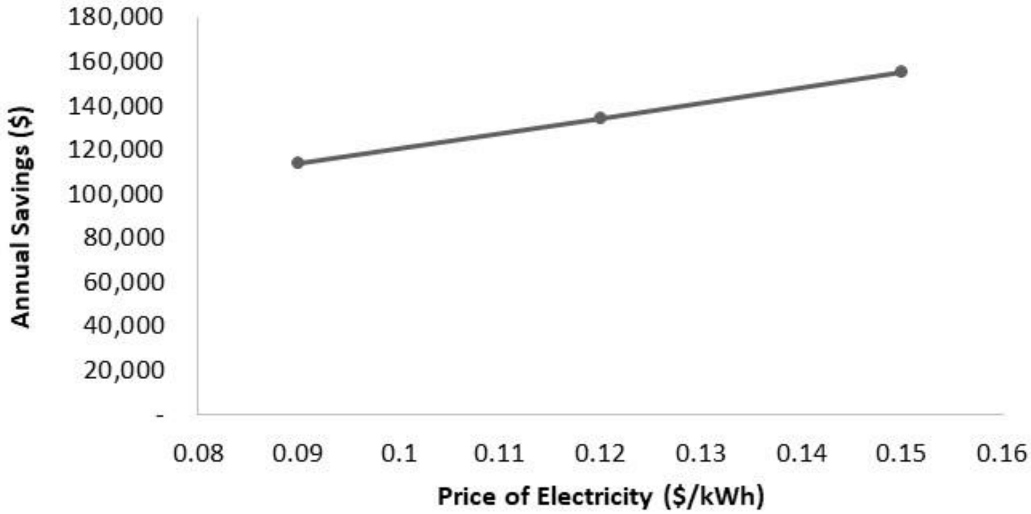
Figure 64: Effect of Polymer Price Change (±25 percent) on West Basin Annual Savings



Source: Kennedy/Jenks Consultants

Figure 64 shows that a 5 percent change from the current polymer price estimate of $0.30/lb (± $0.015) could result in an increase or decrease of $12,300 in annual savings for UF operation at West Basin. However, the polymer price can increase up to $0.44/lb without eliminating the overall savings.

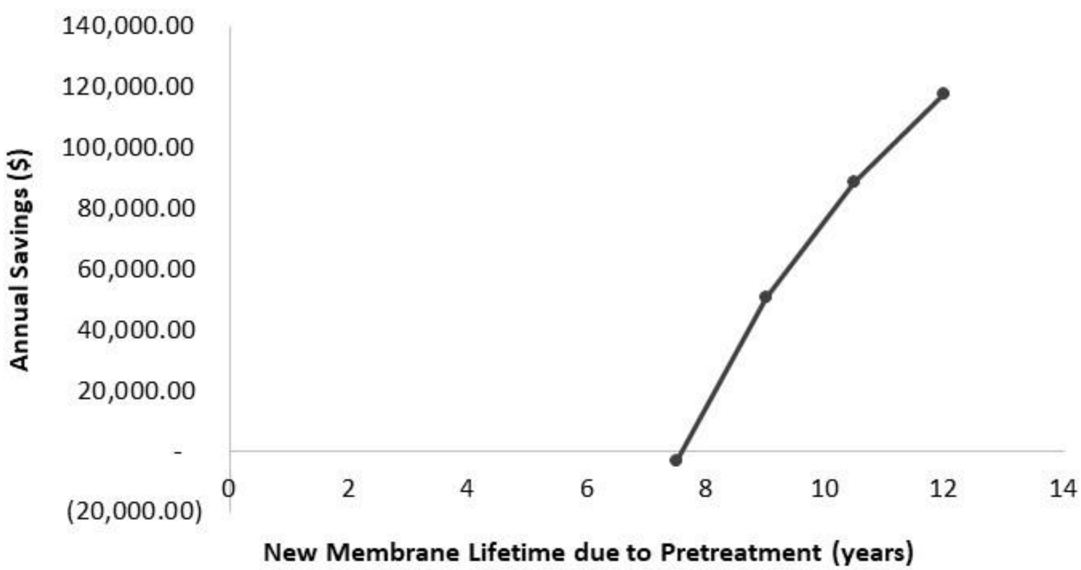
Figure 65: Effect of Electricity Price Change on West Basin Annual Savings



Source: Kennedy/Jenks Consultants

Electricity is currently purchased for the Phase IV processes at West Basin at a rate of $0.09/kWh. Similar to the OCWD analysis, Figure 65 shows that as the electricity price rises from $0.9/kWh to $0.12/ kWh, annual savings would increase to $134,400 per year and at $0.15/kWh, increase to $155,100 per year. Therefore, the rising electricity prices could further incentivize improvements in energy efficiency.

Figure 66: Effect of Membrane Lifetime on West Basin Annual Savings



Source: Kennedy/Jenks Consultants

For the purposes of this analysis, the average membrane lifetime for the UF modules currently installed at West Basin is predicted to be 6 years. Figure 66 shows how the annual savings for West Basin can change if membrane lifetime (or membrane replacement frequency) was extended due to the proposed technology, by 1.5 to 6 years (or 25 percent to 100 percent of the predicted improvement). Results from the sensitivity analysis show that if the membrane lifetime extended to 9 years (50 percent of the anticipated improvement), then annual savings could be $51,000 per year. If membrane lifetime reaches 10.5 years, the annual savings could be $89,000/year. For this analysis, a membrane lifetime of 7.5 years (25 percent of the anticipated improved lifetime) was determined as the breakeven point for annual costs versus savings. Therefore, while membrane lifetime is difficult to accurately predict, the reduced rate of TMP increase and potential reduction in CIP frequency can result in large savings by reducing membrane replacement frequency.

7.4 Statewide Cost Savings

A survey by the American Membrane Technologies Association (AMTA, 2014)[2] indicates that there are approximately 100 microfiltration/ultrafiltration treatment plants with a total design capacity of approximately 400 MGD in California. Industrial membrane treatment facilities are not included in this list. Nearly 90 percent of the flow is treated by MF/UF systems with or without downstream RO treatment. These estimates do not include energy conservation in industrial membrane processes or membrane bioreactors used in wastewater treatment. Energy requirements for MF facilities can vary depending on the water quality characteristics, and savings due to improved membrane operation can be highly site-specific. OCWD was used as a model to approximate an average for expected state-wide savings in California. Potential improvements due to the proposed technology consists of 32 percent energy reduction, 89 percent less chemical cleaning, and 67 percent less membrane replacement frequency.

Table 19 shows the list of system assumptions based on the OCWD case-study, applied to the state-wide use of LPMF for water reclamation. Recent projections on water reuse market in California is estimated to increase by 58 percent between 2016 and 2026 (Water World, 2016). However, the installed capacity of 400 MGD is used as the basis for economic evaluation in this study. Estimated energy savings for treating 400 MGD of water via microfiltration due to the implementation of the proposed technology are summarize in Table 20.

[2] www.AMTAOrg.Com. Accessed in December, 2014.

Table 19: State-Wide Microfiltration/Ultrafiltration Operating Conditions Based on Orange County Water Department Case-Study

System Assumptions Used for Economic Evaluation	
Flowrate	400 MGD
Average energy consumption for MF filtration	0.22 kWh/1000 gallons
Average energy consumption of MF backwash	15% of MF filtration
Energy cost	0.095 $/kWh
Number of MF membrane modules	93, 800 modules
Price of MF modules	750 $/module
Baseline CIP frequency	Every 21 days or upon reaching 12.5 psi
Baseline MF membrane lifetime	7 years
Polymer chemical cost	0.30 $/lb
Required chemical dose	9.5 mg/L of active polymer

Source: Kennedy/Jenks Consultants

Table 20: Statewide Cost Savings Due to Targeted Coagulation System, Based on Orange County Water District Model

Savings in Electricity and Other O&M Costs	Control	Targeted Coagulation System
Energy Use for MF (kWh/yr)	32,077,200	21,860,500
Energy Use for MF Backwash (kWh/yr)	4,811,600	3,279,000
Total Energy Use for MF Filtration and Backwash (kWh/yr)	36,888,700	25,139,600
Total Energy Cost ($/yr)	3,504,400	2,388,300
Energy Savings in MF due to the Installation of Proposed System (kWh/yr)		11,749,200
Savings in Electricity Cost ($/yr)		$1,116,200
Chemical Cost for Cleaning ($/yr)	3,056,000	336,200
Savings in Chemical Cost ($/yr)		$2,719,800
Membrane Replacement Cost ($/7 yrs)	73,881,000	24,627,000
Savings in Membrane Replacement Cost ($/yr)		$7,036,300
Waste Disposal Costs ($/yr)	-	-
Total Savings ($/yr)		$10,872,300
Chemical Cost for Pre-treatment Chemical Demand (g/yr)	-	10,485,720,000
Chemical Cost for Pre-treatment Chemical Demand (lb/yr)	-	28,093,600
Chemical Cost for Pre-treatment Total Spending ($/yr)		$8,428,100
Total Annual Savings		$2,444,000

Source: Kennedy/Jenks Consultants

The state-wide annual savings from implementing the targeted coagulation system consists of savings in energy ($1,116,200), chemical cleaning costs ($2,719,800), and membrane replacement costs ($7,036,300), as well as expenditures for purchasing polymers ($8,428,100). This results in potential annual savings of approximately **$**2.4 million per year for the state of California, if the OCWD MF model was applied. This annual savings estimate is based on a 100 percent market penetration. The wide-spread adoption of this technology throughout California will rely on several conditions. Initial adoption by larger utilities is important to show that significant savings over conventional methods (at least 20 percent) is possible. A proven track record of no negative environmental impacts and the ability to establish a pre-negotiated cost for coagulant polymer will support further adoption of this technology. Increasing membrane costs and electricity costs, as well as market assurance that chemical costs will not fluctuate will increase the incentive for implementing the proposed strategy.

The economic analysis between the two demonstration sites also showed that the estimated savings are very site-specific and will vary depending on local costs and plant operating conditions. Operating conditions that are likely to have the most significant impact on other plants' annual savings are local polymer costs, electricity costs, the source and quality of the feedwater used at that site, and the type of membrane currently used for filtration (that is, pore size and operating protocol).

CHAPTER 8: Production Readiness Plan

This chapter presents the production readiness plan of the targeted coagulant pretreatment system and the implementation of the Nanoparticle Tracking Analysis (NTA) technique in the water treatment train.

Dosing pumps and control systems used for administering coagulation pretreatment are commonly used items within water treatment plants and are considered fully developed and readily available for implementation. The NTA instrument used in this study, an NS500 model from Malvern Panalytical Ltd., was a novel addition to the pretreatment train. It was used without any hardware modifications; however, a special version of software was installed to allow for continuous sampling and data output. This instrument was designed for laboratory conditions; therefore, some adaptations such as a weather-proof enclosure would be necessary to enable long-term use of the device in outdoor environments for water treatment facilities. Control signals to the coagulant dosing pump were provided with a custom interface box using commonly available components to output a 0-5 V control signal.

Subsequent to the study, the NS500 model reached end of sale and is no longer available. The current model, NS300, does not include the peristaltic sample and rinse solution pumps that were an important part of the NS500 operation. The NS300 has the same or better sensor and components, and the same software, so measurement capabilities would not be affected.

To develop a commercially available system suitable for the application described in this study, Malvern Panalytical Ltd. would have to engineer a system that includes the peristaltic sampling and rinsing mechanisms of the NS500, with minor improvements. This new system will incorporate the sensor, pumps and/or valves to introduce sample at the appropriate (low) pressure and flowrate through the measurement chamber, pumps and/or valves for passing a rinse solution through the measurement chamber on a regular basis, and a suitable environmental enclosure to protect against temperature, humidity, and dust. The current software version also needs to be modified to work on a continuous basis, rather than the old prototype version used in the study.

This development project is undergoing discussion at Malvern Panalytical. As the sensor and analytical technique have already proven to be effective for the intended use, the other mechanical modifications are minor and do not pose a technical risk should the development project be approved. The estimated cost of such unit is estimated to be $75,000 to $100,000. In a 2020 update, Malvern indicated that it can install the NS300 units if water reclamation facilities are interested in implementing the colloidal particles monitoring technology to minimize membrane fouling.

In addition to the commercial development of the NTA unit, the path-to-market of the proposed strategy also depends on the interest shown from the wastewater treatment and recycled water plants. The industry partners involved in this study, OCWD and West Basin, were extremely pleased with the results of their respective pilot tests and have expressed interest in continuing their investigation. OCWD is currently performing on-site investigations to evaluate other potential benefits of the NTA technology, such as its use for more accurate quantification of virus removal. Other on-site investigations by interested plants may include additional assessment of source-water quality and the environmental implications of coagulant-contaminated backwash water. Correspondence with vendors to develop a coagulant price model, establishing public acceptance, and developing appropriate chemical handling procedures are also important requirements on the path-to-market for this technology. Finally, the plants will be required to submit a new operating plan and other necessary amendments to the Division of Drinking Water (DDW). The presence of multiple coagulant vendors for PACl and other competitors that develop colloidal particle instruments will ensure costs for this project are controlled during future operations.

CHAPTER 9: Technology Transfer

The technology transfer of an emerging technology in the wastewater treatment and water recycling industry typically begins with conference presentations. It is common that water and wastewater treatment staff attend conferences and associated exhibits to know more about new products, and request testing new products and technologies for their specific plants. This is followed by on-site presentations and site visits by interested utilities. Permitting issues are also assessed, and in some select situations, an on-site demonstration/piloting study is commissioned.

The findings from this study have already been shared with a variety of audiences. In order to define the operational and maintenance benefits of the targeted coagulation system, the project team developed a comprehensive presentation aimed at industry professionals to share project findings and outcomes. To date, the finding from this study have been presented or accepted for presentation in the following conferences:

- Safarik, J. et al. 2017. *Online Monitoring to Detect and Remove Colloidal Particles to Improve Membrane Treatment*. California Annual Water Reuse Conference, San Diego, CA. 19 – 21 March, 2017.
- Safarik, J., Ganesh, R., and Plumlee, M. 2019. Removal of Colloidal Particles through Online Monitoring to Lower Microfiltration Membrane Fouling. Accepted for presentation at American Membrane Technology Association Conference, New Orleans, LA. 26 – 28 February, 2019.
- Ganesh, R., Safarik, J. and Plumlee, M. 2019. Colloidal Particles Removal through Online Monitoring to Lower Membrane Fouling. California Annual Water Reuse Conference, San Diego, CA. 17 – 19 March, 2019.
- Ganesh, R., Safarik, J. and Plumlee, M. 2019. Improving MF and UF Membrane Energy Efficiency Through Real-Time Colloidal Particle Monitoring. California-Nevada Section American Water Works Association Annual Fall Conference, San Diego, CA. 21 – 24 October, 2019.

The abstracts for these conferences are presented below. The presentation slides are included in Appendix G.

9.1 Conference Abstracts

- Safarik, J. et al. 2017. *Online Monitoring to Detect and Remove Colloidal Particles to Improve Membrane Treatment*. California Annual Water Reuse Conference, San Diego, CA. 19 – 21 March, 2017.

  The reclamation of wastewater to allow water reuse is critical to ensuring California's water security in the face of droughts and increasing water demand. However, membrane filtration for the advanced treatment of wastewater, allowing reuse, is energy intensive. This is largely due to the fouling of the membranes over time. Recent studies have shown that membrane fouling and associated increase in energy demand is largely due to deposition of colloidal particles (particles in nanoscale size) in the feed water inside the membrane pores (pore plugging) which increases the transmembrane pressure (TMP).

Currently, no techniques are available to directly measure colloidal particles in the feed water, which will facilitate appropriate pretreatment to remove these particles and prevent their deposition in membrane pores. Surrogate techniques such as measurement of turbidity or organic content are sometimes used for monitoring "foulant" levels (that is,, compounds that "foul" the membranes). These techniques do not correlate well with levels of colloidal particles and hence, lead to ineffective fouling control and inefficient energy use. Because of these limitations many utilities do not pretreat the feed water prior to membrane treatment.

Orange County Water District and Kennedy/Jenks Consultants are involved in field demonstration of a technology that directly measures the colloidal particles concentration and size distribution in the feed water, and hence, can facilitate pretreatment for targeted removal of these particles. This technology (Nanoparticles Tracking Analysis (NTA) by Malvern Instruments) uses light scattering technique to detect colloidal size particles.

The first phase of this ongoing pilot study involves benchmarking colloidal particle profile (concentration and size distribution) in the MF membrane feed water, membrane filtrate, and RO permeate, and documenting corresponding transmembrane pressure (TMP). The data over several weeks of monitoring indicated that the colloidal particles concentration in the feed water varied by about three folds over time. However, the particle size distribution (40 to 1,000 nm), did not significantly vary. Further, no apparent diurnal differences or differences in profile over the days of week were observed. MF permeate contained approximately 3 to 5 percent of the colloidal particle in the feed water. Most of the particles in the permeate are less than 100 nm in size. After three CIP cycles of benchmarking, the pilot will be operated in "treatment phase". In this phase, appropriate pretreatment (coagulant) dose will be triggered to remove colloidal particles in the feed water, based on the profile detected by NTA. The pretreated water will then be treated by microfiltration (MF) membranes. The difference in TMP of untreated (benchmark phase) and pre-pretreated (treatment phase) feed water will be used to estimate the fouling reduction and energy savings due to implementation of the proposed technology. The pilot study data will be used to estimate capital and O&M cost requirements and to perform cost-benefit analyses for the proposed technology. The pilot study at OCWD is expected to be completed by March 2017.

- Safarik, J., Ganesh, R., and Plumlee, M. 2019. *Removal of Colloidal Particles through Online Monitoring to Lower Microfiltration Membrane Fouling*. Accepted for presentation at American Membrane Technology Association Conference, New Orleans, LA. 26 – 28 February, 2019.

  There is an increased emphasis on indirect and direct potable reuse (IPR/DPR) in recent years to meet future water demand. Microfiltration (MF) and ultrafiltration (UF) membranes are integral components of most IPR/DPR processes. However, fouling of these membranes results in increased energy demand, cleaning, and membrane replacement frequency. Recent studies have shown that MF/UF membrane fouling is largely due to deposition of feed water colloidal particles (typically <200 nm) inside the membrane pores.

Currently, no online techniques are available to directly measure colloidal particles in the feed water, which would facilitate appropriate pretreatment and real-time control to remove these particles and prevent their deposition in membrane pores. Surrogate constituents (for example turbidity or organic content) sometimes measured for monitoring "foulant" levels do not correlate well with the levels of colloidal particles and hence, lead to ineffective fouling control. Because of these limitations many utilities do not pretreat the feed water (for example, coagulation of particles) prior to MF/UF treatment.

Orange County Water District and Kennedy/Jenks Consultants completed field demonstration of a real-time monitoring technology, Nanoparticles Tracking Analysis (NTA) by Malvern Instruments, that measures colloidal particles concentration and size distribution in the feed water via a light scattering technique.

The project consisted of i) measurement of diurnal changes in colloidal particles profile in membrane feed water using NTA, ii) bench scale studies for determination of the relationship between colloidal particles and optimum coagulant dose for MF fouling reduction, iii) integration of a feed-forward loop-based chemical feed system that delivers coagulant dose based on feed water colloidal particles profile and concentration and iv) cost-benefit analyses for implementation of this technology. Two MF pilot units fitted with polypropylene membrane elements (typical pore size ~200 nm), one operating as control and another receiving coagulant (commercial polyaluminum chloride), were operated in parallel. The overall results of the project indicated that:

- Diurnal variations existed in colloidal particles profile in the feed water, with peak particle levels about 4 to 5 times higher than during the non-peak period,
- The algorithm developed through bench scale testing was effective in optimizing coagulant dosing,
- The fouling potential (transmembrane pressure) for the coagulant-dosed pilot was only about 20 percent of the control pilot after six weeks. Further, the controlled release of coagulants resulted in minimal bleeding of aluminum in the MF effluent.
- Preliminary economic evaluation using OCWD's full scale plant data indicated that the proposed approach can potentially result in a return on investment (ROI) of less than one year through decreased MF feed pressure, taking into account coagulant costs.

- Ganesh, R., Safarik, J. and Plumlee, M. 2019. *Colloidal Particles Removal through Online Monitoring to Lower Membrane Fouling*. California Annual Water Reuse Conference, San Diego, CA. 17 – 19 March, 2019.

  There is an increased emphasis on indirect and direct potable reuse (IPR/DPR) in recent years in order to meet the future water demand and increase water security. Microfiltration (MF) and ultrafiltration (UF) membranes are integral components of most IPR/DPR processes. However, fouling of these membranes results in increased energy demand, increased cleaning, and membrane replacement frequency. Recent studies have shown that MF/UF membrane fouling is largely due to deposition of feed water colloidal nanoparticles (typically <200 nm) inside the membrane pores (pore plugging).

Currently, no techniques are available to directly measure colloidal particles in the feed water, which will facilitate appropriate pretreatment to remove these particles and prevent their deposition in membrane pores. Surrogate techniques such as measurement of turbidity or organic content are sometimes used for monitoring "foulant" levels in the feed water. These techniques do not correlate well with the levels of colloidal particles and hence, lead to ineffective fouling control. Because of these limitations many utilities do not pretreat the feed water prior to MF/UF membrane treatment.

Orange County Water District and Kennedy/Jenks Consultants are collaborating on a field demonstration of a real-time monitoring technology that measures the colloidal particles concentration and size distribution in the feed water. This approach has the potential to facilitate pretreatment via coagulation or other means for enhanced removal of these particles. This technology, Nanoparticles Tracking Analysis (NTA) by Malvern Instruments, uses a light scattering technique to detect colloidal size particles.

The project work consisted of i) monitoring and measurement of diurnal changes in colloidal particles profile (concentration and size distribution) in membrane feed water using NTA, ii) determination of the relationship between colloidal particle profile and optimum coagulant dose for fouling reduction through bench scale studies, iii) integration of a feed-forward loop-based chemical feed system that delivers coagulant dose based on feed water colloidal particles profile and iv) performance of cost-benefit analyses for implementation of this technology. Two MF pilot units fitted with polypropylene membrane elements (typical pore size ~200 nm), one operating as control and another receiving coagulant (commercial polyaluminum chloride), were operated in parallel to demonstrate the efficiency of the proposed technology in reducing membrane fouling. The overall results of the project indicated that

- Diurnal variations existed in colloidal particles profile in the feed water, and the colloidal particle concentration during the peak period were approximately four to five times higher than that during the period when the levels of colloidal particles were the lowest,
- The algorithm developed through bench scale testing was effective in optimizing coagulant dosing, and
- The fouling potential, measure in terms of transmembrane pressure, for the coagulant dosed pilot was only 27 percent of the control pilot after six weeks of operation. Further, the controlled release of coagulants, based on colloidal particles profile resulted in minimal bleeding of aluminum (or polymer) in the membrane permeate.

In summary, the data indicated that monitoring and removal of colloidal particles using NTA technology was very effective in minimizing MF membrane fouling.

- Ganesh, R., Safarik, J. and Plumlee, M. 2019. *Improving MF and UF Membrane Energy Efficiency Through Real-Time Colloidal Particle Monitoring*. California-Nevada Section

American Water Works Association Annual Fall Conference, San Diego, CA. 21 – 24 October, 2019.

There is an increased emphasis on indirect and direct potable reuse (IPR/DPR) in recent years in order to meet the future water demand and increase water security. Microfiltration (MF) and ultrafiltration (UF) membranes are integral components of most IPR/DPR processes. However, fouling of these membranes results in increased energy demand, increased cleaning, and membrane replacement frequency. Studies have shown that MF and UF membrane fouling is largely due to deposition of feed water colloidal particles (<200 nm) inside the membrane pores. Currently, no online techniques are available to directly measure colloidal particles in this size range in the feed water, which would facilitate appropriate pretreatment and real-time control to remove these particles and prevent their deposition in membrane pores.

In this study, a real-time monitoring technology was implemented to track colloidal particles concentration and size distribution in the feed water to facilitate their targeted removal via more precise coagulant dosing prior to the membrane filtration process. This new fouling control strategy using Nanoparticles Tracking Analysis (NTA) (NanoSight NS500 by Malvern Instruments) was demonstrated at two demonstration sites: Orange County Water District (OCWD) and West Basin Municipal Water District. The demonstration tests conducted at OCWD and West Basin sites were similar with a few key distinctions between the two studies, including the type of coagulants tested, membrane type (MF and UF), feed water quality and the absence of RO testing at West Basin. The notable differences between these two sites helped to define the capabilities and limitations of the online nanoparticle counting system over a range of operating conditions.

The project work consisted of i) monitoring and measurement of diurnal changes in colloidal particles profile (concentration and size distribution) in membrane feed water using NTA, ii) determination of the relationship between colloidal particle profile and optimum coagulant dose for fouling reduction through bench scale studies, iii) integration of a feed-forward loop-based chemical feed system that delivers coagulant dose based on feed water colloidal particles profile and iv) performance of cost-benefit analyses for implementation of this technology.

Results indicated that the fouling potential for the OCWD MF pilot receiving NTA targeted polyaluminum (PACl) coagulation was mitigated, with TMP values reduced by 60 percent after six-weeks compared to the control (no coagulant addition). RO operation was not affected by the coagulation of the MF feed water. Economic evaluation using OCWD’s full scale plant indicated that the proposed approach can reduce energy consumption due to microfiltration by 28-35 percent, resulting in 2,900 MWh/year of projected energy savings and $600,000/year of potential savings in membrane cleaning, replacement and operating costs for a 100-MGD plant. The pilot demonstration at West Basin indicated that targeted PACl coagulation can improve UF performance and energy efficiency compared to the control. However, coagulant choice plays a critical role in the success of the targeted pretreatment strategy, as targeted $FeCl_3$ dosing was not equally successful. Targeted coagulation with PACl slowed the rate of TMP increase by 43 percent compared to control and achieved a 63 percent reduction in energy consumption during pilot operation. This could translate to over 600 MWh/year of energy savings for a 14.4-MGD UF facility and potential savings of over $110,000/year in overall operating and maintenance costs.

CHAPTER 10: Summary and Conclusions

This project demonstrated the technical feasibility of using nanoparticle tracking analysis technology for controlling the coagulation pretreatment of low-pressure membranes to improve performance and energy efficiency. Listed below are the key findings of the project.

10.1 Conclusion and Recommendations from Orange County Water District Pilot Study

Implementing targeted PACl coagulation using the NTA control system led to the following observations for MF operation and maintenance compared to untreated feed water:

- MF pilot receiving targeted coagulation had improved TMP performance translating to 28-35 percent less energy consumption during full-scale operation.

  The pretreatment system was designed to inject PACl dosing based on the colloidal particle concentrations in the secondary treated MF feed water. This targeted removal of colloidal particles helped to minimize coagulant dose, while improving MF performance as observed by a slower increase in TMP. The reduction in membrane fouling and operating TMP correlated to easier filtration and reduced energy demand on the filtrate pumps. Applying the TMP profile observed during pilot demonstration to the full-scale 100-MGD plant at OCWD resulted in projected energy savings of approximately 2,900 MWh/year.

- CIPs were required less frequently, reducing chemical cleaning costs and potentially improving membrane lifetime of MF modules.

  The targeted coagulation system enabled the MF units to operate for longer durations without building-up significant levels of physically irreversible membrane foulant. Most membrane fouling build-up was in the form of cake-layer formation and easily removed via the automated hydraulic backwashing that is already done routinely as part of MF/UF operation (for example, every ~20 minutes) to maintain low TMP. Normally these regular backwashes are coupled with less frequent CIPs (for example, every ~3 weeks), but this study's pilot demonstration results indicated that pretreated (NTA control system) MF membranes can be operated for extended periods (upwards of six months) without requiring a CIP. This allows a reduction in CIP frequency and savings on chemical cleaning costs, reduced cleaning and maintenance downtime, and improved product yield. Fewer CIPs also reduce the chemical strain on membranes, helping to prolong membrane lifetime. Site-specific and longer testing periods with the targeted coagulation system can help determine the extent of this lifetime improvement.

- MF effluent quality and RO operation showed no detectable change due to PACl coagulation.

  Results from the pilot demonstration showed that there is no significant aluminum breakthrough due to the addition of PACl, even under overdosing conditions. However, while overdosing does not significantly affect the aluminum concentration of the MF effluent, it does lead to more rapid MF fouling. Hence, the presence of a targeted dosing system is essential for preventing MF foulant build-up. Aluminum concentrations in the MF effluent were below MCL limits as well as the recommended levels for preventing downstream fouling on the RO. SEM and EDS analyses showed no significant RO fouling during Phase 2 testing, with coagulation and membrane selectivity remaining unchanged. However, due to the short timeframe and several CIPs taking place during the RO testing period, the impact of aluminum coagulation on RO performance requires further investigation to be fully elucidated.

- The installation of the proposed technology results in an estimated annual savings of $611,000 for the 100-MGD MF facility.

  Based on pilot demonstration for the OCWD 100-MGD facility, targeted PACl pretreatment could result in savings of $680,000 per year for reduced MF chemical cleanings, $279,000 per year for reduced electricity consumption, and $1.76 million a year due to reduced membrane replacement frequency. This yields a total of $2,718,000 in savings for energy and other operating and maintenance costs. The additional incurred costs from purchasing and injecting PACl is estimated to be $2,107,000 per year, resulting in overall savings of $611,000. A sensitivity analysis on the variation of electricity and coagulant prices showed that increasing electricity prices can incentivize the application of the proposed technology, and that polymer costs are an important factor for the project's economic feasibility. The anticipated improvement in membrane lifetime (or membrane replacement frequency and cost) was also a critically important factor. While it is difficult to definitively predict membrane lifetime, a sensitivity analysis showed that annual savings will be net positive if at least 50 percent of the predicted membrane improvement was achieved.

10.2 Conclusion and Recommendations from West Basin Pilot Study

Pretreatment with targeted PACl coagulation using the NTA control system was compared to constant PACl dosing, targeted $FeCl_3$ dosing, and untreated feed water to the UF membrane treating more challenging source water at West Basin. The resulting observations for operation and maintenance are summarized below:

- Targeted coagulation with PACl slowed the rate of TMP increase in UF system and improved performance of EFMs in removing physically irreversible fouling.

  The addition of PACl coagulation with constant dosing or targeted dosing based on feed particle loading was able to ameliorate the rate of TMP increase. Compared to feed water receiving no pretreatment, constant PACl dosing reduced the rate of TMP increase by 23 percent on average but showed large variations in its performance. Targeted coagulation with PACl was able to better respond to the changing feed water quality and reduced the rate of TMP increase by 43 percent and with higher consistency. Targeted PACl dosing as a pretreatment system reduced membrane matrix fouling, as shown by SEM and EDS analysis, and improved the EFM performance. EFMs performed on the control UF (no coagulant) gradually declined in their ability to reverse heavy membrane fouling. EFMs performed on the UF membranes receiving targeted

PACl coagulation however, showed enhanced reduction of membrane fouling. This could indicate that UF membranes with the targeted coagulation system could be operated for longer periods of time before requiring a CIP. Targeted coagulation with $FeCl_3$ did not show significant improvements in reducing the rate of TMP increase.

- Pretreatment with constant PACl, targeted PACl, and targeted $FeCl_3$ coagulation system improved UF effluent quality.

  The feed and filtrate of the UF unit during Phase 1 (untreated feed water) showed no significant changes in COD. The addition of coagulant pretreatment, however, was able to reduce COD values for the UF filtrate by 36 to 47 percent. Targeted coagulation with PACl and $FeCl_3$ also improved UF effluent quality by increasing the percentage of colloidal particles removed via filtration. Under no pretreatment, the UF system achieved 83 percent removal of colloidal particles less than 200nm. Targeted PACl and $FeCl_3$ dosing increased the colloidal particle removal to 91 percent and 98 percent, respectively.

- EFM or CIPs can be performed less frequently in the presence of targeted PACl coagulation system, reducing operating expenses as well as energy consumption.

  The filtrate pump for the UF pilot system was more energy efficient when operated at TMPs below 7 psi. Maintaining the TMP below this threshold limit enabled larger energy savings. Targeted coagulation with PACl was able to consistently maintain the TMP below 7 psi for up to 48 hours, while untreated feed water showed declining performance after subsequent EFMs were not able to completely recover the TMP. Therefore, targeted coagulation with PACl was able to reduce energy consumption by 63 percent, while reducing the frequency of EFMs to every 48 hours instead of every 24 hours. In contrast to the demonstration tests at OCWD, filtration pump energy data was not continuously monitored for West Basin's full-scale plant. However, energy efficiencies of the full-scale pumps were regularly tested. Applying the pilot pump performance alongside the full-scale pump efficiencies translated to 600 MWh/ year of energy savings for the 14.4 full-scale UF facility. Additional development work is recommended to further assess the operating advantage and manage assessed risks that come with the full-scale implementation of targeted coagulation on the UF system.

- The installation of the proposed technology results in an estimated annual savings of $113,000 for the 14.4-MGD UF facility.

  Based on pilot demonstration, targeted PACl pretreatment could result in savings of $100,000 per year for reduced chemical cleanings, $62,000 per year for reduced electricity consumption, and $197,600 a year due to reduced membrane replacement frequency. This yields a total of $359,600 in savings for energy and other operating and maintenance costs. The additional incurred costs from purchasing and injecting PACl is estimated to be $245,900 per year, resulting in overall savings of $113,700 for the 14.4-MGD UF facility. A sensitivity analysis on the variation of electricity and coagulant prices showed that increasing electricity prices can incentivize the application of the proposed technology, but polymer cost can vary greatly without affecting the project's economic feasibility for UF systems. This is partly due to the lower concentration of PACl coagulant required for the UF pretreatment system. A sensitivity analysis on the anticipated improvement to membrane lifetime showed that annual savings will be net positive if at least 25 percent of the predicted membrane improvement was achieved.

10.3 Conclusion for Statewide Energy and Cost Savings due to Proposed Technology

Potential savings from implementing the proposed technology are calculated to be $2.4 million per year for the state of California. At 50 percent market penetration, this value is expected to be approximately $1.22 million per year.

California is estimated to have an MF/UF membrane filtration capacity of approximately 400 MGD. Energy requirements for such facilities can vary depending on the water quality characteristics, and savings due to improved membrane operation can be highly site-specific. OCWD was used as a model to approximate an average for expected state-wide savings in California (400 MGD). The overall potential state-wide annual savings of $2 million per year consists of savings in energy ($1,116,200), chemical cleaning costs ($2,719,800), and membrane replacement ($7,036,300), as well as expenditures for purchasing polymers ($8,428,100).

LIST OF ACRONYMS

Term	Definition
AMTA	American Membrane Technologies Association
AWPF	Advanced Water Purification Facility, Fountain Valley, CA
CIP	Clean-in-place membrane chemical cleaning
COD	Chemical oxygen demand
CSTR	Completely stirred-tank reactor
DLS	Dynamic light scattering
DOM	Dissolved organic matter
EDS	Energy dispersive spectroscopy
EFM	Enhanced flux maintenance
ECLWRF	West Basin's Edward C. Little Water Recycling Facility
EPIC	Electric Program Investment Charge
HWRP	City of Los Angeles' Hyperion Water Reclamation Plant
ICP	Inductive coupled plasma
LPMF	Low-pressure Membrane Filtration
MF	Microfiltration
MGD	Million gallons per day
NOM	Natural Organic Matter
NTA	Nanoparticle Tracking Analysis
O&M	Operations and Maintenance
OCSD	Orange County Sanitation District
OCWD	Orange County Water District
PACl	Polyaluminum chloride
PP	Polypropylene
PVDF	Polyvinylidene
RO	Reverse Osmosis
ROI	Return on Investment
sCOD	Soluble chemical oxygen demand
SEM	Scanning Electron Microscopy

Term	Definition
SLS	Static light scattering
SUVA	Specific Ultraviolet Absorption
TMP	Transmembrane pressure
TOC	Total organic carbon
TSS	Total suspended solids
UF	Ultrafiltration

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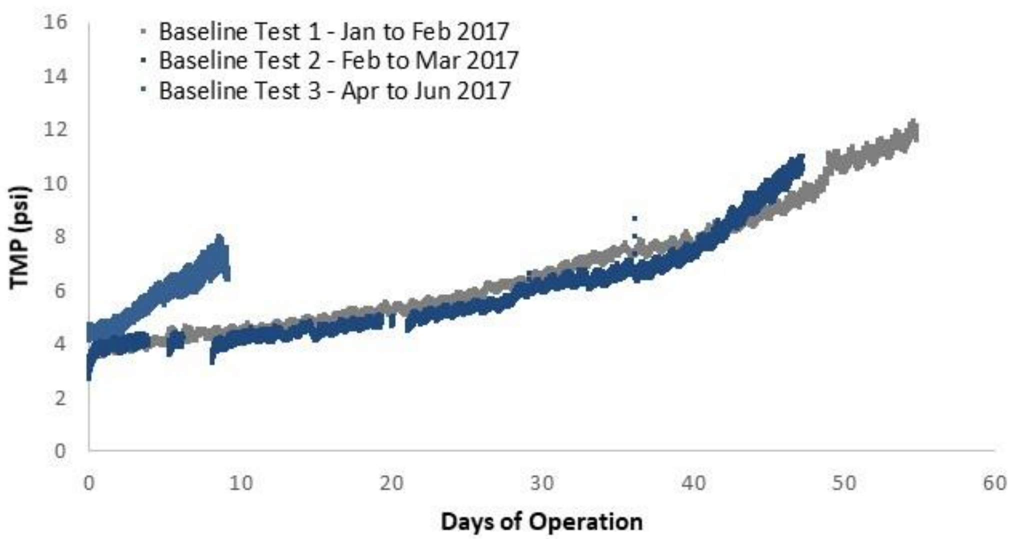
APPENDIX A:
Orange County Water District Baseline Phase 1 Testing - Microfiltration Performance

Data collected during Phase 1 at the OCWD demonstration site captures the baseline performance of the MF membranes, when receiving untreated secondary effluent from OCSD. Figure A-1 depicts the results from three consecutive tests for untreated water. Baseline Test 1 showed a rapidly increasing TMP, that was atypical of the usual operating condition. For this reason, it was terminated prematurely. Based on consequent baseline testing (baseline test 2 and 3) however, the baseline trend for the MF operation was established and showed that TMP reaches ~10 psi after 45 to 50 days of consecutive operation.

Figure A-1: Baseline TMP Performance of the Untreated MF Pilot, During Phase 1 Of OCWD Site Demonstrations

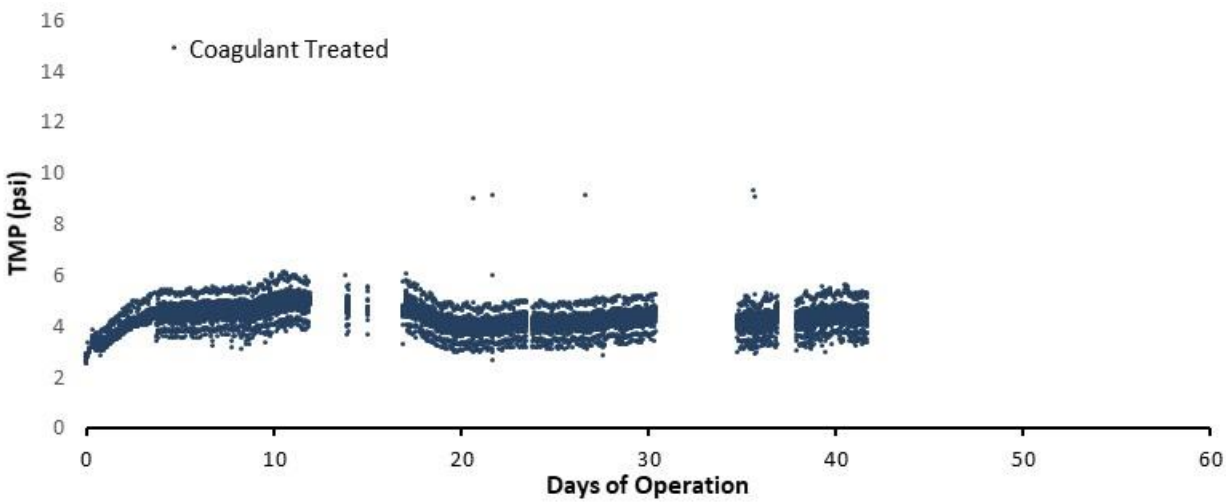


Source: Kennedy/Jenks Consultants

APPENDIX B:
Orange County Water District Phase 2 Testing - Microfiltration Performance

During Phase 2 of the OCWD site demonstration testing, two MF modules were operated in parallel. This allowed for side-by-side comparison of two treatments: pretreatment of MF feed with coagulation, and no MF feed pretreatment. During the initial run of this test, TMP data for the untreated stream was lost. The following figure depicts the TMP recordings for the MF unit receiving targeted coagulant pretreatment. Although the test is missing the untreated TMP performance, the results still support the findings that coagulation is able to maintain a substantially lower TMP across the MF membrane than when MF is untreated (see Appendix A for examples).

Figure B-1: TMP Performance for the Coagulant Treated MF Pilot, During Phase 2 Of OCWD Site Demonstrations



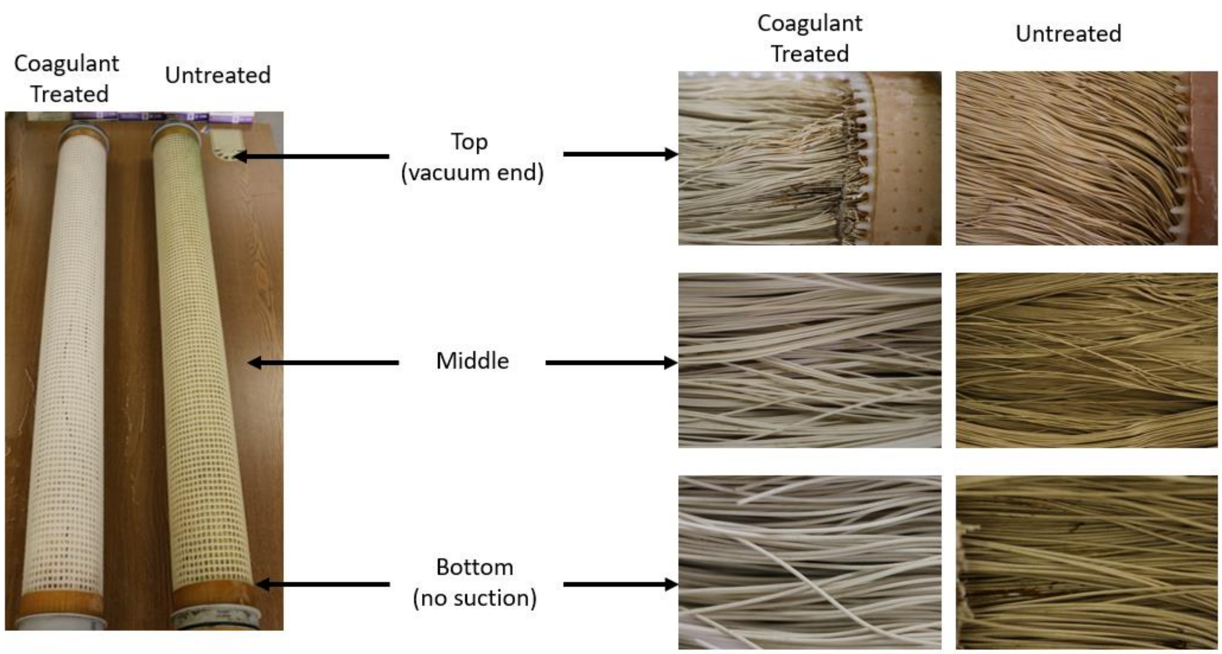
TMP data recordings for the untreated MF unit (operated in parallel) was lost for the initial test.

Source: Kennedy/Jenks Consultants

APPENDIX C: Microfiltration Membrane Discoloration during Phase 2 Pilot Testing

The submerged MF units were removed following the completion of Phase 2 pilot testing. The extent of fiber discoloration for the MF units receiving untreated feed water was significantly more apparent that those receiving coagulated feed water. Figure C-1 shows how the fiber discoloration at the end of Phase 2 pilot testing (55 days after the last CIP) varies across the MF fibers, and between the two treatments. Typically, top of fibers experienced more fouling.

Figure C-1: Samples for MF Membrane Autopsies

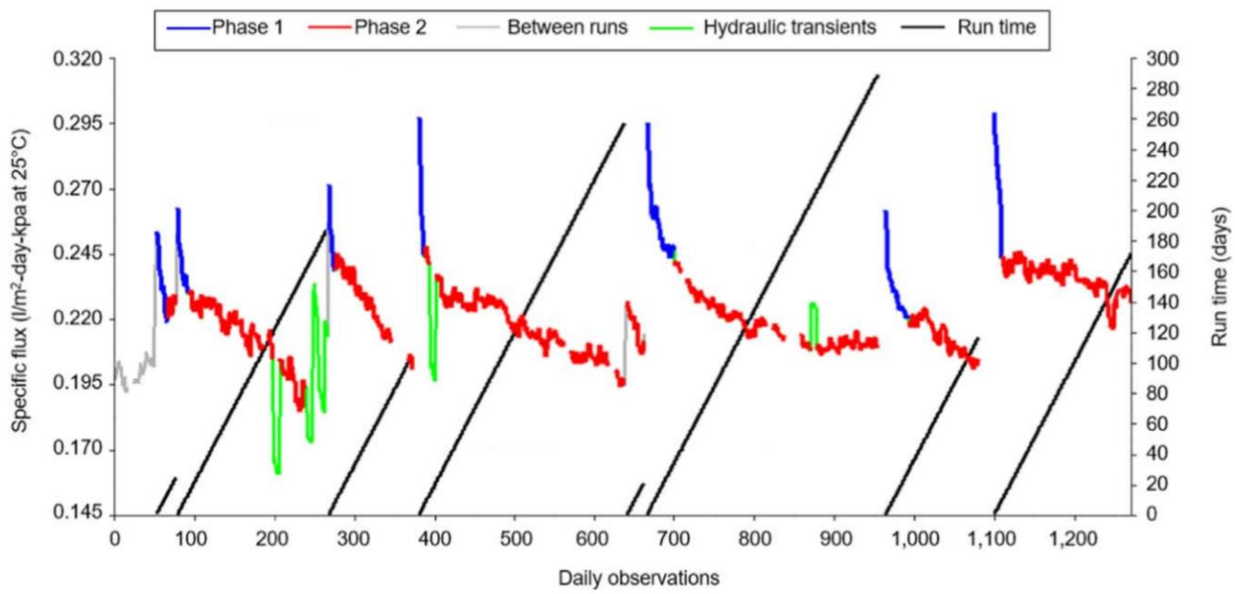


Source: Kennedy/Jenks Consultants

APPENDIX D: Untreated Reverse Osmosis Operation and Cleaning Cycles at Orange County Water District Advanced Water Purification Facility

Figure D-1 shows eight consecutive runs of a RO unit's first stage (Roehl Jr., et al., 2018). After each cleaning, the specific flux initially declined rapidly for a few weeks, after which it declined more slowly until the next cleaning.

Figure D-1: Specific Flux of a Stage 1 RO Unit During Consecutive Runs

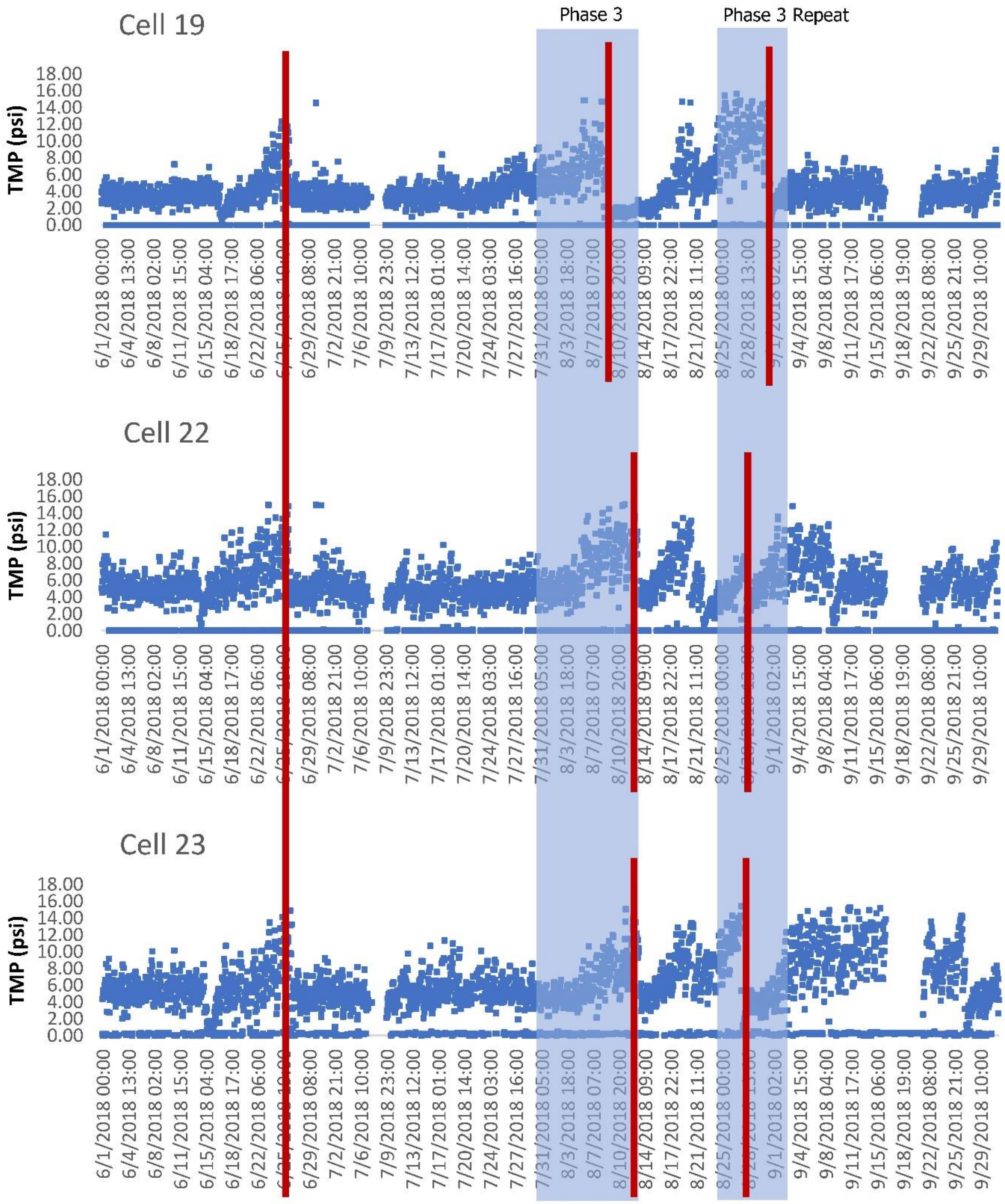


Source: Kennedy/Jenks Consultants

APPENDIX E: West Basin Plant Upset During Phase 3 Repeat

The following figures (Figures E-1 and E-2) show the TMP profile of the filtration cells installed in the main plant at West Basin, which received the same feed water as the pilot skid being used for the study. The areas highlighted in blue are the days when Phase 3 and the repeat for Phase 3 testing was taking place. The red lines indicate that a CIP was performed. Based on normal operation, a CIP would typically take place after approximately 1 to 1.5 months, when terminal TMP is reached at 12.5 psi. Meanwhile, EFM is performed automatically every 24 hours. The repeated Phase 3 test results (beginning August 24, 2018) were excluded from further analysis because a disruption in feed water quality affected the performance of all UF units, even those on the main plant. This disruption can be observed by the rapid increase in TMP values following the first CIP performed in August, making it necessary to perform a second CIP soon after (after only two weeks).

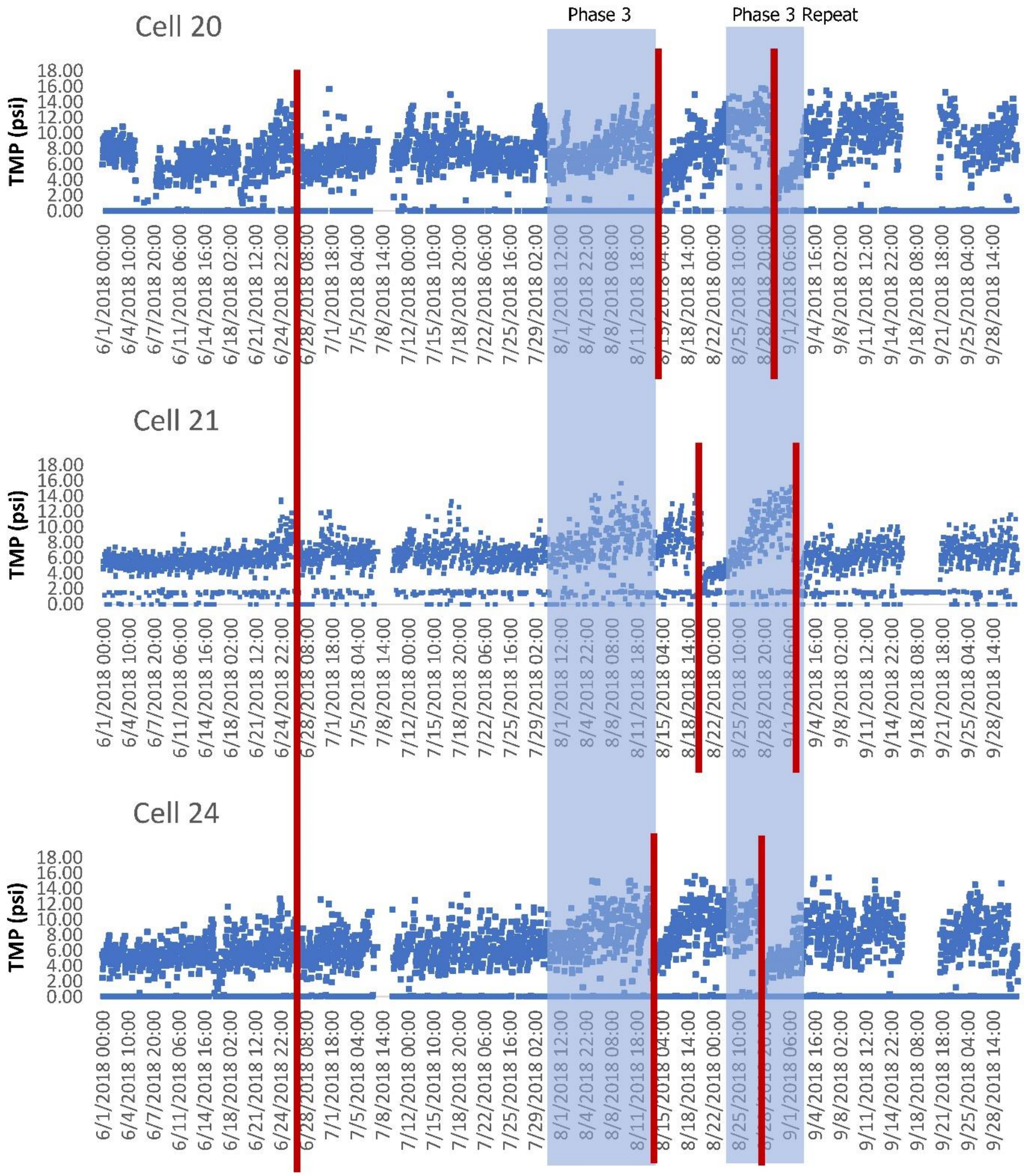
Figure E-1: TMP Readings from the Main UF Units at West Basin for Cell 19, 22, and 23



Blue highlighted areas show times when pilot testing for Phase 3 and Phase 3 repeat were taking place. Red lines indicate CIP. TMP values show that the incoming feed water quality during the Phase 3 repeat experiment was atypical, causing rapid TMP increase and the need for additional CIP taking place for the UF units on the main plant.

Source: Kennedy/Jenks Consultants

Figure E-2: TMP Readings from the Main UF Units at West Basin for Cell 20, 21, and 24



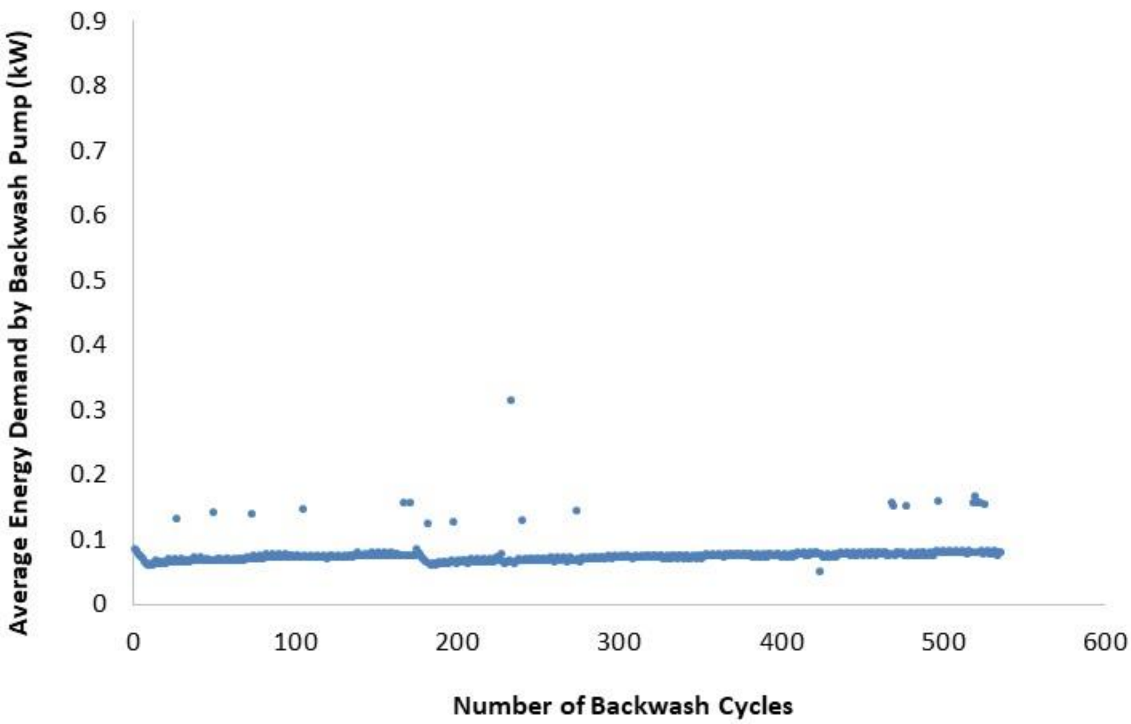
Blue highlighted areas show times when pilot testing for Phase 3 and Phase 3 repeat were taking place. Red lines indicate CIP. TMP values show that the incoming feed water quality during the Phase 3 repeat experiment was atypical, causing rapid TMP increase and the need for additional CIP taking place for the UF units on the main plant.

Source: Kennedy/Jenks Consultants

APPENDIX F:
Backwash Pump Energy Demand at West Basin

Data loggers placed on the backwash pump were used to assess the correlation between energy demand and changing TMP. Figure F-1 shows that throughout multiple backwash cycles, the energy demand of the backwash pump remained relatively low, with small variations between 0.06 and 0.08 kW. Due to the small variation and magnitude of these values compared to the energy demand of the filtrate pump, the energy demand of the backwash pump was considered constant and not included in the overall calculations for energy consumption.

Figure F-1: Energy Demand of Backwash Pump During Consecutive Backwash Cycles at West Basin



Source: Kennedy/Jenks Consultants

APPENDIX G:
Water Reuse Conference Presentations

The following are presentation slides used at the California Annual Water Reuse Conference (San Diego, CA. 19 – 21 March, 2017), the American Membrane Technology Association Conference (New Orleans, LA. 26 – 28 February, 2019), and the California Annual Water Reuse Conference (San Diego, CA. 17 – 19 March, 2019).

Online Monitoring to Detect and Remove Colloidal Particles to Improve Membrane Treatment

Jana Safarik[1], Ganesh Rajagopalan[2], Megan Plumlee[1], Rachael Burk[2], Nicholas Kokotas[2]

[1] Orange County Water District
[2] Kennedy/Jenks Consultants

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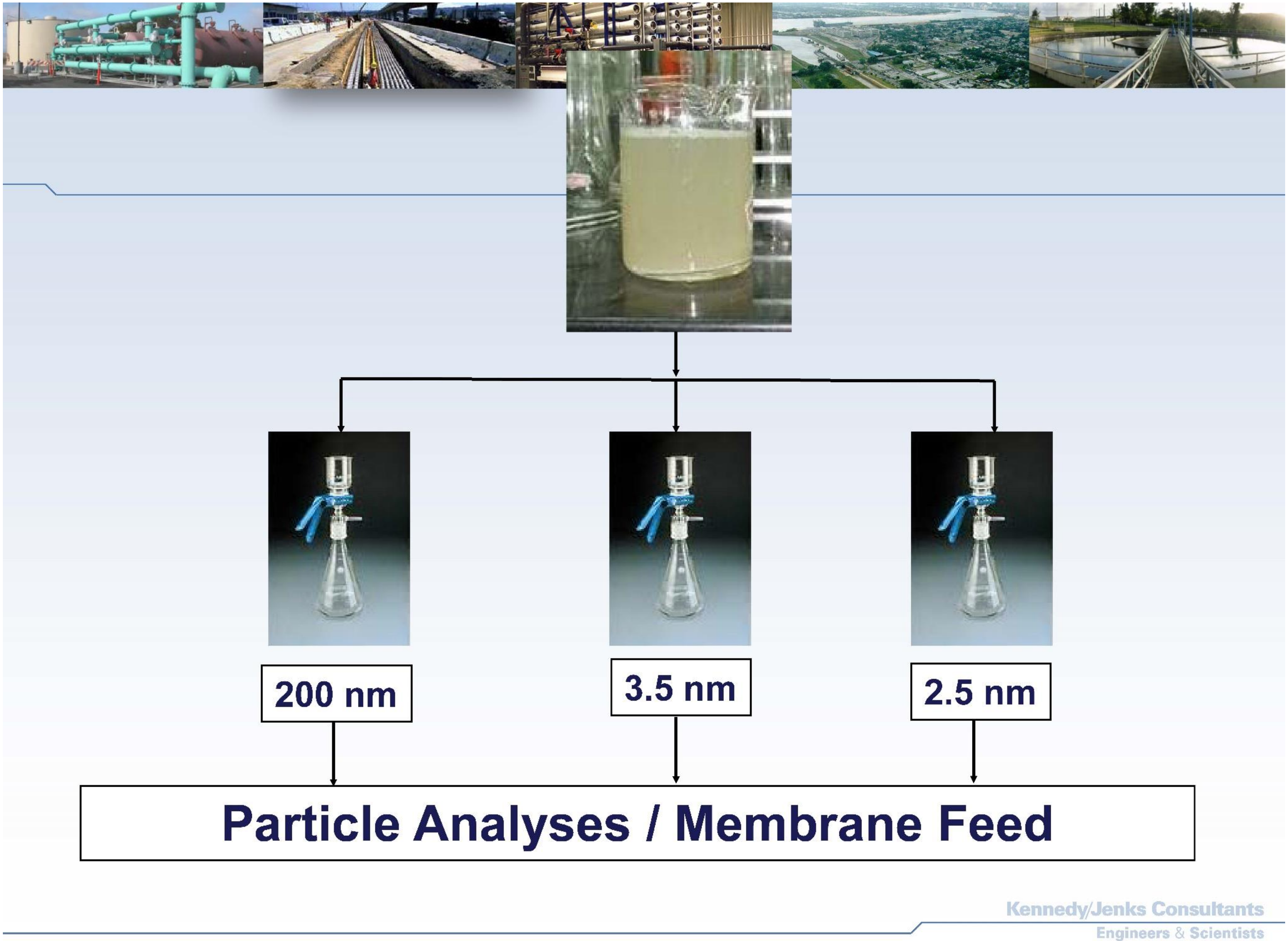
Engineers & Scientists

Today's Presentation

- Background
  - Membrane fouling
  - Role of particle size in membrane fouling
  - Detection and measurement of colloidal particles using Dynamic Light Scattering (DLS) Technology
- Objectives
- Pilot Study at OCWD
- Summary
- Next Steps

Microfiltration (MF) Membrane Fouling

- Characterized by reduction of permeate flux or increased pressure is due to:
  - Pore blocking
  - Pore plugging
  - Concentration polarization
- Extent of fouling depends on:
  - Membrane pore size
  - Solute loading and distribution
  - Membrane polymer material
  - Source water quality and particle load
  - Operational conditions


200 nm
3.5 nm
2.5 nm
Particle Analyses / Membrane Feed
Kennedy/Jenks Consultants
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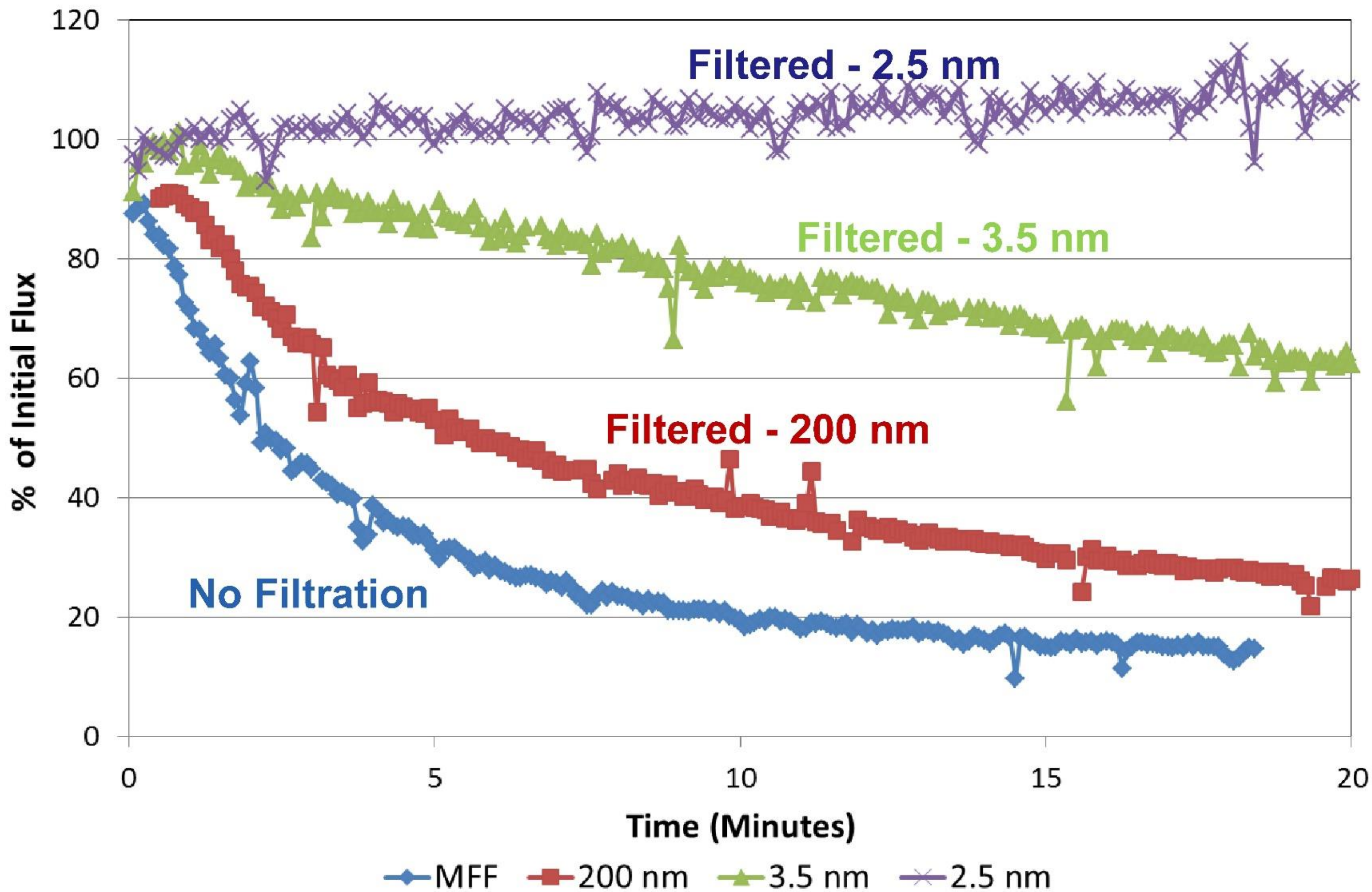
Colloidal Particles >2.5 nm are Responsible for Loss of Flux



Detection and Measurement of Colloidal Particles

- Due to lack of instrumentation the role of colloidal particles <200nm in membrane fouling has not been extensively studied
- Surrogate measurements are not very reliable
  - Turbidity
  - Absorbance
  - COD - chemical oxygen demand
- Emergence of **Nanotechnology** is starting to provide tools to detect nanoscale (colloidal) particles in wastewaters.

Nanoscale Technology Providers

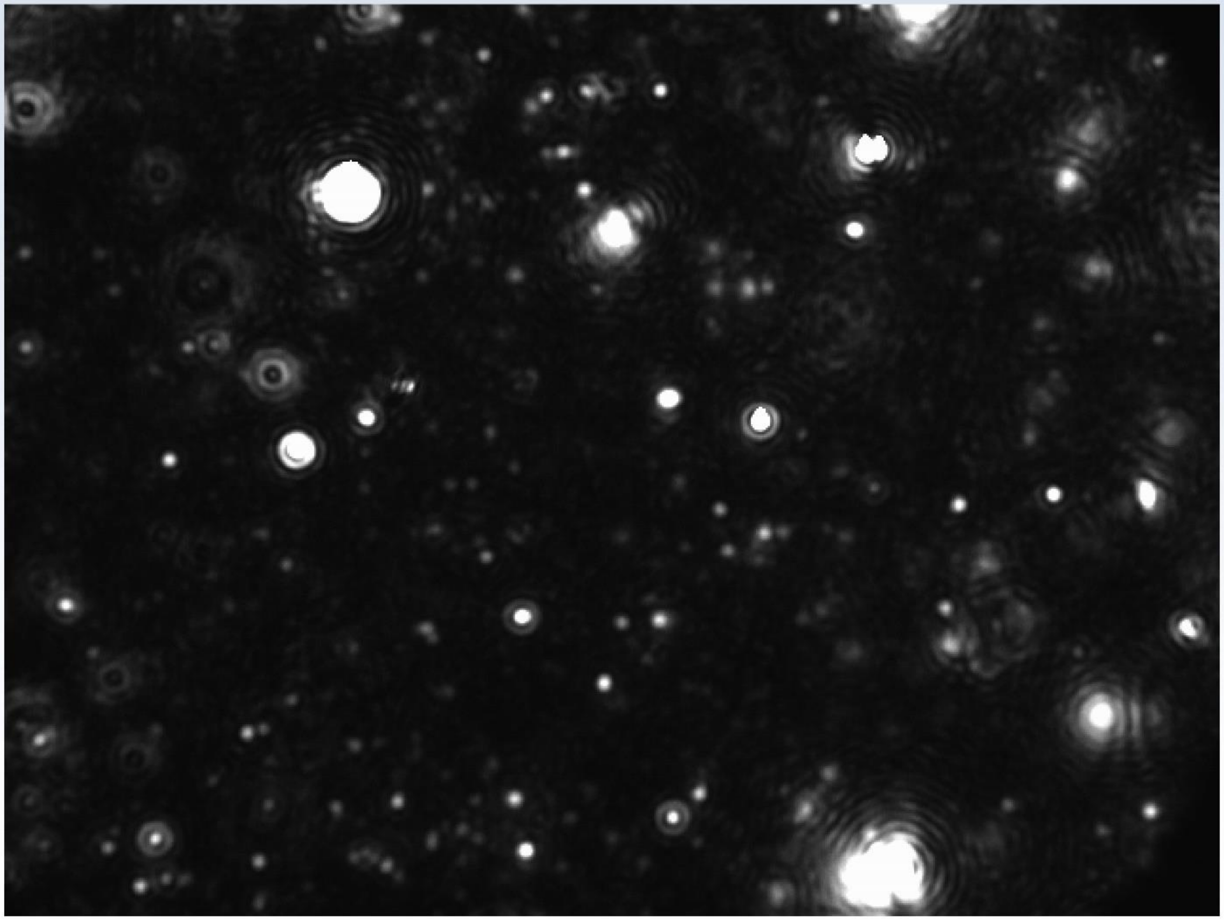
- Malvern Instruments
  - Zetasizer
  - NanoSight - Nanoparticle Tracking Analyses (NTA)
- Beckman
- Brookhaven

NanoSight - NTA

Dynamic Light Scattering (DLS)

- Quick analyses - particle count and size distribution
  - <50 nm to 6,000 nm
- Does NOT provide chemical composition
- Mostly used in medical/electronic/polymer industries
- Rarely used for water/wastewater analyses

Nanoparticle Tracking Analysis (NTA)



Study Objectives

- Transfer the colloidal particle monitoring technology from bench scale to pilot scale
- Choose a coagulant and develop relationship between coagulant dose and colloidal particle removal – Jar Testing
- Develop real time monitoring of colloidal particles during the membrane treatment process
- Develop feedback control system to tailor coagulant dose to colloidal particle concentration
- Estimate fouling reduction, energy efficiency and perform cost-benefit analyses

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OCWD MF and RO Pilots

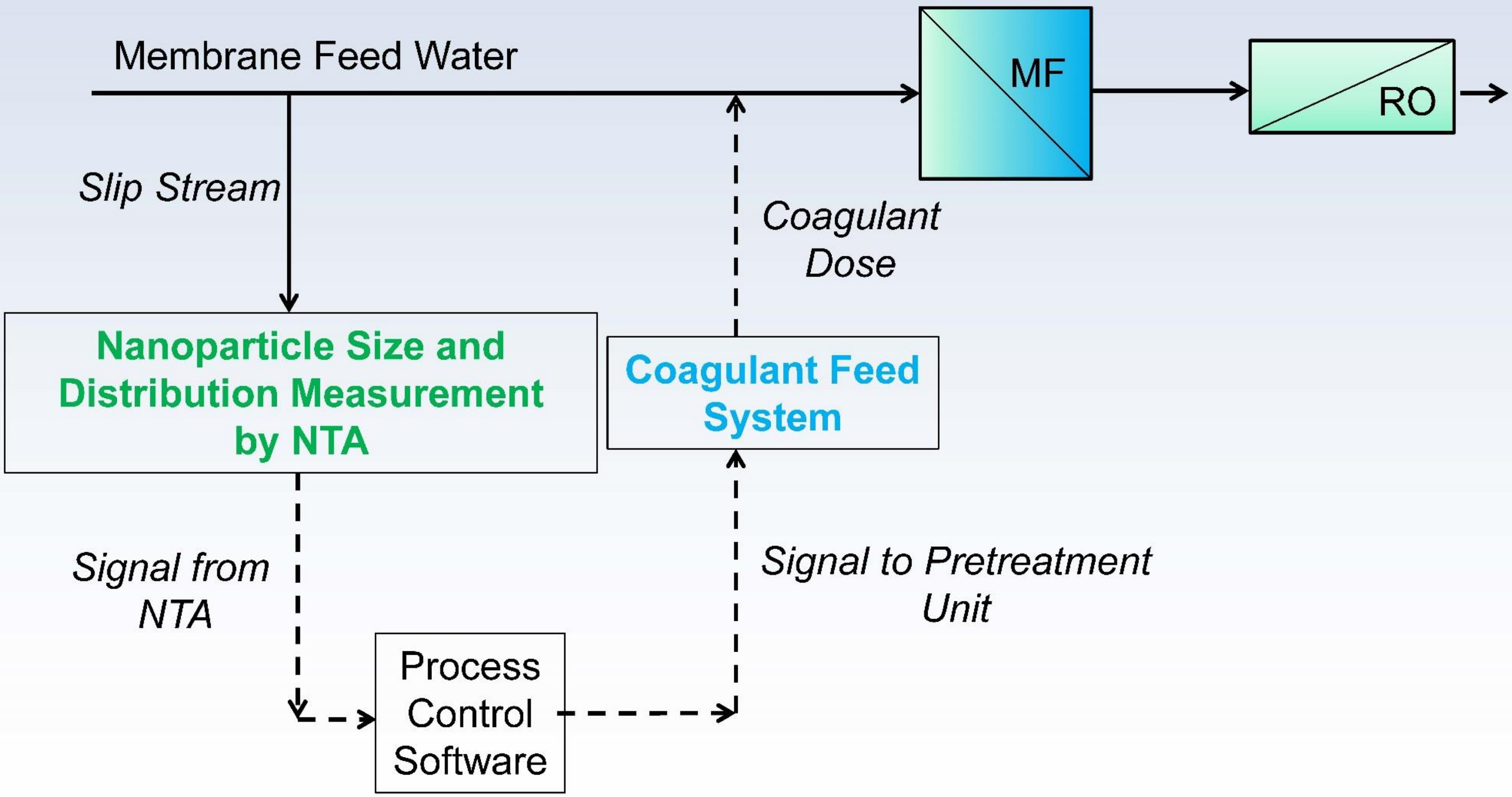
- Feed water
  - Secondary effluent from OCSD
- MF pilot
  - Evoqua 0.2 µm (200 nm) pore size polypropylene membranes
  - 18 gpm flow rate
- RO pilot
  - Hydranautics ESPA2-LD membranes
  - Simulates a three stage 5-mgd RO unit
    - ✓Flux = 12 gfd
    - ✓Recovery = 85%

Pilot Study at OCWD

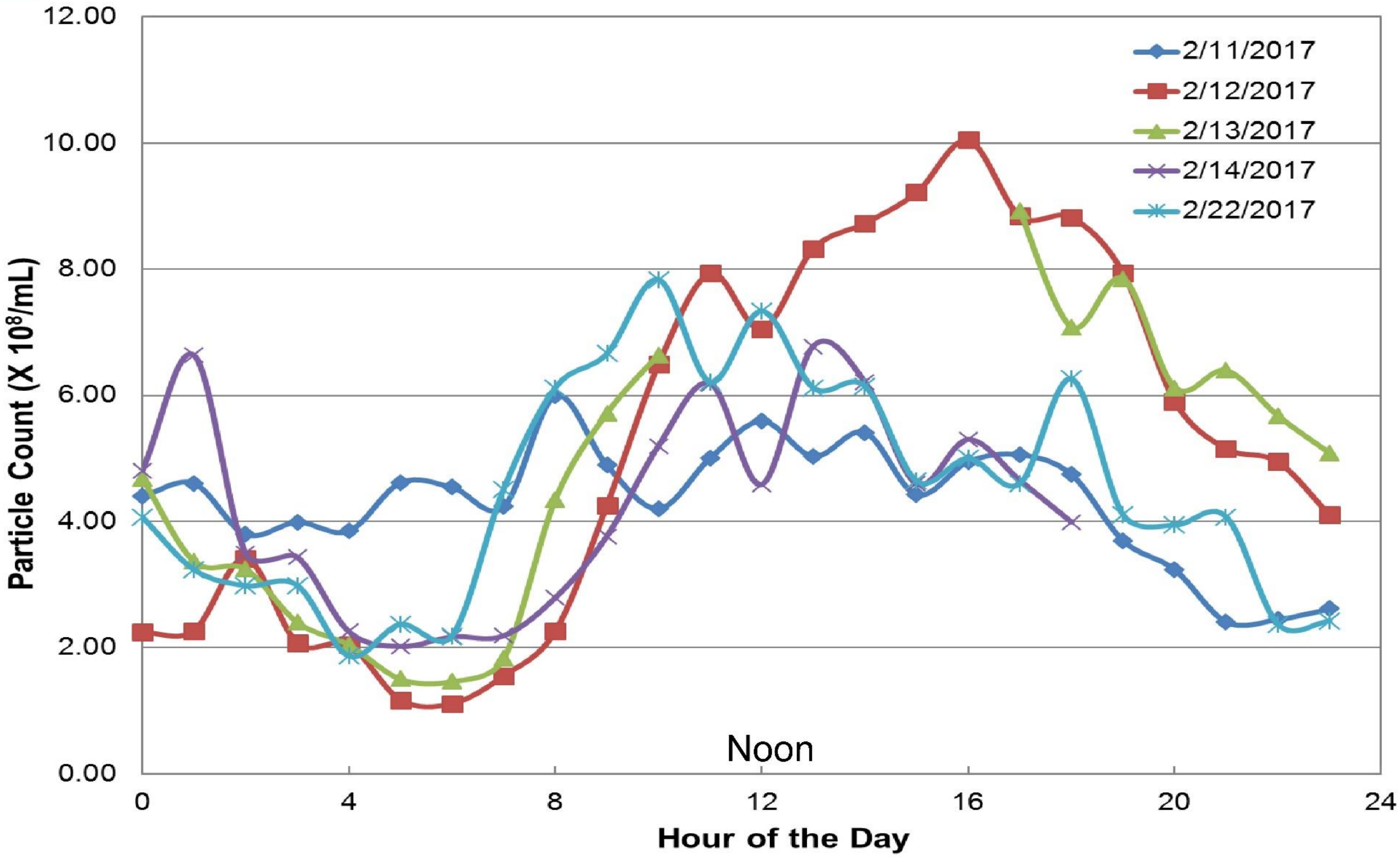
- Phase 1: Establish Baseline Performance
  - Real time colloidal particle measurement
  - No coagulant addition
  - CIP determined through TMP
  - 3 CIP cycles of baseline

- Phase 2: Testing
  - Real time colloidal particle measurement
  - Coagulant dose based on colloidal particles in feed water
  - CIP determined through TMP
  - 3 CIP cycles

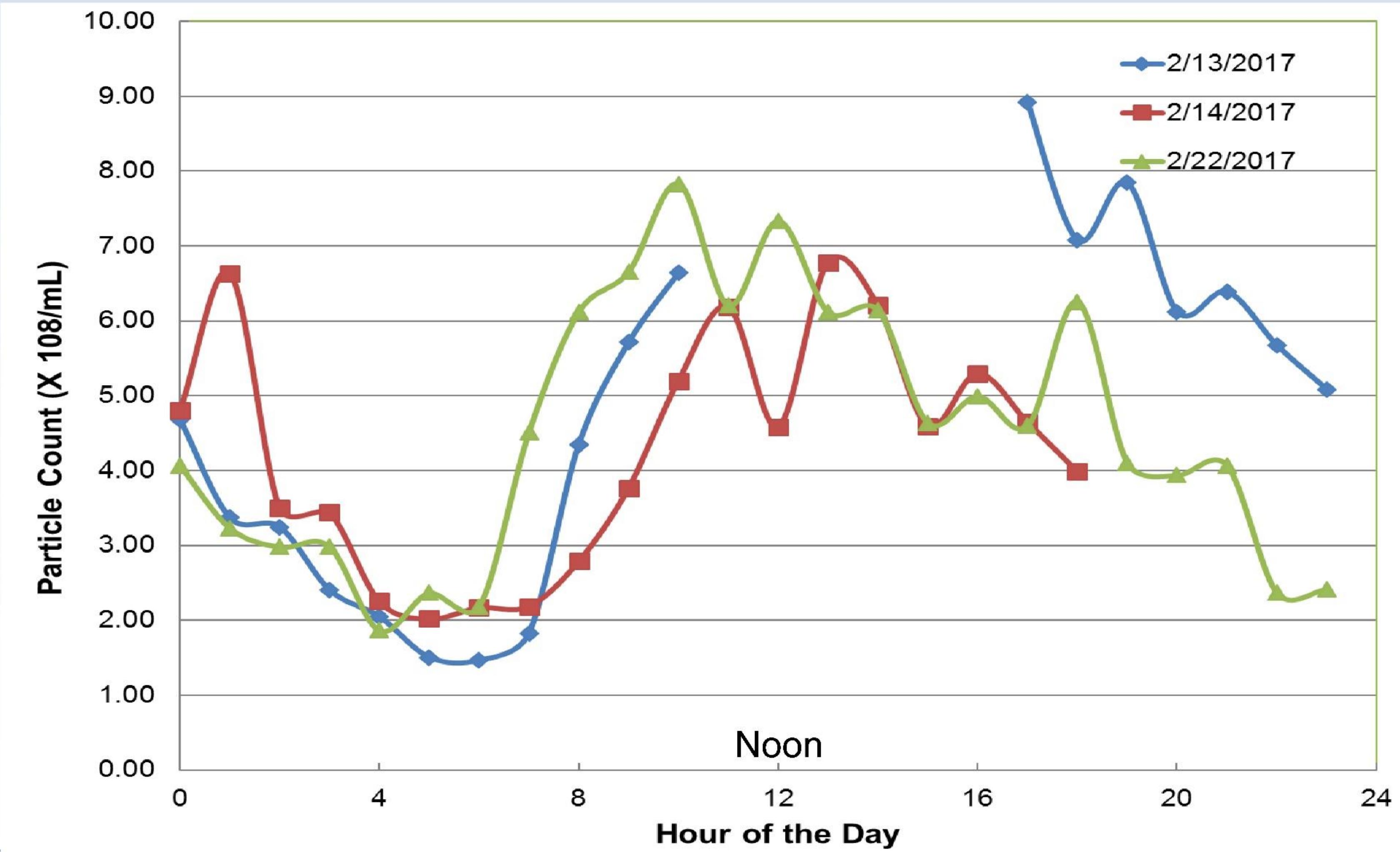
Schematic of Coagulant Dosing



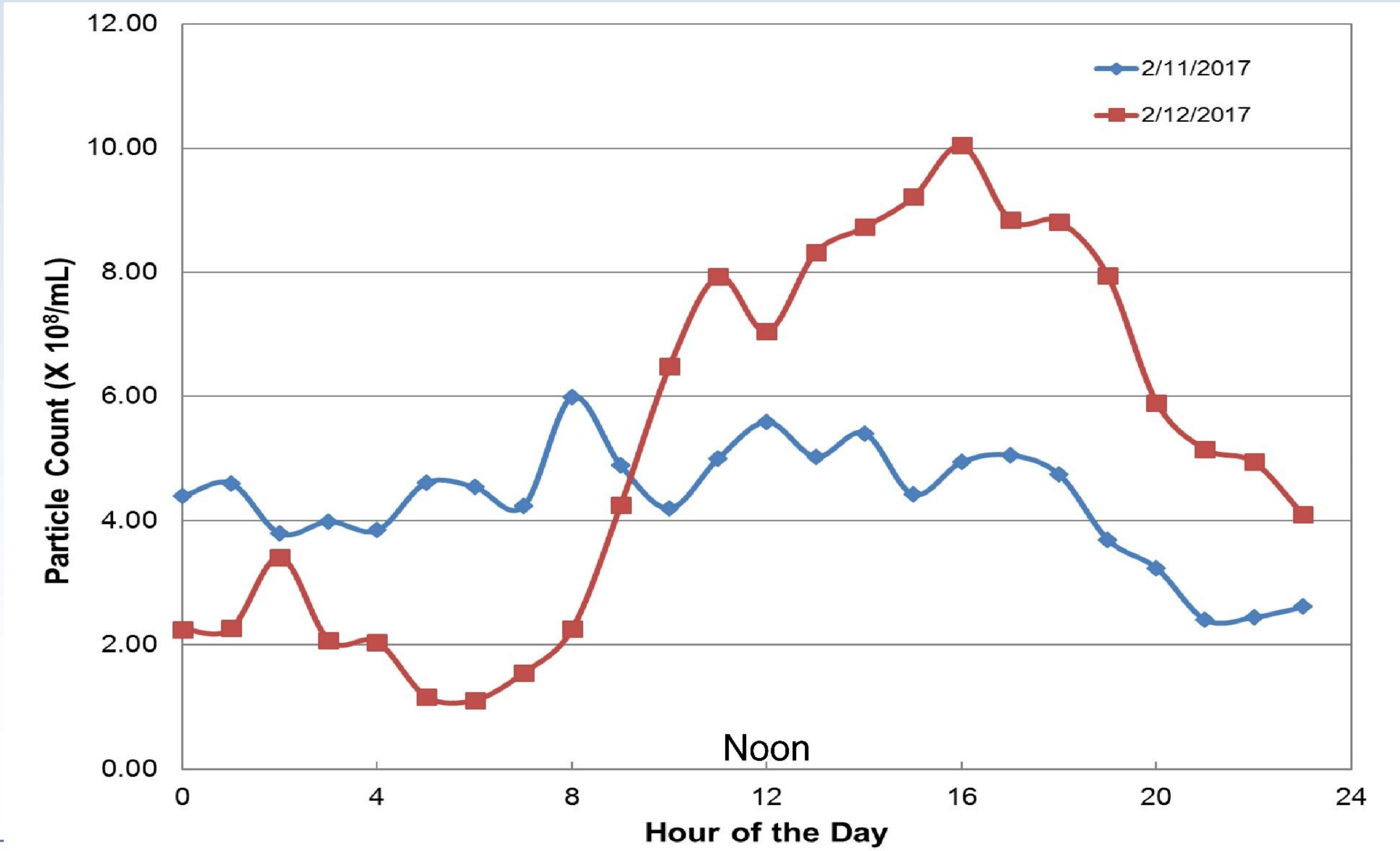
MFF Diurnal Change in Particle Concentration



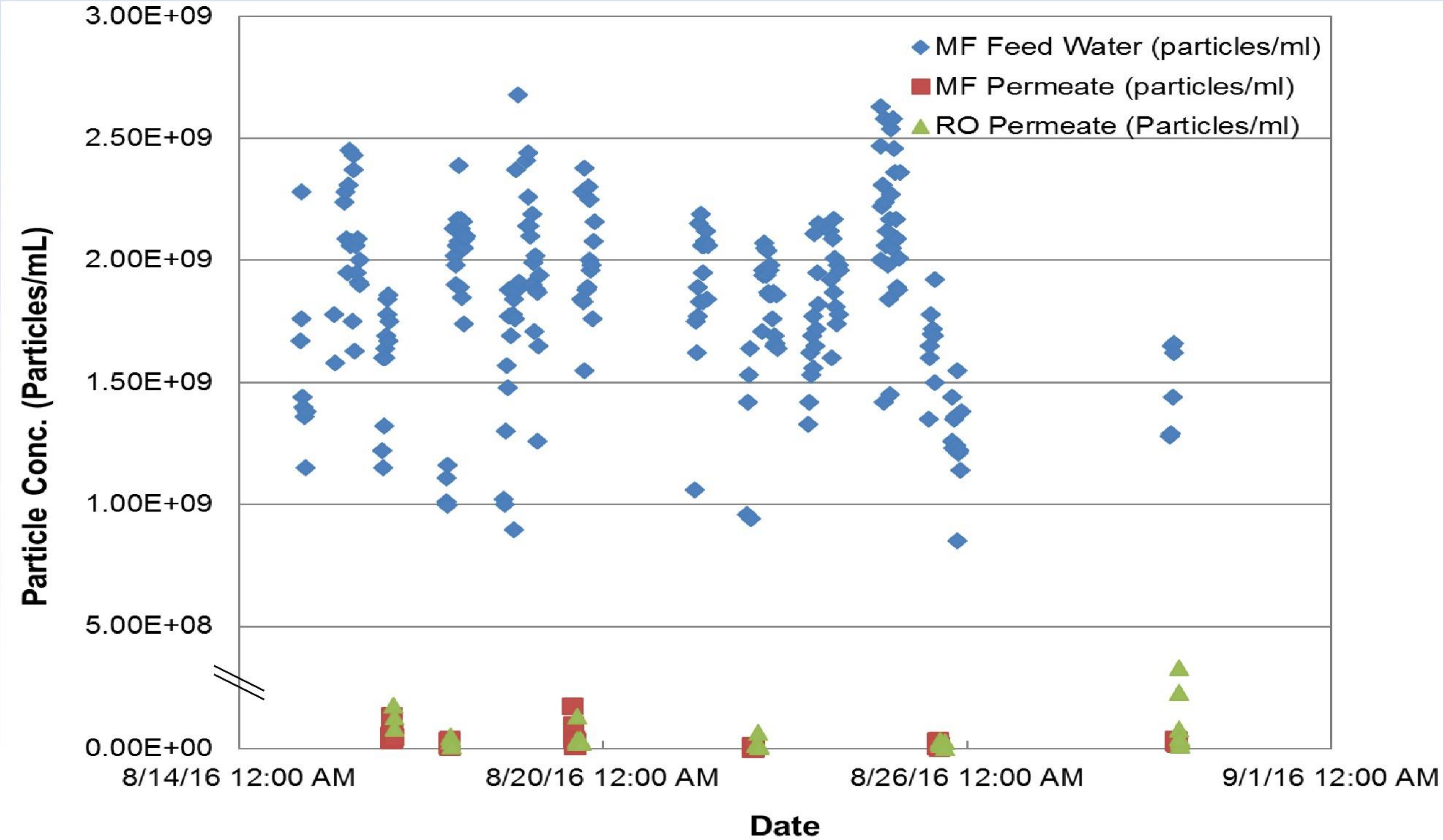
Week Day Diurnal Change in MFF Particle Concentration



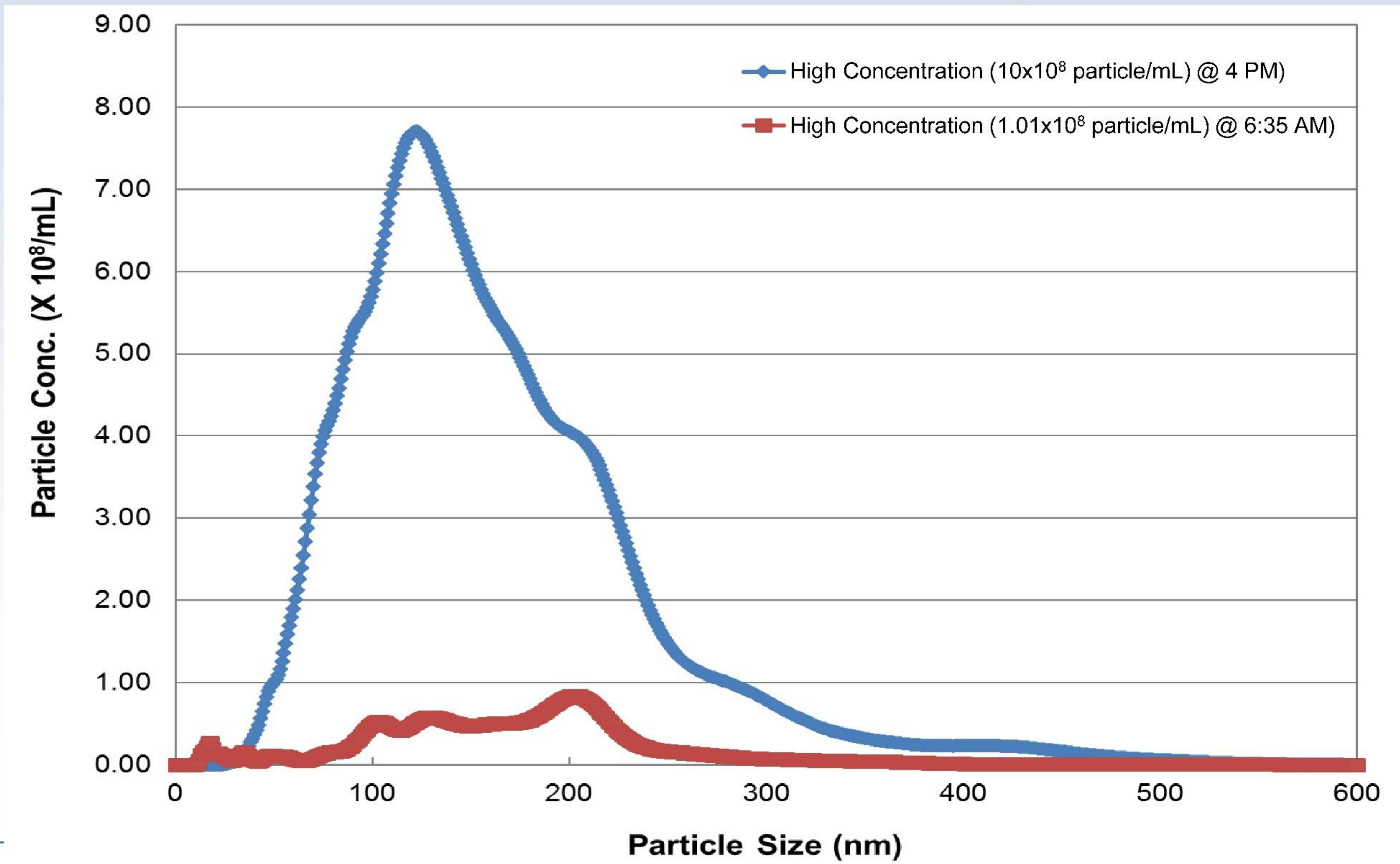
Weekend Diurnal Change in MFF Particle Concentration



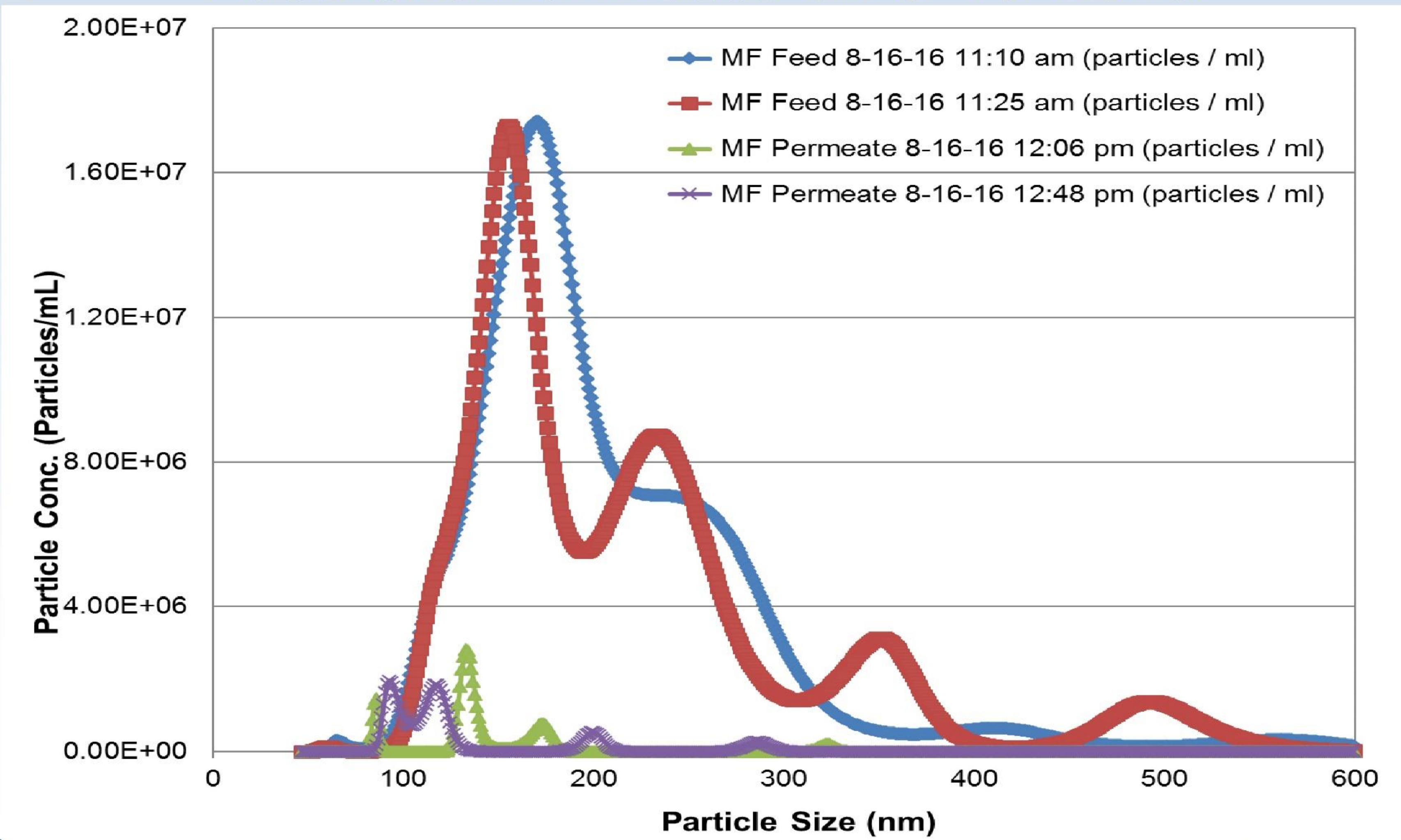
Colloidal Particles Concentration in MFF, MF Permeate and RO Permeate



MFF Colloidal Particle Size Distribution in High and Low Conc. 02-12-17 Samples



Colloidal Particles Size Distribution in MF Feed and Permeate on 8-16-2016



Particle Count Vs Turbidity / UV Absorbance

Coagulant Dose	Particle Conc/ mL	Turbidity (NTU)	Absorbance @ 210 nm
0 mg/L	1.84E+08	0.4	3.35
2 mg/L	2.56E+08	0.3	3.32
5 mg/L	9.43E+07	0.3	3.33
10 mg/L	3.67E+07	0.3	3.37

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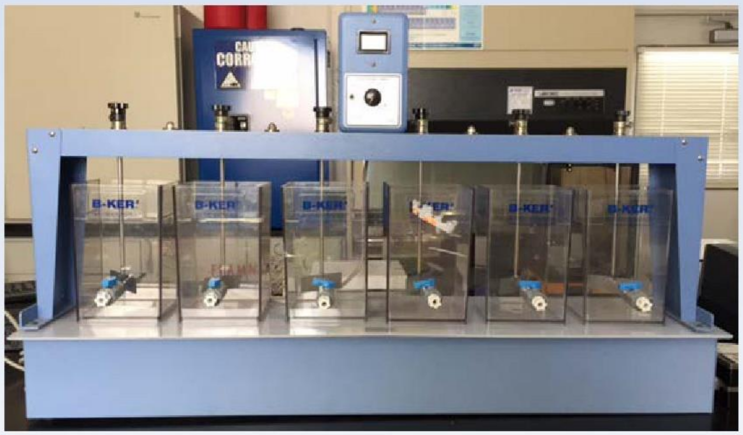
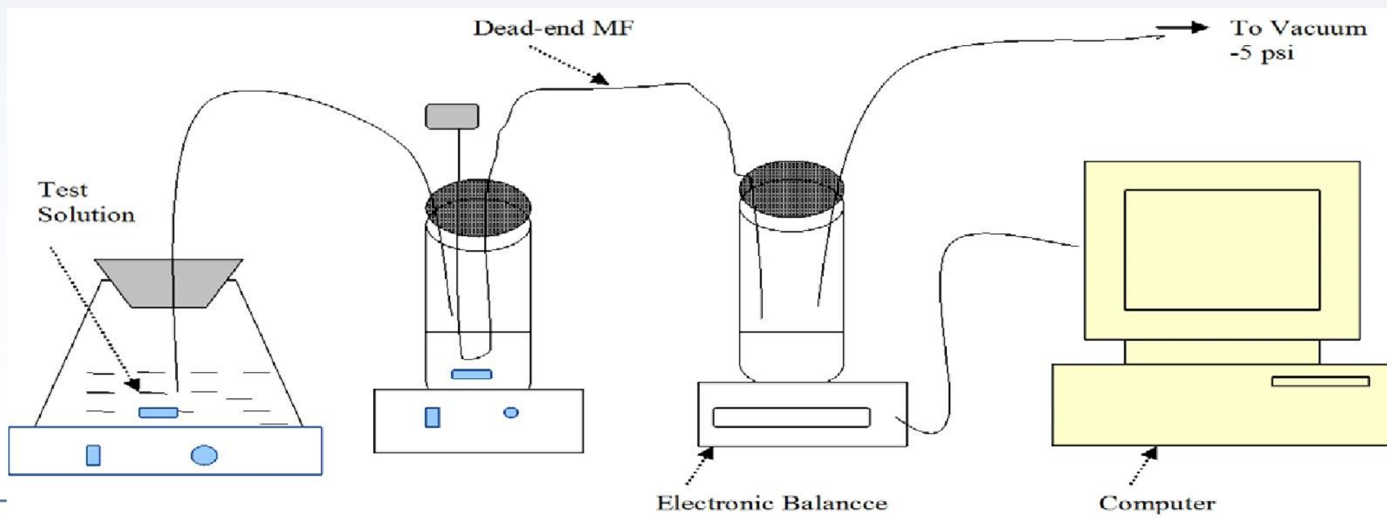
Jar Tests to Develop Relationship between Colloidal Particles and Coagulant Dose

- Jar Tests
  - Test 1: Used MF Feed Water (i.e. same particle concentration) and varied coagulant dose (0, 2, 5 and 10 mg/L)
  - Test 2: Varied Colloidal particle concentration.
    - Using MF backwash or DI water
    - Used same (5 mg/L) coagulant dose
- Performed MF filtration (flux rate) test using bench scale single element dead-end test cell

Jar Test and Bench Scale Membrane Filtration





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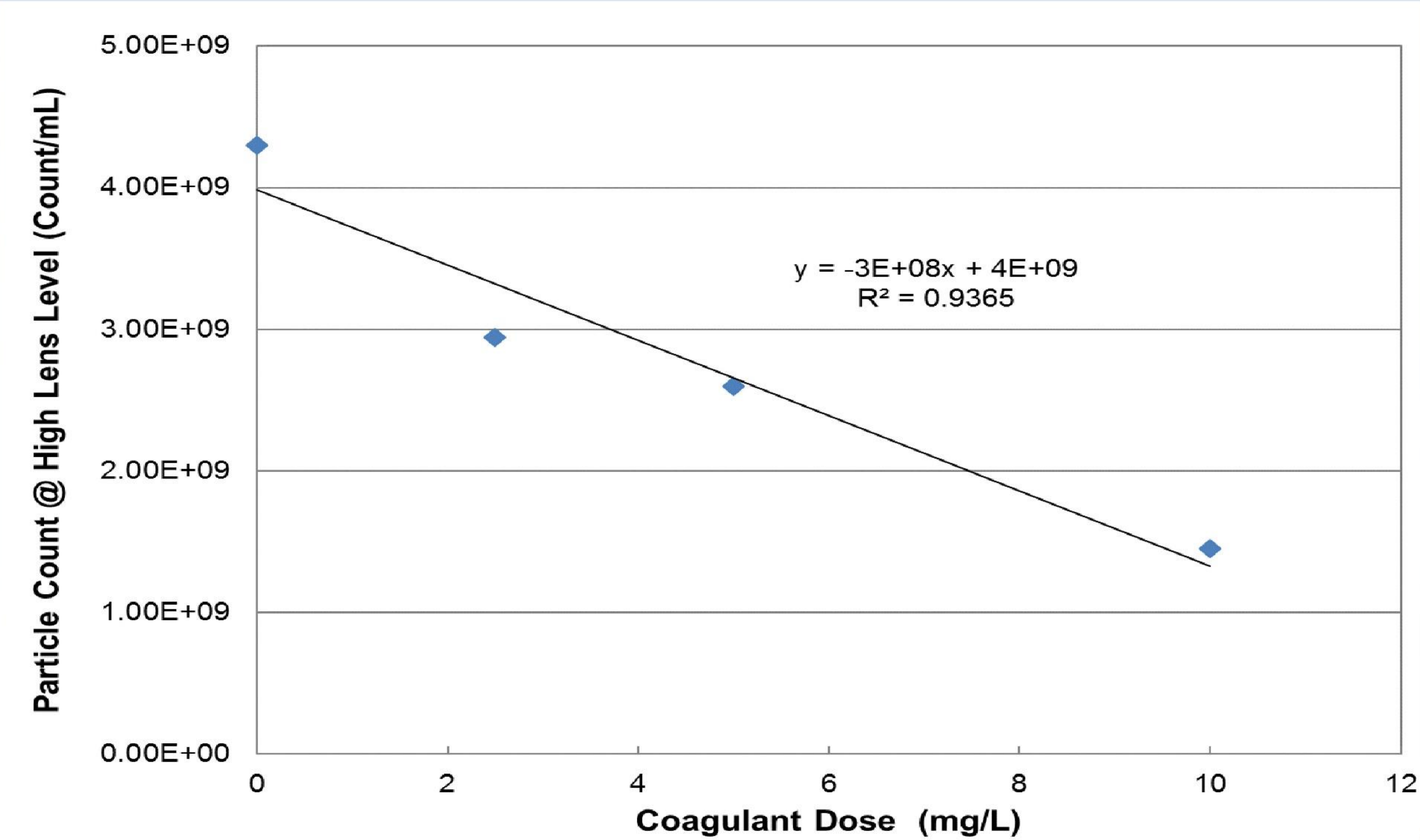
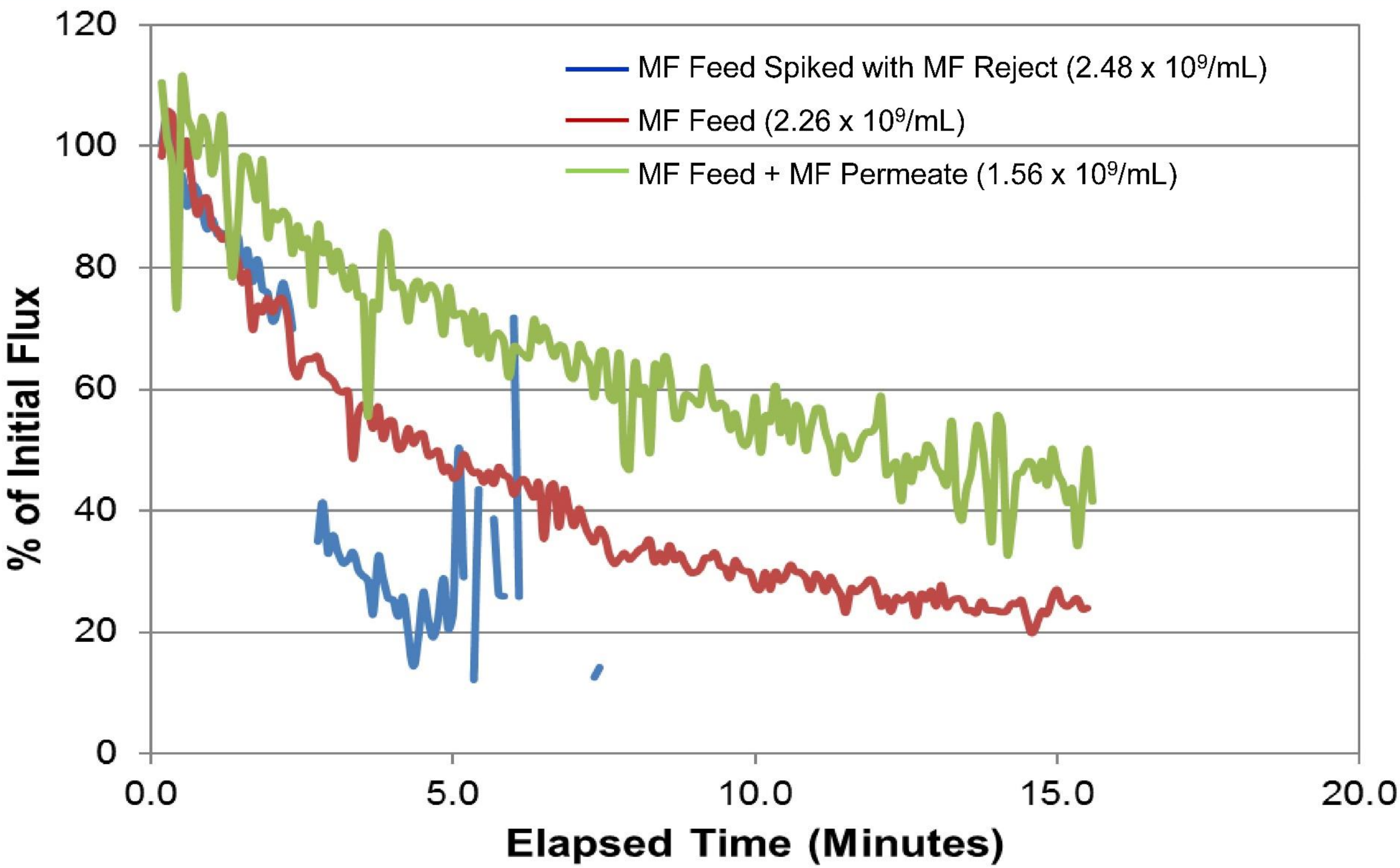
Relationship Between Coagulant Dose and Particle Count



Colloidal Particle Conc Vs % Flux Reduction



Calculated Relationship between Colloidal Particle Conc. and Coagulant Dose

$$C = 5 + \left[\frac{\left(1.978P - 10^{-9}\right) - \left(2.08 * 10^{-9}\right)}{\left(1.978P - 10^{-9}\right)} * 100 - 0.073\right] * \frac{1}{0.0618}$$

Where,
C = Coagulant dose (mg/L)
P = Particle count (per mL) of the untreated water using the "conventional" set up.

Summary

- Colloidal particles cause membrane fouling
- Dynamic Light Scattering (DLS) technology can detect and measure colloidal particles
- Diurnal variations in colloidal particle concentrations were observed in OCWD membrane feed water
- Colloidal particle size distribution may vary over time
- DLS technology, coupled with feed back loop for chemical dosing, can minimize fouling, lower energy use and improve membrane performance

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Next Steps

- Complete baseline testing - May 2017
- Membrane performance evaluation using DLS + Feedback loop - May to October 2017
- Testing at West Basin - November 2017 to June 2018

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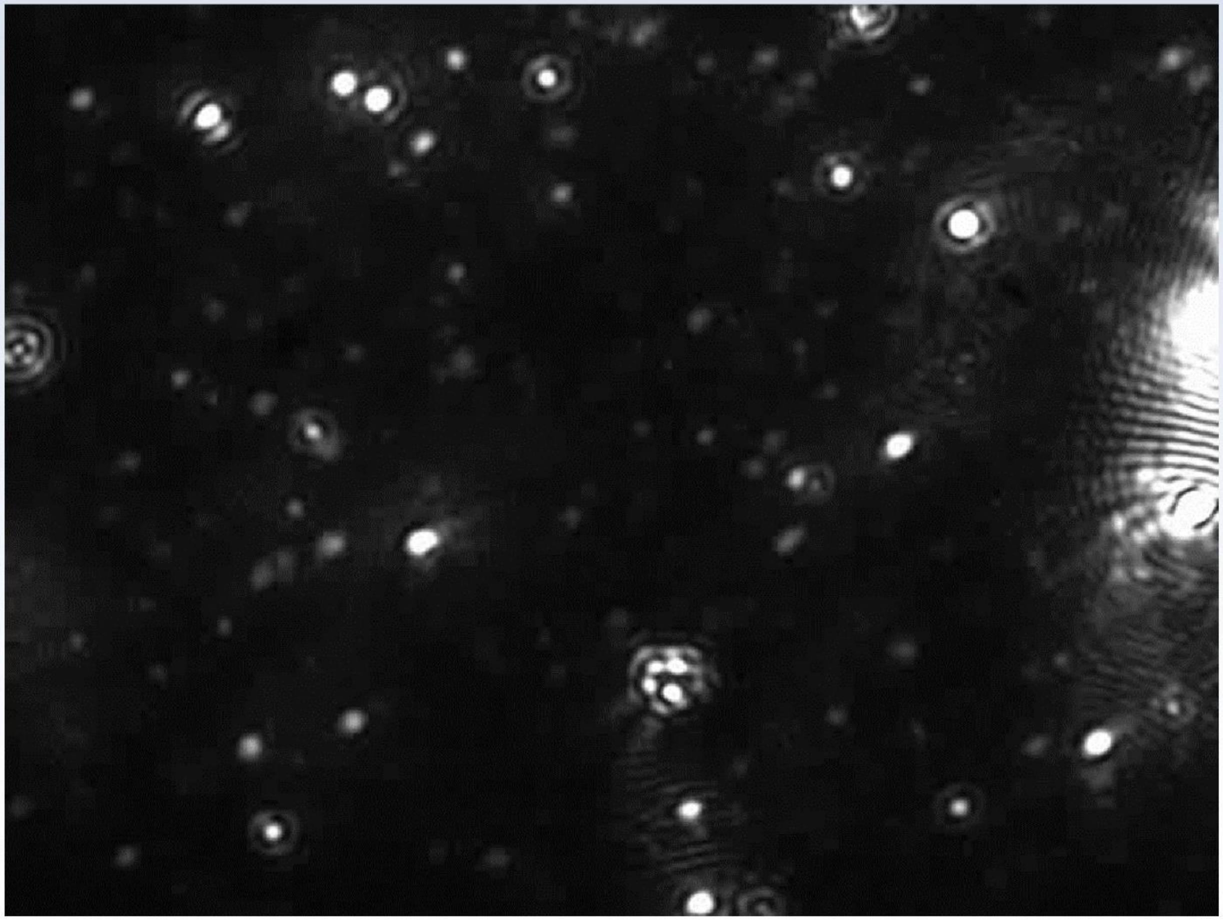
Thank You

Questions?

Jana Safarik
OCWD
E-mail: jsafarik@ocwd.com

Ganesh Rajagopalan, Ph.D., P.E., BCEE
Kennedy/Jenks Consultants
E-mail: rganesh@kennedyjenks.com

Nanoparticle Tracking Analysis (NTA)



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Analyses

- Colloidal Particle Count
  - MF feed
  - MF permeate
  - RO permeate
- UV Absorbance @210 nm
- Turbidity
- COD
- General minerals
- TMP
- Energy use

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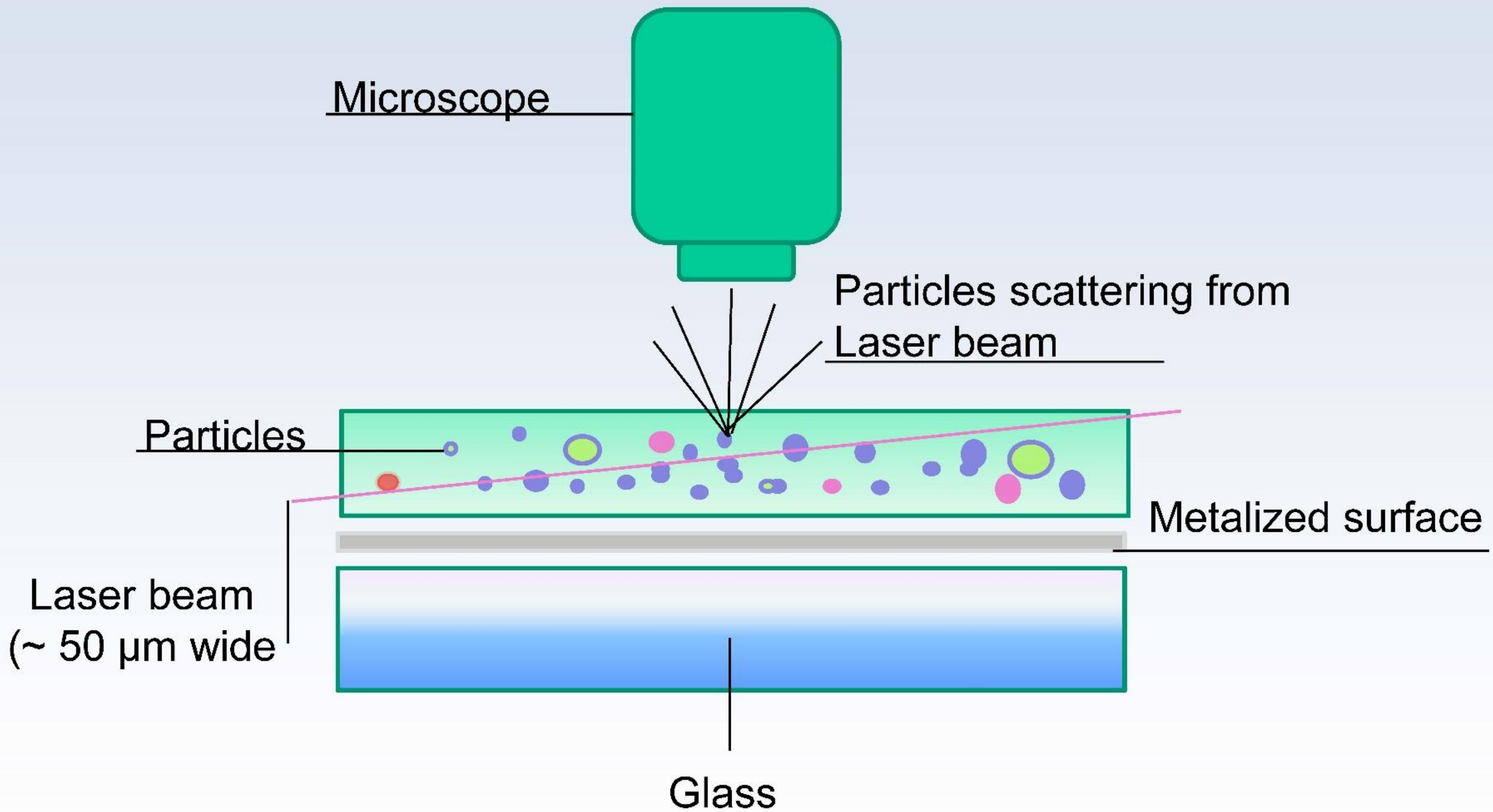
NanoSight NTA & Dynamic Light Scattering



A laser beam is passed through the sample chamber and the particles in suspension in the path of the beam scatter light and is visualized via a long working distance, x20 magnification microscope with a video camera. The camera captures a video file of the particles moving under Brownian motion. The Nanoparticle Tracking Analysis (NTA) software tracks many particles individually and using the Stokes Einstein equation calculates their hydrodynamic diameters.

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2019 Membrane Technology
CONFERENCE & EXPOSITION
Presented by
America's Authority in Membrane Treatment
AMTA
American Membrane Technology Association
Improving America's Waters Through Membrane Treatment and Desalting
American Water Works Association

Removal of Colloidal Particles through Online Monitoring to Lower Microfiltration Membrane Fouling

Jana Safarik[1], Ganesh Rajagopalan[2], Megan Plumlee[1]

[1]Orange County Water District
[2]Kennedy/Jenks Consultants

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Orange County Water District
SINCE 1933

Partners & Acknowledgements

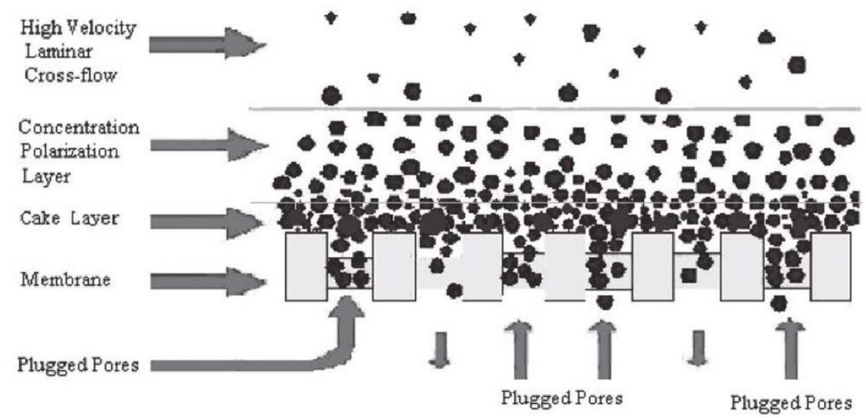
- California Energy Commission
- (Contract # EPC 15-014)
- Kennedy/Jenks Consultants
- Orange County Water District
- West Basin MWD
- Malvern Instruments
- Evoqua Water Technologies

Today's Presentation

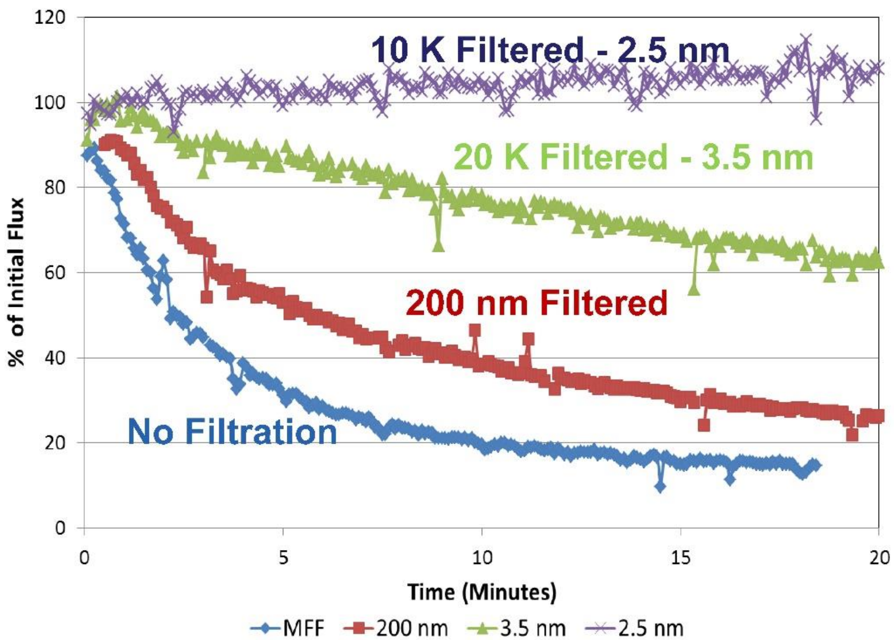
- Role of colloidal particles in microfiltration (MF) membrane fouling
- Detection and measurement of colloidal particles
- Project objectives
- Optimal coagulant dosing
- MF/RO pilot systems
  - Coagulant dosing system
- Results and conclusions

Role of Colloidal Particles in MF Fouling

- Reduce permeate flux or increased pressure by:
  - Pore blocking
  - Pore plugging
  - Concentration polarization
- Extent of fouling depends on:
  - Membrane pore size
  - Solute loading and distribution
  - Membrane polymer material
  - Source water quality and particle load
  - Operational conditions



Colloidal Particles >2.5nm Responsible for Flux Loss



- 200 nm pore size filtration – no significant flux improvement
- 20K and 10K filtration – improved flux rate by 50 and 95%
- Colloidal particles between 2.5 nm and 200 nm are responsible for most of the fouling

Detection and Measurement of Colloidal Particles

- Surrogate measurements are not very reliable
  - Turbidity
  - Absorbance
  - COD – chemical oxygen demand
- Emergence of Nanotechnology is starting to provide tools to detect nanoscale (colloidal) particles in wastewaters
  - Malvern Instruments
  - Beckman
  - Brookhaven

Malvern Instruments - Nanoscale Technology

- NanoSight – Nanoparticle Tracking Analyses (NTA) and Dynamic Light Scattering (DLS)
- Quick analysis – particle count and size distribution
  - Size resolution = <50 nm to 6,000nm
- Does NOT provide chemical composition
- Mostly used in medical/electronic/polymer industries
- Rarely used for water/wastewater analysis

NanoSight - NTA

Project Objectives

- Directly measure colloidal particle concentration and size distribution to allow targeted (real-time) pretreatment and removal via coagulation to minimize membrane fouling
- Identify optimal settings for the coagulant dosing control system using DLS for colloidal particle monitoring
- Improve energy efficiency of MF membrane pretreatment process via reduced fouling/TMP
- Determine the return on investment (ROI) and demonstrate viability of the proposed technology

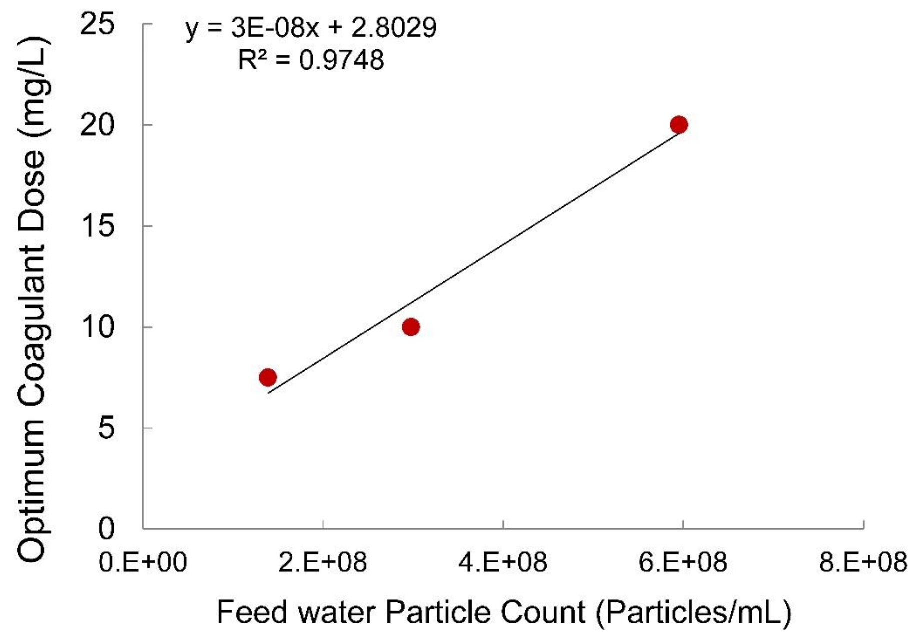
Coagulant – CC2060

- California Aluminum Chemicals, Modesto, CA
- Polyaluminum chloride solution

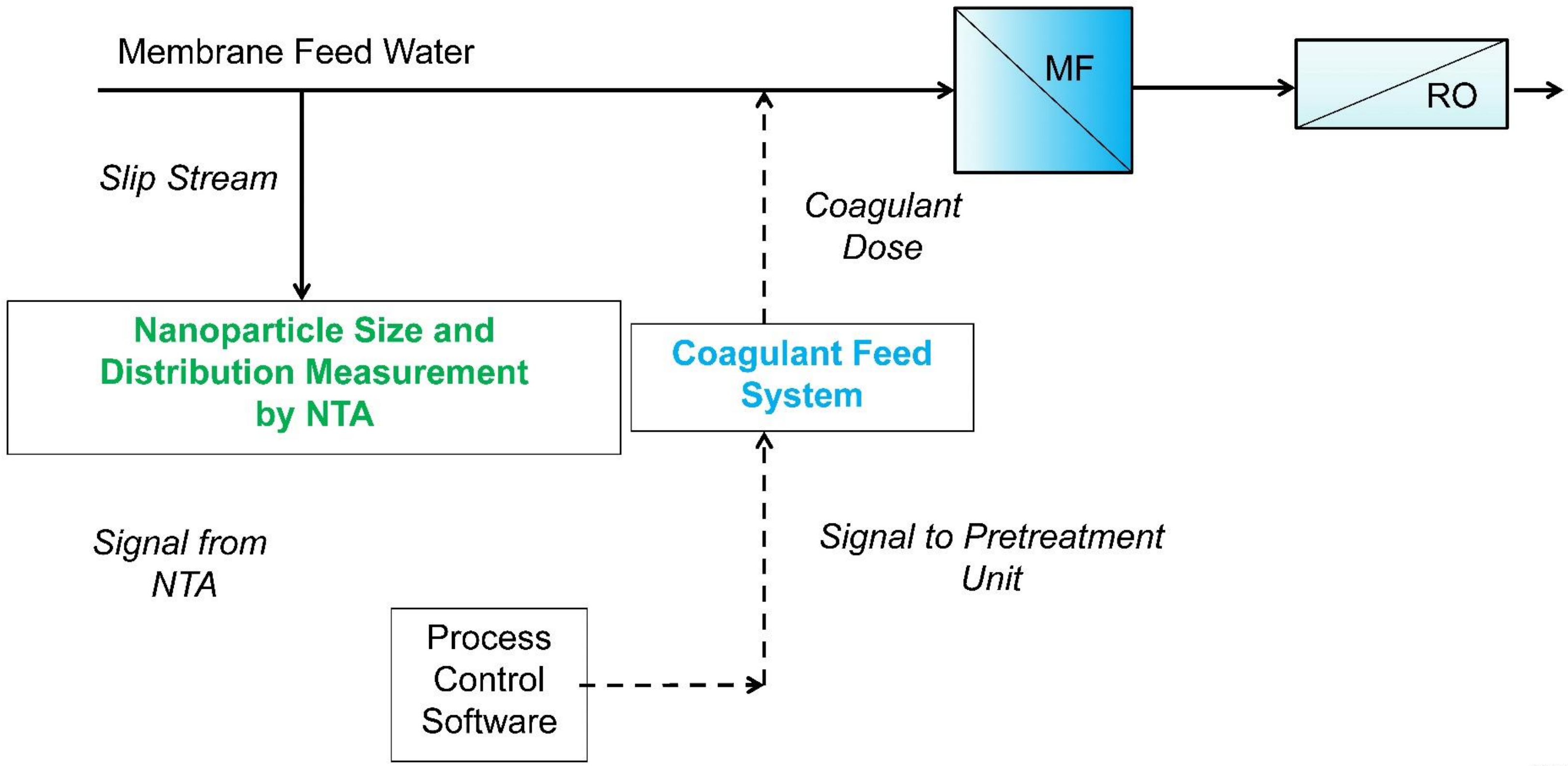
Parameter	Specification
Aluminum (Al^{3+})	9.7 ± 1%
Aluminum Oxide (%Al_2O_3)	18.5 ± 1%
Chloride (%Cl)	15.5 ± 1%
Specific Gravity (@20°C)	1.30 ± 0.01
Appearance	Clear to Slightly Hazy
Solubility in Water	Complete
Freeze Point	15°F

Optimal Coagulant Dosing

- Determined by jar testing and a bench scale single-fiber dead-end MF test cell
- Dosage was determined in response to the colloidal particle count in the feed water
- A calibration curve was developed to predict the optimal coagulant dose as a function of total particle count in the feed water.



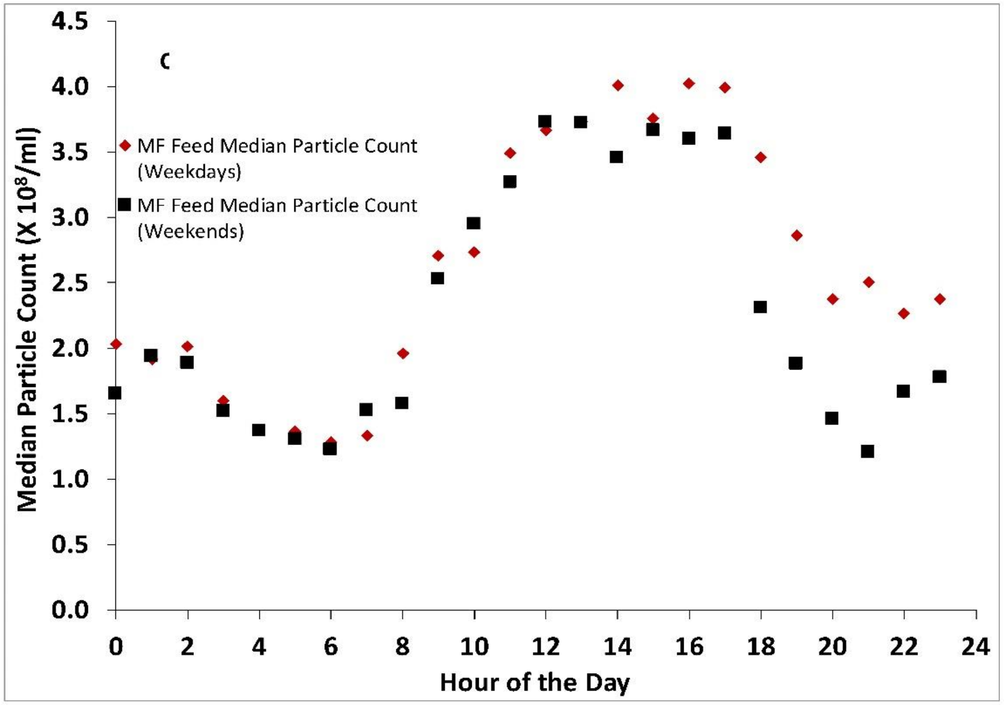
Schematic of Coagulant Dosing



OCWD MF and RO Pilots

- Feed water - secondary effluent
- MF pilots
  - Evoqua 200 nm pore size polypropylene membranes
  - 18 gpm flow rate
  - *Control* - no coagulation
  - *Coagulation* – CC2060
- RO pilot
  - Hydranautics ESPA2-LD membranes
    - ✓Flux = 12 gfd
    - ✓Recovery = 85%

Diurnal Trend of Colloidal Particles

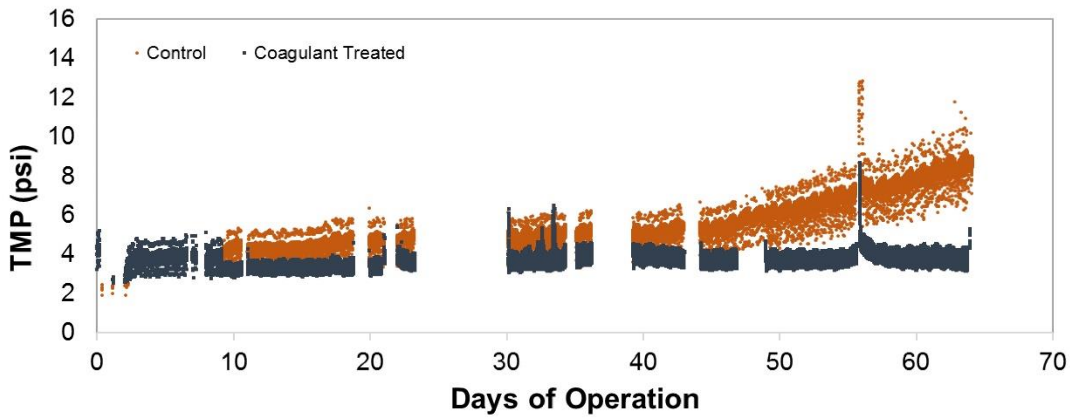


Particle Concentrations

- Vary throughout the day
- Lowest at night
- Peak at noon
- Second uptick around midnight

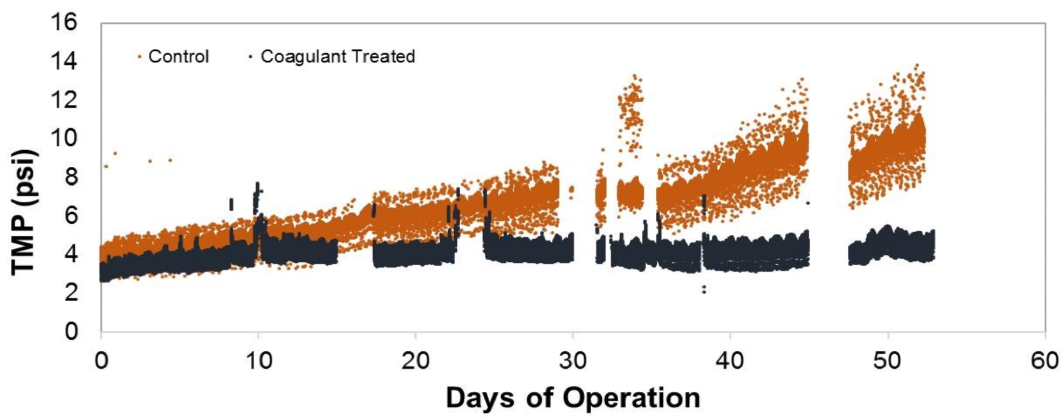
Due to concentration variability, a dosing protocol is needed to respond in real-time to maintain optimal coagulant dosing

Impact of CalChem 2060 on MF Performance



Summary of TMP – Trial 1

	Control	Coagulant-Treated
Average TMP	8.63 psi	3.97 psi
Overall Increase in TMP (ΔTMP)	4.66 psi	0.18 psi



Summary of TMP – Trial 2

	Control	Coagulant-Treated
Average TMP	10.13 psi	4.57 psi
Overall Increase in TMP (ΔTMP)	7.46 psi	1.46 psi

- Coagulant-treated membrane (left) and untreated control membrane (right) after reaching terminal TMP and before CIP
- The coagulant-treated MF membrane was visually cleaner than the untreated

The novel aspect of this study is the targeted coagulant dosing based on real-time nanoparticle measurement to optimized control and minimize coagulant dose

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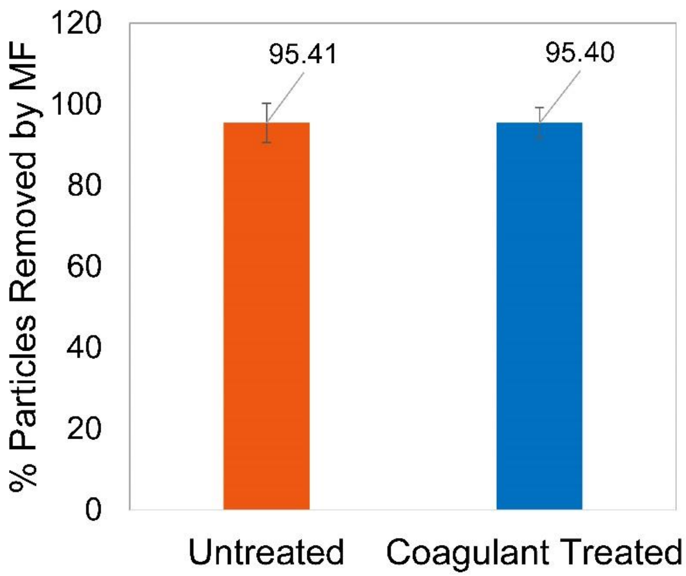
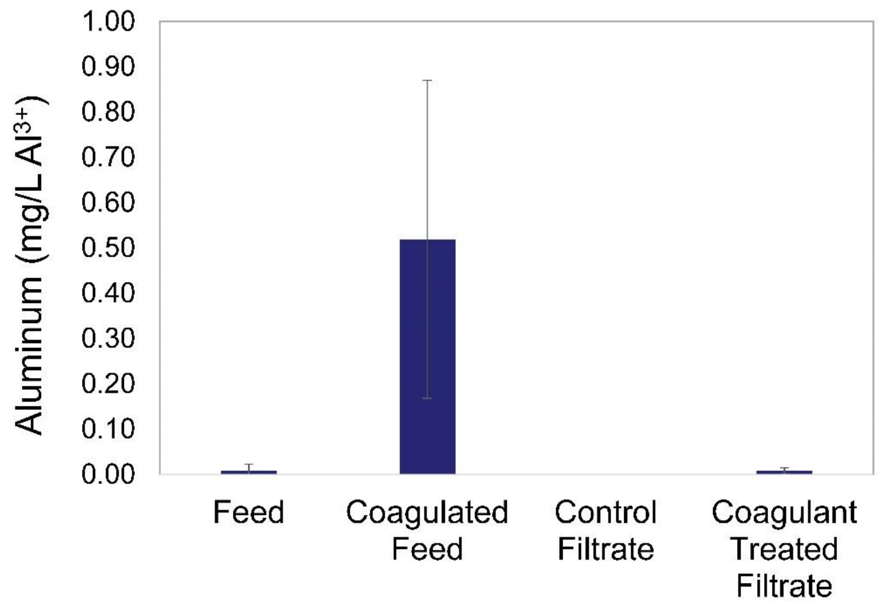
Colloidal Particle Removal by MF



- Number of colloid particles traversing the MF membrane is equal between the two test conditions
- Coagulant pretreatment does not affect MF effluent water quality. No effect on RO was observed.
- Coagulant prevents particles from entering and depositing inside the membrane matrices and are captured on the outside surface and removed during backwash/air scour.

Water Quality Parameters Including Aluminum

- Excess aluminum in MF effluent can increase potential for aluminum to form insoluble silicates
- Addition of poly-aluminum coagulant introduced a significant amount of aluminum in the feed water, however it did not affect filtrate aluminum levels.



Water Quality

	Feed	Coagulated Feed	Control Filtrate	Coagulant Treated Filtrate	Coagulant Treated RO Permeate
COD (mg/L)	37.2 ± 5.4	35.4 ±5.0	28.2 ±7.5	29.0 ±6.7	4.64 ±3.0
Turbidity (NTU)	2.16 ±0.85	3.85 ±1.83	0.14 ±0.28	0.09 ±0.02	0.05 ±0.01
UVA (abs.)	3.37 ±0.03	3.37 ±0.04	3.34 ±0.03	3.32 ±0.03	0.71 ±0.17
Aluminum (mg/L Al^{3+})	0.008 ±0.015	0.52 ±0.35	< DL	0.008 ±0.007	< DL

Economic Evaluation - Overview

System Assumptions used for Economic Evaluation	
Flowrate	105 MGD
Energy consumption for MF filtration	0.21 kWh/1000 gallons
Energy cost	0.095 $/kWh
Number of MF membrane modules	24, 627 modules
Price of MF modules	750 $/module
Baseline MF membrane lifetime	7 years
Baseline CIP frequency	Every 21 days or upon reaching 12.5 psi
Polymer chemical cost	0.30 $/lb

Operating Cost Changes due to Coagulant Pretreatment

Improved MF operating TMP, resulting in 29% reduction in energy use

Reduced CIP frequency to once per 6 months

Prolonged MF membrane lifetime to 21 years

Addition of coagulant polymer based on MF feed quality

$$\textit{Savings (in energy and other O\&M costs)} - \textit{Additional spending (coagulant costs)} = \textit{Net Annual Savings}$$

Economic Evaluation - Savings

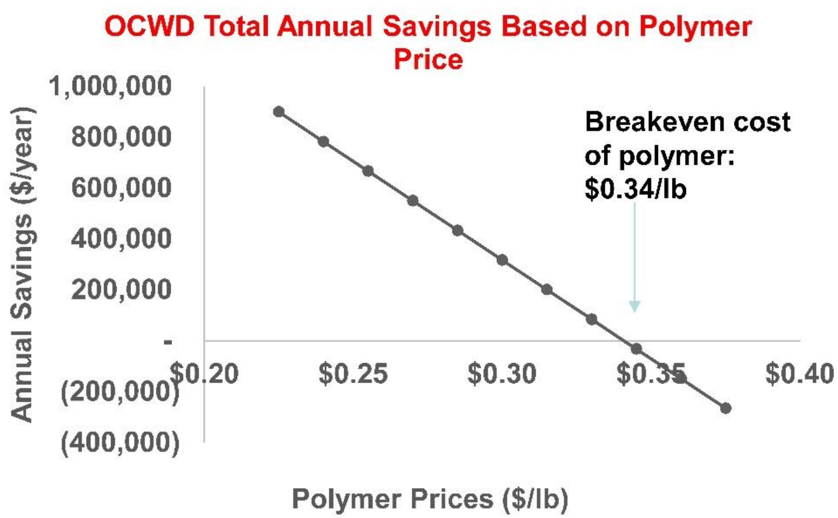
Savings in Electricity and other O&M Costs	
Flow Rate for MF (MGD)	105
Energy Use for MF (KwH/1000 gal)	0.21
Energy Use for MF (kWh/yr)	8,064,700
Energy Use for MF Backwash (kWh/yr)	1,209,700
Percent Energy Savings for MF Operations (%)	29
Energy Savings in MF (kWh/yr)	2,663,300
Electricity Cost ($/kWh)	0.095
Total Energy Cost ($/yr)	$881,000.00
Savings in Electricity Cost ($/yr)	***$253,000.00***
Chemical Cost for Cleaning ($/yr)	$764,000.00
Percent Savings in Cleaning Cost (%)	83
Savings in Chemical Cost ($/yr)	***$634,120.00***
Membrane Replacement Cost ($/yr)	$18,470,250.00
Percent Savings in Membrane Replacement Cost (%)	67
Savings in Membrane Replacement Cost ($/yr)	***$1,759,100.00***
Waste Disposal Costs ($/yr)	-
Total Savings in Membrane Treatment ($/yr)	**$2,646,200.00**

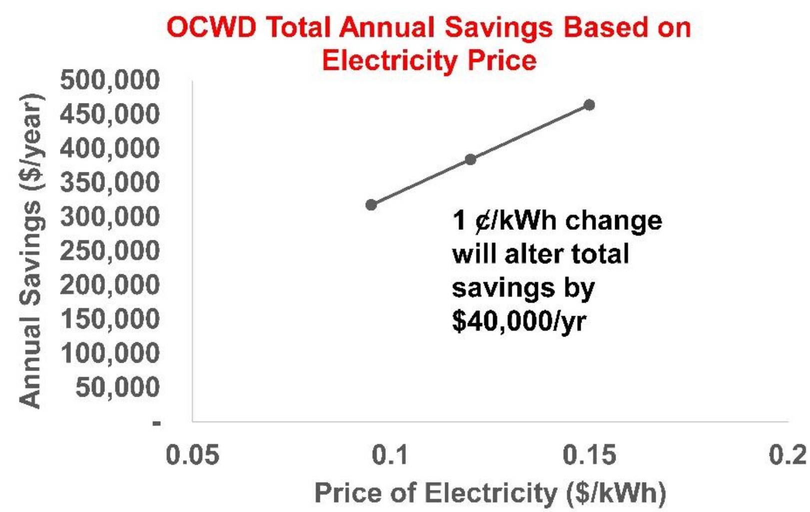
Economic Evaluation - Spending

Chemical Cost for Pre-treatment	
Chemical Dose - Active polymer(mg/L)	10
Percent active polymer in stock (%)	50
Total Chemical Dose	20
Chemical Cost ($/lb)	0.30
Chemical Demand (g/yr)	2,897,370,000.00
Chemical Demand (lb/yr)	7,762,718
Total Chemical Spending ($/yr)	**$2,328,800.00**

Total Annual Savings	***$317,000.00***

Sensitivity Analysis





Annual savings subject to changes in polymer price and electricity costs.

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Results and Conclusions

- MF feedwater colloidal particle concentrations vary throughout the day
- Using NTA and injecting an optimal dose of coagulant (CC2060, cationic poly-aluminum chloride) based on total colloidal particle counts, the MF pilot achieved significant and sustained reduction in TMP
  - ***Targeted coagulation decreased the rise in TMP by 80%***
- Coagulation pretreatment that targets colloidal particle concentrations can help reduce operating costs, cleaning frequencies, and reduce membrane replacements.