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5049

Public Health Benefits and Challenges for Blending of Advanced Treated Water with Raw Water Upstream of a Surface Water Treatment Plant in DPR

CALIFORNIA
Water Boards
STATE WATER RESOURCES CONTROL BOARD
REGIONAL WATER QUALITY CONTROL BOARDS

Public Health Benefits and Challenges for Blending of Advanced Treated Water with Raw Water Upstream of a Surface Water Treatment Plant in DPR

Prepared by:

Giridhar Upadhyaya, Andrew Salveson, Jason Assouline, Gil Crozes
Carollo Engineers, Inc.

Kerry Howe
Kerry Howe Consulting, LLC

Kevin Linder
Aurora Water

Hossein Ashktorab
Valley Water

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For more information, contact:

The Water Research Foundation
1199 North Fairfax Street, Suite 900
Alexandria, VA 22314-1445
P 571-384-2100

6666 West Quincy Avenue
Denver, Colorado 80235-3098
P 303-347-6100

www.waterrf.org
info@waterrf.org

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Prepared by Carollo Engineers, Inc., Kerry Howe Consulting, LLC, Aurora Water, Valley Water

Acknowledgments

Research Team

Principal Investigators:
Gil Crozes, PhD
Giridhar Upadhyaya, PhD, PE *(Now with Brown and Caldwell)*
Andrew Salveson, PE
Carollo Engineers

Kerry Howe, PhD, PE, BCEE
Kerry Howe Consulting, LLC

Kevin Linder
Aurora Water

Hossein Ashktorab, PhD
Valley Water

Project Team:
Jason Assouline
Charlie He
Vincent Hart
Eunyoung Lee
Risa Guysi
Amos Branch
Carollo Engineers

Nastaran Basiri
Valley Water

Madeline Kelsch
Los Angeles Department of Water and Power

Ann Malinaro
Aurora Water

Technical Advisors

Zakir Hirani, PE, BCEE
James Borchardt, PE
Stantec

WRF Project Subcommittee and other Contributors

Joseph A Cotruvo, PhD
Joseph Cotruvo & Associates, LLC

Heather Collins
Metropolitan Water District of Southern California

Daniel Nix
City of Wichita Falls

Clifton Herrmann
State Water Resources Control Board

WRF Staff

John Albert, MPA
Chief Research Officer

H. Grace Jang, PhD
Research Program Manager

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Acronyms and Abbreviations

µg/L	microgram per liter
µm	micrometer
µS/cm	microsiemens per centimeter
•OH	hydroxyl radical
AWTP	advanced water treatment process
ACH	aluminum chlorohydrate
aDOC	anthropogenic dissolved organic carbon
AOP	advanced oxidation process
ARB	antibiotic resistant bacteria
ARG	antibiotic resistance genes
ASU	Arizona State University
ATP	adenosine triphosphates
ATW	advanced treated water
AWPF	advanced water purification facility
AWWSC	American Water Works Service Company
BAC	biologically active carbon
BAF	biological aerated filter
BDOC	biodegradable dissolved organic carbon
BPI	Blue Plan-it®
BV	bed volumes
CA	California
CBAT	carbon-based advanced treatment
CCL	candidate contaminant list
CCPP	calcium carbonate precipitation potential
CDPH	California Department of Public Health
CEC	constituents of emerging concerns
CFU	colony forming unit
cm^{-1}	per centimeter
CSMR	chloride-to-sulfate mass ratio
CT	contact time
CWA	Clean Water Act
D/DBPR	Disinfectants and Disinfection Byproducts Rules
Da	dalton
DBP	disinfection byproducts rules
DI	deionized
DIA	des-isopropyl atrazine
DO	dissolved oxygen
DOC	dissolved organic carbon
DPR	direct potable reuse
EBCT	empty bed contact time
EDC	endocrine disrupting compounds
EPC	electrostatic patch coagulation

FP	formation potential
FWH WRC	F. Wayne Hill Water Resources Center
GAC	granular activated carbon
gc	gene copies
gpm	gallons per minute
gpm/ft^2	gallons per minute per square foot
GS	galvanized steel
HAA	haloacetic acid
HPC	heterotrophic plate count
HRT	hydraulic retention time
IOD	initial ozone demand
IPR	indirect potable reuse
IX	ion exchange
L	liter
L/mg-m	liter per mg per meter
LCR	Lead and Copper Rule
LDI	lined ductile iron
LRV	log reduction value
LSI	Langelier Saturation Index
LT2ESWTR	Long Term 2 Enhanced Surface Water Treatment Rule
MBR	membrane bioreactor
MCL	maximum contaminant levels
MCLG	maximum contaminant level goal
MF	microfiltration
MFGM	membrane filtration guidance manual
mg/L	milligrams per liter
mgd	million gallons per day
mL	milliliter
MOS	margin of safety
MPN/L	most probable number per liter
MS2	MS2 bacteriophage
NDMA	N-nitorosodimethylamine
NF	nanofiltration
ng/L	nanogram per liter
NGWRP	New Goreangab Water Reclamation Plant
nm	nanometer
NOM	natural organic matter
NPDWR	National Primary Drinking Water Regulations
NTU	nephelometric turbidity unit
PACl	polyaluminium chloride
PCE	tetrachloroethylene
PDS	pilot distribution systems
PFAS	per- and poly-fluorinated compounds
PFBS	perfluorobutane sulfonate

PFC	perfluorinated compound
PFHxS	perfluorohexane sulfonate
PFOA	perfluorooctanoic acid
PFPA	perfluoropentanoic acid
PFS	polyferric sulfate
PFSS	polyferric silicate sulfate
pfu	plaque forming unit
PMMoV	pepper mild mottle virus
PPCP	pharmaceuticals and personal care products
PVC	polyvinylchloride
qPCR	quantitative real-time polymerase chain reaction
RBAT	RO-based advanced treatment
RFI	request for information
RNA	ribnonucleic acid
RO	reverse osmosis
RSI	Ryznar stability index
RWA	raw water augmentation
SCADA	supervisory control and data acquisition
SDWA	Safe Drinking Water Act
sMCL	secondary maximum containment levels
SU	standard unit
SUVA	specific UV absorbance
SWTP	surface water treatment plant
SWTR	Surface Water Treatment Rules
T&O	taste and odor
TCE	trichloroethylene
TCEP	tris(2-carboxyethyl)phosphine
TCEQ	Texas Commission on Environmental Quality
TCP	1,2,3-trichloropropane
TDCCP	tris(1,3-dichloro-2-propyl)phosphate
TDS	total dissolved solids
THM	trihalomethane
TWA	treated water augmentation
TOC	total organic carbon
TT	treatment techniques
TTHM	total trihalomethanes
UCF	uniform formation condition
UCI	unlined cast iron
UCMR	Unregulated Contaminant Monitoring Rule
UF	ultrafiltration
UFRV	unit filter run volume
USEPA	United States Environmental Protection Agency
UV	ultraviolet
UVT	ultraviolet transmittance

VOC	volatile organic compounds
Water ARC®	Water Applied Research Center
WMS	whole metagenome sequencing
WRF	The Water Research Foundation
WTP	water treatment plant

Executive Summary

ES.I Key Findings

The bench- and pilot-scale results indicated that blending advanced treated water (ATW) with raw water sources upstream of a surface water treatment plant does not negatively affect plant operation and performance. The key findings from the study are listed below:

- Blending ATW:
  - Improves water quality
  - Lowers chemical demands (coagulant, ozone, and disinfectant)
  - Improves process performance, including:
    - Similar or better total organic carbon (TOC) removal
    - Better filter effluent turbidity
    - Lower filter headloss accumulation rate (i.e., longer filter runs)
    - Better pathogen removal

ES.2 Background and Objectives

Recycled water is an important source of water to help address challenges associated with water scarcity, climate change, population growth, and extensive drought. Direct potable reuse (DPR) has advantages over indirect potable reuse primarily due to less infrastructure needs, lower energy requirements, and lower operations and maintenance costs. Furthermore, DPR provides greater flexibility for monitoring and controlling system performance due to the use of engineering systems compared to an environmental buffer. For DPR, blending ATW with the raw water sources upstream of a surface water treatment plant (SWTP) is an option. However, it is critical to understand the effects of blending ATW with the raw water sources on the SWTP operation and performance, including pathogen log removal.

The objectives of this study were as follows:

- Determine the effects on SWTP operational efficiency and effectiveness (e.g., pathogen and particle removal) when blending ATW with raw water.
- Develop operational strategies and best practices for SWTP when blending ATW with raw water.
- Develop approaches to establish pathogen log reduction credits under DPR regulatory frameworks for SWTP unit processes (i.e., coagulation, flocculation, sedimentation, filtration, and disinfection) when blending ATW with (a) raw water upstream of an SWTP (i.e., raw water augmentation), or (b) SWTP filtered water (i.e., before disinfection).

ES.3 Project Approach

Historical data on water quality at the participating utilities' SWTP and advanced water purification facility (AWPF) and plant performance were reviewed. A blending model was developed using Carollo's Blue Plan-it® Decision Support System and the historical data were used as the model input. The model simulated scenarios for blending ATW with the raw water or filtered water. A literature review was conducted focusing on regulatory considerations, boundaries of SWTP and AWPF operating conditions and performance, potential water quality changes and impacts on SWTP operation and performance, process optimization approaches, and pathogen log reduction credit validation approaches.

Bench-scale tests were conducted with ATW and raw water samples received from six utilities across the country. The bench-scale testing included zeta potential evaluation, jar testing, and qualitative filterability evaluation and tests were conducted with 0% to 40% ATW blending ratios. Pilot-scale tests were conducted at three participating utilities with pilot skids simulating a conventional treatment plant or direct filtration plant. Tests were conducted with 0% to 50% ATW blends to characterize impacts of the ATW blending on water quality, unit process performance, and pathogen removal. Pathogen removal was assessed through MS2 bacteriophage and pepper mild mottle virus (PMMoV) challenge tests.

ES.4 Results

The findings of the study are summarized below:

Water quality – In general, blending ATW with raw water improves the quality of the water to be treated. The blended water quality can be estimated through mass-balance with concentrations of constituents in the raw water and ATW.

Chemical requirement – Blending ATW with raw water can lower ozone (as applicable), coagulant, and disinfectant doses.

Filter performance – Similar or better filter effluent turbidity can be achieved with ATW-blended water. With the improved water quality, headloss accumulation rate declines, resulting in longer filter run length. The effects on headloss accumulation rate and filter run length may not be directly proportional to the percentage increase in blending ratio.

TOC removal – With the ATW-blended water, similar or better TOC removal can be achieved. The improvement in TOC removal is not proportional to the increase in the blending ratio.

Disinfection byproduct formation potential (DBP FP) – The effects on DBP FP can be ATW source- and site-specific.

Pathogen removal – Similar or better pathogen log removal can be achieved with the ATW-blended water. There can be a site-specific threshold for ATW blending ratio.

Particle removal - Similar or better particle removal can be achieved with ATW-blended water.

ES.5 Benefits

Through extensive bench- and pilot-scale testing, this study evaluated potential challenges and benefits associated with blending ATW with raw water sources upstream of an SWTP. The testing results showed that ATW blending with raw water sources generally improves water quality and improves unit process performance. The study also showed that similar or better pathogen log removal can be achieved with ATW-blended water. The findings from this study will be valuable for the entire reuse and drinking water industry. The recommendations (Chapter 7) will help utilities plan, test, and implement ATW blending with raw water sources at an SWTP.

ES.6 Related WRF Research

- Considerations and Blending Strategies for Drinking Water System Integration with Alternative Water Supplies (4953)
- Blending Requirements for Water from Direct Potable Reuse Treatment Facilities (4536)
- Demonstration of High Quality Drinking Water Production Using Multi-Stage Ozone Biological Filtration: A Comparison of Direct Potable Reuse (DPR) with Existing Indirect Potable Reuse (IPR) (4777)

CHAPTER 1

Introduction

1.1 Research Motivation

Water scarcity, climate change, ever-increasing population, and the cost drivers associated with importing limited water resources from long distances are encouraging utilities to expand their water supply portfolio by leveraging all potential water supply sources. Recycled water is increasingly being recognized as an important and reliable water source that can be treated through advanced water treatment processes (AWTP) to supplement potable water supply. Regulators in many states, including California, Colorado, Arizona, and Florida are actively working towards the development of regulations applicable for direct use of this valuable water source for drinking water production (i.e., direct potable reuse [DPR]).

A range of potable reuse projects have been developed across the globe with the early examples mostly focused on groundwater replenishment (i.e., indirect potable reuse [IPR]). However, IPR may face challenges due to:

1. Potentially complex legal provisions.
2. Contamination in the groundwater basin requiring treatment upon extraction.
3. Infrastructure requirements for extraction and distribution.
4. Application limitation due to basin capacity or geology, and aquifer type and water quality.

DPR can be advantageous over IPR, primarily due to limited to no additional infrastructure requirements, such as long pipelines, injection wells, and extraction wells (Lahnsteiner et al. 2018). Reduced energy requirements, reduced capital and operation and maintenance costs, and better monitoring and water quality control are some of the additional benefits identified for DPR compared to IPR (Stanford et al. 2016). DPR also does not face the challenge of potential contamination that IPR can experience if water is stored in a contaminated aquifer.

DPR has two possible blending approaches:

1. Raw water augmentation (RWA), in which ATW is blended with the raw water sources upstream of an SWTP, and
2. Treated water augment (TWA), in which ATW is blended with the filtered water from an SWTP.

While TWA eliminates the need to treat larger volume of water through an SWTP, RWA can provide additional benefits, including public perception benefits (Stanford et al. 2016), with the logic implied in the United States Environmental Protection Agency's (USEPA) Filter Backwash Recycling Rule. A primary question for DPR with the RWA approach is – how does the addition of purified recycled water impact the treatment plant operations and pathogen log reduction credits (often called Log Reduction Value (LRV)? To answer this question, the Water Research Foundation implemented this WRF Project 5049 - *Public Health Benefits and Challenges for Blending of Advanced Treated Water with Raw Water Upstream of a Surface Water Treatment*

Plant in DPR in collaboration with the State Water Resources Control Board in California (CA SWRCB).

1.2 Research Objectives and Hypothesis

The project intended to define benefits and challenges in pathogen removal and develop an approach for using ATW through DPR for supplementing raw water supply at a conventional SWTP. The objectives of the study were to:

- Determine the effects on SWTP operational efficiency and effectiveness (e.g., pathogen and particle removal) when blending ATW with raw water.
- Develop operational strategies and best practices for SWTPs when blending ATW with raw water.
- Develop approaches to establish pathogen log reduction credits under DPR regulatory frameworks for SWTP unit processes (i.e., coagulation, flocculation, sedimentation, filtration, and disinfection) when blending ATW with (a) raw water upstream of an SWTP (i.e., raw water augmentation), or (b) SWTP filtered water (i.e., before disinfection).

To meet the project objectives, the following hypotheses were developed and extensive bench and pilot-scale tests were conducted to test the hypotheses:

Hypothesis 1: Blending ATW changes water chemistry, which can affect coagulation chemistry and floc characteristics. The effects can be understood by assessing the changes on particle charge, TOC removal, and floc characteristics (i.e., whether it is more of a "chemical floc"). Coagulation process optimization through zeta potential evaluation and limiting the blending to a site-specific ratio are approaches for addressing the water quality changes.

Hypothesis 2: Compared to SWTP operation with raw water only (i.e., 0% ATW), plan operation and performance may change due to the changes in water chemistry when ATW is blended with the raw water. However, the required performance can be re-established with coagulation and filter aid polymer optimization.

Hypothesis 3: With the optimized operating conditions, the pathogen removal credits achieved by a conventional SWTP under the SWTR are maintained.

Hypothesis 4: Blending ATW with filtered water (i.e., supplementing filtered water) will impact disinfection requirements and distribution system water quality. The impacts (challenges and benefits) will vary between reverse osmosis (RO)-based advanced treatment (RBAT) and carbon-based advanced treatment (CBAT) systems.

Hypothesis 5: For ATW from both RBAT- and CBAT- advanced water purification facilities (AWPF), SWTP unit processes can provide LRV credits for the DPR system.

1.3 Report Organization

This report is organized as follows:

- **Chapter 2:** Presents project approach, including the materials and methods used during the bench-scale and pilot-scale testing.
- **Chapter 3:** Presents the literature review with detailed discussions of regulatory considerations, typical process performance at a conventional SWTP and AWPF, effects of blending on water quality and treatment process performance, and considerations for blending ATW with filtered water from an SWTP.
- **Chapter 4:** Discusses the results of the bench-scale and pilot-scale testing, and limited modeling completed during the study.
- **Chapter 5:** Discusses various aspects to be considered for full-scale implementation of ATW blending.
- **Chapter 6:** Documents the pathogen log removal evaluation approach used in the study and summarizes the results of the pathogen removal evaluation.
- **Chapter 7:** Summarizes the findings of the study and present recommendations to utilities considering blending ATW with raw water sources.

CHAPTER 2

Project Approach

2.1 Participating Utilities

Table 2-1 presents the list of utilities that either shared historical data or participated in the bench-scale and/or pilot-scale testing. Plants B and F did not participate in bench- or pilot-scale testing but provided historical data.

Table 2-1. Participating Utilities with their SWTP and AWPF Configurations.

Plant	AWPF Type	SWTP Configuration	AWPF Configuration
Plant A	RBAT	Coag/floc/sed/ozone BAF/chlorination	MF/RO/UV-AOP
Plant B[(1)]	CBAT	Coag/floc/sed/ozone/BAF/chlorination	Chemical clarification (lime and polymer)/ two-stage recarbonation with intermittent settling/ multi-media filtration/GAC/IX (for ammonia removal)/chlorination
Plant C	CBAT	Coag/floc/BAC/ chlorination	Softening/UV-AOP/BAC/GAC
Plant D	RBAT	Ozone/coag/floc/deep-bed filtration/chlorination/UV	MF/RO/UV-AOP
Plant E	CBAT	Ozone/coag/floc/BAF/Cl_2	UF/media filtration/ozone/BAC/ozone
Plant F[(1)]	MBR	Ozone/coag/floc/sed/Ozone/ BAF/chloramination	MBR/GAC/UV
Plant G	RBAT	Ozone/coag/floc/sed/ BAF/chlorination	Ozone/BAC/UF/RO/UV-AOP
Plant H	CBAT	N/A	Ozone/BAC/UF/GAC/UV[(2)]

Notes:
(1) Did not participate in bench- or pilot-scale testing. Provided historical data.
(2) Pilot-scale AWPF.
Abbreviations: BAC – biologically active carbon; BAF – biological aerated filter; Coag - coagulation; floc - flocculation; GAC – granular activated carbon; IX – ion exchange; MBR – membrane bioreactor; MF – microfiltration; N/A - not applicable; RO – reverse osmosis; sed – sedimentation; UV-AOP – ultraviolet advanced oxidation process.

2.2 Historical Data Review

Information and historical data on SWTP design and operating parameters, raw water, settled water, filtered water, and finished water quality characteristics; and ATW characteristics were requested from the participating utilities through a request for information (RFI; Appendix A), covering a period of 24 months. The information and data (Appendix B) received from the participating utilities were reviewed and analyzed to assess potential water quality characteristics of the blended water. The historical data were used as input for the blending model developed during the study (discussed below).

2.3 Literature Review

A literature review was conducted, focusing on potential effects of blending ATW with the raw water source at an SWTP. Previously published journal papers, WRF reports, book chapters, conference proceedings, and publications from utilities and universities were reviewed and findings from these sources were summarized with a focus on the following:

- Regulatory considerations.
- Typical SWTP and AWPF performance.
- Potential water quality changes and impacts on SWTP performance.
- Considerations for blending ATW with finished water from an SWTP.
- Process optimization approaches.
- Pathogen log reduction credit validation.

2.4 Modeling

A blending model was developed using Carollo's Blue Plan-it® (BPI) Decision Support System to assess impacts of raw water augmentation with ATW at an SWTP. Blending scenarios were developed for six surface water treatment configurations and five advanced water purification configurations (Table 2-2).

Table 2-2. SWTP and AWPF Configurations Considered in Blending Model.

SWTP Configuration	AWPF Configuration
Coagulation/flocculation/BAC/chlorination	Softening/UV-AOP/BAC/GAC
Coagulation/flocculation/sedimentation/O_3/BAF/chlorination	MF/RO/UV-AOP
Coagulation/flocculation/sedimentation/O_3/BAC/UV/chlorination	O_3/BAC/UF/RO/UV-AOP
Coagulation/flocculation/O_3/filtration/chlorination	O_3/BAC/UF/GAC/UV
O_3/coagulation/flocculation/BAF/chlorination	
O_3/coagulation/flocculation/deep-bed filtration/UV/chlorination	
Notes: Abbreviations: O_3 - ozone; UF - ultrafiltration.	

The model contains a graphical process flow diagram interface with smart block for each unit process and built-in flow and mass balance calculations. The model can track flow and water quality of source waters, treated streams, and residual streams, along with chemical usage (i.e., coagulants, pH adjustment, disinfectant, etc.). It calculates a list of water corrosivity and stability indices. It can also analyze disinfection byproducts (DBP) formation under various blending conditions using built-in mechanistic-based DBP models developed by Arizona State University (ASU; He 2001) which were calibrated for previous projects. The limited set of data collected during this study did not allow the team to calibrate the model specifically for this study.

2.4.1 Simulation Scenarios

The blending model was set up to simulate a wide range of scenarios with the provisions to select the SWTP process configuration, AWPF process configuration, blending location for RWA or TWA scheme, and ATW blending ratio as briefly discussed below.

2.4.1.1 Process Configurations

As mentioned above, six SWTP and four AWPF process configurations have been included in the model representing the process schemes at the participating utilities. Water quality and process performance data based on historical datasets provided by the participating utilities for their SWTPs (Appendix B) were uploaded in the model. Data collected during the bench and pilot-scale testing were used to fill gaps in the historical datasets. Since removal rates could not be derived using the historical data, the rates for turbidity, TOC, UV_{254}, particles, and pathogen removal (Table 2-3) were extracted from the data collected during the pilot testing at Plant A (ATW from an RBAT system) and Plant C (ATW from a CBAT system). The trihalomethane (THM) formation and chlorine decay were modeled using non-linear power function empirical equations developed by the USEPA and ASU (He 2001). Modeling coefficients and parameters calibrated for Colorado River water were used for Plant A, C and D.

Table 2-3. Removal Efficiency with ATW-Blended Water.

Parameter	AWT Process Type							
	RBAT[(1)]				CBAT[(2)]			
	0% Blend	10% Blend	20% Blend	50% Blend	0% Blend	10% Blend	20% Blend	50% Blend
Pathogen (e.g., virus)	97.38	95.30	99.23	99.91	96.02	96.84	99.80	94.99
Particles: 1-2 µm	99.00	99.80	99.87	99.68	NA	NA	NA	NA
Particles: 2-5 µm	90.00	96.84	99.21	96.84	98.00	99.37	99.68	99.00
Particles: >5 µm	99.00	99.84	99.97	99.60	98.42	99.37	99.90	99.37
Turbidity	98.57	99.84	98.98	99.73	96.00	97.00	98.00	95.00
TOC	38.14	24.51	35.05	40.90	28.60	31.40	32.60	24.80
UV_{254}	56.52	58.42	58.17	69.95	51.50	46.70	55.50	47.00

Notes:
1. Based on Plant A pilot testing.
2. Based on Plant C pilot testing.

Abbreviations: µm - micrometers.

2.4.1.2 Assumptions Made for Simulations

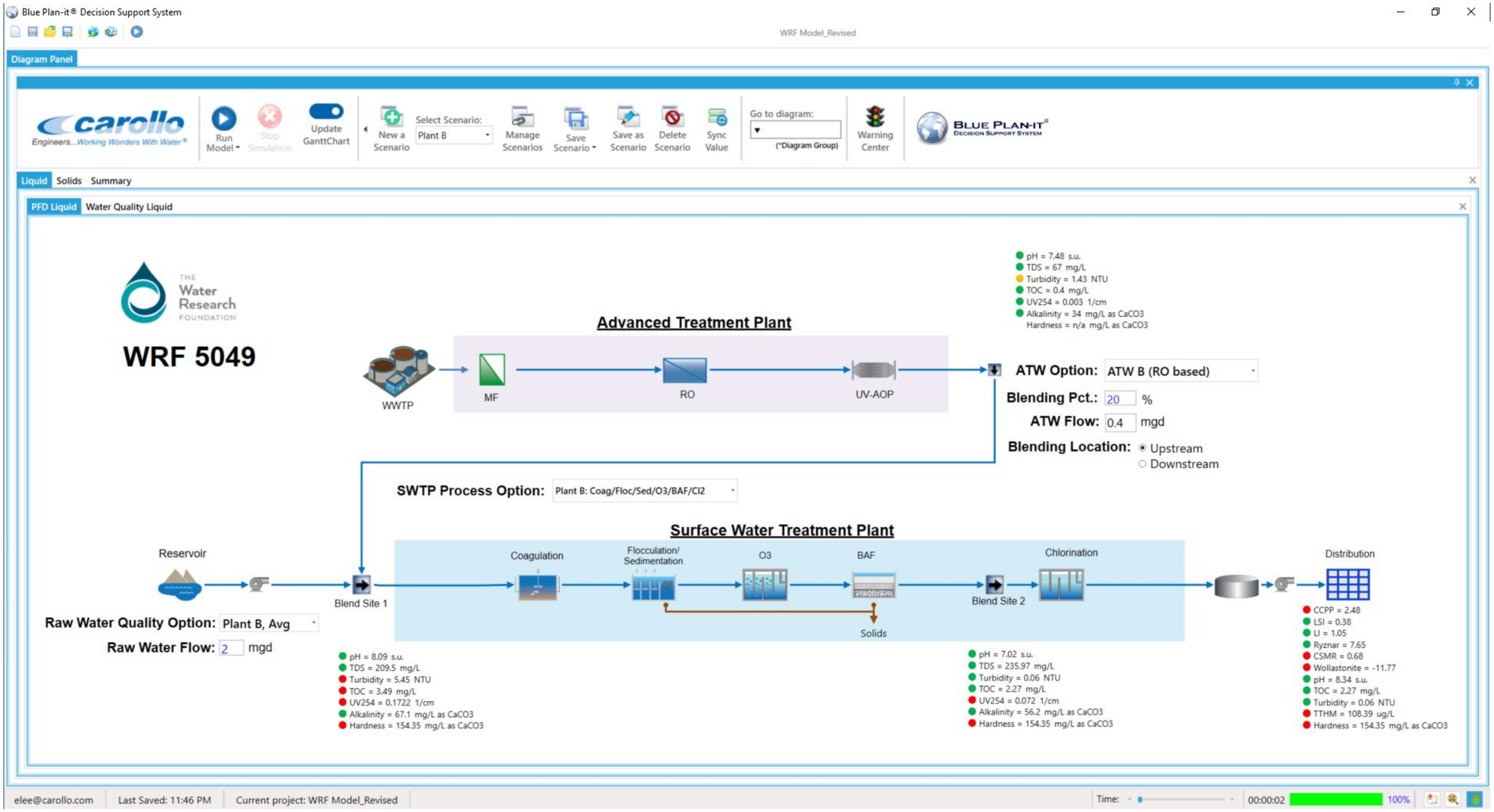
For simulation, the following assumptions were made:

- The removal efficiencies derived from the Plant A pilot testing were used for the modeling for Plant D. Plants A and D share the same raw water source (LA aqueduct) at least partially and both plants considered using ATW from RBAT sources for supplementing raw water sources. It is to be noted that the SWTP processes are slightly different (Table 2-2), as Plant A has ozone and BAF whereas Plant D has deep-bed filtration and ultraviolet (UV) disinfection.
- Given that *Giardia* cysts and *Cryptosporidium* oocysts size range from 5 to 8 µm (Adam 1991) and 3 to 6 µm (Carey et al. 2004), respectively, the log removal rates observed during the pilot testing for 2–5 µm and >5 µm particles were used for assessing *Cryptosporidium* and *Giardia* removal, respectively.

- Log removal for virus was assumed to be the same as MS2 bacteriophage (MS2) log removal observed during the pilot testing.
- The built-in DBP model developed by ASU is applicable for the water sources and treatment plants in this project.
- Chlorine dose for finished water assumed to be 2.5 milligrams per liter (mg/L) in this project.

2.4.1.3 Blending Locations and Ratios

The model considered two blending locations: (1) upstream of an SWTP (i.e., RWA scheme) and (2) downstream of the SWTP filtration process (i.e., TWA scheme), as shown in Figure 2-1 and Figure 2-2. Model simulations were conducted with 0%, 10%, 20%, and 50% ATW blends. The model can be used for simulations for any ATW blending ratio between 0 and 50% with interpolated removal rates, as necessary.



Select Scenario: Plant B

ATW Option: ATW B (RO based)
Blending Pct.: 20 %
ATW Flow: 0.4 mgd
Blending Location: ● Upstream ○ Downstream

SWTP Process Option: Plant B: Coag/Floc/Sed/O3/BAF/Cl2

Raw Water Quality Option: Plant B, Avg
Raw Water Flow: 2 mgd

- ● pH = 7.48 s.u.
- ● TDS = 67 mg/L
- ● Turbidity = 1.43 NTU
- ● TOC = 0.4 mg/L
- ● UV254 = 0.003 1/cm
- ● Alkalinity = 34 mg/L as CaCO3
- Hardness = n/a mg/L as CaCO3

- ● pH = 8.09 s.u.
- ● TDS = 209.5 mg/L
- ● Turbidity = 5.45 NTU
- ● TOC = 3.49 mg/L
- ● UV254 = 0.1722 1/cm
- ● Alkalinity = 67.1 mg/L as CaCO3
- ● Hardness = 154.35 mg/L as CaCO3

- ● pH = 7.02 s.u.
- ● TDS = 235.97 mg/L
- ● Turbidity = 0.06 NTU
- ● TOC = 2.27 mg/L
- ● UV254 = 0.072 1/cm
- ● Alkalinity = 56.2 mg/L as CaCO3
- ● Hardness = 154.35 mg/L as CaCO3

- ● CCPP = 2.48
- ● LSI = 0.38
- ● LI = 1.05
- ● Ryznar = 7.65
- ● CSMR = 0.68
- ● Wollastonite = -11.77
- ● pH = 8.34 s.u.
- ● TOC = 2.27 mg/L
- ● Turbidity = 0.06 NTU
- ● TTHM = 108.39 ug/L
- ● Hardness = 154.35 mg/L as CaCO3

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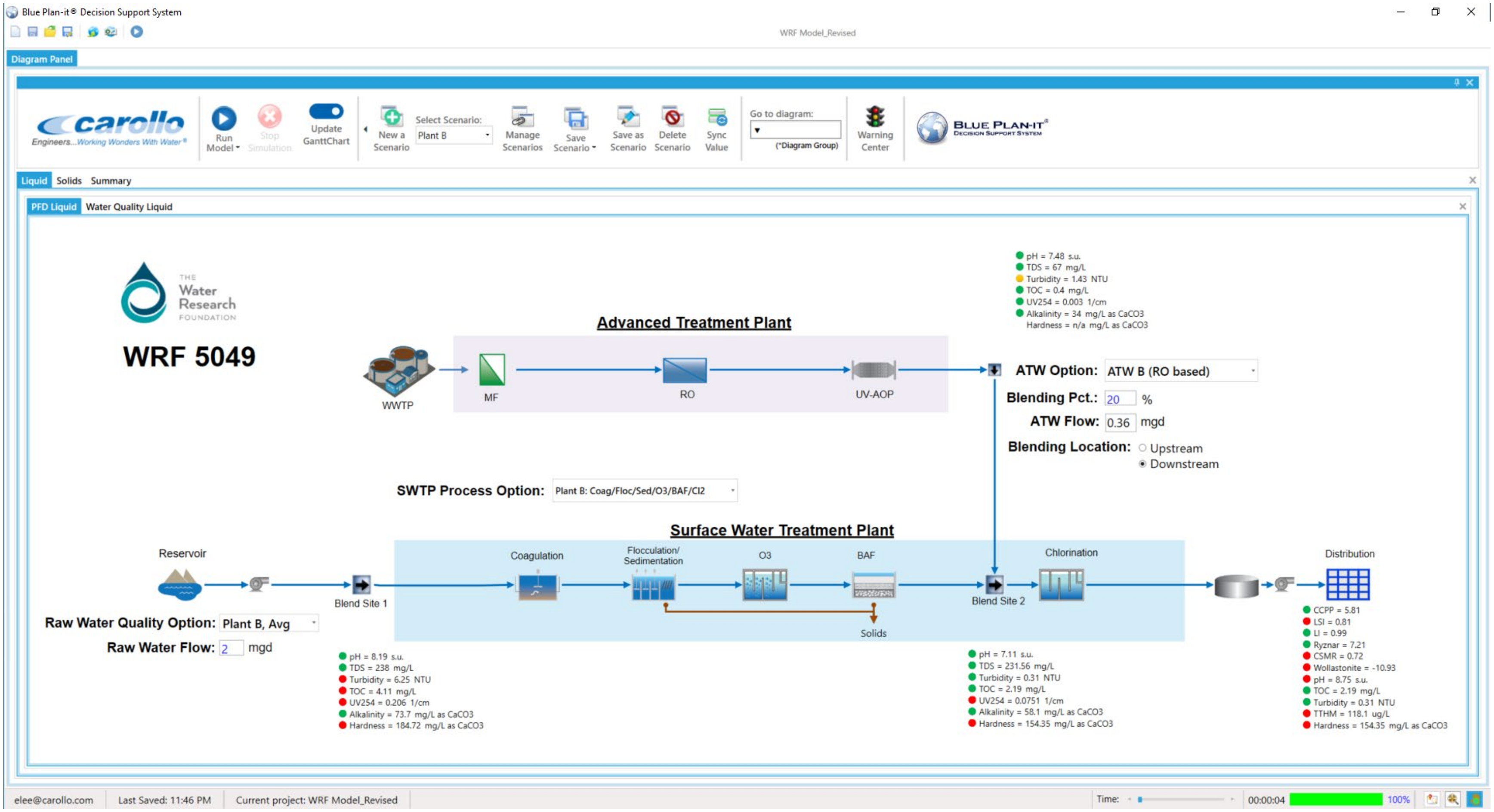
Figure 2-1. Blending Scenario 1: Blending ATW with Raw Water at an SWTP.



Select Scenario: Plant B

ATW Option: ATW B (RO based)

Blending Pct.: 20 %

ATW Flow: 0.36 mgd

Blending Location: ○ Upstream ● Downstream

SWTP Process Option: Plant B: Coag/Floc/Sed/O3/BAF/Cl2

Raw Water Quality Option: Plant B, Avg

Raw Water Flow: 2 mgd

● pH = 7.48 s.u.
● TDS = 67 mg/L
● Turbidity = 1.43 NTU
● TOC = 0.4 mg/L
● UV254 = 0.003 1/cm
● Alkalinity = 34 mg/L as CaCO3
Hardness = n/a mg/L as CaCO3

● pH = 8.19 s.u.
● TDS = 238 mg/L
● Turbidity = 6.25 NTU
● TOC = 4.11 mg/L
● UV254 = 0.206 1/cm
● Alkalinity = 73.7 mg/L as CaCO3
● Hardness = 184.72 mg/L as CaCO3

● pH = 7.11 s.u.
● TDS = 231.56 mg/L
● Turbidity = 0.31 NTU
● TOC = 2.19 mg/L
● UV254 = 0.0751 1/cm
● Alkalinity = 58.1 mg/L as CaCO3
● Hardness = 154.35 mg/L as CaCO3

● CCPP = 5.81
● LSI = 0.81
● LI = 0.99
● Ryznar = 7.21
● CSMR = 0.72
● Wollastonite = -10.93
● pH = 8.75 s.u.
● TOC = 2.19 mg/L
● Turbidity = 0.31 NTU
● TTHM = 118.1 ug/L
● Hardness = 154.35 mg/L as CaCO3

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Figure 2-2. Blending Scenario 2: Blending ATW with Filtered Water.

2.5 Bench-Scale Testing

Bench-scale tests were conducted with raw water and ATW collected from SWTPs and AWPFs of Plants A, C, D, E, G, and H. Plants B and F did not participate in the bench-scale testing. While jar tests were conducted with water samples received from all plants to evaluate coagulation effectiveness and settleability, filterability was assessed for water samples from Plants D and E, which practice direct filtration with pre-ozonation. Additionally, the effects of pre-ozonation were evaluated with the water samples received from Plant D. For the jar testing, coagulant and polymers used at the respective SWTP were also collected in 100- milliliter (mL) bottles.

2.5.1 Water Sample Collection and Handling

Water samples were collected from the SWTPs and AWPFs in 5-gallon carboys from five participating utilities from across the country (Table 2-4). Testing with water samples from Plant C were conducted at the plant itself. Coagulant and polymer used at the respective SWTP were also collected at the time of water sample collection. The water samples were shipped overnight on ice to the testing locations in coolers. Testing was immediately started after the receipt of water samples at the testing locations or stored at 4 degrees Celsius (°C) until used. In general, testing with each set of water samples was completed within 72 hours from the receipt of the samples.

Table 2-4. SWTP Configuration, AWPF Type, and Coagulant and Polymer Used at Participating Plants.

Plant	AWPF Type	SWTP Configuration	Coagulant	Cationic Polymer	Bridging Polymer
Plant A	RBAT	Coag/floc/sed/ozone /BAF/chlorination	Aluminum Sulfate (20 mg/L)(1)	Clarifloc C-308P (0.43 mg/L)	Clarifloc N-120P (0.04)
Plant C	CBAT	Coag/floc/BAC/ chlorination	$FeCl_3$ (21 mg/L)	Clarifloc C-308P (2.1 mg/L)	N/A
Plant D	RBAT	Ozone/coag/floc/deep-bed filtration/chlorination/UV	$FeCl_3$ (1.5 mg/L)	Clarifloc C-318 (1.7 mg/L)	N/A
Plant E	CBAT	Ozone/coag/floc/BAF/Cl2	$FeCl_3$ (0.55 mg/L)	Clarifloc C-308P (0.22 mg/L)	N/A
Plant G	RBAT	Ozone/coag/floc/sed/BAF/ chlorination	$FeCl_3$ (4 mg/L)	Clarifloc C-358 (2 mg/L)	N/A
Plant H(2)	CBAT	N/A	Aluminum Sulfate(3) (N/A)	Clarifloc C-308P(3) (N/A)	N/A

Notes:
(1) The doses in parentheses are historical average doses.
(2) ATW collected from Plant H's pilot-scale AWPF, which was blended with Colorado River water for the testing.
(3) The coagulant and cationic polymer were selected by the project team for testing
Abbreviations: $FeCl_3$ – ferric chloride.

2.5.2 Blending Scenarios and Water Quality Characterization

Grab samples were collected for the raw water, ATW, and blended water and water quality analyses were completed for pH, turbidity, zeta potential, TOC, dissolved organic carbon (DOC), UV_{254} absorbance, alkalinity, conductivity, calcium, magnesium, and total hardness. Table 2-5 presents the blending scenarios evaluated for the participating plants.

Table 2-5. Blending Scenarios for Bench-Scale Testing.

Samples Received From	Blending Ratio (ATW/Blended Water [v/v])
Plant A	0%(1), 10%, 25%, 40%
Plant D(2)	0%, 10%, 20%, 30%, 40%
Plant E	0%, 15%, 25%, 35%
Plant G	0%, 10%, 25%, 40%
Plant H	0%, 15%, 25%, 35%

Notes:
1. 0% blend represents the raw water samples.
2. With the samples from Plant D, testing was conducted with a fixed dose of coagulant and polymer, focusing on assessing the effects of blending ratios and O_3 doses.

Abbreviations: v/v - volume by volume.

2.5.3 Zeta Evaluation

Before jar testing, the impact of coagulant and polymer doses on zeta potential for each blend was determined by conducting a zeta titration except for Plant D. For Plant D, the testing focused on evaluating the effects of ozone dose and blending ratio, and a fixed set of coagulant (i.e., 1.5 mg/L $FeCl_3$) and polymer (1.7 mg/L Calrifloc C-318) doses was used during the jar testing.

Independent zeta titrations were conducted with the coagulant or cationic polymer collected from the participating utilities (Table 2-3) to determine the dose required for achieving near-zero zeta potential. Malvern's zetasizer was used for measuring the zeta potential. Five hundred mL water was mixed using a magnetic stirrer in a 1-Liter (L) beaker, simulating rapid mixing. The mixing was continued for 30 seconds after adding the required volume from a concentrated stock of the coagulant (or polymer) and a grab sample was collected to measure zeta. The coagulant (or polymer) dose was sequentially increased by adding the required volume of the concentrated stock and measuring zeta potential until near-zero zeta was measured. The final coagulant (or polymer) dose and associated zeta potential were confirmed by repeating the test with a fresh batch of water in a separate beaker.

2.5.4 Jar Testing

Except for raw water and ATW received from Plant D, in general, jar testing was conducted with 3 jars as given below:

- Jar 1 - no coagulant or polymer added (Control).
- Jar 2 - coagulant and polymer doses determined in Step 2.
- Jar 3 - replicate of Jar 2.

For the water samples received from Plant D, as discussed above, jar testing focused on the evaluation of the effects of pre-ozonation and blending ratio. Therefore, three sets of jar tests were conducted with 5 jars and 0.25, 0.5, or 0.75 mg/L ozone as discussed below.

2.5.5 Additional Testing

With raw water and ATW from Plants D and E, additional tests were conducted as briefly described below.

2.5.5.1 Effects of Ozone on Coagulation, Flocculation, and Filtration

With raw water and ATW received from Plant D, which practices pre-ozonation, the effects of ozone dose on coagulation, flocculation, and filtration were evaluated through jar testing and filterability testing. Three sets of jar tests were conducted with 0%, 10%, 20%, 30%, and 40% ATW blending ratios and 0.25, 0.5, and 0.75 mg/L O_3 dose. Coagulant ($FeCl_3$) and cationic polymer (Clarifloc C-318) were kept the same (i.e., 1.5 mg/L $FeCl_3$ and 1.7 mg/L Clarifloc C-318) in all jars.

A bench-scale ozone generator was used to generate O_3 gas and bubble into deionized (DI) water in a 3-neck glass reactor. The reactor was immersed into an ice bath to maintain a temperature around 0 °C. Ozone concentration in the ozone stock solution was verified immediately before spiking the water samples in 2-L jars from the jar testing equipment using the HACH ampule method (<1.5 parts per million [ppm] ozone). The ozone stock solution was diluted 50 times for the concentration verification. A glass pipette was used to dose the ozone stock solution into water samples in 2-L jars from the jar testing equipment, targeting the final concentration of 0.25, 0.5, or 0.75 mg/L O_3.

2.5.5.2 Filterability Testing

Filterability testing was conducted with raw water and ATW samples received from Plants D and E. Immediately after the completion of the flocculation stage during jar testing, 200 mL coagulated water samples were collected from the sampling port in the 2-L jars and vacuum filtered through Whatman 40 filter paper. Filter index was calculated for each coagulated and flocculated water by comparing the time required for filtering 200 mL coagulated and flocculated water sample with that for DI water under 4-inch of mercury (Hg) vacuum pressure. Turbidity and pH were monitored in the filtrate.

2.6 Pilot-Scale Testing

Pilot tests were conducted at Plants A, C, and D to evaluate the effects of ATW blending on SWTP performance under continuous flow conditions. Tests were conducted with the raw water or ATW blended water under site-specific coagulant and polymer feeding conditions. Except at Plant D, MS2 bacteriophage (spherical in shape, 24-26 nanometers (nm) in size [Wick and McCubbin 1999]) and PMMoV (rod-shaped; ~312 nm in length [Kitajima et al. 2018]) challenge tests were conducted to determine pathogen log removal across the systems. Particle counts were determined in the floc/sed influent and biofilter effluent samples collected during the MS2/PMMoV challenge tests. Disinfectant requirement and DBP formation potential (FP) under Uniform Formation Conditions (UFC) were evaluated in the biofilter effluent samples collected under each blend testing conditions.

Details of the pilot facilities and tests performed at the three pilot sites are separately described below.

2.6.1 Pilot Testing Schedule and Blending Scenarios

Table 2-6 presents pilot testing periods and blending scenarios evaluated during the pilot testing at Plant A, Plant C, and Plant D.

Table 2-6. Pilot Testing Periods and Blending Scenarios Evaluated during the Pilot Testing.

Plant	Type of AWPF Treatment Train	Pilot Testing Period	Blending Scenarios Evaluated
Plant A	RBAT	Dec 6, 2021 - Feb 18, 2022	0%, 10%, 20%, 50%
Plant C	CBAT	Mar 22, 2022 – Aug 19, 2022	0%, 10%, 20%, 50%
Plant D	RBAT	Aug 23, 2021 - Sept 28, 2021	0%, 20%, 50%

2.6.2 Pilot Facility Description

At Plants A and D, modular pilot skids were used for the pilot testing, the plant's existing pilot-scale facility was used at Plant C. At Plants A and C, the pilot-scale systems simulated a conventional water treatment plant and consisted of coagulation, flocculation, sedimentation, and filtration unit processes. At Plant D, the pilot-scale system simulated a direct filtration plant with pre-ozonation. While the same flocculation/sedimentation (floc/sed) and filtration skids, manufactured by Intuitech and owned by Carollo, were used in series at Plants A and D during the pilot testing, the sedimentation stage was bypassed at Plant D to simulate a direct filtration facility. An ozone skid was placed upstream of the floc/sed skid at Plant D. Details of the pilot facilities and operating conditions are provided below.

2.6.2.1 Pilot-Scale Testing at Plant A

The pilot-scale system simulated a conventional filtration plant with a treatment train consisting of coagulation, flocculation, sedimentation, and filtration and consisted of a floc/sed skid and a filtration skid in series (Figure 2-3). Efforts were made to match the pilot system's operating conditions with Plant A's full-scale SWTP operating conditions to the extent possible (Table 2-7).

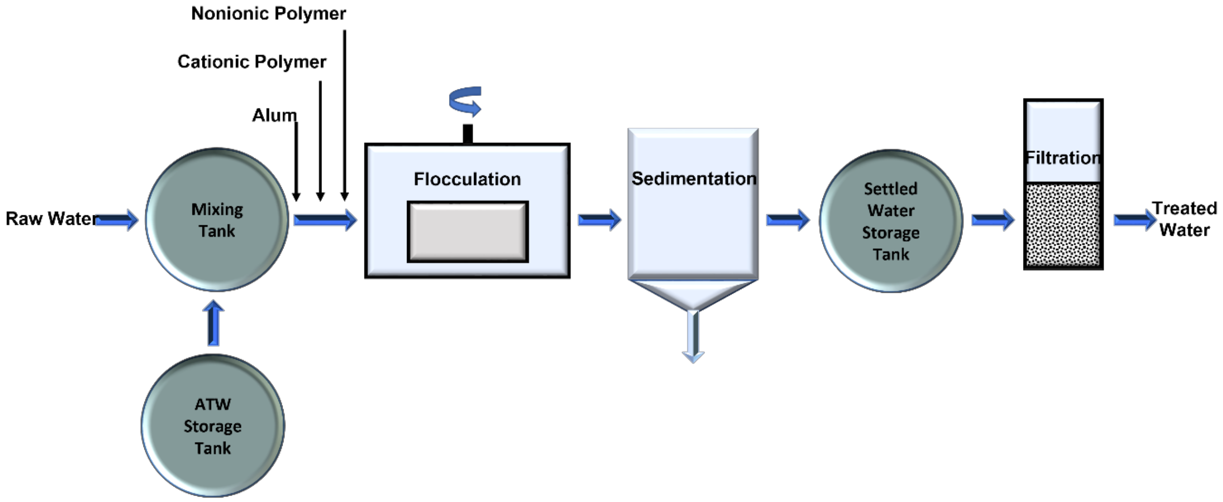


Figure 2-3. Pilot Testing System Process Flow Diagram – Plant A.

The filter column was packed with 42 inches of anthracite (collected from Plant A) over 10 inches of sand (with same specifications as in Plant A). Before loading into the column, the anthracite media was acclimated to the raw water for approximately 2 weeks by placing the media in a container under a continuous flow of raw water from Plant A.

ATW was hauled from the AWPF to the pilot testing site in a 3,700-gallon water truck approximately two times per week and transferred to a 4,500-gallon ATW storage tank. Depending on the ATW blend to be prepared, a transfer pump was used to feed the required ATW volume from the ATW storage tank through a flowmeter into the 4,500-gallon mixing tank. Then, the required raw water volume was fed into the mixing tank with a transfer pump through a flow meter. The blended water was continuously mixed with a recirculation pump.

The floc/sed pilot skid was oversized for this application and did not allow operating the entire system continuously. Therefore, the floc/sed skid was operated only for approximately 2–3 hours per day at a flow rate of 9–10 gallons per minute (gpm). The filtration skid was operated 24/7 with a flow rate of 0.7 gpm. A 4,500-gallon settled water storage tank was used in between the floc/sed skid and filtration skid to allow for continuous filter skid operation.

Table 2-7. Pilot-scale Operating Conditions at Plant A, Plant C, and Plant D.

Parameter	Unit	Plant A	Plant C	Plant D
Ozone Contactor				
Average Flow	gpm	N/A	N/A	2.9
HRT	min			20
O_3 dose	mg/L			0.3 to 0.7
O_3 contact time	min			3
Coagulation/Flocculation/Sedimentation				
Flow	gpm	10(1)	5–10	2.4(2)
Coagulant dose	mg/L	35 mg/L alum	15-40 mg/L $FeCl_3$	0.9–1.5 mg/L $FeCl_3$
Cationic polymer dose	mg/L	0.35 mg/L Clarifloc C-308P	0.5-3.0 mg/L Clarifloc C-308	0.9–1.7 mg/L Clarifloc C-318
Non-ionic polymer dose	mg/L	0.25 mg/L Clarifloc N-120P	N/A	N/A
Rapid Mix				
Velocity gradient (G)	s^{-1}	550	1,000	550
Mixing time	s	30	25	30
Flocculation				
Stage 1 - G	s^{-1}	60	80	N/A
Stage 1 - HRT	min	6.2	6.2	N/A
Stage 2 - G	s^{-1}	40	50	65
Stage 2 - HRT	min	6.2	6.2	21.4
Stage 3 - G	s^{-1}	22	25	45
Stage 3 - HRT	min	6.2	6.2	21.4
Sedimentation				
Plate Settler Loading Rate	gpm/ft^2	0.14	0.14	N/A
Filtration				
Average flow/filter	gpm	0.7	1.0	2.0(3)
Bed depth (anthracite/sand)	inch	42/10	72/12	62
Average filter loading rate	gpm/ft^2	3.6	9.9	10.2
Average EBCT	min	7.3	4.5	1.1
Average UFRV	gal/ft^2	5133	>10,000	12,000

Parameter	Unit	Plant A	Plant C	Plant D
Notes: 1. The floc/sed skid was operated approximately 2-3 hours/day at 10 gpm, generating enough settled water for continuous filtration skid operation. 2. The flow through the rapid mix was 2.4 gpm with an overflow of 0.5 gpm upstream of the rapid mix. 3. The flow through the filter media was 2 gpm with an overflow of 0.4 gpm upstream of the column. Abbreviations: EBCT - empty bed contact time; gpm/ft2 - gallons per minute per square foot; HRT - hydraulic retention time; min - minutes; s^{-1} – per second; UFRV - unit filter run volume.				

In conjunction with a booster pump, the pump on the floc/sed skid was used to feed water from the Mixing Tank into the floc/sed skid. Alum, cationic polymer (Clarifloc C-308P), and non-ionic polymer (Clarifloc N120P) were injected into the rapid mix on the floc/sed skid. The coagulated/flocculated water was directed into the sedimentation basin within the floc/sed skid. The settled water was then directed into a 4,500-gallon Settled Water Storage Tank, from which the pump on the filtration skid fed the water to the filter. The filtered water was discharged to a nearby drain.

2.6.2.2 Plant-Scale Testing at Plant C

The pilot-scale system simulated a conventional filtration plant with a treatment train consisting of coagulation, flocculation, sedimentation, and filtration. The permanently installed pilot system at this facility includes a floc/sed skid and a filtration skid in series (Figure 2-4). The flow rates used for this testing were selected to match the operating conditions of the full-scale system to the extent possible (Table 2-6).

The pilot filter column has 72-inch GAC over 12-inch sand (matching Plant C full scale filter media configuration). The media is fully biologically acclimated as the system has been in operation for more than a year. ATW was pumped from the combined full-scale GAC contactor effluent piping to the pilot skid, co-located in the same building. Manual valves and rotameters were used to adjust the ATW blend feeding the floc/sed skid. Both the floc/sed pilot skid and filtration skids were operated continuously with flow rates in the range of 5-10 gpm through floc/sed and approximately 1 gpm through the filter column.

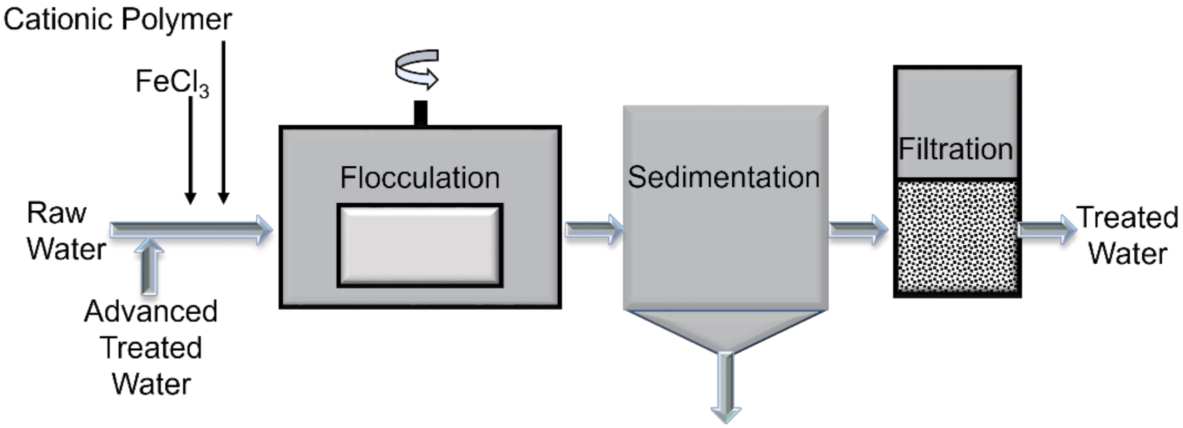


Figure 2-4. Pilot Testing System Process Flow Diagram – Plant C.

2.6.2.3 Pilot-Scale Testing at Plant D

The pilot-scale system simulated a direct filtration plant with a treatment train consisting of pre-ozonation, coagulation, flocculation, and filtration. The pilot skids (i.e., ozone skid, floc/sed skid, and filtration skid) were connected in series (Figure 2-5). The sedimentation stage of the floc/sed skid was bypassed and the flocculation chambers were modified to simulate full-scale operation to the extent possible (Table 2-5). The filter column was packed with anthracite collected from the plant.

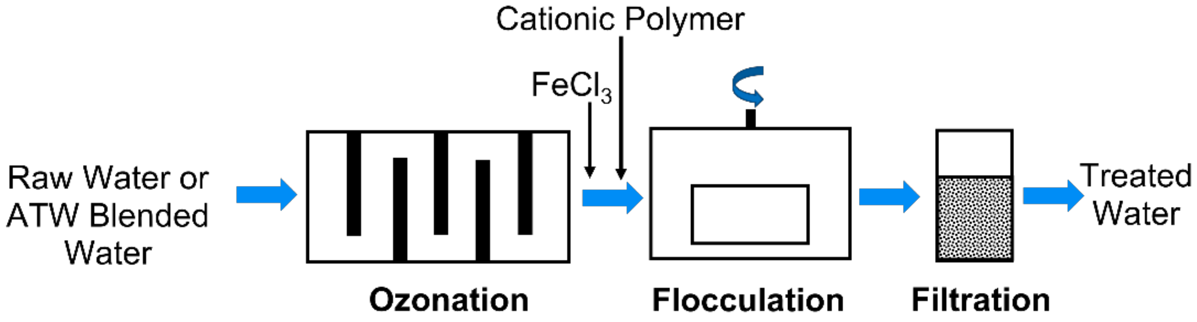


Figure 2-5. Pilot Testing System Process Flow Diagram – Plant D.

2.6.3 Water Quality Characterization

Raw water and ATW water samples were collected and characterized separately by measuring pH, alkalinity, hardness, conductivity, turbidity, TOC, DOC, and UV_{254}. While pH, turbidity, and hardness were monitored on site, samples for other parameters were shipped overnight on ice to Eurofins Analytical for analysis.

2.6.4 Pathogen Log Removal Evaluation

At Plants A and C, pathogen removal challenge tests were conducted. MS2 and PMMoV were injected into the floc/sed influent from a chemical feed tank using a peristaltic pump. The MS2 stock (10^{11} pfu/mL) was obtained from GAP Environmental Services Ltd. The MS2 feed stock was prepared by diluting the purchased stock in raw water, targeting 10^6 pfu/mL in the floc/sed influent. PMMoV feed stock was prepared by diluting a commercial pepper sauce brand in raw water in the same tank with the MS2, targeting a feed concentration of 10^6 gene copies (gc)/L. The amount of pepper sauce to be added was determined before the spiking test through batch tests (discussed in Chapter 6), which indicated that adding 0.1 mL of pepper sauce in 1 L water would result in approximately 10^3 gc/mL PMMoV without significantly affecting pH and TOC concentration in the water.

The MS2 and PMMoV concentrations in the floc/sed influent and filter effluent were converted to log10 concentrations. Pathogen log removal was calculated by subtracting filter effluent log10 concentrations from floc/sed influent log10 concentrations.

2.6.5 Particle Removal

Particles present in the floc/sed influent, and filter effluent samples collected during the MS2 and PMMoV challenge testing at Plant A were quantified using a particle size analyzer with AccuSizer 780 syringe injection sampler (Particle Sizing Systems of Santa Barbara, California). Modified Standard Method 2560C was used, quantifying particles larger than 1 µm. Particle counts were reported with size bins of 1–2 µm, 2–5 µm, and >5 µm. Given that the typical size of virus is in the nm range, whereas *Giardia cysts* (5–8 µm; [Adam 1991]) and *Cryptosporidium* oocysts (typically 3–6 µm [Carey et al. 2004]) sizes are in µm range (Adam, 1991; Medema et al. 1998), the particle size bin of 1-2 µm and >5 µm were of particular interest.

2.6.6 Disinfectant Demand and DBP Formation Potential Testing

Glassware used for the testing was soaked in 500 mg/L free chlorine for 24 hours and washed with deionized water. New amber bottles were used for sample incubation to avoid any cross contamination.

With each blend tested, filter effluent samples were collected in 1-gallon jars and shipped on ice overnight to Carollo's Water ARC® in Boise, Idaho. Disinfection demand was tested on the day of the sample receipt. In a 250-mL beaker, 200 mL biofilter effluent sample was taken and pH was adjusted to 8.0 ± 0.2 standard units (SU) using a borate buffer. 50 mL of the pH adjusted biofilter effluent was transferred to three 250-mL amber bottles. Sodium hypochlorite was used to add three different chlorine doses to the three bottles and preliminary testing was done by monitoring residual chlorine at different time points for a 25-minute period. The free chlorine dose that resulted closer to 1 mg/L free Cl_2 after 25 minutes was selected for a 24-hour incubation testing.

Fifty mL of pH adjusted biofilter effluent was transferred into another set of three 250 mL amber bottles. The chlorine dose determined during the pre-testing was added to all three bottles and incubated in the dark at room temperature (21.6 ± 0.5 °C) for 24 hours. Residual chlorine was monitored in the samples after 24 hours of incubation. Residual chlorine was determined after 24 hours and if free chlorine was 1 ± 0.4 mg/L, the dose was used for the DBP FP testing.

DBP FP was evaluated under UFC as previously described (Summers et al. 2020). Briefly, approximately 1 L filter effluent sample (stored at 4 °C) was transferred to a 2-L beaker and allowed to adjust to room temperature. The pH was adjusted to 8.0 ± 0.2 SU. The chlorine dose determined during the disinfection demand testing was dosed to the water and the chlorinated water was transferred to three 250-mL amber bottles (headspace free). The bottles were incubated in dark at room temperature (21.6 ± 0.5 °C) for 24 hours. After the incubation, grab samples for THMs and haloacetic acids (HAA9) were collected (headspace free) in the sample vials provided by Eurofins Analytical and sent overnight for analysis. Residual free chlorine was also monitored in the incubated samples.

CHAPTER 3

Literature Review

3.1 Regulatory Considerations

Establishing regulatory provisions can encourage the development and evaluation of competing technologies (Mickwitz et al. 2008), primarily due to enhanced public confidence through reduction in risk perceptions. It has been recognized that collaborative and transparent risk-based regulations and guidelines are the key to increased public acceptance and effective implementation of any technology (Mukherjee and Jensen 2020).

To facilitate effective implementation of DPR with broader public acceptance, regulators in many states, including California, Colorado, Arizona, Florida, and elsewhere are actively developing regulations applicable to DPR. Even Texas, which already has had several operating DPR facilities, has recently committed to developing formal regulatory guidance to make the permitting process for DPR more transparent.

In general, drinking water regulations are developed by setting water quality standards (i.e., threshold concentrations for chemical and biological parameters) that are designed to protect public health and welfare. Regulatory provisions typically include monitoring and reporting requirements, acceptable threshold exceedance rates, regulation enforcement mechanisms, remedial actions, and penalties. The following sections discuss the existing regulatory structures and regulatory gaps.

3.1.1 Existing Regulatory Framework

Drinking water regulations are set by both federal and state agencies. The USEPA sets and enforces federal drinking water regulations through the Safe Drinking Water Act (SDWA) and its amendments, including the National Primary Drinking Water Regulations (NPDWR). The NPDWRs include legally enforceable primary standards and treatment techniques (TT) enacted to protect the public health by limiting the exposure to chemical and biological contaminants.

To minimize public health risks associated with upstream wastewater discharges, the Clean Water Act (CWA) requires treating wastewater before disposing into water bodies.

Each state has its own surface water quality standards for all waters of the state, as required by the CWA. While state or governments have the primary responsibility for monitoring and enforcing the regulations, municipalities and utilities have the responsibility to implement and abide by the regulations.

3.1.2 Existing Drinking Water Regulations

Under the SDWA, the NPDWRs specify maximum contaminant levels (MCLs) for multiple chemical and biological contaminants, including microorganisms, metals, pesticides, chlorinated solvents, DBPs, disinfectants, and radionuclides. The following rules are included within the NPDWRs:

- **Surface Water Treatment Rules (SWTR)**. These rules are aimed to control exposure to pathogens through TT requirements. Contaminants of interest under SWTRs include *Cryptosporidium*, *Giardia lamblia*, heterotrophic plate count (HPC), Legionella, Total Coliforms, enteric viruses, and turbidity. The rule and its amendments (USEPA 1989, 1998, and 2006b) require a water treatment plant (WTP) to provide a minimum of 3-log, 4-log, and 2 to 5.5-log removal and/or inactivation of *Giardia* cysts, viruses, and *Cryptosporidium* oocysts, respectively.
- **Stage 1 and 2 Disinfectants and Disinfection Byproducts Rules (D/DBPR)**. These rules are designed to minimize exposure to disinfectants and DBPs, including bromate, chlorite, HAA5, and total trihalomethanes (TTHM). Disinfectants included in this set of rules are chloramines, chlorine, and chlorine dioxide:
    - The Stage 1 DBP Rule requires utilities to include treatment processes for natural organic matter (NOM) removal to mitigate DBP formation when source water (1) is derived from surface water or groundwater under the direct influence of surface water and (2) has greater than 2 mg/L TOC). With the establishment of MCLs for TTHMs (80 micrograms per liter [µg/L]) and HAA5 (60 µg/L), the rule requires the implementation of enhanced coagulation at conventional treatment plants to improve the removal of DBP precursors (USEPA 1999).
    - The Stage 2 DBP Rule tightened monitoring and regulatory compliance requirements to ensure the removal of TTHMs and HAA5 forming DBP precursors at each compliance monitoring location. This rule applies to systems using a primary disinfectant other than UV light.
- **Chemical Contaminant Rules.** These rules target limiting exposure to chemical contaminants through drinking water. There are 16 inorganic and 53 organic chemical contaminants, and 4 radionuclides, including metals and metalloids (e.g., arsenic [As], cadmium [Cd], chromium [Cr], and selenium [Se]), cyanide, nitrate, nitrite, atrazine, benzine, carbofuran, tetrachloroethylene (PCE), trichloroethylene (TCE), 1,2,3-trichloropropane (TCP), dioxin, alpha and beta particles, radium, and uranium, for which MCLs have been established.

In addition to regulating contaminants through MCLs, USEPA has established secondary maximum containment levels (sMCL), which are non-mandatory standards for 15 chemical compounds to maintain a pleasing aesthetic. Because these standards primarily address taste and odor, rather than health issues, they are often used only as a guideline.

The USEPA Lead and Copper Rule (LCR), initially promulgated in 1991 and recently updated in December 2020, establishes an action level for lead of 0.015 mg/L and for copper of 1.3 mg/L, and MCLGs of 0 mg/L for lead and 1.3 mg/L for copper. An exceedance of the action level is not a violation, but triggers additional action including water quality parameter monitoring, corrosion control treatment, source water monitoring/treatment, public education, and lead service line replacement. This represents control through treatment technique as opposed to a numerical standard (i.e., MCL).

Building on the Stage 1 and Stage 2 D/DBPRs, the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) strengthened disinfection requirements to ensure protection against microbial pathogens such as *Cryptosporidium*. While the earlier recognition that the additional log removal (i.e., a 5-log for *Giardia* and 6-log for viruses) would be necessary for highly impacted source waters (USEPA 1991), the LT2ESWTR rule was focused only on *Cryptosporidium,* for which it established the source water quality-based treatment requirements and a "bin classification" system (Table 3-1) based on raw water sampling (USEPA 2006b).

Table 3-1. Summary of Bin Classification Requirements under the Long Term 2 Enhanced Surface Water Treatment Rule.

Source: USEPA 2006b.

***Cryptosporidium* Concentration (Oocysts/L)[1]**	**Bin Classification**	**Total *Cryptosporidium* Treatment Requirement[3]**
< 0.075[2]	1	> 2.0-log
0.075 to < 1.0	2	> 4.0-log
1.0 to < 3.0	3	> 5.0-log
≥ 3.0	4	> 5.5-log

Notes:

1. Average (mean) value measured over 24 consecutive monthly sample results.
2. A 10-L sample volume is required per LT2ESWTR, so this average value threshold requires that several results are non-detect (counted as a value of 0).
3. Total treatment requirements can vary slightly depending on which type of treatment is provided. The values shown here represent the requirements based on "alternative filtration" techniques, which are listed explicitly in LT2ESWTR (compared to "additional requirements" listed for conventional treatment facilities).

3.2 Unregulated Chemical Constituents

Besides the chemical constituents explicitly regulated through MCLs, the presence of anthropogenic and recalcitrant constituents of emerging concerns (CEC), such as pharmaceuticals and personal care products (PPCP), endocrine disrupting compounds (EDC), and per- and poly-fluorinated compounds (PFAS), in drinking water sources and treated potable water is of growing public concern. The control of CECs and PFAS is of particular interest for DPR. A wealth of research has been conducted to document the occurrence and treatment efficacy for various water and wastewater treatment unit processes (Benotti et al. 2009a; Hedgespeth et al. 2012; Schaider et al. 2014). Several studies have demonstrated contaminant- and process-specific removal efficiency (Benotti et al. 2009b; Bundy et al., 2007; Chuang et al. 2017; Dickenson et al. 2018; Monsalvo et al. 2014; Steinle-Darling et al. 2010; Tufail et al. 2020; Wang et al. 2020). The USEPA's Unregulated Contaminant Monitoring Rule (UCMR) has established a framework to identify unregulated contaminants. During each five-year period, the USEPA collects data on the occurrence, treatment, and health effects of the chemicals included in the UCMR candidate contaminant list (CCL). The current contaminants (UCMR5) are focused on perfluorinated compounds (PFC) with per- and polyfluoroalkyl substances comprising 29 of the 30 contaminants specified.

The 1986 Amendments to the SDWA established requirements for the USEPA to publish a list of chemical and microbial contaminants, the CCL, every five years to review for potential regulation. Every 5 years, the USEPA is required to identify five of the contaminants from that list for regulation determination. The regulatory determination could be either a decision to regulate or a decision not to regulate, in which case the contaminant is removed from future

CCLs. The UCMR, also set forth in the 1986 SDWA Amendments, requires that the USEPA publish a list every five years of contaminants designated for occurrence monitoring to support assessment of whether regulation would provide meaningful health risk reduction.

3.3 Approaches to Mitigating Microbial Risks

Several states, including Arizona, California, Florida, Hawaii, Idaho, Massachusetts, Nevada, North Carolina, Oklahoma, Oregon, Pennsylvania, Texas, Virginia, and Washington, have developed and implemented state-specific IPR regulations (USEPA 2018). To date, no states have developed regulations for DPR, though Texas has fully permitted two DPR facilities, both of which have been operational, using a case-by-case approval approach allowed by its state drinking water regulations. A third Texas DPR project in El Paso, which will be the first municipal finished drinking water augmentation DPR project in the United States, is currently at the final design stage and working its way through the case-by-case permitting process.

The fundamental basis for meeting microbial risk standards in potable reuse is common between the approaches taken by California IPR regulations and the Texas regulators' case-by-case approach to DPR: both are based on achieving less than 1 in 10,000 annual risk of infection for virus, *Giardia*, and *Cryptosporidium*, which is already more stringent than the basis of current conventional drinking water regulations (compare, for example, to the implied risk levels associated with the bin classification system for *Cryptosporidium* under LT2ESWTR). The finished water pathogen concentrations for enteric virus, Giardia and Cryptosporidium associated with this risk-based water quality goal are provided in Table 2.1 of *Direct Potable Reuse Monitoring* published by the Texas Water Development Board (Steinle-Darling et al. 2016).

In California, the regulations for IPR via groundwater augmentation requires a minimum of 12-log and 10-log, removal of viruses and protozoa (*Giardia* and *Cryptosporidium*), respectively (CDPH 2014), calculated from raw wastewater to finished drinking water. The maximum densities of culturable enteric viruses, *Giardia lamblia*, and *Cryptosporidium* spp. in raw sewage were used to derive these LRVs (Soller et al. 2018). The 12/10/10 approach applies a generous safety factor to provide a safeguard against potential outbreak conditions (Trussell et al. 2013). When awarding LRV credits, California regulators rely heavily on results of challenge tests and treatment datasets for each treatment process. Some portion of those LRVs can be achieved during wastewater treatment, and California's regulations provide LRV credits for primary and secondary wastewater treatment processes (Water Replenishment District, 2013). Demonstrated removals of virus via application of sub-residual ozone doses and UV validations as per the NWRI standard for reclaimed water projects are sufficient to receive LRV credits.

In March 2021, the CA SWRCB released a DPR addendum for public comment with 20/14/15-log reduction requirements through the treatment train, which must contain ozone/BAC upstream of RO and UV-AOP (CA SWRCB 2021). The treatment train must consist of at least four treatment processes specific for each pathogen category and the LRV must be validated through a study. An O_3:TOC ratio greater than 1 must be applied and the ozone/BAC process must provide at least 1-log reduction of formaldehyde using the minimal EBCT of 15 minutes. If TOC in the RO permeate exceeds 0.15 mg/L continuously for more than five days, which will require investigation of membrane integrity through conductivity profiling to identify the underperforming RO vessel or RO element. If the RO permeate TOC exceeds 0.1 mg/L continuously for more than 24 hours, a 5-day total trihalomethane FP must be assessed. The finished water TOC must be monitored at least every five minutes and must not exceed 0.5 mg/L. DBP formation must be assessed through chemical characterization and assessment of DBP precursors and treatment byproducts. Provisions should be included for optimizing process operation to minimize potential public health impacts of treatment byproducts. Additional requirements include sewer shed surveillance to provide early warning of a potential occurrence of contaminants that could affect the DPR treatment performance.

In contrast, the approach established by the TCEQ recognizes treated wastewater as the starting point and no LRV credits are given to the upstream wastewater treatment processes. LRV targets (and other treatment requirements) are established case-by-case on the basis of a comprehensive source water characterization study. The approach for pathogens is modeled in concept after the *Cryptosporidium* binning process under LT2ESWTR. The pathogen log removal requirements for the Big Spring and Wichita Falls DPR projects demonstrate these differences in LRV requirements based on the source water characterization (Steinle-Darling, 2016).

Consistent with its approach to regulation of DPR in close alignment with existing federal drinking water regulations and guidance, the TCEQ also approves LRV credit on the basis of federal drinking water guidance, which has limited the credit available for advanced treatment processes in that state. For example:

1. This approach requires strict adherence to contact time (CT) requirements (e.g., for ozone LRV credit), which does not allow any credit for the substantial virus inactivation achieved at sub-residual doses.
2. The approach also limited LRV credit given to date for UV by requiring strict adherence to the USEPA's UV Disinfection Guidance Manual (USEPA 2006a). Until the recent release of updated EPA guidance (USEPA 2020) for UV validation, this means projects were constrained to 4-log virus credit (and 3-log credit for *Cryptosporidium* and *Giardia*), even for UV-AOP systems with UV doses significantly in excess of the amount needed to surpass 6-log inactivation for all three pathogen groups.
3. Finally, in order to receive LRV credit, membrane-based processes must be able to meet all criteria in USEPA's Membrane Filtration Guidance Manual (USEPA 2005). This guidance was not written with high-pressure membranes RO and nanofiltration in mind. This means the approaches therein cannot easily be performed for RO membranes and therefore the TCEQ has to date not currently granted any LRVs for RO membranes.

Thus, both California and Texas apply significant levels of conservatism in their approaches to potable reuse.

3.4 Baseline Treatment Performance

3.4.1 Surface Water Treatment Plant Processes and Performance

SWTPs typically include coagulation, flocculation, sedimentation, filtration, and disinfection. Generally, a wide variety of particulate impurities, including organic matter, clay particles, metals and metalloids, and microbes (i.e., virus, bacteria, protozoa, and algae), are present in natural waters. The coagulation process entails the addition of a chemical (e.g., metal salt) to neutralize the surface charge of colloidal particles (<1 µm with high surface to volume ratio), resulting in micro floc formation. In combination with the flocculation and sedimentation processes, filtration provides an important final barrier for particles and microorganisms. Depending on the granular media used, filters may also remove contaminants that can be removed through adsorption (e.g., NOM, color, and some CECs removal with biofiltration and/or GAC).

3.4.1.1 Coagulation

Coagulation chemistry and particle removal through the clarification process is not only important for reducing the solids loading on the filters, but also fundamental in reducing TOC. As a surrogate for DBP precursors, TOC removal is an important requirement of the USEPA's D/DBPR. Based on the source water TOC and alkalinity, a minimum percent removal for TOC is required for the SWTP (Table 3-2). And, in SWTPs that do not have biological filtration, flocculation and clarification is the only process capable of TOC removal.

Table 3-2. Required TOC Removal Through Enhanced Coagulation at Conventional Treatment Plant.
Source: USEPA 1999.

Source Water TOC (mg/L)	Source Water Alkalinity (mg/L as $CaCO_3$)		
	0 - 60	>60 - 120	>120
>2.0 to 4.0	35.0%	25.0%	15.0%
>4.0 to 8.0	45.0%	35.0%	25.0%
>8.0	50.0%	40.0%	30.0%

Enhanced coagulation refers to optimized coagulation at lower pH, targeting NOM removal rather than turbidity, primarily for compliance with the D/DBPR. NOM can also impart color and taste and odor (T&O) to the treated water and, if not removed, can support biological regrowth, corrosion, and DBP formation. However, previous studies have shown limited CEC removal even with enhanced coagulation (Saxena et al. 2018). NOM removal efficiency through enhanced coagulation is affected by many factors, including NOM characteristics, coagulant type and dose, mixing conditions, pH, alkalinity, ionic strength, and temperature. Excess coagulant can reduce NOM removal due to charge reversal and increase residual coagulant (i.e., metal) concentration in settled water (Saxena et al. 2018). Specific UV absorbance (SUVA), calculated by dividing UV absorption at 254 nanometer (nm) wavelength (i.e., UV_{254}) by DOC concentration, is an effective parameter to determine NOM characteristics and its potential effect on coagulant dose requirements. Source waters with SUVA greater than 4 L/mg-m are amenable to NOM removal with enhanced coagulation, whereas poorer NOM removal has been observed in water with SUVA <2 L/mg-m. To this end, the USEPA grants an alternative compliance for conventional SWTPs with SUVA less than 2 L/mg-m. While the enhanced coagulation process does not change the pathogen LRV associated with the conventional SWTP treatment process, the reduction of TOC can improve the performance of downstream ozone, filtration, and chlorine disinfection by reducing oxidant demand and potentially turbidity loading.

3.4.1.2 Filtration

Filtration is applied to remove particulate material from the filter influent. The major difference between conventional treatment and direct filtration is that conventional filtration focuses on generating settleable flocs, whereas direct filtration relies on the formation of filtrable flocs. Similar to conventional treatment, the type and dose of coagulant (with or without coagulant aid) and charge neutralization target are key factors for stable and effective direct filtration performance.

Direct filtration is employed for treating high quality surface water sources with relatively lower turbidity and TOC, and therefore is not compatible with enhanced coagulation. To maintain low solids loading on the downstream filters, low coagulant doses are applied in direct filtration. Direct filtration plants do not include sedimentation (Culp 1977) and rely on deep bed filters to retain small flocs formed in the upstream coagulation and flocculation process within the filter bed. Particle removal mechanisms in direct filtration include (1) particle transport - gravity settling, interception, diffusion, and rotation, and (2) attachment to the media and on particles previously attached (McCormick and King 1982). Over time, particles shear off the media surfaces and fill the pore spaces. With continued operation, flocs migrate deeper into the bed as the upper pores cannot retain any more flocs. Eventually headloss or turbidity breakthrough occurs, requiring backwashing the bed.

Balancing excess head loss is a major challenge in direct filtration and the backwash water requirement can be considerably more compared to a conventional filtration (McCormick and King 1982). Early turbidity breakthrough, especially when aluminum-based coagulants are used, is another challenge often faced in direct filtration (Eikebrokk 1999; McCormick and King 1982). Additionally, if source water quality fluctuates seasonally or degrades over time, the direct filtration process may struggle to maintain acceptable filter run times. To address filter performance issues, a filter aid polymer is typically used in direct filtration (Hutchison 1976; McCormick and King 1982), especially when filter loading rate is greater than 4 gpm/ft^2 (Bellamy et al. 1993). The benefits of using filter aid polymer include reduction in coagulant dose, improved treated water quality, sludge volume reduction, improved sludge dewatering, and reduced issues associated with pH and alkalinity. Colloidal re-stabilization can also be experienced when using cationic polymer in direct filtration due to the relatively clean source water with low particle concentrations. Hutchison (1976) successfully avoided turbidity breakthrough in a pilot-scale direct filtration study with raw water turbidity as high as 175 nephelometric turbidity unit (NTU) with the use of non-ionic filter aid polymers. Polymer feeding was essential for addressing raw water turbidity spikes. Polymer dose optimization was critical as too little polymer delayed turbidity breakthrough, whereas filter blinding was observed when excess doses were used (Hutchison 1976).

Since sedimentation is not included in the process, direct filtration SWTPs are limited in their capacity to remove organics. To enhance TOC removal in direct filtration, biofiltration can be included, which also helps remove CEC, when ozone treatment is implemented upstream of the biofilter.

Direct filtration also receives less virus and *Giardia* removal credit compared to conventional treatment. According to the SWTR, direct filtration received 1-log virus and 2-log *Giardia* credit (compared to 2-log and 2.5-log, respectively). The log removal credits for *Cryptosporidium* are the same for conventional treatment and direct filtration, assuming that any source water that is of high enough quality for direct filtration would also be considered Bin 1 according to the LT2ESWTR.

Membrane process is a size exclusion/straining filtration process, which is different than the treatment mechanisms associated with media filtration. Membrane processes can be classified into various categories depending on membrane materials, pore size, driving force, contaminant separation mechanism, etc. In general, MF and UF are typically employed low pressure (<2 bar) membranes for contaminant removal in membrane filtration plant. The pore size of MF and UF membranes typically range from 0.1–1 µm and 0.01–0.1 µm, respectively (Warsinger et al. 2018). While MF membranes remove suspended and colloidal particles, protozoa, and bacteria, UF membranes can also remove viruses. In drinking water plants, membrane processes have been employed with or without upstream coagulation/flocculation/sedimentation processes, depending on the site-specific raw water characteristics.

Daily, semi-weekly, or weekly pressure decay tests are conducted on membrane system to measure the membrane integrity, as stipulated by the Membrane Filtration Guidance Manual (MFGM). Membranes are excellent barriers for protozoa and provide a very consistent filtrate water quality with low turbidity and receive 3-log to 4-log credit for protozoa removal. Since viruses are in the 0.01 to 0.1 range, UF can receive virus removal credit for SWTPs, however 4-log virus and 0.5-log *Giardia* is required by chemical disinfection and therefore virus credit is generally not pursued for SWTPs using membrane filtration.

Membranes do not remove organics (bulk or trace) unless coagulation is provided and can foul when organics (including polymer) are present in the feed water. The control of organics is essential for DBP control as well as membrane performance. There are examples of surface water treatment facilities with sedimentation followed by membrane filtration. If coagulant aids are used, they must be selected carefully to prevent membrane fouling.

3.4.1.3 Turbidity and Pathogen Removal

Monitoring coagulation, flocculation, and sedimentation performance allows effectively optimizing and controlling particle removal in filtration. Particle removal is primarily affected by coagulation chemistry. McTigue et al. (1998) conducted a national study on particle removal across drinking water treatment facility. The study surveyed 100 SWTPs and analyzed American Water Works Service Company’s (AWWSC) two databases. Effective particle removal was observed with a median particle log removal of 2.8 (McTigue et al. 1998). Additionally, the survey showed that 90% of particle spikes occurred during the ripening period, whereas occasional spikes were also observed during the middle and end of the filter runs, mostly due to operational and hydraulic events, which could be controlled and minimized (McTigue et al. 1998). Approaches for controlling passage of particles and pathogens into the finished water during ripening include (1) using a filter-to-waste cycle, (2) polymer filter aids, (3) addition of coagulants or filter aids to the backwash water near the end of the backwash cycle, and (4) optimized backwash practices.

Cysts release can be observed during a particle spike (McTigue et al. 1998). While median turbidity in filtered water remained less than 0.2 NTU, particle count and turbidity were not always correlated.

Cryptosporidium and *Giardia* were found in 15% and 14% of the filtered water samples, respectively. In general, increasing particle count was associated with increasing pathogen count and the correlation coefficients between particles and *Cryptosporidium* and *Giardia* was 0.67 and 0.68 in the AWWSC datasets, respectively. The survey results suggested a median log pathogen reduction of 1.7. Based on the results, the authors concluded that particles could be a potential indicator of water treatment plant performance and pathogen removal (McTigue et al. 1998). Other studies have also shown the effectiveness of particle count as an indicator for pathogen removal (Nieminski and Ongerth, 1995). Turbidity may not be a reliable indicator for pathogen log reduction across a treatment plant, especially with low-turbidity source water, primarily due to the limited LRV that can be measured with turbidity (Nieminski and Ongerth, 1995; Ongerth, 1990).

Nieminski and Ongerth (1995) evaluated pathogen removal by conventional and direct filtration. Heat inactivated *Cryptosporidium* parvum oocysts and formalin inactivated *Giardia lamblia* cysts were spiked to the filter influent. Alum and cationic polymer were used for coagulation. Raw water characteristics and turbidity removal performance affected cyst removal. While particle removal was well correlated with cyst removal, no relation was observed between turbidity removal and cyst removal or between cysts and HPCs. *Giardia* and *Cryptosporidium* removal ranged from 3.3-log to 3.4-log and 2.97-log to 2.98-log, respectively.

While McTigue et al. (1998) reported higher particle counts and pathogens in the filtered water compared to conventional filtration based on a national survey, Nieminski and Ongerth (1995) observed comparable pathogen and particle log removal in both conventional and direct filtration.

3.4.1.4 TOC Removal

Zhang et al. (2015) reviewed NOM removal in different drinking water treatment unit processes, including coagulation, adsorption, oxidation, membrane filtration, and biological treatment. They reported 10 - 50% NOM removal in conventional treatment plants, while 26% - 80% NOM removal can be observed at plants practicing enhanced coagulation. Controlling pH is key for effective NOM removal. In general, Iron (Fe[III]) and Aluminum (Al[III]) salts are used as coagulants in drinking water treatment. The best pH range for Fe(III) and Al(III) metal salts range from 5-8 and 5-7 SU, respectively. Cationic polymers precipitate at pH less than 7, while precipitation of anionic polymers occurs at pH >7 SU. In general, coagulation pH in colder temperatures (winter) should be higher than for warm water in the summer (Bellamy et al. 1993). When ozone is applied upstream of coagulation, the ozone and coagulant doses should be carefully optimized. While lower ozone dose enhances coagulation, higher ozone dose can disrupt the coagulation process due to the generation of hydrophilic NOM fractions, which are difficult to coagulate.

MF membranes can provide >99% removal of fine suspended particles and 3-6-log reduction of protozoa cysts and coliform bacteria (Warsinger et al. 2018). Intact UF membranes provide near-complete removal of suspended solids, protozoan cysts, coliform bacteria, and can provide up to 7-log reduction of viruses (Warsinger et al. 2018). In general, MF and UF membranes are not effective in removing dissolved organic constituents (Warsinger et al. 2018) unless coagulation is provided upstream to bind organics to particles that are then removed by the membranes.

3.4.2 Advanced Water Purification Facility Treatment Performance

A typical RBAT process includes MF or UF, RO, and UV-AOP, whereas ozone, BAC, and UV (or UV-AOP) are generally included in a typical CBAT process train. Recent studies have demonstrated that GAC contactor downstream of ozone/BAC must be considered as an integral part of a CBAT treatment train for ensuring effective removal of TOC and DBP FP (Barazesh et al. 2019; Summers et al. 2020). Previous studies (for example Salveson et al. [2018] and Trussell et al. [2016]) often compared performance of a CBAT treatment train without a GAC with an RBAT treatment train, requiring careful interpretation of the results.

Both RBAT (Hooper et al. 2020; Rodriguez et al. 2009; Tackaert et al. 2019) and CBAT (Gerrity et al. 2014; Noibi et al. 2020; Tackaert et al. 2019; van Rensburg 2016) trains have been demonstrated to effectively remove contaminants and protect public health. Recent studies have demonstrated that CBAT can be an economical, sustainable, and low-energy alternative to RBAT without compromising treatment performance (Gerrity et al. 2014; Lee et al. 2012; Noibi et al. 2020; Trussell et al. 2016). Particularly, RBAT schemes are less practical for inland locations due to challenges associated with waste (i.e., RO concentrate) management and disposal. Recent studies have also demonstrated that implementing ozone/BAC upstream of an RBAT system can further enhance contaminant removal and ensure additional protection against health risks (Tackaert et al. 2019).

As discussed above, both RBAT and CBAT schemes include multiple barriers to ensure public safety. Each of the unit processes included in advanced treatment processes has one or more treatment objectives. For potable reuse, control of organic matter in the treated effluent is critical due to either potential toxicity of the mixture of residual CECs, DBP formation potential after chemical disinfection, or biological regrowth in the distribution system. The following paragraphs discuss treatment performance of the typical unit processes included in advanced water treatment plants.

3.4.2.1 Low Pressure Membranes

MF and UF unit processes effectively remove particles, turbidity, and pathogens (Burris 2019; Pecson et al.2017). Thus, MF or UF is used as a pretreatment process for RO (Pearce 2008). A study of the nation’s first operating DPR facility in Big Spring, Texas, found no protozoa after MF despite substantial concentrations present in the feed to the facility (Steinle-Darling et al. 2016). Similarly, during the demonstration of the 1 million gallons per day (mgd) Advanced Water Purification Demonstration study at the North City Water Reclamation Plant (North City), the City of San Diego achieved protozoa and bacteria removal to below detection (Steirer et al. 2013). While MF provided more than 99% virus removal, greater removal was observed with

UF, primarily due to the smaller pore size. In another study that evaluated the removal and regrowth of microorganisms across a pilot-scale DPR facility consisting of ozonation, chloramination, parallel MF and UF, parallel nanofiltration (NF) and RO, UV-AOP, and GAC, Miller et al. (2020) also reported the maximum total and intact microbial cells removal by MF (4.18-log total cells; 3.67-log intact cells) and UF (4.97-log total cells; 4.83-log intact cells). In general, MF and UF are not effective in removing TOC, but the removal efficiencies can increase over time due to pore plugging, pore size reduction, and cake formation (Miller et al. 2020).

3.4.2.2 Reverse Osmosis

RO is highly effective for removing a wide variety of dissolved constituents, including bulk organic matter, CECs, ions, and other contaminants (Drewes et al. 2005). However, it does not completely remove low-molecular weight (<100 Dalton [Da]) organic molecules, such as N-nitorosodimethylamine (NDMA) or 1,4-dioxane. To remove these compounds, typically UV-AOP is implemented downstream of RO unit process. Typically, TOC removal in the RO process can be greater than 98%, resulting in concentrations lower than 0.5 mg/L in the RO permeate (Burris 2019; Snyder et al. 2014). It also provides near-complete removal of CECs and significant reduction in total dissolved solids (TDS) concentration (Gerrity et al. 2013). TOC and electrical conductivity are typically used as surrogates for RO performance (Pecson et al. 2017). However, the RO process “over treats” water, resulting in the requirement of product water stabilization through the addition of chemicals, such as lime, sodium hydroxide, calcium carbonate, or calcium chloride, to prevent downstream pipe corrosion and potential leaching of substances from the environment (Gerrity et al. 2013). The re-stabilization of the AWPF product water is an important consideration when blending RO-treated ATW with raw water at an SWTP; the blended water pH, alkalinity, TOC, and turbidity will impact the operation of the coagulation/flocculation processes.

3.4.2.3 Ultraviolet Treatment

While UV systems are used for pathogen inactivation, a UV-AOP process degrades low-molecular weight organic compounds, such as 1-4, dioxane, formaldehyde, acetone, and NDMA, that are not removed by the RO process (Tackaert et al. 2019). In combination with membrane processes (i.e., MF or UF or RO), UV-AOP processes provide a robust barrier against pathogens (Gerrity et al. 2013). While UV photolysis provides NDMA destruction, the UV-AOP (e.g., UV in combination with hydrogen peroxide [H_2O_2] or sodium hypochlorite [NaOCl]) provides significant CEC oxidation (Gerrity et al. 2013). During the demonstration testing at North City, UV/H_2O_2-AOP consistently provided 1.2-log and 0.5-log removal of NDMA and 1,4-dioxane, respectively (Steirer et al. 2013).

3.4.2.4 Ozone/Biofiltration

Ozone is a strong oxidant and disinfectant, and can directly oxidize some NOM components (e.g., partial oxidation of fulvic acid fraction) or achieve advanced oxidation through the generation of reactive hydroxyl (•OH) radicals (Zhang et al. 2015). Ozone reacts with recalcitrant NOM and breaks high-molecular weight organic compounds into lower molecular-weight fractions, generating readily biodegradable organic fractions with hydroxyl, carbonyl, and carboxyl functional groups (Hozalski et al. 1999; Snyder et al. 2014; Urfer et al. 1997; Zou 2015). In general, ozone doses typically applied at drinking water treatment facilities are insufficient for complete mineralization of organics (Arnold et al. 2018; Hollender et al. 2009). When used upstream of a biofilter, ozone promotes better organic compound removal across the biofiltration process. Previous studies have demonstrated effective removal of NOM (Lauderdale et al. 2014; Zou 2015), DBP precursors (Price 1994; Sun et al.,2018), taste and odor compounds (McDowall et al. 2009), inorganic contaminants (e.g., iron and manganese) (Kohl and Dixon 2012), and CECs (Lee et al. 2012; Sun et al. 2018) with ozone and biofiltration (ozone/BAF).

Typically, the baseline ozone dose in reuse applications is determined based on a target O_3:TOC ratio as opposed to maintaining a residual ozone concentration. Nitrite is an ozone scavenger which imposes a large demand (O_3: nitrogen dioxide [NO_2] ratio of 3.4) and if the ATW contains nitrite, its concentration must be considered when designing the ozone treatment system. While the actual ozone dose applied depends on source water quality and treatment goals, O_3:TOC ratios as low as 0.5 significantly inactivate microorganisms and provide effective destruction of a wide range of CECs (Plumlee et al. 2014; Snyder et al. 2014). Previous studies have demonstrated the applicability of ozone/BAF as a major component of the CBAT train for potable reuse (Bell et al. 2016; Funk et al. 2018; Gifford et al. 2018; Lee et al. 2012; Snyder et al. 2014). The application of ozone upstream of MF or UF in an RBAT scheme has also been shown to enhance bulk organic transformation and lower membrane fouling (Gerrity et al. 2013; Stanford et al. 2011). When used in an RBAT scheme, ozonation also helps improve RO concentrate quality due to reduced pathogen and CEC loadings to the RO membrane (Gerrity et al. 2013).

3.4.2.5 Granular Activated Carbon Adsorption

GAC is effective at adsorbing many organic chemical constituents, including CECs (Ma et al. 2018). In addition, microbial colonization over time results in the establishment of biodegradation as one of the contaminant removal mechanisms. CEC removal through adsorption on GAC depends on the contaminant's affinity for adsorption onto GAC. For example, persistent CECs, such as iohexol, meprobamate, sucralose, flame retardants, tris(2-carboxyethyl)phosphine (TCEP), tris(1-chloro-2-propyl) phosphate, and tris(1,3-dichloro-2-propyl)phosphate (TDCPP) were measured in the GAC effluent of a pilot- and demonstration-scale study that evaluated the effectiveness of a treatment train with ozone, BAC, and GAC for the removal of 96 CECs (Vaidya et al. 2020). While biodegradation in the upstream BAC was ineffective in removing these contaminants with up to 10 minutes EBCT, 57.6% CEC removal was observed in the GAC contactor with previously exhausted GAC with a 20 minutes EBCT. Biodegradation in the GAC was likely responsible, at least partly, for the CEC removal with the longer EBCT. When fresh GAC media was used with a 15 min EBCT, all CECs were removed to below detection until 10,000 bed volumes (BV). After 20,000 BVs, only 70% removal was achieved for seven CECs (sucralose, iohexol, acesulfame-K, meprobamate, cotinine, primidone, and acetaminophen).

Thus, with a multiple barrier strategy, both RBAT and CBAT can effectively remove chemical contaminants and pathogens, minimizing health risks. For example, in a pilot-scale study that evaluated RBAT and CBAT process schemes treating a denitrified tertiary effluent for the removal of TOC, CECs, pathogens, and DBP FP, both treatment trains reliably produced ATW that met all SDWA regulations, lowering the contaminants to below their respective MCLs (Vaidya et al. 2019). The CBAT scheme included flocculation/sedimentation, ozone/BAF, GAC, and UV, whereas the RBAT scheme included UF, RO, UV/H_2O_2-AOP. Both treatment trains effectively removed TOC and, with 8 hours of free chlorine contact, trihalomethanes (THM) and HAAs were below their respective MCLs in the finished water from both trains. Bromate was effectively controlled in the CBAT scheme with the addition of monochloramine. While the CBAT treatment train lowered NDMA to less than 10 nanograms per liter (ng/L) with a 10-minute EBCT in the BAC filter, there was not a barrier for TDS and concentrations often exceeded the secondary MCL (598.7 ± 71.1 mg/L [average ± standard deviation]) in the CBAT product water. Pathogen LRV was evaluated through MS2 challenge test and assessment of PMMoV, a non-pathogenic fecal indictor, present in the source water. The CBAT train (chlorination and UV not included) provided greater than 7-log and 6-log reduction of MS2 and PMMoV, respectively, which was similar to that achieved with the RBAT train (i.e., > 7.5-log removal [UV-AOP not included]). The two trains completely removed viruses upstream of the UV and UV-AOP unit processes.

Similarly, finished water from the RBAT treatment train at the advanced water purification demonstration facility at North City Water Reclamation Plant met all drinking water quality standards and anticipated reuse regulations (Steirer et al. 2013). Based on the Orange County Water District's 2019 Annual Report, the groundwater replenishment system produced 91.8 mgd (average daily production) purified water with non-detect or below the permit limits inorganics (e.g., Al, Cr), VOCs, pesticides, and other synthetic organics (Burris 2019). CECs, such as endocrine disrupting compounds and pharmaceuticals were either below detect limits or below their threshold levels for causing health risks. The treatment train provided 12.3-log reduction of *Giardia* and *Cryptosporidium,* and 6-log reduction for viruses. Additional 4- to 5-log reduction for viruses were obtained through underground retention.

Trussell et al. (2016) reported TOC removal in RBAT trains from an influent of 6 mg/L to between 0.1 and 0.2 mg/L, whereas it was reduced to only 3 to 4 mg/L in ozone/BAC consisting CBAT trains with EBCT in the BAC as high as 20 minutes. The treatments trains did not include GAC and the authors recognized that additional TOC could be removed by implementing GAC downstream of ozone/BAC. The addition of GAC downstream of ozone/BAC would also help remove CECs (Barazesh et al. 2019; Summers et al. 2020; Vaidya et al. 2020) and DBP formation potential (Summers et al. 2020).

In the study that evaluated the efficacy of alternative potable reuse treatment trains, Trussell et al. (2016) observed concentrations of CECs well below the limits in secondary effluents and that full-scale AWTP may not necessarily be designed for CECs removal. They adopted a margin of safety (MOS; calculated as risk-based action level/observed concentration) approach for assessing CECs removal in AWTPs. The MOS values ranged from slightly less than 1 for bromate in the CBAT treatment train consisting of UF-ozone-BAC-UV to 1,700,000 for sucralose in the RBAT treatment train consisting of MF-RO-UV/H_2O_2-Cl_2. While all the treatment trains had acceptable MOSs for the CECs evaluated, perfluorooctanoic acid (PFOA) had an MOS of 33, which would have been even lower if evaluated under newer guidelines for PFOA than the 70 ng/L Health Advisory Level used at the time of the study. For polishing with respect to recalcitrant CECs, such as PFAS, RBAT treatment trains should thus include an adsorptive GAC step in addition to a purely biological BAC component.

The New Goreangab Water Reclamation Plant (NGWRP) in Windhoek, Namibia distributes drinking water with a blend of up to 35% ATW as a direct to distribution DPR system and fully complies with all applicable regulations. The final water specification and actual operational results from the NGWRP system are summarized in Table 2 of *Direct Potable Reuse–A Feasible Water Management Option,* published in the Journal of Water Reuse and Desalination (Lahnsteiner et al. 2018). The pre-ozonation, coagulation, flocculation, and dissolved air floatation stages remove the majority of the DOC (40.2%), whereas the dual media filtration, ozonation, BAC, GAC, and UF provide additional 10.5, 3.8, 11.6, 15.2, and 0.6% DOC removal, respectively, with 81.9% total DOC removal across the plant.

3.5 Blending ATW with Conventional Water Sources

3.5.1 Associated Challenges

The RO membranes central to the RBAT approach are important barriers for pathogens and chemicals, however, the near-complete removal of ions, alkalinity, and hardness results in corrosive water that requires chemical stabilization. While blending ATW with SWTP's raw water sources may help improve the quality of the surface water, the potential challenges associated with blending the two significantly different water sources are not fully understood.

When blending ATW with raw water supply at an SWTP, there are following concerns:

- **Water Quality Changes:** The ATW characteristics can be very different than the SWTP, especially when a non-stabilized RBAT treated ATW is used. Non-stabilized ATW from RBAT trains typically has very low ionic strength, alkalinity, hardness, TOC, and turbidity. In contrast, ATW from CBAT trains may have similar or higher concentrations of TOC, alkalinity, and hardness compared to raw water (Salveson et al. 2018).
- **SWTP Operations:** The operability of the SWTP unit processes will be dictated by changes in water chemistry, which affects coagulation chemistry, floc formation and settling characteristics, filterability, disinfection requirements, and DBP formation. Blending the two water sources should be implemented in a way that does not affect the overall treatment performance across the SWTP and the treatment remains compliant with all regulatory provisions, including SDWA and SWTRs. A DPR pilot study conducted at Gwinnett County (Funk et al. 2018; Hooper et al. 2020) demonstrated no adverse effects on conventional treatment plant operation when ATW from a CBAT process was blended with Lake Lanier water.

  Blending the ATW can lower TOC and alkalinity, affecting the level of TOC removal required as per the requirements for enhanced coagulation (Table 3-2, Section 3.4.1.1) due to the changes in TOC and alkalinity bins. Furthermore, blending the ATW may lower SUVA, which establishes the applicability of alternate compliance requirement when lower than 2 liters per milligram per meter (L/mg-m).
- **Pathogen Removal in SWTPs:** RBAT trains (Pecson et al. 2017; Soller et al. 2017; Soller et al. 2018) and CBAT treatment trains (Funk et al. 2018; Wallmann et al. 2021) are proven to effectively reduce viable microbial load in ATW. Therefore, blending ATW from an RBAT

facility with raw water at STWP is expected to effectively reduce microbial counts in the blended water and treated final effluent.

- **Additional LRV Credit:** DPR regulatory approaches require specific LRVs for pathogens, including viruses, *Giardia,* and *Cryptosporidium.* The SWTP can serve as an important additional pathogen barrier for the blended DPR supply. Maintaining the effectiveness of the SWTP unit processes is an important consideration when applying the full LRV credits for the DPR system as well as maintaining the LRV credits required for treatment of the surface water source.
- **Potential Spread of Antibiotic Resistance Genes:** Secondary effluent typically has higher concentrations of antibiotics, antibiotic resistant bacteria (ARB), and antibiotic resistance genes (ARG). While findings from a few previous studies have indicated incomplete antibiotics removal across an AWPF (Watkinson et al. 2007), more recent studies have demonstrated ARG reduction to below detection (Harb et al., 2019; Wallmann et al. 2021). Therefore, depending on the AWPF processes implemented, ARB and ARGs can potentially persist to the SWTP (Alexander et al. 2016). While ARGs and ARBs have been detected in drinking water sources, the removal efficiency of these contaminants in a drinking WTP depends on the type of ARGs and unit processes applied (Hu et al. 2019; Sanganyado and Gwenzi 2019). Hu et al. (2019) observed considerable removal of integrase gene intI 1 and forty-one ARG subtypes in coagulation, flocculation, sedimentation, and sand filtration, while the ARGs increased in the GAC contactor and chlorine disinfection. Enhanced ARB and ARG removal can be achieved by implementing UV-AOP (Sanganyado and Gwenzi 2019).
- **Disinfectant Demand, DBP Formation, Corrosion, and Water Stability:** When blending ATW with raw water source upstream of an SWTP, potential changes in water quality can affect disinfectant demand and stability, water stability, biological regrowth and nitrification, metal solubility and stability of pipe scales. Optimizing coagulation process may allow addressing these challenges.

3.5.2 Effects of Blending ATW with Raw Water

Blending two water sources changes water quality, which in turn can affect unit process operation and performance, including coagulation, flocculation, filtration, and disinfection. The water quality changes can also impact stability of pipe scales, metal solubility, microbial regrowth and nitrification, and disinfectant residual in premise plumbing. Therefore, when considering blending a new water source with drinking water supply, the potential impacts must be carefully evaluated.

For ATW blending two primary locations in a drinking water treatment/distribution system are considered: (1) with the raw water upstream of the SWTP, and (2) with the filter effluent at the SWTP (i.e., before chlorination and distributing the finished water). While, with the logic implied in the USEPA’s Filter Backwash Recycling Rule, blending upstream of the SWTP treatment train provides additional benefits, including public perception benefits (Stanford et al. 2016), it is also to be recognized that blending RBAT-treated stabilized ATW with filter effluent at an SWTP may provide economical advantage as (i) this approach avoids potential challenges to the SWTP unit process operation and performance and (ii) lower volume would need to be treated compared to when blending upstream of the SWTP.

Various studies have evaluated the effects of blending different water sources, such as groundwater and surface water (Salveson et al. 2018; Taylor et al. 2008), desalinated water and traditionally distributed drinking water (Duranceau et al. 2011) on water quality, water stability, and pipeline corrosion. However, there are multiple aspects of DPR, such as contaminant concentrations including CECs and microbial characteristics, that require careful assessment when evaluating the effects of blending ATW either upstream of SWTP or before the distribution system. The following subsections briefly discuss the potential effects of blending raw water with ATW.

3.5.2.1 Effects on Water Quality

In general, ATW produced from municipal wastewater using an RBAT process contains very low organic carbon, turbidity, pH and alkalinity (unless the RO effluent is stabilized), nutrients, salts, and microbiology (Burris 2019; Salveson et al. 2018). Therefore, when blending RBAT-treated ATW with a raw water source, TOC and turbidity generally declines, while the blended water can be corrosive in nature. In contrast, TOC, alkalinity, and hardness in the ATW from a CBAT system can be similar to the surface water sources (Hooper et al. 2020; Salveson et al. 2018). Therefore, TOC, alkalinity, and hardness in the blended water can be similar to the raw water when ATW from a CBAT process is blended. RBAT-treated ATW will have negligible microbiological indicators. Previous studies have also demonstrated that microbiological characteristics of ATW from a CBAT system can be equal or better than the drinking water source (Hooper et al. 2020).

While there may be advantages to blending RBAT-treated ATW with finished water from an SWTP after stabilizing the water and implementing corrosion control measures with the blended water, it may also be practically possible to blend ATW produced from a CBAT-train consisting of GAC. Such possibilities should be carefully evaluated on a case-by-case basis. Table 3-3 summarizes expected water quality when ATW from an RBAT- or a CBAT- system is blended with raw water at an SWTP.

Table 3-3. Comparison of Blended Water Quality When Blending with ATW from an RBAT or a CBAT Process.

Parameter	Blending Raw Water With	
	ATW from an RBAT(1)	ATW from a CBAT
pH	Lower	Similar
Alkalinity	Lower	Similar
Pathogens	Lower pathogen load	Lower pathogen load
TOC	Lower	Similar TOC
Turbidity	Lower turbidity	Lower turbidity
CECs	Lower CECs	Lower CECs
Chlorine Effectiveness	Likely improve chlorine effectiveness	Similar chlorine effectiveness
DBPs	Lower DBPs	Similar or slightly higher THMs and HAAs. Increased brominated, iodinated, and nitrogenous DBPs
Corrosivity	Increased corrosivity (due to lower pH and alkalinity) unless ATW is stabilized	Similar or increased corrosivity (due to greater TDS)
Notes: 1. That has not been stabilized.		

Depending on the secondary treatment process and treatment goals, and advanced water purification process schemes, ATW may contain ammonia, nitrate, and nitrite with significant variability (daily and seasonally). In general, RO is less effective in removing ammonia and the presence of ammonia in the RO-treated water can present operational challenges, such as disinfectant speciation, increased chlorine demand, and CT compliance issues (Stanford et al. 2016). These challenges may be more significant when ATW from a CBAT system is used. While ammonia and nitrite can be effectively oxidized to nitrate with ozone/BAF (Wang et al. 1989), the increased nitrate concentration can be a limiting factor for blending ATW (Hooper et al. 2020). Furthermore, nitrite and nitrate can result in cyanide through a chain of sequential reaction with chlorine and organic compounds during chlorination (Hooper et al. 2020).

ATW water temperature is typically higher than the raw water at an SWTP (Hooper et al. 2020; Stanford et al. 2016). While this could result in increased biological activity in BAF unit process in the CBAT train (Funk et al. 2018), the higher temperature may affect DBP formation.

Salveson et al. (2018) evaluated changes in water quality when blending surface water or groundwater sources with ATW from an RBAT system or ozone/BAF treated water at four utilities. Both pre- and post- conventional treatment blending scenarios were evaluated. While blending with surface water sources was evaluated under pre-conventional treatment, blending with groundwater sources was evaluated under post-conventional treatment. When the surface water source had conductivity exceeding the California secondary MCL (900 µS/com), conductivity in all blends ozone/BAC-treated ATW exceeded the California secondary MCL. When surface water sources were blended with ATW, all tested blends had either low TOC, TTHM, and HAA5 concentrations or had SUVA below 2 L/mg-m and met the alternative compliance criteria for TOC removal. Higher alkalinity, sulfate, and chloride concentrations were observed in the groundwater sources and the maximum possible ATW percentage was determined by sulfate concentrations (Salveson et al. 2018). TOC concentrations in the groundwater sources were below the Stage 1 D/DBPR threshold of 2 mg/L.

A pilot study was conducted to evaluate the efficacy of a conventional SWTP when treating Lake Lanier water blended with ATW from the CBAT process at the F. Wayne Hill Water Resources Center (FWH WRC) in Gwinnett County, Georgia (Funk et al. 2018; Hooper et al. 2020). Blending ratios (i.e., volume of ATW to volume of blended water) of 15%, 25%, 50%, and 100% were tested. Turbidity in the pilot influent (i.e., blended water) decreased with increasing blending ratio, whereas alkalinity and hardness increased with the blending ratio. Similarly, with average TOC concentrations of 1.7 and 2.9 mg/L in Lake Lanier water and ATW, respectively, TOC concentrations increased with the blending ratio (Funk et al. 2018). In general, CEC concentrations also increased with increasing blending ratio due to the higher CEC concentrations in the ATW.

Increasing the blending ratio resulted in decreasing UV transmittance (UVT). The decreasing UVT and increasing TOC resulted in slightly decreasing SUVA with the increasing blending ratio. The ATW contained 16.2 ± 5.2 mg/L N nitrate, whereas the lake water had very low nitrate, which resulted in less than 10 mg/L N (i.e., MCL) with blending ratios 0 through 50% (Funk et al. 2018).

HPC concentrations in the ATW and Lake Lanier water was 4-log and 2-log colony forming units (CFU)/100 mL, respectively (Funk et al. 2018). Both water sources contained 2-log CFU/100 mL total coliforms, whereas fecal coliforms and Enterococcus were detected only in the lake water at low concentrations. MS2 coliphage was detected once during the testing period in the lake water, while somatic coliphage, Legionella, *Cryptosporidium*, and *Giardia* were not detected. Overall, blending the ATW resulted in reduction in the microbial indicators evaluated during this study.

3.5.2.2 Effects on Treatment and Process Performance

Only a few DPR studies have evaluated the possibility of blending ATW with raw water sources for drinking water production and limited information exists on the effects of blending ATW with raw water sources on SWTP performance. Therefore, a broader approach was taken and findings from previous studies on the effects of water quality changes on various aspects of SWTP operation and performance is summarized in the following sections. Findings from previous blending evaluations for DPR are summarized in each subsection as appropriate.

Effects on Oxidant Demand

Oxidant demand is directly related to concentrations of oxidizable constituents in water, including bulk organics, such as NOM, CECs, and reduced species (e.g., metal species). While initial ozone demand (IOD) and ozone decay rate constants (k_{O3}) are functions of water quality, previous studies have reported IOD per unit ozone dose from 0.22 to 0.64 and k_{O3} from 0.09 to 3.78 revolutions per minute in secondary effluent (Gamage et al. 2013; Gifford et al. 2018).

Given that RBAT schemes remove most chemical constituents, blending RBAT-treated ATW with source water is expected to significantly lower ozone demand. Similarly, blending ATW from a CBAT process is also expected to lower ozone demand since the organic carbon present in the ATW would be pre-exposed to ozone and passed through biofiltration.

In the pilot-scale DPR study conducted at Gwinnett County, Lake Lanier water had higher ozone demand compared to the CBAT-treated ATW, likely due to the ozone treatment in the CBAT scheme at FWH WRC (Funk et al. 2018). This resulted in declining ozone dose demand with increasing the blending ratio. the O_3:TOC ratio also decreased as the blending ratio increased. As expected, higher water temperature required higher ozone dose. No relationships were observed during the pilot study between chlorine demand and ATW blending ratio (Funk et al., 2018). Furthermore, there were no trends in chlorine demand and concentration of organics.

Effects on Coagulation

Suspended particle removal and/or NOM removal is one of the major water treatment goals of an SWTP, which is primarily achieved through coagulation, flocculation, sedimentation (if applicable). Coagulants, such as ferric chloride, ferric sulfate, aluminum sulfate, aluminum chlorohydrate, low-molecular-weight organic cationic polymer, are typically used to neutralize negatively charged particles in the water. Factors affecting coagulation include concentration of particles and NOM, chemical species and characteristics, pH, alkalinity, hardness, type and dose of coagulant, coagulant speciation, precipitated solids (e.g., metal hydroxides), and applied mechanical shear (Pernitsky and Edzwald 2006).

When blending ATW, these water quality parameters (i.e., turbidity, organic matter concentration and characteristics, particle charge, pH, alkalinity, and hardness) can be considerably changed, which in turn affect coagulant dose required for charge neutralization. The following discusses the importance of these water quality parameters on coagulation in relation to ATW blending.

- **Particle and NOM Characteristics:**
    - Blending ATW can change particle charges and NOM characteristics. Effectiveness of coagulation depends on electrostatic characteristics of particles and NOM. Given that NOM can have up to 15 times higher charge density than silt/sand particles (Hart 2020; Saxena et al. 2018), it can be the factor determining coagulant dose and coagulation performance (Au et al. 2011; Pernitsky and Edzwald 2006). Previous studies have also demonstrated that settled turbidity does not necessarily reflect filterability, especially for water with low turbidity (Hart 2020; Jiao et al. 2017).
- **pH:**
    - Blending ATW, especially if non-stabilized finished water from an RBAT train is used, can change water pH, which affects turbidity and NOM removal due to changes in coagulant, particle, and floc speciation in water (Jiao et al. 2015; Saxena et al., 2018). Furthermore, pH can affect coagulant speciation and coagulation performance. For example, Al_{13} (i.e., the tridecameric polymer - $AlO_4Al_{12}(OH)_{24}(H_2O)_{12}^{7+}$) species were responsible for humic acid (HA) removal through charge neutralization under acidic pH conditions, whereas sweep coagulation due to amorphous $Al(OH)_3$ solid formation determined the coagulation efficiency at alkaline pH (Liu et al., 2009). Comparing the effects of pH on coagulation behavior and floc properties when polyferric silicate sulfate (PFSS) and polyferric sulfate (PFS), BaiChuan et al. (2010) observed excellent turbidity and NOM removal from Yellow River water with both coagulants at pH 5.5 SU. Both coagulants reached closer to the isoelectric point when pH ranged from 5.5 to 6 SU. With pH higher than 5.5 SU, turbidity removal was not affected, while UV_{254} removal declined with increasing pH.
- **Turbidity:**
    - Turbidity is another parameter that affects floc characteristics (i.e., floc growth rate and size). Typically, rapid formation of larger flocs is observed when water with high turbidity is coagulated (Jiao et al., 2017). Since ATW typically has turbidity less than 0.1 NTU, blending the ATW with raw water will reduce turbidity in the blended water, which may affect the selection of coagulant type and dose, and turbidity removal during coagulation (Jiao et al., 2015).
- **Alkalinity:**
    - Alkalinity can also be considerably lowered when RBAT-treated non-stabilized ATW is blended with raw water. Alkalinity affects coagulant hydrolysis process, coagulant dose, and can have profound effects on coagulation efficiency (Saxena et al. 2018; Ye et al. 2007). Since higher alkalinity tends to maintain higher pH, it also plays a key role in NOM removal through enhanced coagulation (Ye et al. 2007). When alkalinity is lower than 30 mg/L calcium carbonate, challenges can be observed in removing turbidity (Tseng et al. 2000). pH adjustment with lime and sodium hydroxide addition may allow addressing this issue. In general, increasing alkalinity can extend the zone of coagulation through precipitation charge neutralization (polychlorinated naphthalenes; the

dominant mechanism observed with the alum) and electrostatic patch coagulation (EPC; the dominant mechanism with the polyaluminium chlorides [PACl]), which may result in higher coagulant demand (Ye et al. 2007).

- **Hardness:**
    - Similar to alkalinity, depending on the coagulant used, increasing total hardness may improve overall coagulation efficiency, but the higher total hardness may require longer reaction time due to slower floc aggregation (Wang et al. 2009). While monomer aluminum species effectively removed HA in high-hardness water, the coagulation efficiency of Al_{13} species was the highest with low-total hardness water. However, when Al-based coagulant is used, the competition between the hardness ions (i.e., Ca^{2+} and Mg^{2+}) with Al^{3+} can result in poor organic matter removal, especially in the pH range from 6.5 to 8.5 SU (Zhou et al. 2017).
- **Temperature:**
    - Blending ATW may also change water temperature, which also can affect coagulation. Lower temperature results in slower and smaller floc formation (Fitzpatrick 1998; Morris and Knocke 1984). Given that ATW may have higher temperature than the raw water source, temperature will likely not affect coagulation. However, implementing higher shear during flocculation can lead to floc breakage, which is more pronounced at higher temperatures (Fitzpatrick 1998).

Overall, blending ATW with raw water at an SWTP can change water quality depending on the ATW source, which in turn can positively or negatively affect coagulation and downstream treatment processes. In general, blending RBAT-treated ATW with raw water at an SWTP may adversely affect the existing coagulation process by (1) reducing the alkalinity (if non-stabilized water is used) and necessitating alkalinity adjustments to ensure effective coagulation, and (2) decreasing turbidity and affecting particle removal in coagulation/flocculation/sedimentation steps, potentially lowering the pathogen log reduction credit typically granted to conventional treatment. Conversely, blending a CBAT-treated ATW with a raw water source may not affect coagulation process as the water quality of the two sources can be comparable.

In the pilot study conducted at Gwinnett County, Funk et al. (Funk et al. 2018) realized the benefit of blending ATW with Lake Lanier water during the lake changeover (seasonal challenge). The raw water turbidity was significantly higher than the CBAT-treated water, which resulted in turbidity breakthrough from filter treating only Lake Lanier water (i.e., 0% ATW). Higher polymer doses were required to control filter effluent turbidity. In contrast, filter effluent turbidity was not affected when treating ATW blended water despite the higher filter influent turbidity.

Adelman et al. (2020) conducted a bench-scale study that evaluated the effects of blending ATW produced from a treatment train consisting of ozonation, BAC, UF, RO, and UV/AOP with raw water at Alvarado WTP in San Diego, CA. Unconditioned, lime-treated, lime and soda-treated, and lime-treated and CO_2-conditioned ATW with blending ratios of 25%, 75%, 90%, and 100% ATW were tested. Jar testing was conducted with $FeCl_3$ and PACl and settled water was pushed through 5 µm cartridge filter to assess filterability of the flocs. They reported effective treatment of the blended water. While alkalinity was the limiting factor for treatability, conditioning by the addition of hardness and alkalinity ensured effective coagulation even with the 100% blend. Calcium carbonate indices in the conditioned treated water matched the finished water at the WTP, whereas all blended water had significantly higher chloride-to-sulfate mass ratio (CSMR), indicating greater corrosivity.

3.5.2.3 Effects on Filter Performance

The effectiveness of coagulation dictates performance of downstream unit processes, including filtration. As discussed above, if coagulation fails in generating filterable flocs, poor filtration performance with increased hydraulic challenges can be expected.

Headloss across filters is a function of hydraulic and particle loading rates onto the filters. Filter performance is directly affected by coagulation chemistry and particle separation in upstream coagulation, flocculation, and sedimentation (as applicable) processes in an SWTP. In an SWTP that employs sedimentation, if coagulation fails in generating settleable solids, increased particle loading onto the filters can be expected, which in turn adds hydraulic challenges in the filters. Similarly, in direct filtration plants, if coagulation fails to generate filterable flocs, particle breakthrough will occur.

In general, since an RBAT scheme produces ATW with very low turbidity, blending RBAT-treated ATW with raw water is expected to result similar or lower headloss accrual rates and terminal headloss in filters compared to raw water (i.e., 0% ATW) treatment. Similarly, a CBAT-treated ATW will have lower turbidity and blending CBAT-treated water with the raw water is expected to lower overall particle loading on to the filters, resulting in similar or lower headloss accrual rates. However, given that filter ripening, and performance are dependent on having sufficient particles in the filter influent, blending ratios must be carefully evaluated, particularly when blending ATW with high quality surface waters.

In the pilot study conducted at Gwinnett County, under normal Lake Lanier water conditions, terminal headloss was always higher when treating Lake Lanier water (i.e., 0% blend) than with ATW-blended water (Funk et al., 2018). Headloss accumulation rates remained similar with 0, 15, 25, and 50% ATW blended water. However, headloss accumulation rate was 50% lower (i.e., 0.01 feet per hour) when treating 100 percent ATW, confirming that the lake water was the major contributor of particle loading onto the filters. During the lake turnover period when the lake water turbidity was significantly higher, compared to 0% blend (i.e., 100% lake water), headloss accrual rate was much lower with 50% blend, resulting in a 30- and 10-hour increase in anthracite and GAC filter runtime, respectively.

3.5.2.4 Effects on Turbidity and Chemical Constituents Removal Across a Treatment Plant

Both RBAT and CBAT trains can effectively remove turbidity, typically lowering turbidity to less than 0.05 NTU. Similarly, both RBAT and CBAT provide significant removal of chemical constituents. Therefore, when blending ATW with raw water, turbidity and chemical constituent removal across an SWTP may not be adversely affected. However, the requirements for optimum coagulation in conventional treatment plant operation should be carefully assessed when blending ATW.

Effects on Turbidity Removal

Turbidity in the treated effluent of the DPR pilot system at Gwinnett County declined with the increase in blending ratio. With all blending ratios evaluated, both anthracite and GAC filter effluent turbidity was below 0.11 NTU with 95% of measurements equal to or less than 0.06 NTU. During the lake turnover, despite the increased filter influent turbidity, the filter effluent turbidity was maintained without adjusting the polymer dose when ATW-blended water was treated. In contrast, when treating the lake water (i.e., 0% ATW), the filter effluent turbidity significantly increased, requiring higher polymer doses.

Effects on Organic Constituents Removal

While ATW blending may provide opportunities for some utilities to reduce the TOC concentration upstream of coagulation. Blending with ATW from an RBAT train can significantly contribute to the reduction of the overall TOC of the blended source water. This can affect TOC removal requirements as required for enhanced coagulation. For example, if the source water TOC and alkalinity are >8 mg/L and between 60 to 120 mg/L, respectively, the TOC removal requirement is 40% (Table 3-2, Section 3.4.1.1). However, after blending ATW, if the TOC and alkalinity in the blended water declines to 4 to 8 mg/L and below 60 mg/L, respectively, the TOC removal requirement will rise to 45%. In general, lower finished water TOC will likely lead to lower DBP concentrations. Furthermore, if blending ATW lowers TOC and SUVA to less than 2 mg/L and 2 L/mg-m, respectively, compliance criteria alternative to TOC requirement for enhanced coagulation may be applicable.

In the pilot-scale CBAT treatment evaluated at Gwinnett County, while TOC concentration did not change across the ozone contactors, the anthracite and GAC biofilters removed 12–28% and 17–36% TOC, respectively (Funk et al. 2018). The absolute TOC removal across the biofilters remained similar with all blending ratios evaluated, resulting in lower percentage TOC removal with higher blends as the biofilter influent TOC concentrations were higher. However, the testing with higher blends were likely affected by lower temperature. UVT increased across the ozone contactor and biofilter by 3% and 1%, respectively, suggesting changes in aromaticity and/or size of organic carbon across these unit processes, which was confirmed through fluorescent excitation emission matrix spectra. The CBAT DPR train was not effective in removing PFAO (Funk et al. 2018); PFOA in the chlorinated filter effluent was below detection to 9.1 ng/L when treating 100% ATW. Concentrations of CECs (perfluorobutane sulfonate [PFBS], perfluorohexane sulfonate [PFHxS], perfluoropentanoic acid (PFPA), 1,4-dioxane, sucralose, iohexol), TCEP, 4-nonylphenol, carbon disulfide, des-isopropyl atrazine [DIA]) increased with the blending ratio.

Effects on Other Chemical Constituents Removal

In the DPR pilot study conducted at Gwinnett County, alkalinity in the CBAT-treated ATW ranged from 85 to 139 mg/L, whereas the lake water alkalinity ranged from 16 to 20 mg/L (Funk et al. 2018). Alkalinity and hardness did not change appreciably in the DPR pilot system. The authors anticipated less corrosivity due to the increased alkalinity in the ATW blended water.

Nitrate concentrations did not change across the DPR pilot system since both ATW and lake water had nitrite and ammonia concentrations close to detection limits. The chlorinated filter effluent contained nitrate concentrations greater than the MCL when 100% ATW was treated.

In general, the treated water from the pilot-scale DPR complied with all MCLs and sMCLs with 15% ATW, whereas higher ATW blends resulted in exceedance of one or more MCLs or sMCLs (Funk et al. 2018). Bromate concentrations in the chlorinated pilot filter effluent was greater than 10 µg/L (MCL) with 50 and 100 % ATW. In general, TDS was the limiting factor for blending ATW as higher blending ratios resulted in TDS greater than 500 mg/L in the blended water.

3.5.2.5 Effects of Changes in Water Quality on Disinfection Performance and DBP Formation

When coagulation is implemented for NOM removal, if organics removal is incomplete, it can result in increased disinfectant demand and DBP FP. Inadequate particle removal and residual metal ions in coagulated water can significantly affect UV disinfection. UV disinfection efficiency is directly proportional to UVT, which represents the percentage of UV energy that is available for pathogen inactivation (Shang and Leung 2007). UVT is affected by turbidity, UV lamp intensity, lamp age, and fouling on UV lamp (Lu et al. 2012). Furthermore, metal ions originating from coagulants can absorb UV, reducing the UV disinfection efficiency (Templeton et al. 2005) and the effects are much more pronounced when iron-based coagulant is used (Lu et al. 2012). However, given that RBAT-treated ATW lowers TOC, ATW blending likely lowers coagulant dose requirement, minimizing the potential presence of excess metal species in the UV influent.

RO effectively removes DBP precursors and therefore, in general, RBAT trains provide better removal of halogenated DBPs compared to CBAT trains. It is to be noted that the CBAT trains did not include GAC downstream of the ozone/BAC process, which is required to polish the treated effluent in order to lower TOC and TTHMs to below 2 mg/L and 60 µg/L, respectively (Summers et al. 2020). In a previous study that evaluated formation of 35 regulated and unregulated halogenated DBPs with chloramination under UFC, the MF/RO effluent had 4 to 12-fold lower total concentration of DBPs compared to ozone/BAC effluent (~ 8 µg/L in MF/RO effluent versus ~89 µg/L in ozone/BAC effluent) (Trussell et al. 2016). UV/H_2O_2 and UV/hypochlorous acid (HOCl)-AOP treatment of the ozone/BAC effluent increased the total DBPs under chloramine UFC, resulting in ~100 and ~150 µg/L, respectively, whereas only 10 to 15 µg/L total DBPs was measured in the RO effluent regardless of the oxidant used in the UV-AOP treatment. Given that the CBAT train did not include GAC downstream of the ozone/BAC unit processes, the results should be interpreted carefully.

Total toxicity-weighted DBP concentrations can be significantly higher in ozone/BAC effluent than in MF/RO effluent (Trussell et al. 2016). However, given that GAC contactor, which effectively lowered DBP FP from ozone/BAC effluent (Summers et al. 2020), was not implemented downstream of the ozone/BAC, the results should be carefully interpreted. Inclusion of ozone/BAC upstream of MF/RO can be an effective approach for significantly lowering toxicity weighted DBP concentrations in MF/RO effluent. While UV/H_2O_2-AOP reduces the contributions of nitrosamines and most halogenated DBPs to the total toxicity-weighted DBPs with a preferential removal of brominated DBP species, UV/HOCl-AOP results in increased total toxicity-weighted DBP concentrations due to the formation of chlorinated and brominated

DBPs. An RBAT train with ozone/BAC/MF/RO/UV-H_2O_2-AOP can ensure effective control of nitrosamines and halogenated DBPs (Trussell et al. 2016).

Literature suggests that specific DBP FP range from 25 to 50 µg THMs/mg of TOC (or DOC) and 10 to15 ug HAA5/mg of TOC (or DOC) under uniform formation conditions, which correspond to approximately 1.6-3.2 mg/L TOC target for compliance with the MCL (Gifford et al. 2018). In the study that compared performance of an RBAT (UF, RO, UV/H_2O_2 AOP) with a CBAT (flocculation, sedimentation, ozone, BAF, GAC, UV) treatment train, the simulated distribution system testing showed THMs and HAA5 below their MCLs (i.e., 80 TTHMs µg/L and 60 µg/L HAA5).

Arnold et al. (2018) investigated the impacts of ozone dose and EBCT on DBP FP in ozone/BAF with anthracite and BAC media and evaluated the possibility of using DBP FP as an alternative guideline for TOC removal in potable reuse. DBP FP was evaluated using UFC approach with chlorination. Tested O_3:TOC ratio and EBCT ranged from 0.1 to 2.25 and 2 to 20 minutes, respectively. Ozone effectively transformed TOC with 10 to 30% reduction in DBP FP, whereas the ozone/BAF combination removed TTHM and HAA5 FP by 26% and 51%, respectively (Arnold et al. 2018). A weak positive correlation between DBP FP reduction and O_3:TOC ratio was observed, with considerable variability when the O_3:TOC ratio was lower than 1.0. DBP FP and UV_{254} reductions were well correlated.

Summers et al. (2020) assessed the efficacy of ozone/BAF/GAC in potable reuse for TOC removal and DBP formation control. Four treatment trains consisting of ozone/BAF/GAC, BAF/GAC, GAC, or coagulation/ozone/BAF/GAC were evaluated. TTHM and HAA5 removal targets of 60 and 60 µg/L, respectively, were developed, which corresponded to a TOC target of 2 mg/L. The ozone/BAF combination removed 32% TOC and lowered TTHM HAA5 formation by 31% and 59%, respectively, with 30 min EBCT. While the average TTHM concentration in the ozone/BAF treated effluent was significantly higher (141 µg/L), the GAC (downstream of the BAF) reduced TTHM to of 60 µg/L. The GAC also lowered TOC to below 2 mg/L (Summers et al. 2020).

Previous studies have shown that NDMA removal in RO can range from 11% to 70% (Sedlak and Kavanaugh 2006; Trussell et al. 2016). However, the application of UV/H_2O_2 downstream of RO unit process in the RBAT scheme effectively removes NDMA (Munoz et al. 2020). While ozone treatment can increase NDMA concentration, the implementation of BAC treatment downstream of ozone contactor can effectively remove 61% to 95% of NDMA from the BAC influent (Barazesh et al. 2019; Trussell et al. 2016).

In the DPR pilot study conducted at Gwinnett County, chlorine demand did not correlate with the percent of ATW when treating ATW blended water. With 50% and 100% ATW, bromate concentrations in the DPR pilot filtered effluent exceeded the MCL (i.e., 10 µg/L) (Funk et al. 2018). While bromoform and bromodichloromethane were detected in the chlorinated filter effluent with each blending ratio evaluated, THMs were below the MCL of 80 µg/L. Similarly, HAAs were below 60 µg/L (MCL) despite the detection of dichloroacetic acid at levels higher than its maximum contaminant level goal (MCLG) with all blending scenarios. The biofilters lowered effectively DBP FP. Low concentrations of unregulated DBPs were present across the

DPR treatment train, originating from organic carbon and nitrogen precursors. The chlorination of the filter effluent resulted in significant concentrations of nitrogenous DBPs (e.g., haloquinones), which were not detected in samples from the upstream sampling locations. Variable effects of ATW blending on pilot filter effluent NDMA concentrations were observed. NDMA concentrations in the pilot filter effluent exceeded the California public health goal (i.e., 0.01 µg/L) only with 25% and 50% ATW, while it was below detection with other blending ratios. The variability in filter effluent NDMA concentrations were attributed to the potential variability of NDMA or precursor concentrations in the AWPF effluent.

3.5.2.6 Effects Water Quality on Water Stability and Corrosion - Post-Treatment Requirements

RO-treated water is typically corrosive in nature, requiring post-treatment to prevent corrosion of watermains and household plumbing. Post-treatment approaches typically include pH adjustment and water stabilization. Blending RBAT-treated ATW with raw water can help stabilize the water depending on the blending ratio. Additional approaches for water stabilization include (1) increasing calcium concentration through lime treatment, (2) adding CO_2 along with lime treatment, and (3) adding corrosion inhibitors (Applegate 1944). Sodium hydroxide, sodium carbonate, or lime is typically used for adjusting the pH. Decarbonation can also be practiced for minimizing chemical requirement for the pH adjustment. To characterize the corrosiveness of water, parameters, such as Langelier Saturation Index (LSI) (Langelier 1936), Ryznar Stability Index (RSI) (Ryznar 2019), and Calcium Carbonate Precipitation Potential (CCPP) (Wojtowicz 2001) are typically used. CBAT-treated ATW may not require pH adjustment to the extent required by an RBAT-treated water as the water characteristics are typically similar to raw water sources.

Both RBAT and CBAT trains have been shown to lower microbes to below detection in finished water (Burris 2019; Hooper et al. 2020; Trussell et al. 2016). Microbial regrowth can occur in premise plumbing and distribution systems if biological stability is not fully achieved. In a study that evaluated assimilable organic carbon in ATW from six full-scale AWPF in Japan, Thayanukul et al. (2013) reported 37 µg/L AOC in RO-treated reclaimed water. In another study that evaluated removal and growth of microorganisms in a pilot-scale DPR treatment train consisting of ozonation, chloramination, parallel MF and UF, parallel NF and RO, UV/H_2O_2-AOP, and GAC along with simulated distribution system, Miller et al. (2020) reported reliable rejection of wastewater derived bacterial cells with effective removal of AOC to 60 ± 37 µg/L in the GAC effluent. Given that average AOC concentration in distribution systems of drinking water utilities can be 100 µg/L (Volk and LeChevallier 2000), AOC concentrations in ATW can be within the range observed in a typical drinking water distribution system. Therefore, blending ATW with raw water sources may not enhance microbial regrowth and corrosion in distribution system.

3.6 Considerations for Blending ATW with Finished Water from an SWTP

When introducing a new water source into an existing distribution system, one of the major concerns is the potential disruption of existing scales on pipe surfaces, which can lead to release of undesirable corrosion products and biological components in the distributed water. Additional concerns include disinfectant stability, microbial regrowth and nitrification, and DBP formation. The major water quality parameters dictating pipe corrosion are alkalinity, pH, chloride, and sulfate.

Tang et al. (2006) evaluated the effects of blending groundwater, surface water, and saline water on iron release from aged groundwater distribution pipes (unlined cast iron [UCI], lined ductile iron [LDI], galvanized steel [GS], and polyvinylchloride [PVC]) in a pilot scale study. They reported iron release from pilot distribution systems (PDS) when water with different quality from historical groundwater was introduced. Decreasing alkalinity resulted in significantly increasing iron release from the UCI and GS pipes.

Taylor et al. (2005) observed the lowest iron release with high-alkalinity water. Increasing chlorides, sulfate, sodium, dissolved oxygen (DO), and temperature resulted in higher color and iron release. In contrast, higher alkalinity, sulfate, and temperature resulted in increased copper release. Lower pH and silica concentrations also resulted in higher copper release. Lead release was driven by decreases in pH and increases in alkalinity, with some correlation to decreased sulfate and increased chloride. Calcium, DO, chlorine residual did not correlate to copper or lead release (Taylor et al. 2005).

If RBAT-treated ATW is blended with filtered water from an SWTP without stabilization, it has the potential to aggravate corrosion, even though it may not add challenges regarding disinfection demand and stability, microbial regrowth, and DBP formation. In contrast, blending CBAT-treated ATW downstream of filtration has the potential to result in increased microbial regrowth, unstable disinfection residuals, increased DBPs, and lower aesthetic quality (Salveson et al. 2018). However, CBAT treated ATW is less likely to present the corrosion challenges associated with RBAT-treated ATW when blended with filtered water.

Garner et al. (2019) evaluated the impact of blending various water sources downstream of a conventional treatment on biostability and regrowth potential. Four potable utility waters, including groundwater, surface water, RBAT-treated ATW, and ozone/BAF-treated ATW (i.e., not a complete CBAT treatment train), were used in the blending evaluations. Most conditions exhibited regrowth of bacteria; however, the traditional potable water often stimulated the most regrowth, suggesting that blending ATW may produce more biologically stable water. Opportunistic pathogen marker genes qnrA, vanA, and intI1 were not significantly greater in RBAT-treated water or biofilm compared to potable water (Garner et al. 2019). The authors concluded that blending ATW does not necessarily enhance the growth of total bacteria, opportunistic pathogens, or ARGs in premise plumbing.

Salveson et al. (2018) quantified water quality changes in simulated premise plumbing systems when RBAT-treated ATW or ozone/BAC effluent samples from four utilities were blended with surface water and groundwater sources with or without stabilization. Both pre- and post-conventional treatment blending scenarios were evaluated. While ammonia concentrations did not change significantly in the pipe rigs, indicating absence of nitrification, higher ammonia concentrations were observed with chlorine compared to chloramine. Similarly, no changes in pH, alkalinity, chloride, conductivity, or sulfate concentrations were observed with or without the stabilizing of the ATW. With chloramination, effective disinfection was achieved with limited (<10 pg adenosine triphosphates [ATP]/mL) or no increase in biological activity and DBP concentrations did not change (Salveson et al. 2018). The use of RBAT-treated ATW (without stabilization) resulted in metal leaching. The simulated rig testing showed lower HPCs with ATW blended waters compared to surface water or groundwater sources. Similar levels of biological corrosion (facilitated by sulfate reducing and sulfate producing bacteria) were observed with ATW blended water compared to surface water or groundwater sources (Salveson et al. 2018). All tested scenarios were highly effective in controlling regrowth of ARGs containing bacteria.

Overall, while literature suggests that blending stabilized RBAT-treated ATW with filtered water may not exacerbate biological regrowth, disinfection residual, or metal corrosion in premise plumbing, the potential effects should be carefully evaluated for each facility.

3.7 Optimization Approaches and Considerations

Blending ATW with raw water at an SWTP can result in changes in water quality, requiring optimization of various operating parameters to minimize the potential impacts. Some of the potential optimization approaches are discussed below.

3.7.1 Optimizing Blending Ratio

Optimizing the blending ratio is one approach for minimizing potential impacts of blending the two water sources. In general, blending ATW from an RBAT system is expected to improve water quality, especially when ATW is pre-stabilized (i.e., pH and alkalinity adjusted). The availability of ATW may be the factor limiting the maximum blending ratio. Conversely, blending ratio can be dictated by the concentrations of various water quality parameters when considering CBAT-treated ATW. For example, in the pilot study conducted at Gwinnet County, the maximum possible ATW blending ratio was 15%, which allowed meeting all primary and secondary MCLs when treated in the pilot scale SWTP (Hooper et al. 2020).

3.7.2 Optimization of Unit Processes

The effects of water quality changes due to blending ATW with raw water can be minimized by optimizing unit processes at an SWTP. Some of the potential unit process optimization approaches are discussed hereunder.

3.7.2.1 Coagulation

RBAT-treated ATW is expected to improve turbidity and TOC in the blended water, whereas ATW from a CBAT system may result similar TOC concentrations in the blended water. Depending on raw water and ATW characteristics, blending the ATW can make the blended water unamenable to enhanced coagulation or enhanced softening. However, depending on the TOC concentration and alkalinity and SUVA levels in the blended water, alternative compliance criteria can still be applied (USEPA 1999). The alternative compliance criteria include: (1) source water or treated water TOC is <2 mg/L, (2) source water or treated water SUVA equal or less than 2 L/mg-m, (3) raw water TOC < 4 mg/L with alkalinity > 60 mg/L calcium carbonate ($CaCO_3$), and TTHM and HAA5 less than 40 and 30 µg/L, respectively, and (4) TTHM and HAA5 concentrations <40 and <30 µg/L with chlorine as the disinfectant.

As discussed in previous sections, optimizing coagulation chemistry can effectively address challenges associated with water quality changes due to blending ATW with raw water source. Optimizing coagulation will allow improving or maintaining process performance in the downstream unit processes. Selection of type and dose of coagulant, use of cationic polymer in combination with primary coagulant, pH and alkalinity adjustment for enhanced coagulation are some of the approaches for optimizing coagulation process.

Zeta titration can be used as the primary tool for understanding and optimizing coagulation process (Hart 2020). However, zeta titration may not work equally for every water (e.g., water with high organics) as zeta potential changes rapidly after coagulant addition. In such situations, zeta evaluation after rapid mixing for 30 seconds can be an effective approach for assessing zeta potential (Hart 2020). Target zeta potential can be lower with ferric-based coagulants or when pre-oxidation is applied compared to aluminum-based coagulants. However, previous studies have shown reduced attachment of metal hydroxides absorbed NOM on filter media when aluminum or iron-based coagulants are used (Becker et al. 2004).

Balancing charge with TOC removal is the primary goal of coagulation process optimization. If TOC removal is the primary goal, pH depressing coagulants (i.e., metal-based coagulants) can be used. Furthermore, compared to ferric-based coagulants, alum has pH and alkalinity limitations. When charge neutralization and turbidity removal is the primary goal, significant cost savings through less chemical use and sludge minimization can be achieved by using a cationic polymer along with the primary coagulant (Hart 2021). When using a cationic polymer with the primary coagulant, the sequence and time between the chemical addition are important parameters (Hart 2021); greater benefits are achieved when the primary coagulant is added first with a time gap of minimum 30 seconds between the chemical addition (Hart 2021). In previous works, the maximum benefits were observed when a 3-minute time separation was applied between coagulant and polymer addition. pH neutral coagulants, such as aluminum chlorohydrate (ACH) and PACl allow TOC removal without depressing pH.

3.7.2.2 Filtration

ATW from an RBAT system is essentially particle free and expected to add negligible challenges to filtration when blending with raw water sources. Previous studies have also demonstrated that a complete CBAT train with GAC downstream of ozone/BAC essentially maintains very low turbidity and particle load in the treated water (Barazesh et al. 2019). Therefore, blending ATW from a CBAT system also is not expected to add any challenges to filtration.

Filtration optimization is driven by particle removal. Two major approaches for filtration optimization are (1) optimizing the coagulation process for filterable flocs and (2) employing pre-oxidation. As discussed in previous sections, type, dose, and combination of coagulants and polymer can affect particle and turbidity removal in a media filter by generating filterable flocs.

When pre-oxidation is practiced, the oxidant can alter particle size and NOM characteristics, affecting particle removal across the filter. Often, compared to no pre-oxidation, lower particle counts are observed in filtered water when a pre-oxidant is used (Becker et al. 2004). Pre-oxidation results in reduction in adsorption density and thickness of hydrodynamic layer of NOM on particle surfaces, and thus lowers particle stability. The improved particle removal with the use of a pre-oxidant was not translated to improved treatment performance in the study conducted by Becker et al. (2004), primarily because turbidity was less than 0.1 NTU in all experiments. However, recent experience has shown improved turbidity removal when pre-chlorination was practiced targeting barely measurable residual concentration in filter influent (Hart 2021). While pre-oxidation may lead to modest increases in headloss accrual rate across the filters (Becker et al. 2004), coagulation optimization through zeta potential evaluation can effectively alleviate headloss issues, resulting in significantly improved filter run and UFRV (Hart 2021). This also minimizes overall water volume required for backwashing due to the requirement of less frequent backwashing.

In contrast to media filtration, turbidity and particle removal in membrane filtration can be independent of coagulation performance. However, filter influent with higher particle and organic loads can affect flux, requiring more frequent cleaning due to membrane fouling.

In general, unless the conventional raw water is unusually clean, the particle concentrations within the blended water will be dominated by those of the conventional raw water and are thus expected to decrease with increasing blending ratios. This means that increasing blend ratios are also expected - in general - to decrease headloss, increase filter run times, and reduce cleaning frequency for membrane filters.

3.7.2.3 Disinfection

Blending ATW from an RBAT system lowers organics concentrations in the blended water, which is expected to lower disinfection demand, improve disinfection stability, and reduce regulated DBP formation. However, there is potential for additional DBPs, such as NDMA to be partially removed even in RBAT systems. Therefore, blending ratios need to be carefully optimized to minimize DBP presence in the blended water. When ATW from a CBAT system is used, TOC concentrations in the blended water can be similar or lower to that in the source water. Therefore, disinfection requirements and DBP formation will likely remain similar to that without the blending.

Optimization of the disinfection process focuses on minimizing disinfectant demand and DBP formation and ensuring disinfectant stability. Disinfectant demand, stability, and DBP formation can be effectively controlled by lowering organic carbon concentrations in filtered water. As discussed earlier, TOC concentrations in filtered water can be controlled by optimizing coagulation process. Furthermore, if an SWTP includes ozone/BAF in the treatment train, optimizing biofiltration can further enhance organics removal across the treatment plant and address challenges associated with disinfection requirements and DBP formation.

3.7.2.4 Post Disinfection

When blending upstream of an SWTP, the potential water quality changes and associated challenges can be effectively addressed by optimizing unit processes in the SWTP. If ATW from an RBAT-system is considered for blending with filtered water from an SWTP, corrosion and metal leaching can be the major challenges. While blending with filtered water will partially address the issues related lower pH and alkalinity, additional treatment including pH adjustment, water stabilization, and corrosion control measures may be required (Salveson et al. 2018). In contrast, disinfectant requirement and stability, microbial regrowth, and DBP formation can be the challenges when blending a CBAT-treated ATW downstream of filtration at an SWTP. Given these challenges, it may be beneficial to blend CBAT-treated ATW with raw water sources.

In summary, the impacts of blending ATW with raw water source can be minimized by optimizing unit processes (primarily the coagulation process).

3.8 Treatment Performance Monitoring

Regular monitoring is critical for effectively assessing process performance, and timely detecting and addressing any performance concerns. In general, key monitoring parameters typically monitored at an SWTP (Table 3-4) will remain the same when blending ATW, but sampling frequency may need to be increased to ensure robust monitoring. Many of the key parameters listed in Table 3-4 are typically monitored and recorded using supervisory control and data acquisition (SCADA) system.

Table 3-4. Key Monitoring Parameters.

Key Monitoring Parameters	
Operating Parameters	
Plant flow/unit process influent flow	Hydraulic loading rate
Hydraulic retention time/contact time	Chemical feed doses/chemical levels
Headloss/pressure drop (filters/membranes)	Backwash pressure (packed-bed filters)
Filter runtime	Unit filter run volume (calculated parameter)
Water Quality Parameters	
Temperature	pH
Alkalinity	Turbidity
Total hardness	TOC/DOC
UV_{254}	Contaminants/degradation products
Residual disinfectant	DBP precursors
DBPs	Bromide/bromate
AOC (occasional)	BDOC (occasional)
Microbial Parameters	
Heterotrophic pate counts	Total coliform
Escherichia coli	ATP (during biofilter acclimation or system recovery)
Extracellular polymeric substances (when hydraulic issues are observed in biofilter)	Microbial community characterization (for baseline characterization and assessing deviation from baseline when performance issues are experienced)
Abbreviations: BDOC – Biodegradable organic carbon.	

Given that blending ratio can affect water quality, which in turn can affect unit process performance at an SWTP, continuous monitoring of blending ratio may need to be included in the monitoring plan, especially if in-line blending is practiced. Characterizing microbes present in media filter after implementing ATW blending and comparing that with the baseline microbial community will help understand the changes in microbial community due to exposure to ATW. Recent studies have used quantitative real-time polymerase chain reaction (qPCR) along with whole metagenome sequencing (WMS) to compare microbial communities before and after a certain event. For example, Brumfield et al. (2021) used these techniques to supplement traditional culture techniques with *E. Coli* and *Enterococci* to compare temporal shifts in microbial communities before and after rainfall. While highly informative, these tools are expensive, time consuming, and require expertise for sample collection, processing, analysis, and data interpretation.

3.9 Pathogen Log Reduction Credit Validation

Direct quantification of microbial species of health concern in water sources is often challenged by the density of the specific species (Antony et al. 2012) and, in some cases, by the limitation of analytical methods, requiring collection of enormous water volumes (Antony et al. 2014). To minimize the volume of water sample to be collected and analyzed, methods have been developed to concentrate target organisms for analysis (Kunze et al. 2015). For the verification of pathogen log removal or methods for concentrating target organisms, several indicator and surrogate parameters that can be monitored more frequently and cost effectively are typically used. The surrogate indicator organisms are generally harmless and their presence in the source water is correlated with the organism of health concern. For example, E. coli and MS2 bacteriophage are frequently used as indicator for bacterial pathogens and viruses, respectively. Furthermore, it has also been established that bacteria are less resistant to disinfection compared to viruses and protozoa and the inactivation of viruses and protozoa would ensure inactivation of bacteria also (Trussell et al. 2013). The removal of the surrogate organism in a treatment system is typically lower than the target organism, providing a conservative assessment of log removal across the system (Pipe-Martin 2010).

The F-specific ribonucleic acid (RNA) bacteriophage MS2 (diameter 0.024 µm) is often used as the surrogate virus for waterborne viruses due to the following characteristics: (1) its morphological and structural characteristics resemble that of enteric viruses, (2) it is easy to seed and quantify, (2) it is commonly found in wastewater effluent and its survival characteristics match that of enteric viruses in aquatic environments, (3) its presence is directly correlated with the presence of enteric viruses, and (4) chemical and UV disinfection kinetics for MS2 are known (Steinle-Darling et al. 2016). Other surrogate viruses often used for pathogen log reduction evaluation include, F-specific RNA bacteriophages Qβ (diameter 0.025 µm) (Antony et al. 2014; Shirasaki et al. 2010) and PRD1 (Antony et al. 2014), GA (diameter 0.026 µm) (Antony et al. 2012; Hébrant et al. 2014), and SP (Antony et al. 2012).

Pathogen log reduction validation with the use of indicator organism follows the general protocol given below:

- Record the feed water characteristics and operating conditions (e.g., influent flow rate, filter loading rate, characteristics of media used in the filter, etc.).
- Seed the indicator organism to the system influent in high concentrations for a long enough period to reach steady state conditions.
- Collect grab samples of influent and effluent. Often, tracer studies are conducted to determine the optimal sample collection time point after seed injection (Nieminski and Ongerth 1995).
- Determine the concentrations of the indicator organism in the influent and effluent. Often, a double layer agar method is used for determining the concentration of the indicator organism, for example MS2 (Antony et al., 2014).
- Calculate LRV using the relation given below:

  - LRV = log10 ($C_{influent}/C_{effluent}$)
- Repeat the steps and use the lowest LRV obtained as the conservative LRV that can be achieved with the treatment process.

While both batch and continuous seeding approaches have been used, the batch seeding requires a tank (or reservoir) large enough to supply feed for the entire testing duration. A chemical feed pump is used to seed indicator organism in continuous seeding through in-line injection port upstream of the treatment process. Proper introduction and mixing of the seed organism in the influent flow is critical. A static mixer or enough pipe length will be required between the injection port and the treatment process to ensure proper mixing and suspension of the indicator organism in the feed water.

Before testing log reduction of a surrogate organism in the field, it is recommended to evaluate potential inhibition of the indicator organism in the water matrix that will be evaluated. In previous studies, when MS2 bacteriophage 'die off' was observed in non-stabilized water samples from an RBAT treatment train (personal communication).

Previous studies have also indicated limitations of microbial challenge testing approach and bacteriophage enumeration technique. These limitations include (1) time consuming and time sensitive nature of the approach, (2) difficulty in differentiating physical-chemical retention and inadvertent biological inactivation, which may lead to overestimation of LRV, (3) requirement of expertise in sample collection and handling to minimize inactivation after sample collection (Antony et al. 2014). Accordingly, non-microbial indicators have also been evaluated for estimating pathogen log removal across a treatment process (Antony et al. 2014).

Previous studies have also demonstrated the possibility of utilizing particle count as a surrogate for assessing pathogen log reduction in treatment processes (McTigue et al. 1998; Nieminski and Ongerth 1995). However, given the differing correlations observed in these studies between particle count and pathogen log reduction, the possibility of using this parameter as a surrogate indicator should be evaluated for each case.

3.10 Summary

The effects of blending ATW with raw water at an SWTP can be site-specific, requiring careful evaluation for each case. While ATW from an RBAT train is expected to lower TOC and turbidity in the blended water, it can also result corrosive blended water if the ATW is not stabilized before blending. In contrast, turbidity in the blended water will decline when ATW from a CBAT train is blended, whereas TOC concentration in the blended water will depend on TOC concentrations of the raw water and the CBAT treated ATW.

Blending ATW with raw water has the potential to change water quality. However, the negative effects can be minimized by optimizing the coagulation process through zeta potential evaluation. Coagulation process optimization will also help improve filterability of flocs formed during the coagulation and flocculation stages. Under optimized coagulation/flocculation conditions, TOC and turbidity removal across the coagulation, flocculation, sedimentation, and filtration processes can be optimized to maintain filter effluent water quality similar to that before blending (i.e., when treating raw water only). This will ensure disinfection requirements and DBP formation similar to that when only raw water is being treated.

RBAT-treated ATW can also be blended directly with the filtered water at an SWTP, especially when the ATW is stabilized. However, it may be more practical to blend a CBAT-treated ATW to raw water source upstream of the SWTP as blending the ATW with the filtered water has the potential to enhance microbial regrowth and affect disinfectant residual can corrosion in premise plumbing and distribution systems.

Previous studies have demonstrated low microbial presence in the ATW from both RBAT and CBAT trains compared to raw water sources. Therefore, blending the ATW with the raw water or filtered water is not expected to increase microbial density in the blended water. However, given that a CBAT-treated ATW can contain relatively higher organic carbon, blending CBAT-treated water with the filtered water has the potential to enhance microbial growth in the premise plumbing.

Pathogen log reduction across the treatment unit processes at an SWTP after blending ATW with raw water should be carefully evaluated for each case using indicator microorganisms, such as MS2 or PMMoV.

CHAPTER 4

Impact on SWTP Operation and Water Treatment Performance

The impact of blending ATW with raw water upstream of an SWTP was evaluated through extensive bench-scale and pilot-scale testing. Bench-scale testing were conducted with raw water and ATW collected from six utilities across the country, whereas pilot testing were conducted at Plant A, Plant C, and Plant D. This Chapter presents the results of the testing and summarizes the findings.

4.1 Bench Testing Results

The bench-scale testing focused on understanding the effects of ATW blending on coagulation effectiveness and floc settleability. While jar tests were conducted with all water samples received from the participating plants, qualitative evaluation of filterability of the flocs generated was also performed with the water samples received from Plants D and E. The effects of ozone pretreatment was evaluated with the water samples received from Plant D.

4.1.1 Plant A – Bench-Scale Testing Results

The ATW received from Plant A was from an RBAT train. Grab samples (approximately 1 L) of ATW and raw water were collected to determine the water quality. Table 4-1 presents baseline water characteristics (i.e., without any treatment) for the blends tested. As expected, turbidity, TOC, and alkalinity in the RBAT-treated ATW were significantly lower than in the raw water. TOC concentrations and SUVA[1] were greater than 2 mg/L and 2 L/mg-m, respectively, in the raw water and all blends. The relative stability of SUVA with increasing blend percentages should be noted, suggestive that TOC reduction through enhanced coagulation may remain consistent across the blend ratios.

Table 4-1 Plant A Bench-Scale Testing – Baseline Water Quality Characteristics (Before Treatment).

Parameter	Blending Ratio				
	0% (Raw Water)	10%	25%	40%	100% (ATW)
Temperature (°C)	13.1	16.8	14.4	12.7	17.1
pH (SU)	7.8	7.8	7.8	7.9	7.6
Turbidity (NTU)	2.3	2.3	2.3	1.7	0.1
Conductivity (µS/cm)	564	531	518	449	105
UV_{254} (cm^{-1})	0.140	0.112	0.095	0.079	0.004
Zeta potential	-15.8	-12.5	-11.9	-12.6	-2.3
TOC (mg/L)$^{(1)}$	4.70	4.26	3.60	2.94	0.30
DOC (mg/L)$^{(1)}$	4.6	4.17	3.53	2.88	0.30
Alkalinity (mg/L - $CaCO_3$)$^{(1)}$	120	111	99	86	34
Ca (mg/L)$^{(1)}$	33	30	25	20	ND (<1.0)
Mg (mg/L)$^{(1)}$	19	17	14	11	ND (<0.1)

---

[1] Waters with higher SUVA are more amenable to TOC removal with enhanced coagulation.

Parameter	Blending Ratio				
	0% (Raw Water)	10%	25%	40%	100% (ATW)
Ca + Mg Hardness (mg/L $CaCO_3$)	160	17	14	11	ND
SUVA (L/mg-m)	3.0	2.7	2.7	2.8	1.2
TDS (mg/L)(2)	361	332	288	244	67

Notes:

1. TOC, DOC, alkalinity, calcium, and magnesium concentrations for blending ratios 10%, 25%, and 40% were calculated based on the raw water and ATW concentrations.
2. Calculated using empirical relation TDS (mg/L) = 0.64 * Conductivity (microSiemens per centimeter [µS/cm]).

Figure 4-1 shows zeta titration results with alum and Clarifloc C-308P. While 60 mg/L alum achieved near-zero zeta potential in the raw water, in general, blending ATW slightly lowered the alum dose requirement for achieving similar zeta potential. Regarding the polymer, approximately 1.7 mg/L Clarifloc C-308P was required to achieve near-zero zeta potential in the raw water, with no discernable pattern based upon blend percentage.

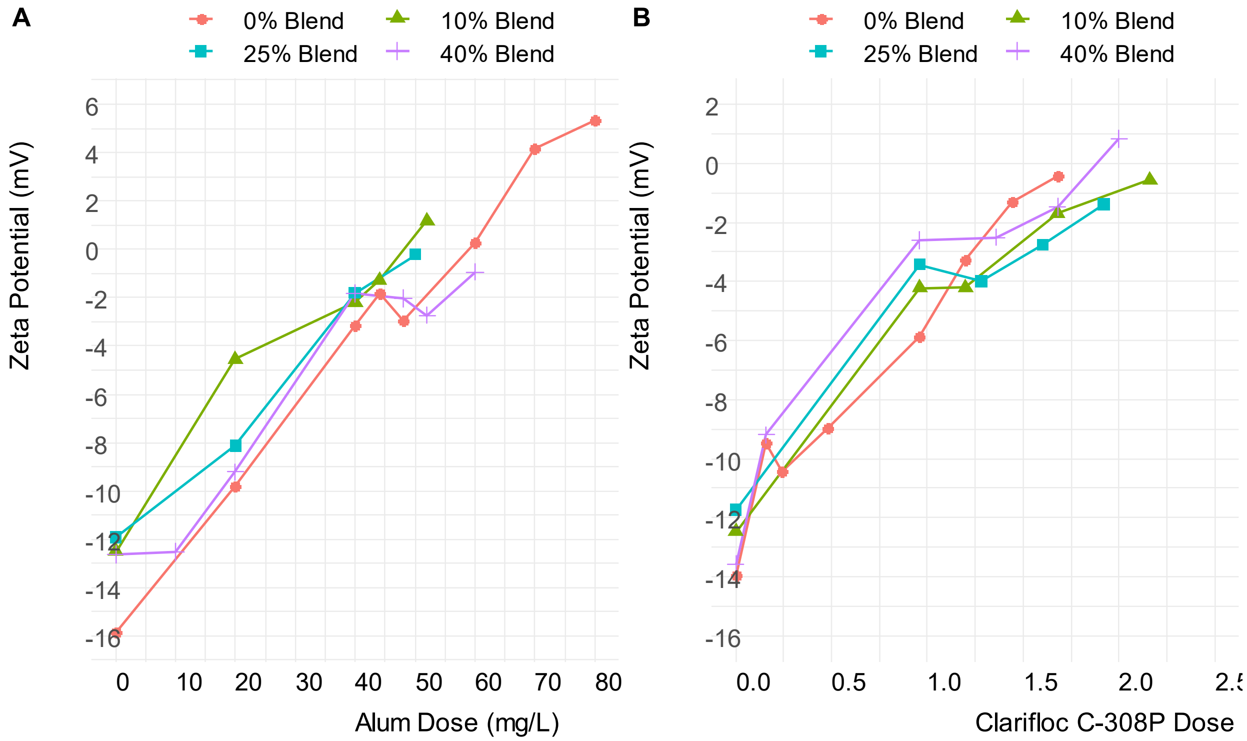


Figure 4-1. Plant A Bench-Scale Testing – Zeta Potential with Alum (A) and Clarifloc C-308P (B).

Based on the zeta titration results, zeta potential was evaluated in the blends with simultaneous use of the coagulant and cationic polymer. Various combinations of the coagulant and cationic polymer doses were evaluated. Figure 4-2 presents the results of the testing. The combination of 35 mg/L alum and 0.7 mg/L polymer achieved near-zero zeta potential in the raw water (i.e., 0% blend), whereas the chemical doses required for achieving near-zero zeta potential declined with the blending ratio.

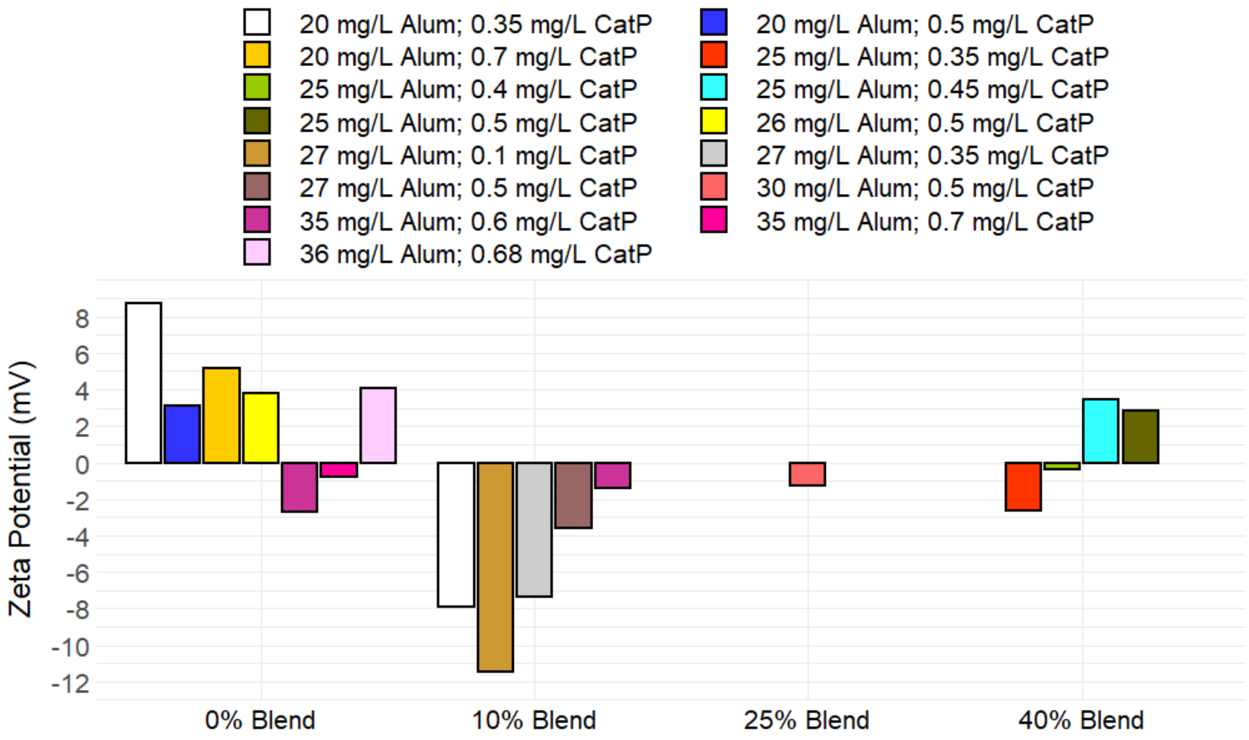


Figure 4-2. Plant A Bench-Scale Testing – Zeta Potential with both Coagulant (Alum) and Cationic Polymer (Clarifloc C-308P).

Jar tests were conducted with 20 mg/L alum and 0.35 mg/L cationic polymer to evaluate TOC removal. Given that Plant A uses non-ionic polymer (Clarifloc N-120P) at the last stage of flocculation, 0.25 mg/L non-ionic polymer was also added at the beginning of the 4th stage flocculation. Additional jar testing was conducted with 10% blended water using 35 mg/L alum and 0.6 mg/L cationic polymer with and without the non-ionic polymer. Figure 4-3 shows TOC removal achieved after 45 minutes of settling. It was noted that settling was incomplete at the time of sampling.

In the absence of the coagulant or cationic polymer (i.e., in the control jars), TOC removal was less than 6% (data not shown). Under similar chemical dose conditions of 20 mg/L alum and 0.35 mg/L cationic polymer, TOC removal was 19%, 21%, 33%, and 31% for blends of 0% blend, 10% blend, 25% blend, and 40% blend, respectively (Figure 4-3). With the 10% blend, increasing the doses to 35 mg/L alum and 0.6 mg/L polymer increased the TOC removal slightly (increased from 21% to 23%) compared to the test with 20 mg/L alum and 0.35 mg/L polymer. The addition of non-ionic polymer (i.e., Clarifloc N-120P) decreased the TOC removal in all blends. An explanation for the adverse effect of non-ionic polymer on TOC removal was not identified. It should be noted that the non-ionic polymer dose (0.25 mg/L), which matched the dose applied at the full-scale plant on the day of raw water sample collection, was considerably higher than the historical average (0.04 mg/L), likely reflecting the difference in source water quality.”

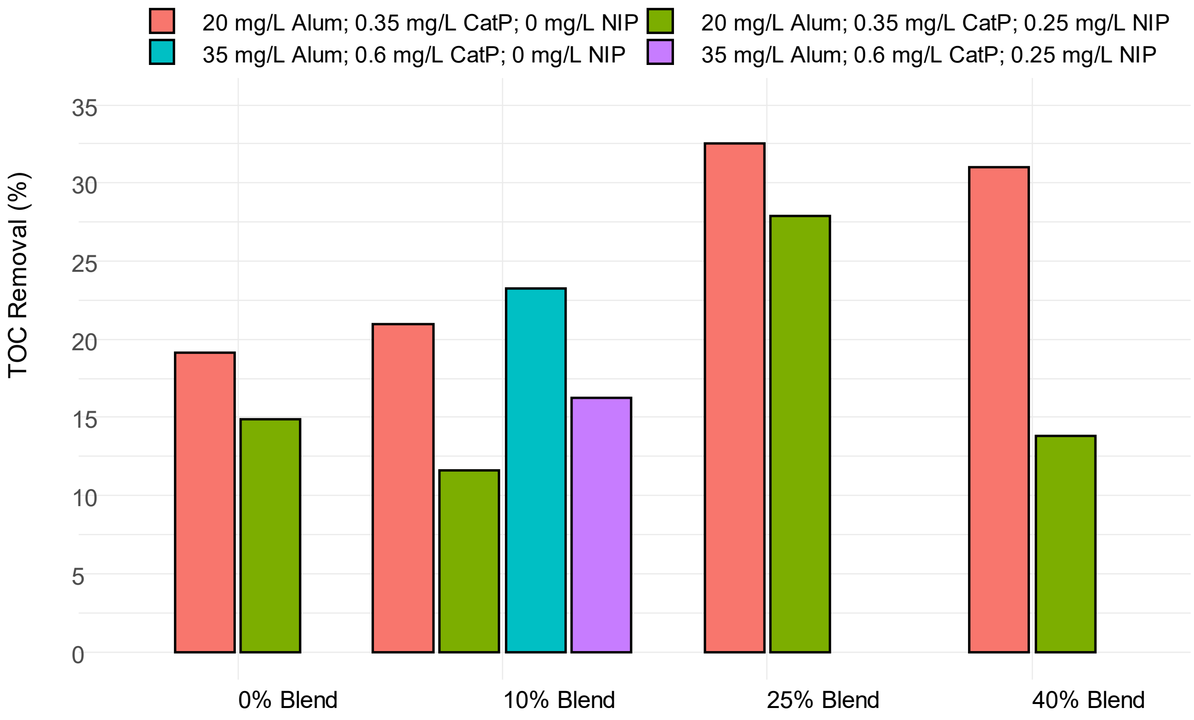


Figure 4-3 Plant A Bench-Scale Testing – TOC Removal after 45-minute Settling.
Average of two sets of testing are presented for 0%, 25%, and 40% blends.

Figures 4-4 through 4-7 present turbidity at different times during settling with the 0% blend, 10% blend, 25% blend, and 40% blend, respectively. Figure 4-8 presents turbidity removal observed with the 0% blend, 10% blend, 25% blend, and 40% blend. The turbidity removal was normalized to turbidity measurements after 1 minute since the beginning of the settling process. The settled water quality characteristics are presented in Table 4-1.

The following observations can be made based on Figures 4-4 through 4-8:

- Under similar chemical dose conditions of 20 mg/L alum and 0.35 mg/L cationic polymer, turbidity removal (with reference to turbidity after 1 minute settling) was 86%, 48%, 75%, and 58% for the 0% blend, 10% blend, 25% blend, and 40% blend, respectively (Figure 4-8). However, in general, the lower turbidity removal observed with the higher blend ratios was due to the lower starting turbidity (i.e., after a 1-minute setting).
- With the 10% blend, increasing the doses to 35 mg/L alum and 0.6 mg/L polymer resulted in 85% turbidity removal.
- The blending ratio did not appear to affect the final settled turbidity. Except in the 10% blend, turbidity removal in the jars that used non-ionic polymer were similar to that in the jars that did not use non-ionic polymer (Figure 4-5).
- Though filterability was not evaluated during the testing, turbidity (and TOC) will be further reduced during filtration.

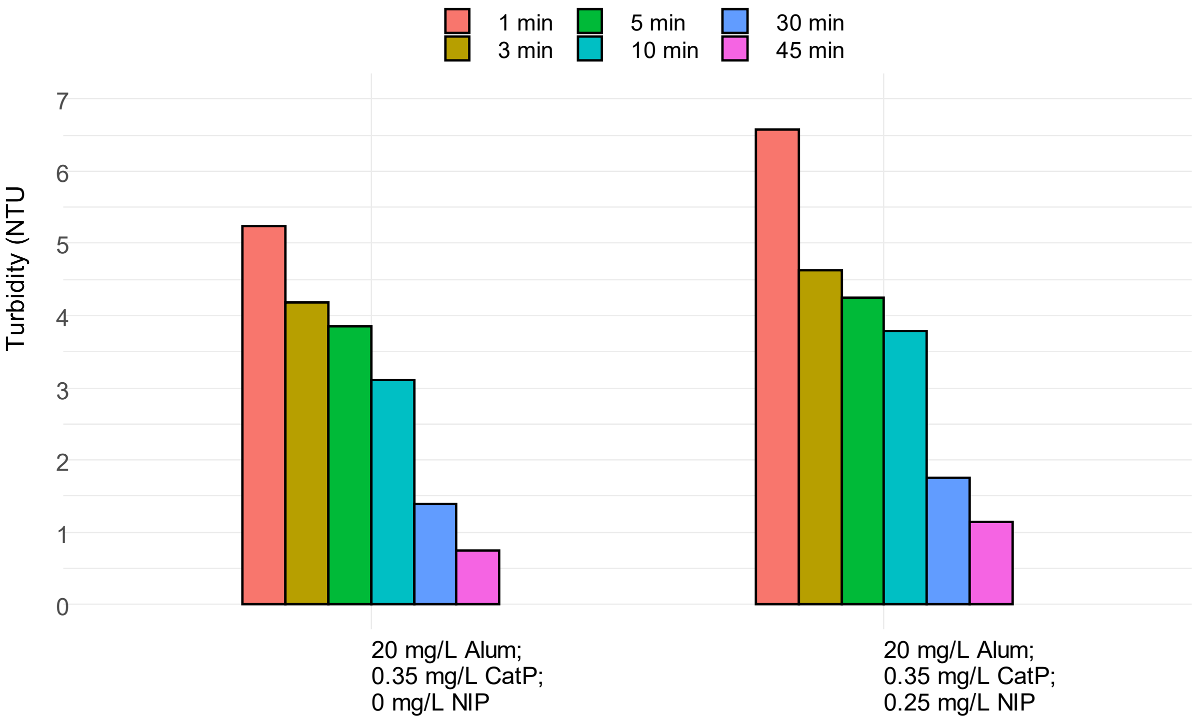


Figure 4-4 Plant A Bench-Scale Testing – Turbidity in Coagulated/Flocculated 0% Blend Water at Various Time Points during Setting.

The bars represent average turbidity in two jars.

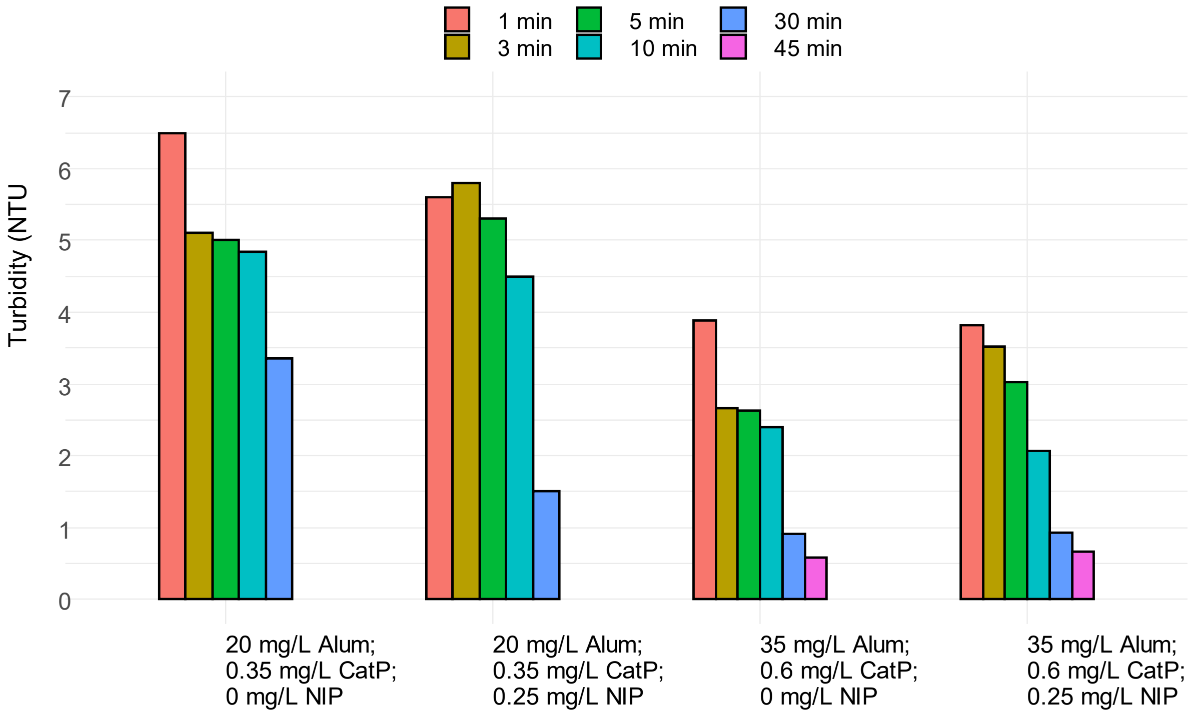


Figure 4-5. Plant A Bench-Scale Testing – Turbidity in Coagulated/Flocculated 10% Blend. Water at Various Time Points during Setting.

The bars represent average turbidity in two jars.

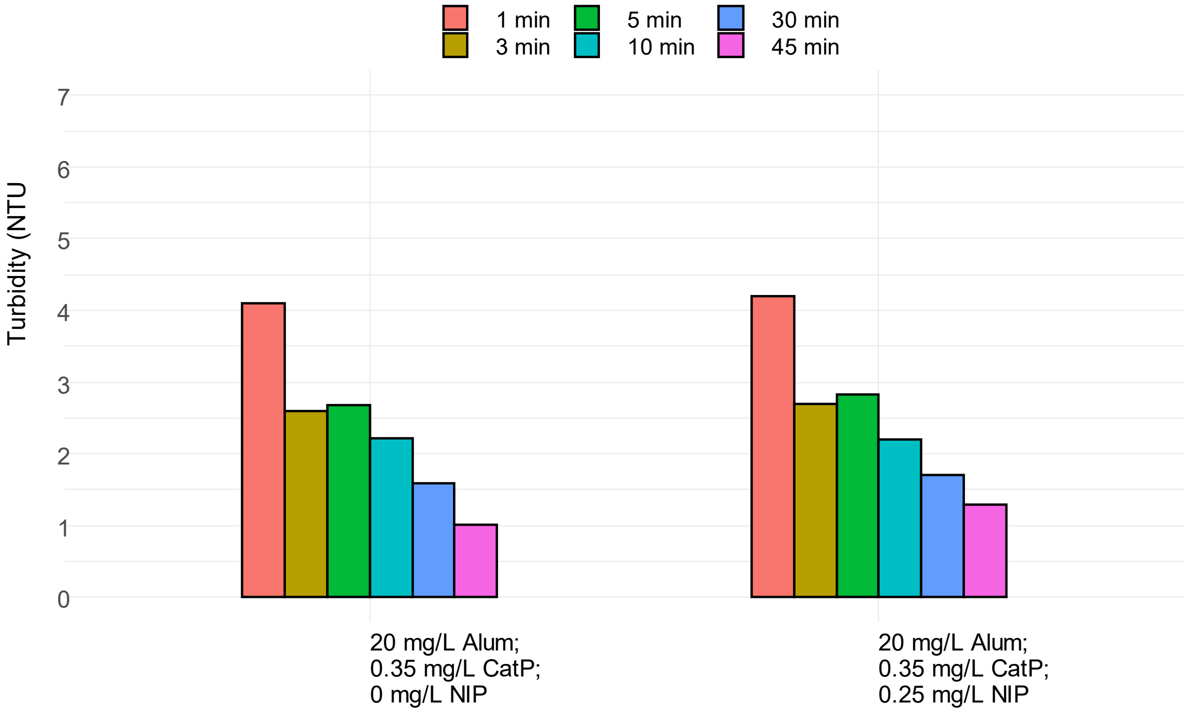


Figure 4-6. Plant A Bench-Scale Testing – Turbidity in Coagulated/Flocculated 25% Blend Water at Various Time Points during Setting.

The bars represent average turbidity in two jars.

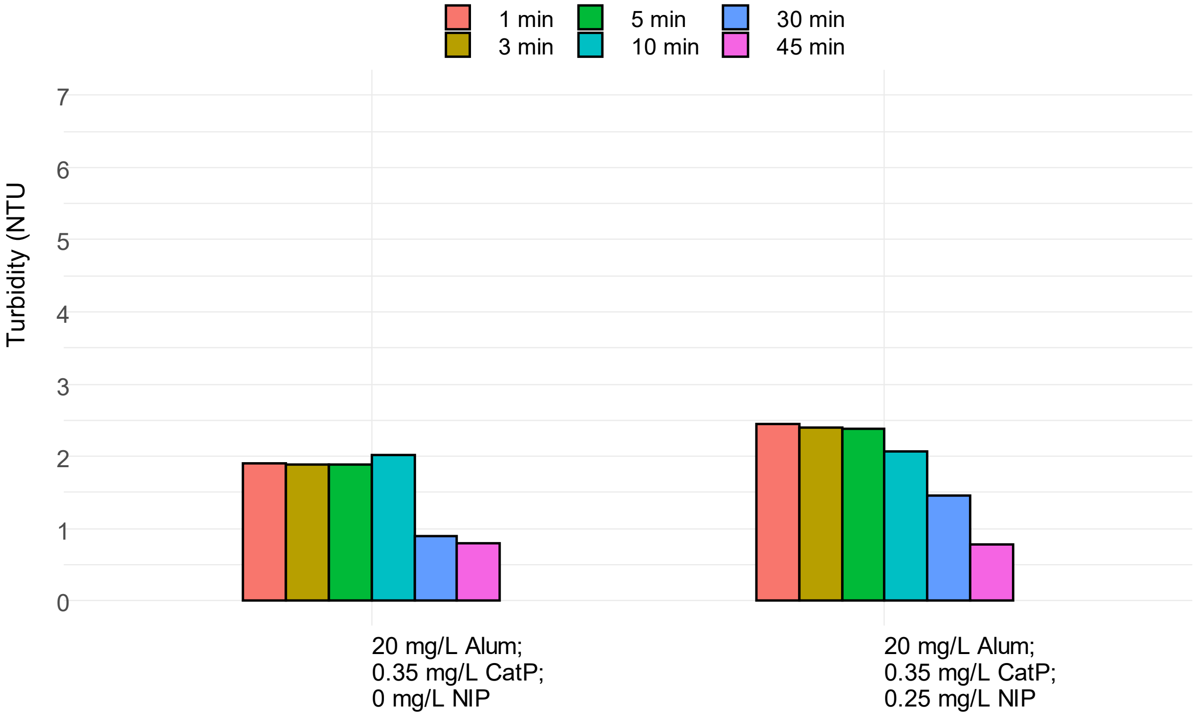


Figure 4-7. Plant A Bench-Scale Testing – Turbidity in Coagulated/Flocculated 40% Blend Water at Various Time Points during Setting.

The bars represent average turbidity in two jars.

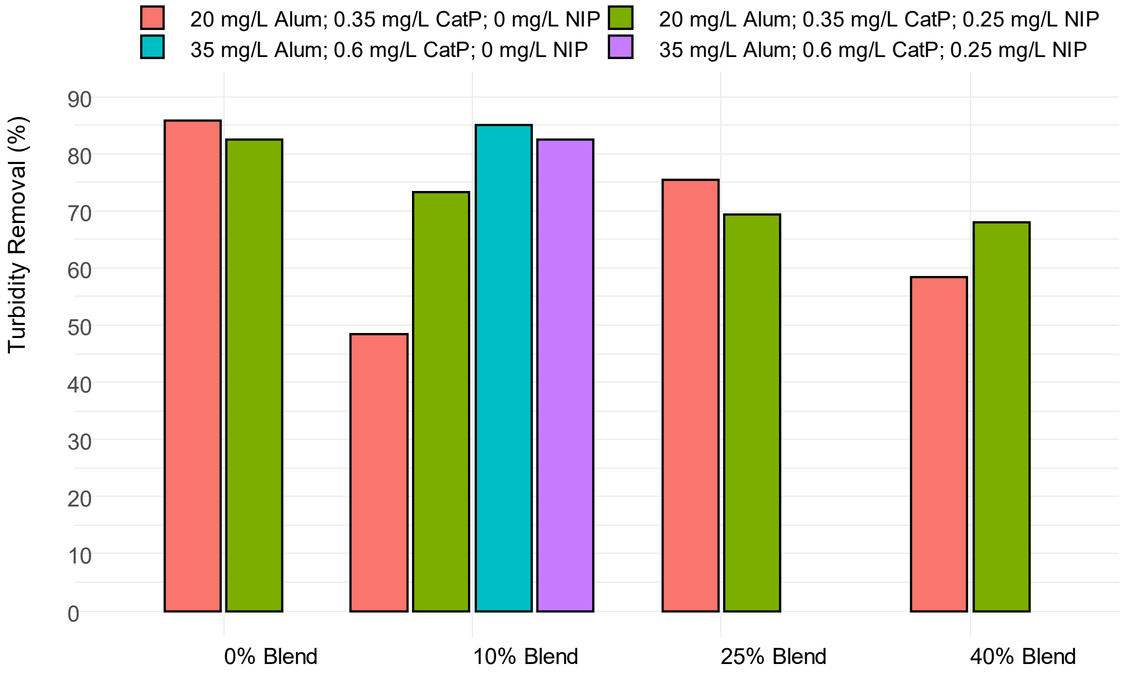


Figure 4-8. Plant A Bench-Scale Testing - Turbidity Removal.

The bars represent average turbidity in two jars. Turbidity removal was calculated using the turbidity after 1 minute settling as the initial turbidity.

4.1.1.1 Summary of Plant A – Bench-Scale Testing Findings

The following conclusions can be made based on the results:

- In general, a slightly lower alum dose was required for achieving near-zero zeta potential as the blending ratio increased.
- While significantly lower cationic polymer is required compared to alum for achieving near-zero zeta potential, the blending ratio does not affect cationic polymer dose requirements.
- As expected, using alum and cationic polymer together for coagulation significantly lowers alum dose requirement for charge neutralization. The blending ratio did not appear to affect the doses for effective coagulation when alum and cationic polymer were used together.
- TOC reduction, in general, remained similar in all the blends, except the 40% blend, suggesting that blending ATW did not affect TOC removal. It is recognized that overall TOC removal across the treatment plant will be increased through filtration (which will be evaluated during the pilot testing). Different coagulant and polymer doses can be considered for the pilot testing to increase TOC removal.
- While turbidity removal appeared to decline with the increase in blending ratio, the decline was an artifact of lower initial turbidity (i.e., after 3-min settling). In general, blending ratios did not appear to affect settled water turbidity and similar turbidities were measured after 45-minute settling.
- The use of 0.25 mg/L non-ionic polymer decreased TOC removal at the doses used in these tests. Settled water turbidity was also higher in the jars with non-ionic polymer.

4.1.2 Plant C – Bench-Scale Testing Results

The ATW received from Plant C was from a CBAT system. The bench-scale testing conducted with the ATW and raw water samples from Plant C included zeta titration and jar testing. While zeta titration was conducted with 0%, 5%, 15%, 25%, and 50% ATW blends, jar tests did not include the 0% blend. Table 4-2 presents baseline characteristics of the raw water and ATW received from Plant C. Blending the ATW reduced TOC concentration in the blended water (i.e., the CBAT treated water reduced the TOC in the blended water). The CBAT-treated ATW had an order of magnitude lower turbidity than in the raw water. However, conductivity, alkalinity, and TDS were significantly higher in the ATW compared to the raw water.

Table 4-2. Plant C Bench-Scale Testing – Baseline Water Quality Characteristics.

Parameter	Blend					
	0% (Raw Water)	5%	15%	25%	50%	100% (ATW)
Temperature (°C)	14.3	--(3)	--	--	--	18.1
pH (SU)	7.4	--	--	--	--	7.8
Zeta potential	-11.2	-12.3	-10.0	-9.2	-7.6	-5.9
Turbidity (NTU)	1.1	--	--	--	--	0.1
Alkalinity (mg/L - $CaCO_3$)(1)	89	92	98	104	118	147
Hardness (mg/L - $CaCO_3$)(1)	130	130	131	132	134	138
Conductivity (µS/cm)(1)	368	404	476	548	728	1088
TDS (mg/L)(2)	235	258	304	350	466	696
TOC (mg/L)	2.86	3.0	2.8	2.7	2.5	2.10
DOC (mg/L)	2.86	3.0	2.8	2.6	2.6	--
UV_{254} (cm^{-1})	0.052	0.051	0.048	0.046	0.043	--
SUVA (L/mg-m)	1.82	1.69	1.72	1.74	1.69	N/A

Notes:

1. Conductivity, alkalinity, and hardness values for 5%, 15%, 25%, and 50% blends were calculated based on the 0% and 100% blends.
2. Calculated using empirical relation TDS (mg/L) = 0.64 * Conductivity (µS/Cm).
3. Empty cells represent parameters not measured; N/A- not applicable.

Zeta titrations were conducted with the coagulant (i.e., $FeCl_3$) and cationic polymer (i.e., Clarifloc C-308P) used at Plant C. Figure 4-9 presents the zeta titration results from the tested blends. While the coagulant dose required to achieve near-zero zeta potential in the ATW (i.e., 100% blend) was distinctly higher than that required for the 0% blend (i.e., raw water), the results with the ATW might have been affected by the significantly lower turbidity. The coagulant doses required for charge neutralization in the 5%, 15%, 25%, and 50% blends were similar (Figure 4-9), suggesting minimal impact (increase or decrease) in coagulant dose for most blending applications. Compared to the coagulant, zeta potential was very sensitive to the cationic polymer dose and blends of any type require more coagulant than the zero-blend scenario. However, no apparent relation was observed between the polymer dose required for charge neutralization and blending ratio.

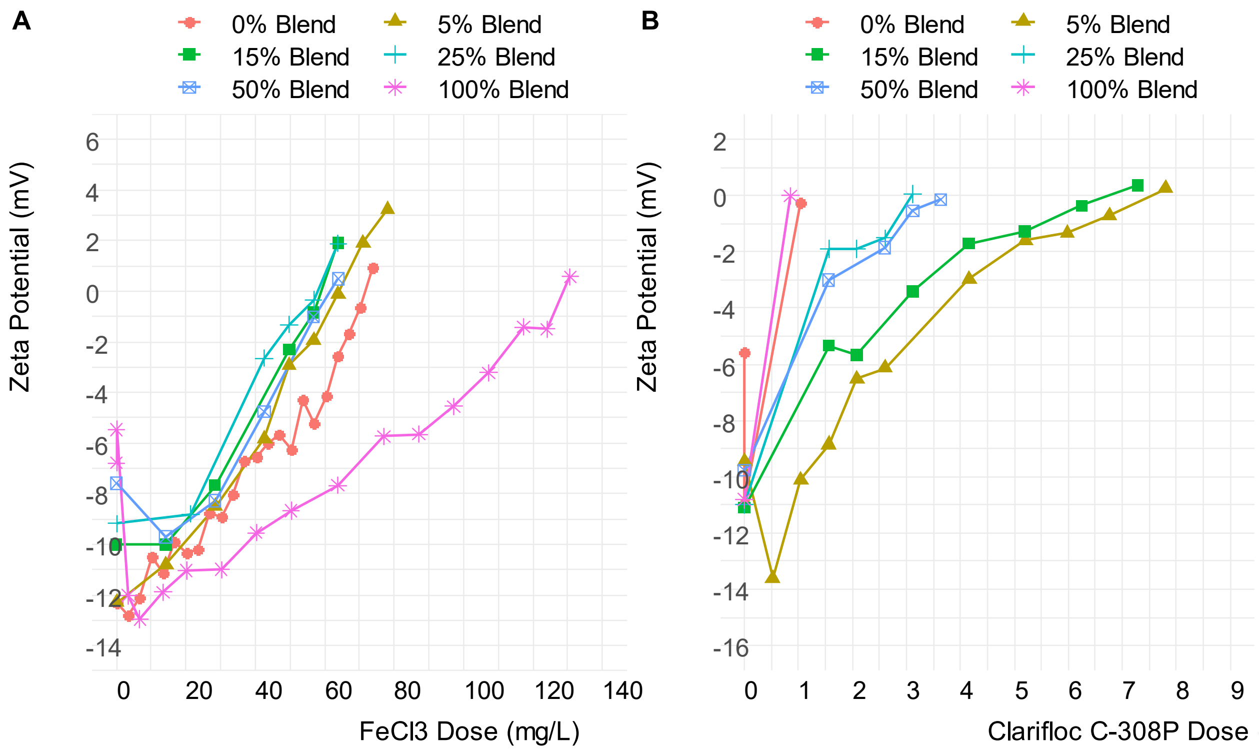


Figure 4-9. Plant C Bench-Scale Testing – Zeta Titration Results with $FeCl_3$ (A) and Clarifloc C-308P.

Jar tests were conducted with the 5%, 15%, 25%, and 50% blends. Six jars were run for each blend with the following coagulant and polymer doses:

- Jar 1 – 17 mg/L $FeCl_3$ + 1.7 mg/L polymer.
- Jar 2 – 19 mg/L $FeCl_3$ + 1.9 mg/L polymer.
- Jar 3 – 21 mg/L $FeCl_3$ + 2.1 mg/L polymer.
- Jar 4 – 23 mg/L $FeCl_3$ + 2.3 mg/L polymer.
- Jar 5 – 25 mg/L $FeCl_3$ + 2.5 mg/L polymer.
- Jar 6 – 28 mg/L $FeCl_3$ + 2.8 mg/L polymer.

Figures 4-10 and 4-11 present settled water TOC and percentage TOC removal in the jars, respectively, after 20-minutes settling. The following observations can be made based on Figures 4-10 and 4-11:

- The blending ratio did not affect settled water TOC concentration in the blends.
- Settled water TOC concentration in each blend declined with increasing coagulant and polymer dose.
- The effects of the blending ratio on TOC removal were not apparent; while TOC removal slightly increased when the blending ratio increased from 5% to 15%, the removal was lower in the 25% and 50% blends (Figure 4-11).
- The lower TOC removal observed with the higher blends could be due to the lower TOC concentrations in the untreated water.

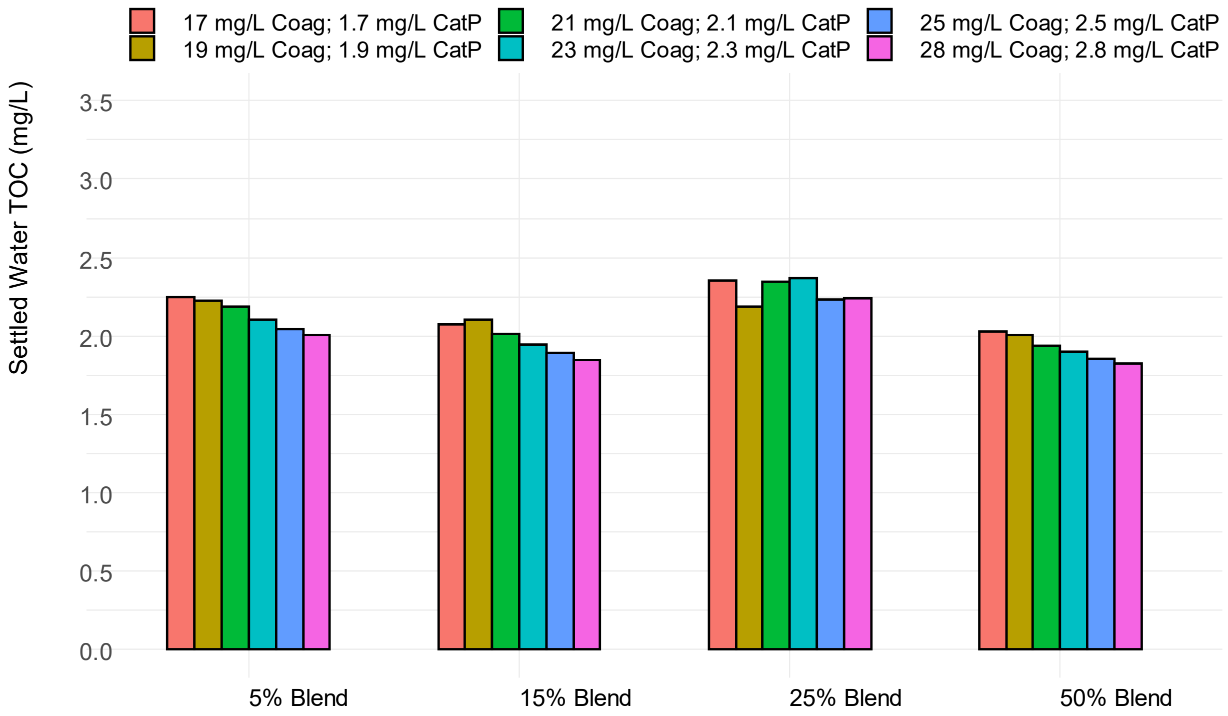


Figure 4-10. **Plant C Bench-Scale Testing – Settled Water TOC Concentrations after 20-minute Settling.**

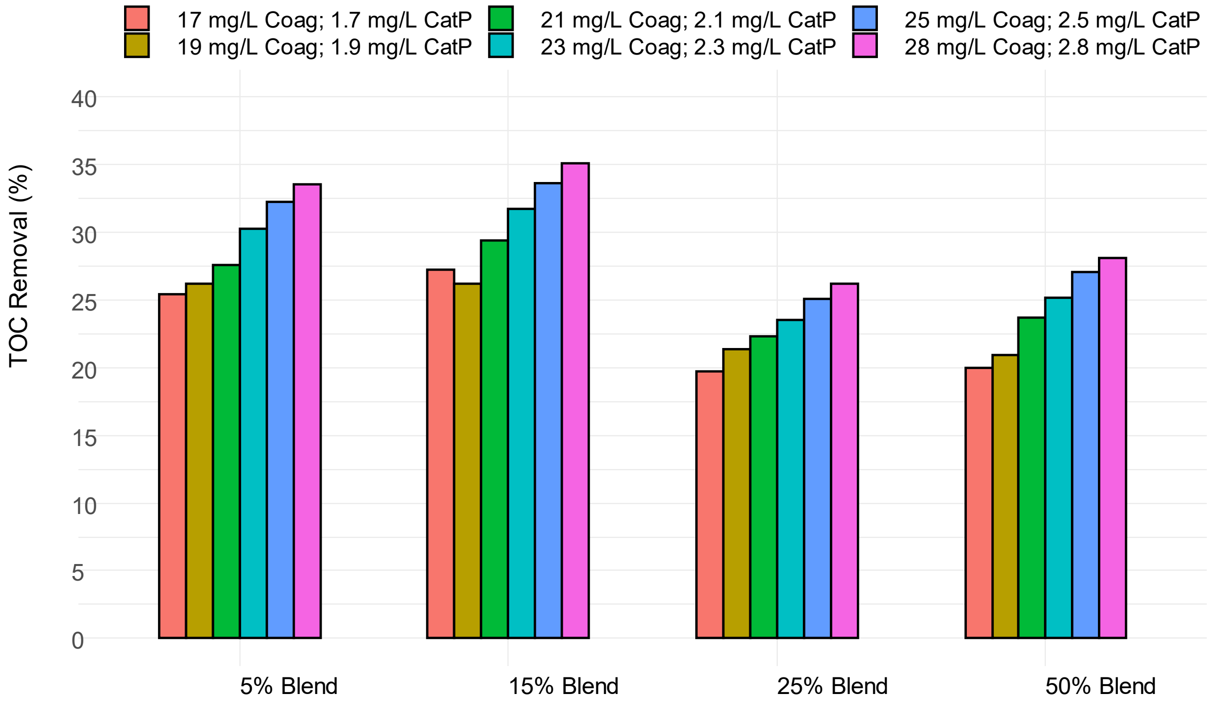


Figure 4-11. Plant C Bench-Scale Testing – TOC Removal after 20-minute Settling.

Figure 4-12 presents settled water turbidity and turbidity removal (calculated based on turbidity after 1 min settling) in the jars. Turbidity in the settled water was less than 1 NTU with all chemical doses and ATW blends tested except the 15% blend with 25 mg/L $FeCl_3$ and 2.5 mg/L cationic polymer. While a quantitative conclusion on turbidity impact cannot be made, the data does suggest lower settled water turbidity for higher blend ratios (Figure 4-13).

However, this result is believed to be due to the much lower turbidity in the CBAT water compared to the raw water. Settled water characteristics are presented in Table C-2 of Appendix C.

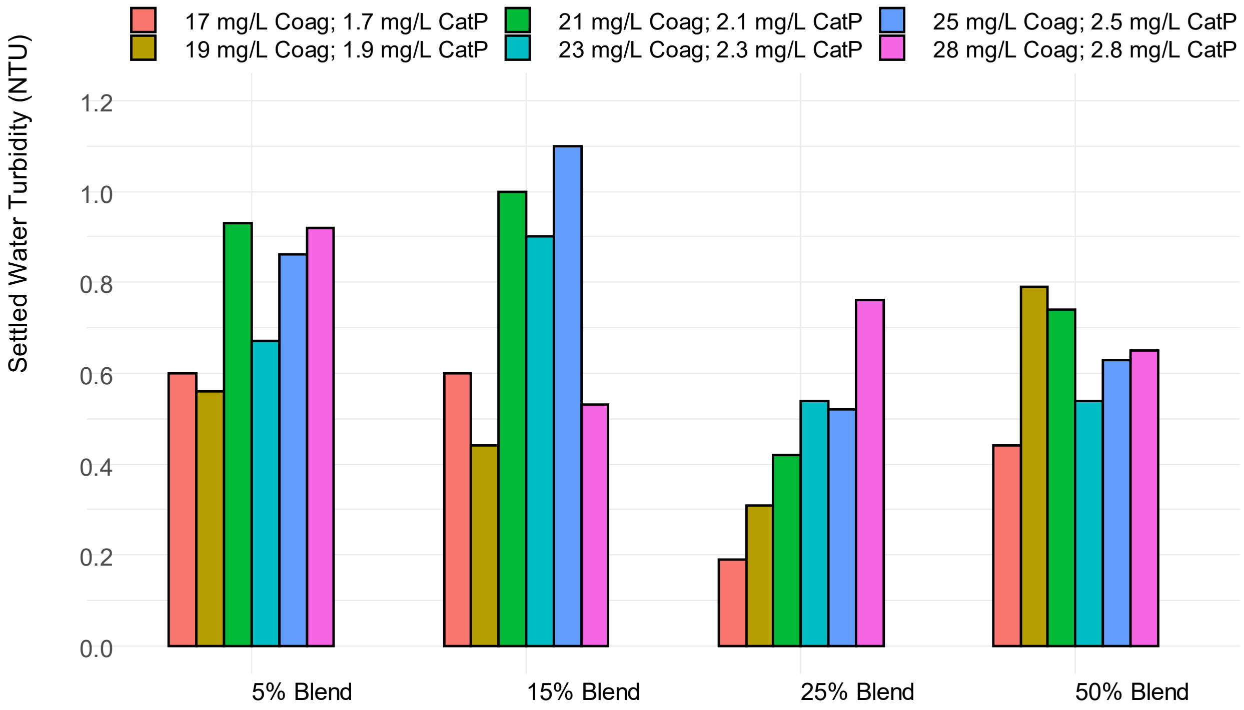


Figure 4-12. Plant C Bench-Scale Testing – Settled Water Turbidity after 20-minute Settling.

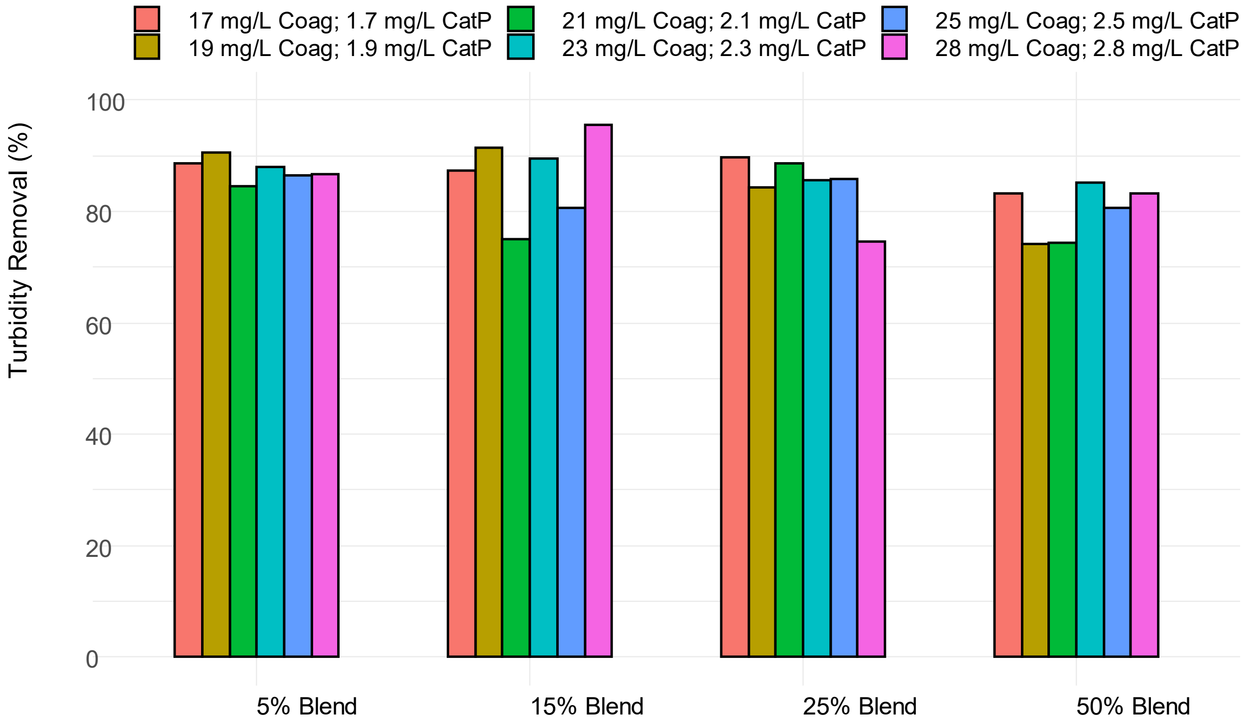


Figure 4-13. Plant C Bench-Scale Testing – Turbidity Removal after 20-minute Settling.

4.1.2.1 Summary of Plant C – Bench-Scale Testing Findings

- Increasing the ATW blending ratio reduced turbidity and TOC concentrations prior to treatment.
- As expected, increasing the chemical doses resulted in improved TOC removal.
- In general, settled water TOC was similar for all testing scenarios and the effects of ATW blending on TOC removal were not apparent. While TOC removal was higher in the 15% blend than the 5% blend, lower TOC removal was observed with the 25% and 50% blends, likely due to lower initial TOC concentrations.
- Turbidity removal or settled water turbidity was not affected by blending ATW.

4.1.3 Plant D – Bench-Scale Testing Results

The ATW received from Plant D was from an RBAT system. The existing SWTP uses approximately 0.25 mg/L ozone (historical average) to aid flocculation. Depending on the plant flow rate, the time gap between the ozone contactors and the coagulation location ranges from 3 to 14 minutes, and, typically, ozone is completely consumed upstream of the coagulation unit process. At the bench scale, ozone decay was evaluated with 0.25, 0.5, and 0.75 mg/L ozone doses, using a 3-minute or 10-contact time.

Zeta titration was not performed with the water samples received from this plant. Three jar tests were performed in series with 0.25, 0.5, and 0.75 mg/L O_3 dose added to 0%, 10%, 20%, 30%, and 40% blended water. After ozone addition, coagulant (1.5 mg/L $FeCl_3$) and cationic polymer (1.7 mg/L Clarifloc C-318) were added. Ozone was completely consumed before the coagulant addition.

Table 4-3 presents the baseline characteristics of each blend. As expected, the RBAT-treated ATW had very low turbidity, TOC, DOC, and alkalinity compared to the raw water. For example, TOC in the raw water was 2 mg/L compared to the ATW with 0.2 mg/L TOC.

Table 4-3. Plant D Bench-Scale Testing – Baseline Water Quality Characteristics.

Parameters	Blend					
	0% (Raw Water)	10%	20%	30%	40%	100% (ATW)
Temperature (°C)	23.3	--	---	--	--	24.1
pH (SU)	8.42	8.41	8.43	8.25	8.05	7.75
Zeta potential	-18.9	-19.98	-9.48	-20.12	-20.25	-11.8
Turbidity (NTU)	4.93	4.89	4.25	3.67	3.16	0.554
Alkalinity (mg/L - $CaCO_3$)	121	112	104	95	86	34
Calcium (mg/L)	32.0	32.8	33.6	34.4	35.2	40.0
Magnesium (mg/L)	8.5	7.8	7.2	6.5	5.8	1.9
Ca + Mg Hardness (mg/L $CaCO_3$)	115	114	113	113	112	108
Conductivity (µS/cm)	441	462	491	505	524	644
TDS (mg/L)(1)	282	296	314	323	335	412
TOC (mg/L)	2.0	1.8	1.6	1.4	1.3	0.2

Parameters	Blend					
	0% (Raw Water)	**10%**	**20%**	**30%**	**40%**	**100% (ATW)**
DOC (mg/L)	1.8	1.7	1.5	1.4	1.2	0.2
UV_{254} (cm^{-1})	0.043	0.039	0.030	0.026	0.023	0.004
SUVA (L/mg-m)	2.3	2.3	2.0	1.9	1.9	2.5

Notes:

1. Calculated using empirical relation TDS (mg/L) = 0.64 * Conductivity (µS/Cm).
2. Conductivity, alkalinity, calcium, magnesium, and hardness concentrations for 10%, 20%, 30%, and 40% blends were calculated based on the 0% and 100% blends.

Figure 4-14 shows residual ozone in the jars with 3 minutes and 10 minutes contact times. Results show that higher blending ratios result in greater ozone residual, indicating lower ozone demand with the increase in ATW blending ratio. Results are repeatable for both 3-minute and 10-minute contact times with longer contact time resulting in less residual as expected.

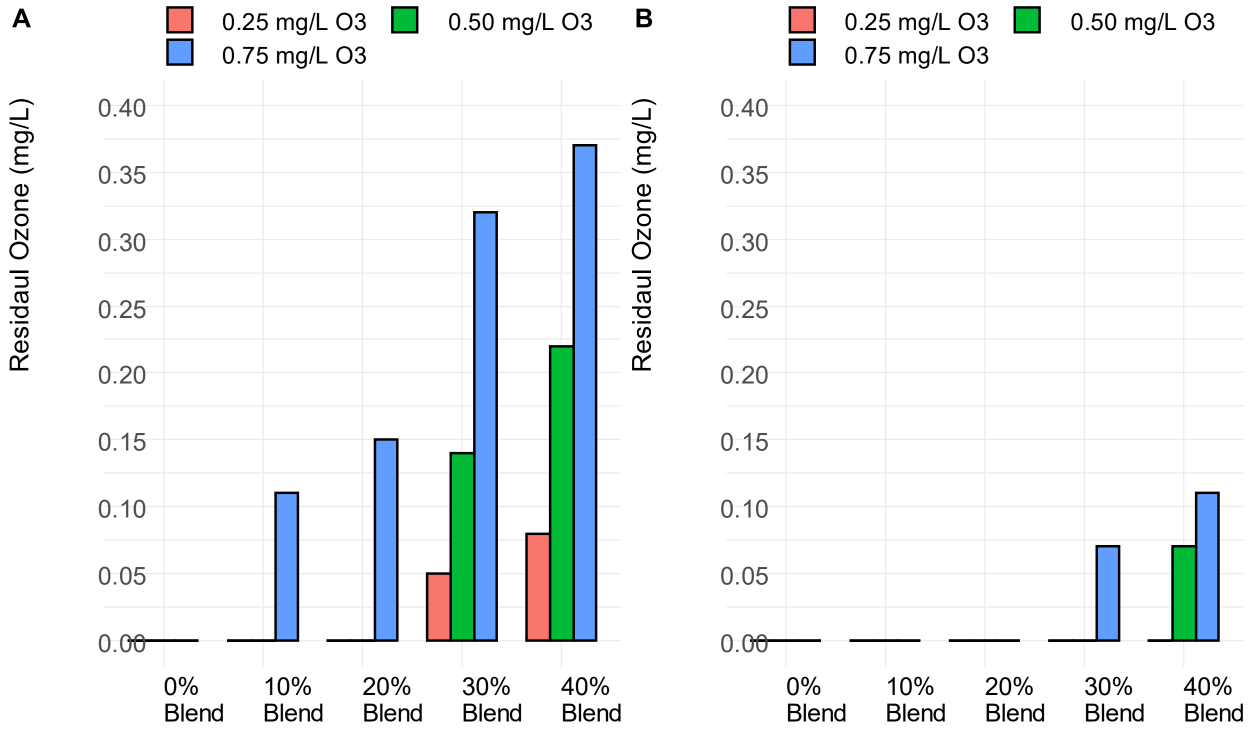


Figure 4-14. Plant D Bench-Scale Testing – Residual Ozone in the Jar with 3-minute (A) and 10-minute (B) Contact Time.

With each blend, jar tests were performed after ozone treatment with 0.25, 0.5, and 0.75 mg/L ozone doses. Residual ozone was below detection in all jars (data not shown) before adding coagulant (1.5 mg/L $FeCl_3$) and cationic polymer (1.7 mg/L Clarifloc C-318). Figure 4-15 presents settled water TOC and turbidity concentrations after 45 minutes of settling. Settled water TOC concentrations declined with increasing blending ratio but were not apparently affected by ozone dose. In general, settled water turbidity declined with an increase in blending ratio. Settled water turbidity was consistently higher in the 0.75 mg/L ozone-treated blends for no apparent reason.

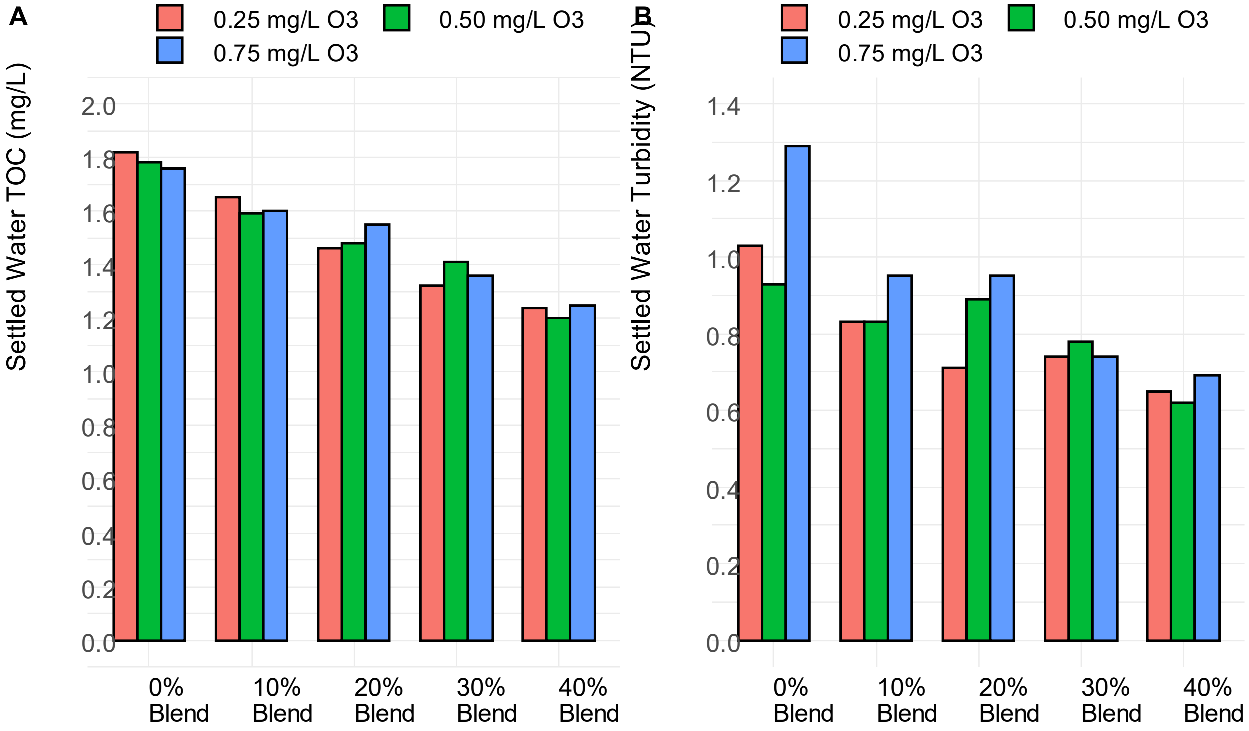


Figure 4-15. Plant D Bench-Scale Testing –
Settled Water TOC (A) and Settled Water Turbidity (B) after 45-Minute Settling.
All jars were spiked with 1.5 mg/L $FeCl_3$ and 1.7 mg/L Clarifloc C-318 for coagulation.

Figure 4-16 presents TOC and turbidity removal after 45-minute settling. In general, TOC removal declined with the increase in blending ratio (Figure 4-16 [A]), likely due to lower initial TOC concentrations (i.e., before chemical addition) in the 30% (1.4 mg/L) and 40% (1.2 mg/L) blends. With the lower initial TOC and lower TOC removal (less than 10%), it was difficult to discern any trends. It is to be noted that Plant D practices direct filtration and TOC removal is not the primary goal for this plant. Even if TOC removal was to be considered, alternate compliance criteria would be applicable for the blends evaluated due to the lower initial TOC concentrations (i.e., <2 mg/L TOC) in the blended water. In the 0% and 10% blends, TOC removal appeared to improve with increasing ozone dose. However, the trend was not apparent in the 30% and 40% blends.

The blending ratio did not affect turbidity removal (Figure 4-16 [B]). The turbidity after 1-minute settling was used as the initial turbidity for the calculations. Ozone concentration did not affect turbidity removal except in the 10% blend, in which removal declined with increasing ozone concentration. Settled water characteristics are presented in Table C-3 of Appendix C.

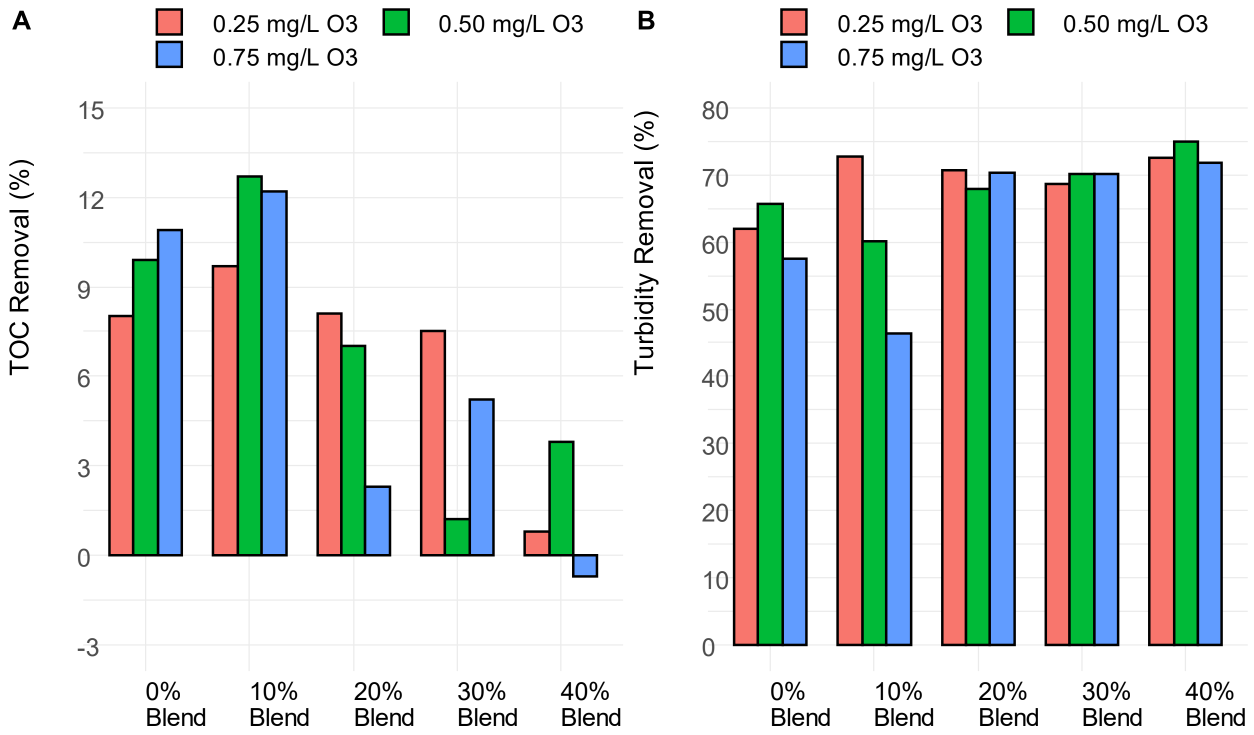


Figure 4-16. Plant D Bench-Scale Testing – TOC Removal (A) and Turbidity Removal (B) after 45-Minute Settling.
All jars were spiked with 1.5 mg/L $FeCl_3$ and 1.7 mg/L Clarifloc C-318 for coagulation.

Filter index, which qualitatively characterizes the filterability of flocs formed during coagulation/ flocculation, was calculated using the following relation:

$$Filter\ Index = \frac{Time\ for\ Sample}{Time\ for\ DI\ Water}$$

The filter indices were used to assess the effects of blending ratio and ozone dose on the filterability of flocs. Turbidity was also measured in the filtered water. Figure 4-17 presents filter index and filtered water turbidity. No clear relationships were observed between ozone dose or blending ratio and filter index. The filter index ranged from 3.3 to 5.5, indicating that the flocs had similar filterability characteristics. In general, filtered water turbidity declined with the increase in blending ratio (Figure 4-17).

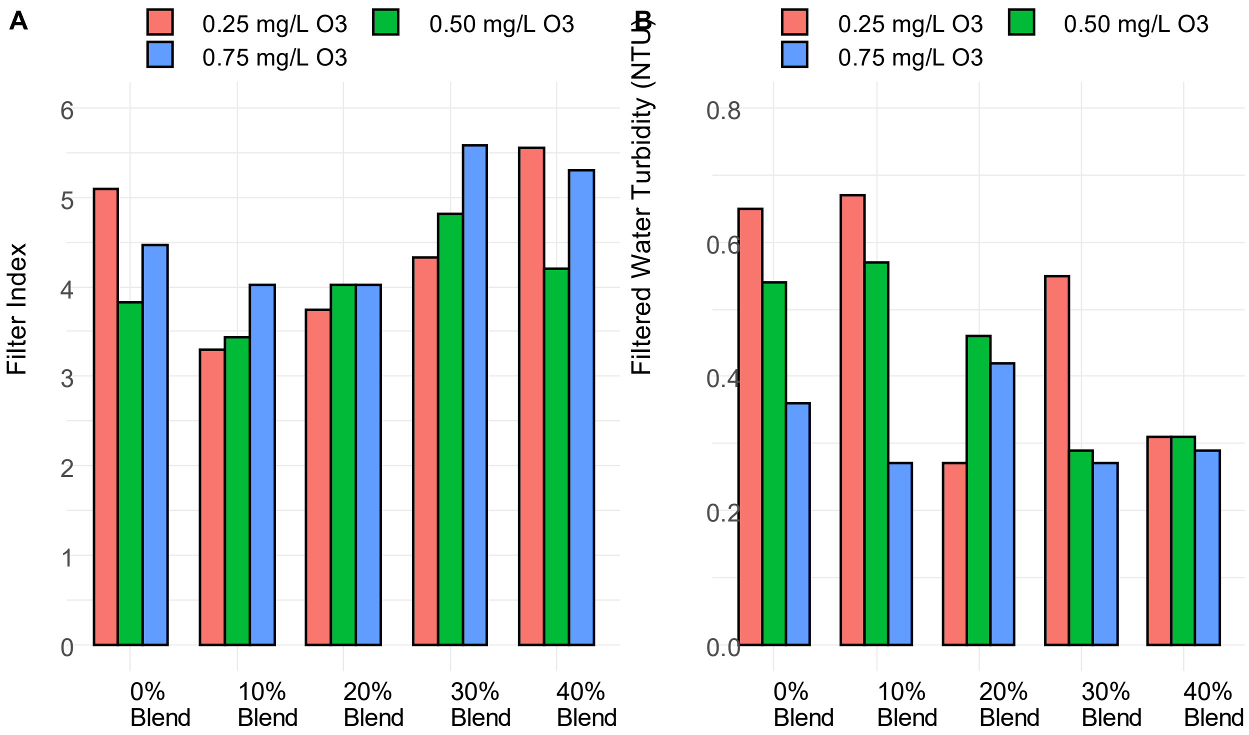


Figure 4-17. Plant D Bench-Scale Testing – Filter index (A) and Filtered Water Turbidity (B).
Filter indices were calculated by dividing the time to filter 200 mL sample through a Whatman 40 filter paper by that for DI water. All jars were spiked with 1.5 mg/L $FeCl_3$ and 1.7 mg/L Clarifloc C-318 for coagulation.

4.1.3.1 Summary of Plant D – Bench-Scale Testing Findings

- As expected, increasing the blend of ATW reduced the turbidity and TOC concentrations in the untreated and settled water.
- The residual ozone concentration increased with the blending ratio, indicating that increasing the ATW blend ratio could reduce ozone demand.
- Increasing the ozone dose apparently improved TOC removal in 0% (raw water) and 10% blends, but the trend did not hold with higher blends.
- Settled water TOC declined with increasing blending ratio.
- In general, increasing the blending ratio resulted in decreasing TOC removal, primarily because the starting TOC concentrations were lower in the higher blends (Table 4-3).
- ATW blending did not affect turbidity removal.
- Ozone dose did not affect turbidity removal.
- The blending ratio and ozone dose did not appear to affect filterability.

4.1.4 Plant E – Bench-Scale Testing Results

The bench-scale testing for Plant E included jar tests and filterability evaluations with CBAT-treated ATW and raw water. Table 4-4 presents baseline characteristics for the 0% (raw water), 15%, 25%, 35%, and 100% (ATW).

Table 4-4. Plant E Bench-Scale Testing – Baseline Water Quality Characteristics.

Parameter	Blend Ratio				
	0% (Raw Water)	15%	25%	35%	100% (ATW)
Temperature (°C)	15.2	22.2	15.9	17.1	12.2
pH (SU)	6.92	7.5	7.28	7.71	7.4
Zeta potential (mV)	-14.37	-10.47	-13.30	-10.72	-7.40
Turbidity (NTU)	0.767	0.795	0.582	0.532	0.118
Alkalinity (mg/L - $CaCO_3$)⁽¹⁾	13	29	40	50	120
Calcium (mg/L)(1)	3	5.4	7.0	8.6	19
Magnesium (mg/L)(1)	1.6	6.2	9.2	12.2	32
Ca + Mg Hardness (mg/L $CaCO_3$)(2)	14	19	55	72	179
Conductivity (µS/cm)	48	149	243	282	724
TDS (mg/L)(3)	31	95	156	180	463
TOC (mg/L)(1)	1.3	1.6	1.8	2.0	3.3
DOC (mg/L)(1)	1.4	1.7	1.9	2.0.	3.2
UV_{254} (cm^{-1})	0.035	0.037	0.035	0.039	0.017
SUVA (L/mg-m)	2.5	2.2	1.9	1.9	0.6

Notes:
1. TOC, DOC, alkalinity, calcium, and magnesium concentrations for blending ratios 15%, 25%, and 35% were calculated based on the raw water and ATW concentrations.
2. Calculated based on calcium and magnesium concentrations.
3. Calculated using empirical relation TDS (mg/L) = 0.64 * Conductivity (µS/Cm).

While turbidity was considerably lower in the ATW compared to raw water, TOC, TDS, conductivity, alkalinity, and hardness were significantly higher in the ATW. TOC concentrations in the 0%, 15%, 25%, and 35% blends did not exceed 2 mg/L. SUVA decreased with increased blending percentage, whereas alkalinity and hardness increased with increased blending percentage.

Figure 4-18 presents zeta titration results when various doses of coagulant ($FeCl_3$) or Clarifloc C-308P were added. The coagulant dose required for achieving near-zero zeta potential increased with the increase in the ATW blending ratio. In contrast to zeta titration with the coagulant, no clear relation was observed between the blending ratio and cationic polymer dose requirement for achieving near-zero zeta potential.

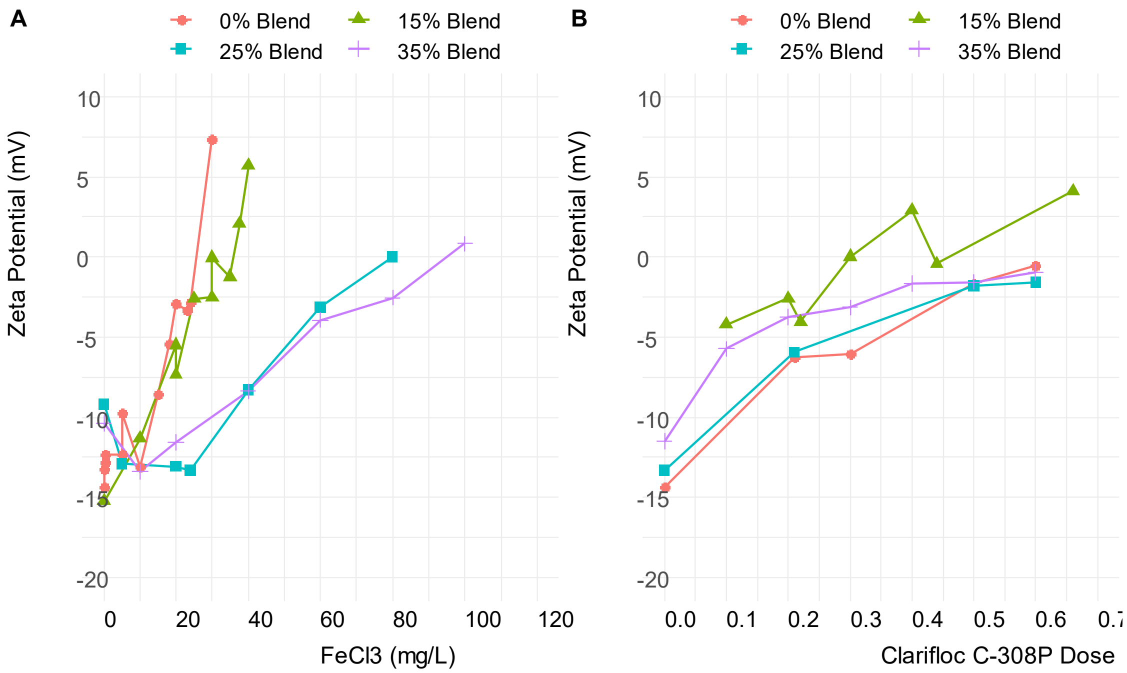


Figure 4-18. Plant E Bench-Scale Testing – Zeta Potential with $FeCl_3$ (A) and Clarifloc C-308P (B).

Zeta potential was further evaluated in the blends when both $FeCl_3$ and Clarifloc C-308P were added together. The zeta titration results are presented in Figure 4.19. Coagulant and polymer dose required for charge neutralization increased with increasing blending ratio; the chemical doses required for the 0% blend were significantly lower than for the 35% blend. As expected, the addition of polymer resulted in a lower coagulant dose required to achieve charge neutralization (Figure 4-19).

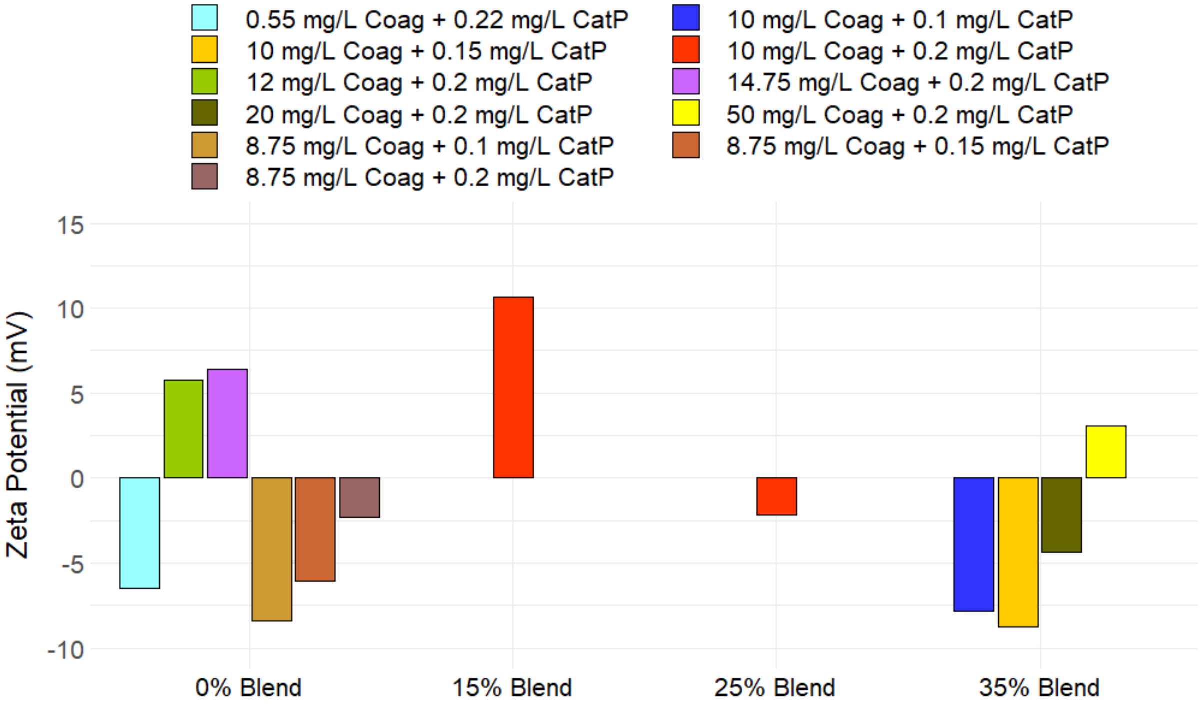


Figure 4-19. Plant E Bench-Scale Testing – Zeta Potential with $FeCl_3$ and Clarifloc C-308P Addition.

Given that zeta potential was very sensitive to the cationic polymer and a very low dose of the cationic polymer was required to achieve near-zero zeta potential when both chemicals were added together, jar testing was conducted with only the coagulant. The coagulant (i.e., $FeCl_3$) doses for the jar testing were determined based on the zeta titration with only the coagulant. To achieve near-zero zeta potential, approximately 24.5, 30, 80, and 95 mg/L $FeCl_3$ was required for the 0%, 15%, 25%, and 35% blend, respectively (Figure 4-18 [A]).

Figure 4-20 shows initial and settled water TOC, and TOC removal in the blends evaluated. With the $FeCl_3$ doses applied, greater than 20% TOC removal was achieved in all blends except the 15% blend after 45 minutes of settling.

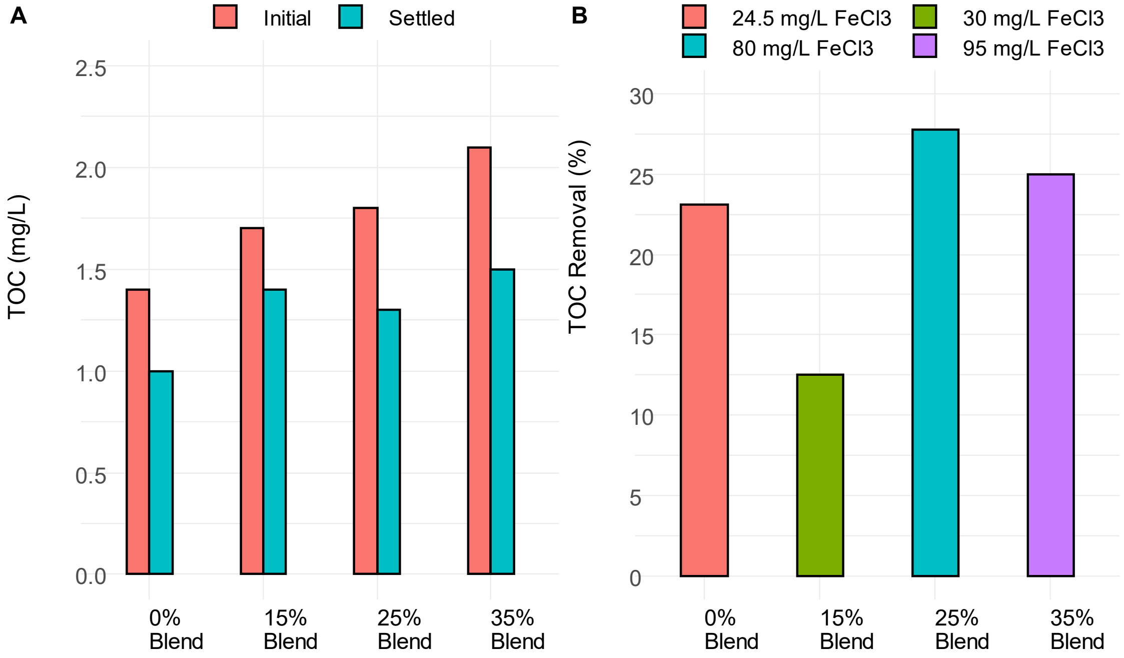


Figure 4-20. Plant E Bench-Scale Testing – Initial and Settled Water TOC Concentrations (A) and TOC Removal after 45-minute Settling.

With the applied coagulant doses, turbidity in the settled water (i.e., after 45-minute settling) was similar in all blends (Figure 4-21 [A]). Turbidity removal was higher in the 25% and 35% blends than in the 0% and 15% blends (Figure 4-21 [B]), primarily because of the initial higher turbidity (measured after 1-minute settling). Settled water characteristics are presented in Table C-4 of Appendix C.

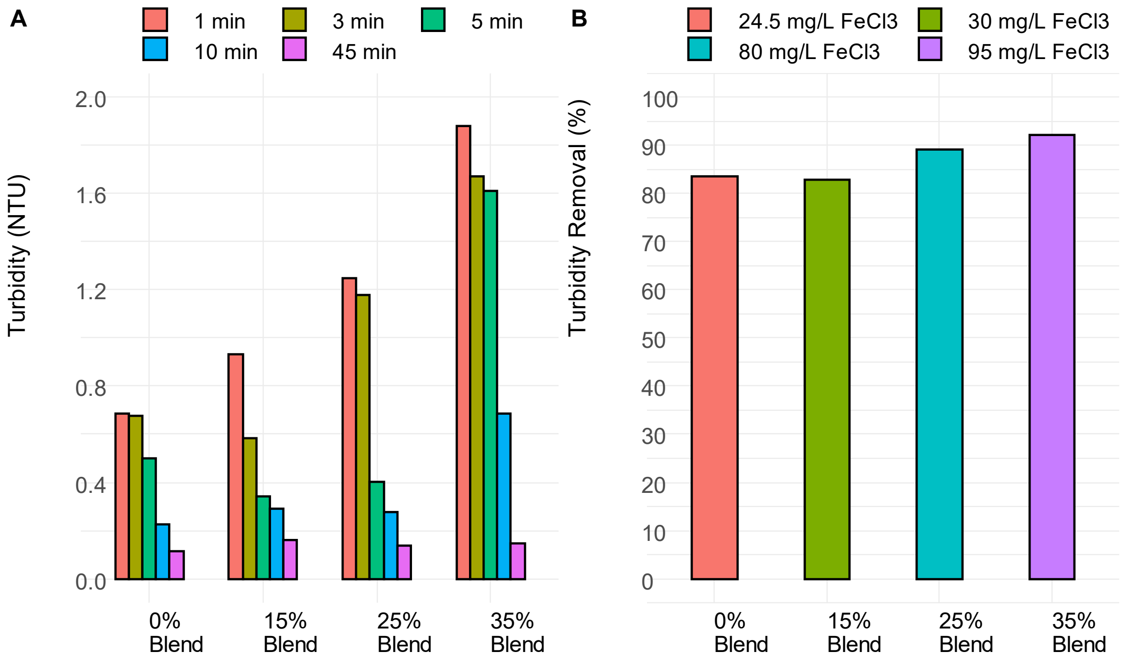


Figure 4-21. Plant E Bench-Scale Testing – Turbidity in Coagulated/Flocculated Water during Settling (A) and Turbidity Removal after 45-minute Settling.

4.1.4.1 Summary of Plant E – Bench-Scale Testing Findings

- TOC, alkalinity, hardness, and TDS in the blended water increased with the blending ratio, whereas turbidity declined.
- The required coagulant dose for charge neutralization increased with the blending ratio, whereas the trend was not clear with the cationic polymer as the zeta potential was very sensitive to Clarifloc C-308P dose.
- With the optimized coagulant doses, blending ATW did not appear to affect TOC removal, and greater than 20% TOC removal was achieved in all blends except the 15% blend.
- With the chemical doses used, settled water turbidity was similar in all blends. Turbidity removal apparently increased with increasing blending ratio, but this was more related to the higher initial turbidity and similar settled water turbidity.
- Overall, while a higher coagulant dose was required to achieve charge neutralization with an increasing blending ratio, blending the ATW did not appear to affect TOC and turbidity removal.

4.1.5 Plant G – Bench-scale Testing Results

Bench-scale testing was conducted with raw water and RBAT-treated ATW received from Plant G. Table 4-5 presents baseline water quality characteristics of the blends evaluated.

Table 4-5. Plant G Bench-Scale Testing – Baseline Water Quality Characteristics.

Blend	Blending Ratio				
	0% (Raw Water)	10%	25%	40%	100% (ATW)
Temperature (°C)	18.0	21.2	15.2	21.7	20.3
pH (SU)	8.3	7.9	7.8	8.0	7.5
Zeta potential	-12.3	-13.1	-12.8	-13.0	-4.7
Turbidity (NTU)	0.6	0.5	0.4	0.3	0.1
Alkalinity (mg/L - $CaCO_3$)$^{(1)}$	120	111	98	84	30
Calcium (mg/L)$^{(1)}$	70	63	53	42	<1.0
Magnesium (mg/L)$^{(1)}$	25	23	19	15	<0.1
Ca + Mg Hardness (mg/L $CaCO_3$)$^{(2)}$	278	250	208	167	ND
Conductivity (µS/cm)	821	749	641	533	102
TDS (mg/L)$^{(3)}$	525	479	410	341	65
TOC (mg/L)$^{(1)}$	3.10	2.82	2.40	1.97	0.28
DOC (mg/L)$^{(1)}$	3.1	2.82	2.40	1.98	0.3
UV_{254} (cm^{-1})	0.037	0.035	0.030	0.024	0.003
SUVA (L/mg-m)	1.18	1.24	1.24	1.21	1.13

Notes:

1. TOC, DOC, alkalinity, calcium, and magnesium concentrations for blending ratios 10%, 25%, and 40% were calculated based on the raw water and ATW concentrations.
2. Calculated based on calcium and magnesium concentrations.
3. Calculated using empirical relation TDS (mg/L) = 0.64 * Conductivity (µS/Cm)

The RBAT-treated ATW had considerably lower turbidity, TOC, and alkalinity compared to the raw water. Calcium and magnesium were below detection in the ATW. Blending the ATW significantly reduced turbidity and TOC in the blended water.

Figure 4-22 shows zeta potential in the 0%, 10%, 25%, and 40% blends when various doses of the coagulant (i.e., $FeCl_3$) or cationic polymer (Clarifloc C-358) were added. In general, the coagulant dose required for charge neutralization declined with the increase in ATW blending ratio (Figure 4-22 [A]). The cationic polymer concentrations required to achieve near-neutral zeta potential also decreased with increasing ATW blending ratio (Figure 4-22 [B]).

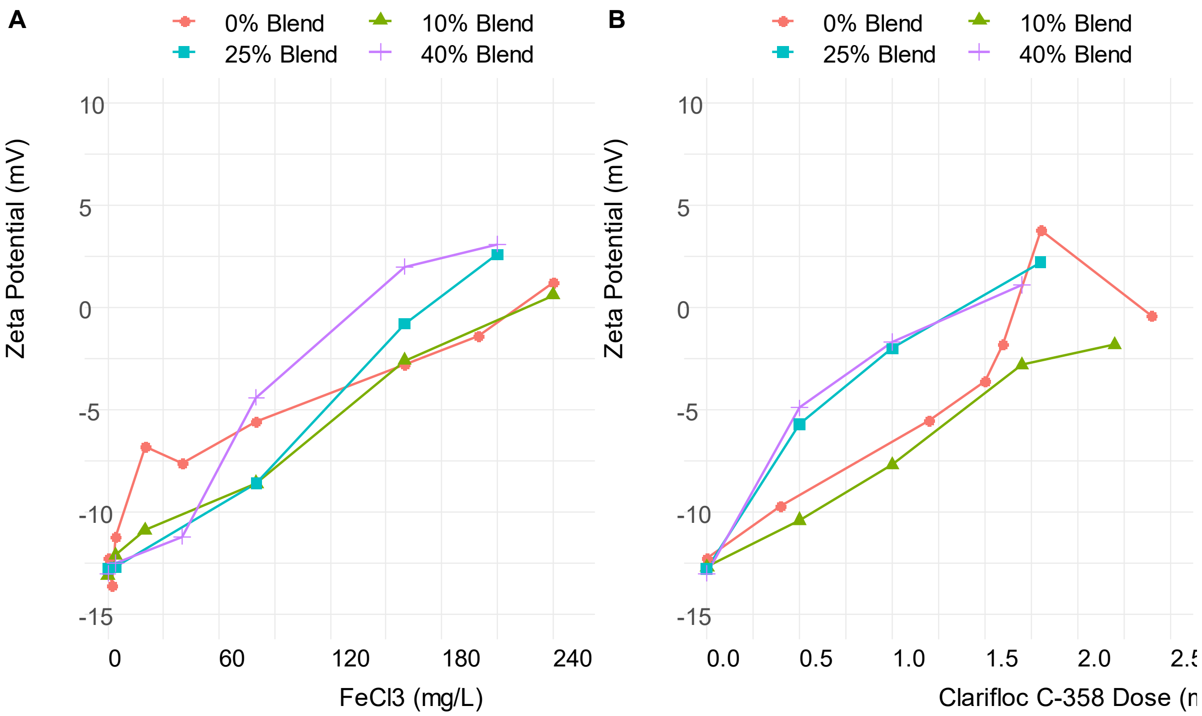


Figure 4-22. Plant G Bench-Scale Testing – Zeta Potential in Blended Water with $FeCl_3$ (A) and Clarifloc C-358 (B).

Zeta potential was evaluated in the raw water with various combinations of the coagulant and cationic polymer doses. The zeta potential varied significantly with the combinations of coagulant and polymer doses tested (Figure 4-23) and jar tests were conducted with only the coagulant, focusing on TOC removal.

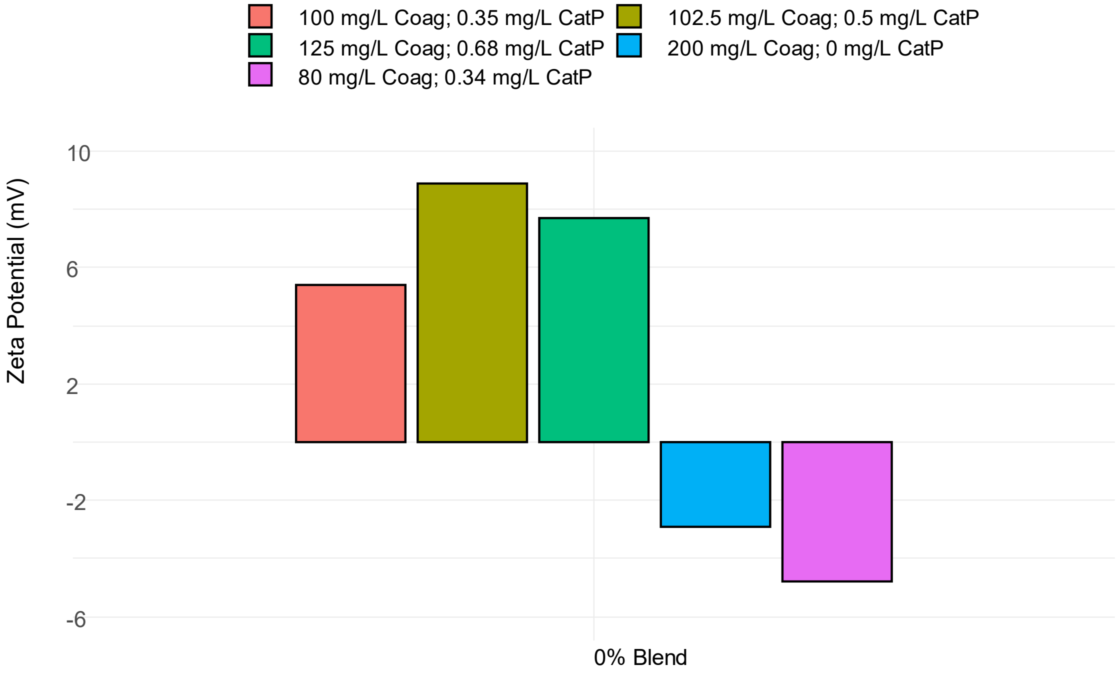


Figure 4-23. Plant G Bench-Scale Testing – Raw Water Zeta Potential with Various Combinations of $FeCl_3$ and Clarifloc C-358 Doses.

Figure 4-24 shows initial and settled water TOC concentrations in the jars, and TOC removal after settling. With a constant dose of 210 mg/L $FeCl_3$, in general, TOC removal increased with the increasing ATW blending ratio (Figure 4-24 [B]) despite the declining initial (i.e., before chemical addition) TOC concentration (Figure 4-24 [A]).

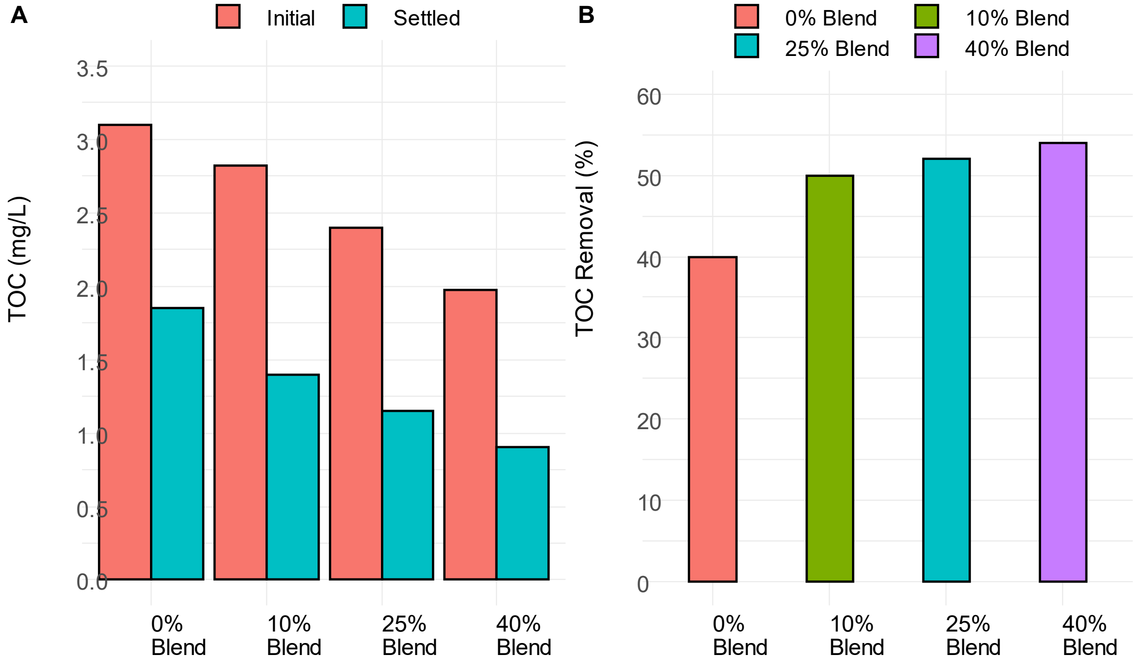


Figure 4-24. Plant G Bench-Scale Testing –
Initial and Settled TOC Concentrations (A) and TOC Removal after 45-minute Settling.
The bars present average TOC concentrations in two jars.

Figure 4-25 presents turbidity in the jars at different time points during settling and turbidity removal after 45-minute settling. With the constant dose of 210 mg/L $FeCl_3$, greater than 90% turbidity removal (calculated using turbidity after 1 minute settling as the initial turbidity) was observed in all blends (Figure 4-25 [B]). The settled water turbidity after 45 minutes of settling was less than 0.5 NTU except with the 10% blend (Figure 4-25 [A]). The settled water characteristics are presented in Table C-5 of Appendix C.

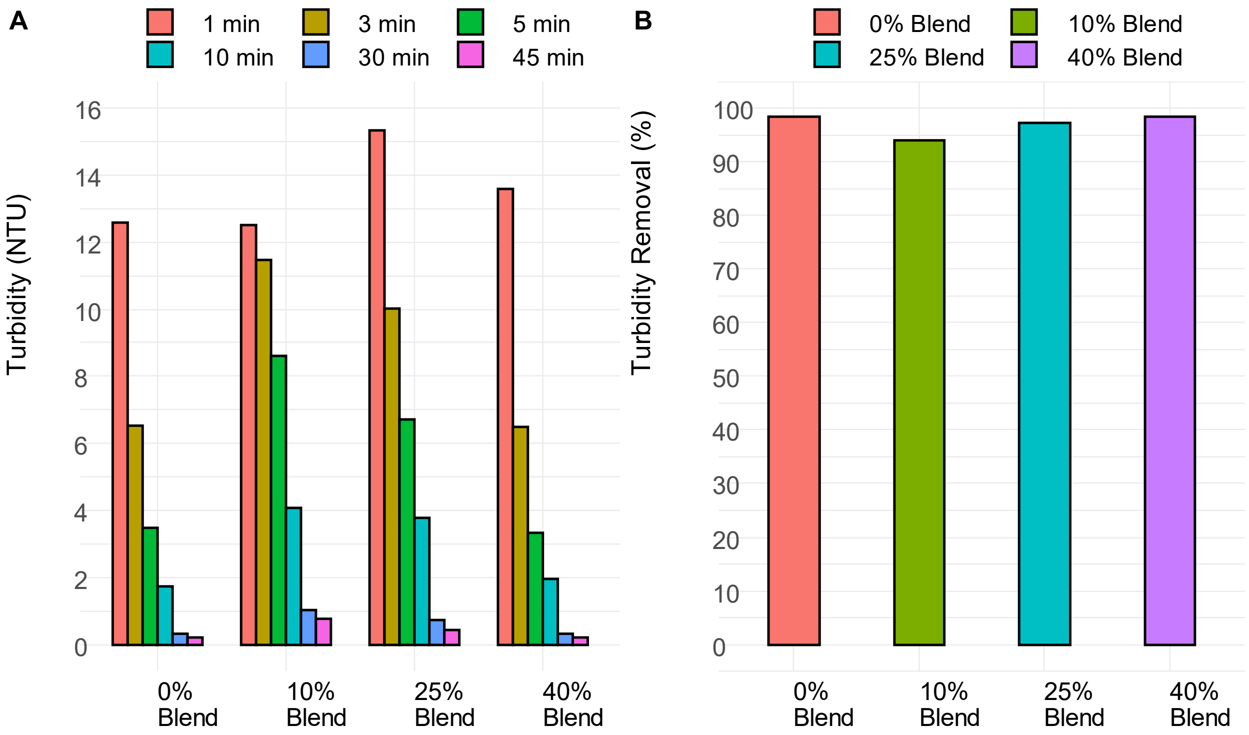


Figure 4-25. Plant G Bench-Scale Testing – Turbidity in Coagulated/Flocculated Water at Various Timepoints during Settling (A) and Turbidity Removal (B) after 45-minute Settling.

Turbidity removal was calculated by considering the turbidity after 1 minute settling as the initial turbidity.

4.1.5.1 Summary of Plant G – Bench-Scale Testing Findings

- Turbidity, TOC, and alkalinity were lower in the ATW compared to the raw water.
- TOC, UV_{254}, and turbidity declined in the untreated water with the increase in ATW blending ratio.
- In general, the coagulant or cationic polymer dose required for charge neutralization declined with an increase in blending ratio.
- With 210 mg/L $FeCl_3$, TOC removal increased with the increase in ATW blending ratio.
- Blending ATW did not affect turbidity removal and greater than 90% removal was achieved in all blends.

4.1.6 Plant H – Bench-Scale Testing Results

Plant H is a groundwater treatment facility instead of an SWTP. Therefore, the ATW received from the plant's pilot-scale CBAT system was blended with Colorado River water collected from Metropolitan Water District (MWD) in Southern California. Table 4-6 presents the baseline characteristics of the raw water, ATW, and the blends used during the study.

Table 4-6. Plant H Bench-Scale Testing – Baseline Water Quality Characteristics.

Blend	Blending Ratio				
	0% (Raw Water)(1)	15%	25%	35%	100% (ATW)
Temperature (°C)	11.7	22.3	19.1	17.4	10.7
pH (SU)	8.2	8.0	7.9	7.8	7.24
Zeta potential	-15.8	-13.1	-14.5	-13.1	-8.58
Turbidity (NTU)	0.7	0.7	0.5	0.4	0.132
Alkalinity (mg/L - $CaCO_3$)(2)	130	125	121	118	95
Ca (mg/L)(2)	73	68	64	61	38
Mg (mg/L)(2)	26	24	22	20	9.7
Ca + Mg Hardness (mg/L - $CaCO_3$)(3)	289	266	251	235	135
Conductivity (µS/cm)	972	922	860	820	568
TDS (mg/L)(4)	622	590	550	525	364
TOC (mg/L)(2)	2.90	2.95	2.98	3.01	3.20
DOC (mg/L)(2)	2.8	2.88	2.93	2.98	3.3
UV_{254} (cm^{-1})	0.034	0.036	0.037	0.037	0.055
SUVA (L/mg-m)	1.2	1.2	1.3	1.3	1.7

Notes:

1. Colorado River Water.
2. TOC, DOC, alkalinity, calcium, and magnesium concentrations for blending ratios 15%, 25%, and 35% were calculated based on the raw water and ATW concentrations.
3. Calculated based on calcium and magnesium concentrations.
4. Calculated using empirical relation TDS (mg/L) = 0.64 * Conductivity (µS/Cm).

Except for TOC, DOC, and UV_{254}, the Colorado River water had higher concentrations for other key water quality parameters compared to the ATW. When the ATW was blended with the raw water, TOC increased in the blended water, whereas the other water quality parameters declined with the increase in the blending ratio.

For zeta potential evaluation and jar testing, aluminum sulfate and Clarifloc C-308P were used. Figure 4-26 present zeta titration results with alum or Clarifloc C-308P, which show no clear effects of blending ratio on zeta potential. Zeta potential was very sensitive to the cationic polymer and wide swings were observed with very small changes in polymer dose (Figure 4-26 [B]). There was no clear relationship between the blending ratio and polymer dose required for charge neutralization.

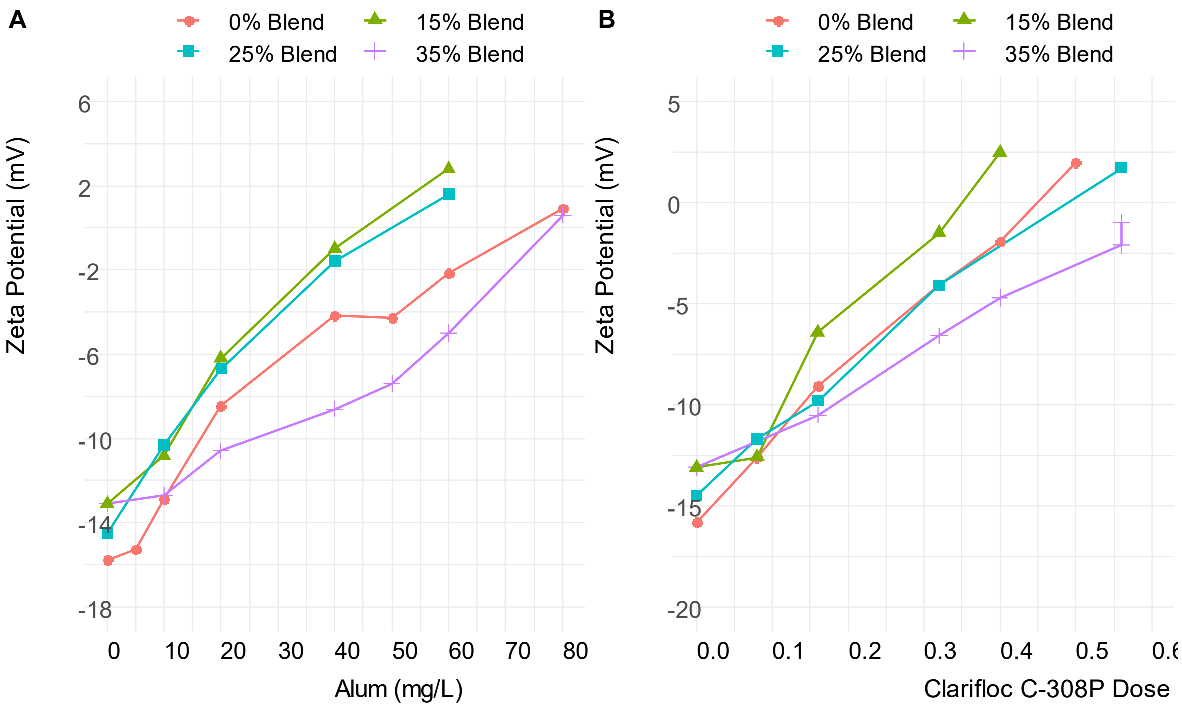


Figure 4-26. Plant H Bench-Scale Testing –Zeta Potentials with Alum (A) and Clarifloc C-308P (B).

Figure 4-27 presents results of zeta potential evaluations with the blended water when different alum doses were added along with 0.04 mg/L cationic polymer. In the 0% (i.e., the Colorado River water), 15%, and 25% blends, near-zero zeta potential was achieved with 41 mg/L alum and 0.04 mg/L Clarifloc C-308P . Higher coagulant dose was required to achieve similar results in the 35% blend.

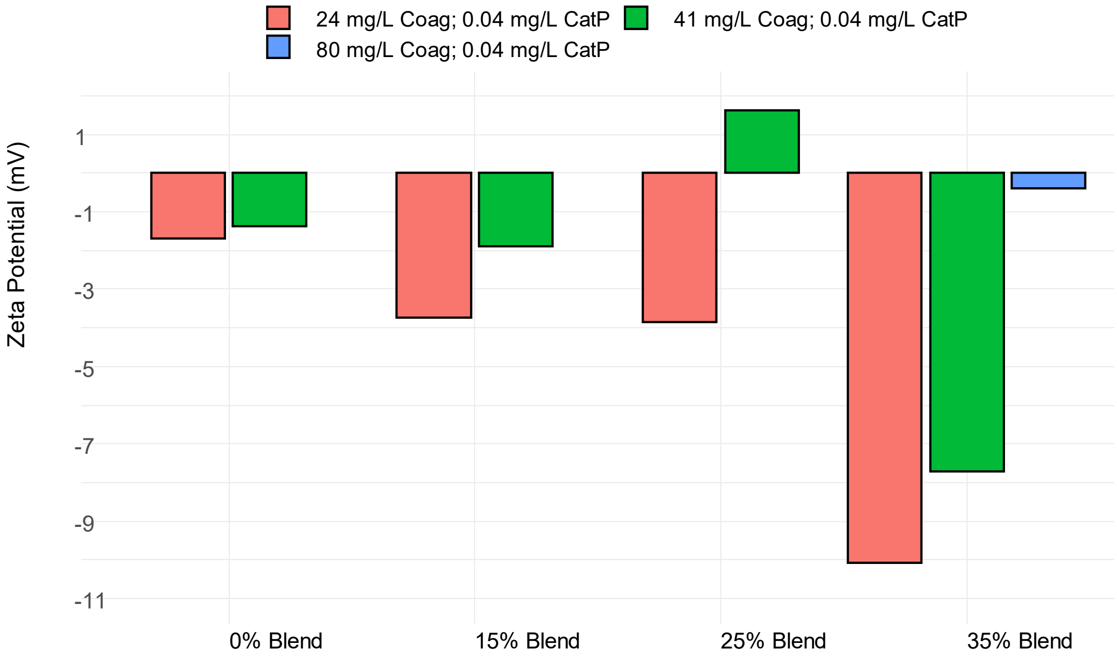


Figure 4-27. Plant H Bench-Scale Testing – Zeta Potential in 0% and 15% Blends when Alum and Clarifloc C-308P were Added to the Water.

Given that zeta potential was very sensitive to small changes in polymer dose (data not shown), jar tests were conducted with 41 mg/L alum only. Though the apparent TOC removal was lower in the ATW blended waters than in the 0% blend, the TOC removals were not much different given that the absolute TOC concentrations before chemical addition (i.e., initial) and after 60 minutes settling (i.e., settled) remained similar in the jars (Figure 4-28).

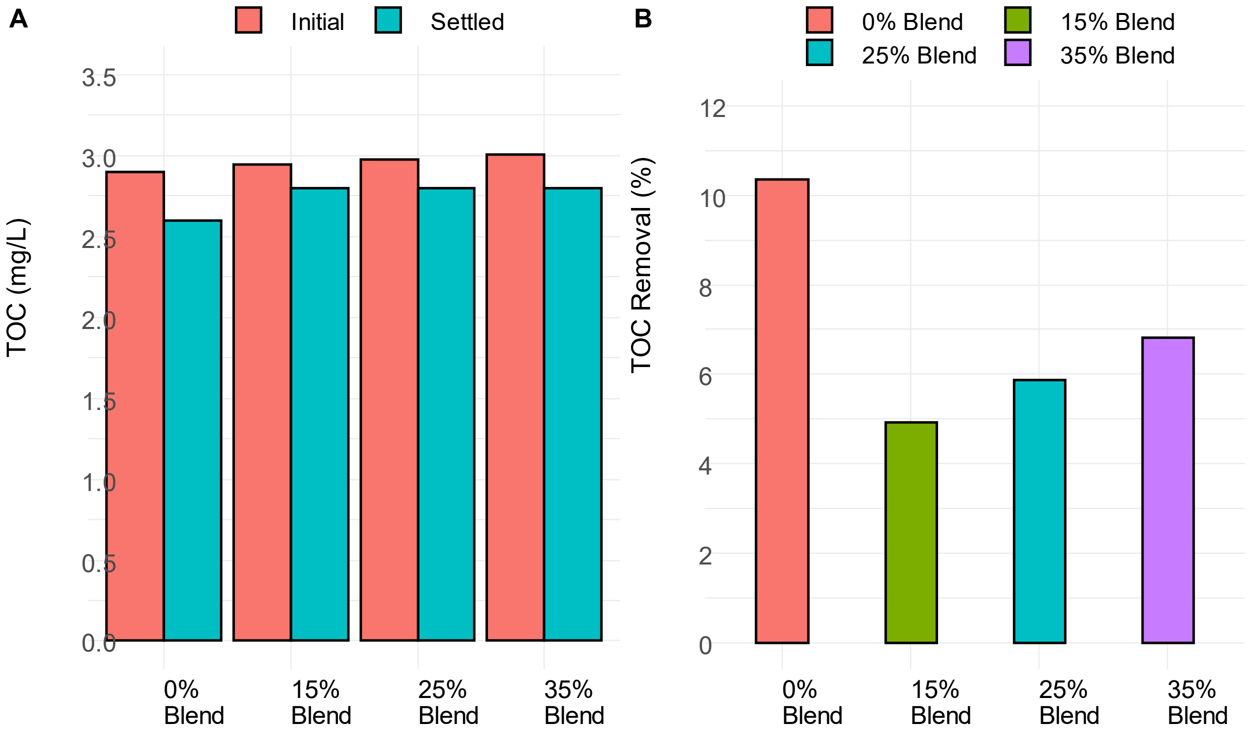


Figure 4-28. Plant H Bench-Scale Testing – TOC Concentrations in the Blended Water (A) and TOC Removal (B) after 60-minute Settling.

In all jars, 41 mg/L alum was added for coagulation.

ATW blending did not appear to affect turbidity removal (Figure 4-29). The flocs in all blends required a significantly longer time for settling. With 41 mg/L alum, turbidity removal (turbidity after 1-minute settling was used as the initial turbidity) was similar in the 0% and 35% blends. The turbidity removal in blends 15% and 25% were not much different. Settled water characteristics are presented in Table C-6 of Appendix C.

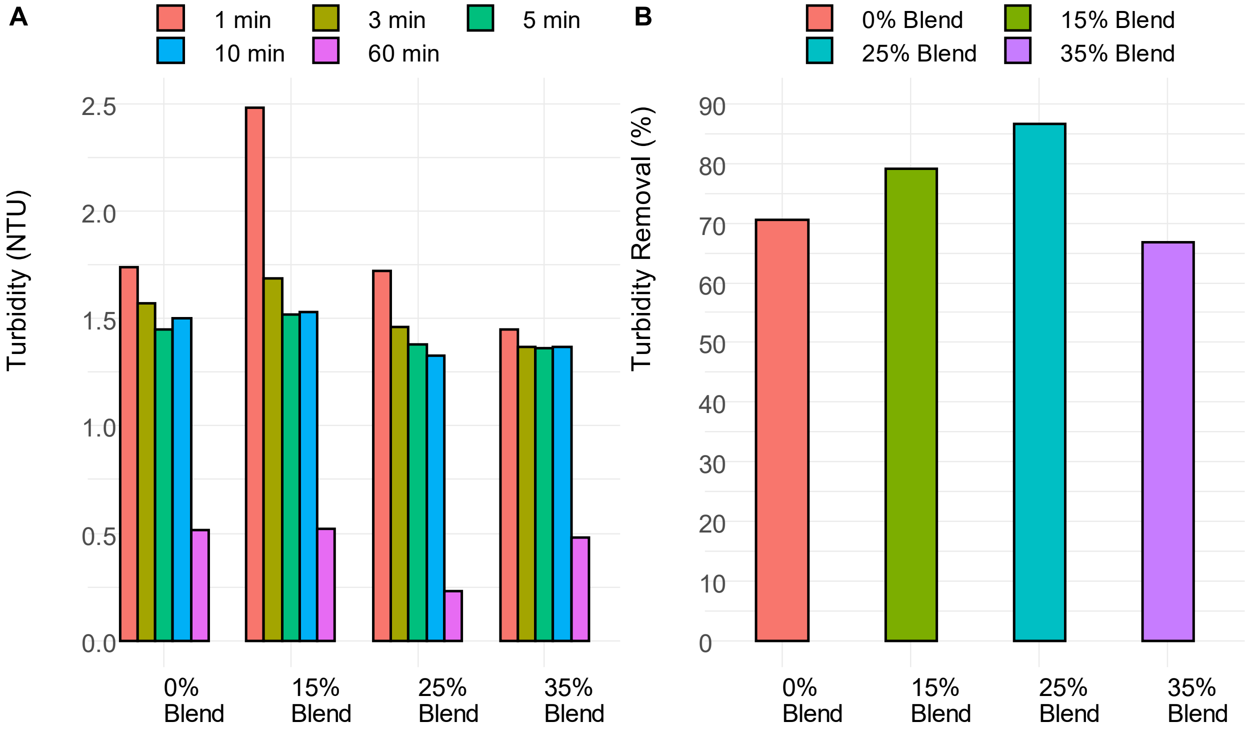


Figure 4-29. Plant H Bench-Scale Testing – Turbidity at Different Timepoints during Settling (A) and Turbidity Removal after 60-minute Settling (B).
In all jars, 41 mg/L alum was added for coagulation.

4.1.6.1 Summary of Plant H – Bench-Scale Testing Findings

- Except for TOC, DOC, and UV_{254}, concentrations of other key water quality parameters were higher in Colorado River water compared to the ATW.
- The effects of the blending ratio on zeta potential were not apparent. Zeta potential was very sensitive to cationic polymer concentration.
- With the constant dose of 41 mg/L alum, TOC removal in all blends did not differ much and remained less than 10%, suggesting that ATW blending does not affect TOC removal for this water.
- With the constant dose of 41 mg/L alum, greater than 67% turbidity removal was achieved in all jars.
- Slowly settling flocs were generated regardless of the blending ratio.
- Settling performance remained similar with 0% and 35% blends and with 15% and 25% blends.

4.1.7 Summary of Bench-Scale Testing Results

Overall, the bench-scale testing results indicate that the effects of blending ATW are treatment- and site-specific. Depending on the raw water source, in some cases, blending ATW can result in higher turbidity and TOC in the blended water, while in other cases, the concentration of these parameters can decline. If blending ATW reduces TOC concentration, it may also lower ozone demand. In general, when blending ATW reduced TOC concentrations in the blended water, the coagulant dose required for charge neutralization declined with increasing blending ratio. The results also indicated that optimal coagulant dose can be determined through zeta evaluation-based jar testing. In general, blending ATW does not appear to add challenges to coagulation, flocculation, and sedimentation processes.

Table 4-7 summarizes findings of the bench-scale testing.

Table 4-7. Summary of Bench-Scale Testing Results.

Plant	ATW From	Blended TOC (mg/L)	Blended SUVA (L/mg-m)	Effects of Blending	
Plant A	RBAT	> 2 mg/L In All Blends	> 2 L/mg-m In All Blends	Blended Water Characteristics	
				Alkalinity	Decreased
				Turbidity	Decreased
				Conductivity	Decreased
				Calcium	Decreased
				Magnesium	Decreased
				TOC	Decreased
				SUVA	Decreased
				Coagulant dose	Decreased
				Polymer dose	No clear trend
				TOC removal	Increased Required – 25%* Achieved – 19%–33%**
				Turbidity removal	Decreased with increasing blending ratio due to lower initial turbidity
Plant C	CBAT	2 mg/L In All Blends	< 2 L/mg-m In All Blends	Blended Water Characteristics	
				Alkalinity	Increased
				Turbidity	Decreased
				Conductivity	Increased
				Hardness	Increased
				TOC	Decreased
				SUVA	Decreased
				Coagulant dose	N/A as tests were conducted with the same dose for all blends
				Polymer dose	N/A as tests were conducted with the same dose for all blends
				TOC removal	No clear trend
				Turbidity removal	No clear trend

Plant	ATW From	Blended TOC (mg/L)	Blended SUVA (L/mg-m)	Effects of Blending	
Plant D	RBAT	< 2 mg/L in all blends	≥ 2 L/mg-m in 10% and 20%; <2 L/mg-m in 30%, 40%, and 50%	Blended Water Characteristics	
				Alkalinity	Decreased
				Turbidity	Decreased
				Conductivity	Increased
				Calcium	Increased
				Magnesium	Increased
				TOC	Decreased
				SUVA	Decreased
				Coagulant dose	N/A as fixed dose (1.5 mg/L) used
				Polymer dose	N/A as fixed dose (1.5 mg/L) used
				TOC removal	Decreased due to lower initial TOC Alternate compliance criteria applicable as initial TOC < 2 mg/L Achieved – 1%–13%
				Turbidity removal	Not affected
Plant E	CBAT	<2 mg/L in 15%, and 25%; equal to 2 mg/L in 35%	< 2 L/mg-m in 25% and 35%; ≥2 L/mg-m in 15%	Blended Water Characteristics	
				Alkalinity	Increased
				Turbidity	Decreased
				Conductivity	Increased
				Calcium	Increased
				Magnesium	Increased
				TOC	Increased
				SUVA	Decreased
				Coagulant dose	Increased with increasing blending ratio
				Polymer dose	Very sensitive to polymer. No clear trend
				TOC removal	No clear trend Alternate compliance criteria applicable as initial TOC < 2 mg/L and/or initial SUVA < 2 L/mg-m Achieved – 13%–28%
				Turbidity removal	Increased

Plant	ATW From	Blended TOC (mg/L)	Blended SUVA (L/mg-m)	Effects of Blending	
Plant G	RBAT	< 2 mg/L in 40%; > 2 mg/L in 10% and 25%	< 2 L/mg-m in all blends	Blended Water Characteristics	
				Alkalinity	Decreased
				Turbidity	Decreased
				Conductivity	Decreased
				Calcium	Decreased
				Magnesium	Decreased
				TOC	Decreased
				SUVA	No clear trend
				Coagulant dose	Decreased with increasing blending ratio
				Polymer dose	Decreased with increasing blending ratio
				TOC removal	Increased Alternate compliance criteria applicable as initial SUVA < 2 L/mg-m Achieved – 39%–5r%
				Turbidity removal	Not affected
Plant H	CBAT	> 2 mg/L In All Blends	< 2 L/mg-m In All Blends	Blended Water Characteristics	
				Alkalinity	Decreased
				Turbidity	Decreased
				Conductivity	Decreased
				Calcium	Decreased
				Magnesium	Decreased
				TOC	Increased
				SUVA	Increased
				Coagulant dose	Decreased with increasing blending ratio
				Polymer dose	Very sensitive to polymer. No clear trend
				TOC removal	Not affected Alternate compliance criteria applicable as initial SUVA < 2 L/mg-m Achieved – 5%–10%
				Turbidity removal	No clear trend

4.2 Pilot Testing Results

Pilot-scale tests were conducted at Plants A, C, and D to further assess the effects of ATW blending on coagulation, flocculation, sedimentation (as applicable), and filtration process performance under continuous flow conditions. The specific objectives of the pilot testing were:

1. Assess the effects of ATW blending on water quality.
2. Assess the effects of pre-ozonation on floc formation and filterability.
3. Under the same set of coagulant and polymer feeding conditions:
   a. Assess the coagulation/flocculation performance with and without ATW blending.
   b. Determine filter performance with and without ATW blending.

4. Determine pathogen log removal across the system through MS2 bacteriophage and PMMoV challenge tests.
5. Evaluate if particle removal can be correlated with pathogen log removal.
6. Determine the effects of ATW blending on disinfectant demand and disinfection byproduct formation potential (DBPFP).

4.2.1 Plant A – Pilot Testing

The pilot-scale system at Plant A simulated a conventional water treatment plant with coagulation, flocculation, sedimentation, and filtration. The tests included evaluation of ATW blending on water quality, and unit process performance, including pathogen and particle removal.

4.2.1.1 Effects of Blending on Water Quality (Prior to Treatment)

Raw water and ATW water samples were collected during the pilot testing to characterize the source waters before blending. The ATW was collected from Plant A's AWPF. Table 4-8 presents statistical summary of the analysis results for the two water sources. As expected, the ATW had significantly lower TOC, DOC, and UV_{254} compared to the raw water. Alkalinity, hardness, and conductivity were also considerably lower than the raw water.

Table 4-8. Plant A Pilot Testing – Statistical Summary of Raw Water and ATW Characteristics.

	UV_{254} (cm^{-1})		Turbidity (NTU)		Conductivity (µS/cm)		pH (SU)		TOC (mg/L)		DOC (mg/L)		Alkalinity ($CaCO_3$ mg/L)		Hardness ($CaCO_3$ mg/L)	
	Raw Water	ATW	Raw Water	ATW	Raw Water	ATW	Raw Water	ATW	Raw Water	ATW	Raw Water	ATW	Raw Water	ATW	Raw Water	ATW(1)
Counts	68	10	68	8	21	4	68	8	6	5	6	5	6	6	6	6
Minimum	0.139	0.002	2.99	0.25	326	82	6.52	7.10	4.0	0.3	4.1	0.3	83	32	120	<3
Maximum	0.286	0.015	21.40	1.78	452	87	8.58	7.88	6.2	0.5	6.3	0.6	120	35	150	7
Average	0.206	0.005	7.34	0.78	404	84	7.75	7.48	5.2	0.4	5.1	0.5	93	34	128	<3
Standard Deviation	0.043	0.004	3.33	0.49	33	2	0.35	0.28	0.9	0.1	0.8	0.1	14	1	12	N/A

Notes:

1. Only one sample had detectable hardness (7 mg/L $CaCO_3$)

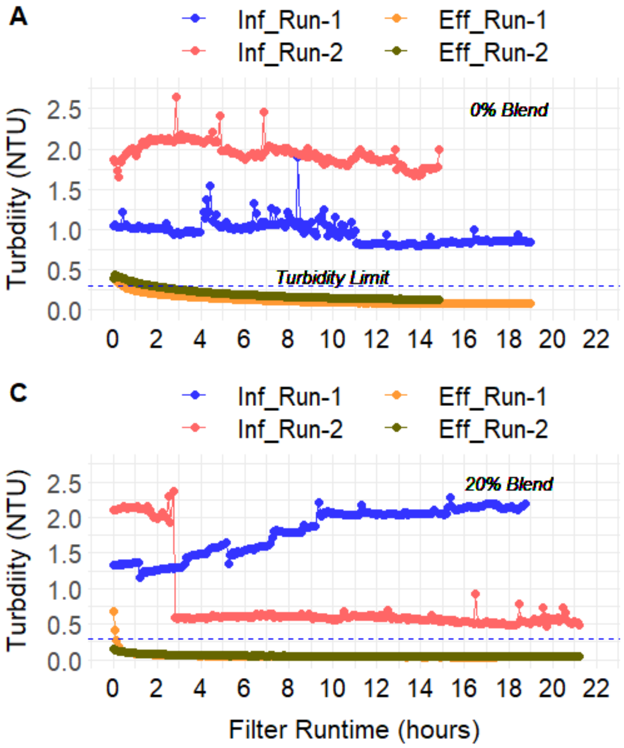
Based on the water quality characteristics of the raw water and ATW, blending ATW with the raw water can significantly improve blended water quality due to dilution. For example, while approximately 9% TOC reduction from the raw water concentration (i.e., from 5.2. to 4.7 mg/L TOC) can be achieved with a 10% ATW blend, a 50% ATW blend will result in approximately 46% reduction in the TOC concentration (i.e., from 5.2 to 2.8 mg/L TOC). In general, the measured concentrations were quite close to the calculated concentrations (Table C-7, Appendix C).

4.2.1.2 Effects of ATW Blending on Filter Performance

The average filter loading rate for the full-scale filters at Plant A is 3.2 gpm/ft^2 with a capacity to operate at loading rate up to 7.5 gpm/ft^2 (with one filter backwashing). The pilot-scale filter was operated with a filter loading rate of 3.6 gpm/ft^2 throughout the pilot testing. Turbidity breakthrough (i.e., >0.3 NTU) and terminal headloss (i.e., 3.5 ft) were set as the triggers for backwashing the pilot-scale filter. A 20-min filter-to-waste step was implemented immediately after each backwash and, depending on the filter influent turbidity, the turbidity limit was increased (up to 1 NTU) for a short duration immediately after the backwash to avoid run termination due to high turbidity (discussed below). Alum, cationic polymer (Clarifloc C-308P), and non-ionic polymer (Clarifloc N-120P) were fed immediately upstream of the rapid mix, targeting a final dose of 35 mg/L alum, 0.35 mg/L cationic polymer, and 0.25 mg/L non-ionic polymer, which matched the dose tested during the bench-scale testing except the cationic polymer dose. For the pilot testing, the cationic polymer dose was kept at 10% of the alum dose.

Figure 4-30 presents filter effluent turbidity in representative filter runs with the 0%, 10%, 20%, and 50% ATW blends. During a filter run, turbidity typically remained well below 0.1 NTU except during the testing with the 0% ATW. Raw water turbidity significantly fluctuated during the pilot testing, resulting in variations in settled water turbidity. For example, when treating the raw water (i.e., 0% ATW blend), filter influent turbidity (i.e., settled water turbidity) ranged from 0.7 to 1.5 NTU and 1.6 to 2.2 NTU during Run 1 and Run 2, respectively (Figure 4-30 [A]). Despite the filter operation with a 20-minute filter-to-waste step, filter effluent turbidity immediately after the backwash remained higher when the 0% blend was tested, requiring operating the filter with a higher turbidity-limit (i.e., 1 NTU) for 30 min (Run 1) or 1.5 hours (Run 2). Optimization of the coagulant and polymer doses was beyond the scope of the pilot testing, and, as mentioned above, all the tests were conducted with the same set of coagulant and polymer doses.

During the tests with the 10% blend, filter influent turbidity was below 1 NTU and filter effluent turbidity was below the limit of 0.3 NTU (Figure 4-30 [B]). When testing the 20% blend, during filter Run 1, the filter effluent turbidity remained low although the influent turbidity appeared to steadily increase throughout the filter run (Figure 4-30 [C]). The elevated influent turbidity was also observed at the beginning of Run 2 but cleaning the turbidimeter (at approximately 2.8 hours of filter runtime) resulted in a subsequent drop in the influent turbidity while the filter effluent turbidity remained consistently below 0.1 NTU throughout the two runs. With the 50% blend, the ATW blending resulted in significantly lower filter influent turbidity (typically <0.3 NTU) and filter effluent turbidity was below 0.04 NTU (Figure 4-30 [D]).



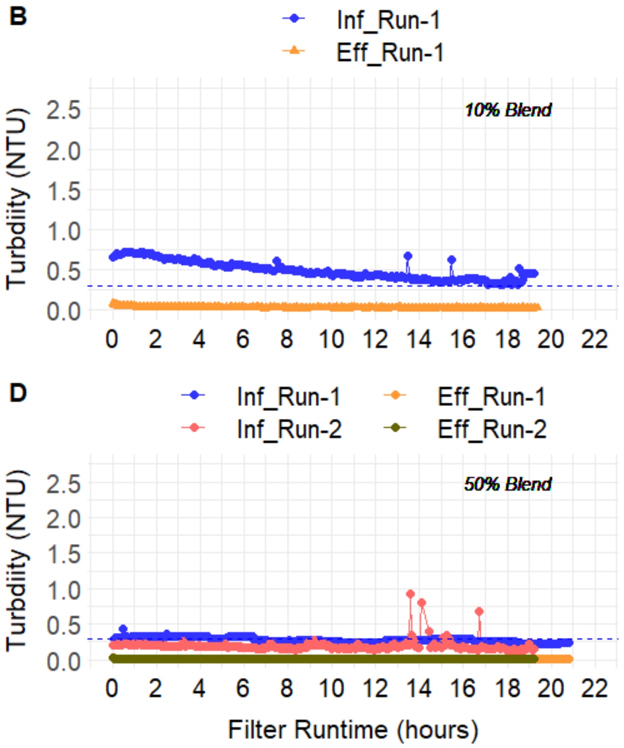


Figure 4-30. Plant A Pilot-Scale Testing – Filter Influent and Effluent Turbidity with the 0% Blend (A), 10% Blend (B), 20% Blend (C) and 50% Blend (D).

Figure 4-31 presents representative headloss accumulation trends in the filter with the ATW blends tested. Except Run 2 with the 20% blend, the filter run terminated due to high headloss (i.e., >3.5 feet). While it is not clear why headloss accumulation rate abruptly changed in a few of the filter runs (e.g., around 14 hours and 19 hours of filter runtime during Run 1 and Run 2 with the 20% blend), in general, blending ATW appeared to lower headloss accumulation rate in the filter.

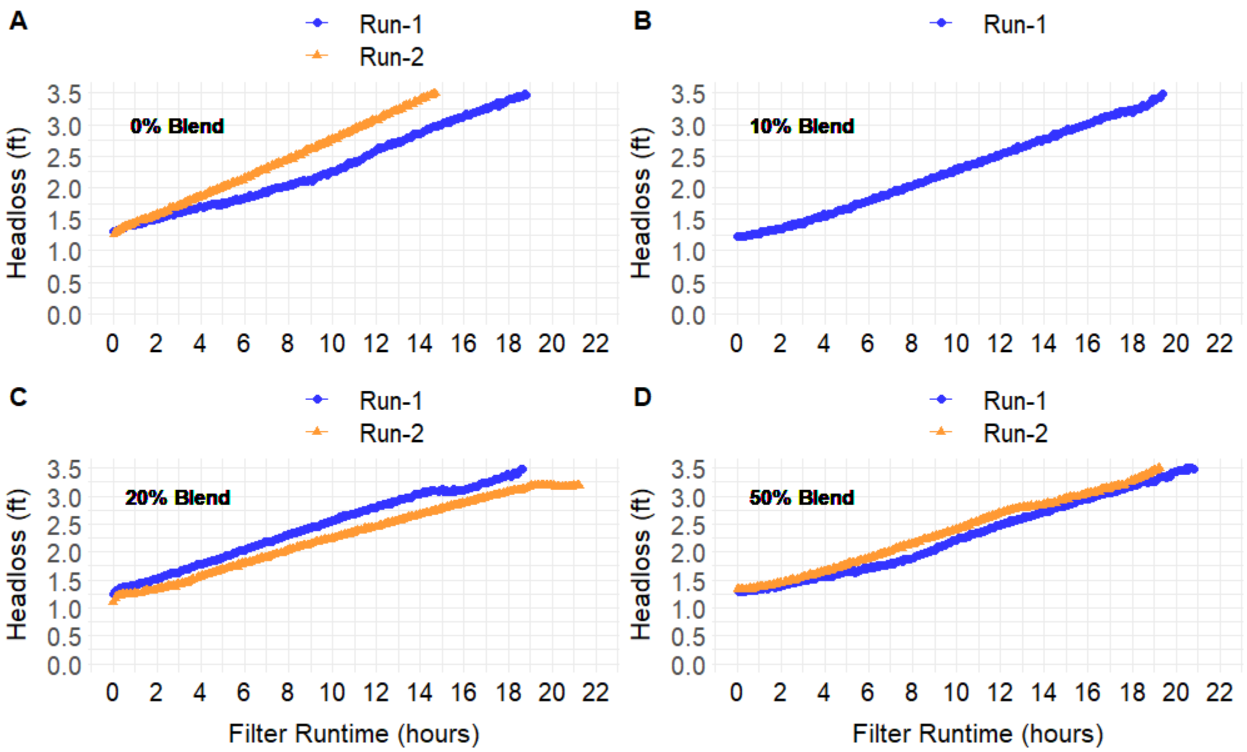


Figure 4-31. Plant A Pilot-Scale Testing – Filter Headloss with the 0% Blend (A), 10% Blend (B), 20% Blend (C), and 50% Blend (D).

Tables 4-9 and 4-10 summarize the turbidity and headloss data presented in Figures 4-30 and 4-31, respectively. Overall, lower filter effluent turbidity and lower headloss accumulation rates were observed with increasing ATW blending ratio. The decrease in headloss accumulation rates observed with the ATW-blended water compared to the raw water cannot be fully explained by the dilution effect. For example, with the 0% the headloss accumulation rate was 1.62 inch/hour. If dilution was the only reason for the observed decrease in headloss accumulation rate, the headloss accumulation rate would be approximately 0.81 inch/hour. However, considerably higher headloss accumulation rate (i.e., 1.32 inch/hour) was realized with the 50% blend.

Table 4-9. Plant A Pilot-Scale Testing – Filter Influent and Effluent Turbidity.

	Filter Influent Turbidity (NTU)				Filter Effluent Turbidity (NTU)			
	0% Blend	10% Blend	20% Blend	50% Blend	0% Blend	10% Blend	20% Blend	50% Blend
Run 1	0.96	0.52	1.8	0.278	0.12	0.02	0.06	0.01
Run 2	1.95	N/A	0.77	0.19	0.2	N/A	0.05	0.01
Average	1.46	0.52	1.29	0.23	0.16	0.02	0.06	0.01

Table 4-10. Plant A Pilot-Scale Testing – Statistical Summary of Headloss in the Filter.

		Headloss (feet)			
		0% Blend	10% Blend	20% Blend	50% Blend
Run Length (hours)	Run-1	19.0	19.4	18.7	20.8
	Run-2	14.8	N/A	21.2	19.2
	Average	16.9	19.4	19.95	20.0
Clean-bed Headloss (feet)	Run-1	1.30	1.22	1.25	1.29
	Run-2	1.25	N/A	1.11	1.32
	Average	1.28	1.22	1.18	1.31
Terminal Headloss (feet)	Run-1	3.52	3.48	3.51	3.50
	Run-2	3.53	N/A	3.19	3.50
	Average	3.53	3.48	3.35	3.50
Headloss Accumulation Rate (inch/hour)	Run-1	1.40	1.40	1.45	1.27
	Run-2	1.84	N/A	1.18	1.36
	Average	1.62	1.40	1.32	1.32

Based on Figures 4-32 and 4-33 and Tables 4-9 and 4-10, it can be concluded that blending ATW did not affect turbidity removal, but rather lowered headloss accumulation rate with the increasing ATW blending ratio.

4.2.1.3 Effects of ATW Blending on Overall Water Treatment Performance

pH and Alkalinity

Carbonate chemistry is a fundamental and well-characterized concept in water treatment. Coagulation is rooted in particle charge destabilization (measured directly by zeta potential and indirectly by pH). In tandem with pH, alkalinity affects coagulant dose and overall coagulation process. While pH/alkalinity range depends on water source and can vary seasonally, the addition of a metal-based coagulant, such as ferric chloride and alum, depresses pH by consuming alkalinity. While a minimum alkalinity is critical to provide sufficient hydroxide for the formation of metal hydroxides during the coagulation process, excessive alkalinity can result in a higher buffer capacity, requiring excess coagulant dose to achieve optimal pH conditions for coagulation. Both from charge neutralization and TOC removal standpoints, effective coagulant performance is typically observed at pH below 7 SU (Gebbie 2006; Naceradska et al., 2019).

Alkalinity affects both charge neutralization and electrostatic interactions during coagulation and with the same dose of coagulant, organic matter removal is poorer in high alkalinity water (Ye et al. 2007). Typically, acid addition and high coagulant dose application are necessary to overcome the buffering capacity of the water and reduce the pH to below 7. However, a minimum amount of alkalinity (> 20 mg/L as $CaCO_3$) is also necessary for coagulation and if alkalinity in the water is low, coagulant addition can depress the pH below optimal coagulation level, resulting in poorly settling flocs. Maintaining a buffer above this minimal alkalinity also provides stability in the finished water pH, which is important for mitigating distribution system corrosion (i.e., lead and copper corrosion).

The raw water and RBAT-treated ATW had similar pH (i.e., 7.75 ± 0.35 and 7.48 ± 0.28 SU, respectively; Table 4-8 above). Alkalinity in the raw water varied considerably (92.8 ± 13.7 mg/L $CaCO_3$), whereas the ATW had 33.6 ± 1.14 mg/L $CaCO_3$. Therefore, blending the ATW with the raw water was not expected to change water pH significantly. The coagulant and polymer addition to the floc/sed influent decreased water pH by approximately 0.4 to 0.8 SU (90th percentile was 0.6 SU) in the filter influent (Figure 4-32). In general, pH remained within 6.6 to 8.2 SU in the blended samples.

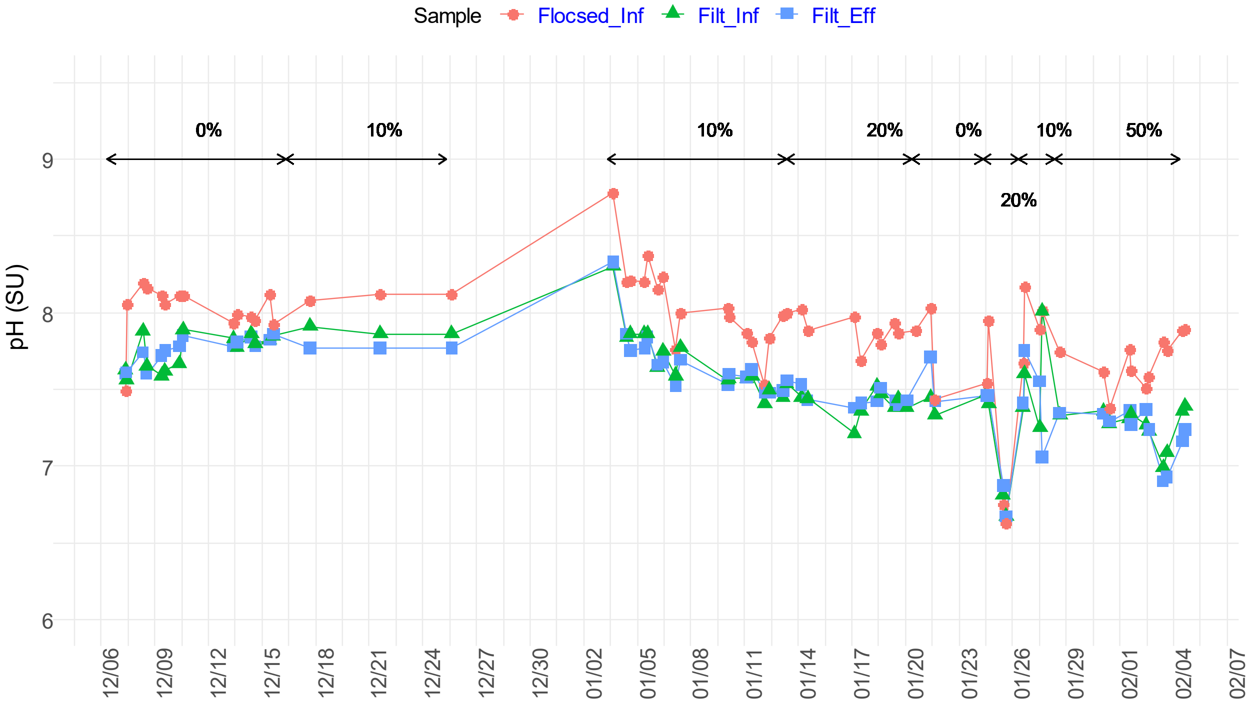


Figure 4-32. Plant A Pilot-Scale Testing – pH Across the Pilot System.

Given that alkalinity in the raw water and the ATW was 91.3 ± 14.5 and 33.6 ± 1.14 mg/L $CaCO_3$, respectively, increasing the ATW blending ratio resulted in decreasing alkalinity in blended water (i.e., Floc/sed influent) (Figure 4-33). The blended water alkalinity ranged from 57 to 110 mg/L $CaCO_3$ and was within the acceptable range for effective coagulation.

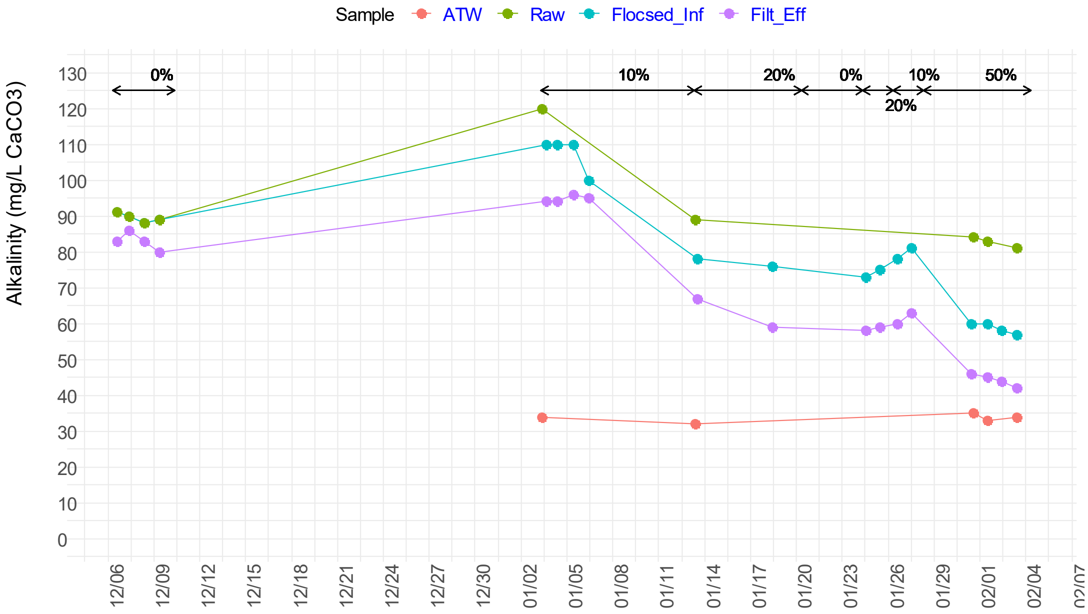


Figure 4-33. Plant A Pilot-Scale Testing – Alkalinity in the Raw Water, ATW, Blended Water, and Filter Effluent.

Hardness

Hardness affects floc aggregation and previous studies has demonstrated improved coagulation efficacy with increasing hardness (Kaleta and Puszkarewicz 2019; Wang et al. 2009). Hardness in the raw water was 125 ± 10.8 mg/L, whereas it was <3 mg/L in the ATW except for one data point (6.7 mg/L $CaCO_3$). Therefore, blending the ATW significantly decreased hardness in the blended water (i.e., Floc/sed influent) (Figure 4-34). In general, hardness in the floc/sed influent and filter effluent did not differ.

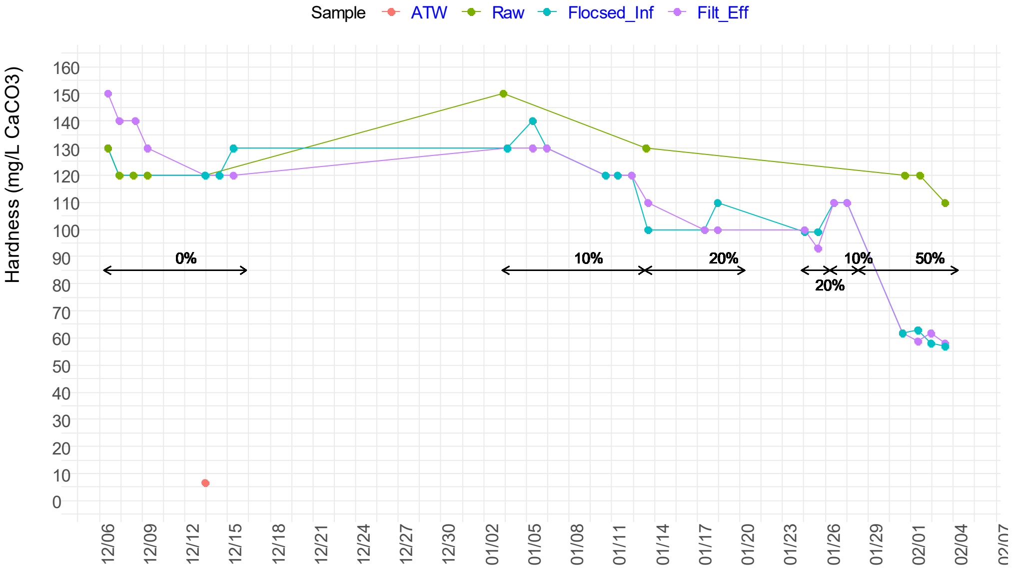


Figure 4-34. Plant A Pilot-Scale Testing – Total Hardness in the Raw Water, ATW, Floc/Sed Influent, and Filter Effluent.

Organic Matter Removal

Average absolute TOC removal across the system (i.e., across the coagulation, flocculation, sedimentation, and filtration) with the 0% (i.e., raw water), 10%, 20%, and 50% blend was 1.7 ± 0.5, 1.2 ± 0.25, 1.6 ± 0.2, and 1.3 ± 0.2 mg/L (Figure 4-35 [A]). A single-factor ANNOVA test was conducted to determine if the absolute TOC removals were significantly different. The test result (p= 0.001789) indicated that the average absolute TOC removals were not statistically similar. However, percentage TOC removals (Figure 4-35 [B]) were statically similar with the 0% and 20% blends (p=0.1073) and 0% and 50% blends (p=0.195). Percent TOC removal with the 10% blend was significantly lower than with the 0% blend.

Table 4-11 compares the achieved percent removal with the required removal (based on blended water TOC and alkalinity). While the required TOC removal with each blend was 35%, the actual removals were lower with the 10% and 20% blends. It is to be noted that the tests were conducted with a fixed set of coagulant and polymer doses and optimizing the chemical doses would support achieving TOC removal equal or greater than the required levels.

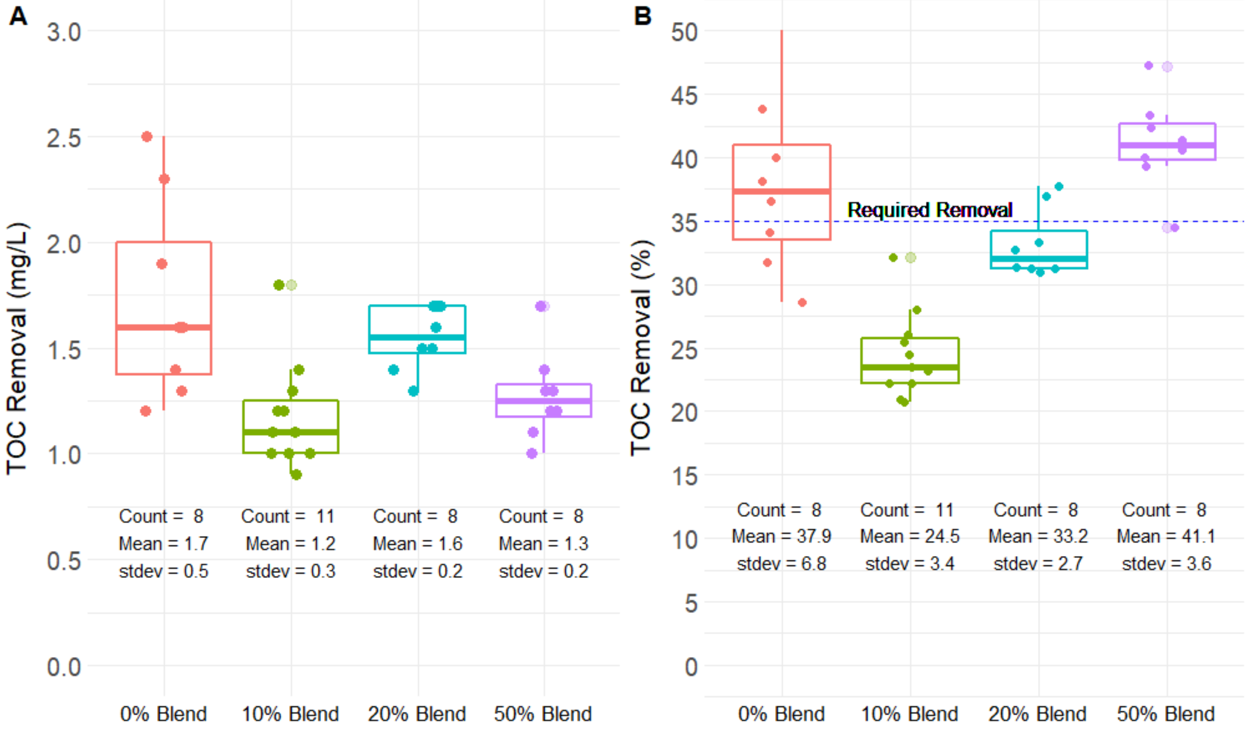


Figure 4-35. Plant A Pilot-Scale Testing – TOC Removal: Absolute (A) and Percent Removal (B).

Table 4-11. Plant A Pilot-Scale Testing – Comparison of Actual TOC Removal with the TOC Removal Requirements.

Parameter	0% Blend	10% Blend	20% Blend	50% Blend
Average blended water TOC (mg/L)	4.51	4.80	4.68	3.09
Average blended water alkalinity (mg/L $CaCO_3$)	87.6	88.9	66.6	54.4
Required TOC removal	35%	35%	35%	35%
Actual TOC removal	37.9%	24.5%	33.2%	41.1%

Significant UV_{254} removal was observed through the coagulation, flocculation, and sedimentation processes (Figure 4-36), suggesting that humic components of the influent organic matter was effectively removed. The UV_{254} removal improved with the increase in ATW blend ratio.

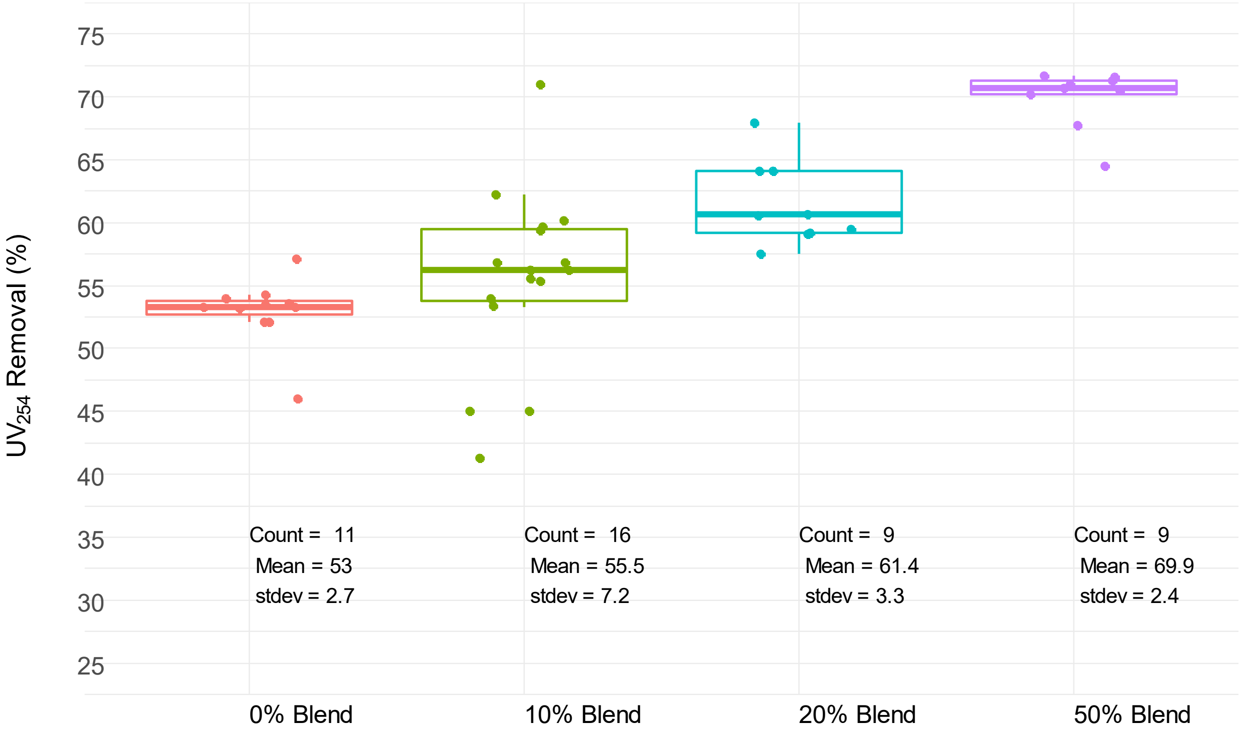


Figure 4-36. Plant A Pilot-Scale Testing – UV_{254} Removal Across the Pilot System.

4.2.1.4 Effects of ATW Blending on Disinfectant Demand and DBP Formation

Plant A practices free chlorination as the primary disinfection process at their SWTP. Water quality changes resulting from the ATW blending can affect disinfection CT operation (e.g., reduced chlorine demand) and DBP FP (e.g., less DBPs due to less DOC). To assess the potential impacts of ATW blending, disinfection demand and DBP FP tests were conducted with filter effluent samples. Table 4.12 presents the water quality characteristics of the filter effluent samples collected for this testing. As mentioned earlier, the raw water quality changed during the pilot testing, which is also reflected in the water quality characteristics of the 10% ATW blend.

Table 4-12. Plant A Pilot-Scale Testing – Water Quality Characteristics of Filter Effluent Samples Collected for Chlorine Demand and DBP FP Testing.

Parameter	ATW Blend			
	0% Blend	10% Blend	20% Blend	50% Blend
Free chlorine (mg/L)	0.01	0.01	0	0
Total chlorine (mg/L)	0.02	0.02	0.01	0.01
pH (SU)	7.04	7.54	7.33	7.19
Temperature (oC)	21	19.3	20.5	21.4
Alkalinity (mg/L $CaCO_3$)	68	90	59	44
Hardness (mg/L $CaCO_3$)	122	139	205	55
Zeta potential (mV)	-12.88	-10.69	0.4656	-1.961

Parameter	ATW Blend			
	0% Blend	10% Blend	20% Blend	50% Blend
TOC (mg/L)	4.52	3.30	2.63	1.90
DOC (mg/L)	4.47	3.26	2.62	1.93

With each filter effluent sample, 24-hour chlorine demand was evaluated with various targeted free-chlorine doses (Figure 4-37). Blending the ATW resulted in decrease in chlorine demand. The chlorine decay rate was 0.19 ± 0.03 mg/L-hr, 0.11 ± 0.02 mg/L-hr, 0.14 ± 0.03 mg/L-hr, and 0.10 ± 0.02 mg/L-hr for the 0%, 10%, 20%, and 50% ATW blend, respectively, suggesting that blending the ATW reduced the chlorine decay rate.

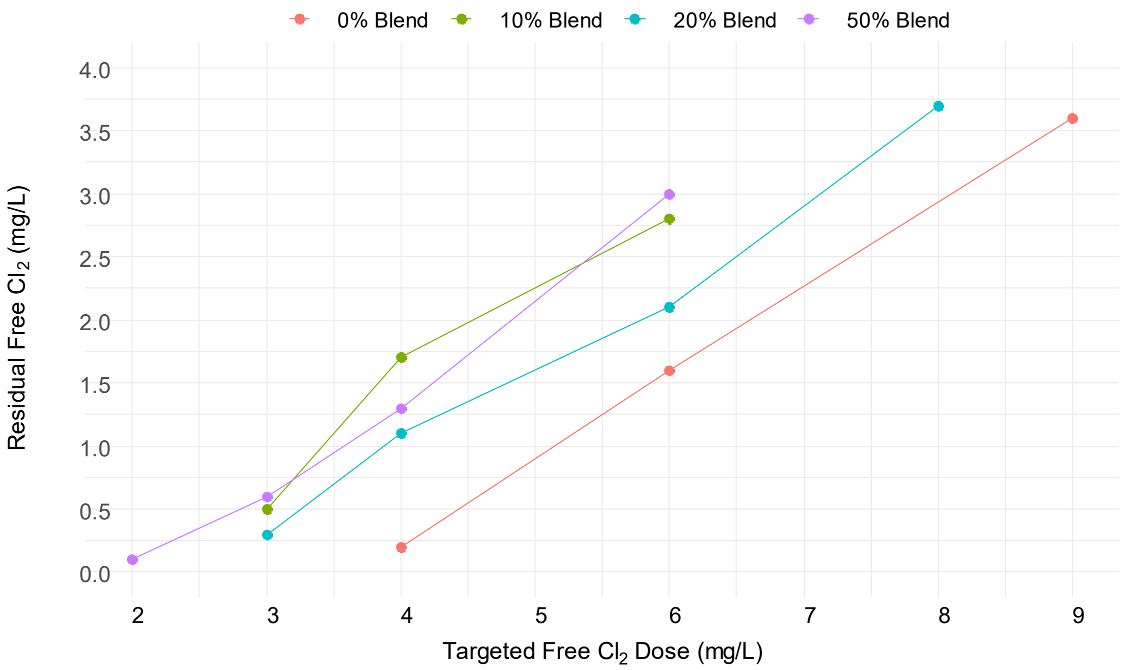


Figure 4-37. Plant A Pilot-Scale Testing – Residual Free Chlorine in Filter Effluent as a Function of Targeted Free Chlorine Dose.

The 24-hour chlorine demand testing results were used to determine the free chlorine target dose for DBP FP testing. Table 4-13 presents the results of DBP formation testing after 24 hours of incubation under UFC at room temperature. While DBP FP declined with increasing blending ratio, the total decrease cannot be attributed to the dilution effect. For example, the decrease in TTHM FP and HAA9 FP with the 50% blend compared to the 0% blend was approximately 74% and 71%, respectively, which are significantly higher than the expected 50% decrease due to the dilution. While changes in raw water characteristics between the days of the testing with the 0% and 50% blend might have partly affected the results, the data indicated that ATW blending helps minimize DBP formation in the filter effluent.

Table 4-13. Plant A Pilot-Scale Testing – DBP Formation in the Filter Effluent under UFC after 24 Hours of Incubation.

Blend	Target Free Cl_2 Dose (mg/L)	pH after 24-hour Incubation (SU)	Residual Cl_2 after 24-hour Incubation (mg/L)	Total THM (µg/L)	HAA9 (µg/L)
0% Blend	5.16	7.8	1.3	177	140
10% Blend	3.27	7.9	1.0	100	66
20% Blend	3.57	8.1	1.4	96	51
50% Blend	3.41	7.3	1.2	46	41
The results are average of 3 replicates.					

4.2.1.5 Summary of Plant A – Pilot Testing Findings

The findings from Plant A pilot testing are summarized below:

1. Water quality (including turbidity, TOC, DOC, alkalinity, hardness, Ca, and Mg) of the blends was consistent with expected quality based on the calculated mixture of the two sources.
2. Increasing blends of ATW did not significantly affect TOC removal across the pilot-scale system. With the same set of coagulant and polymer doses, TOC removal higher than the required level was observed with the 0% and 50% ATW blends. However, with the 10% and 20% ATW blends, TOC removal (i.e., 24.5% and 33.2%, respectively) was lower than the required removal (i.e., 35%). While coagulant and polymer dose optimization was beyond the scope of the study, TOC removal could be improved through coagulant and polymer dose optimization.
3. With the 10%, 20%, and 50% blends, filter effluent turbidity remained similar or better than the 0% blend.
4. Alkalinity and hardness in the blended water declined with increasing ATW blending ratio. However, the changes in the blended water alkalinity and hardness did not appear to affect TOC or turbidity removal across the system.
5. With the same terminal headloss, filter runtime increased with increasing ATW blending ratio. However, the percentage increase in filter run length is less than the percentage increase in the blending ratio, indicating that the performance improvement is not directly proportional to the percentage blending. The increase in filter run length resulted in decreasing headloss accumulation rate with increasing ATW blending ratio.
6. DBP formation declined with increasing ATW blending ratio and the percentage decrease in DBP concentrations was greater than the increase in blending ratio.

Overall, the results indicate that blending ATW with the raw water source at Plant A does not negatively affect coagulation, flocculation, and filtration process performance. In fact, ATW blending clearly provided operational benefits (i.e., longer filter runs) and better treated water (i.e., water with lower DBP FP).

4.2.2 Plant C Pilot Testing

The pilot-scale system at Plant C simulated a conventional water treatment plant with coagulation, flocculation, sedimentation, and filtration. Changes in water quality, unit process performance, pathogen removal, and particle removal were evaluated with various blends of ATW.

4.2.2.1 Effects of Blending on Water Quality (Prior to Treatment)

Grab samples of raw water and CBAT-treated ATW-blended water were collected for measuring concentrations of various water quality parameters. In general, with the increasing blending ratio, while alkalinity and conductivity increased in the blended water, pH, hardness, TOC, and UV_{254} decreased (Table 4-14).

Table 4-14. Plant C Pilot-Scale Testing – Statistical Summary of Blended Water Characteristics.

Parameter	Blend	Count	Minimum	Maximum	Average
pH (SU)	0% Blend	5	8.6	8.7	8.7
	10% Blend	3	7.0	7.2	7.1
	20% Blend	2	7.0	7.1	7.1
	50% Blend	6	7.0	7.1	7.0
Conductivity (µS)	0% Blend	5	328.0	342.0	334.6
	10% Blend	3	433.0	445.0	440.0
	20% Blend	2	491	508	500
	50% Blend	6	567.0	681.0	630.5
Alkalinity (mg/L $CaCO_3$)	0% Blend	5	88.0	89.2	88.7
	10% Blend	3	90.0	91.4	90.9
	20% Blend	2	96	98	97.0
	50% Blend	6	95.0	107.0	100.2
Total Hardness (mg/L $CaCO_3$)	0% Blend	5	133.0	136.0	134.8
	10% Blend	3	122	124	123
	20% Blend	2	124	124	124
	50% Blend	6	113	118	115
TOC (mg/L)	0% Blend	5	3.0	3.1	3.0
	10% Blend	3	2.0	2.7	2.4
	20% Blend	2	2.4	2.5	2.4
	50% Blend	6	1.6	2.0	1.9
UV_{254} (cm^{-1})	0% Blend	6	0.054	0.069	0.063
	10% Blend	3	0.049	0.050	0.050
	20% Blend	2	0.051	0.056	0.054
	50% Blend	6	0.030	0.048	0.038

4.2.2.2 Effects of ATW Blending on Filter Performance

The average filter loading rate during the pilot testing was 8.8 gpm/ft^2. Turbidity breakthrough (i.e., >0.1 NTU) and terminal headloss (i.e., 14 feet) were set as the triggers for backwashing the filter. A filter-to-waste step was implemented immediately after each backwash until the filter effluent turbidity was equal to or below 0.1 NTU. Ferric chloride and cationic polymer (Clarifloc C-308P) were fed immediately upstream of the rapid mix, targeting a final dose of 31 mg/L $FeCl_3$ and 3 mg/L cationic polymer, respectively. The doses were selected based on the full-scale operation at the time of the testing and were higher than that tested during the bench-scale evaluation. The tests with the 0%, 10%, 20%, and 50% blends were conducted with considerable time gaps between the phases (Table 4-15) due to system shutdowns for full-scale maintenance.

Table 4-15. Plant C Pilot-Scale Testing – Statistical Summary of Turbidity.

Phase	Blend	Testing Period	
		From	To
Phase I	0% Blend	March 22, 2022	April 7, 2022
Phase II	10% Blend	June 16, 2022	June 22, 2022
Phase IV	50% Blend	June 28, 2022	July 19, 2022
Phase III	20% Blend	August 15, 2022	August 19, 2022

Figure 4-38 presents filter influent and effluent turbidity in representative filter runs with the 0%, 10%, 20%, and 50% ATW blends. Seasonal variability in raw water quality was observed due to the time gaps between the phases, which is reflected in the raw water turbidity (Table 4-16). With average filter influent turbidity less than 0.5 NTU, the filter effluent turbidity remained well below 0.1 NTU regardless of the blend tested (Figure 4-38 and Table 4-16).

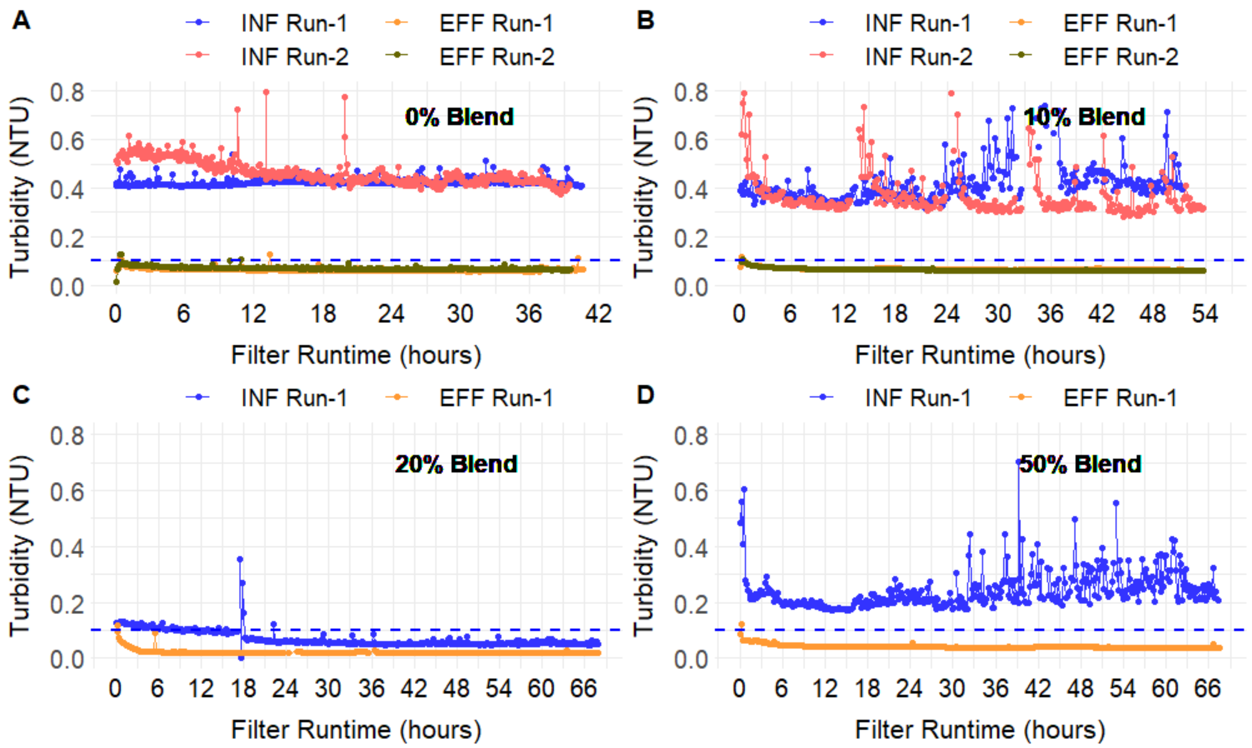


Figure 4-38.Plant C Pilot-Scale Testing – Filter Influent and Effluent Turbidity with the 0% Blend (A), 10% Blend (B), and 50% Blend (C).

Figure 4-39 presents representative headloss accumulation trends in the filter with the ATW blends tested. For these runs, filter run terminated due to high headloss (i.e., 14 feet). The longest filter run was observed with the 20% blend, which was tested at the end of the pilot testing (Table 4-15) when the raw water had significantly lower turbidity (Table 4-16). However, the results from the 0% blend and 10% blend testing suggest that filter performance was better with the ATW-blended water: headloss accumulation rate was lower with the 10% blend than with the 0% blend (Table 4-17). Therefore, it can be concluded that increasing ATW blend ratio resulted in lower headloss accumulation rate and terminal headloss (Figure 4-39), which was translated into longer filter runs with ATW-blended water. This observation is in agreement with that during the pilot-scale testing at Plants A and D.

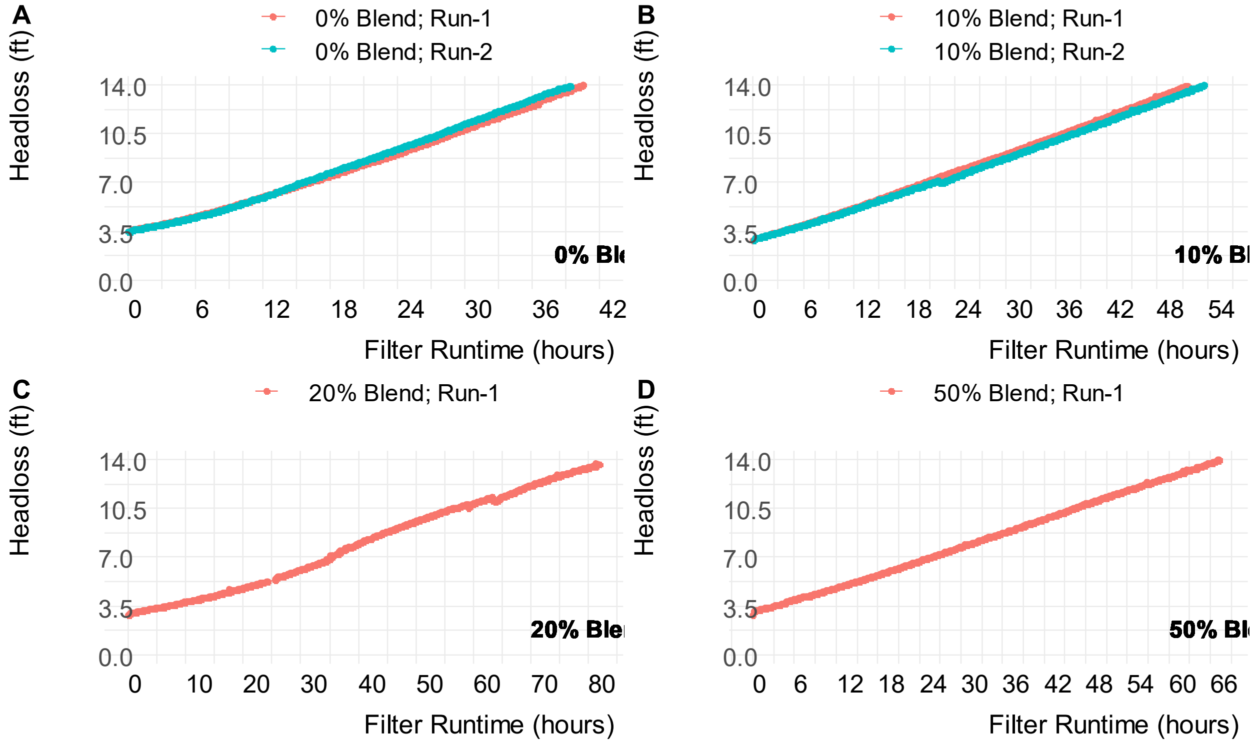


Figure 4-39. Plant C Pilot-Scale Testing – Filter Headloss with the 0% Blend (A), 10% Blend (B), 20% Blend (C), and 50% Blend (D).

Based on Figures 4-38 and 4-39 and Tables 4-16 and 4-17, it can be concluded that blending ATW did not affect turbidity removal, but rather lowered headloss accumulation rate with the increasing ATW blending ratio. However, the percentage decrease in headloss accumulation rate was not directly proportional to the percentage increase in blending ratio. For example, the decrease in headloss accumulation rate with the 10% blend compared to 0% blend was ~16%.

Table 4-16. Plant C Pilot-Scale Testing – Filter Influent and Effluent Turbidity.

	Raw Water Turbidity (NTU)*				**Filter Influent Turbidity (NTU)**				**Filter Effluent Turbidity (NTU)**			
Blend	**0%**	**10%**	**20%**	**50%**	**0%**	**10%**	**20%**	**50%**	**0%**	**10%**	**20%**	**50%**
Run 1	0.525	0.169	0.173	0.152	0.420	0.475	0.068	0.246	0.063	0.067	0.022	0.042
Run 2	0.562	0.161	N/A	N/A	0.468	0.427	N/A	N/A	0.070	0.064	N/A	N/A
Average	0.544	0.165	0.173	0.152	0.444	0.451	0.068	0.246	0.067	0.066	0.022	0.042

Table 4-17. Plant C Pilot-Scale Testing – Statistical Summary of Headloss in the Filter.

Blend	Run	Runtime (hours)	Headloss (feet)		Headloss Accumulation Rate (inch/hour)
			Clean-Bed	Terminal	
0% Blend	Run-1	40.6	3.4	14.0	3.1
	Run-2	39.5	3.4	14.0	3.2
	Average	40.05	3.4	14.0	3.1
10% Blend	Run-1	51.7	2.9	14.0	2.6
	Run-2	53.7	2.9	14.0	2.5
	Average	52.7	2.9	14.0	2.6
20% Blend	Run-1	84.0	2.8	14.0	1.6
50% Blend	Run-1	67.5	2.8	14.0	2.0

4.2.2.3 Effects of ATW Blending on Overall Water Treatment Performance

pH and Alkalinity

As seen in Table 4.14, blending the raw water with the ATW lowered the blended water pH with increasing blending ratio. Alkalinity in the floc/sed influent (range - 88 mg/L $CaCO_3$ to 100 mg/L $CaCO_3$) increased with the increasing blending ratio (Figure 4-40). The total drop in alkalinity across the coagulation, flocculation, and sedimentation was 13.0% ± 1.5%, 10.7% ± 1.4%, 12.0% ± 1.7%, and 9.2% ± 3.1% with the 0% blend, 10% blend, 20% blend, and 50% blend, respectively. The coagulant and polymer addition to the floc/sed influent decreased water pH by approximately 1.6 SU when treating the 0% blend, whereas the pH drop due to chemical addition was approximately 0.3 SU with both the 10% and 50% blends (Figure 4-41) due to higher alkalinity in the blended water.

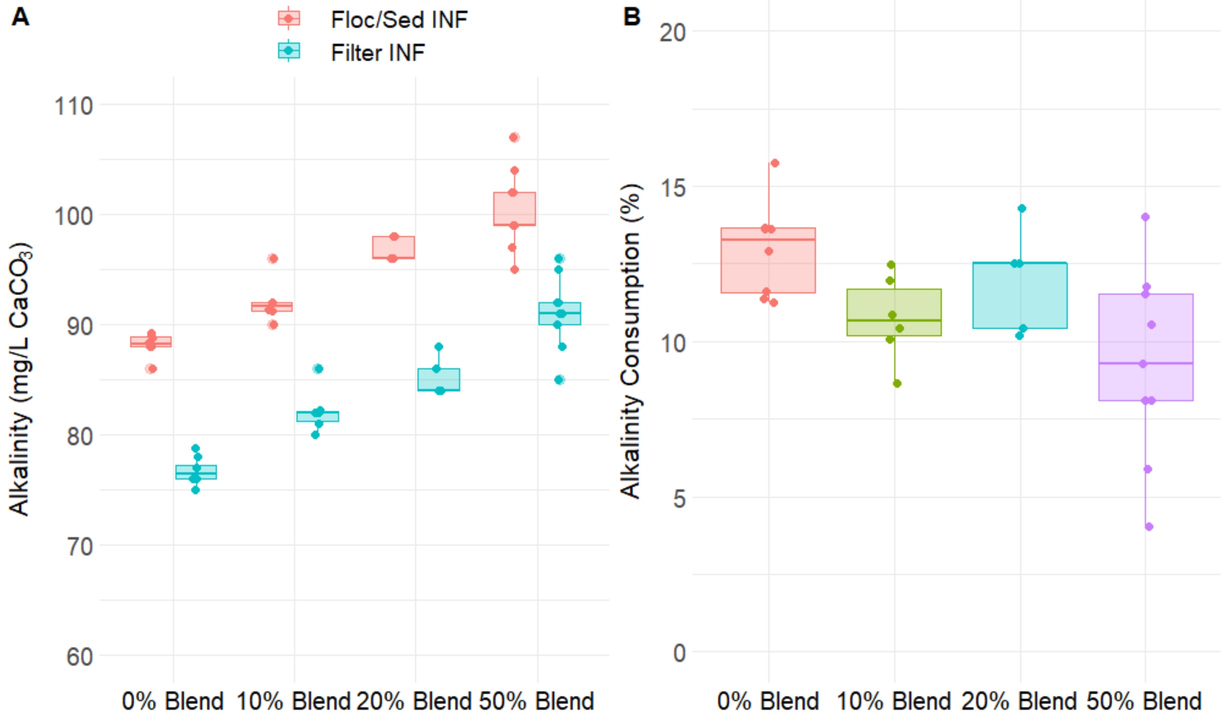


Figure 4-40. Plant C Pilot-Scale Testing – Alkalinity in the Floc/Sed Influent and Filter Effluent (A) and Alkalinity Consumption across the Pilot System (B).

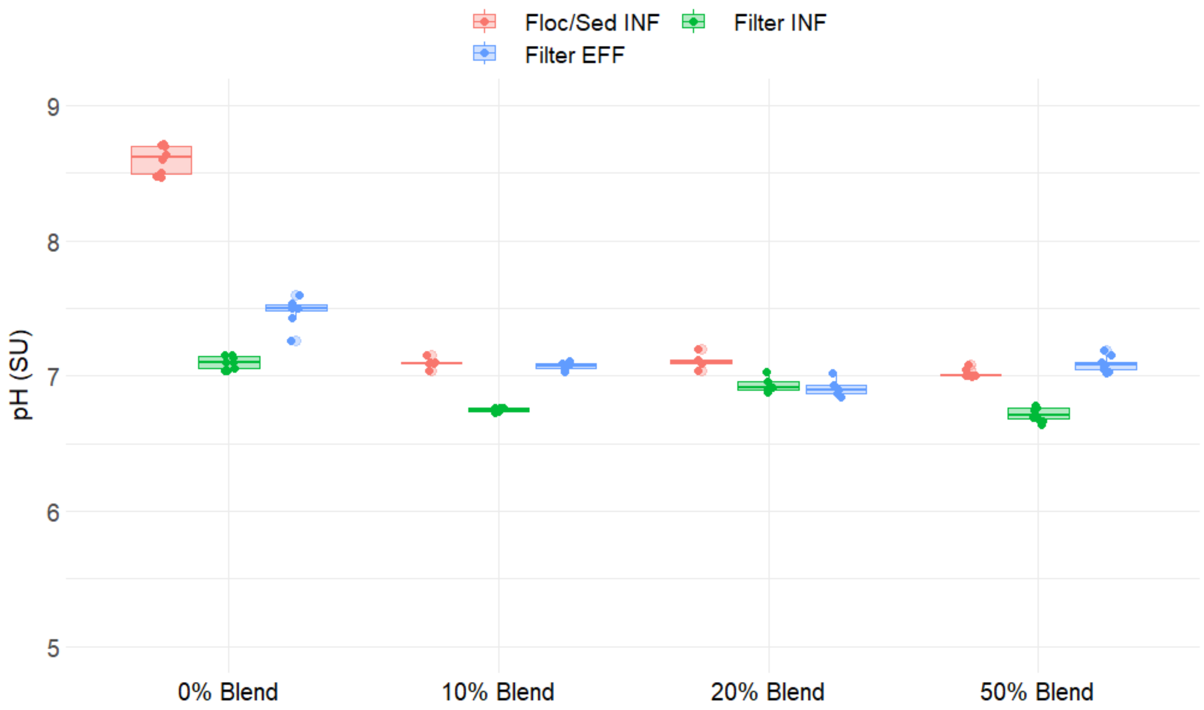


Figure 4-41. Plant C Pilot-Scale Testing – pH in the Floc/Sed Influent, Filter Influent, and Filter Effluent.

Hardness

Blending the ATW decreased hardness in the blended water (i.e., Floc/sed influent) (Figure 4-42). In general, hardness in the floc/sed influent and filter effluent did not differ much.

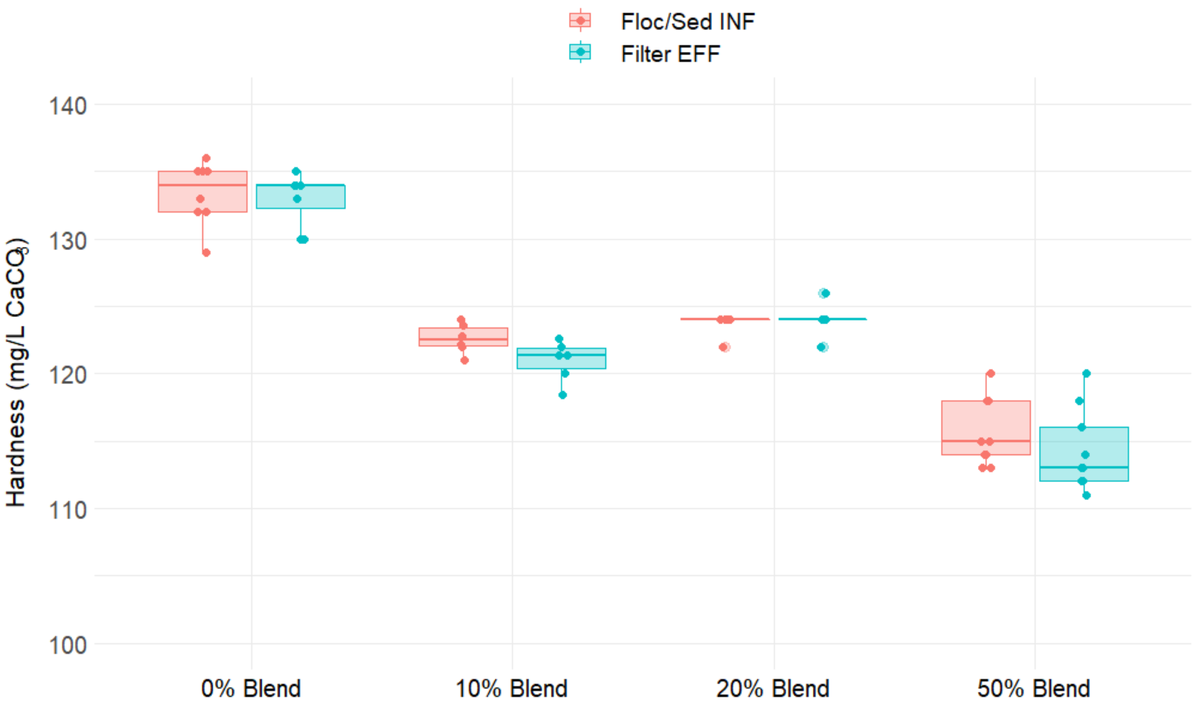


Figure 4-42. Plant C Pilot-Scale Testing – Total Hardness in the Floc/Sed Influent and Filter Effluent.

Organic Matter Removal

TOC concentrations in the blended water (i.e., floc/sed influent) was 3.0±0.1 mg/L, 2.6±0.3 mg/L, 2.7±0.2 mg/L, and 1.9±0.2 mg/L with the 0% blend, 10% blend, 20% blend, and 50% blend, respectively (Figure 4-43). TOC removal across the coagulation, flocculation, sedimentation, and filtration was 29±3%, 31±6%, 33±5%, and 25±7%, with the 0%, 10%, 20%, and 50% blend, respectively (Table 4-18). Compared to the TOC removal with the 0% blend, the TOC removal with the 10% blend (p=0.183), 20% blend (p=0.091), and 50% blend (0.091) were statistically similar, indicating that the ATW blending did not affect TOC removal.

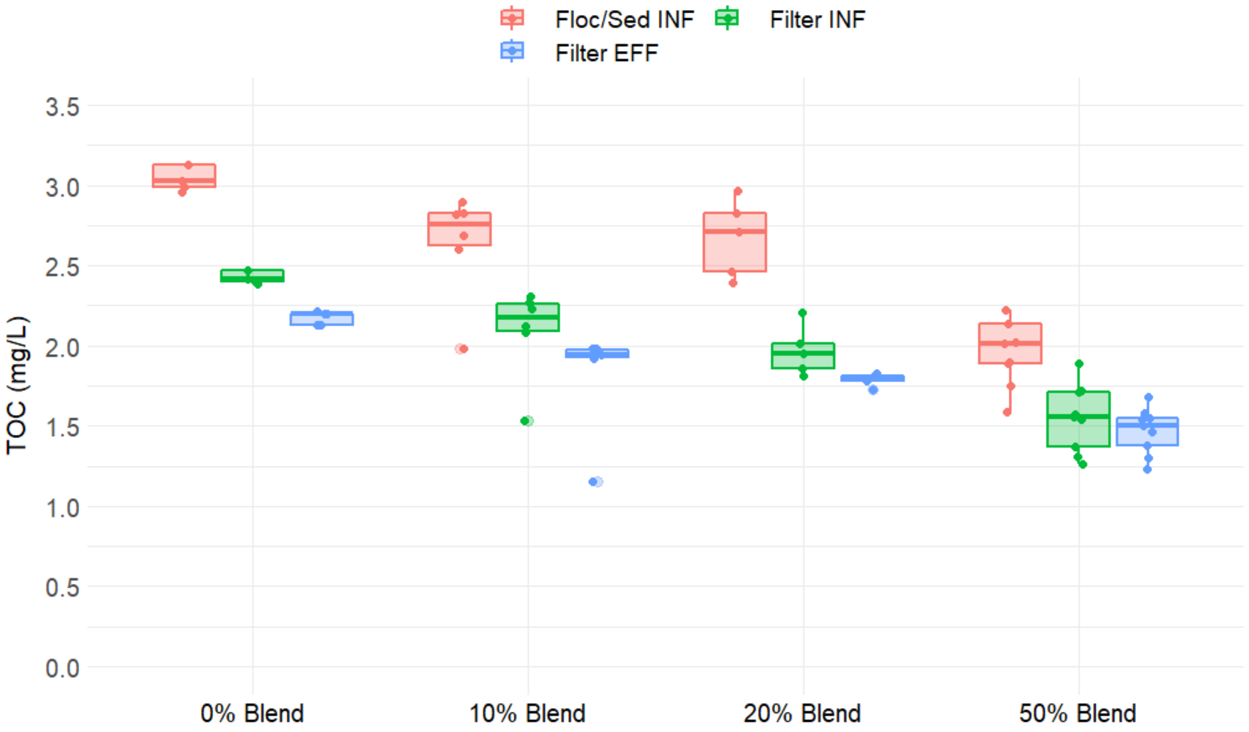


Figure 4-43. Plant C Pilot-Scale Testing – TOC Concentrations in the Floc/Sed Influent, Filter Influent, and Filter.

Table 4-18. Plant C Pilot-Scale Testing – Statistical Summary of TOC Removal Across the System.

Parameter	0% Blend	10% Blend	20% Blend	50% Blend
Minimum	25%	24%	27%	17%
Maximum	32%	42%	39%	39%
Average	29%	31%	33%	25%
Standard Deviation	3%	6%	5%	7%
90th Percentile	32%	38%	38%	32%

Table 4-19 compares the achieved TOC removal with the required removal (based on blended water TOC and alkalinity as defined by the D/DBP Rule). While the required TOC removal with each blend was 25%, the average achieved removals were equal or greater than 25%, indicating that TOC removal across the system was not affected by the ATW blending.

Table 4-19. Plant C Pilot-Scale Testing –
Comparison of Actual TOC Removal with the TOC Removal Requirements.

Parameter	0% Blend	10% Blend	20% Blend	50% Blend
Bended water TOC (mg/L)	3.0±0.1	2.6±0.4	2.7±0.2	2.0±0.2
Blended water alkalinity (mg/L $CaCO_3$)	88±1	92±2	97.0±1.1	100±4
Required TOC removal (%)	25%	25%	25%	25%
Actual TOC removal (%)	29±3%	31±6%	33±5%	25±7%
Notes: The numbers represent average ± standard deviation.				

Blending the ATW significantly lowered the humic components of the organic matter (measured as UV absorption at 254 nm wavelength) in the floc/sed influent (Figure 4-44 [A]). The humic components were effectively removed across the pilot system (average removal rate ranged from 43% to 56%) with most of the removal occurring in the filter (Figures 4-44[A] and 4-44[B]). While the average removals were not statistically different with the 0% blend, 10% blend, and 50% blend (for 0% blend and 10% blend; p = 0.116; for 0% blend and 50% blend; p = 0.162), the removal with the 20% blend was statistically higher (for 0% blend and 20% blend; p=0.006). In general, the results indicated that the removal of humic components of the organic matter was not affected by the ATW blending.

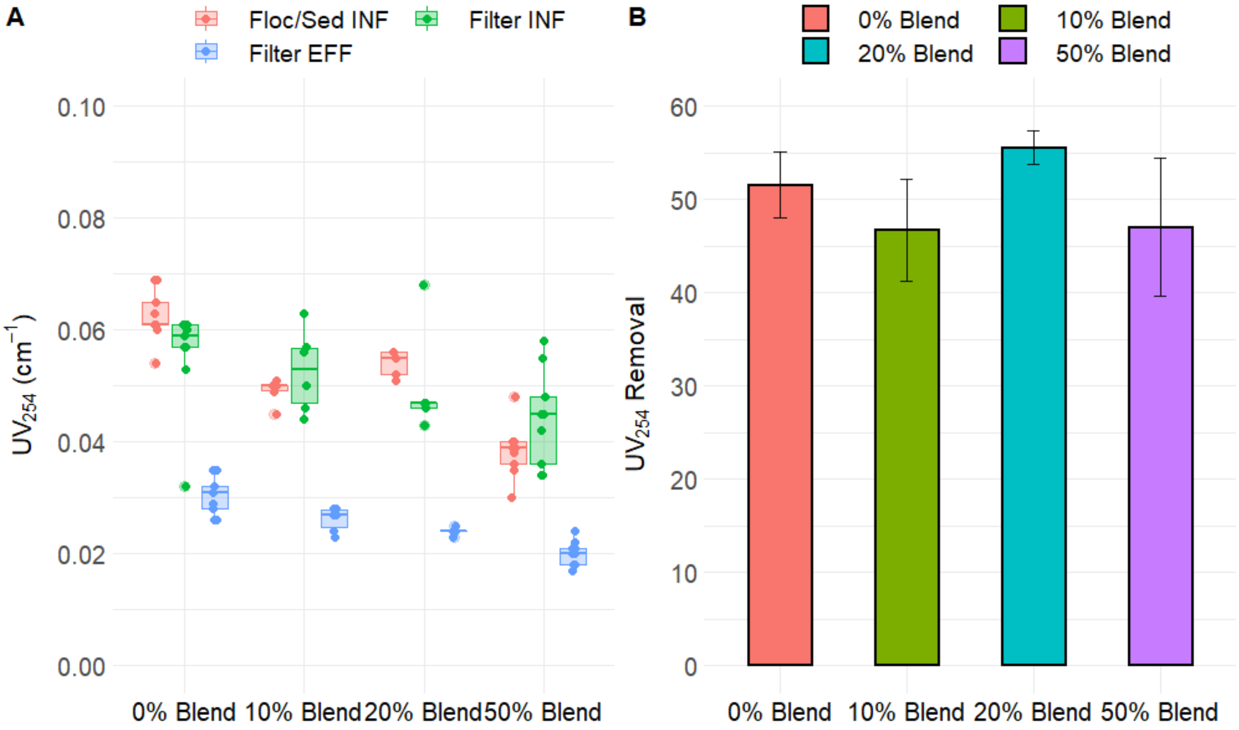


Figure 4-44. Plant C Pilot-Scale Testing – UV_{254} Concentrations in the Floc/Sed Influent, Filter Influent, and Filter Effluent (A) and UV_{254} Removal across the Pilot System (B).

4.2.2.4 Effects of ATW Blending on Disinfectant Demand and DBP Formation

To assess the potential impacts of ATW blending, disinfection demand and DBP FP tests were conducted with filter effluent samples. Table 4-20 presents the results of the testing after 24 hours of incubation at room temperature. While pH was adjusted in the samples, targeting approximately 8 SU in the samples before incubation, the test was conducted with a constant dose of 1 mg/L free chlorine before incubation. The residual free chlorine after 24 hours of incubation increased with the increase in ATW blending ratio, confirming that blending the ATW lowered the disinfectant demand. While TTHM concentration increased with the increasing blending ratio, HAA5 concentrations were similar in all blends tested.

Compared to the results from the pilot testing at Plant A, the results were very different. At Plant A, both TTHM and HAA9 FP significantly declined with the increase in the ATW blending ratio (Table 4-13), whereas TTHM FP increased with the increasing blending ratio at Plant C (Table 4-20). However, it cannot be ruled out that the higher disinfectant requirement (reflected by the significantly lower residual free chlorine) in the 0% blend (i.e., raw water) at Plant C likely affected the DBP formation. In contrast to TTHM FP, the HAA5 FP was similar to the blends tested (Table 4-20). Furthermore, there was no direct relationship between the percentage increase in the TTHM FP and the percentage increase in the ATW blending ratio. Given the tests were conducted with a single sample for each blend, additional testing is warranted for confirmation of the results.

Table 4-20. Plant C Pilot-Scale Testing – DBP Formation in the Filter Effluent under UFC after 24 Hours of Incubation.

Blend	Target Free Cl_2 Dose (mg/L)	pH before 24-hour Incubation (SU)	Residual Cl_2 after 24-hour Incubation (mg/L)	Total THM (µg/L)	HAA5 (µg/L)
0% Blend	1.0	8.09	0.05	26.5	12.6
10% Blend	1.0	8.08	0.18	29.6	12.9
20% Blend	1.0	8.12	0.20	29.5	13.5
50% Blend	1.0	8.03	0.22	40.1	13.3

4.2.2.5 Summary of Plant C Pilot Testing

The findings from Plant C pilot testing are summarized below:

1. Alkalinity and hardness increased with increasing blending ratio, whereas concentrations of other water quality parameters decreased.
2. With the same set of coagulant and polymer doses, statistically similar TOC removals were observed with the 0%, 10%, and 50% blends. The average TOC removals were higher than the required removal (i.e., 25% based on the blended water TOC and alkalinity) irrespective of the blends tested.
3. Filter effluent turbidity remained similar with all blends tested and was consistently equal or less than 0.07 NTU.
4. With the same terminal headloss, filter runtime increased with increasing ATW blending ratio. Thus, headloss accumulation rate decreased with increasing ATW blending ratio. However, the decrease in headloss accumulation rate was not directly proportional to the increase in blending ratio.
5. Disinfectant demand declined with increasing ATW blending ratio. While TTHM concentration increased with increasing blending ratio, similar HAA5 formation was observed with all blends tested.

Overall, the results of pilot scale testing at Plant C indicate that blending ATW with the raw water source would not negatively affect coagulation, flocculation, and filtration process performance. In fact, ATW blending can provide additional operational benefits (i.e., lower headloss in the filter and longer filter runs).

4.2.3 Plant D Pilot Testing

The pilot-scale system at Plant D simulated a direct filtration system with pre-ozonation and consisted of ozone treatment, coagulation, flocculation, and filtration in series. The testing focused on evaluating the effects of pre-ozonation on turbidity removal along with the effects of blending on coagulation, flocculation, and filtration process performance.

4.2.3.1 Effects of ATW Blending on Water Quality (Prior to Treatment)

Raw water and ATW water samples were collected during the pilot testing to characterize the source waters before blending. Table 4-21 presents statistical summary of the analysis results for the two water sources. As expected, the ATW had considerably lower TOC, DOC, alkalinity, and UV_{254} compared to the raw water. Hardness and conductivity in the ATW were significantly higher than the raw water because stabilized ATW (stabilized with calcium chloride and sodium hydroxide) was collected for the pilot testing. Based on the average TOC and turbidity concentrations in the raw water and ATW, significant reduction in TOC concentrations and turbidity can be achieved due to dilution upon blending the ATW. For example, while approximately 8 % TOC reduction from the raw water concentration (i.e., from 2.72 to 2.51 mg/L TOC) was achieved by blending ATW by 10%, the 40% ATW blend resulted in approximately 44% reduction in the TOC concentration (i.e., from 2.72 to 1.89 mg/L TOC). In general, the measured concentrations matched the calculated concentrations, suggesting the dilution effect when blending ATW with the raw water (Table C-8, Appendix C).

Table 4-21. Plant D Pilot-Scale Testing – Statistical Summary of Lab Results for the Raw Water and ATW.

	UV$_{254}$ (cm^{-1})		Turbidity (NTU)		Conductivity (µS/cm)		pH (SU)		TOC (mg/L)		DOC (mg/L)		Alkalinity (CaCO$_3$ mg/L)		Hardness (CaCO$_3$ mg/L)	
	Raw Water	ATW	Raw Water	ATW	Raw Water	ATW	Raw Water	ATW	Raw Water	ATW	Raw Water	ATW	Raw Water	ATW	Raw Water	ATW
Count	10	6	8	6	8	6	8	6	10	6	9	6	9	6	9	6
Minimum	0.052	0.008	1.41	0.16	316	544	8.48	7.85	2.38	0.34	2.29	0.37	135	32	84	110
Maximum	0.075	0.017	3.02	0.87	328	679	8.61	8.17	3.68	1.53	3.37	1.55	138	81	94	118
Average	0.064	0.011	1.90	0.45	323	622	8.55	7.99	2.72	0.65	2.59	0.68	136	45	90	113
Standard Deviation	0.008	0.004	0.53	0.25	4.4	52.5	0.05	0.12	0.38	0.46	0.32	0.45	1	18	4	3

4.2.3.2 Effects of Pre-Ozonation

The ozone skid contained five 6-inch columns with the provision for introducing ozone gas into the bottom of the first 2 columns. During this pilot testing, ozone was bubbled into the water only in the first column and dissolved ozone was measured in the mid-section of the second column. The ozone skid was operated with a target dissolved ozone concentration ranging from 0.3 to 0.7 mg/L. In agreement with previous studies (Amirsardari et al. 1997; Jekel 1983; Prendiville 1986) and experience at Plant D, pre-ozonation was critical for maintaining low turbidity in the filter effluent (Figure 4-45). When dissolved ozone concentration was below detection, the turbidity started rising and attained the maximum level. After re-establishing the ozone concentration, turbidity declined. The time lag (approximately 1 hour) observed between the ozone dose adjustment and filter effluent turbidity was associated with the total hydraulic retention time across the pilot-scale system.

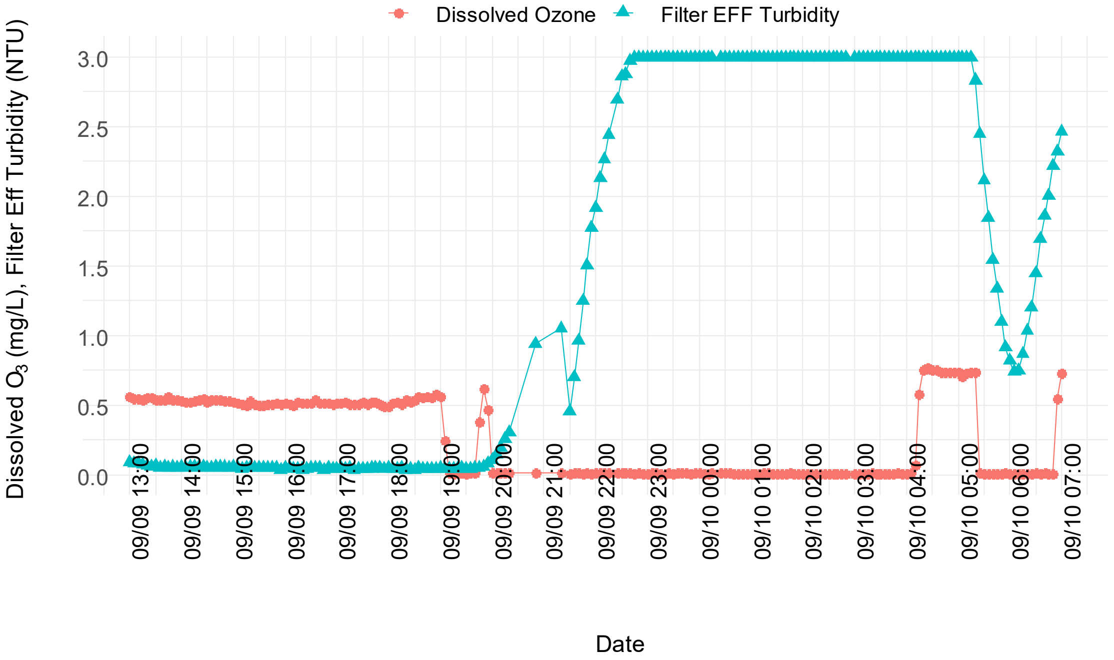


Figure 4-45. Plant D Pilot-Scale Testing – Effects of Pre-ozonation on Filter Effluent Turbidity. Effects of ATW Blending on Filter Performance.

The average filter loading rate for the full-scale filters at Plant D is 7.5 gpm/ft^2 with a capacity to operate at loading rate up to 13.2 gpm/ft^2. The pilot-scale filter was operated with a filter loading rate of 10.2 gpm/ft^2, which is the maximum possible loading rate based on the pilot-scale filter design, throughout the pilot testing. Turbidity breakthrough (i.e., >0.3 NTU), terminal headloss (i.e., 4.5 feet), and UFRV (12,000 gal/ft^2; equivalent to a filter runtime of 19.6 hours) were set as the triggers for backwashing the filter. Figures 4-46 presents filter effluent turbidity in representative filter runs with the 0% blend, 20% blend, and 50% blend, respectively. Both ferric chloride and cationic polymer were fed, targeting a dose of 0.9 mg/L in the floc/sed skid influent during these filter runs.

During a filter run, filter effluent turbidity typically remained well below 0.2 NTU. During the first filter run with the 0% blend, the filter was accidentally operated with a filter loading rate of

2.55 gpm/ft^2 from runtime 0 to 2 hours, which resulted in significantly lower filter effluent turbidity (Figure 4-46 [A]). The importance of consistent ozone feed for ensuring low turbidity in the filter effluent was observed again during the first filter run with the 20% blend. From filter runtime 0 to 9 hours, ozone could not be fed continuously due to some operational challenges with the ozone skid, which resulted in filter effluent turbidity up to 0.35 NTU (Figure 4-46 [B]). During the second filter run with the 50% ATW blend (Figure 4-46 [C]), while no filter ripening was observed, turbidity breakthrough occurred towards the end of the run. This was likely related to the relatively higher turbidity observed throughout this run, indicating that the backwash prior to this run was likely not effective.

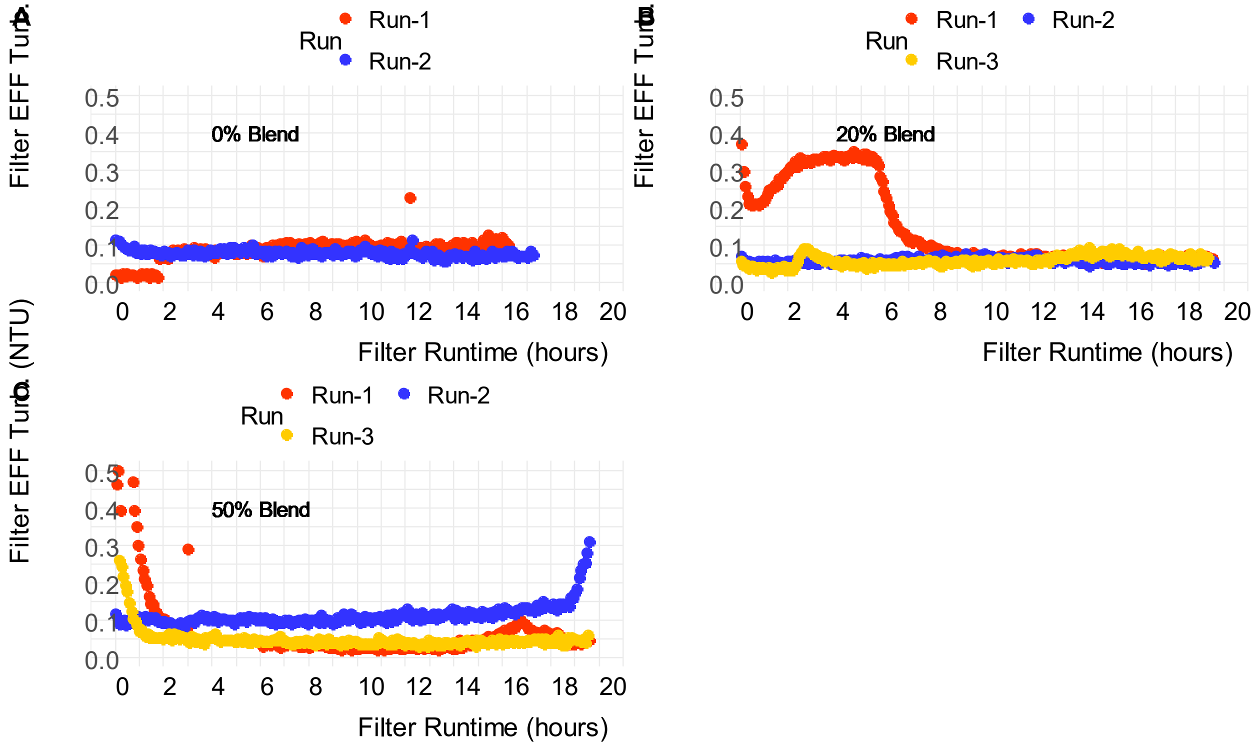


Figure 4-46. Plant D Pilot-Scale Testing – Filter Effluent Turbidity with the 0% Blend (A), 20% Blend (B), and 50% Blend (C).

Figure 4-47 presents headloss accumulation trend in the filter with the 0% blend, 20% blend, and 50% blend, respectively. With the 0% blend, headloss accumulation (the limit was 4.5 feet) triggered the backwash (Figure 4-47 [A]), whereas the filter runtime limit (i.e., 19.6 hours) triggered the backwash when treating the 20% and 50% blends (Figures 4-47 [B] and 4-47 [C]). In other words, the headloss accumulation rate and terminal headloss (i.e., the headloss at the end of the filter run) declined with the increase in ATW blending percentage. The accidental filter operation with 2.55 gpm/ft^2 filter loading rate during the first filter run with the 0% blend resulted in significantly lower headloss (Figure 4-47 [A]).

Tables 4-22 and 4-23 summarize the filter effluent turbidity and headloss in the filter with the 0%, 20%, and 50% blends.

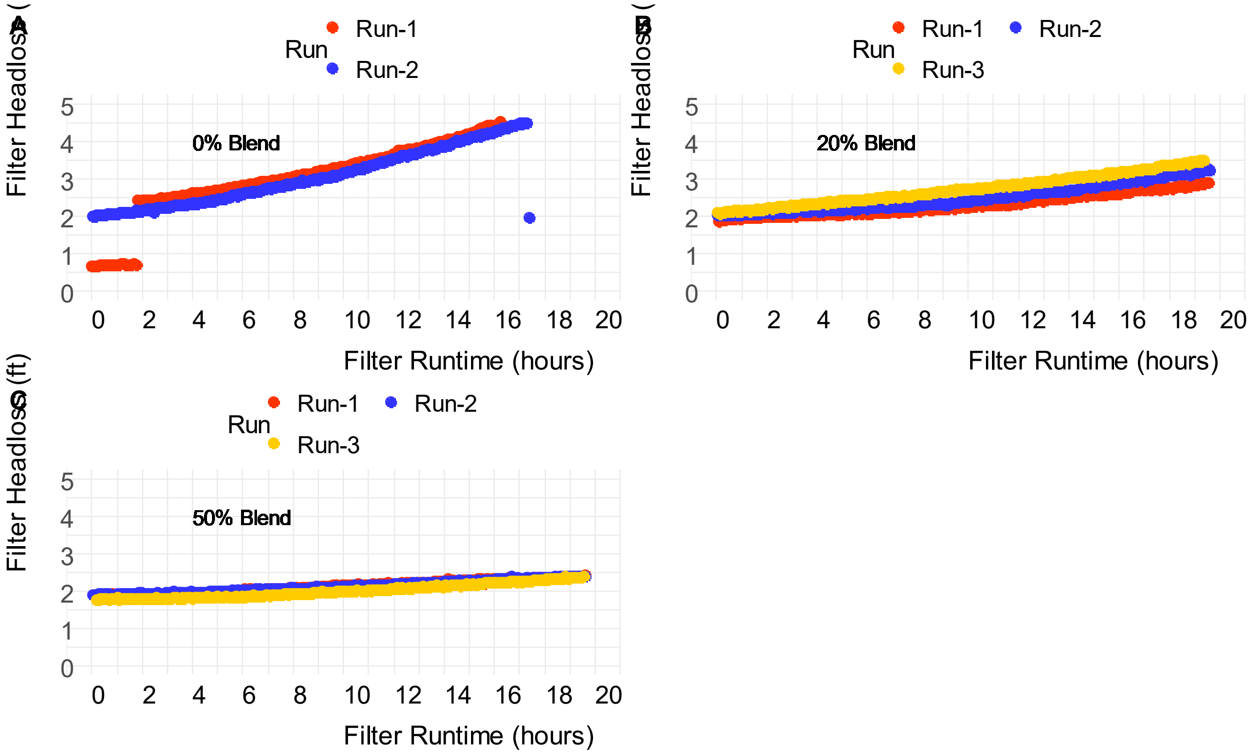


Figure 4-47. Plant D Pilot-Scale Testing – Filter Headloss with the 0% Blend (A), 20% Blend (B), and 50% Blend.

Table 4-22. Plant D Pilot-Scale Testing – Filter Effluent Turbidity.

	Filter Run Length (hour)	Average Filter Effluent Turbidity (NTU)		
		0% Blend	20% Blend	50% Blend
Run 1	16.2	0.10[(1)]	0.06[(2)]	0.08
Run 2	17.4	0.09	0.06	0.11
Run 3	N/A	N/A	0.06	0.05
Average	16.80	0.09	0.06	0.08

Notes:

1. Turbidity data for the period with 2.55 gpm/ft2 filter loading rate (i.e., from 0 to 2 hours runtime) were removed for the calculations.
2. Turbidity data for the inconsistent ozone feed period (i.e., from 0 to 9 hours runtime) were removed for the calculations.

Table 4-23. Plant D Pilot-Scale Testing – Statistical Summary of Headloss in the Filter.

Headloss Summary		ATW Blend		
		0% Blend	20% Blend	50% Blend
Run Length (hours)	Run-1	16.24	19.54	19.58
	Run-2	17.36	19.62	19.59
	Run-3	NA	19.36	19.55
	Average	16.80	19.51	19.57
Clean-bed Headloss (feet)	Run-1	2.40[(1)]	1.86	1.88
	Run-2	1.99	2.02	1.89
	Run-3	NA	2.08	1.76
	Average	2.20	1.99	1.84
Terminal Headloss (feet)	Run-1	4.51	2.90	2.41
	Run-2	4.49	3.23	2.40
	Run-3	NA	3.50	2.38
	Average	4.50	3.21	2.40

Headloss Summary		ATW Blend		
		0% Blend	20% Blend	50% Blend
Headloss Accumulation Rate (Inch/hour)	Run-1	1.56(1)	0.64	0.33
	Run-2	1.72	0.74	0.31
	Run-3	NA	0.88	0.38
	Average	1.64	0.75	0.34

Notes:

1. Headloss data for the period with 2.55 gpm/ft2 filter loading rate (i.e., from 0 to 2 hours runtime) were removed for the calculations.

Based on Figures 4-47 and 4-48, and Tables 4-22 and 4-23, it can be concluded that ATW blending did not affect turbidity removal. Furthermore, headloss accumulation rate and terminal headloss declined with the increasing ATW blending ratio.

4.2.3.3 Effects of ATW Blending on Overall Water Treatment Performance

pH and Alkalinity

The RBAT-treated ATW used for the pilot testing was stabilized before collection with calcium chloride and sodium hydroxide. As shown in Table 4-19 in Section 4.2.3.1, the raw water and ATW pH was 8.55 ± 0.05 and 7.99 ± 0.12 SU, respectively. Alkalinity in the raw water and the ATW was 135.8 ± 0.9 and 45.3 ± 17.7, respectively. Therefore, blending the ATW with the raw water was not expected to change water pH significantly. The coagulant addition to the ozone skid effluent decreased water pH by approximately 0.2 to 0.3 SU in the filter influent (Figure 4-48). However, in general pH remained within 8 to 8.5 SU in the samples irrespective of the blending ratio.

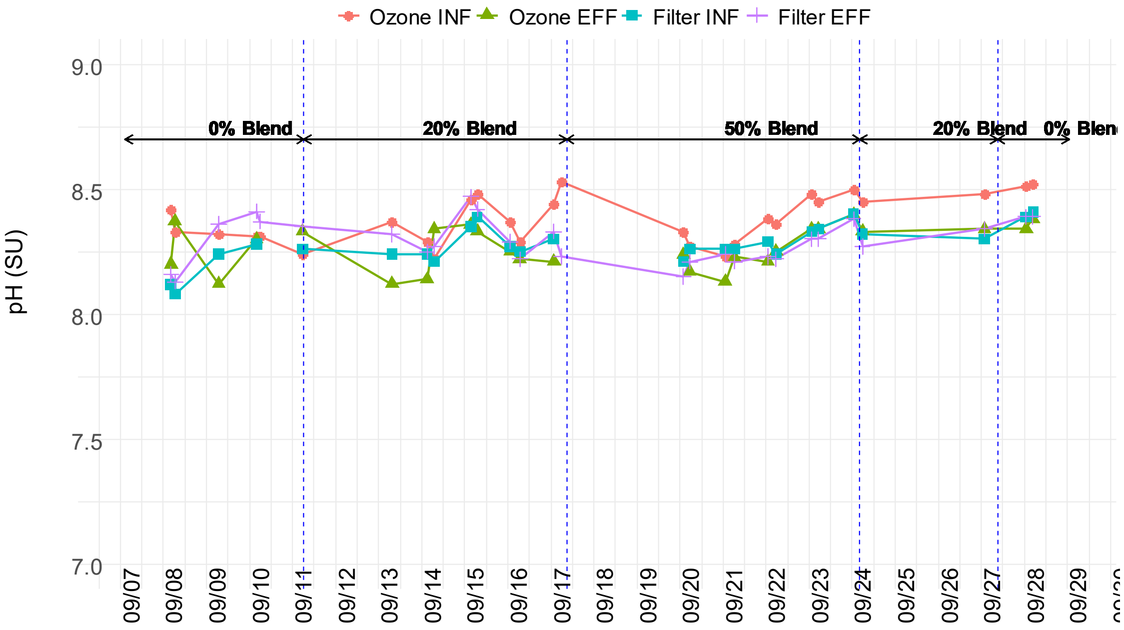


Figure 4-48. Plant D Pilot-Scale Testing – pH Across the Pilot System.

Given that the alkalinity in the raw water and the ATW was 135.8 ± 0.9 and 45.3 ± 17.7, respectively, increasing the ATW blending ratio resulted in decreasing alkalinity in the ozone skid influent (Figure 4-49). In general, alkalinity was not much affected across the system. The average alkalinity in the 0% blend, 20% blend, and 50% blend was 136.6, 117.3, and 93.3 mg/L as $CaCO_3$, respectively, and was within an acceptable range for coagulation.

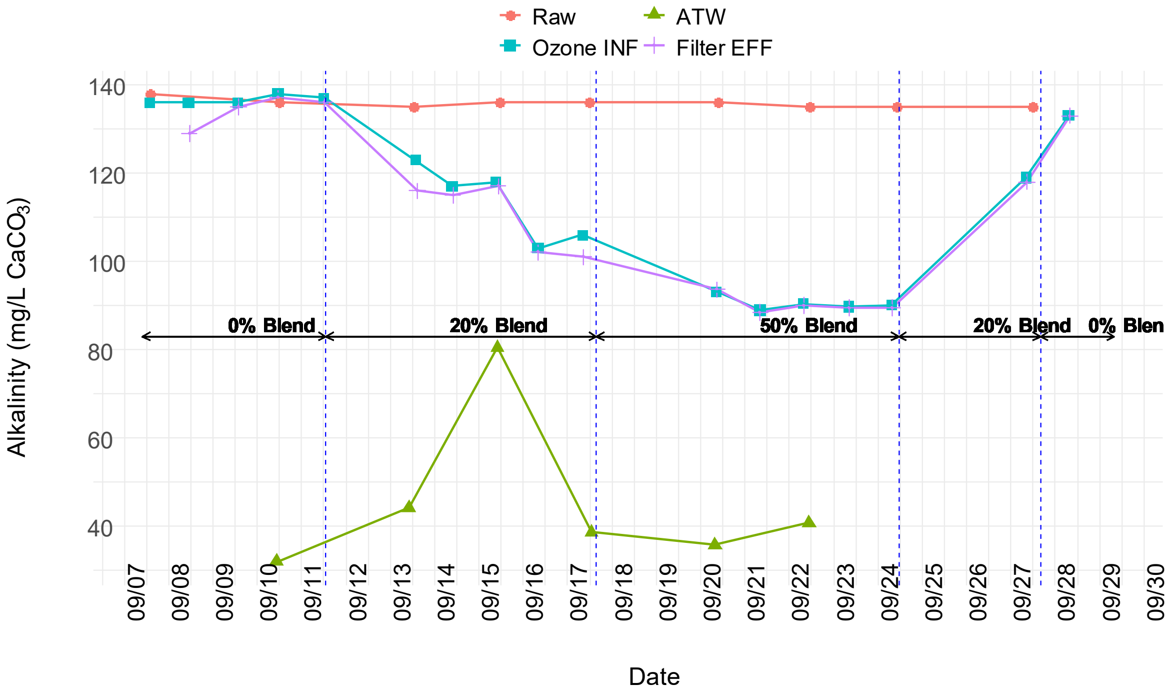


Figure 4-49. Plant D Pilot-Scale Testing – Alkalinity in the Raw Water, ATW, Ozone Skid Influent and Filter Effluent.

Hardness

Given that stabilized ATW was used for the pilot testing, total hardness increased with increasing ATW blending ratio (Figure 4-50), suggesting that better coagulation efficiency might be observed with increased ATW blending ratio. In general, hardness was not much affected across the pilot-scale system.

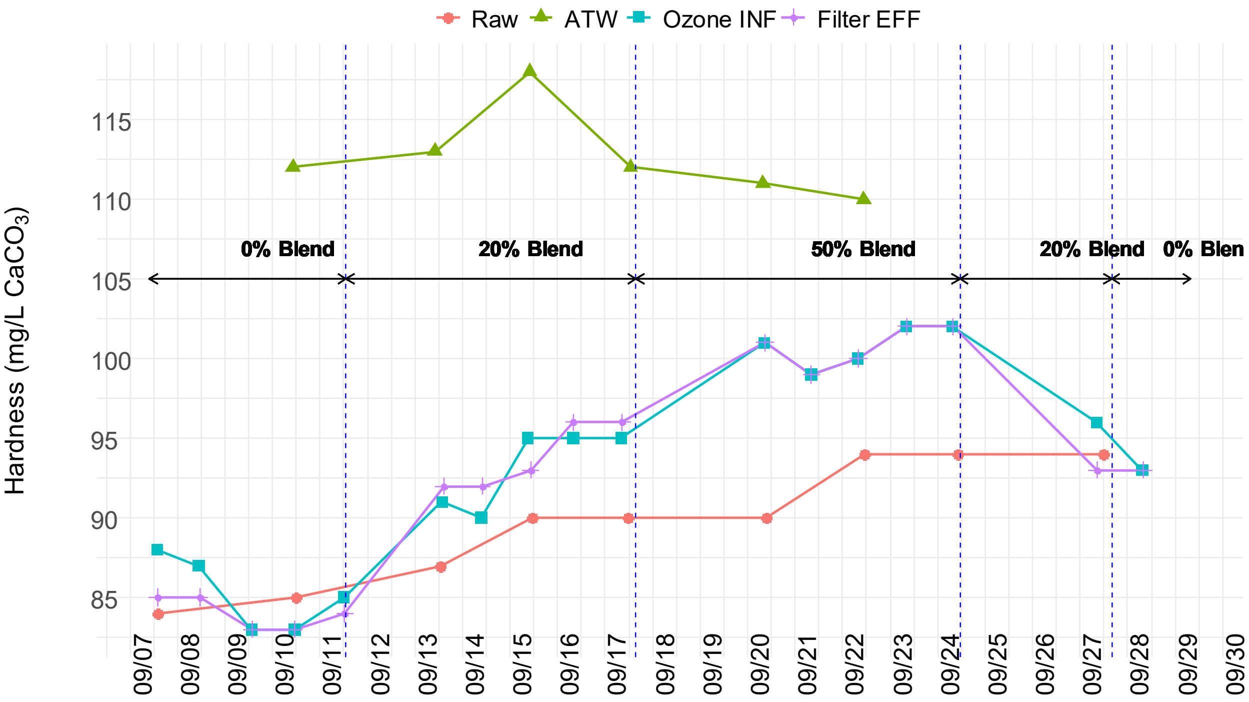


Figure 4-50.Plant D Pilot-Scale Testing – Total Hardness in the Raw Water, ATW, Ozone Skid Influent and Filter Effluent.

Organic Matter Removal

Figure 4-51 presents ozone skid influent (i.e., blended water) and filter effluent TOC concentrations. Increasing the ATW blending ratio resulted in decreasing TOC concentration in the blended water (i.e., the ozone skid influent) and the filter effluent. While absolute TOC removal was lower with the 20% blend and 50% blend than the 0% blend (Figure 4-52 [A]) likely due to lower influent TOC concentrations, the percentage removals were statistically similar in the three blends evaluated (Figure 4.52 [B]).

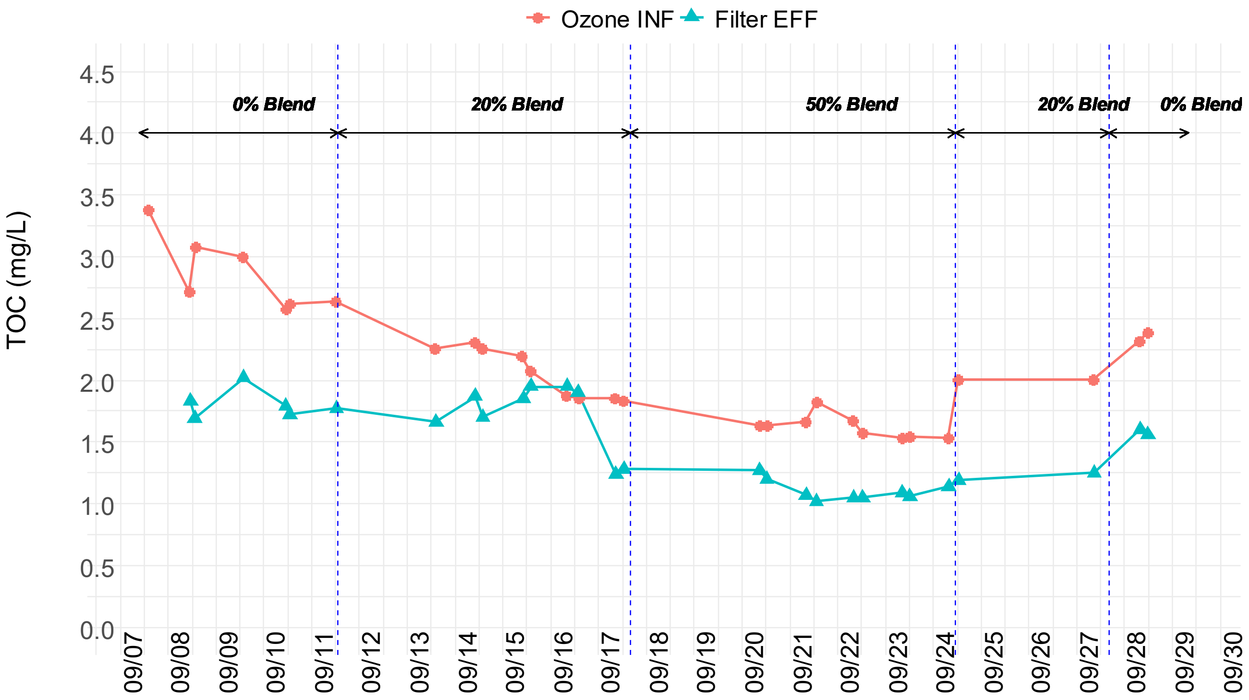


Figure 4-51. Plant D Pilot-Scale Testing – TOC Concentrations across the System (A) and Absolute TOC Removal.

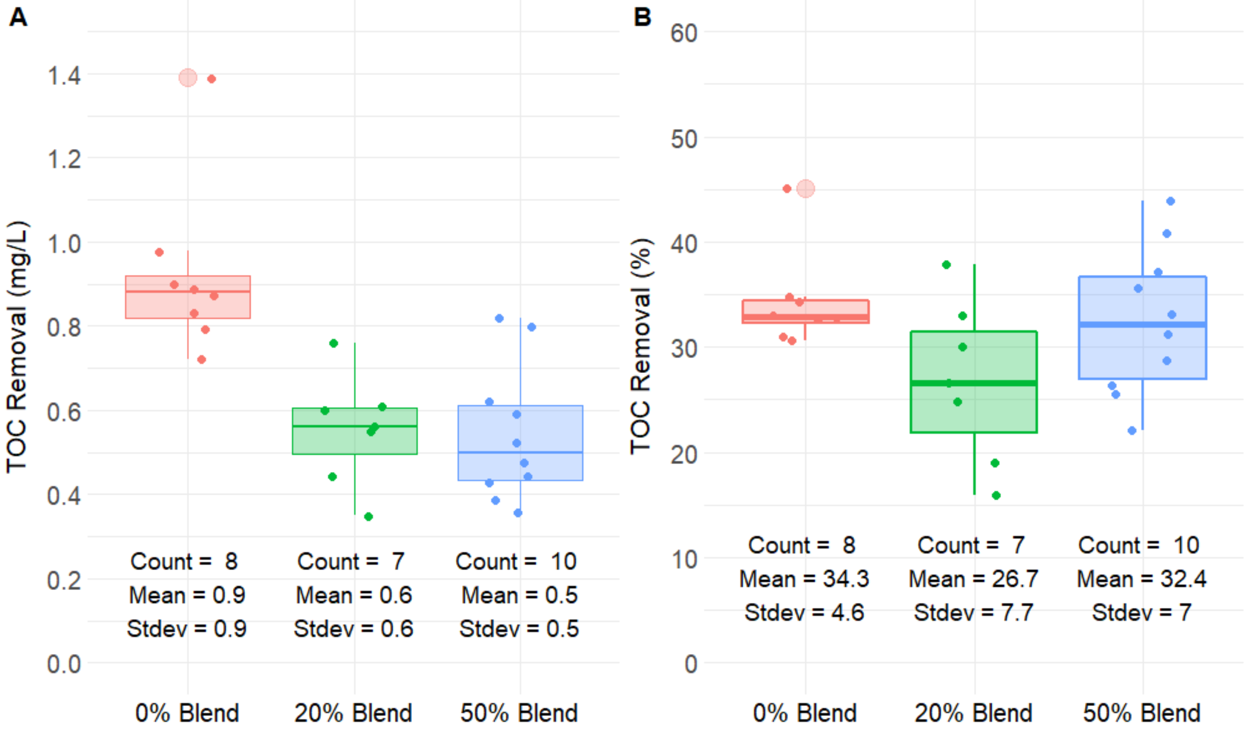


Figure 4-52. Plant D Pilot-Scale Testing – TOC Removal across the System: Absolute Removal (A) and Percent Removal (B).

Though Plant D is a direct filtration facility and TOC removal is not the primary treatment goal, the average actual TOC removal was compared with the TOC removal requirement for coagulation (Table 4-24). The actual TOC removal achieved in the system exceeded the required percentage TOC removal for each ATW blend.

Table 4-24. Plant D Pilot-Scale Testing – Comparison of Actual TOC Removal with the TOC Removal Requirements.

Parameter	0% Blend	20% Blend	50% Blend
Average Blended Water TOC (mg/L)	2.86	2.12	1.69
Average Blended Water Alkalinity (mg/L $CaCO_3$)	136.6	117.3	93.3
Required TOC removal	15%	25%	Alternative compliance criteria will be applicable.(1)
Actual TOC Removal	34.3%	26.7%	32.4%

Notes:
1. Since the blended water TOC was <2 mg/L, alternative compliance criteria would be applicable.

As expected, the RBAT treated ATW had considerably lower UV$_{254}$ concentration (i.e., 0.011 ± 0.004 cm^{-1}) compared to the raw water (0.064 ± 0.008; Table 4-19 in Section 4.3.2.1). Accordingly, increasing the ATW blending ratio resulted in decreasing UV$_{254}$ in the ozone skid influent (blended water). Despite the differences in the blended water UV$_{254}$ concentrations, the filter effluent was more or less similar throughout the pilot testing (Figure 4-53), suggesting that humic component of the organic matter was effectively removed through coagulation, flocculation, sedimentation, and filtration.

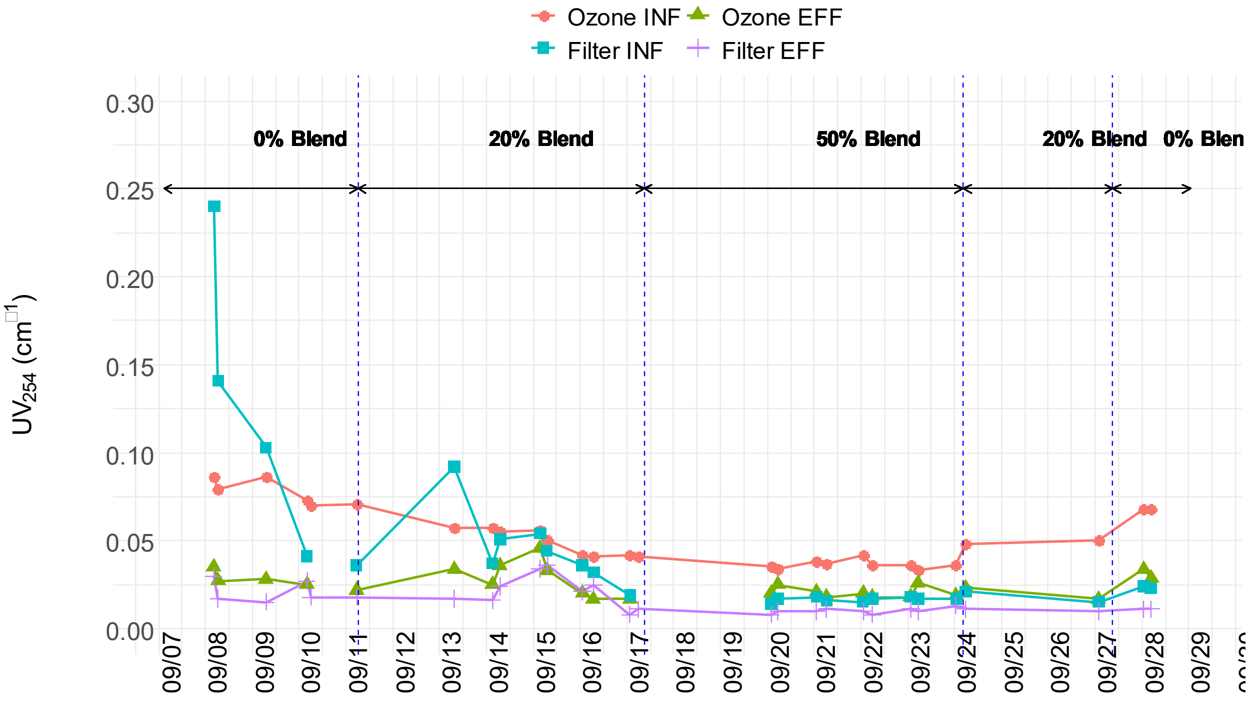


Figure 4-53. Plant D Pilot-Scale Testing – UV$_{254}$ Across the Pilot System.

4.2.3.4 Effects of ATW Blending on Disinfectant Demand and DBP Formation

Plant D practices chloramination as the primary disinfection process after UV disinfection. Changing water qualities resulting from the ATW blending can affect disinfection CT requirements and DBP formation potential. To assess the potential impacts of ATW blending, disinfection demand and DBP FP testing were conducted with biofilter effluent.

To determine the chlorine (Cl_2) dose to be applied with the 0% blend, a pre-test was done with three different free chlorine doses and residual chlorine was monitored at different time points until 25 minutes as shown in Table 4-25. The 2.5 mg/L dose resulted in 1.08 mg/L residual free Cl_2 after 25 minutes. Therefore, the 24-hour chlorine demand testing was conducted with approximately 2.5 mg/L residual free Cl_2 dose. Similar pre-testing was conducted with the biofilter effluent collected during the 20% ATW blend testing (data not shown). Table 4-26 presents the 24-hour chlorine demand testing results. ATW blending resulted in decreased chlorine demand.

Table 4-25. Plant D Pilot-Scale Testing – Preliminary Test to Determine Chlorine Demand in the Biofilter Effluent from the 0% Blend (i.e., Raw Water) Testing Period.

Time	Residual Free Cl_2 (mg/L)		
	Trial 1	Trial 2	Trial 3
0 min (starting dose)	6	2	2.5
30 seconds	5.2	--	--
3 minutes	>4.6	1.47	1.56
5 minutes	--	1.36	1.51
10 minutes	--	1.22	1.31
25 minutes	--	1.05	1.08

Table 4-26. Plant D Pilot-Scale Testing – 24-Hour Chlorine Demand Testing Results.

Blend	Replicate	Free Cl_2 Dose (mg/L)	Residual Free Cl_2 (mg/L) after 24- hour Incubation
0% Blend	Rep 1	2.4	0.9
	Rep 2	2.4	0.9
	Rep 3	2.4	0.9
20% Blend	Rep 1	2.1	0.9
	Rep 2	2.1	0.9
	Rep 3	2.1	0.9

Table 4-27 presents the results of DBP formation testing after 24 hours of incubation under UFC. While low levels of TTHMs and HAA9 were observed after the 24-hour incubation, the TTHM and HAA9 concentrations were similar with the 0% and 20% blends, indicating that blending the ATW did not affect DBP FP in the biofilter effluent. These results were very different compared to that observed during the testing at Plant A, in which DBP FP significantly declined with the increasing blending ratio.

Table 4-27. Plant D Pilot-Scale Testing – DBP Formation in the Biofilter Effluent under UFC after 24 Hours of Incubation.

Blend	Replicate	pH after 24-hour Incubation (SU)	Residual Cl_2 (mg/L)	Total THM (µg/L)	HAA9 (µg/L)
0% Blend	Rep 1	8.13	0.9	28	23
	Rep 2	8.05	0.9	28	23
	Rep 3	8.09	0.9	28	23
20% Blend	Rep 1	8.07	0.9	32	21
	Rep 2	7.99	0.9	32	22
	Rep 3	8.06	0.9	33	22

4.2.3.5 Summary of Plant D Pilot Testing

The findings of the pilot testing at Plant D are summarized below:

1. Blending ATW did not significantly affect TOC removal across the pilot-scale system.
2. Filter effluent turbidity remained similar irrespective of the ATW blend tested.
3. Alkalinity in the blended water declined slightly with increasing ATW blending ratio. However, the changes in the blended water alkalinity did not affect TOC or turbidity removal across the system.
4. Blended water hardness increased with the increase in ATW blending ratio (due to re-stabilization chemicals added to the ATW), but the potential benefits of increased hardness on TOC removal were not apparent.
5. Terminal headloss after the same filter runtime decreased with increasing ATW blending ratio, suggesting that ATW blending may provide filter performance benefits.
6. Compared to the 0% blend, disinfection demand was lower with the 20% ATW blend. However, in general, ATW blending did not affect DBP FP in the biofilter effluent.

Overall, the results indicate that blending ATW with the raw water source at Plant D does not affect coagulation, flocculation, and filtration process performance.

4.2.3.6 Overall Summary of Pilot Testing Results

Table 4-28 summarizes the results from the pilot-scale testing conducted at Plants A, C, and D. Particle and pathogen removal results are discussed in Chapter 6.

Table 4-28. Summary of Pilot-Scale Testing Results.

Plant	ATW From	Blends Tested	Average Blended Water TOC (mg/L)	TOC Removal (%)		Effects of Blending	
				Required(1)	Achieved		
Plant A	RBAT	0% 10% 20% 50%	4.51 4.80 4.68 3.09	35% 35% 35% 35%	37.9% 24.5%(2) 33.2%(2) 41.1%	Alkalinity	Decreased
						Turbidity	Decreased
						Conductivity	Decreased
						Calcium	Decreased
						Magnesium	Decreased
						TOC	Decreased
						TOC Removal	No Clear Trend
						Filter Effluent Turbidity	Similar or Better
						Filter Run Length	Increased
						Headloss Accumulation Rate	Decreased
						Chlorine demand	Decreased
						DBP FP in Filter Effluent	Decreased
						Particle Removal	
						Pathogen Removal	
Plant C	RBAT	0% 10% 20% 50%	3.0 2.4 2.4 1.9	25% 25% 25% 25%	29% 31% 33% 25%	Alkalinity	Increased
						Turbidity	Decreased
						Conductivity	Increased
						Calcium	Decreased
						Magnesium	Decreased
						TOC	Decreased
						TOC Removal	No clear trend
						Filter Effluent Turbidity	Similar
						Filter Run Length	Increased
						Headloss Accumulation Rate	Decreased
						Chlorine Demand	Declined
						DBP FP in filter effluent	TTHM FP increased; Similar HAA5 FP
						Particle removal	Increased except for 50% blend
						Pathogen removal	Increased except for 50% blend

Plant	**ATW From**	**Blends Tested**	**Average Blended Water TOC (mg/L)**	**TOC Removal (%)**		**Effects of Blending**	
				Required[1]	**Achieved**		
Plant D	RBAT	0% 20% 50%	3.0 2.4 1.9	15% 25% AC[3]	34.3% 26.7% 32.4%	Alkalinity	Decreased
						Turbidity	Decreased
						Conductivity	Decreased
						Calcium	Increased[4]
						Magnesium	Increased[4]
						TOC	Decreased
						TOC removal	Statistically similar
						Filter effluent turbidity	Similar
						Filter run length	NA as a fixed filter run length was used.
						Headloss accumulation rate	Decreased
						Chlorine demand	Decreased
						DBP FP in filter effluent	Similar
						Particle removal	Not evaluated
						Pathogen removal	Not evaluated

Notes:

1. TOC removal requirement as per D/DBPR.
2. Pilot testing was conducted with a fixed set of coagulant and polymer doses. Optimizing the chemical doses would help meet the TOC removal requirement.
3. Since the blended water TOC was <2 mg/L, alternate compliance criteria would be applicable.
4. The ATW collected for the testing was pre-stabilized with calcium chloride and sodium hydroxide.

4.3 Modeling Results

This section presents the results of the ATW blending assessment using the Blue Plan-it® blending model. The modeling results are presented for Plant A and Plant C, which practice RBAT and CBAT advanced treatment, respectively. For each plant, simulations were conducted for blending ATW upstream of the surface water treatment plant and blending ATW with filtered water. Average concentrations observed in the historical data were used as inputs for the modeling. For water quality parameters with no data in the historical data set, data collected during the bench-scale and pilot-scale testing were used.

4.3.1 Simulations for Plant A

The simulations predicted similar finished water concentrations for parameters other than TOC and turbidity under the RWA or TWA scenario (Table 4-29). The differences in finished water TOC concentrations under the RWA and TWA were primarily due to the fact that SWTPs can provide additional TOC removal under the RWA scenario. The difference in the finished water TOC concentrations would be visible with ≥20% ATW blend (Figure 4-54). While finished water turbidity would be higher under the TWA scenario, the model predicted <0.1 NTU in all blends evaluated (i.e., up to 50%; Figure 4-55).

Table 4-29. Plant A Simulated Water Characteristics.

Item	When Blending ATW with Raw Water upstream of an SWTP								When Blending with Filtered Water			
	Blended Raw Water				Finished Water				Blended Finished Water			
Blending Ratio%	**0%**	**10%**	**20%**	**50%**	**0%**	**10%**	**20%**	**50%**	**0%**	**10%**	**20%**	**50%**
Alkalinity (mg/L $CaCO_3$)	74	70	66	54	74	70	66	54	74	70	66	54
Bromide (mg/L)	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Calcium (mg/L)	48	44	39	25	48	44	39	25	48	43	39	25
Chloride (mg/L)	27	26	24	18	27	26	24	18	27	26	24	18
pH (SU)	8.19	8.14	8.07	7.86	8.19	8.14	8.07	7.87	8.19	8.14	8.07	7.86
Sodium (mg/L)	37	38	39	42	37	38	39	42	37	38	39	42
Sulfate (mg/L)	28	26	24	19	28	26	24	19	28	26	24	19
TDS (mg/L)	238	222	204	153	238	222	204	153	238	221	204	153
Temperature (°C)	18.2	18.1	18.0	17.6	18.2	18.1	18.0	17.6	18.2	18.1	18.0	17.6
TOC (mg/L)	4.11	3.77	3.37	2.26	2.55	2.35	2.25	1.33	2.55	2.34	2.12	1.48
Turbidity (mg/L)	6.25	5.69	5.02	3.18	0.09	0.01	0.05	0.01	0.09	0.09	0.09	0.09
UV_{254} (cm^{-1})	0.206	0.188	0.166	0.106	0.090	0.078	0.069	0.032	0.090	0.081	0.073	0.047

As reported in Section 4.2.1, during the pilot testing, the average TOC removal with the 0%, 10%, 20%, and 50% blend was 37.9%, 24.5%, 33.2%, and 41.1% (Table 4-11). Accordingly, the average filter effluent TOC concentrations were 3.3 mg/L (n=8), 4.2 mg/L (n=11), 3.5 mg/L (n=8), and 1.9 mg/L (n=8) with the 0%, 10%, 20%, and 50% blends. While the model predicted filter effluent TOC concentrations (Figure 4-54) were lower compared to the concentrations observed during the pilot testing, in general, the model prediction captured the trend in TOC concentrations with the increasing blend. The error in the TOC concentration prediction was likely due to the use of the average TOC removal as the input parameter in the model.

The predicted turbidity matched the average finished water turbidity observed during the pilot testing.

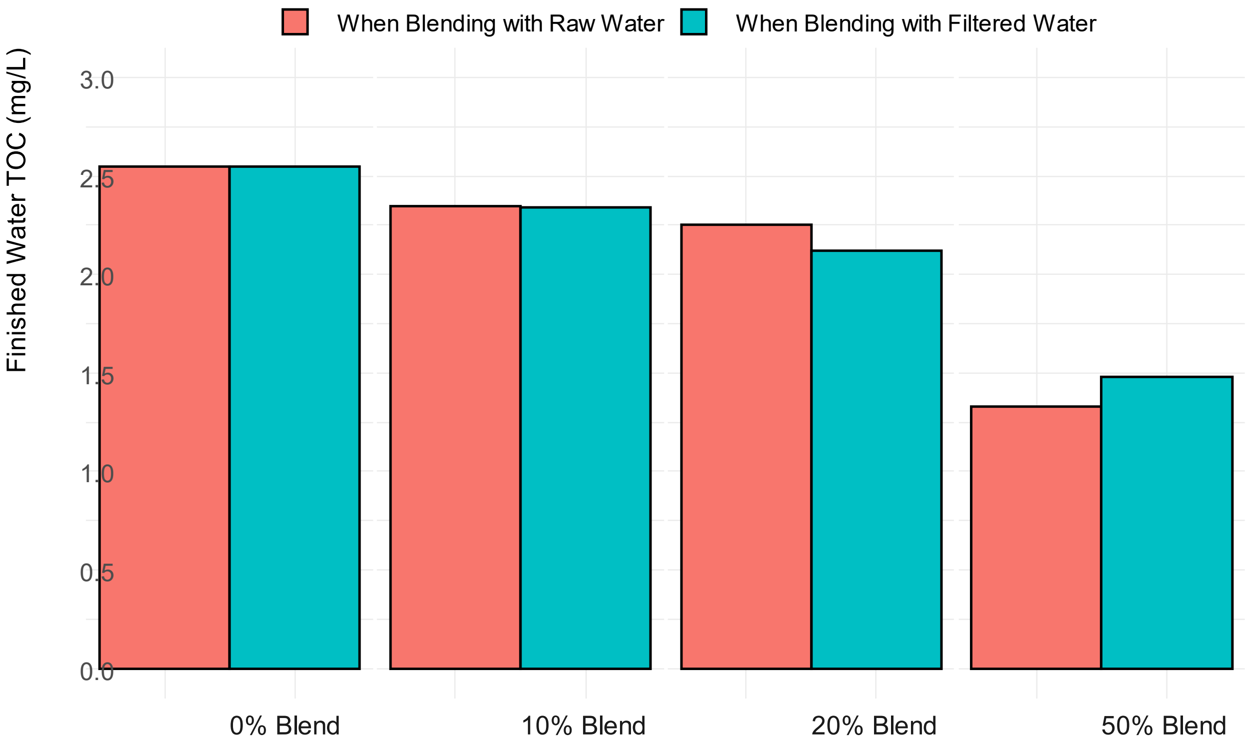


Figure 4-54. Plant A - Simulated Finished Water TOC Concentrations.

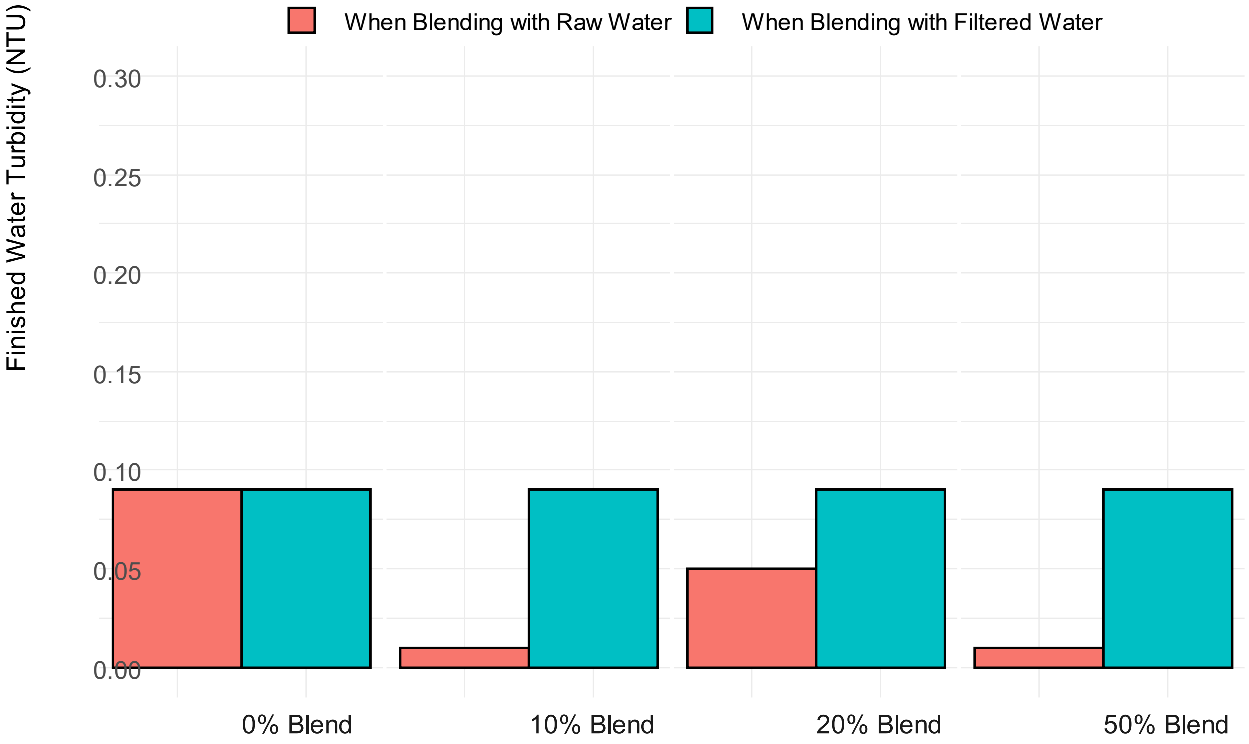


Figure 4-55. Plant A Simulated Finished Water Turbidity for Plant A.

Potential pipe corrosion and water stability were assessed by calculating CCPP, LSI, Larson Index (LI), Chloride Sulfate Mass Ratio (CSMR), and Ryznar Index (RI). CCPP, LSI, LI, and CSMR decreased with the increase in ATW blending ratio (Table 4-30), whereas the Ryznar index increased. Except for LSI with ATW blends up to 20%, the values were outside of the typical range for the parameters (CCPP: 4 to 10 mg/L as $CaCO_3$; LSI: >0, Ryznar: <7, LI < 0.5, CSMR < 0.5). CCPP, LSI, and RIs are pH dependent and can be easily corrected through pH adjustment. The effects of blending location and blending ratio on the other pH-independent indices (i.e., LI and CSMR) were minimal.

Table 4-30. Plant A Corrosion and Water Stability Indices.

Raw WQ Option	When Blending ATW with Raw Water upstream of an SWTP								When Blending ATW with Filtered Water			
Item	**Blended Raw Water**				**Finished Water**				**Blended Finished Water**			
Blending Ratio %	**0%**	**10%**	**20%**	**50%**	**0%**	**10%**	**20%**	**50%**	**0%**	**10%**	**20%**	**50%**
CCPP (mg/L $CaCO_3$)	2.80	1.78	0.60	-2.43	2.80	1.78	0.60	-2.31	2.80	1.71	0.62	-2.36
LSI	0.36	0.24	0.09	-0.39	0.36	0.24	0.09	-0.38	0.36	0.23	0.09	-0.38
LI	0.92	0.9	0.89	0.83	0.92	0.9	0.89	0.83	0.92	0.9	0.89	0.83
Ryznar	7.55	7.73	7.96	8.71	7.55	7.73	7.96	8.7	7.55	7.74	7.95	8.7
CSMR	0.99	0.98	0.97	0.94	0.99	0.98	0.97	0.94	0.99	0.98	0.97	0.94

The simulation estimated similar chlorine residual after 24 hours (except with the 50% blend) when the finished water is treated with 2.5 mg/L Cl_2 regardless of the blending location (Figure 4-56). The chlorine residual slightly increased with increasing ATW blending ratio. As observed during the pilot testing, decreasing TTHM formation was estimated with the increasing ATW blending ratio (Figure 4-57). Compared to blending with the filtered water, lower concentrations were predicted when the ATW would be blended with the raw water upstream of an SWTP (Figure 4-57).

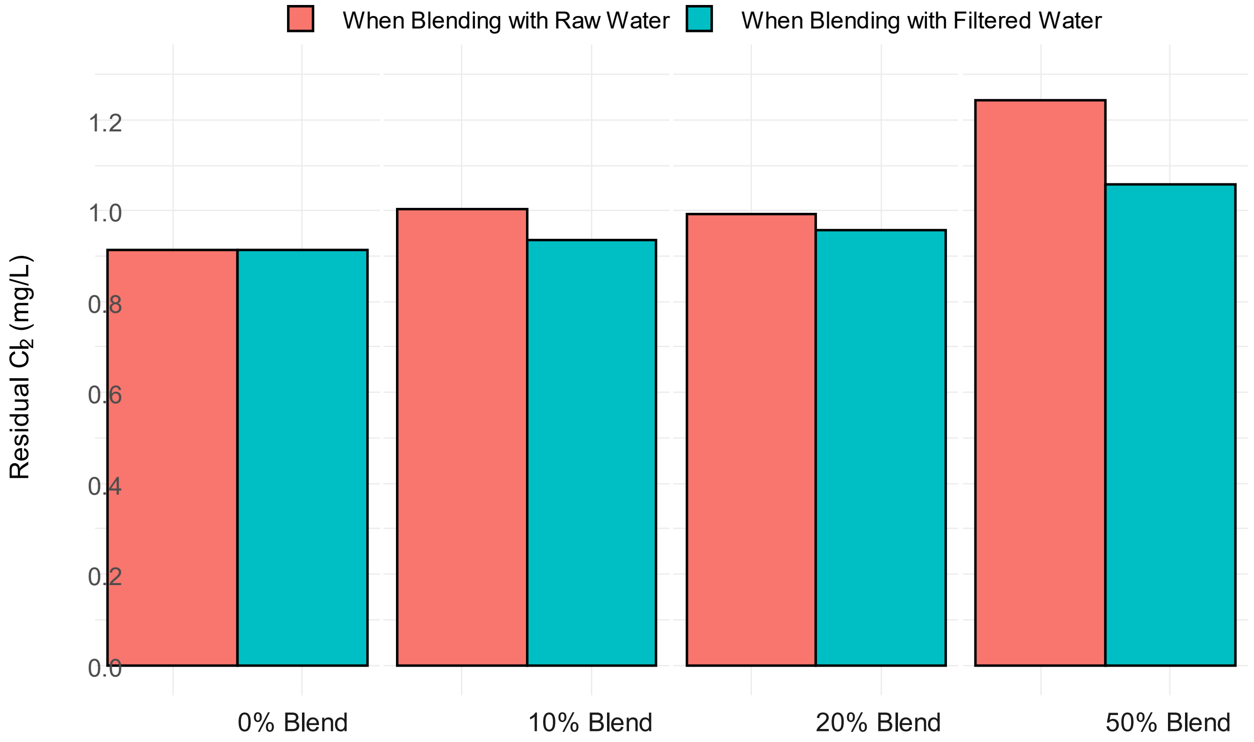


Figure 4-56. Plant A - Simulated Residual Chlorine in the Finished Water.

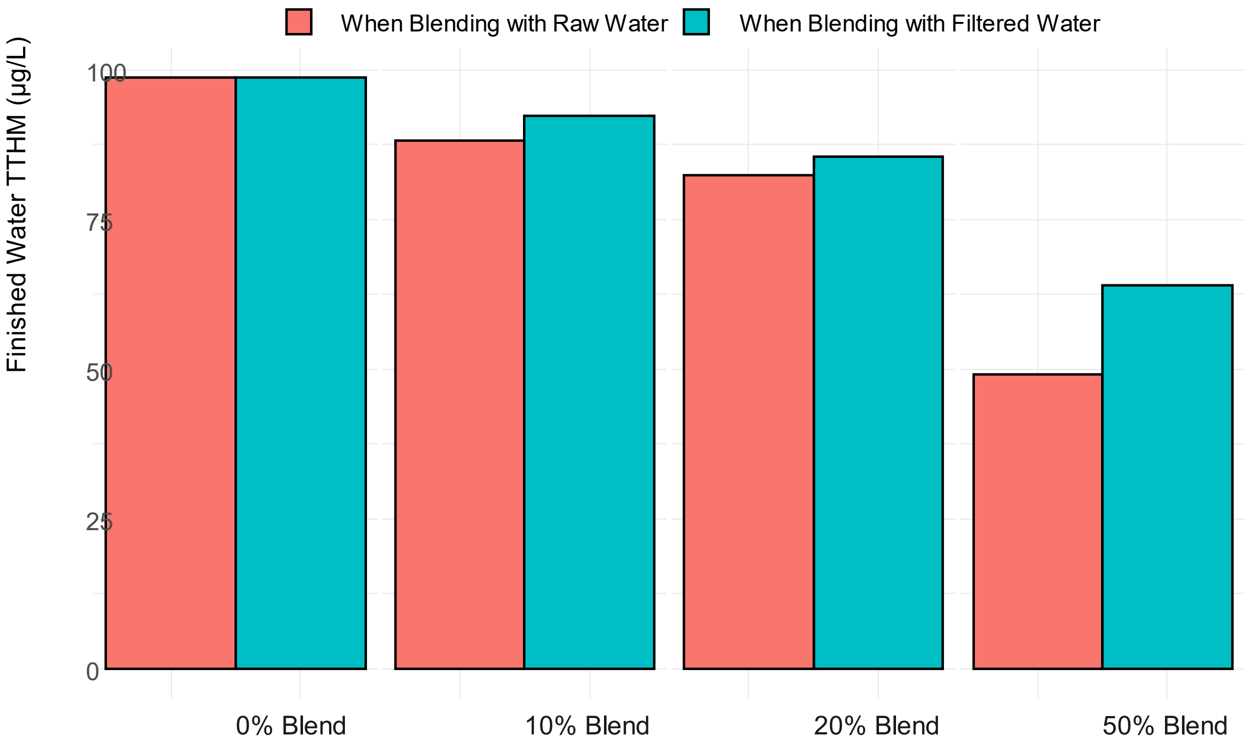


Figure 4-57. Plant A - Simulated Finished water TTHM Concentrations.

Pathogen removal was estimated assuming a total of 2.5-log removal for *Cryptosporidium*, 3-log removal for *Giardia lamblia*, and 4-log removal for viruses as required by LT2ESWTR (USEPA 2006b). The simulation results showed increasing virus log removal with the increase in ATW blending ratio (Table 4-31). *Cryptosporidium* and *Giardia* log removal with the ATW-blended water up to the 20% blend compared to the 0% blend (i.e., the raw water). Though the removal in the 50% blend was lower compared to the 20% blend, it was still higher than in the 0% blend. In agreement with the pilot testing results, increasing virus log removal was predicted with the increase in blending ratio. Overall, the model predicted that blending the ATW would not affect pathogen log removal.

Table 4-31. Plant A Simulated Pathogen Log Removal.

	When Blending ATW with Raw Water				**When Blending ATW with Treated Water**			
Blending Ratio %	**0%**	**10%**	**20%**	**50%**	**0%**	**10%**	**20%**	**50%**
Cryptosporidium	1.00	1.50	2.10	1.50	1.00	1.50	2.10	1.50
Giardia lamblia	2.00	2.80	3.50	2.40	2.00	2.80	3.50	2.40
Viruses	1.58	1.33	2.12	3.06	1.58	1.33	2.12	3.06

4.3.2 Simulations for Plant C

For Plant C that used ATW from a CBAT system, the finished water TOC concentrations were predicted to increase with increasing ATW blending ratio (Figure 4-58). Blending the ATW with the filtered water would result in a slightly higher TOC in the finished water, which would be more pronounced with the higher ATW blending ratio. Regardless of the blending location, the finished water turbidity was predicted to be significantly less than 0.1 NTU with all blends

(Figure 4-59). Table 4-32 presents the simulated concentrations of various water quality parameters in the finished water.

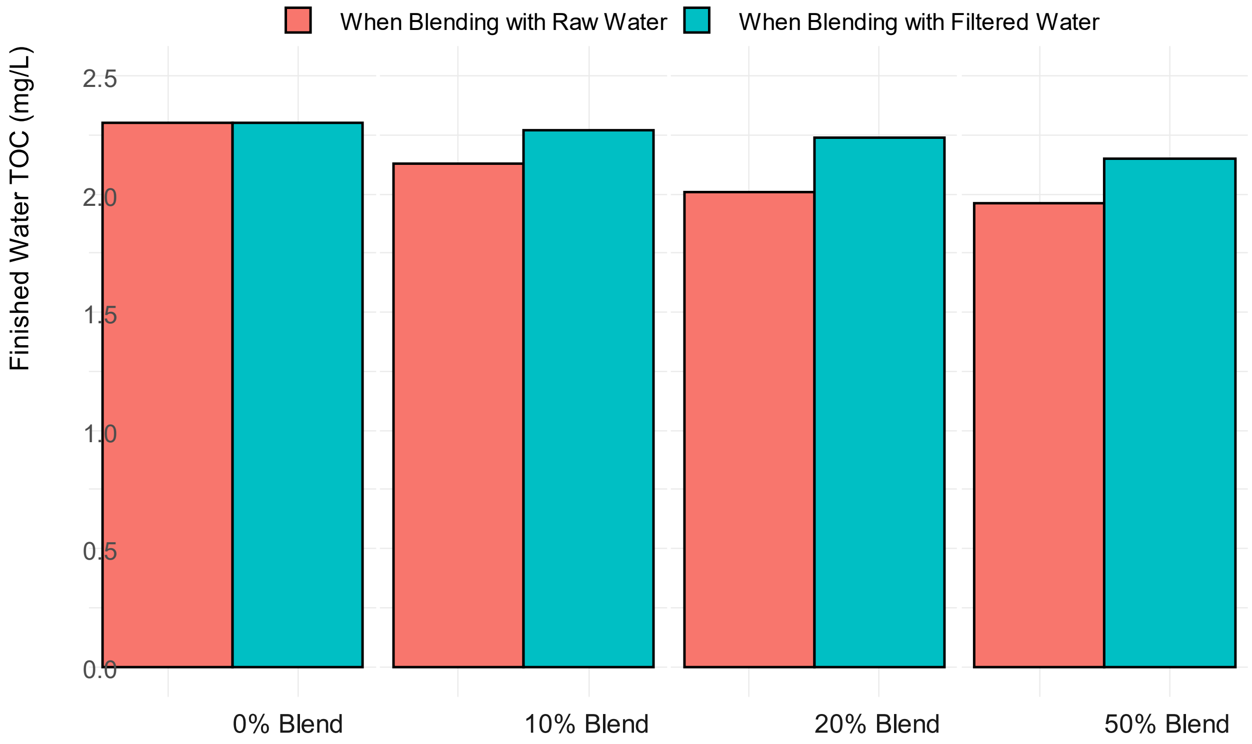


Figure 4-58. Plant C – Simulated Finished Water TOC Concentrations.

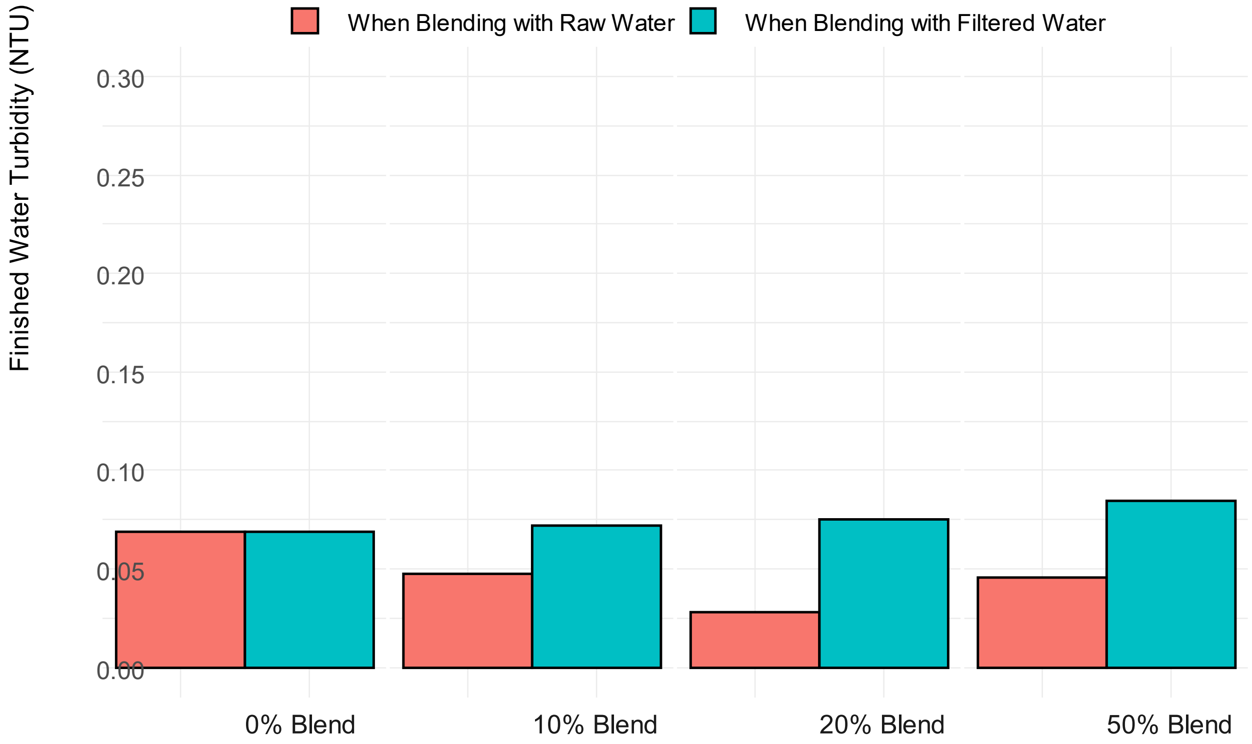


Figure 4-59. Plant C – Simulated Finished Water Turbidity.

Table 4-32. Plant C Simulated Water Characteristics.

Item	When Blending ATW with Raw Water upstream of an SWTP								When Blending ATW with Filtered Water			
	Blended Raw Water				Finished Water				Finished Water			
Blending Ratio%	**0%**	**10%**	**20%**	**50%**	**0%**	**10%**	**20%**	**50%**	**0%**	**10%**	**20%**	**50%**
Alkalinity (mg/L $CaCO_3$)	95	98	100	108	95	98	100	108	95	98	100	108
Bromide (mg/L)	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Calcium (mg/L)	43	43	43	43	43	43	43	43	43	43	43	43
Chloride (mg/L)	26	26	26	26	26	26	26	26	26	26	26	26
pH (SU)	7.58	7.49	7.40	7.23	7.60	7.50	7.40	7.24	7.6	7.5	7.41	7.24
Sodium (mg/L)	37	37	37	37	37	37	37	37	37	37	37	37
Sulfate (mg/L)	45	45	45	45	45	45	45	45	45	45	45	45
TDS (mg/L)	207	207	207	207	207	207	207	207	207	207	207	207
Temperature (°C)	10.5	11.3	12.2	14.7	10.5	11.3	12.2	14.7	10.5	11.4	12.2	14.7
TOC (mg/L)	3.22	3.11	2.98	2.61	2.3	2.13	2.01	1.96	2.3	2.27	2.24	2.15
Turbidity (mg/L)	1.72	1.57	1.40	0.91	0.07	0.05	0.03	0.05	0.07	0.07	0.08	0.08
UV_{254} (cm^{-1})	0.048	0.058	0.070	0.104	0.023	0.031	0.031	0.055	0.023	0.037	0.051	0.091

Similar to that observed with Plant A, the corrosion and water stability indices were outside of the typical range (Table 4-33). CCPP, LSI, and LI declined with the increasing blending ratio, whereas Ryznar index increased with the increase in the ATW use. CSMR did not change with the change in the blending ratio. As mentioned above, the pH dependent indices (i.e., CCPP, LSI, and Ryznar) can be easily corrected by adjusting pH. The impacts of blending location and ratio on LI and CSMR were minimal.

Table 4-33. Plant C Corrosion and Water Stability Indices.

Raw WQ Option	When Blending ATW with Raw Water upstream of an SWTP								When Blending ATW with Filtered Water			
Item	**Blended Raw Water**				**Finished Water**				**Finished Water**			
Blending Ratio %	**0%**	**10%**	**20%**	**50%**	**0%**	**10%**	**20%**	**50%**	**0%**	**10%**	**20%**	**50%**
CCPP (mg/L as $CaCO_3$)	-5.46	-7.61	-10.1	-16.5	-5.13	-7.44	-10.1	-16.3	-5.13	-7.53	-9.99	-16.3
LSI	-0.30	-0.37	-0.43	-0.53	-0.29	-0.37	-0.43	-0.53	-0.29	-0.37	-0.43	-0.53
LI	0.87	0.85	0.83	0.77	0.87	0.85	0.83	0.77	0.87	0.85	0.83	0.77
Ryznar	8.26	8.30	8.34	8.37	8.24	8.30	8.34	8.37	8.24	8.30	8.33	8.37
CSMR	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57

Chlorine residual after 24 hours would slightly decrease with increasing blending ratio when the finished water is treated with 2.5 mg/L Cl_2 (Table 4-34). While higher TTHM concentrations would be expected with increasing blending ratio regardless of the blending location, the increase in TTHM concentration would be more pronounced when blending the ATW with the filtered water. These results agreed with the pilot testing results.

Table 4-34. Plant C Disinfectant Stability and DBP Formation.

	When Blending ATW with Raw Water upstream of an SWTP				When Blending ATW with Filtered Water			
Blending Ratio %	**0%**	**10%**	**20%**	**50%**	**0%**	**10%**	**20%**	**50%**
TTHM	21	26	26	37	21	29	35	52
Chlorine Residual	1.83	1.56	1.52	1.15	1.83	1.46	1.25	0.92

Pathogen removal with and without UV disinfection were estimated (Table 4-34), assuming a total of 2.5-log removal for *Cryptosporidium*, 3-log removal for *Giardia lamblia*, and 4-log removal for viruses would be achieved across the plant in accordance with LT2ESWTR (USEPA 2006b). Similar to that observed in simulations for Plant A, log reduction for viruses would increase with the increase in blending ratio (Table 4-35). Protozoa removal would be better with the ATW-blended water compared to the raw water (i.e., 0% blend).

Table 4-35. Plant C Simulated Pathogen Log Removal.

Blending Ratio %	When Blending ATW with Raw Water				When Blending ATW with Treated Water			
	0%	**10%**	**20%**	**50%**	**0%**	**10%**	**20%**	**50%**
Cryptosporidium	1.7/2.5*	2.2/2.5	2.5/2.5	2/2.5	1.7/2.5	2.2/2.5	2.5/2.5	2/2.5
Giardia lamblia	1.8/3	2.2/3	3/3	2.2/3	1.8/3	2.2/3	3/3	2.2/3
Viruses	1.4/4	1.5/4	2.7/4	NA	1.4/4	1.5/4	2.7/4	NA
Notes: * Pathogen log removals are presented as without UV disinfection/ with UV disinfection								

4.3.3 Summary of Modeling

The simulation results can be summarized as:

1. Regardless of the ATW source, blending ATW with raw water upstream of an SWTP would be beneficial compared to blending with filtered water.
2. While similar TOC concentrations were estimated in the finished water when the ATW from an RBAT system was blended with raw water or the filtered water; lower TOC concentrations were predicted when CBAT-based ATW is blended with the raw water than with the filtered water.
3. Turbidity would be significantly lower when the ATW is blended with the raw water compared to the filtered water.
4. The pipe corrosion and water stability indices were predicted to be outside of the typical ranges, suggesting the need to address corrosion and water stability.
5. Greater pathogen log removal would be expected with the ATW-blended water compared to the raw water (i.e., 0% blend)

4.4 Overall Summary

Extensive bench-scale and pilot-scale tests, and limited modeling were conducted to test the hypotheses developed. Bench-scale tests were conducted with water samples collected from six participating utilities from across the country. The bench-scale testing focused on determining the effects of blending ATW with raw water on water quality, chemical dose requirements, and coagulation, flocculation, and sedimentation. The bench-scale testing results showed that water chemistry changed after blending ATW and the effects were source water-specific. Zeta potential evaluation can help determine the optimal coagulant dose regardless of the ATW blending ratio. In general, blending ATW lowered ozone dose and/or coagulant dose requirements, while achieving similar or better TOC and turbidity removal.

Pilot tests were conducted at three participating utilities. At Plant A and Plant C, the pilot systems simulated conventional treatment plant, whereas direct filtration was simulated at Plant D. Blending the ATW resulted in better effluent turbidity and similar or better TOC removal compared to that without blending (i.e., raw water). The achieved TOC removals were higher than the required removals for enhanced coagulation. Improved hydraulic performance was observed in filters with ATW-blended water. Most importantly, increased pathogen log removal was observed with the ATW-blended water. While disinfectant demand declined with the use of ATW-blended water, DBP FP in the filtered water was site-specific.

Both bench-scale and pilot-scale results showed water quality improvement when blending raw source water with ATW. For most of the water quality parameters, the blended water quality could be estimated through mass balance calculations. In general, no clear effects of ATW blending on TOC removal were observed based on the bench- or pilot-scale testing.

In general, the modeling results agreed with the pilot-scale testing results.

CHAPTER 5

Considerations for Full-Scale Implementation of ATW Blending for Raw Water Augmentation

DPR has tremendous potential to help address ever-increasing water supply demands, whether that is through RWA or TWA. Blending ATW with raw water sources upstream of an SWTP changes water quality characteristics in the blended water, which may present both benefits and challenges to SWTP plant operations, pathogen removal across the treatment processes, disinfectant demand and DBP formation in the treated water, and water stability and corrosion in the distribution system. Careful planning followed by bench- and/or pilot-scale testing should be undertaken to help accurately assess the site-specific implications associated with the ATW blending. The following sections briefly discuss various considerations under planning, evaluation, and implementation and monitoring phases for full-scale implementation of DPR with ATW blended raw water sources at an SWTP.

5.1 Planning Phase

ATW blending can augment a drinking water supply source. However, since it carries some potential risks, ATW blending with a raw water source upstream of an SWTP requires careful considerations and planning before testing or implementing the approach. The following sections briefly discuss aspects to be considered when planning ATW blending with more conventional raw (surface or ground) water.

5.1.1 Identifying Potential Benefits and Challenges

Identification of all benefits, challenges, opportunities, and concerns is a critical first step in considering ATW blending. The use of RWA has distinct benefits to the overall DPR treatment train, but also comes with a few specific added challenges, as follows:

- Benefits:
    - Augments water supply with a drought resistant source.
    - Provides dilution of ATW for chemical control as required by the State of California Water Resources Control Board. (CA SWRCB, 2021).
    - May reduce turbidity and organic concentrations in the blended water.
    - May provide additional benefits, including:
        - When blending ATW from an RBAT with raw water source with significant alkalinity and hardness, the raw water can offset some of the necessary chemical stabilization of the ATW, resulting in cost saving due to reduction in chemical (i.e., lime or sodium hydroxide) use.
        - Reduction in overall microbiological and pathogen concentrations due to the dilution effect.
        - Improved hydraulic performance across filters.
        - Reduction in coagulant dose, which may result in lower operating costs.

    - Reduction in disinfectant demand and DBP FP, due to the reduction in organic concentration. This may also result in lower overall operating costs.
- Challenges:
  - Reliance upon the SWTP for pathogen and chemical removal as part of a DPR treatment train may require modifications to the SWTP treatment, monitoring, and control systems to meet more stringent treatment criteria.
  - In the event of not meeting the DPR treatment criteria, the entire flow (including the conventional source water) may need to be diverted and flushed from the plant. However, the impacts can be minimized with provisions to divert only the ATW upstream of the blending location.
  - If the ATW blending lowers pH and alkalinity significantly, it may result in challenges in the coagulation process.
  - If the blended water has low pH and alkalinity (when using RBAT-treated ATW without stabilization) or high TDS (when using CBAT-treated ATW), the water can be corrosive and can potentially impact the stability of pipe scales, metal solubility, microbial regrowth and nitrification, and disinfectant residual in the distribution system.
  - Finished water stability is anticipated to change for projects that use RBAT-treated ATW without stabilization.
  - Depending on the type of potable reuse treatment, blending ATW may increase the load of antibiotic resistant bacteria and antibiotic resistance genes on the SWTP (Alexander et al. 2016; Watkinson et al. 2007).

During the planning phase, these benefits and challenges should be carefully identified through the review of water quality characteristics of the two water sources to be blended.

5.1.2 Understanding Regulatory Framework and Public Perception

Public perception and regulatory requirements can affect how DPR is implemented. The utility should be fully informed on regulations set by federal and state agencies, such as the SWTR, Stage 1 and 2 D/DBPR, CCR, LCR revisions (LCRR), and LT2ESWTR. As the science of DPR is constantly evolving, the utility should also track information on the latest development on unregulated chemicals and approaches for mitigating microbial risks.

5.1.3 Understanding Water Characteristics

It is critical to assess the potential water characteristics of the raw water and ATW to determine the potential water quality changes and impacts on unit process performance after blending the two water sources. Reviewing at least 24 months of data would allow a more complete understanding of seasonal variability and associated potential impacts to plant operation and performance.

5.1.4 Process Modifications

The SWTP should be assessed, including plant capacity, treatment train unit processes, performance of each unit process, and the potential process modifications required for treating ATW-blended water. Additional infrastructure (e.g., plumbing, pumps, mixing zone/tank, etc.), and monitoring and control systems may be required along with increased monitoring frequency to meet more stringent treatment criteria. Furthermore, operational changes such as changes in chemical feed doses, may need to be implemented to address water quality changes. Provisions may be needed to stabilize the ATW (i.e., pH and alkalinity adjustments) before blending the ATW.

5.1.5 Bench and Pilot Testing

Bench and pilot testing are essential activities during planning. Testing can identify process efficacy, potential upsets and challenges, potential mitigation strategies to address the challenges, and process limitations. The selection of the testing scale depends on the availability of potential water supplies and the objectives of the testing. A utility should consider conducting bench-scale testing (jar testing) at a minimum to determine potential water quality changes and the effects on coagulation, flocculation, and sedimentation. When possible, pilot-scale testing should also be considered, which will help determine site-specific process requirements, acclimation requirements (when the SWTP includes biofiltration), chemical dose requirements, HRTs and EBCTs in unit processes (as applicable), process limitations, and potential optimization and troubleshooting strategies. Pilot testing also helps refine performance monitoring plan and develop full-scale design criteria for new plants. In the pilot-scale testing, pathogen log removal across the system can be evaluated by conducting challenge tests with MS2, PMMoV, *Cryptosporidium* oocysts, or *Giardia* cysts.

5.1.6 Performance Monitoring Plan

In general, existing techniques and protocol for monitoring an SWTP's performance would be applicable for characterizing process performance with or without ATW blending. Additional monitoring locations will need to be added to determine water characteristics of the two water sources and blended water. The most relevant water quality parameters for assessing unit process performance at a conventional SWTP include temperature, pH, alkalinity, hardness, turbidity, organic carbon (TOC, DOC, UV_{254}), oxidant residual, DBP FP, contaminants of interests and CECs (as applicable). During the planning phase, a monitoring plan should be developed to identify key and easy-to-monitor water quality, hydraulic, and microbial parameters that would help assess process performance across the plant. Table 5.1 lists a few key monitoring parameters and potential sampling locations. Additional monitoring parameters should be included in the monitoring plan as appropriate. The monitoring parameters should be tested and refined during the Evaluation phase, selecting the parameters that allow effective assessment of plant performance.

Table 5-1. Potential Monitoring Parameters.

Parameter	Sampling Location
Water Quality Parameter	
Temperature	Coag INF, Biofilter INF
pH	Coag INF, Settled water, Filter/Biofilter EFF
Alkalinity	Coag INF, Filter/Biofilter INF and EFF
Hardness	Coag INF, Filter/Biofilter INF and EFF
Zeta potential	Coag INF, Filter/Biofilter INF
DO	Biofilter INF, Plant EFF
Turbidity	Coag INF, Settled water, Filter/Biofilter EFF
TOC	Coag INF, Settled water, Filter/Biofilter EFF
DOC	Coag INF, Settled water, Filter/Biofilter EFF
UV_{254}	Coag INF, Settled water, Filter/Biofilter EFF

Parameter	Sampling Location
SUVA (calculated)	Filter/Biofilter INF and EFF
Nutrients (N, P)	Filter/Biofilter INF
Carboxylic acids	Biofilter INF and EFF
Contaminant of interest (e.g., iron, Mn, geosmin/MIB, ammonia, trace organics)	Coag INF, Settled water, Filter/Biofilter EFF
Residual preoxidant (e.g., residual O3, residual Cl2)	Downstream of the pre-oxidation stage, Biofilter INF
Disinfectant demand	Filter/Biofilter EFF
DBP FP	Filter/Biofilter EFF
Particle counts	Coag INF, Filter/Biofilter INF and EFF
Operational Parameters	
Chemical doses	Coag INF, Pre-oxidation, Biofilter INF (if nutrients are fed), Disinfection
HRT/EBCT (calculated)	Across each unit process as applicable
Flow rate	Plant INF, Filter/Biofilter INF, any other locations as appropriate
Filter runtime	Filter/Biofilter
Headloss	Across Filter/Biofilter
UFRV (calculated)	Filter/Biofilter
Backwash flow rate	Filter/Biofilter
Backwash pump discharge pressure	Filter/Biofilter
Underdrain differential pressure	Filter/Biofilter
Microbial Parameters	
HPCs	Filter/Biofilter EFF, after disinfection
E. coli	Filter/Biofilter EFF, after disinfection
Total coli	Filter/Biofilter EFF, after disinfection
Extra cellular polymeric substances(1)	Biofilter
Enzyme activity (i.e., Phosphatase and glycosidase)(2)	Biofilter
ATP	Filter/Biofilter
Cryptosporidium oocysts, *Giardia* cysts, MS2, PMMoV(3)	Coag INF, Filter/Biofilter EFF
Notes: 1. Only when hydraulic challenges are experienced. 2. Only when evaluating if biofilters are phosphorus-limited. 3. Only when required to assess or demonstrate pathogen LR.	

5.2 Evaluation Phase – Testing at the Bench- and Pilot-Scale

Evaluation is the most critical aspect to determine how to implement ATW blending most effectively with raw water sources at a full-scale as testing can identify key treatment considerations, process limitations that must be addressed, and enhance operational confidence. Figure 5-1 presents some tasks that might need to be considered during the evaluation phase.

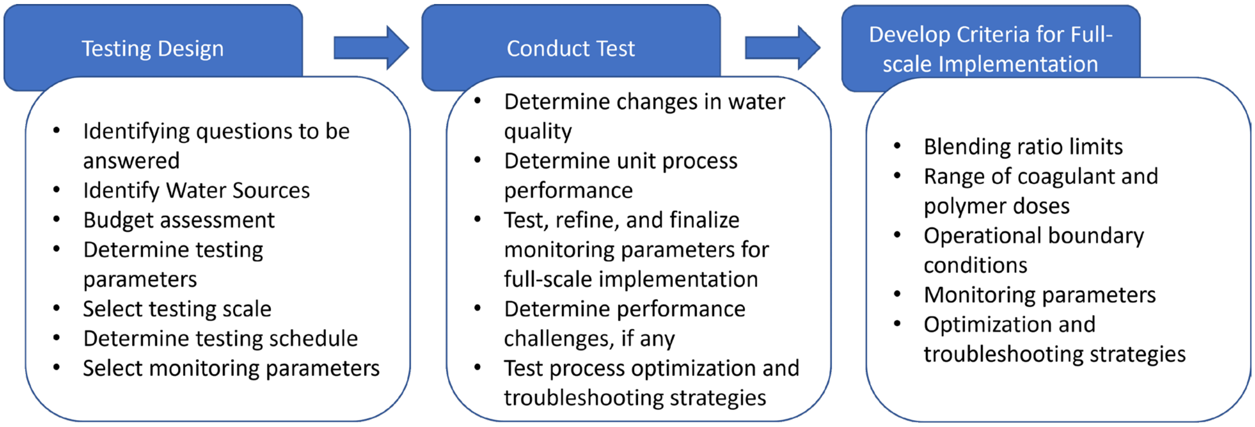


Figure 5-1. Potential Tasks to be Considered during Evaluation Phase.

5.2.1 Testing Design

The following should be considered when designing a testing plan.

5.2.1.1 Questions to be Answered

Testing design starts with understanding the testing goals and identifying questions the testing must answer. The list below provides some example questions of interest when evaluating ATW blending with raw water sources at an SWTP:

1. How does the ATW blending affect blended water and treated water quality?
2. What range of blending ratios will the plant use?
3. How does the changes in raw water and ATW quality affect coagulation efficacy and coagulant and/or polymer doses? Can the coagulation performance be re-established by adjusting the chemical doses?
4. How will the water quality changes affect the TOC removal requirements?
5. How much TOC removal can be achieved across the plant?
6. What are the effects on floc characteristics? Will the settleability and filterability of the flocs be affected?
7. What is the maximum blending ratio that could be used without affecting overall plant performance?
8. How does the blending with ATW affect pathogen removal across the plant?
9. To what extent will the ATW blending affect disinfection performance and residual stability?
10. Will DBP FP change when ATW is blended with the surface water sources? Will the distribution of individual THM or HAA species change (e.g., increase or decrease of brominated species) as a result of blending?
11. How does the blending affect treated water biostability?
12. Will the blending affect corrosion and water stability in the distribution system?

5.2.1.2 Water Sources to be Treated

Water characteristics drive unit process performance. When blending ATW with raw water sources, it is critical to fully characterize the two water sources and the proposed range of blends.

5.2.1.3 Budgeting

Budget requirements are dependent on testing scale, duration, and monitoring requirements, which are in turn determined by the testing goals. In general, bench-scale testing is less costly (range from a few thousands to tens of thousands) due to the short-termed nature of the testing with limited analytical requirements. In contrast, pilot-scale testing typically requires an order of magnitude higher budget due to the pilot equipment, long-term operations, and higher number of sampling and analytical requirements. Establishing the testing budget should be done in parallel to developing the testing plan to verify that the testing plan and budget are aligned and will generate meaningful data/information.

5.2.1.4 Testing Parameters

The primary goal of the testing is to determine how unit process performance at an SWTP is affected by blending ATW with raw water sources. Some of the potential testing aspects are listed below:

1. Effects of ATW blending ratio on blended water characteristics (e.g., pH, alkalinity, turbidity, TOC, UV_{254}).
2. Effects of the water quality changes on coagulation, flocculation, sedimentation, and filtration.
3. Effects of pre-oxidation on coagulation, flocculation, sedimentation, and filtration when treating blended water.
4. Effects of pre-oxidation on turbidity removal across the filters when treating blended water
5. Effects of blending on turbidity and TOC removal across the plant.
6. Changes in disinfectant requirements and DBP FP with the ATW blending.
7. Pathogen log removal across the plant.

While a few of these aspects can be evaluated at the bench-scale, some of them will require evaluation at the pilot-scale.

5.2.1.5 Testing Scale

Testing scale is dictated by the testing goals and available budget. In general, a bench-scale testing is used for preliminary assessment and proof-of-concept evaluation. Accordingly, the scope of bench-scale testing can be limited. For evaluating the effects of blending ATW with raw water sources at an SWTP, bench-scale testing scope may include one or more of the following:

1. Blending evaluation and water quality characterization.
2. Evaluating effects of pre-oxidants on floc formation and settleability.
3. Jar testing to evaluate floc formation and settleability.
4. Evaluating effects of blending on TOC and turbidity removal.
5. Filterability evaluation along with disinfectant demand and DBP FP evaluations.

Zeta potential evaluation can be incorporated in bench-scale testing, which help determine the optimal coagulant and/or polymer doses during the jar testing. While the results from bench-scale testing can be informative for full-scale implementation, especially regarding the chemical feed doses and optimal coagulation conditions, bench-scale testing fails to capture the effects on blending due to temporal water quality changes. Furthermore, bench-scale testing cannot accurately evaluate filter performance. Therefore, pilot testing should be conducted, using the bench-scale testing results as the benchmark, to better understand the effects of temporal and seasonal water quality changes for both water sources.

Pilot-scale testing typically provides more experimental flexibility with better correlation with full-scale plant operation and performance than bench-scale testing. Therefore, results from a pilot-scale testing can be used for developing design and operating criteria for a full-scale implementation. Pilot-scale testing can address a wider variety of questions and concerns, building on the data gathered through bench-scale testing. Pilot-scale testing will help accurate assess:

1. The maximum ATW blending ratio.
2. Changes in water quality characteristics.
3. Coagulant and polymer dose ranges.
4. Settleability and filterability of the flocs.
5. Turbidity and organic carbon removal.
6. Changes in hydraulic performance across the process.
7. Pathogen log removal assessment method and results.
8. Disinfectant demand and DBP FP.
9. Identification of operational challenges and development of strategies for addressing the challenges.
10. Process optimization and troubleshooting strategies.

5.2.1.6 Testing Location

In most cases, AWPF and SWTP will not be located in the same geographical area. Therefore, when considering a testing location, water transport and system sizing requirements should be carefully assessed.

5.2.1.7 Instrumentation and Data Collection

Including an automated pilot system which includes a SCADA component is recommended for efficient water quality and process operating data recording. An automated pilot system with provisions for remote monitoring and operation can also be beneficial.

5.2.1.8 Test Schedule

While budget, staff, and equipment availability are the major factors that determine the length of a testing, pilot testing should be designed to capture potential seasonal water quality changes. If budget availability limits long-term (i.e., six to twelve months) pilot testing with multiple ATW blends, it may be practical to first focus on confirming whether ATW blending affects system performance with a shorter testing period (e.g., 2 to 8 weeks) and determining the maximum ATW blending ratio that can be applied. Then, long-term testing could be conducted with the maximum blending ratio to quantify the effects of seasonal variability.

Control Testing. Evaluation should always include testing under baseline (Control) conditions. When evaluating the effects of blending, testing with 0% ATW blend (i.e., the raw water) will be the Control condition. Unit process performance with a specific ATW blend should be compared with the performance during the Control condition evaluation. Ideally, testing with the raw water and various ATW blends should be conducted with two parallel treatment trains. However, since the use of parallel treatment trains significantly escalates the piloting cost, testing with the raw water and ATW blends should at least be conducted within a somewhat consistent water quality period.

5.2.2 Develop Full-Scale Criteria

Once the testing is fully designed and budget, staffing, and pilot-testing equipment availability is confirmed, the bench- or pilot-scale test should be conducted with the overall goal of quantifying the water quality changes and characterizing unit process performance with each blend to be tested. The monitoring parameters selected during the planning phase should be tested, focusing on finalizing the list of parameters that are easily monitored and most effective in reflecting the system performance. The collected pilot-testing data should be analyzed and evaluated as frequently as possible to assess whether the pilot is operating properly and to allow for course corrections, alternate testing conditions, or side studies during the pilot operation, which are not possible if data analysis is not performed until after the pilot operation is complete. Process optimization and troubleshooting strategies, if implemented, should be catalogued as a reference document for full-scale implementation. The results from the pilot-testing should be summarized and translated into design and operating criteria for the full-scale implementation.

CHAPTER 6

Pathogen Removal

This chapter focuses on documenting the approach to pathogen log removal evaluation, strategies used to address the issues during the testing in this project, and a discussion of the results from the pathogen removal evaluation.

6.1 Pathogen Removal Considerations

6.1.1 LRV Crediting Practice

In wastewater, significantly variable pathogen concentrations have been reported (Salveson et al. 2018; Salveson and Soller 2019). For example, after reviewing previously published papers and reports, Salveson et al. (Salveson et al. 2018) reported 3 to 1,300 culturable viruses/L – which corresponded to 10^7 to 10^9 viruses/L based on qPCR analysis – and 6 to 17,000 protozoa/L in wastewater. The presence of these waterborne pathogens with substantial variability in wastewater results in significant health risks for potable reuse unless robust pathogen barriers are put in place.

The fundamental basis for meeting microbial risk standards in potable reuse is based on the goal of achieving less than 1 in 10,000 annual risk of infection for virus, *Giardia*, and *Cryptosporidium*. The finished water pathogen concentration limits to achieve this risk-based water quality goal are $<6.8 \text{ X } 10^{-6}$ cysts/L for *Giardia*, $<3.0 \text{ X } 10^{-5}$ oocysts/L for *Cryptosporidium*, and $<2.2 \text{ X } 10^{-7}$ MPN/L for enteric virus (Steinle-Darling et al. 2016). There are different regulatory approaches as to how to achieve these pathogen control goals in each state.

In California, the regulations for IPR requires a minimum of 12-log and 10-log, removal of viruses and protozoa (*Giardia* and *Cryptosporidium*), respectively (CA SWRCB 2018) with a safety factor applied to provide a safeguard against potential outbreak conditions (Trussell et al., 2013). The newly released California draft DPR addendum requires 20-log, 14-log, and 15-log reduction for virus, *Giardia*, and *Cryptosporidium*, respectively, through an advanced water purification treatment train, which must include at least four treatment processes specific for each pathogen category with ozone/BAC[2] upstream of RO and UV/AOP (CA SWRCB 2018).

In California, LRV credits for treatment processes are awarded based on USEPA tables (USEPA, 2006a) and results of challenge tests for treatment processes. Examples of LRV credits assignment based on challenge tests include credits for primary and secondary wastewater treatment processes (Water Replenishment District 2013), demonstration of virus removal with the use of ozone or UV treatment processes as per the NWRI standard (National Water Research Institute, 2012) and use of WaterVal (WaterSecure, 2017) from Australia for free chlorine credits.

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[2] For very low blending percentages of purified recycled water with conventional water supply, the use of ozone/BAC is not required.

In contrast to the approach in California, LRV credits are approved in Texas on the basis of federal drinking water guidance (USEPA, 2006a), limiting the credit available for some advanced treatment processes in the state (e.g., RO). The LRV targets are established on a case-by-case basis through comprehensive source water characterization of pathogens. The source water characterization establishes the treatment "gap" between pathogen concentrations in the secondary effluent and the finished water quality goals for each case, which must be closed through pathogen removal and inactivation provided by the advanced treatment facility.

For a DPR project with RWA, the final pathogen removal step is at the SWTP. At an SWTP, processes with proven surrogates independent of solids, such as ozone or chlorine (credited by CT), UV (credited by dose), and MF/UF (credited by pressure-driven test [PDT]), LRV credits are assigned following USEPA criteria. Table 6-1 presents filtration credits for pathogen removal as per the LT2ESWTR.

Table 6-1. Filtration Credits for Pathogen Log Removal.

Source: USEPA, 2006a.

Filtration Treatment Technology	Combined Filter Effluent Turbidity (95% Monthly/Max; NTU)	Maximum Log Credits for Physical Removal			Minimum Log Inactivation Needed by Disinfection	
		Cryptosporidium	***Giardia***	**Viruses**	***Giardia***	**Viruses**
Conventional Filtration	0.3/1	2.0	2.5	2.0	0.5	2.0
Direct Filtration	0.3/1	2.0	2.0	1.0	1.0	3.0

When blending ATW with the raw water sources, the LRV crediting approach for the unit processes with proven surrogates independent of solids is not expected to be changed primarily because these unit processes have provisions for measuring and responding to the water quality changes. Thus, when implementing RWA for DPR, the primary question related to pathogen removal is whether blending ATW will affect LRV credits for solids removing unit processes at an SWTP (i.e., coagulation, flocculation, sedimentation, and media bed filtration). Therefore, this Chapter focuses on pathogen removal through coagulation, flocculation, sedimentation, and media bed filtration.

6.1.2 Pathogen Removal Testing

Physical removal of protozoan parasites, such as *Cryptosporidium parvum* and *Giardia lamblia*, has been the most effective approach for preventing passage of these microorganisms through drinking water treatment and protecting public health. A wide range of *Cryptosporidium* removal has been reported in previous studies, ranging from 0- to greater than 5-log removal (Dugan et al. 2001; Nieminski and Ongerth 1995; States et al. 2002) across a surface water treatment plant. Similarly, previous studies have reported 3- to greater than 4-log reduction of surrogates for pathogenic viruses through coagulation, flocculation, sedimentation, and filtration (Boudaud et al. 2012; Shirasaki et al. 2010). Low concentration of these microbial species complicates the direct quantification and evaluation of log removal, requiring collection of enormous water volumes (Antony et al., 2014). To address the low concentration issue, methods have been developed for concentrating the target microorganisms (Kunze et al. 2015). Furthermore, indicator microorganisms (Brown and Cornwell 2007; Garvey et al. 2013), non-biological surrogates (Emelko and Huck, 2004; Liu et al. 2019), or parameters (Bastos et al.

2013; Garvey et al. 2013; Gregory, 1994; Nieminski and Ongerth 1995) have been identified and tested, proving cost-effective monitoring and assessment of pathogen log removal.

In general, when designing a pathogen removal evaluation, the following key questions should be considered:

- What are the target microorganisms of interest?
- What is the potential concentration of the target microorganisms in the source water and treated water? Is it practically possible to quantify the target microorganism in the raw water and the treated water?
- What are the potential indicator microorganisms that can be used for demonstration?
- Where can the indictor microorganisms be obtained from?
- Can any potential monitoring parameters be used as surrogate monitoring parameters for the microorganism of interest?
- Will the indicator microorganisms tolerate the water matrix? Does the water have any inhibitory components?
- What is the potential recovery rate for the indicator microorganisms of interest?
- How and where should the indicator microorganism be inoculated in the treatment train? What should be the target concentration for inoculation?
- What will be the sample collection, handling and shipping, and storage protocols?
- Which method will be used for quantifying the indicator microorganisms? Which analytical laboratory will be used for the analysis?
- Will the challenge testing approach be accepted by the regulatory agency?
- What could be the potential credit obtained over the baseline LRV credits assigned in accordance with the LT2ESWTR?

The following sections briefly discuss various aspects of pathogen log removal evaluation.

6.1.3 Indicator Selection

In general, the presence of indicator microorganisms in the source water should be well correlated with the microorganisms of health concern. A good indicator microorganism for pathogen removal evaluation should ideally exhibit similarities to the target microorganisms with respect to:

- Viability and regrowth in the water and across the plant.
- Size, shape, and surface charge characteristics.
- Propagation and retention characteristics.
- Response to treatment processes (e.g., UV and chlorine).
- Spatial distribution in the source and treated water.

Additional key characteristics of an indicator microorganism include:

- Harmless to human health.
- Easily available.
- Cost effective.
- Easy to seed and quantify.

- Provide a conservative log removal in comparison to the microorganism of health concern.

Except the viability and regrowth, the above-mentioned characteristics are equally applicable for non-biological indicators. Many microbial indicators have been previously used and demonstrated for the evaluation of pathogen log removal across a drinking water treatment plant. For example, *E. coli* has been used as a microbial indicator for bacteria, whereas aerobic spores and anaerobic spores have been used as microbial indicators for *Cryptosporidium* (Garvey et al. 2013; Headd and Bradford 2016; Nieminski et al. 2000). MS2 bacteriophage, F-specific RNA bacteriophage MS2 (diameter 0.024 µm), F-specific RNA bacteriophages Qβ (diameter 0.025 µm) and GA (diameter 0.026 µm) were used as the microbial indicators for virus (Antony et al. 2012; Hébrant et al. 2014; Nieminski et al., 2000; Shirasaki et al. 2010). In a review of pathogen LRVs reported for membrane bioreactors, Branch et al. (2020) reported *Clostridium perfringens* as the most often reported microbial indicator for *Cryptosporidium*. They selected *E. coli* as the suitable microbial indicator for LRV demonstration for bacteria.

Due to the health risks associated with the use of viable *Cryptosporidium* oocysts, chemically inactivated oocysts (Nieminski and Ongerth 1995) have often been used, which has been questioned due to the potential changes in particle characteristics due to the chemical treatment. However, in a bench-scale evaluation, Emelko (2003) demonstrated that formalin-inactivated oocysts can be reliable indicator for viable oocysts.

Previous studies have also indicated limitations of microbial challenge testing approaches and enumeration techniques primarily due to considerable skill and time requirements, and difficulty in differentiating physical-chemical retention and inadvertent biological inactivation (Antony et al. 2014). Accordingly, a few studies evaluated non-biological indicators for assessing pathogen LRV. For example, Emelko and Huck (Emelko & Huck 2004) and Liu et al. (Liu et al. 2019) demonstrated the use of polystyrene microspheres as the indicators for *Cryptosporidium* parvum in filtration.

The microbial or non-biological indicator to be used for a pathogen log removal evaluation should be carefully selected with consideration for the representativeness of the results to guide the potential log removal of pathogen in a specific treatment system. Besides the microbial and non-biological indicators, the possibility of utilizing particle count as a surrogate parameter for assessing pathogen log reduction in treatment processes has been previously evaluated (McTigue et al. 1998; Nieminski and Ongerth 1995). However, given the differing correlations observed between particle count and pathogen log removal in these studies, the possibility of using particle count as a surrogate parameter should be carefully evaluated for each case.

The potential overestimation of LRV due to inadvertent biological inactivation was less of a concern for this project, especially since the overall goal of the project was to assess the effects of blending on pathogen removal and results between various ATW blends were compared. Operating conditions, indicator preparation and injection, sample collection, handling, and analysis were kept the same to the extent possible to avoid any unintentional introduction of error in the results. Furthermore, qPCR-based quantification was relied upon when calculating LRVs to avoid any differences resulting from inhibitory effects of the water matrix. The possibility of using particle count as a surrogate parameter for assessing pathogen log removal was also evaluated by comparing pathogen log removal and particle removal from the same set of samples.

6.1.4 Pre-Assessment of the Impact of Water Matrix

Before testing log reduction of an indicator microorganism in the field, it is a good practice to evaluate potential inhibition of the indicator microorganism in the water to be tested. When considering evaluating pathogen log removal with ATW blended water, inhibition assessment in the minimum and maximum ATW blend to be tested would provide information on the effects of water matrix on the indicator microorganism. If the preliminary inhibition testing indicates that the water matrix affects the viability of the indicator microorganism, pathogen log removal evaluation may still be possible with qPCR-based quantification approach. In this study, though the initial MS2 'die off' test did not indicate negative effects of the ATW source, inhibition was observed in the real samples collected during the pilot testing and the qPCR-based MS2 quantification approach was relied upon for assessment of pathogen log removal.

6.1.5 Feed Stock Preparation

The feed stock of the indicator should be prepared in batches with high concentration (typically 6-log or higher) to ensure quantifiable indicator presence in the treated effluent. In general, a tank large enough to supply feed for the entire testing duration is needed to continuously seed the indicator. However, filter runtimes at an SWTP can be longer than 24 hours depending on the source water quality and viability of the indicator organisms may change if a single batch of feed stock is used for the entire duration of the filter run. To avoid errors resulting from long-term use of a single feed batch, preparing feed stock every day as needed is recommended. A mechanical mixer should be used to keep the indicator in suspension in the feed tank. The speed of the mechanical mixing should be adjusted to not affect viability of the indicator microorganism.

6.1.6 Indicator Injection Location

The indicator should be injected through an injection port upstream of the unit process across which the LRV is to be determined. When evaluating the effects of blending ATW with raw water sources, ideally, the indicator would be injected upstream of the rapid mix. However, if the goal is to determine pathogen log removal only in filters, the indicator should be injected upstream of the filtration unit process.

6.1.7 Feed Stock Injection

Proper injection and mixing of the indicator in the bulk flow is critical. The distance between the indicator injection port and the influent sampling port should be long enough to ensure proper mixing of the indicator in the raw water. A static mixer, located between the injection and sampling port, can enhance mixing and ensure representative influent samples. The indicator should be injected continuously using a chemical feed pump for a period long enough to reach steady conditions. Before the challenge testing, test feeding should be considered to verify that a homogenous feed is injected to the system and the targeted indicator microorganism concentration is measured at the first sampling location. Tracer studies may be conducted to determine the total residence time in the system and the optimal sample collection time point after injecting the seed (Nieminski and Ongerth, 1995). In general, 3 to 4 total residence times should be allowed across the influent and effluent sampling locations (i.e., across the unit processes for which the LRV is being determined) after starting the indicator injection for establishing steady state conditions before collecting the first set of samples.

6.1.8 Sample Collection, Handling, and Analysis

Grab indicator-spiked samples should be collected from the influent and effluent sampling ports following the sample collection instructions received from the analytical lab. Sample containers should be stored and shipped to the analytical laboratory following the instructions received from the laboratory. Typically, when using indicator microorganisms, the sample should be stored on ice (or at 4 °C) immediately after collection and shipped overnight to the laboratory on ice.

Sample analysis should be conducted at a qualified/certified laboratory following standard analytical method. Often, culture-based analysis with a double layer agar method is used for determining the concentration of the indicator organism, for example MS2 (Antony et al. 2014). However, quantitation may also be done targeting specific genes through quantitative real-time PCR.

6.1.9 General Protocol for LRV Evaluation

Pathogen log reduction validation with the use of indicator microorganisms follows the general protocol given below:

- Record feed water characteristics and operating conditions (e.g., influent flow rate, filter loading rate, characteristics of media used in the filter, feed water pH, temperature, TOC, etc.).
- Prepare batch feed stock with high concentrations (typically 6-log) and use a mechanical mixing to keep the indicator in suspension.
- Start injecting the indicator and continue for 3 to 4 total residence times across the treatment processes to be evaluated.
- Collect grab samples of influent and effluent following the standard sample collection procedure.
- Ship the sample overnight on ice to the analytical laboratory.
- Determine the concentrations of the indicator in the influent and effluent.
- Calculate LRV using the relation given below:
    - $LRV = \log10 (C_{influent}/C_{effluent})$
- Repeat the steps, analyze the data, and determine the LRV for the treatment process.

6.2 Pathogen Log Removal Evaluation Results

The goal of the pathogen removal evaluation in this study was to understand the effects of ATW blending on pathogen removal across a conventional SWTP. The pathogen removal evaluations were conducted at Plants A and C during the pilot testing through challenge testing with MS2 and PMMoV. These challenge tests were not intended to represent protozoa removal but the results generate valuable information for potential virus removal. The LRVs achieved with the challenge testing could be used as conservative LRVs for protozoa removal at the participating utilities.

MS2 and PMMoV were used as the indicator microorganisms for the testing due to the following reasons:

1. Easy availability – MS2 bacteriophage can be easily sourced from commercial labs, which also provide analytical services. A hot paper sauce was used as the source of PMMoV.
2. Non-pathogenic nature – both MS2 and PMMoV are non-pathogenic and commonly found in the environment.
3. Representative characteristics – These indicator microorganisms have similar size compared to enteric viruses.
4. Inexpensive – These indicator microorganisms can be obtained in high concentrations at low cost.
5. Conservative LRV – Since these indicator microorganisms are smaller in size than protozoan pathogens, conservative LRVs would be assessed through the use of these microorganisms.

A commercial hot pepper sauce was used as the source of PMMoV, which was spiked into the floc/sed influent (upstream of the rapid mix) along with MS2 from a single feed tank. The feed dose of PMMoV was determined through a batch experiment by spiking a certain volume of the pepper sauce into 1 L raw water collected from Plant A. Based on the results (Table 6-2), 0.1 mL/L of the hot pepper sauce was selected as the working feed dose for the pilot testing to achieve approximately 10^3 to 10^4 gc/mL PMMoV without appreciably changing pH, turbidity, or TOC concentration in the water.

Table 6-2. Results of Pepper Sauce Spiking Batch Experiment.

Details	PMMoV Concentration (gc/mL)	pH (SU)	Turbidity (NTU)	TOC (mg/L)
Control (pepper sauce not added)	3.75E-01	8.20	3.693	3.52
0.01 mL/L pepper sauce	9.89E+01	8.18	3.715	3.96
0.1 mL/L pepper sauce	5.15E+03	7.96	4.701	6.77
1.0 mL/L pepper sauce	6.25E+04	6.84	14.50	39.21

Using an inline or bench-top particle size analyzer, particle counts in the floc/sed influent and filter effluent samples collected during the MS2 and PMMoV challenge testing were determined. The inline analyzer used at Plant C was capable of counting particles ranging from 2 µm to greater than 45 µm, whereas the bench-top analyzer used for counting particles in the samples received from Plant A was able to count particles ranging from 1 µm to >5 µm. The particle count data for Plant A were binned into 1–2 µm, 2-5 µm, >5 µm sizes, whereas the particle count data for Plant C were binned into 2–5 µm, 5–15 µm, and >15 µm bins. Given the size range of *Giardia* cysts (i.e., 5 to 8 µm) and *Cryptosporidium* oocysts (i.e., 3 to 6 µm) (Adam 1991; Medema et al. 1998), the particle size bins evaluated in this study would potentially provide indicative information on protozoa removal and virus removal across the system.

The following sections present the results from the pilot testing at Plants A and C.

6.2.1 Plant A – Pathogen Removal Evaluation Results

6.2.1.1 MS2 Log Removal

At Plant A, initially, both culture-based and qPCR-based methods were used for MS2 quantification, whereas PMMoV was quantified through qPCR-based method only. However, the MS2 culture-based results of the 0% and 10% blends suggested MS2 inhibition in the ATW blended water (data not shown). While discussing the results with the plant operators, it was determined that the ATW contained approximately 1 mg/L total chlorine. Additional inhibition confirmation tests were conducted with a fresh batch of ATW with and without the use of sodium thiosulfate (to dechlorinate the water). The test results confirmed that the presence of chlorine in the ATW resulted the MS2 inhibition (Figure 6-1).

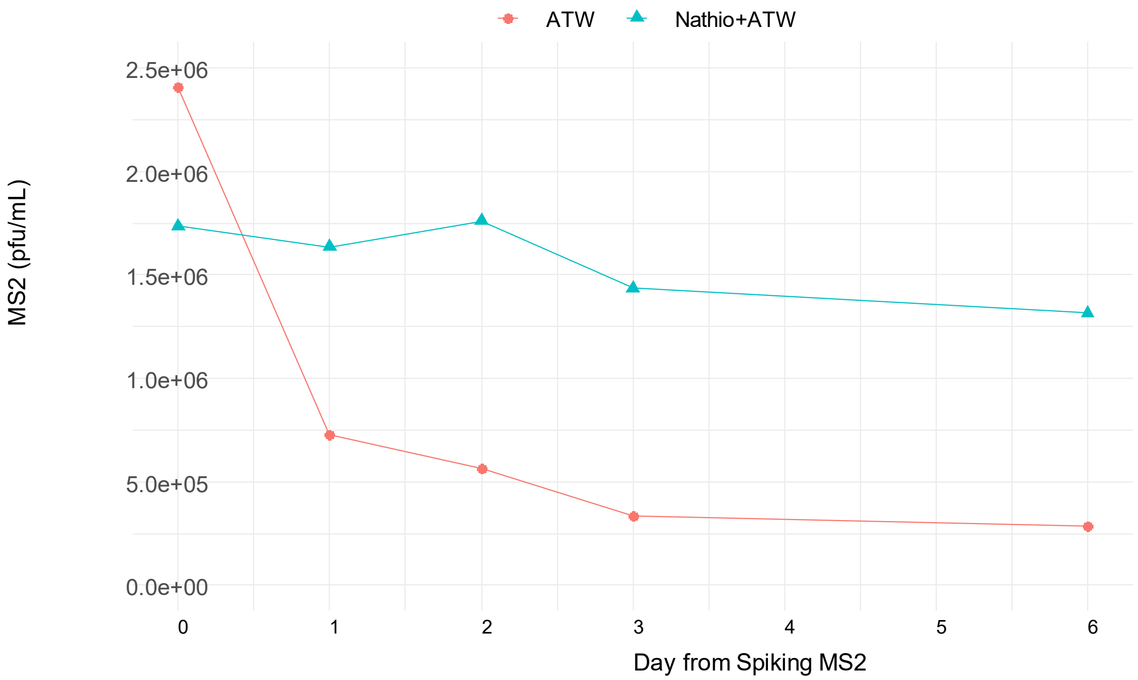

Figure 6-1. Plant A Pilot Testing - MS2 Inhibition by ATW.

Abbreviations: Nathio+ATW – sodium thiosulfate treated ATW.

Since the presence of chlorine did not affect qPCR-based MS2 quantification, MS2 log removal was assessed using qPCR results only. In the floc/sed influent, the average MS2 gc/mL ranged from 6.1 to 7.3 log (Figure 6-2), whereas 2.9 to 6 log gc/mL were observed in the filter effluent. The average MS2 removal was 1.6-log, 1.3-log , 2.1-log, and 3.0-log (as gc/mL) for the 0% (number of samples, n=3), 10% (n=3), 20% (n=3), and 50% (n=3) blend, respectively (Figure 6-3). While the log removal with the 0% and 10% were not statistically different (p=0.31047), the removals observed with the 20% and 50% blend were significantly different (p=0.0474 and p=0.0045, respectively). The results indicated increasing the blending ratio improved MS2 log removal across the coagulation, flocculation, sedimentation, and filtration.

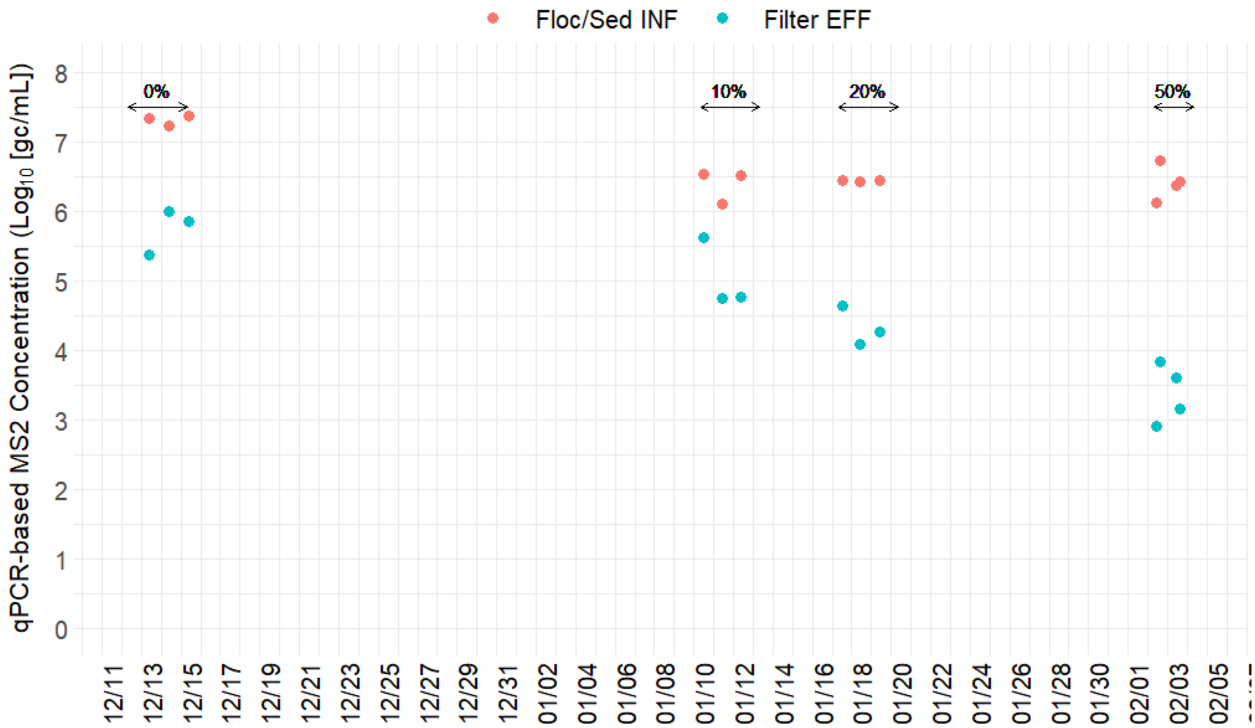

Figure 6-2. Plant A Pilot Testing - MS2 Concentrations in the Floc/Sed Influent and Filter Effluent.

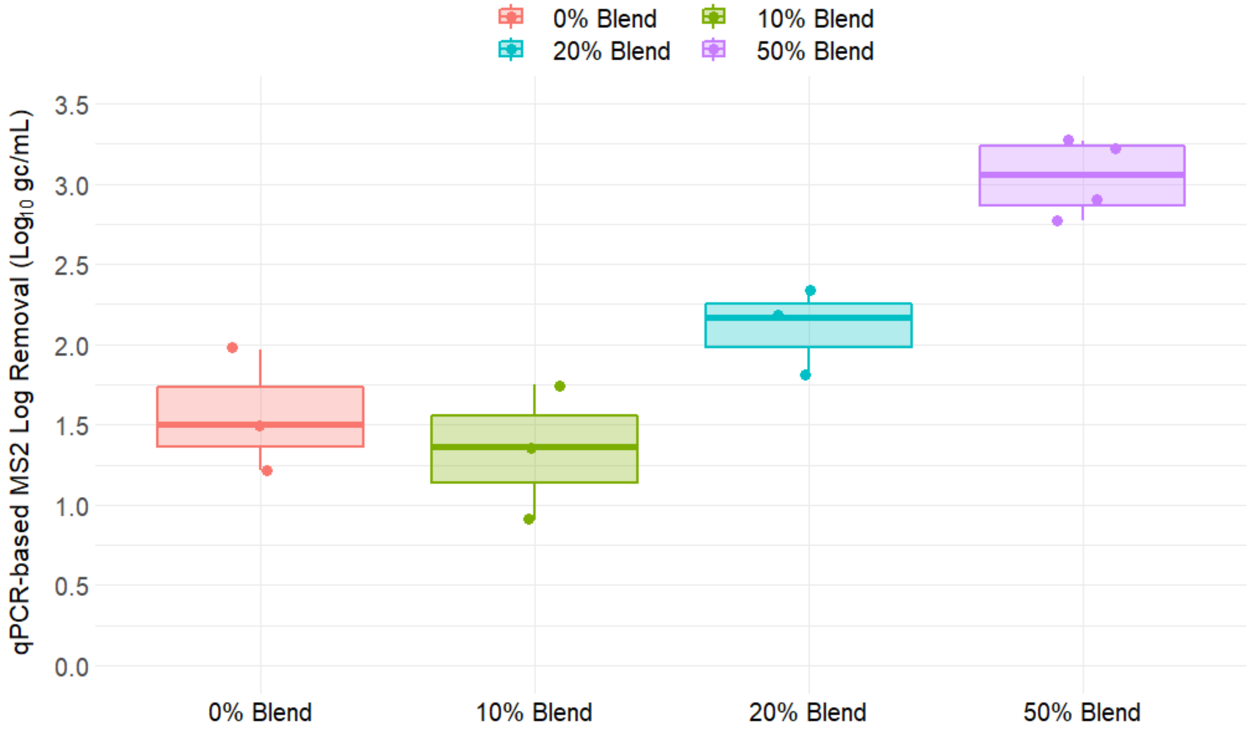

Figure 6-3. Plant A Pilot Testing - MS2 Log Removal Across the System.

6.2.1.2 PMMoV Log Removal

PMMoV concentrations in the floc/sed influent and filter effluent ranged from 1.7- to 3.9- and -0.2- to 1.4-log, respectively (Figure 6-4). Accordingly, the average PMMoV removal was 1.9-log, 1.5-log, 1.9-log, and 2.6-log with the 0% blend, 10% blend, 20% blend, and 50% blend, respectively (Figure 6-5). While the removals observed with the 10% and 20% blends were not statistically different than the 0% blend (p = 0.1178 and p = 0.4858, respectively), the removal observed at the 50% blend was significantly higher (p = 0.0319). Therefore, similar or better PMMoV log removal can be expected when blending ATW with the surface water source at Plant A, results that agree with the limited MS2 work presented above.

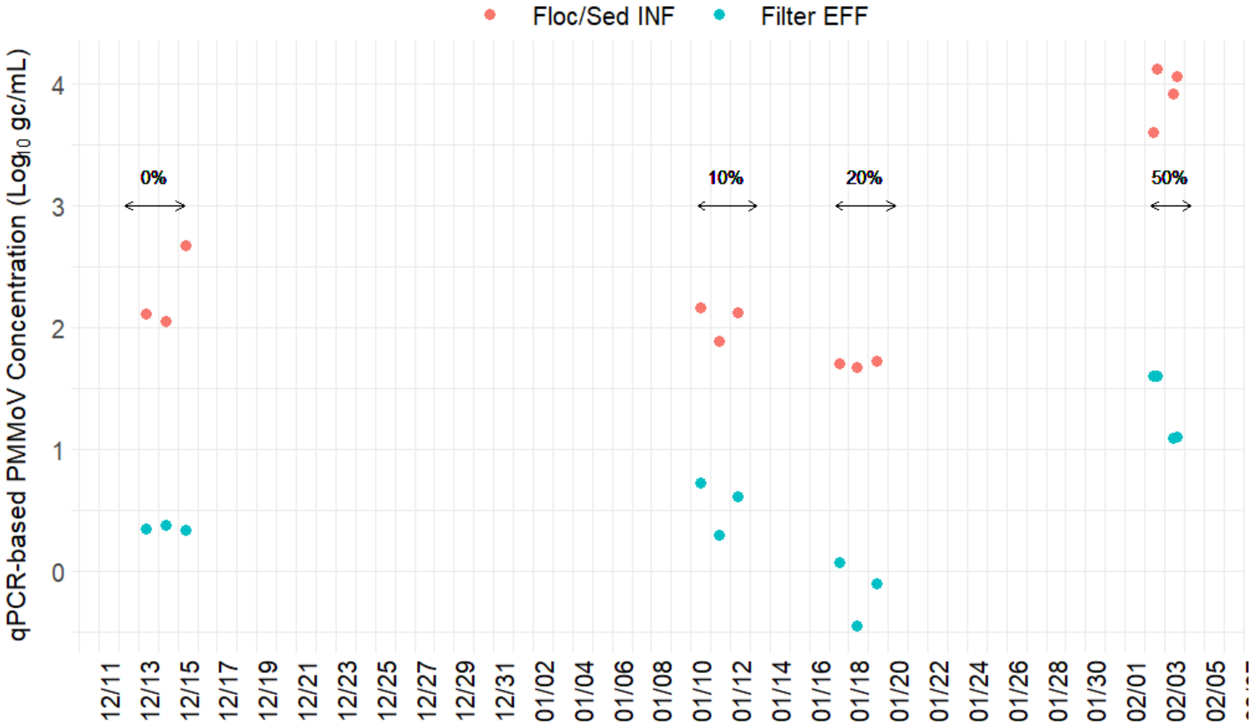

Figure 6-4. Plant A Pilot Testing - PMMoV Concentration in the Floc/Sed Influent and Filter Effluent.

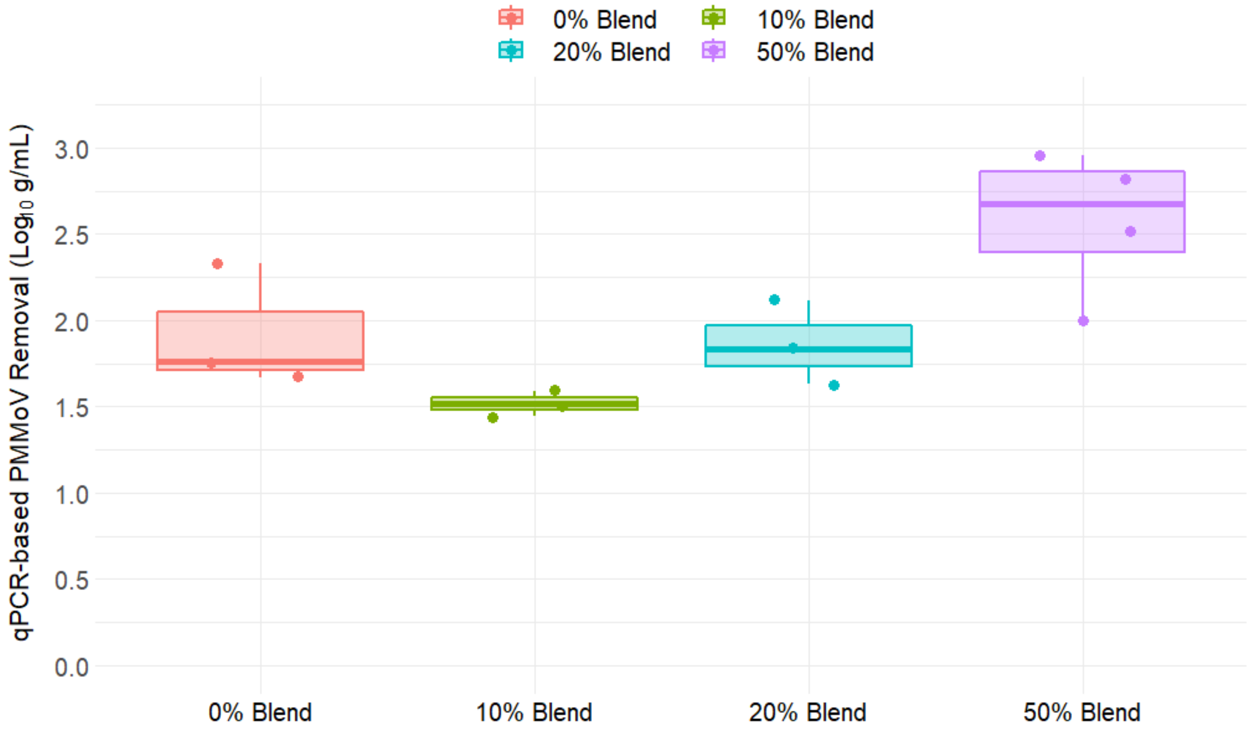

Figure 6-5. Plant A Pilot Testing - PMMoV Log Removal Across the System.

6.2.1.3 Particle Removal

Figure 6-6 presents particle log removal across the system. With the 0%, 10%, 20%, and 50% ATW blend, average removal of 1–2 µm was 2.0-log, 2.7-log, 2.9-log, and 2.5-log, respectively. Similarly, for particles >5 µm, the average removal was 2.0-log, 2.8-log, 3.5-log, and 2.4-log for the 0% blend, 10% blend, 20% blend, and 50% blend, respectively. Average removal for the 2-5 µm range particles remained 1.0-log, 1.5-log, 2.1-log, and 1.5-log, respectively, with the 0% blend, 10% blend, 20% blend, and 50% blend. While particle log removal with the 50% blend was lower compared to the 10% and 20% ATW blends, the results suggest that ATW blending will not affect particle removal across the system.

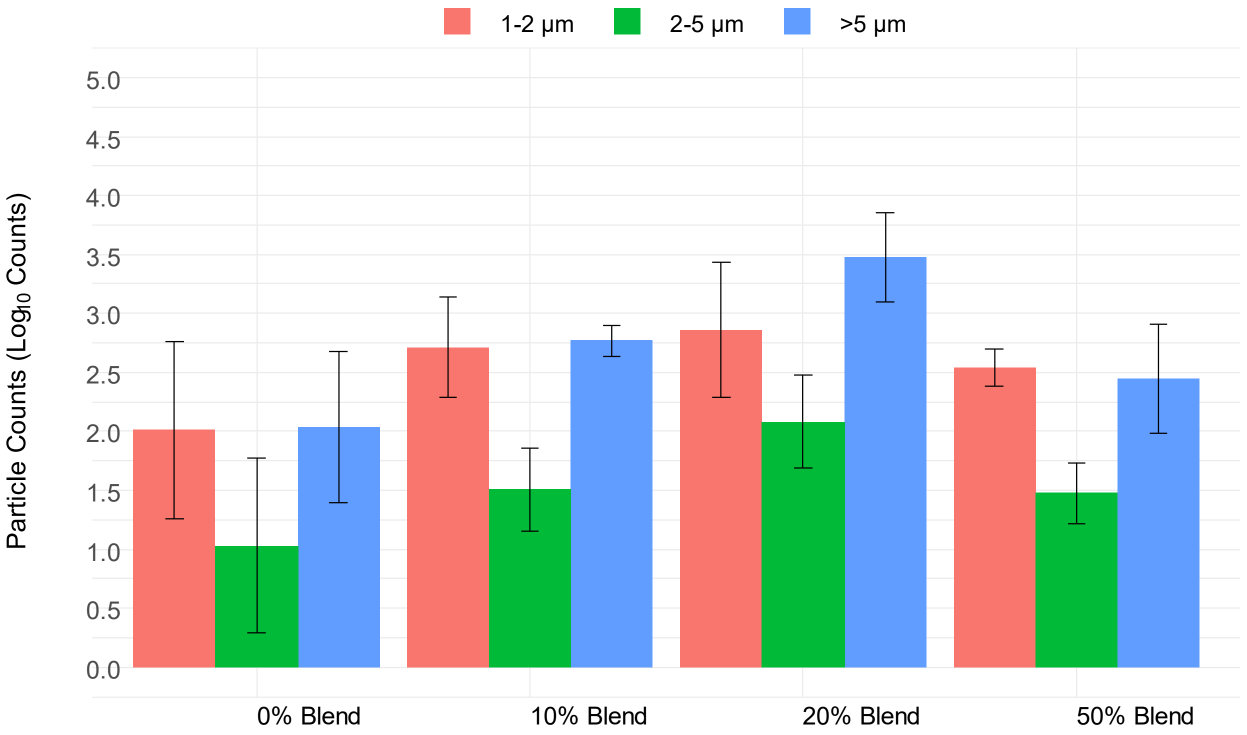

Figure 6-6. Plant A Pilot Testing - Particle Removal Across the System.

Based on Figures 6-2 through 6-6, as expected, particle removal did not reflect pathogen removal due to the size difference of the indicator organisms (MS2 - 24-26 nm diameter [Wick and McCubbin 1999]; PMMoV – 18 nm in diameter and 300 to 310 nm in length [Canh et al. 2019; Kitajima et al. 2018]) and the particles monitored.

6.2.1.4 Summary of Plant A Pathogen Removal Evaluation

The findings of pathogen removal evaluation are summarized below:

- qPCR-based MS2 quantification was not affected by the presence of disinfectant in the ATW and was used for the MS2 removal evaluation.
- MS2 and PMMoV log removals increased with increasing ATW blending ratio.
- Particle removal was not affected by the ATW blending.
- As expected, MS2 or PMMoV log removals were not correlated with particle removal due to the size differences.

6.2.2 Plant C – Pathogen Removal Evaluation Results

6.2.2.1 MS2 Log Removal

MS2 log removal was assessed through both culture-based and qPCR-based analyses. Figure 6-7 and Figure 6-8 present culture-based and qPCR-based MS2 concentrations, respectively. While culture-based results indicated 4.3-log to 5.1-log PFU/mL MS2 concentrations in the floc/sed influent (Figure 6-7), the qPCR-based results showed 5.1-log to 6.8-log MS2 gc/mL (Figure 6-8).

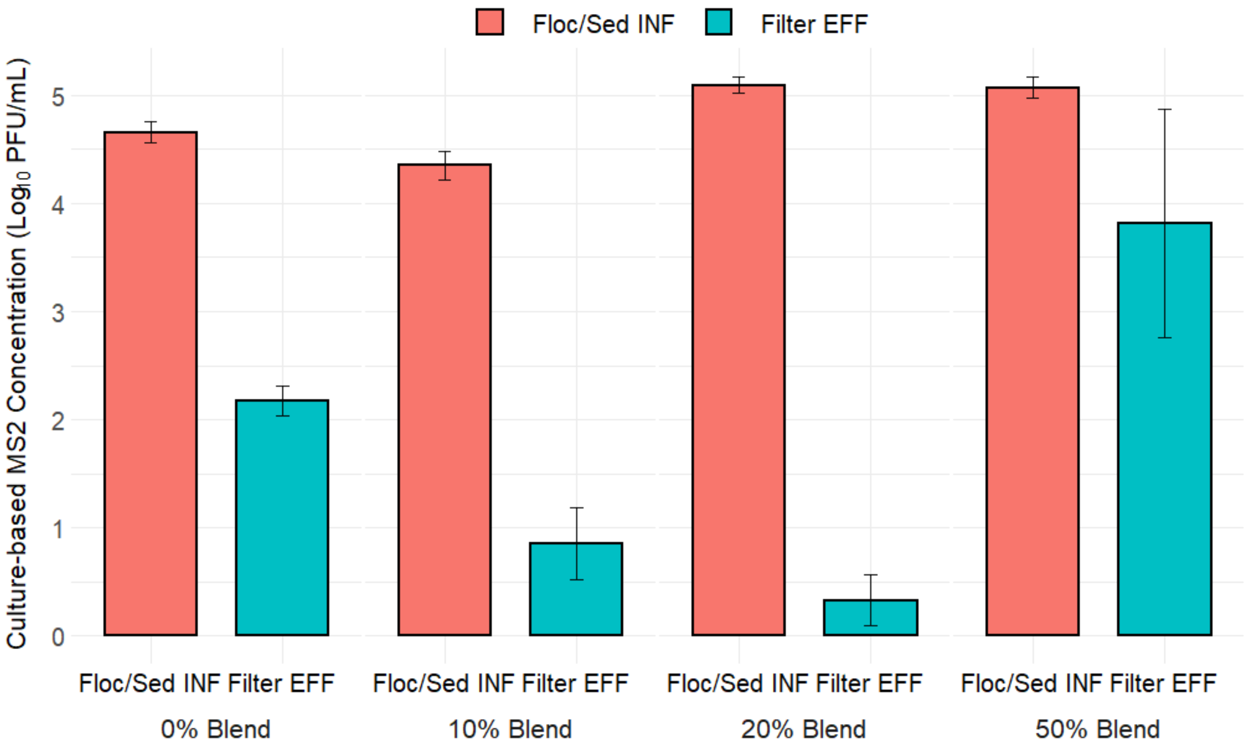

Figure 6-7. Plant C Pilot Testing - Culture-Based MS2 Concentrations in the Floc/Sed Influent and Filter Effluent.

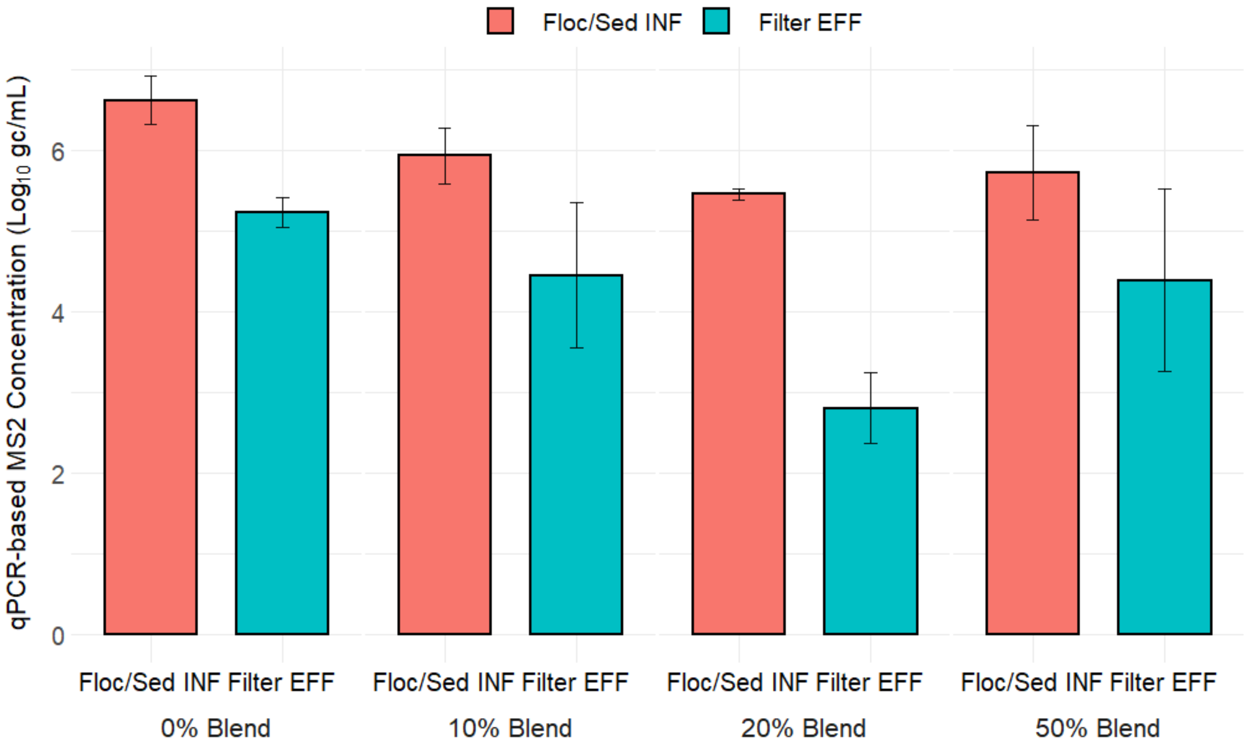

Figure 6-8. Plant C Pilot Testing - qPCR-based MS2 Log Concentrations in the Floc/Sed Influent and Filter Effluent.

Based on the culture-based results, MS2 log removal improved (Figure 6-9) from the 0% blend to 10% blend (p=0.002) and from 10% blend to 20% blend (p=0.001). The improved MS2 log removal with the increasing percentage agreed with the observations from Plant A pilot testing. Compared to the 20% blend, the removal significantly decreased (p=0.019) when testing the 50% blend (Figure 6-9). However, compared to the 0% blend, the MS2 log removal with the 50% blend was not statistically different (p=0.112). Given the significant wide variations in the results with the 50% blend, it cannot be ruled out that the results were likely affected by potential human errors (e.g., system operation error, sample collection error, and analytical error). Overall, the culture-based results indicated that similar or better MS2 removal could be achieved when treating ATW-blended water. The decrease in pathogen log removal with the 50% blend compared to the 20% blend indicated that there may be a site-specific blending ratio threshold, beyond which the pathogen log removal may be challenged.

While the MS2 log removal trend based on the qPCR results matched the trend observed with the culture-based results, considerably lower log removals were observed with the qPCR method (Figures 6-9 and 6-10). Based on the **qPCR results** (Figure 6-10), the MS2 log removal was statistically similar between the 0% blend and 10% blend (p=0.432) and 0% blend and 50% blend (p=0.447), whereas the log removal with the 20% blend was significantly higher than the 0% blend (p=0.018). Overall, the qPCR-based results confirmed that MS2 log removal would not be affected by blending the ATW with the raw water.

The differences in the culture-based and qPCR-based results warrant additional sampling and analysis for further verification of the results, which was beyond the scope of the project.

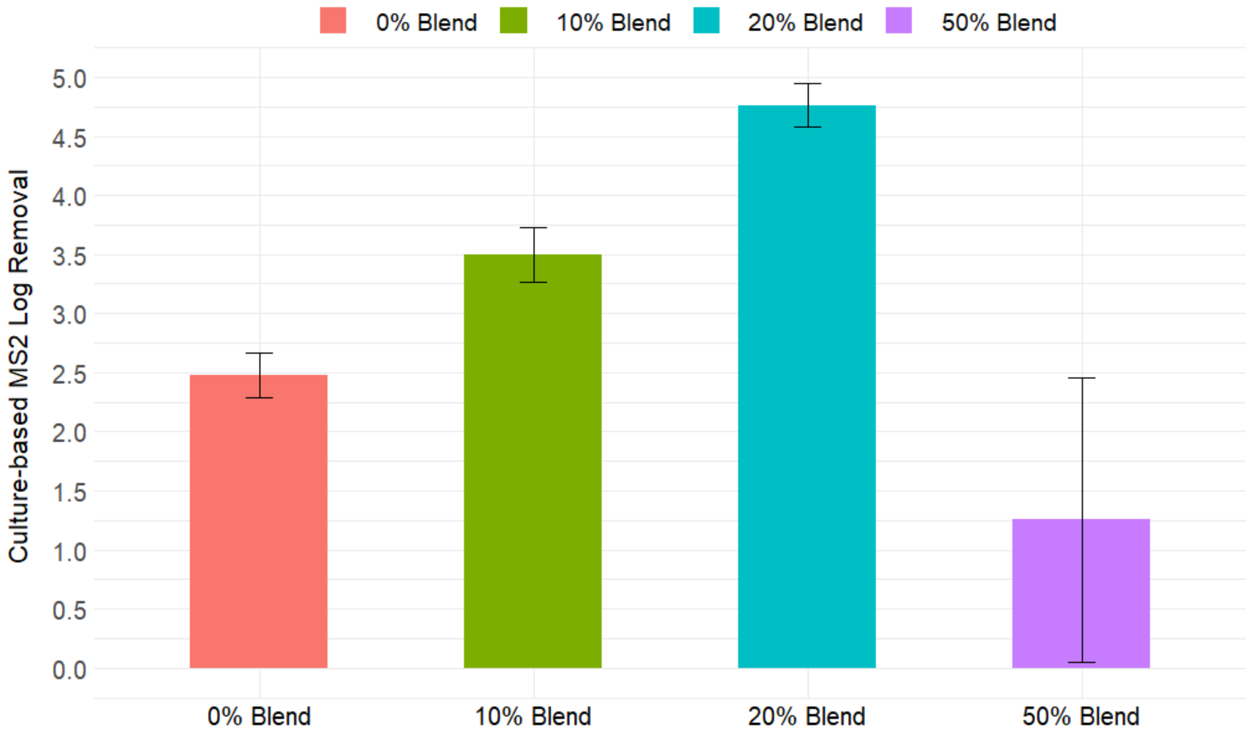

Figure 6-9. Plant C Pilot Testing - Culture-Based MS2 Log Removal Across the System.

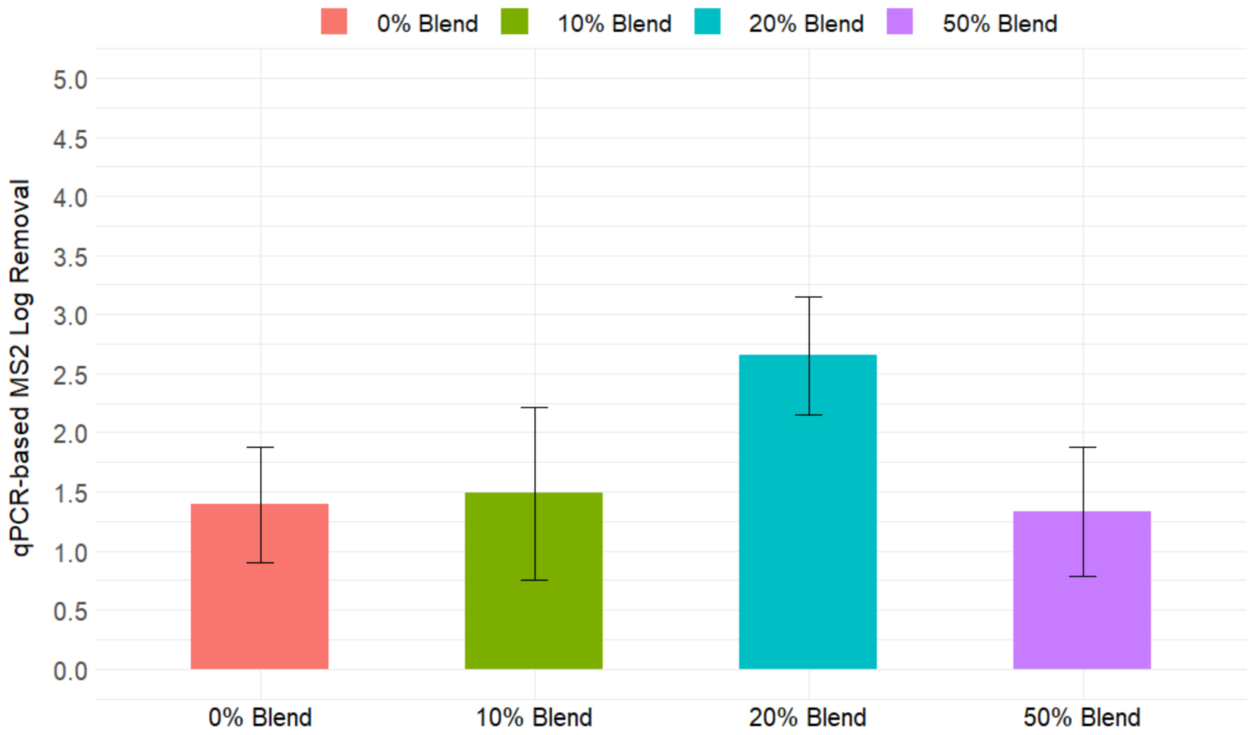

Figure 6-10. Plant C Pilot Testing - qPCR-Based MS2 Log Removal.

6.2.2.2 PMMoV Log Removal

A commercial hot pepper sauce was used as the source of PMMoV, which was spiked into the floc/sed influent by simultaneously feeding MS2 and PMMoV from a single feed tank. qPCR-based analysis was conducted to enumerate PMMoV concentrations in the floc/sed influent and filter effluent. The average PMMoV concentrations in the floc/sed influent ranged from 4.3 $\log_{10}$ gc/L to 6.5 $\log_{10}$ gc/L (Figure 6-11). Compared to the PMMoV log removal with the 0% blend (Figure 6-12), the removals with the 10% blend (p=0.332) and 20% blend (p=0.224) were statistically similar, whereas the log removal with the 50% blend was significantly lower (p=0.021), primarily due to lower floc/sed influent concentration. In general, the results indicated that blending the ATW with the raw water source did not affect PMMoV removal across the pilot-scale system. Note, this data on PMMoV and MS2, combined with the particle data shown below, suggests that there may be a reduction in pathogen removal performance at the highest blend ratio (50%) compared to lower blend ratios and further evaluation should be considered.

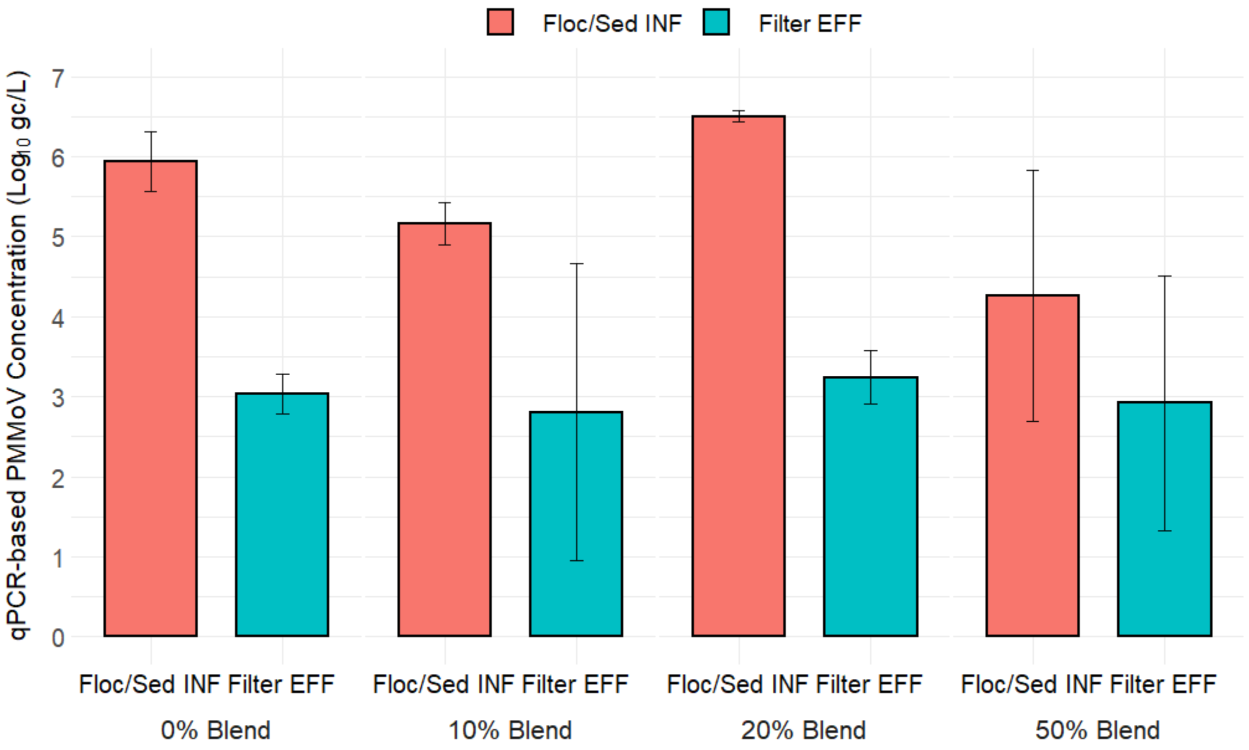

Figure 6-11. Plant C Pilot Testing - qPCR-based PMMoV Concentration.

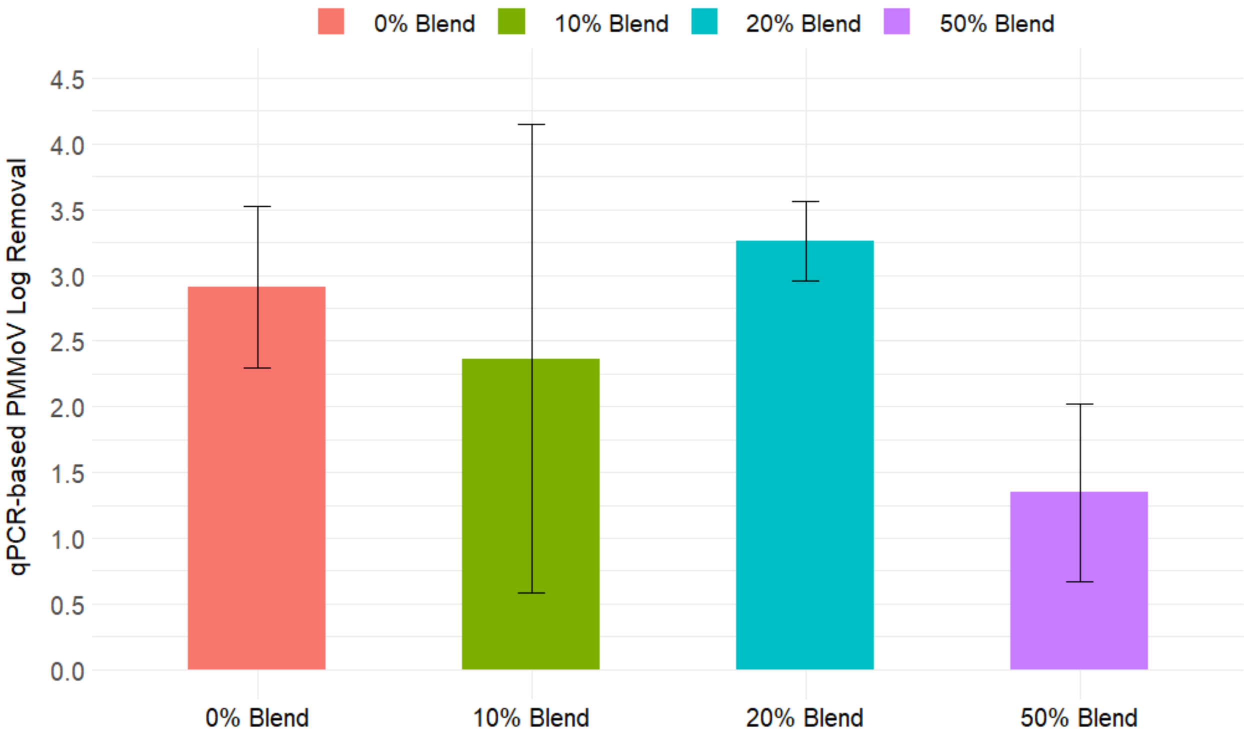

Figure 6-12. Plant C Pilot Testing - PMMoV Log Removal.

6.2.2.3 Particle Removal

Particle counts in the floc/sed influent and filter effluent samples were monitored using in-line particle counter. Particles were binned into 2–5 µm, 5–15 µm, 15–20 µm, 20–25 µm, 25–30 µm, 30–35 µm, 35–40 µm, 40–45 µm, and >45 µm bins. Particles smaller than 2 µm could not be quantified due to the limitations of the particle size analyzer. However, given the size range of *Giardia* cysts (i.e., 5 to 8) and *Cryptosporidium* oocysts (i.e., 3 to 6 µm), particles only in the range of 2–5 and 5–15 µm size range are reported below.

In the floc/sed influent, the average counts of particles 2–5 µm and 5–15 µm ranged from 3.3-log to 4.2-log and 2.5-log to 4.3-log, respectively (Figure 6-13). For both 2–5 µm and 5-15 µm bins, particle removal improved from 0% blend to 10% blend and from 10% blend to 20% blend ($p<0.05$). Compared to the 20% blend, particle removal was significantly lower for the 2-5 µm ($p=0.000$) and 5–15 µm ($p=0.002$) bins (Figure 6-14). However, the removal observed with the 50% blend was statistically better than the 0% blend for the 2–5 µm bin ($p=0.001$), whereas the removals were similar with the 0% blend and 50% blend for the 5-15 µm bin ($p=0.064$). The results indicated that similar or better particle removal was achieved when ATW-blended water was used.

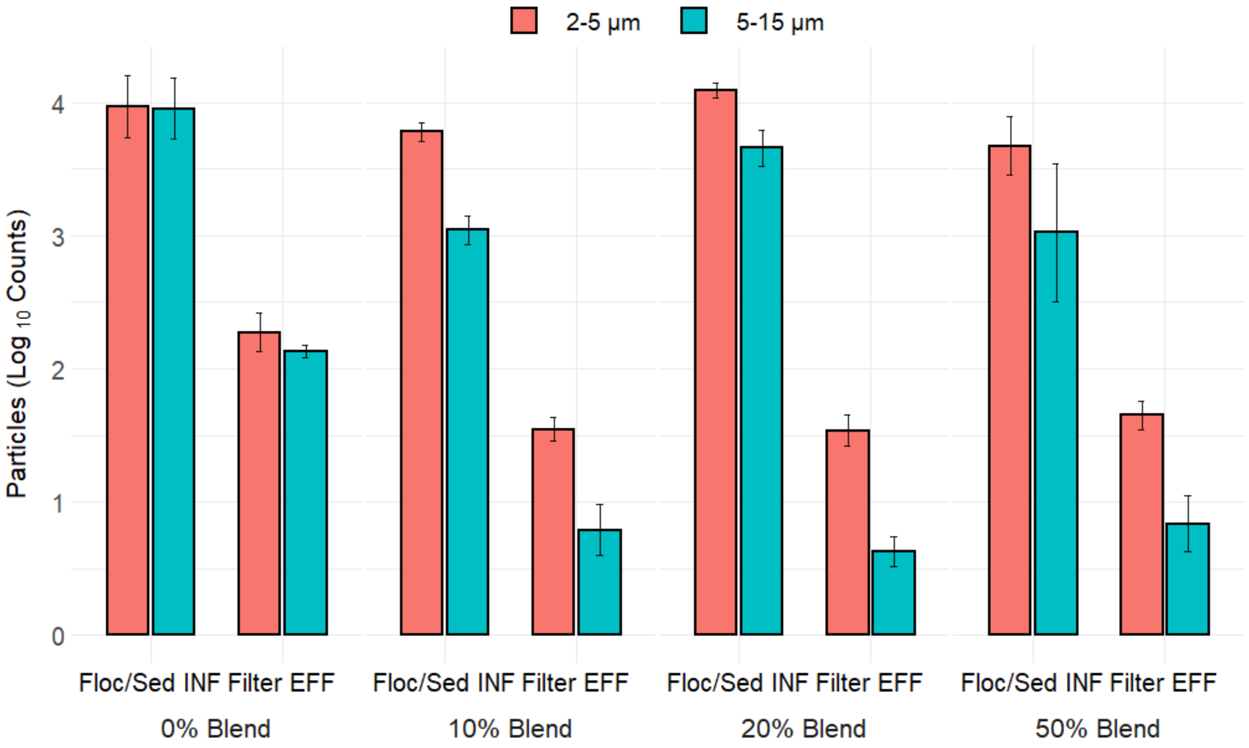

Figure 6-13. Plant C Pilot Testing - Particles in the Floc/Sed Influent and Filter Effluent.

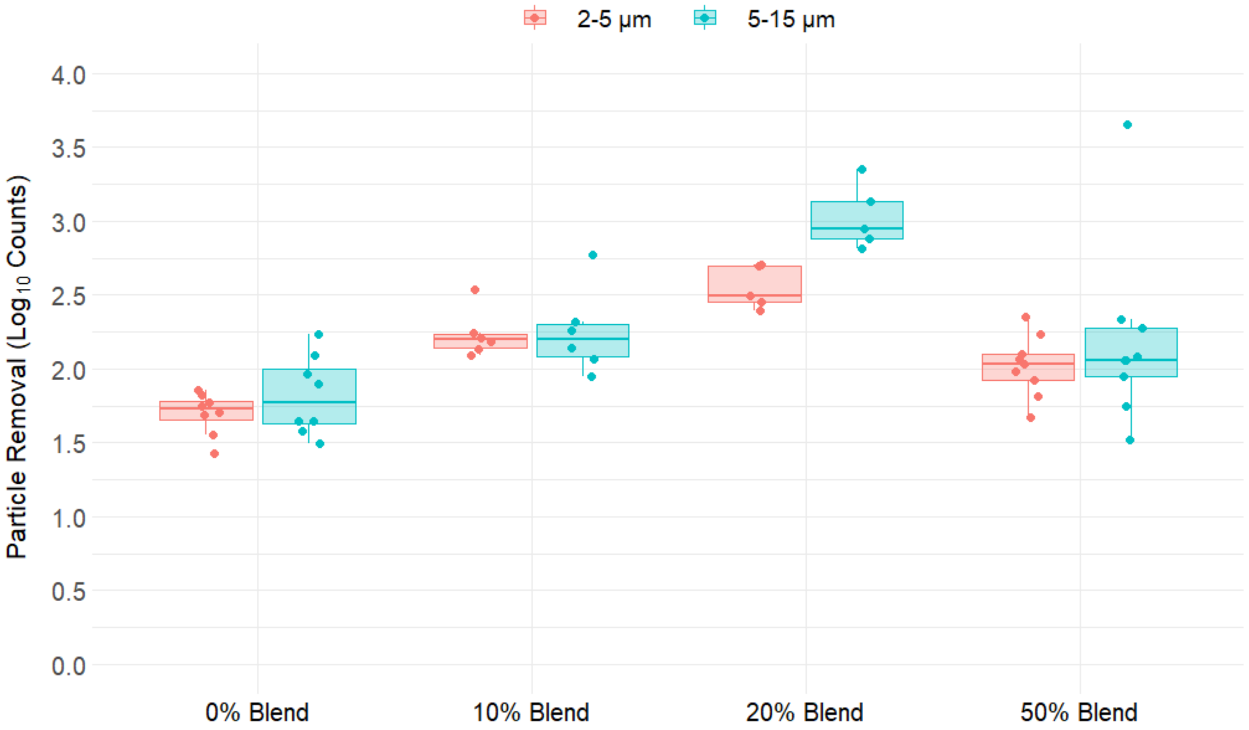

Figure 6-14. Plant C Pilot Testing - Particles Removal.

6.2.2.4 Summary of Plant C Pilot Testing

The findings of pathogen log removal and particle removal are summarized below:

1. Based on culture-based analysis, similar or better MS2 log removal would be achieved when treating ATW-blended water.
2. Though the MS2 concentrations estimated using the qPCR-based method were lower compared to the culture-based method, the results further confirmed that blending the ATW did not affect MS2 removal across the pilot-scale system for most analyses.
3. PMMoV log removal was statistically similar with the 0% blend, 10% blend, and 20% blend, but the removal with the 50% blend was significantly lower, primarily due to lower floc/sed influent concentration.
4. Compared to the 0% blend, higher particle removal was observed with the ATW-blended water.
5. The MS2, PMMoV, and particle data does suggest a reduction in performance at the highest blend ratio. The replicability and significance of this reduction needs further evaluation.

Overall, the pilot testing results from Plant C showed that pathogen removal would be similar or better with the ATW-blended water compared to the raw water.

CHAPTER 7

Conclusions and Recommendations

With the ever-increasing challenges associated with population growth and climate change, recycled water has become one of the most important and reliable water sources. Most of the previous research has focused on important issues associated with the advanced treatment of wastewater, such as the implications of chemical contaminants and pathogen risk associated with DPR (Salveson et al. 2014; Soller et al. 2017). This project attempted to answer one of the unanswered questions for DPR – how does the raw water augmentation impact the operations and performance of an SWTP? Extensive bench- and pilot-scale tests were conducted with ATW from RBAT or CBAT systems and raw surface water from several participating utilities across the US. In general, the bench- and pilot-scale results showed that raw water augmentation can be advantageous due to:

- Improvement in the quality of water to be treated.
- Better filter performance – lower headloss accumulation rate and longer filter runs.
- Similar or better filter effluent turbidity.
- Similar or better particle removal across the plant.
- Reduced chemical dosing requirements.
- Similar or better TOC removal across the treatment plant.
- Lower disinfectant requirement.
- Potentially lower DBP formation potential.
- Potentially improved pathogen removal.

As discussed in Chapter 5, the best approach for assessing the effects of ATW blending with raw water source is to conduct bench-scale and/or pilot-scale evaluations. While bench-scale testing can provide insight on coagulation chemistry, pilot-scale testing is critical to understand the effects of seasonal water quality changes and, most importantly, to assess filter performance and pathogen risk reduction.

Table 7-1 summarizes the hypotheses and conclusions based on the findings from the study.

Table 7-1. Plant C Simulated Pathogen Log Removal.

Hypothesis	Observation/Conclusion
Hypothesis 1 Blending ATW changes water quality.	Blending ATW with raw water changes water quality. Mass-balance-based calculations can be used to predict the blended water quality.
Hypothesis 2 Unit process operation and performance at an SWTP may change when ATW is blended with raw water.	Blending ATW with raw water resulted in: • Lower chemical dose (ozone, coagulant, and disinfectant) requirements. • Similar or better filter effluent turbidity. • Increased filter run length and decreased headloss accumulation rate. • Similar or better TOC removal. • Improved pathogen log removal. • Similar or better particle removal. • Site-specific DBP FP in the filter effluent. The effects were not directly proportional with the percentage ATW blending.
Hypothesis 3 Under optimized conditions, pathogen removal credits achieved at an SWTP under the SWTR are maintained when using ATW-blended water.	Pilot testing results showed improved pathogen removal with the ATW-blended water, suggesting that LRV credits achieved at an SWTP under the SWTR will not be compromised. There can be a site-specific threshold for ATW blending ratio beyond which the log removal can decline.
Hypothesis 4 Blending ATW with the filtered water will affect disinfectant requirements and water stability. The effects will differ depending on the ATW source (i.e., whether an RBAT or CBAT).	Pilot testing results confirmed that blending ATW can affect DBP FP in the filter effluent. The effects were site-specific, suggesting that the effects can be not only AWPF-system specific, but also site-specific.
Hypothesis 5 SWTP unit processes can provide LRV credits for the DPR system.	Similar or higher LRV were obtained with the ATW-blended water compared to the raw water, suggesting that the SWTP can provide LRV credits for DPR system. There can be a site-specific threshold for ATW blending ratio beyond which the log removal can decline.

The following sections summarize the findings from this study and present relevant recommendations.

7.1 Water Quality Improvement

The bench- and pilot-scale tests conducted with ATW from RBAT and CBAT systems showed that the quality of the water to be treated at an SWTP generally improves when raw water sources are blended with the ATW.

Potential water quality changes upon blending ATW with the raw water sources can be estimated through mass-balance calculations with concentrations of constituents in the raw water and ATW. The results of this preliminary assessment should be verified during the bench-scale or pilot-scale testing by characterizing the two water sources to be blended.

7.2 Coagulation, Flocculation, and Sedimentation

The test results indicated that the water quality changes (e.g., decrease in alkalinity) observed during the testing did not negatively affect coagulation. With the ATW blending, coagulant dose decreased and, in general, TOC removal was similar or better with the ATW-blended water. While coagulant dose optimization was beyond the pilot-scale testing scope, in general, the achieved TOC removals were higher than the required TOC removal for enhanced coagulation. Overall, the ATW blending did not negatively affect coagulation, flocculation, and sedimentation processes and opportunities for optimization could be evaluated on a utility-specific basis.

Jar testing in combination with the zeta potential evaluation should be conducted with various ATW blends to determine the effects of water quality changes on coagulation, flocculation, and sedimentation.

7.3 Filtration

Similar or better filter effluent turbidity was observed in the three pilot-scale tests regardless of the ATW source (i.e., RBAT or CBAT). Headloss accumulation rate decreased with increasing blending ratio, which resulted in increasing filter runs. However, the effects on filter run length or headloss accumulation rate were not directly proportional to the percentage blending.

Whenever possible, utilities should consider pilot-scale testing to assess the filterability of the flocs generated with various ATW blends. In combination with the evaluation of turbidity removal, the pilot-scale testing helps determine any potential operational benefits thorough the evaluation of headloss accumulation trends, filter runs, backwash requirements, and most importantly, pathogen risk reduction.

7.4 Disinfectant Requirement and DBP Formation

Blending the ATW with the raw water decreased disinfectant requirements. However, the effect on DBP FP were site-specific. At Plant A, significantly lower TTHMs were observed with the ATW-blended water than raw water, whereas DBP FP was similar at Plant D irrespective of the blending ratio. At Plant C, TTHM FP increased with the increasing blending ratio.

Utilities should consider evaluating disinfectant requirements and stability, and DBP formation in the treated water to better understand the effects of ATW blending.

7.5 Pathogen Log Removal

Pathogen log removal was evaluated at Plant A and Plant C with ATW from an RBAT and CBAT source, respectively. The results of MS2 and PMMoV challenge tests showed similar or better pathogen removal with ATW-blended water compared to the raw water (i.e., 0% blend). The results from pilot-scale testing at Plant A showed that qPCR-based method could be a reliable monitoring approach, especially when disinfectant can be present in the water even at very low levels.

The results from the pilot-scale testing at Plant C also indicated that there can be a site-specific threshold for ATW blending beyond which the log removal can decline. Therefore, utilities should consider pilot-scale testing to determine the potential pathogen log removal across the treatment system. While qPCR-based MS2 quantification was used for assessing MS2 log removal at Plant A, the qPCR-based results predicted significantly lower MS2 log removal compared to the culture-based method at Plant C. If utilities plan to evaluate pathogen log removal using MS2, it is recommended to use both culture-based and qPCR-based methods to better understand the most practical approach for pathogen log removal assessment at full-scale.

APPENDIX A

Request for Information

A.1 Background

Water scarcity, climate change, ever-increasing population, and the cost drivers associated with importing limited water resources from long distances are encouraging utilities to expand their water supply portfolio by leveraging all potential water supply sources. Recycled water is increasingly being considered as an important water source that can be treated through AWTPs for supplementing potable water supply. Figure 2A-1 presents the general scheme of supplementing drinking water sources with ATW.

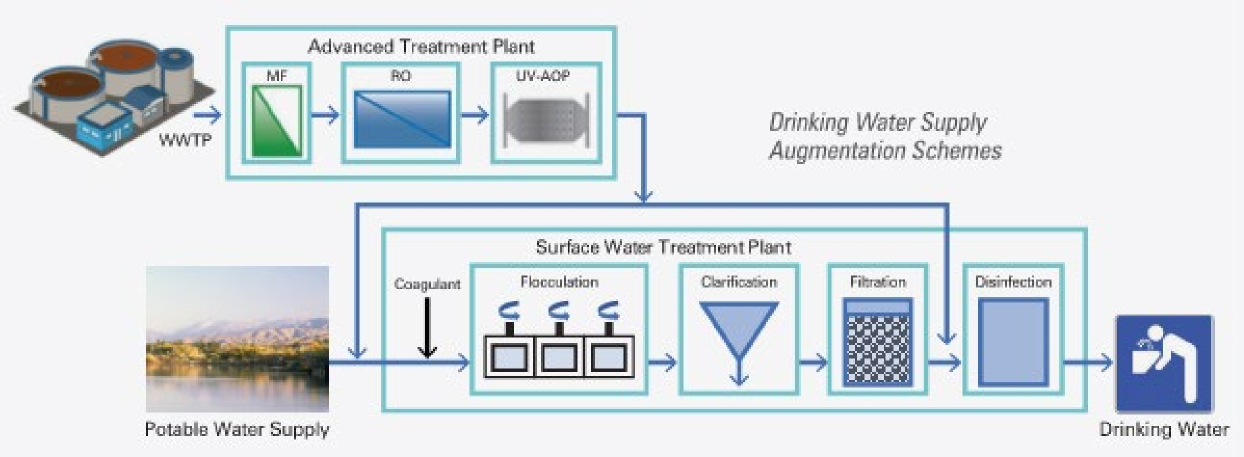

Figure A-1. Scheme for Supplementing Drinking Water Supply with ATW.

Blending ATW with raw water source at an SWTP may potentially add operational challenges in achieving drinking water treatment goals due to significant differences in source water and ATW qualities. It is critical to understand the ability of an SWTP to remove pathogens in the ATW and whether the SWTP provides full or partial pathogen log reduction value (LRV) credit. To address all these concerns and develop an approach for assigning LRV credits for an SWTP treating ATW blended raw water source, the WRF and the CA SWRCB co-funded Project 5049: *Benefits and Challenges in Pathogen Removal when Blending Advanced Treated Water with Raw Water upstream of a Surface Water Treatment Plant in DPR.*

A.2 Study Objectives

This project will define benefits and challenges in pathogen removal and develop robust engineering solutions and guidance associated with using ATW through DPR for supplementing raw water supply at a conventional SWTP. The objectives of the study are to:

1. Determine the effects on SWTP operational efficiency and effectiveness (e.g., pathogen and particle removal) when blending ATW with raw water;
2. Develop operational strategies and best practices for SWTP when blending ATW with raw water; and

3. Develop approaches to establish pathogen log reduction credits under DPR regulatory frameworks for SWTP unit processes (i.e., coagulation, flocculation, sedimentation, filtration, and disinfection) when blending ATW with: a) raw water upstream of an SWTP (i.e., raw water augmentation), or b) SWTP filtered water (i.e., before disinfection).

A.3 Historical Data Requested

To document baseline performance for SWTP and AWTP (as applicable) and understand the potential for blending ATW with surface water at the SWTP at your facility, we are requesting approximately 2-year historical data for the parameters in Tables A-1 and A-2.

Table A-1. SWTP Historical Data.
(Approximately Two Years)

<table>
<tr><th colspan="5">Design and Operating Parameters</th></tr>
<tr><td colspan="5">Filter media characteristics (UC, effective size, bed depth)</td></tr>
<tr><td colspan="5">Loading rate/EBCT in filters</td></tr>
<tr><td colspan="5">Source water (river/lake/reservoir)</td></tr>
<tr><td colspan="5">Coagulant type and dose</td></tr>
<tr><td colspan="5">Disinfectant type, dose, and CT</td></tr>
<tr><td colspan="5">Charge-based polymer type and dose</td></tr>
<tr><td colspan="5">Bridging polymer type and dose</td></tr>
<tr><td colspan="5">Pre-ozonation (if applicable) dose</td></tr>
<tr><th rowspan="2">Water Quality Parameters</th><th colspan="4">Sampling Location</th></tr>
<tr><th>Raw Water</th><th>Settled Water</th><th>Filtered Water</th><th>Finished Water</th></tr>
<tr><td>Temperature</td><td>X</td><td></td><td></td><td></td></tr>
<tr><td>pH</td><td>X</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>Alkalinity</td><td>X</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>Hardness</td><td>X</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>Conductivity</td><td>X</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>Cations/metals (i.e., Ca, Mg, Na, Fe, Mn)</td><td>X</td><td></td><td></td><td></td></tr>
<tr><td>Anions (i.e., chlorine, sulfate, nitrate, bromide, silica)</td><td>X</td><td></td><td></td><td>X</td></tr>
<tr><td>TDS</td><td>X</td><td></td><td></td><td>X</td></tr>
<tr><td>TSS</td><td>X</td><td>X</td><td>X</td><td></td></tr>
<tr><td>Turbidity</td><td>X</td><td>X</td><td>X</td><td></td></tr>
<tr><td>Particle count</td><td>X</td><td>X</td><td>X</td><td></td></tr>
<tr><td>TOC</td><td>X</td><td>X</td><td>X</td><td></td></tr>
<tr><td>DOC</td><td>X</td><td>X</td><td>X</td><td></td></tr>
<tr><td>UV_{254}</td><td>X</td><td>X</td><td>X</td><td></td></tr>
<tr><td>SUVA</td><td>X</td><td>X</td><td>X</td><td></td></tr>
<tr><td>THMs</td><td></td><td></td><td></td><td>X</td></tr>
<tr><td>HAA5</td><td></td><td></td><td></td><td>X</td></tr>
<tr><td>DBP FP</td><td></td><td></td><td></td><td>X</td></tr>
<tr><td>Pathogens (<i>Cryptosporidium</i>, <i>Giardia</i>, <i>Enteroviruses</i>, etc.)</td><td>X</td><td></td><td>X</td><td>X</td></tr>
<tr><td>Temperature</td><td>X</td><td></td><td></td><td></td></tr>
</table>

Table A-2. AWTP Historical Data.
(Approximately Two Years)

Treatment Train Finished Water Quality	
pH	Turbidity
Alkalinity	Hardness
TOC	Pathogen log reduction

APPENDIX B

Historical Data

Table B-1. Plant A – SWTP Historical Water Quality Data.

Parameter	Unit	Min	Max	90th Percentile	Average	SD	N
Raw Water							
Calcium	mg/L	12	31	29	22	6.5	8
Magnesium	mg/L	4.0	7.0	6.9	5.7	1.2	8
Sodium	mg/L	7.4	30.7	24.5	17.0	5.8	37
Iron	µg/L	42	2,200	899	468	431	46
Manganese	mg/L	37	609	435	189	150	59
Chloride	mg/L	12	45	36	25	9	22
Sulfate	mg/L	9	43	33	21	10	22
Bromide	mg/L	0.013	0.044	0.036	0.025	0.008	24
TDS	mg/L	94	286	193	155	44	22
TSS	mg/L	0.9	5.4	4.2	2.6	1.2	22
TOC	mg/L	2.8	368.3	6.7	12.5	53.6	46
Filtered Water							
TOC	mg/L	1.3	130.8	2.7	7.3	26.3	24
Finished Water							
Chloride	mg/L	25	55	48	37	8.8	22
Sulfate	mg/L	11	44	34	22	9.3	22
Bromide	mg/L	0.006	0.023	0.019	0.013	0.005	22
TDS	mg/L	128	250	207	170	33.3	22
THMs	µg/L	3.76	25.57	17.32	12.47	5.20	30
HAA5	µg/L	2.48	16.68	12.86	8.29	3.82	30

Table B-2. Plant B – SWTP Historical Water Quality Data.

Parameter	Unit	Min	Max	90th Percentile	Average	SD	N
Raw Water							
Temperature	°C	10	26.7	24	18.2	4.3	703
pH	SU	7.13	8.74	8.13	7.87	0.23	712
Alkalinity	mg/L as $CaCO_3$	31	130	106	74	21	325
Hardness	mg/L as $CaCO_3$	31	150	124	89	28	350
Conductivity	µmhos/cm	116	724	27.0	364.5	138.1	324
Calcium	mg/L as $CaCO_3$	24.9	78.4	67.6	48.1	14.4	48
Magnesium	mg/L	4.7	17.3	15.7	11.4	3.5	48
Sodium	mg/L	0.5	87.6	54.4	36.6	17.0	48
Iron	µg/L	40	1,300	440	286	259	40
Manganese	µg/L	12.5	110	26.4	36.9	17.6	73
Sulfate	mg/L	8.5	59.8	43.98	27.8	11.4	179
Nitrate	mg/L	0.1	1.3	0.9	0.6	0.3	80
Bromide	mg/L	0.07	0.5	0.319	0.2	0.1	182
Silica	mg/L	5.2	18.5	16.48	11.8	3.1	43
TDS	mg/L	146	300	283.2	238	52.7	8
TSS	mg/L	10	10	10	10	0	2
Turbidity	NTU	2	27	12	6.5	4.1	293
TOC	mg/L	2.56	7.1	5.3	4.1	0.9	155

Parameter	Unit	Min	Max	90th Percentile	Average	SD	N
THMs	µg/L	0.5	0.5	0.5	0.5	0	2
Cryptosporidium Oocysts	oocysts/L	<0.1	<0.1	<0.1	<0.1	0	33
Giardia	cysts/L	<0.1	<0.1	<0.1	<0.1	0	33
Settled Water							
pH	SU	6.29	7.36	7.18	6.94	0.19	712
Alkalinity	mg/L as $CaCO_3$	26	26	26	26	0	1
Turbidity	NTU	0	4.7	1.6	0.8	0.6	731
THMs	µg/L	7	7	7	7	0	2
Filtered Water							
pH	SU	6.35	7.99	7.26	6.96	0.24	712
Alkalinity	mg/L as $CaCO_3$	32	32	32	32	0	1
Iron	µg/L	6,100	6,100	6,100	6,100	0	1
Manganese	µg/L	56,700	56,700	56,700	56,700	0	1
Turbidity	NTU	0	1.48	0.03	0.03	0.06	727
Particle Count, Total		5.8	1,075	258	116	124	727
TOC	mg/L	1.44	2.8	2.1	2.0	0.3	12
THMs	µg/L	11	11	11	11	0	1
Finished Water							
Temperature	°C	10	27.9	24	18.3	4.2	710
pH	SU	6.58	7.88	7.64	7.55	0.09	688
Alkalinity	mg/L as $CaCO_3$	31	122	103	70	20	326
Hardness	mg/L as $CaCO_3$	31	149	123	89	27	349
Conductivity	umhos/cm	159	786	600	413	146	324
Calcium	mg/L as $CaCO_3$	159	786	600	413	14	324
Magnesium	mg/L	4.8	17	15.8	11.5	3.3	48
Sodium	mg/L	17.6	95.1	69.6	45.8	17.9	48
Iron	µg/L	20	20	20	20	0	8
Manganese	µg/L	10	21.8	10	10.6	2.6	20
Sulfate	mg/L	18.3	81.4	66.3	44.9	15.97	179
Bromide	mg/L	0.05	0.23	0.19	0.1	0.04	179
Silica	mg/L	5.1	17.1	14.0	10.6	2.5	43
TDS	mg/L	138	484	371	295	99	8
Turbidity	NTU	0.1	0.38	0.2	0.1	0.1	87
TOC	mg/L	1.14	3.93	2.97	2.2	0.6	151
THMs	µg/L	15	61	35	28	6.8	153
HAA5	µg/L	4	20	28	15	3.5	45
Note: Detection limit for *Cryptosporidium* Oocysts and *Giardia* is 0.1 oocysts/L and cysts/L							

Table B-3. Plant B – AWPF Water Quality Data.

Parameter	Unit	Min	Max	90th Percentile	Average	SD	N
Finished Water							
TOC	mg/L	0.3	0.3	0.3	0.3	0.0	47
Turbidity	NTU	0.0	0.8	0.1	0.1	0.1	44
Total Alkalinity	mg/L	6.0	46.0	33.0	6.0	6.0	47
pH	SU	6.6	8.2	7.5	7.1	0.3	82
Hardness	mg/L	10.0	10.0	10.0	10.0	0.0	45
Note: Detection limits for TOC, Turbidity, and hardness was 0.3 mg/L, 0.1 NTU, and 10 mg/L, respectively.							

Table B-4. Plant C – SWTP Historical Water Quality Data.

Parameter	Unit	Min	Max	90th Percentile	Average	SD	N
Raw Water							
Temperature	°C	0.00	18.10	15.57	10.54	3.73	5979
pH	SU	6.22	8.48	8.27	7.58	0.62	5979
Alkalinity	mg/L as $CaCO_3$	80	177	101	93.52	2.87	995
Hardness	mg/L as $CaCO_3$	118	160	143	135.57	3.79	998
Conductivity	mS/cm	0	20	0.39	0.35	0.26	5979
Calcium	mg/L	36	52	49.00	42.78	4.34	50
Iron	µg/L	9.9	68.8	48.7	28.4	14.2	90
Manganese	µg/L	10	203	144.6	58.66	53.9	73
Chloride	mg/L	23	30	28	25.77	1.60	48
Sulfate	mg/L	38	51	49	44.83	3.59	48
Nitrate	mg/L	0.30	0.45	0.33	0.31	0.03	47
TDS	mg/L	185	238	226	207	8	17
Turbidity	NTU	0.37	35.21	2.68	1.72	0.85	5979
Particle Count, Total	Counts	0	28000	21531	8464	6672	5978
Particle Count, 2-5um	Counts	0	18896	16334	6508	5163	5978
TOC	mg/L	2.80	3.80	3.58	3.22	0.10	92
UV_{254}	1/cm	0.042	0.056	0.052	0.048	0.00	92
Total Bacteria	MPN/100 mL	1	2420	1203	343	320	92
E.coli	MPN/100 mL	1	115	65	24	35	86
Settled Water							
Temperature	°C	0	25.71	17.31	12.00	4.49	5977
pH	SU	0	8.40	6.97	6.73	0.84	5977
Turbidity	NTU	0	5.00	0.21	0.17	0.17	5977
TOC	mg/L	1.99	2.58	2.40	2.20	0.14	82
UV_{254}	1/cm	0	0.963	0.141	0.067	0.07	5976
Filtered Water							
Conductivity	mS/cm	0.28	0.76	0.42	0.39	0.03	1000
TDS	mg/L	237	266	250	244	6.38	26
Turbidity	NTU	0	0.20	0.03	0.02	0.005	6037
Particle Count, Total	Counts	0	1112	38	23	45	6037
Particle Count, 2-5um	Counts	0	1043	34	20	40	6037
TOC	mg/L	1.21	2.29	2.11	1.85	0.20	90
UV_{254}	1/cm	0	0.826	0.028	0.019	0.01	6036

Table B-5. Plant C – AWPF Historical Water Quality Data.

Parameter	Unit	Min	Max	90th Percentile	Average	SD	N
Raw Water							
Temperature	°C	5.20	22.30	18.30	13.92	3.30	871
pH	SU	7.10	8.70	7.80	7.48	0.21	871
Alkalinity	mg/L as $CaCO_3$	117	199	178	170	6.46	1000
Hardness	mg/L as $CaCO_3$	125	400	320	294	20.60	890
Conductivity	mS/cm	0.59	1.17	1.14	1.05	0.07	871
Calcium	mg/L	81	110	106	97	7.37	40
Iron	µg/L	10.00	74.40	10.00	11.43	7.79	76
Manganese	µg/L	5.00	296.00	31.51	17.25	40.46	58
Chloride	mg/L	119	176	163	141	15.10	40
Sulfate	mg/L	163	220	208	192	11.92	40
Nitrate	mg/L	1.71	3.99	3.25	2.62	0.57	39

Parameter	Unit	Min	Max	90th Percentile	Average	SD	N
TDS	mg/L	596	964	743	705	84.77	14
Turbidity	NTU	0.08	1.70	0.37	0.23	0.17	871
Particle Count, Total		0	17,826	1,973	1,227	1,621	871
Particle Count, 2-5um		0	9,832	1,320	771	971	871
TOC	mg/L	2.18	3.31	2.84	2.62	0.22	56
UV_{254}	1/cm	0.03	0.07	0.06	0.05	0.01	76
Total Bacteria	MPN/100 mL	2	2,420	2,420	495	786	76
E.coli	MPN/100 mL	1	2,420	233	157	486	76
Settled Water							
pH	SU	4.20	8.63	8.52	7.76	0.64	874
Turbidity	NTU	0.17	1.44	0.91	0.66	0.20	874
Filtered Water							
Conductivity	mS/cm	0.11	1.22	1.16	1.09	0.09	854
Turbidity	NTU	0.01	0.91	0.04	0.03	0.04	874
Particle Count, Total		0	2102	72	36	99	874
Particle Count, 2-5um		0	1641	57	30	79	874
TOC	mg/L	1.83	2.96	2.65	2.37	0.24	73
UV_{254}	1/cm	0.03	0.11	0.07	0.05	0.02	337

Table B-6. Plant E – SWTP Historical Water Quality Data.

Parameter	Unit	Min	Max	90th Percentile	Average	SD	N
Raw Water							
Alkalinity	mg/L	13	28	17	15.72	1.38	361
pH	SU	6.42	7.09	7.02	6.88	0.17	25
Temperature	°C	14.25	22.25	20.75	16.81	1.96	25
Iron	mg/L	0.01	0.96	0.06	0.04	0.05	361
Manganese	mg/L	0	4.29	0.02	0.02	0.17	361
Hardness	mg/L	11	24	15	13.49	1.41	155
TOC	mg/L	1.09	1.94	1.44	1.32	0.15	56
E.coli	P/A	0	0	0	0	0	246
Total Coliform	P/A	0	0	0	0	0	246
Cryptosporidium	oocysts/L	0.087	0.091	0.089	0.089	0.001	9
Giardia	cysts/L	0.087	0.091	0.089	0.089	0.001	9
HPCs	cfu/mL	20	50	50	37.5	15	4
Filtered Water							
Alkalinity	mg/L	12	14	14	13.24	0.54	38
pH	SU	9.07	9.55	9.41	9.32	0.08	135
TOC	mg/L	0.70	1.10	0.98	0.89	0.08	61
Turbidity	NTU	0.017	0.269	0.049	0.035	0.019	680
Finished Water							
Alkalinity	mg/L	17	28	25	21.11	2.37	313
pH	SU	6.9	7.72	7.35	7.22	0.11	726
Bromide	mg/L	0	0	0	0	0	102
Chloride	mg/L	5.5	8.2	7.59	6.55	0.71	102
Sulfate	mg/L	1.9	3.2	2.9	2.50	0.34	102
Fluoride	mg/L	0.7425	1.01	0.914	0.87	0.05	135
Iron	mg/L	0	0.05	0.01	0.01	0.00	726
Manganese	mg/L	0	0.02	0	0.001	0.003	726
Hardness	mg/L	19	31	28	23.41	2.68	313
Calcium Hardness	mg/L	14	26	23	17.51	3.00	313

Parameter	Unit	Min	Max	90th Percentile	Average	SD	N
TOC	mg/L	0.88	1.2	1.07	0.98	0.07	24
Bromate	mg/L	0.001	0.004	0.003	0.002	0.001	24
E.coli	P/A	0	0	0	0	0	499
Total Coliform	P/A	0	0	0	0	0	499
Cryptosporidium	oocysts/L	0.98	0.98	0.98	0.98	0	10
Cryptosporidium	log rem	0.98	0.98	0.98	0.98	0	10
Giardia	cysts/100L	0.98	0.98	0.98	0.98	0	10

Table B-7. Utility E – AWPF Historical Water Quality Data.

Parameter	Unit	Min	Max	90th Percentile	Average	SD	N
Raw Water							
pH	SU	0.53	10.09	7.17	6.87	0.48	9419
Turbidity	NTU	0.05	96.00	2.32	2.21	5.44	9419
Filtered Water							
pH	SU	3.97	10.79	9.42	8.11	1.05	9419
Turbidity	NTU	0.01	0.36	0.04	0.03	0.01	9253
Finished Water							
pH	SU	6.60	7.80	7.50	7.21	0.19	702
Turbidity	NTU	0.00	0.80	0.14	0.08	0.06	702
Alkalinity	mg/L	60	244	126	108	15	1385
TOC	mg/L	2.5	7.7	4	3.4	0.5	694

Utility F: Tables 2B-8 and 2B-9 present historical data from Utility F's SWTP and AWPF, respectively. Data were available for a few parameters for the settled water and filtered water at the SWTP. This utility provided historical data for additional parameters (i.e., parameters not included in the RFI), such as nitrate, TKN, ammonia, TSS, and COD, for the AWPF finished water. As expected, TOC and alkalinity in the AWPF finished water remained similar or higher than the SWTP source water.

Table B-8. Utility F – SWTP Historical Water Quality Data.

Parameter	Unit	Min	Max	90th Percentile	Average	SD	N
Raw Water							
Temperature	°C	3	31	28	17.03	8.28	720
pH	SU	7.44	8.61	8.42	8.1	0.2	721
Alkalinity	mg/L as $CaCO_3$	52	158	135	106.7	21.6	720
Hardness	mg/L	74	206	176	140.2	27.1	720
Iron	mg/L	0.003	1.15	0.1882	0.1	0.1	720
Manganese	mg/L	0.003	0.403	0.093	0.0	0.1	720
TOC	mg/L	1.1	5.1	2.8	2.1	0.9	19
Turbidity	NTU	0.84	180.9	26.4	10.9	16.5	721
Pathogens	P/A	<1	2419.6	184.06	74.7	227.7	377
Settled Water							
Turbidity	NTU	0.11	1.22	0.47	0.34	0.11	721
Filtered Water							
pH	SU	6.92	8	7.67	7.5	0.1	721
Turbidity	NTU	0.02	0.12	0.07	0.05	0.01	721

Parameter	Unit	Min	Max	90th Percentile	Average	SD	N
Finished Water							
pH	SU	7.2	7.71	7.53	7.4	0.1	721
Alkalinity	mg/L as $CaCO_3$	45	148	120	96.1	19.5	720
Hardness	mg/L	73	202	176	141.1	27.2	720
Phosphate	mg/L	1.03	1.96	1.38	1.3	0.1	720
Iron	mg/L	0	0.113	0.007	0.003	0.005	720
Manganese	mg/L	0	0.024	0.01	0.007	0.003	720
TOC	mg/L	1	1.7	1.49	1.2	0.2	8
Turbidity	NTU	0.02	0.10	0.06	0.04	0.01	721
Conductivity		210	459	421.5	323.8	103.8	4
THMs	µg/L	31.5	31.5	31.5	31.5	0.0	1
HAA5	µg/L	8.51	8.51	8.51	8.51	0.0	1
Pathogens	P/A	<1	<1	<1	<1	0	767

Table B-9. Utility F – AWPF Historical Water Quality Data.

Parameter	Unit	Min	Max	90th Percentile	Average	SD	N
Finished Water							
Nitrate	mg/L	0	14.14	4.51	1.8	1.9	501
Ammonia	mg/L	0	1.38	0.019	0.0	0.1	501
NOx	mg/L	0.091	14.7	5.14	2.9	1.9	731
TKN	mg/L	0.054	1.37	0.615	0.5	0.2	731
Total Nitrogen	mg/L	0.251	15.291	5.582	3.3	1.9	731
Total Phosphorus	mg/L	0	1.16	0.06	0.0	0.1	731
TSS	mg/L	0	8.3	0.3	0.1	0.4	730
COD	mg/L	0	11.2	7.95	4.4	2.6	731
E.coli	CFU /100 mL	1	10	1	1.0	0.3	730
DO	mg/L	7.1	10.3	9	8.3	0.5	731
pH	SU	6.3	7.7	7.4	7.2	0.2	731
Alkalinity	mg/L	1	165	130	98.7	23.8	491
TOC(1)	mg/L	0	2.99	2.12	1.19	0.69	731
UV_{254}(1)	1/cm	0	0.06	0.04	0.02	0.01	731

Notes:

1. Estimated based on 10 mg/L COD = 2.67 mg/L TOC = 0.05 abs/cm UV_{254}.

APPENDIX C

Settled Water Characteristics

Table C-1. Settled Water Characteristics.

Parameters	0% Blend			10% Blend					25% Blend			40%		
	0 Alum + 0 CP + 0 NIP(1)	20 Alum + 0.35 CP + 0 NIP(1)	20 Alum +0.35 CP +0.25 NIP(1)	0 Alum +0 CP +0 NIP(1)	20 Alum +0.35 CP + 0 NIP	20 Alum + 0.35 CP + 0.25 NIP(1)	35 Alum +0.6 CP +0 NIP	35 Alum +0.6 CP +0.25 NIP	0 Alum +0 CP +0 NIP	20 Alum +0.35 CP +0 NIP	20 Alum +0.35 CP +0.25 NIP(1)	0 Alum +0 CP +0 NIP	20 Alum +0.35 CP +0 NIP	20 Alum +0.35 CP +0.25 NIP(1)
pH (SU)	7.73	7.66	7.655	8.2	7.42	7.53	7.82	7.83	8	7.83	7.69	8.2	7.84	7.76
Zeta Potential (mV)	0	-3.1	-1.65	--	-0.7	-4.30	-6.9	-5.3	-13.2	-3.2	-2.7	--	0	0.35
Conductivity (µS/cm)	592	574	561	411	522	517.00	518	520	464	443	439	357	360	369
Turbidity (NTU)	2.265	1.185	1.635	2.23	3.35	0.63	0.581	0.669	1.42	1.01	1.286	1.26	0.796	0.7825
TOC (mg/L)	5.2	3.8	4	4.1	3.4	3.95	3.3	3.6	3.4	2.9	3.1	2.8	2	2.5
DOC (mg/L)	4.55	3.55	3.6	3.4	3	3.40	3.2	3.2	3.5	2.5	2.75	2.7	2.2	2.15
UV_{254} (cm^{-1})	0.1245	0.074	0.0745	0.111	0.074	0.08	0.069	0.07	0.093	0.057	0.0565	0.076	0.061	0.052

Notes:

1. Average of two jars are presented.

Abbreviations: CP – cationic polymer (Clarifloc C-308P); NIP – non-ionic polymer (Clarifloc N-120P).

Table C-2. Plant C – Settled Water Characteristics.

Parameters	5% Blend						15% Blend					
	17 mg/L FeCl$_3$ + mg/L Poly 1.7	19 mg/L FeCl$_3$ + mg/L Poly 1.9	21 mg/L FeCl$_3$ + mg/L Poly 2.1	23 mg/L FeCl$_3$ + mg/L Poly 2.3	25 mg/L FeCl$_3$ + mg/L Poly 2.5	28 mg/L FeCl$_3$ + mg/L Poly 2.8	17 mg/L FeCl$_3$ + mg/L Poly 1.7	19 mg/L FeCl$_3$ + mg/L Poly 1.9	21 mg/L FeCl$_3$ + mg/L Poly 2.1	23 mg/L FeCl$_3$ + mg/L Poly 2.3	25 mg/L FeCl$_3$ + mg/L Poly 2.5	28 mg/L FeCl$_3$ + mg/L Poly 2.8
pH	6.99	6.91	6.94	6.85	6.85	6.81	7.04	6.98	6.95	6.46	6.84	6.89
Zeta	-5.71	-6.59	-7.1	-5.76	-5.08	-4.81	-12.7	-6.06	-5.42	-4.37	-4.57	-4.62
Conductivity (µS/cm)	425	424	424	427	425	427	507	510	507	510	505	506
TOC	2.25	2.225	2.184	2.102	2.044	2.004	2.073	2.102	2.01	1.944	1.89	1.847
DOC	2.193	2.169	2.124	2.089	2.013	1.985	2.049	2.022	2.029	1.918	1.888	1.832
UV$_{254}$	0.036	0.034	0.037	0.034	0.036	0.033	0.038	0.038	0.035	0.037	0.041	0.036
Temp	18.8	18.3	18	18.5	18.5	18.9	17.8	17.7	17.8	18.2	17.9	17.9
Alkalinity	76	74	72	68	66	64	82	78	78	76	74	70
Hardness	76	74	72	68	66	64	134	134	134	134	134	134
	25% Blend						50% Blend					
pH	7	7	6.95	6.94	6.86	6.81	6.96	6.98	6.94	6.89	6.87	6.92
Zeta	-7.77	-7.5	-6.56	-5.75	-4.2	-5.37	-7.07	0.361	-6.46	-6.07	-6.17	-5.46
Conductivity (µS/cm)	596	600	602	610	604	606	716	726	728	726	729	731
TOC	2.35	2.186	2.345	2.367	2.232	2.237	2.032	2.009	1.939	1.9	1.853	1.827
DOC	2.346	2.188	2.511	2.346	2.23	2.188	2.029	1.954	1.927	1.891	1.838	1.837
UV$_{254}$	0.04	0.035	0.041	0.038	0.041	0.032	0.043	0.04	0.041	0.04	0.037	0.038
Temp	17.9	17.8	17.9	17.6	17.5	17.8	18	17.9	18	17.9	18	18.3
Alkalinity	88	85	83	82	82	78	94	90	90	87	86	83
Hardness	135	133	135	135	135	135	133	133	133	133	133	133

Table C-3. Plant D – Settled Water Characteristics.

Blend	O_3 Dose (mg/L)	pH (SU)	Zeta Potential (mV)	Conductivity (µS/cm)	Turbidity (NTU)	TOC (mg/L)	DOC (mg/L)	UV_{254} (cm^{-1})
0% Blend	0.25	8.12	-1.74	442	1.03	1.82	1.54	0.019
	0.5	8.39	-1.15	436	0.93	1.78	1.60	0.016
	0.75	8.03	-0.97	477	1.29	1.76	1.57	0.015
10% Blend	0.25	8.17	0.62	467	0.83	1.65	1.47	0.016
	0.5	8.20	1.07	464	0.83	1.59	1.43	0.015
	0.75	8.30	1.90	454	0.95	1.60	1.41	0.013
20% Blend	0.25	8.31	3.03	487	0.71	1.46	1.31	0.014
	0.5	8.35	5.04	473	0.89	1.48	1.30	0.013
	0.75	8.30	6.11	472	0.95	1.55	1.31	0.010
30% Blend	0.25	8.36	7.81	491	0.74	1.32	1.11	0.011
	0.5	8.07	12.11	494	0.78	1.41	1.12	0.011
	0.75	8.06	13.96	497	0.74	1.36	1.12	0.009
40% Blend	0.25	8.01	10.44	522	0.65	1.24	1.11	0.011
	0.5	8.04	13.06	549	0.62	1.20	1.00	0.008
	0.75	8.03	14.74	518	0.69	1.25	1.10	0.008

Table C-4. Plant E – Settled Water Characteristics.

Parameter	0% Blend		15% Blend		25% Blend		35% Blend	
	0 mg/L $FeCl_3$	24.5 mg/L $FeCl_3$	0 mg/L $FeCl_3$	30 mg/L $FeCl_3$	0 mg/L $FeCl_3$	80 mg/L $FeCl_3$	0 mg/L $FeCl_3$	95 mg/L $FeCl_3$
pH (SU)	7.62	7.02	7.68	7.29	7.74	6.89	7.93	6.95
Zeta Potential (mV)	-19.6	-5.9	-10.4	-7.7	-10.2	-4.8	-11.0	-5.9
Conductivity (µS/cm)	54	56	151	154	215	226	278	293
Turbidity (NTU)	0.65	0.11	0.60	0.16	0.58	0.14	0.45	0.15
TOC (mg/L)	1.4	1.0	1.7	1.4	1.8	1.3	2.1	1.5
DOC (mg/L)	1.4	1.0	1.6	1.4	1.7	1.3	2.0	1.5
UV_{254} (cm^{-1})	0.032	0.026	0.033	0.042	0.035	0.031	0.037	0.032

Table C-5. Plant G – Settled Water Characteristics.

Parameters	0% Blend			10% Blend			25% Blend			40% Blend		
	0 mg/L $FeCl_3$	210 mg/L $FeCl_3$	210 mg/L $FeCl_3$	0 mg/L $FeCl_3$	210 mg/L $FeCl_3$	210 mg/L $FeCl_3$	0 mg/L $FeCl_3$	210 mg/L $FeCl_3$	210 mg/L $FeCl_3$	0 mg/L $FeCl_3$	210 mg/L $FeCl_3$	210 mg/L $FeCl_3$
pH (SU)	7.8	7.1	6.9	7.8	6.6	6.7	7.1	6.4	6.3	7.1	6.3	6.1
Zeta (mV)	-12.0	-3.5	-1.6	-12.4	-2.1	-2.1	-11.1	-2.1	1.0	-13.8	-4.4	-2.2
Conductivity (µS/cm)	949	986	1016	836	871	875	724	750	780	609	650	677
Turbidity (NTU)	0.53	0.19	0.22	0.48	0.65	0.86	0.34	0.42	0.41	0.21	0.18	0.28
TOC (mg/L)	3.1	1.8	1.9	2.9	1.4	1.4	2.4	1.2	1.1	2.8	0.9	0.9
DOC (mg/L)	2.9	1.7	1.9	2.8	1.4	1.4	2.3	1.1	1.1	1.9	0.9	0.9
UV_{254} (cm^{-1})	0.038	0.025	0.025	0.044	0.026	0.027	0.027	0.024	0.027	0.023	0.017	0.016

Table C-6. Plant H – Settled Water Characteristics.

Parameter	0% Blend		15% Blend		25% Blend		35% Blend	
	0 mg/L Alum	41 mg/L Alum	0 mg/L Alum	41 mg/L Alum	0 mg/L Alum	41 mg/L Alum	0 mg/L Alum	41 mg/L Alum
pH (SU)	8.1	7.7	8.1	7.6	7.9	7.6	7.9	7.6
Zeta (mV)	-13.2	-6.8	-12.2	-6.2	-12.9	-7.2	-14.6	-6.6
Conductivity (µS/cm)	971	974	923	906	871	897	811	833
Turbidity (NTU)	0.27	0.51	0.30	0.52	0.26	0.23	0.26	0.48
TOC (mg/L)	3.40	2.60	3.20	2.80	3.30	2.80	3.20	2.80
DOC (mg/L)	3.00	2.40	3.20	2.40	3.00	2.50	3.00	2.60
UV_{254} (cm^{-1})	0.033	0.025	0.034	0.026	0.035	0.029	0.037	0.030

Table C-7. Plant A Pilot Testing – Measured and Calculated Blended Water Quality Characteristics.

Date	Blend	ATW	Raw	Blended Water		ATW	Raw	Blended Water	
				Measured	Calculated			Measured	Calculated
TOC (mg/L)						**DOC (mg/L)**			
12/13/21 9:38	0%	0.4	4.1	4.1	4.1	0.4	4.5	4.7	4.5
1/3/22 8:30	10%	0.3	5.2	4.5	4.7	0.4	5.2	4.7	4.7
1/13/22 8:40	20%	0.5	5.5	4.2	4.5	0.3	5.3	4.2	4.3
1/31/22 14:00	50%	0.3	6.1	3.0	3.2	0.6	6.3	3.4	3.4
2/1/22 12:00	50%	0.5	6.2	3.3	3.3	0.6	4.9	3.4	2.7
2/3/22 10:00	50%	ND	5.6	2.8	2.8	0.4	5.6	3.0	3.0
Alkalinity (mg/L $CaCO_3$)						**Magnesium (mg/L)**			
12/13/21 9:38	0%	34	90	89	90	1	15	15	15
1/3/22 8:30	10%	34	120	110	111	ND	18	16	16
1/13/22 8:40	20%	32	89	78	78	ND	16	13	13
1/31/22 14:00	50%	35	84	60	60	ND	14	7	7
2/1/22 12:00	50%	33	83	60	58	ND	14	7	7
2/3/22 10:00	50%	34	81	57	58	ND	13	7	7
Calcium (mg/L)						**Total Hardness (mg/L $CaCO_3$)**			
12/13/21 9:38	0%	1	22	23	22	7	120	120	120
1/3/22 8:30	10%	ND	32	27	29	ND	150	130	135
1/13/22 8:40	20%	ND	26	21	21	ND	130	100	104
1/31/22 14:00	50%	ND	24	13	12	ND	120	62	60
2/1/22 12:00	50%	ND	24	13	12	ND	120	63	60
2/3/22 10:00	50%	ND	23	12	12	ND	110	57	55
Turbidity (NTU)						ND were replaced with 0 for the calculations.			
1/3/22 9:45	0%	1.00	10.50	9.24	10.50				
1/13/22 8:40	20%	0.40	5.69	5.90	4.63				
1/21/22 10:00	0%	1.78	8.01	7.55	8.01				
1/28/22 15:30	50%	1.05	5.69	3.50	3.37				
2/1/22 13:00	50%	0.25	6.61	3.52	3.43				
2/3/22 10:00	50%	0.58	6.29	4.21	3.44				
2/14/22 15:30	10%	0.69	15.30	12.30	13.84				

Table C-8. Plant D Pilot Testing – Measured and Calculated Concentrations in the Blended Water.

Date	Blend	ATW	Raw	Blended Water		ATW	Raw	Blended Water	
				Measured	Calculated			Measured	Calculated
TOC (mg/L)						**DOC (mg/L)**			
9/13/2021	20% Blend	0.5	2.7	2.3	2.3	0.53	2.6	2.2	2.2
9/15/2021	20% Blend	1.5	2.8	2.1	2.6	1.55	2.7	2.0	2.5
9/17/2021	50% Blend	0.4	2.7	1.8	1.5	0.382	2.5	1.8	1.5
9/20/2021	50% Blend	0.4	2.7	1.6	1.6	0.456	2.6	1.6	1.5
9/22/2021	50% Blend	0.3	2.5	1.6	1.4	0.368	2.4	1.5	1.4
Alkalinity (mg/L CaCO$_3$)						**Magnesium (mg/L)**			
9/13/2021	20% Blend	44.1	135	123	117	3.02	6.79	6.17	6.0
9/15/2021	20% Blend	80.5	136	118	125	3.8	6.98	6.28	6.3
9/17/2021	50% Blend	38.6	136	106	87	2.52	6.94	9.26	4.7
9/20/2021	50% Blend	35.8	136	93.1	86	2.21	7.01	5.26	4.6
9/22/2021	50% Blend	40.8	135	90.4	88	2.46	7.15	5.03	4.8
Calcium (mg/L)						**Total Hardness (mg/L CaCO$_3$)**			
9/13/2021	20% Blend	40.4	23.5	26.2	26.9	113	87	91	92
9/15/2021	20% Blend	52.6	24.6	27.8	30.2	118	90	95	96
9/17/2021	50% Blend	40.8	24.5	37.6	32.7	112	90	132	101
9/20/2021	50% Blend	40.8	24.5	31.9	32.7	111	90	101	101
9/22/2021	50% Blend	40.1	25.8	31.9	33.0	110	94	100	102
Turbidity (NTU)						**UV$_{254}$ (cm^{-1})**			
9/13/2021	20% Blend	0.16	1.55	2.88	1.27	0.008	0.065	0.057	0.054
9/15/2021	20% Blend	0.24	1.9	2.30	1.57	0.014	0.064	0.056	0.054
9/17/2021	50% Blend	0.41	1.55	2.24	0.98	0.008	0.064	0.042	0.036
9/20/2021	50% Blend	0.44	2.18	2.11	1.31	0.01	0.067	0.035	0.039
9/22/2021	50% Blend	0.55	1.54	2.75	1.05	0.0174	0.056	0.042	0.037

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