THE
Water
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PROJECT NO.
4833

Understanding the Impacts of Wastewater Treatment Performance on Advanced Water Treatment Processes and Finished Water Quality

THE METROPOLITAN WATER DISTRICT
OF SOUTHERN CALIFORNIA

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

Understanding the Impacts of Wastewater Treatment Performance on Advanced Water Treatment Processes and Finished Water Quality

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Abstract and Benefits

Abstract:

The overarching goal of this research project is to help utilities decide the best path towards potable reuse with a given water resource recovery facility (WRRF) treatment configuration and effluent water quality. Five inter-dependent modules were developed around common WRRF- advanced water treatment (AWT) combinations to systematically evaluate identified challenges or "soft spots" within each WRRF-AWT combination, and how to best address such challenges. Results from each module plus specific case studies were reviewed to understand the cost trade-offs at the WRRF-AWT interface and inform where to prioritize the investment among WRRF upgrades, AWT facilities, or elsewhere. In general, it is usually more cost-effective to add additional treatment at the AWT, rather than to upgrade the WRRF – unless there are additional drivers beyond the goal of implementing potable reuse. Case studies also illustrated that treatment decisions for AWT cannot be made on the basis of cost trade-offs alone: in all three case studies, other factors are at the center of utilities' decisions about what AWT is appropriate for them.

Benefits:

- This project reviews the potable reuse treatment approach from a holistic perspective across a range of water resource recovery facility (WRRF) and advanced water treatment (AWT) combinations.
- This research helps utilities chart a path to potable reuse from an existing WRRF treatment configuration and effluent quality.
- Pathfinding is done by identifying challenges associated with potential treatment combinations and providing tools to evaluate cost trade-offs between WRRF and AWT.
- This project provides detailed data within this final report as well as short and graphically engaging guidance materials that are accessible to a wider, less technical audience.

Keywords: potable reuse, advanced water treatment, cost trade-offs, pass-through constituents, operational impacts, effluent water quality, wastewater treatment approaches, microfiltration, ultrafiltration, reverse osmosis, ultraviolet light advanced oxidation process, ozone, biologically active carbon, granular activated carbon, disinfection.

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Acronyms and Abbreviations

%	Percent
AFFF	Aqueous film forming foam
AOP	Advanced Oxidation process
AWDF	Annual weather dry flow
AWT	Advanced water treatment
AWTF	Advanced Water Treatment Facility
BAC	Biologically active carbon
BAF	Biological active filtration
BDOC	Biodegradable dissolved organic carbon
BNR	Biological nutrient removal
BOD	Biochemical oxygen demand
BV	Bed volumes
$CaCO_3$	Calcium carbonate
CA-NL	California notification level
CBAT	Carbon-based advanced treatment
CBOD	Carbonaceous biochemical oxygen demand
$CBOD_5$	5-day carbonaceous biochemical oxygen demand
CCI	Construction Cost Indices
CCL4	Contaminant Candidate List 4
CEC	Contaminant of emerging concern
CFU	Colony forming units
CIP	Clean-in-place
COD	Chemical oxygen demand
CT	Contact time
CWRF	Cabezon Water Reclamation Facility
DEET	N-diethyl-meta-toluamide
DBP	Disinfection byproduct
DO	Dissolved oxygen
DOC	Dissolved organic carbon
DOM	Dissolved organic matter
EBCT	Empty bed contact time
EDC	Electron-donating capacity
EfOM	Effluent organic matter
ENR	Engineering News Record
EPS	Extracellular polymerase substances
ESC	Enhanced source control
FAT	Full advanced treatment
F/M	Food to mass ratio
FOG	Fats, oil, and grease
GAC	Granular activated carbon

GFD	Gallons per square foot per day
GMF	Granular media filtration
HAA5	Five regulated haloacetic acids
HAAs	Haloacetic acids
HALs	Health Advisory Levels
HPO	High purity oxygen
HPOAS	High purity oxygen activated sludge
HRT	Hydraulic retention time
HSW	High strength waste
ICM	Iodinated X-ray contrast media
IPR	Indirect potable reuse
JWPCP	Joint Water Pollution Control Plant
kWh/m^3	Kilowatt hours per cubic meter
LACSD	Los Angeles County Sanitation District
lb/yr	Pounds per year
LOD	Limits of detection
LRV	Log reduction values
LVMWD	Las Virgenes Municipal Water District
MBR	Membrane bioreactor
MCLs	Maximum contaminant levels
MF/UF	Microfiltration/ultrafiltration
MG	Million gallons
mg-C/L	Milligrams of carbon (or organic carbon) per liter
mgd	Million gallons per day
mg/L	Milligrams per liter
mJ/cm^2	Millijoules per square centimeter
mL	Milliliter
MLE	Modified Ludzack-Ettinger
MLSS	Mixed liquor suspended solids
MRL	Maximum residue level
mV	Millivolt
MWD	Metropolitan Water District of Southern California
NMOR	N-Nitrosomorpholine
NaOCl	Sodium hypochlorite
NDMA	N-nitrosodimethylamine
NdN	Nitrification/denitrification
ng/L	Nanogram per liter
NH_3	Ammonia
NH_4	Ammonia nitrogen
NMED	New Mexico Environment Department
NMOR	N-trosomopholine
NOM	Natural organic matter

NOx	Nitrogen oxides
NRCY	Nitrified recycle
NTU	Nephelometric turbidity unit
O_3	Ozone
O&M	Operation and maintenance
OP	Orthophosphate
ORP	Oxidation reduction potential
PFAS	Polyfluoroalkyl substances
PFBA	Perfluorobutanoic acid
PFCA	Perfluoroalkyl carboxylic acid
PFHxA	Perfluorohexanoic acid
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctanesulfonic acid
PFPeA	perfluoropentanoic acid
PFPnA	Perfluoropentanoic acid
RAS	Return activated sludge
RBAT	RO-based advanced treatment
RDT	Rotary drum thickener
RO	Reverse osmosis
sCOD	Soluble chemical oxygen demand
scf/lb	Standard cubic feet per pound
SDI	Silt density index
SRT	Solids retention time
sTKN	Soluble Total Kjeldahl Nitrogen
TCEP	Tris (2-chloroethyl) phosphate
TDS	Total dissolved solids
THMs	Trihalomethanes
TIN	Total inorganic nitrogen
TMDL	Total maximum daily load
TMP	Transmembrane pressure
TOC	Total organic carbon
TN	Total nitrogen
TP	Total phosphorus
TS	Total solids
TSR	Thermochemical sulfate reduction
TTHM	Total trihalomethanes
TVSS	Total volatile suspended solids
µg/L	Micrograms per liter
µm	Micrometer
UFC	Uniform formation conditions
USEPA	United States Environmental Protection Agency
UV	Ultraviolet

UVA	UV absorbance
UVT	UV transmittance
VS	Volatile solids
WLA	Waste load allocation
WRRFs	Water resource recovery facilities
WWTP	Wastewater treatment plant

Executive Summary

ES.1 The Central Issue

Traditional water resource recovery facilities (WRRFs) typically focus on meeting effluent water quality requirements for discharge, an entirely different focus compared to producing high-quality recycled water for advanced water treatment (AWT) for potable reuse. With the increased prevalence of indirect and direct potable reuse, there is a need to understand the feasibility and costs of AWT, starting from diverse treatment configurations at WRRFs and various effluent qualities. This research project was aimed at bridging the gap between conventional WRRFs and AWT facilities through examination of whole-system performance and economics.

ES.2 Technical Approach

The technical approach involves the development of five interdependent modules to systematically identify challenges or “soft spots” within each WRRF-AWT combination. Results from each module were reconciled and integrated to elucidate the cost trade-offs at the WRRF-AWT interface and inform where to prioritize the investment among WRRF upgrades, AWT facilities, or elsewhere. The overarching goal of this research project is to help utilities decide the best path forward to potable reuse with a given WRRF treatment configuration and effluent water quality.

Module A evaluated how performance at a WRRF can impact AWT with regard to either treatment performance (e.g., RO system recovery) or purified water quality. In this module, historical data including operating conditions and corresponding process performance at both the WRRF and the AWT were collected from five utilities across the United States. Daily operational and/or water quality data were processed to develop 3-day, 7-day, 15-day, and 30-day lookback averages for WRRF and AWT parameters to identify whether a time-lag would have an impact on AWT performance evaluation. All available data were analyzed using multi-linear regression and supervised machine learning to identify the potential correlative relationship between the existing wastewater treatment characteristics (e.g., primary, secondary, tertiary, solids, and sidestream treatment) and the AWT performance.

This work analyzed large historical datasets for multiple utilities with hundreds of monitored parameters. The results of this study provide a preliminary understanding of the interrelationship among WRRF parameters and key AWT performance. The analytical approaches used in this module identified several key parameters that appear to have an impact on AWT performance, thereby highlighting potential targets for expanded evaluations. While some of the identified parameters are intuitive (e.g., solids retention time), additional work is necessary to understand whether the other identified parameters have a direct or indirect impact on AWT performance. It is noteworthy that results of the multilinear regression models and supervised learning models do not specifically conclude whether the WRRF parameters identified have a causative effect. Rather, this work identified potential WRRF parameters that may influence AWT performance, either directly or indirectly. Future work is needed to further understand the explanatory and mechanistic nature of these relationships.

Module B focused on the impacts of WRRF effluent quality on carbon-based advanced treatment (CBAT), which typically includes ozone (O_3), biologically active filtration (BAF), and granular activated carbon (GAC). Operational performance and effluent water quality at the WRRF can impact the level of treatment that must be achieved by CBAT to produce purified water that is protective of public health and meets regulatory requirements. Furthermore, WRRF effluent quality can impact process selection, design, performance, maintenance, and economics of the downstream AWT train.

To identify challenges or “soft spots” associated with CBAT, a list of pass-through constituents was first identified in this module. A pass-through constituent is defined as a constituent that was originally present in the wastewater effluent or is formed during AWT and is still present at a level of human health concern in the purified water. Several constituents of emerging concern (CECs), including *N*-nitrosomorpholine (NMOR), iohexal, 1,4-dioxane, short-chain per- and polyfluoroalkyl substances (PFAS), can pass through CBAT. Other pass-through constituents include ozone byproducts (e.g., *N*-nitrosodimethylamine [NDMA] and bromate) and inorganic constituents originally present in the WRRF effluent (e.g., bromide, nitrate, iodide, and total dissolved solids). To mitigate these pass-through constituents, source control or additional “support treatment,” such as UV photolysis, nanofiltration, anion exchange, and advanced oxidation may be required in addition to the core CBAT processes.

Another “soft spot” of CBAT is associated with system operation and optimization due to wide range of possible dosing combinations and operational conditions (e.g., ozone dose, biofilter and GAC empty bed contact time [EBCT]). For this reason, interfering constituents were identified to facilitate the development of mitigation strategies to address this “soft spot.” An interfering constituent is defined as a constituent that may be present in the WRRF effluent and interfere with CBAT operation and diminish performance. Interfering constituents, including turbidity, total organic carbon (TOC), free chlorine, and nitrite, can increase ozone demand, shorten filter run times, more rapidly exhaust GAC adsorption capacity, and more. Mitigation strategies for interfering constituents include enhanced source control, optimized secondary treatment for biological nutrient removal, tertiary filtration with or without pre-coagulation, and enhanced coagulation as a pretreatment process upstream of CBAT.

The final component of Module B considered the cost implications for CBAT in the context of variable upstream WRRF treatment. Capital and operation and maintenance (O&M) cost estimates were developed for the ozone and BAF components of a hypothetical CBAT train, specifically focusing on the implications of different ozone doses and EBCTs. Cost differences are mainly driven by ozone feed TOC concentration and therefore the applied ozone dose. However, additional costs for CBAT may need to be considered for any “support treatment” selected for the pass-through constituents. These costs are site-specific and depend on both source water quality and purified water quality goals.

Module C aimed to understand the relationship between WRRF effluent water quality and the operations and performance of an AWT approach that starts with microfiltration (MF) or ultrafiltration (UF). Design and operation of MF/UF systems for potable reuse is typically considered very site-specific, with on-site pilot studies and significant empirical iteration necessary to define the design flux and cleaning regimes for a future full-scale design. This module leveraged pilot- and full-scale data from 16 facilities that included MF or UF membranes as the first step in AWT to provide a more semi-quantitative evaluation of what effluent water quality parameters affect MF/UF design and operation, and how. Specifically, the objective of this module was to assess the impacts of water quality and upstream water treatment processes on flux and translate these impacts to full-scale costs associated with MF/UF.

Existing utility data was compiled and reviewed in detail. Various correlations were developed, but only a single key membrane system design parameter, design flux, rose to the forefront because it overwhelmingly drives the cost of MF/UF systems. Based on this realization, two major efforts were undertaken as part of this module: (1) develop correlations between WRRF characteristics and effluent water quality parameters versus design flux for the partner utility installations, and (2) develop capital cost curves for MF/UF systems as a function of flow capacity and design flux. Three major WRRF effluent parameters were found to correlate significantly with membrane system design flux: solids retention time ($R^2 = 0.73$), effluent TOC ($R^2=0.64$), and effluent ammonia ($R^2=0.83$). While not unexpected, and certainly not without cross-correlation, these quantitative relationships would allow a prospective potable reuse utility to calculate the cost impact, or "value" to a membrane-based AWT design of making improvements upstream.

Additionally, a rapid bench-scale fouling protocol was developed to evaluate the impact of different WRRF effluent water qualities and pre-treatment strategies for membrane-based AWT. Three different effluents subjected to various pretreatment conditions resulted in seven waters tested for fouling potential. This testing was able to qualitatively reproduce the results observed at pilot-scale, and this approach could be used in the future to appropriately size pilot-scale (or perhaps even full-scale) facilities for membrane-based AWT.

Module D tracked and established the status quo of membrane bioreactor (MBR)-based AWT, including the most recent advances in the industry's knowledge of MBR-based AWT. The specific "soft spots" identified for MBR-based AWT were (1) demonstrating pathogen log reduction values (LRVs) through the MBR process and (2) characterizing impacts on downstream RO membranes when MBRs are used in lieu of MF/UF. Finally, cost evaluations established the value of MBR filtrate as a feed to RO-based AWT.

Literature and ongoing parallel projects were reviewed. These include Salveson et al. 2021, Branch et al. 2023, and efforts underway at Metropolitan Water District of Southern California (MWD), Los Angeles Sanitation and Environment Hyperion Plant, and Kubota Membrane USA Corporation research at Lake of the Pines Wastewater Treatment Plant in Auburn, CA. In summary, a three-tier validation process for establishing MBR LRVs is proposed in which the first (lowest) tier of LRV credits is awarded on the basis of meeting certain design and operating criteria. The second (higher) tier of LRVs is awarded based on site-specific challenge testing under conservative operating conditions and requires ongoing performance monitoring. The third (highest) tier of LRVs would require a direct correlation between the pathogens and a surrogate that can be monitored online. To date, no surrogate has been proposed that would meet Tier 3 validation requirements.

A detailed review of test results from MWD's MBR-RO research efforts to establish the potential fouling impacts of MBR filtrate on the RO membranes and upstream cartridge filters is also provided. Mixed liquor breakthrough as a result of both intentional MBR membrane cutting and unanticipated damage from snail growth (*Physella gyrina*) provided a substantial challenge test case for the RO system. Cartridge filters especially experienced an increase in the rate of differential pressure increase and therefore changeout frequency. RO fouling (i.e., reduction in normalized flux) was also observed after the discovery of snails in the MBR system. RO membrane integrity, however, remained stable throughout testing as evidenced by salt passage data and autopsy results.

Module E evaluated the combination of MBR and CBAT based on evaluations conducted at the City of Rio Rancho's Cabezon Water Reclamation Facility (CWRF). The initial goal of evaluating a sub-residual ozone dose under an alternative "ozone-to-TOC ratio" dose concept as an alternative to hydrogen peroxide addition for bromate mitigation was ultimately achieved by demonstrating >5 log MS2 bacteriophage inactivation at a nitrite-corrected ozone: TOC mass dose ratio of 0.8 -- a dose at which no ozone residual was measurable and bromate formation was minimal. In the process of its evaluations, the project team's work also underscored the importance of accurate instrumentation and consistent MBR process operation to achieve full nitrification in maintaining the effectiveness of ozone for both disinfection and CEC destruction.

Finally, semi-quantitative cost trade-offs were evaluated on the basis of cost curves and a number of case studies. These case studies, as well as general comparison of the typical scale of WRRFs compared to smaller-scale AWTs revealed that in almost all cases, it is more cost-effective to add additional treatment at the AWT, rather than to upgrade the WRRF, unless there are additional drivers beyond the goal of implementing potable reuse. In addition, treatment decisions for AWT cannot be made on the basis of cost trade-offs alone: in all three case studies, other factors (AWT reliability, RO concentrate disposal challenges, or AWT cost equivalency driving other factors to the forefront) are at the center of utilities' decisions about what AWT is appropriate for them.

ES.3 Related WRF Research

- Evaluation of Tier 3 Validation Protocol for Membrane Bioreactors to Achieve Higher Pathogen Credit for Potable Reuse (4959)
- Evaluation of CEC Removal by Ozone/BAF Treatment in Potable Reuse Applications (4832)
- Assessing Water Quality Monitoring Needs, Tools, Gaps, and Opportunities for Potable Water Reuse (5079)
- Potable Reuse Demonstration Design & Communication Toolbox (4979)

CHAPTER 1

Introduction

1.1 Background

Traditional water resource recovery facilities (WRRFs) and advanced water treatment (AWT) facilities typically operate as separate entities with entirely different focuses and goals. WRRFs are generally focused on meeting effluent discharge requirements, with less concern regarding the effluent quality provided to AWT. With increased prevalence of potable reuse, it is necessary to understand the impacts of various effluent qualities on advanced processes and the range of effluent qualities acceptable. Whole system impacts (i.e., from WRRF across AWT), performance, and economics must be considered to bridge the gap between WRRF and AWT and determine integrated treatment approaches for potable reuse. Viewing WRRF and AWT as “one system” is a new paradigm, and the goal of this project is to better understand the interconnections of this “one system”.

One significant challenge in potable reuse is the unexpected input of materials or contaminants upstream that can pass through the WRRF and cause issues at the AWT or the final product water. Several previous (Steinle-Darling et al. 2020, Nading et al. 2023, Salveson et al. 2023) WRF projects are focused on the topic of enhanced source control (ESC). It is therefore not discussed further here, except inasmuch as some of the WRRF challenges discussed may ultimately be related to disruptions from upstream. Certainly, ESC programs are one of the critical barriers necessary to the success of potable reuse.

In looking at challenges and disruptions at the WRRF, a number of issues may carry forward into AWT. Disruption to primary clarification can subsequently impact the biological efficiency or sludge settleability during secondary treatment. Secondary treatment is crucial in reducing the organic, nutrient, and solids load delivered to AWT processes, especially through sufficient aeration and solids retention time (SRT). Low quality secondary effluent may contain higher organics load, correlating to higher contaminant of emerging concern (CEC) concentrations (Salveson et al., 2012), disinfection byproduct (DBP) formation potential (Schimmoller et al., 2018; Mitch and Sedlak 2004), and increased pathogen concentrations (Salveson et al., 2018)

Different effluent qualities can also adversely affect AWT operations. Lower quality effluent will likely increase fouling of microfiltration/ultrafiltration (MF/UF) membranes, resulting in a range of impacts from requiring a small amount of additional energy and treatment chemicals, to permanent loss of treatment capacity or extensive long-term operation and maintenance (O&M) costs. As described in WateReuse Research Foundation project No. 14-20 (Tchobanoglous et al., 2015), advanced purification systems benefit from a stable and high-quality source water.

However, many real-world potable reuse systems, and some of our largest, operate successfully with lower-quality effluent as feed water, suggesting a potential path forward for potable reuse given any wastewater treatment process and effluent water quality. This project aimed at identifying modifications to the WRRF that could improve AWT performance and efficiency, understanding the level of AWT needed following different WRRF systems, and investigating the cost trade-offs between making improvements at the WRRF and AWT.

1.2 Research Objectives

The overarching question of this project is: "*What is the best path to potable reuse starting with a given WRRF process and water quality?*" To answer this, relationships between WRRFs and AWTs must be evaluated. The objectives were to:

- Identify modifications to the WRRF that could improve purification system performance and efficiency
- Understand the AWT needed following different WRRF systems to meet water quality goals, and
- Identify optimal cost trade-offs between making improvements at the WRRF, AWT, or elsewhere.

1.3 Technical Approach

In order to focus what would otherwise have been an exceedingly broad evaluation, the project team developed two concepts:

1. Common combinations of WRRF and AWT were defined and examined for specific “soft spots,” i.e., areas in which that treatment combination has potential challenges or flaws, such that our guidance can focus on charting potential paths to addressing those flaws.
2. Specific WRRF effluent water quality parameters, dubbed *Interface Parameters*, were identified to provide a framework for a more semi-quantitative "cause and effect" evaluation of the trade-offs between WRRF and AWT performance.

1.3.1 Modules

To systematically and efficiently evaluate the common WRRF-AWT combinations, the project was separated into five relatively independent "modules", each led by members of the PI team. This enabled the project to progress on parallel tracks with similar, but different milestones, and converge at the end for a comprehensive assessment of trade-offs and recommendations for various AWTs with a given effluent quality.

The five major modules include:

- Module A- Identifying WRRF Impacts on AWT Performance
- Module B- WRRF Effluent Impacts on Carbon-based advanced treatment (CBAT)
- Module C- WRRF Effluent Impacts on Microfiltration and Ultrafiltration (MF/UF)
- Module D- Membrane bioreactor (MBR) Impacts on Reverse Osmosis (RO)
- Module E- MBR Impacts on CBAT

1.3.2 Interface Parameters

In order to provide a framework for evaluating each module, an "interface" for each WRRF/AWT combination was defined. The list of interface parameters defined for each module defined the list of parameters included in data requests to partner utilities in Task 1 and focused the core of investigative/ analytical efforts in Task 2, ensuring stream-lined and coordinated efforts between the modules. A simple causal flow graphic in Figure 1-1 illustrates the logic of this interface.

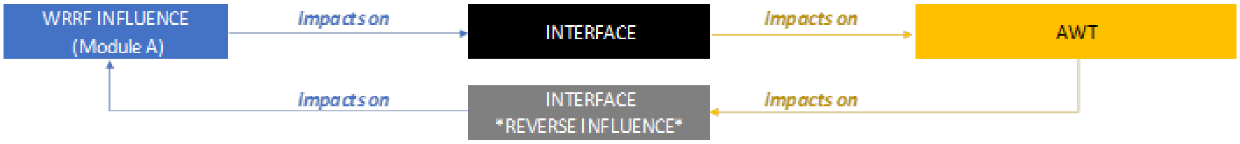


Figure 1-1. Logical Flow of Causal Relationships Between WRRF and AWT are Standardized Using a Common List of "Interface Parameters."

The power of this approach is that it allowed the research in each module to proceed without the need for constant coordination with other modules, as long as the data collected contained or could be directly correlated to the parameters in the agreed-upon and limited list of "interface parameters." This allowed the datasets from the individual modules to be connected once work was complete in each. The approach does not fully ignore direct relationships (for example, the effect of secondary treatment solids retention time (SRT) on downstream MF/UF design flux as shown in Figure 4-2) but concentrates the coordination between the modules on this interface.

With this approach, data requests from utility partners were streamlined by a couple of simple questions in each module. For Module A, those questions were: "What within the WRRF can impact the [black] interface parameters and how?" and "How do the [gray] 'reverse parameters' affect my WRRF?" For the AWT modules, the questions are the logical reverse: "How do the interface parameters affect my AWT?" and "What within my AWT can impact the 'reverse parameters' and how?"

1.3.3 Task Summary

Focusing on evaluating the interface of each module, our partnership with 24 utilities provided access to unpublished reports, historical and ongoing operational data, and process experience on the various WRRF/AWT combinations. Task 1 of each module included data collection, through published and unpublished literature, case studies, and review of historical data from partner utilities. This was done to identify and/or confirm process specific challenges or "soft spots" for each module.
Following data collection, all modules continued with data analysis and/or generation of new data with a focus on addressing the soft spots and eventually developing strategies to address them. New data was generated with bench or pilot testing to fill soft spots identified during data collection or as separate case studies at the full-scale.

Findings from all modules were reconciled in Task 3 to evaluate cost trade-off relationships at the WRRF/AWT interface and develop solutions to challenges identified in Tasks 1 and 2. Solutions were translated to capital and O&M costs for each option to understand impacts between implementing upgrades at the WRRF versus additional treatment costs or processes at the AWT. The final task of the project includes guidance and practical tools such as cause-and-effect maps and decision support tools to help utilities determine the best path to implement potable reuse with a given WRRF starting point.

CHAPTER 2

Module A: Identifying WRRF Impacts on AWT Performance

2.1 Background

Traditionally, WRRFs main focus is meeting effluent discharge requirements. For utilities considering implementation of AWT for producing water suitable for potable reuse, understanding the synergistic relationship between wastewater treatment—both liquids and solids—and AWT can help inform the design, modification, and operation of these facilities to meet the water quality requirements necessary to ensure the safe reuse of water.

The key goal of Module A is to document how performance at a WRRF can impact AWT processes. These impacts may be process specific, related to operation and maintenance, water quality impacts that increase health risks (either acute or chronic) or impact treatability (health/treatability), or a combination of O&M and health/treatability impacts. Identifying the cause and effects of WRRF on AWT performance is intended to help address the challenges often encountered when implementing advanced treatment including:

- Significant diversity in the process configurations and operating strategies employed at WRRFs.
- Treatment goals at WRRFs are sufficiently distinct from AWT goals.
- Monitoring at WRRFs can be insufficient to quantify impacts on AWT.
- Intrinsic variability in wastewater influent, environmental conditions, and biological processes can prevent elucidation of cause and effect.

2.2 Methods

Historical operating data was collected from five utilities across the United States. Table 2-1 is a summary of the utilities evaluated for Module A. The historical data included process performance and operational parameters for the WRRF and AWT facilities within a utility.

Table 2-1. Utilities Evaluated in Module A.

Utility No.	Utility Location	WRRF/AWT Facility on the Same Site	WRRF Train	AWT Train	AWT Scale
1	Virginia, USA	No	Primary, Secondary Nitrification/Denitrification, Biological Phosphorus Removal, Struvite Recovery	O_3/BAC/GAC/UV	Pilot/Demonstration
2	California, USA	No	Primary, Secondary (High Purity Oxygen)	MBR/RO/UV-AOP	Full
3	Georgia, USA	Yes	Primary, Secondary Nitrification, Biological Phosphorus Removal, Tertiary Filter/Ultrafiltration	Tertiary filtration/Ultrafiltration, O_3/BAC/O_3	Full
4	Virginia, USA	Yes	Primary, Secondary Nitrification/Denitrification, Membrane Bioreactor	BAC/GAC	Full
5	Arizona, USA	No	Primary, Secondary Nitrification/Denitrification, Tertiary Filter	MF/RO/UV	Full

2.2.1 Data Processing

To develop an understanding of the interconnectivity of WRRF and AWT parameters, the following approach was utilized.

- Target AWT performance and/or operating parameters were identified for evaluation at each utility. These parameters were selected based on treatment train configuration and available monitoring/process data. Non-membrane facilities typically have multiple barriers in place to meet the target treatment goals, therefore, water quality based AWT parameters were primarily selected for evaluation. Alternatively, membrane facilities where the majority of constituent removal is achieved through RO and produce consistently high-quality product water, operational parameters were selected to understand the impact of WRRF on AWT performance.
- Daily historical data was processed to develop 3-day, 7-day, 15-day, and 30-day lookback average trends for WRRF and AWT parameters to identify whether time-lag data had an impact on AWT. In general, the 7-day, 15-day, and 30-day lookback averages were observed to provide stronger correlations than the daily or 3-day average datasets due to the richness of the data and number of pairwise data available.
- A series of data analyses were performed to understand the relationship between WRRF and AWT performance including multi-linear regression analyses and machine learning.

2.2.2 Multilinear Regression

Multilinear regression is a type of regression where the combination of more than one distinct independent variable (i.e., WRRF parameters) predict the outcome an independent variable (i.e., target AWT parameter). The WRRF parameters were selected to perform multilinear regression had a statistical significance with p-values < 0.05, where p-value is the probability value. The p-values < 0.05 generated from a multi-linear regression analysis indicates whether a WRRF parameter is statistically significant in predicting the value of the interface parameter. The multilinear regression analysis generates an equation to describe the relationship between one or more WRRF parameter(s) and target AWT parameter, described by the equation below:

$$Y = b_0 + b_1X_1 + b_2X_2 + \cdots + b_nX_n$$

Where Y is the expected value of the target AWT parameter, b_0 is the value of Y when all independent variables (X_1 through X_n) are zero, and b_1 through b_n are the estimated regression coefficients. A key assumption of multi-linear regression modeling is that each regression coefficient represents a change in the Y relative to one unit change of the dependent variable while holding all other independent variables constant.

The daily and lookback averaged data were analyzed using multi-linear regression analyses to identify the WRRF parameters that have a correlative relationship with the target AWT parameters. Parameters that were infrequently monitored and had 50 percent or more datapoints missing from the dataset were removed from the analysis due to lack of data richness.

Prior to the multi-linear regression analysis, a Spearman correlation analysis was performed for each AWT parameter against the WRRF parameters. A Spearman's rank correlation is a nonparametric measure of the statistical dependence between two variables and assess whether the relationship can be described by a monotonic function. Parameters exhibiting a Spearman coefficient ≥ 0.30 or ≤ –0.30 were selected for multi-linear regression analyses. A Spearman's coefficient threshold of +/- 0.30 was selected because values less than that are considered to have a low correlation (Mukaka, 2012).

A challenge related to multilinear regression analyses is the impact of multicollinearity. Multicollinearity is the phenomenon where two or more predictors in a regression model are correlated. Multicollinearity can lead to misleading regression models and reduces the precision of the estimated coefficients, weakening the statistical power of the regression model. Multicollinearity was addressed by performing a variation inflation factor (VIF) analysis. The VIF assesses the amount the variance of an estimated regression coefficient increases when predictors are correlated (Akinwande, et al. 2015). In general, a VIF equal to one indicates no multicollinearity, a VIF between one and five indicates moderate correlation among the independent variables, and a VIF greater than 5 indicates high multicollinearity. For the VIF analysis, WRRF parameters that exhibited a VIF greater than 5 were removed. The remaining WRRF parameters with a VIF < 5 were considered to have no or only moderate correlation with one another.

2.2.3 Supervised Learning

A subset of machine learning, called supervised learning, was performed to further help identify potential linkages between WRRF parameters and AWT performance. Supervised learning finds regularities between target variables (i.e., AWT parameter) and potential predictors from observations (i.e., WRRF parameters). This method allows us to infer target variable distributions from new observations, without the necessity to understand why a combination of input parameters achieves certain predictions.

For each target AWT parameter, Bayesian networks (BN) were constructed and evaluated using the software BayesiaLab (Changé, France). BN are probabilistic graphical models that represent interdependency between different dataset variables with a graph model that has directed acyclic edges. The graph is built based on known conditional dependence and joint probability distributions of the dataset (Mulhern et al. 2021).

In BN we perform discretization on the data. Discretization is the process through which we can transform continuous variables, models, or functions into a discrete form. Missing values were also inferred by using different algorithms such as Structural Expectation-Maximization (or Structural EM). Structural EM methods are dynamic imputation algorithms which means they infer missing values from the distribution of data by learning the relationships between the missing data and the available data and use an optimization algorithm to select the most likely value for the missing data (Conrady et al., 2015). After missing values are inferred, the BN model was built using supervised algorithms to find the underlying structure of the data.

The final selected model for each target AWT parameter includes the corresponding mutual information of each WRRF parameter within the model. Mutual information is defined as the amount of information gained on variable X (i.e., AWT parameter) by observing variable Y (i.e., WRRF parameter) (Conrady et al., 2015). The benefit of a BN network model is that it recognizes the interrelationships (patterns of connections and effects) of the independent variables. This differs from a multilinear regression model which assumes that if one variable changes, the others remain the same. This is much more representative of real-world applications in WRRFs where there are many interrelationships among the monitored parameters.

The supervised learning models were evaluated based on various goodness of fit parameters, including overall precision, the ROC index, and R^2. Precision is one of the accuracy metrics that can be used for a classification problem and can be calculated by dividing the True Positive rate by (True Positive + False Positive). The ROC index is an indicator of how well the predictive model falls within a classification range. An ROC index of 0.5 indicates no classification capacity, 0.8 indicates good classification, and 1.0 indicates perfect classification (Safari et al. 2016, Roostaei et al., 2021). The overall precision of the model indicates the proportion of positive identifications that are correct. The R^2 provides an indication of how well the model predicts a specific value.

2.3 Results

2.3.1 Utility No. 1: Virginia, USA

2.3.1.1 Background

Utility No. 1, located in Virginia, USA, has a design annual average flow of 30 million gallons per day (mgd). Liquid treatment consists of screening (1/2-inch bar screens), grit removal, primary clarification, 5-stage biological nutrient removal (BNR) with an average SRT of 15 days, secondary clarification, chlorination and dechlorination prior to a portion of effluent discharged to surface water. Figure 2-1 is a process flow diagram of the WRRF. Solids treatment consists of in-tank thickening or gravity belt thickening (GBT) of primary solids (PS), GBT of waste activated sludge (WAS) followed by mesophilic anaerobic digestion (MAD). Digested sludge is dewatered using solid bowl centrifuges and the dewatered cake is transported offsite for further treatment or disposal. Since May 2010, Utility No. 1 has utilized sidestream phosphorus recovery.

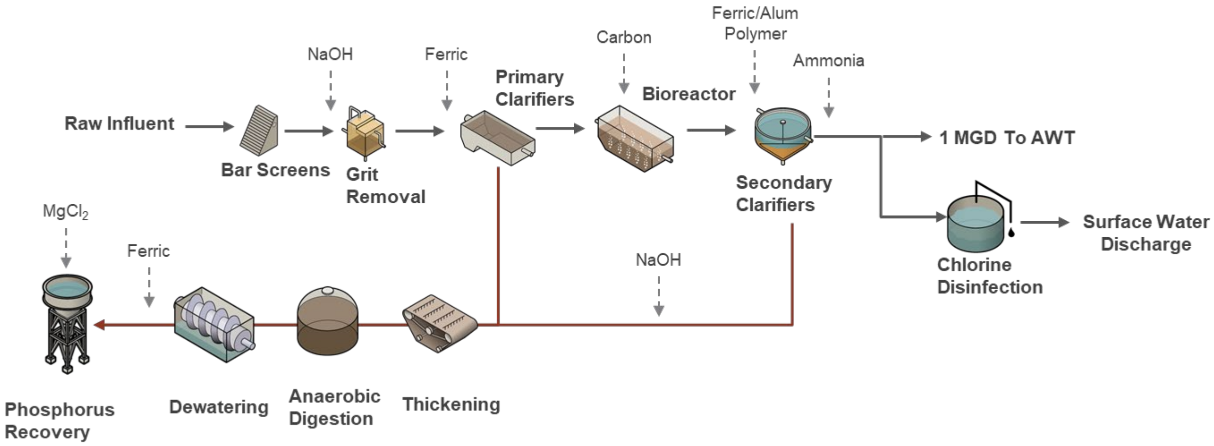


Figure 2-1. Utility No. 1 Process Flow Diagram of the Water Resource Reclamation Facility.

One mgd of secondary effluent flow is conveyed to the advanced treatment demonstration facility. The 1 mgd advanced treatment demonstration facility includes flocculation sedimentation, ozone contact, biologically active filtration (BAF), GAC contactors, UV disinfection, chlorine contact, and aquifer recharge. Figure 2-2 is a process flow diagram of the AWT facility.

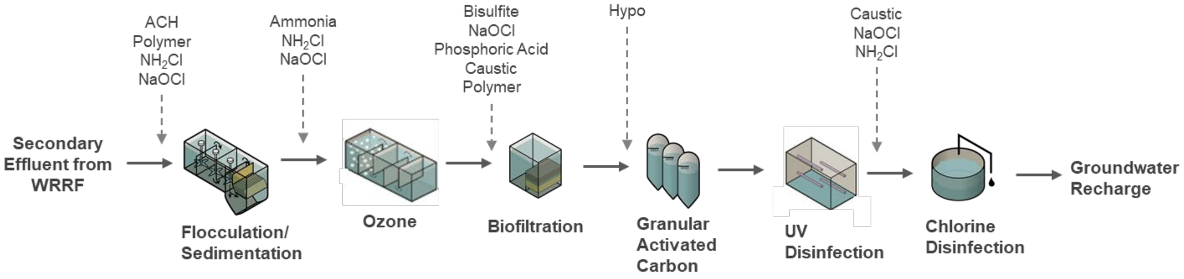


Figure 2-2. Utility No. 1 Process Flow Diagram of the Advanced Water Treatment Facility.

Five target advanced water treatment parameters were identified for evaluation in Utility No. 1. These parameters include:

- Ozone effluent bromate (milligrams per liter [mg/L])
- GAC effluent NDMA
- GAC effluent Total Kjeldahl Nitrogen (TKN)
- GAC effluent TOC
- AWT effluent 1,4-dioxane

Table 2-2 summarizes the WRRF parameters that appear to influence the AWT target parameter based on the multilinear regression model and supervised learning model. The detailed model results, including model accuracy, are provided in Appendix A. Figure 2-3 is a plot of the measured ozone effluent bromate and multi-linear regression and supervised learning predictive models to demonstrate the accuracy of the predictive models.

Table 2-2. Utility No. 1 Model Comparison.

AWT Parameter	Basis of Selection	Parameters Suggested by Multilinear Regression	Parameters Suggested by Supervised Learning
GAC Effluent Bromate	Quality based parameter; Bromate is a disinfection byproduct formed by oxidation of bromide during ozonation. Bromate is a regulated drinking water contaminant with a MCL of 10 µg/L.	• Raw influent quality (e.g., sulfate, COD, sCOD, total volatile solids suspended solids (TVSS)) • Primary ferric chloride addition • Secondary clarifier surface overflow rate • Sidestream phosphorus recovery TP removal • Thickening GBT and dewatering centrifuge polymer use • Digester temp • GBT filtrate COD (mg/L)	• Raw influent quality (e.g., chemical oxygen demand (COD), soluble chemical oxygen demand (sCOD), soluble Total Kjeldahl Nitrogen (sTKN), orthophosphate (OP), total volatile suspended solids (%TVSS), conductivity, chloride, magnesium, and temperature) • WAS flow • Digester feed %TS • Total biological oxygen demand (BOD) and total phosphorus (TP) removal performance
GAC Effluent TKN	Quality based parameter; TN is a regulated contaminant for this utility with a water quality target of 5 mg/L (monthly average)	• Primary CBOD removal • Number of secondary clarifiers in service • Digester detention time • Centrifuge feed TS load	• Raw influent composition (e.g., temp, %TVSS, total dissolved solids [TDS], sulfate) • Number of grit tanks in service • Primary clarifier BOD removal, and number of clarifiers in service • WAS flow
GAC Effluent TOC	Quality based parameter; TOC is a regulated contaminant for this utility with a water quality target of 4 mg/L (monthly average)	• Scrubber sodium hypochlorite (NaOCl) dose • Primary effluent total volatile suspended solids (%TVSS) • Food to mass ratio (F/M) reaction rate • Total suspended solids (TSS) removal • GBT filtrate orthophosphate (OP)	• Number of primary clarifiers in service and primary clarifier CBOD removal • Secondary clarifier ferric addition and WAS flow • Digester feed total volatile solids load • Centrifuges recycle TSS load
GAC Effluent NDMA	Quality based parameter; NDMA is a probable human carcinogen that is included on the EPA Contaminant Candidate List 4 (CCL4). This compound is monitored at this utility as a non-regulatory	• Raw influent carbonaceous biological oxygen demand to total phosphorus ratio (CBOD:TP) • Primary ferric chloride use • Primary TSS removal • TP removal in the sidestream recovery process	• Raw influent composition (e.g., OP, CBOD:TP, TS, conductivity) • Primary ferric chloride use • Primary clarifier TSS removal performance and surface overflow rate • Bioreactor aerobic HRT and F/M ratio

AWT Parameter	Basis of Selection	Parameters Suggested by Multilinear Regression	Parameters Suggested by Supervised Learning
	public health performance indicator with a limit of 10 nanograms per liter (ng/L).	• Odor control scrubber NaOCl dose	• Total BOD removal performance
AWT Effluent 1,4-Dioxane	Quality based parameter; NDMA is a probable human carcinogen that is included on the EPA Contaminant Candidate List 4 (CCL4). This compound is monitored at this utility as a non-regulatory public health performance indicator with a limit of 10 ng/L.	• Raw influent TSS load • Number of primary clarifiers in service • Dewatering centrifuge polymer dose	• Raw influent composition (e.g., sCOD, pH, and alkalinity) • Bioreactor aerobic SRT • Secondary clarifier sludge blanket depth • WRRF final effluent BOD load • Digester feed and centrifuge cake %TS • Odor control scrubber sodium hypochlorite use

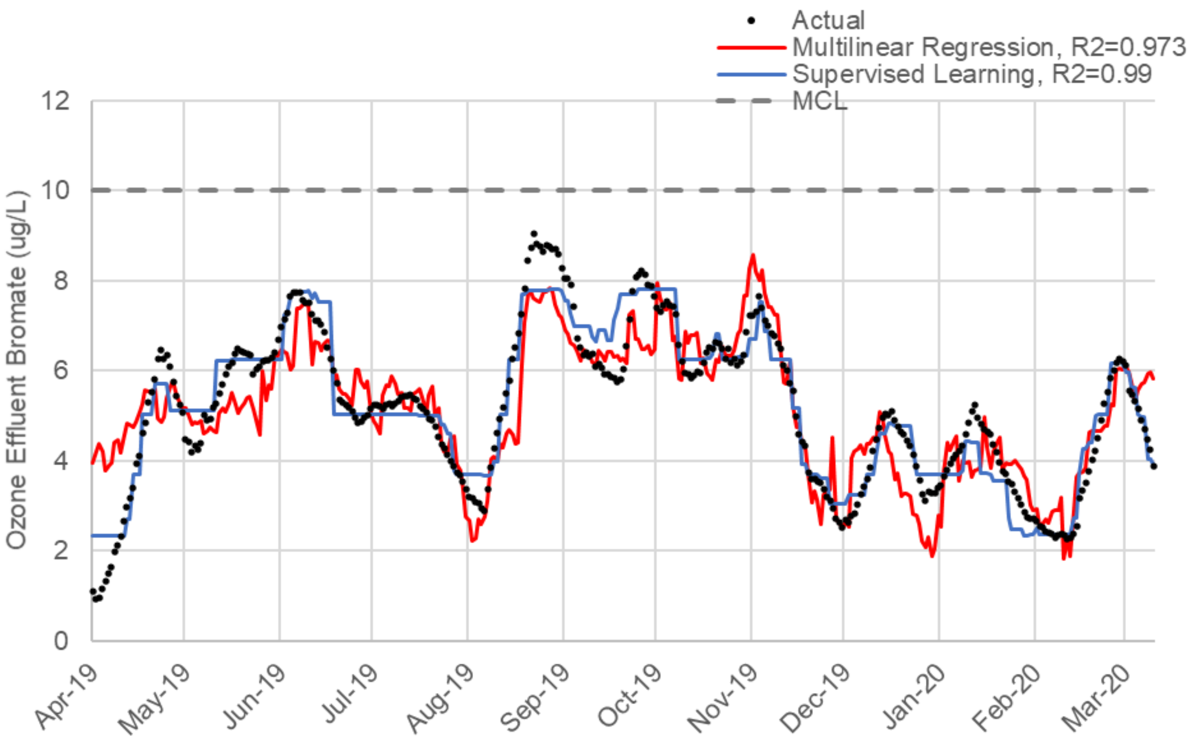


Figure 2-3. Utility No. 1 Ozone Effluent Bromate Monitored Data Compared to the Predictive Multilinear Regression Model and Supervised Learning Model.

2.3.2 Utility No. 2: California, USA

2.3.2.1 Background

Utility No. 2, located in California, USA, has a maximum daily flow capacity of 450 mgd and includes preliminary treatment (mechanical screening, aerated grit removal), enhanced primary treatment (clarification with ferric chloride and anionic polymer addition), secondary treatment (high purity oxygen [HPOA] treatment and secondary clarification). Approximately 40 mgd of treated effluent is discharged via an ocean outfall and the remaining flow is conveyed to the AWT facility. Biosolids handling includes primary sludge and waste activated sludge thickening, anaerobic digestion and dewatering and offsite beneficial reuse. Effluent permit limits for average monthly effluent total suspended solids (TSS) concentration and 5-day carbonaceous biochemical oxygen demand ($CBOD_5$) at 20°C are 30 mg/L and 30mg/L, respectively. Figure 2-4 is a process flow diagram of the WRRF.

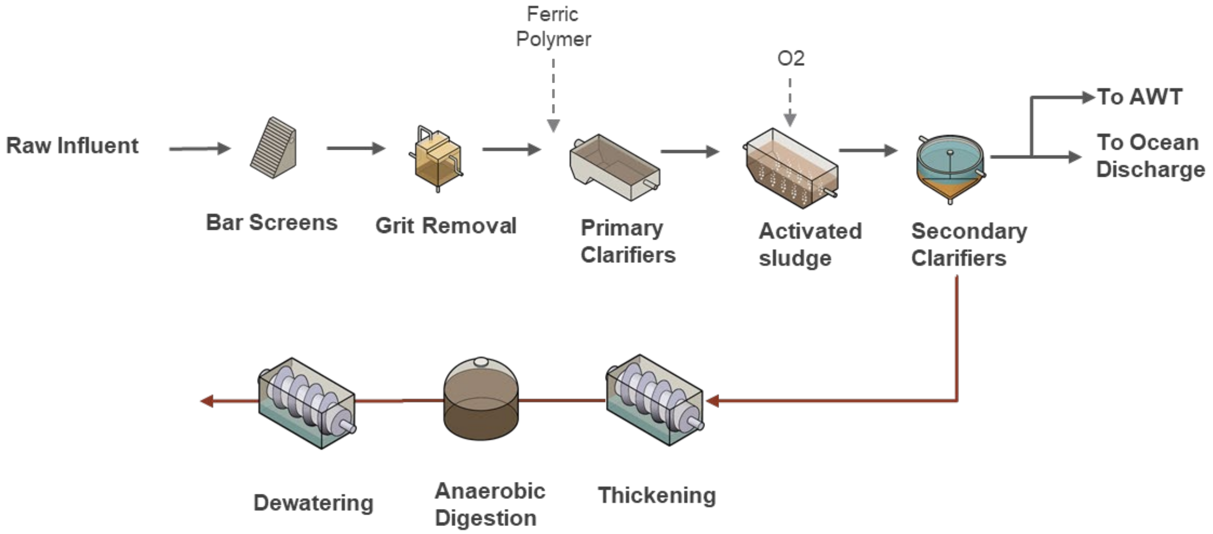


Figure 2-4. Utility No. 2 Process Flow Diagram of the Water Resource Reclamation Facility.

The AWT facility receives effluent from the secondary clarifiers and undergoes microfiltration treatment, reverse osmosis, UV advanced oxidation, decarbonation and stabilization before aquifer recharge. Figure 2-5 is a process flow diagram of the AWT facility.

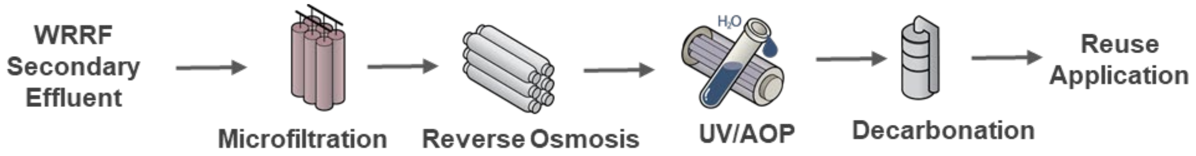


Figure 2-5. Utility No. 2 Process Flow Diagram of the Advanced Water Treatment Facility.

Four target advanced water treatment parameters were identified for evaluation in Utility No. 2. These parameters include:

- Microfiltration normalized transmembrane pressure
- Microfiltration specific flux
- Reverse osmosis total recovery
- Reverse osmosis specific flux

2.3.2.2 Results

Table 2-3 summarizes the WRRF parameters that appear to influence the AWT target parameter based on the multilinear regression model and supervised learning model. The detailed model results, including model accuracy, are provided in Appendix A. Figure 2-6 is a plot of the measured temperature-corrected microfiltration specific flux, multi-linear regression, and supervised learning predictive models to demonstrate the accuracy of the predictive models.

Table 2-3. Utility No. 2 Model Comparison.

AWT Parameter	Basis of Selection	Parameters Suggested by Multilinear Regression	Parameters Suggested by Supervised Learning
Microfiltration Specific Flux	Operations based parameter; specific flux is an indicator of membrane fouling	• Secondary clarifier hydraulic retention time (HRT) • HPOA lb oxygen applied per lb BOD • Centrate recycle flow	• Raw influent oil & grease • Primary ferric chloride dose • Primary influent flow and primary sludge flow • Secondary influent BOD and 30-minute sludge volume index (SVI) • Secondary clarifier solids loading rate and blanket depth • Digester solids load
Microfiltration Transmembrane Pressure	Operations based parameter; transmembrane pressure is the amount of force necessary to push water through a membrane and is impacted by membrane fouling	• Recycles flow to primary treatment • Return activated sludge (RAS) load • HPOA lb oxygen applied per lb BOD • HPOA reactor HRT • Primary effluent TSS • Dewatering centrifuge operating hours	• Raw influent oil & grease and TSS load • Primary ferric chloride concentration • Primary influent flow and BOD removal • HPOA oxygen purity and pressure, and BOD concentration • Digester temperature and influent solids load • Dewatering polymer dilution and flow • Centrate recycle load
Reverse Osmosis Specific Flux	Operations based parameter; specific flux is an indicator of membrane fouling	• HPOA reactor HRT • HPOA lb oxygen applied per lb BOD • Mixed liquor suspended solids (MLSS) SVI • Secondary clarifier HRT • Dewatering centrifuge dilute polymer flow • Dewatering centrifuge operating hours	• Raw influent flow, oil, and grease, and TSS concentration • Primary ferric chloride dose • Primary clarifier TSS removal • HPOA reactor solids retention time, MLSS, SVI, influent TSS load, organic loading rate, HPOA lb oxygen applied per lb BOD • Secondary clarifier solids loading rate, blanket depth, secondary effluent settled solids concentration • Biosolids production, dewatering solids loading rate
Reverse Osmosis Total Recovery	Operations based parameter; percentage of feed water converted into permeate or product water	• Primary effluent TSS • Secondary clarifier scum flow • HPOA reactor HRT • HPOA lb oxygen applied per lb BOD	• Primary clarifier TSS removal • WAS yield • Digester primary solids load and bypass flow • Dewatered centrate recycle flow

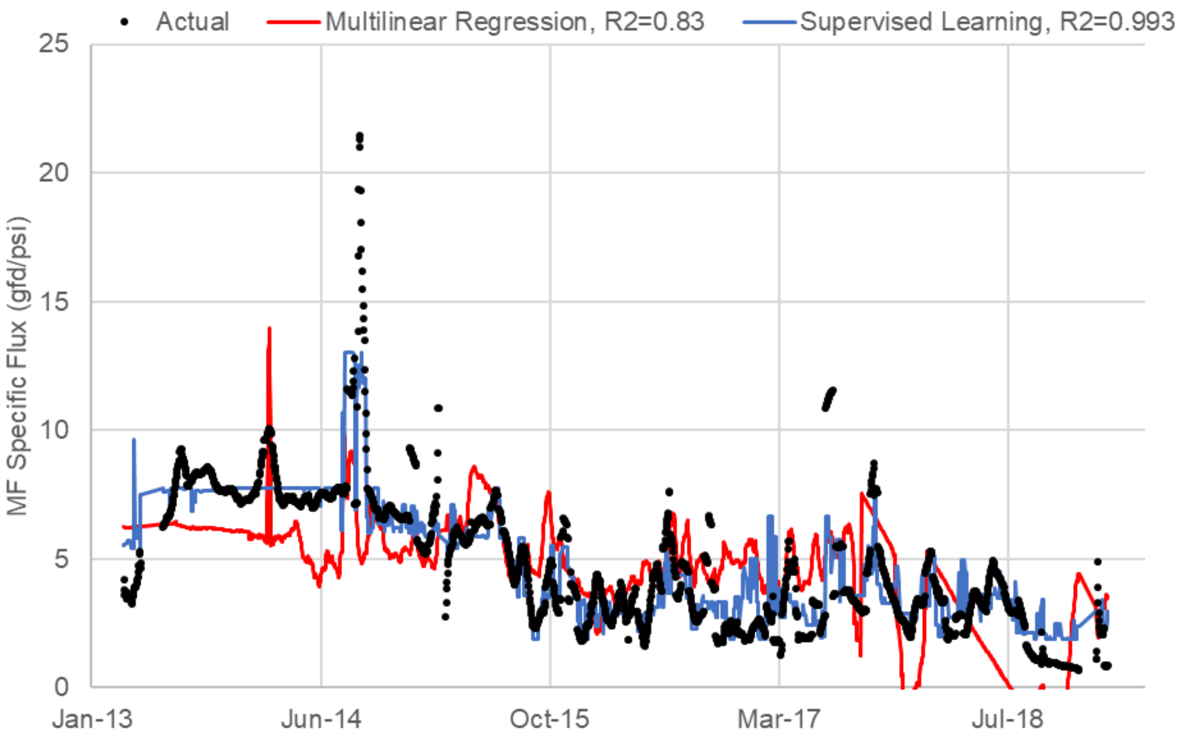


Figure 2-6. Utility No. 2 Microfiltration Specific Flux Monitored Data Compared to the Predictive Multilinear Regression Model and Supervised Learning Model.

2.3.3 Utility No. 3: Georgia, USA

2.3.3.1 Background

Utility No. 3, located in the Georgia, USA, began operation in March 2001 as a 20 mgd advanced water resource recovery facility. An upgrade and expansion to 60 mgd was completed in 2006. The advanced water treatment train is integrated within the whole plant, Figure 2-7 delineates the boundary between secondary treatment and advanced treatment.

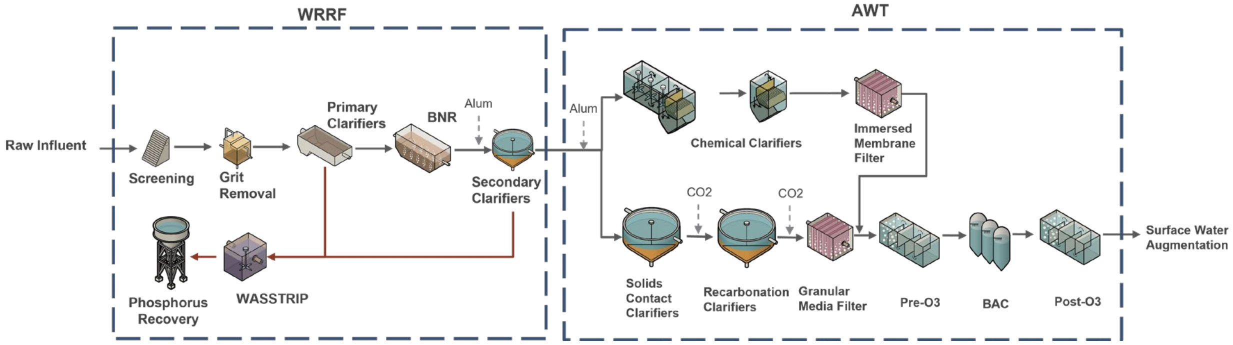


Figure 2-7. Utility No. 3 Process Flow Diagram of the Advanced Water Resource Reclamation Facility.

Existing unit processes at the plant include screening and grit removal, primary clarification, biological nutrient removal activated sludge basins, and secondary clarification. After secondary treatment, secondary effluent flow is split into two advanced treatment trains. The first treatment train is rated for 20 mgd and includes tertiary chemical clarification and granular media filtration (GMF). The second treatment train is rated for 40 mgd and includes chemical coagulation/flocculation/sedimentation and ultrafiltration membrane filtration. The effluent is combined and treated through pre-ozonation, GAC filtration, ozone disinfection, and tertiary effluent pumping.

Solids handling includes a primary sludge and waste activated sludge co-thickening rotary drum thickener (RDT) facility, followed by mesophilic anaerobic digestion, and dewatering of digested and chemical sludge using centrifuges. Existing facility also includes co-generation of sludge with fats, oil, and grease (FOG) and high strength waste (HSW), nutrient recovery, and cogeneration capabilities. Utility No. 3 is permitted to discharge 60 mgd for surface water augmentation. The monthly average surface water discharge limits are 18 mg/L COD, 3 mg/L TSS, 0.4 mg/L NH4-N, 0.08 mg/L TP, 2.0 number/100 mL fecal coliform, pH 6-9, minimum 7.0 mg/L dissolved oxygen (DO), and turbidity of 0.5 NTU

Three target advanced water treatment parameters were identified for evaluation in Utility No. 3. These parameters include:

- AWT effluent COD concentration
- AWT effluent fecal coliform concentration
- AWT effluent total phosphorus concentration

Table 2-4 summarizes the WRRF parameters that appear to influence the AWT target parameter based on the multilinear regression model and supervised learning model. The detailed model results, including model accuracy, are provided in Appendix A. Figure 2-8 is a plot of the measured AWT effluent COD and multilinear regression and supervised learning predictive models to demonstrate the accuracy of the predictive models.

Table 2-4. Utility No. 3 Model Comparison.

AWT Parameter	Basis of Selection	Parameters Suggested by Multilinear Regression	Parameters Suggested by Supervised Learning
AWT Effluent COD Concentration	Quality based parameter; permitted effluent limit of 18 mg/L (monthly average)	• Primary clarifier TP removal • Bioreactor dissolved oxygen (DO) • Secondary clarifier alum dose • Rotary drum thickener polymer dose	• Number of primary clarifiers in service • Primary solids flow • Primary clarifier surface overflow rate • Bioreactor daily yield • Number of bioreactors online • Secondary clarifier alum use • Secondary clarifiers solids loading rate
AWT Effluent Fecal Coliform	Quality based parameter; permitted effluent limit of 2 colony forming units (CFU)/100 mL (monthly average)	• Primary clarifier TP removal • Secondary clarifier effluent NH_4-N • Rotary drum thickener polymer dose	• Influent pH • Primary clarifier surface overflow rate and blanket depth • Number of bioreactors online • Bioreactor DO and MLSS • Secondary clarifier alum use and blanket depth • Dewatering centrifuge polymer dose and feed rate
AWT Effluent TP Concentration	Quality based parameter; permitted effluent limit of 0.08 mg/L (monthly average)	• Bioreactor DO • Secondary clarifier alum use • Dewatering centrifuge feed rate	• Raw influent alkalinity load • Number of primary clarifiers in service • Bioreactor MLSS • Secondary clarifier alum dose and surface overflow rate

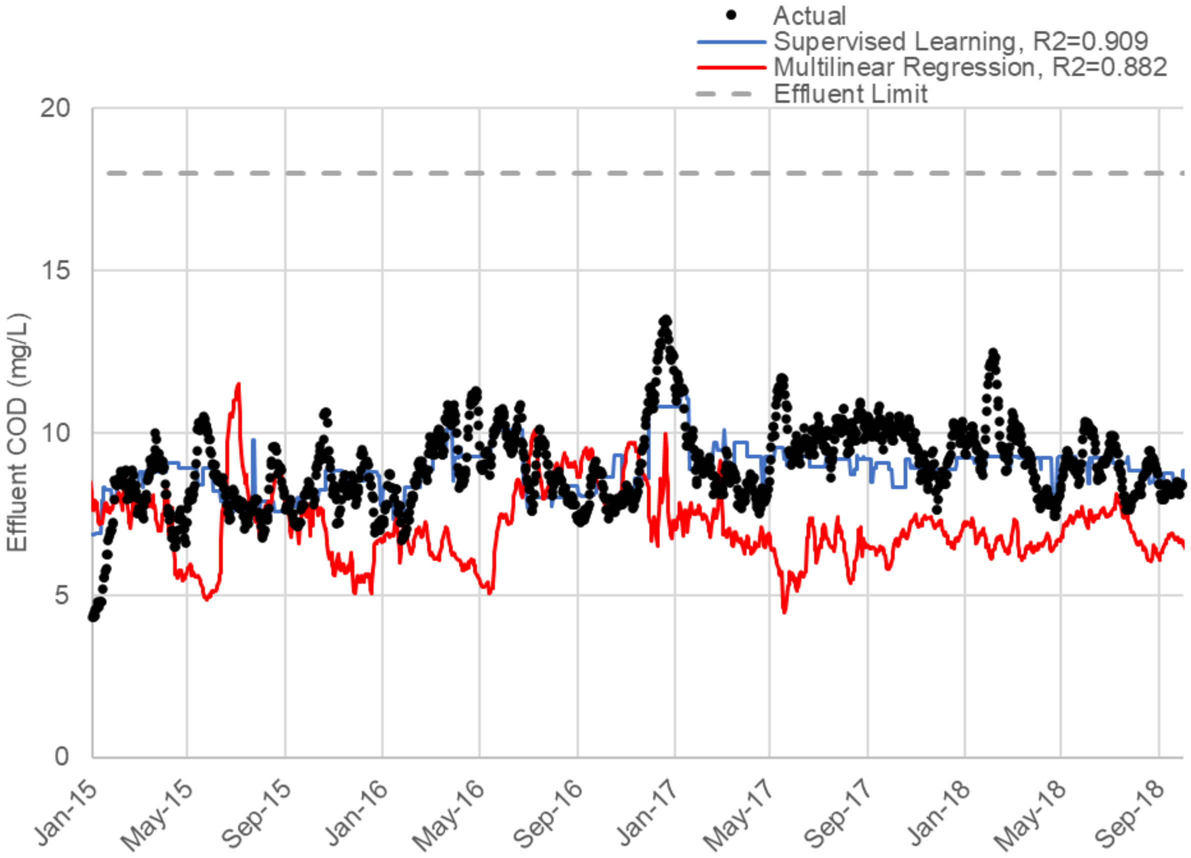


Figure 2-8. Utility No. 3 AWT Monitored Effluent COD Data Compared to the Predictive Multilinear Regression Model and Supervised Learning Model.

2.3.4 Utility No. 4: Virginia, USA

2.3.4.1 Background

Utility No. 4, located in Virginia, USA, is currently designed and permitted for an annual average treatment flow capacity of 11 mgd. This facility is a water resource reclamation facility with advanced treatment to comply with stringent effluent standards intended to protect human health and the environment and are reflective of the Utility No. 4's location relative to downstream drinking water.

Utility No. 4 utilizes a five-stage biological nutrient removal (BNR) membrane bioreactor (MBR) configuration, followed by GAC filters and ultraviolet (UV) disinfection. The advanced water treatment train is integrated within the whole plant, Figure 2-7 delineates the boundary between secondary treatment and advanced treatment.

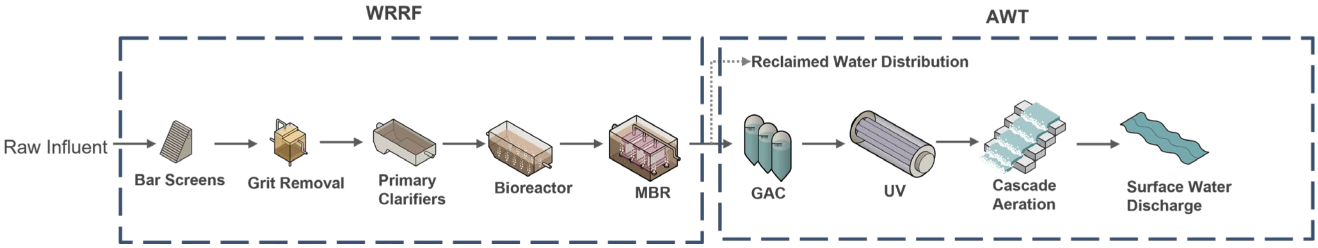


Figure 2-9. Utility No. 4 Process Flow Diagram of the Advanced Water Resource Reclamation Facility.

Utility No. 4 is subject to nutrient limits per the Chesapeake Bay total maximum daily load (TMDL) with a waste load allocation (WLA) of 134,005 pounds per year (lb/yr) for total nitrogen (TN) and 3,350 lb/yr for total phosphorous (TP). At the rated capacity of 10 mgd annual average flow, this equates to annual average concentration limits of 4.0 mg/L and 0.10 mg/L for TN and TP, respectively.

Two target advanced water treatment parameters were identified for evaluation in Utility No. 4. These parameters include:

- AWT effluent COD
- AWT effluent TN
- AWT effluent TP

Table 2-5 summarizes the WRRF parameters that appear to influence the AWT target parameter based on the multilinear regression model and supervised learning model. The detailed model results, including model accuracy, are provided in Appendix A. Figure 2-10 is a plot of the measured AWT effluent TN and multilinear regression and supervised learning predictive models to demonstrate the accuracy of the predictive models.

Table 2-5. Utility No. 4 Model Comparison.

AWT Parameter	Basis of Selection	Parameters Suggested by Multilinear Regression	Parameters Suggested by Supervised Learning
AWT Effluent TN	Quality based parameter; permitted effluent limit of 4 mg/L (monthly average)	• Primary molar alum to OP ratio • Dewatering polymer use • Digester gas production (standard cubic feet per pound [scf/lb] thermochemical sulfate reduction [TSR])	• Primary clarifier blanket depth, solids loading rate • Primary solids %TS, %VS • Thickened WAS %VS • Bioreactor DO • Dewatering polymer use • Digester VFA
AWT Effluent COD	Quality based parameter; permitted effluent limit of 10 mg/L (monthly average)	• Raw influent NOx • Equalization flow • Bioreactor oxidation reduction potential (ORP), DO, pH • Tertiary UVT/chemical oxygen demand (COD) ratio • Digester gas recovery	• Raw influent quality (e.g., sCOD, NOx) • Septage flow • Plant recycle NH3 • Primary sodium hypochlorite use • Primary solids flow • Bioreactor DO • Digester volatile fatty acids, (volatile solids) VS load, TS load) • Dewatered cake VS, centrate TS
AWT Effluent TP	Quality based parameter; permitted effluent limit of 0.1 mg/L (monthly average)	• Equalization flow • Septage flow • Raw influent NOx (mg/L) • Rainfall • Primary lb alum per lb OP	• Raw influent composition (e.g., TDS load, TP load) • Equalization flow • Septage flow • Primary clarifier alum use, surface overflow rate, blanket depth • MBR effluent OP and TP • RAS flow • Secondary alum use • Digester influent TS load • Digester gas production • Dewatered centrate TKN

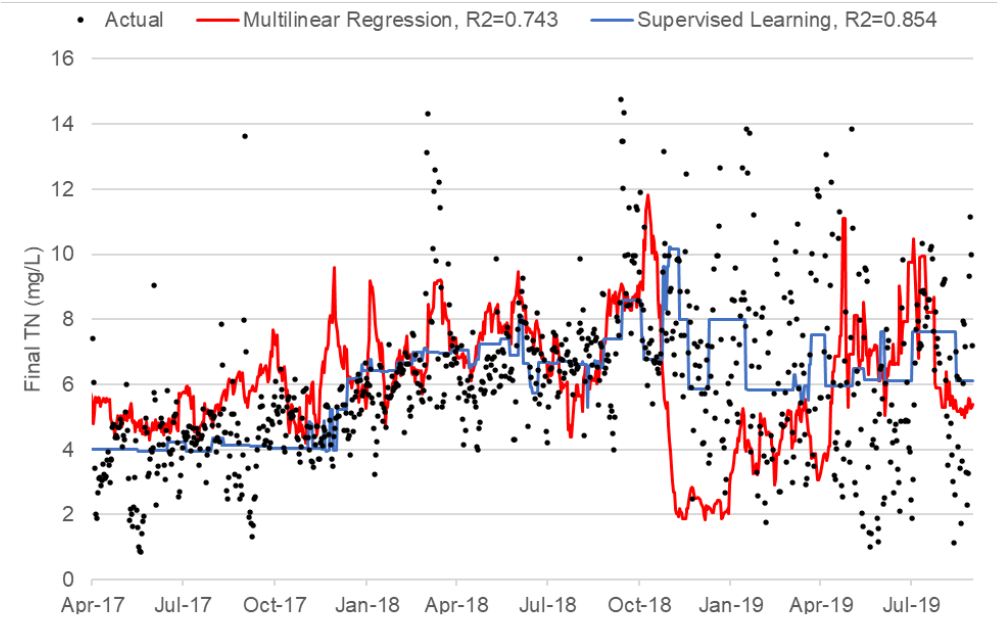


Figure 2-10. Utility No. 4 Monitored AWT Effluent TN Data Compared to the Predictive Multilinear Regression Model and Supervised Learning Model.

2.3.5 Utility No. 5: Arizona, USA

2.3.5.1 Background

Utility No. 5, located in Arizona, USA, as an average daily flow capacity of 20 mgd and includes preliminary treatment (screening), primary sedimentation, secondary treatment (aeration basins and secondary sedimentation), and tertiary filtration. Figure 2-11 is a process flow diagram of the WRRF.

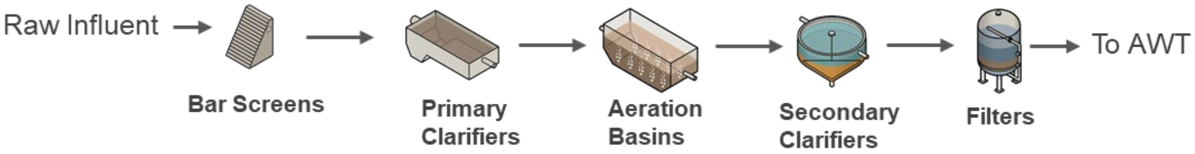


Figure 2-11. Utility No. 5 Process Flow Diagram of the Water Resource Reclamation Facility.

The AWT facility receives tertiary effluent from the WRRF and further treats it through ozonation, microfiltration, three-stage RO, and UV disinfection before aquifer recharge. Figure 2-12 is a process flow diagram of the AWT facility.

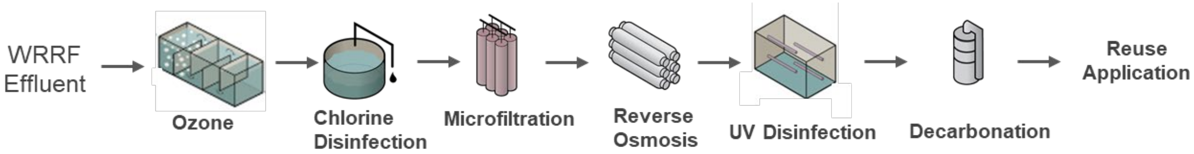


Figure 2-12. Utility No. 5 Process Flow Diagram of the Advanced Water Treatment Facility.

Two target advanced water treatment parameters were identified for evaluation in Utility No. 5. These parameters include:

- Microfiltration specific flux
- Reverse osmosis specific flux

Table 2-6 summarizes the WRRF parameters that appear to influence the AWT target parameter based on the multilinear regression model and supervised learning model. The detailed model results, including model accuracy, are provided in Appendix A. Figure 2-13 is a plot of the measured microfiltration specific flux, multilinear regression model, and supervised learning model to demonstrate the accuracy of the predictive models.

Table 2-6. Utility No. 5 Model Comparison.

AWT Parameter	Basis of Selection	Parameters Suggested by Multilinear Regression	Parameters Suggested by Supervised Learning
Microfiltration Specific Flux	Operations based parameter; specific flux is an indicator of membrane fouling	• Raw influent ammonia, COD, pH • Primary % TSS removal • Secondary solids retention time, sludge volume index, WAS flow • Secondary clarifier blanket depth, effluent TSS	• Influent COD, flow • Primary % COD removal, effluent orthophosphate • Secondary % TN removal, scum flow, was flow, effluent alkalinity, COD, ammonia, nitrate, TDS, turbidity • Total % COD removal, % TSS removal
Reverse Osmosis Specific Flux	Operations based parameter; specific flux is an indicator of membrane fouling	• Raw influent ammonia, COD, TSS, pH • Primary % TSS removal • Secondary solids retention time, SVI, WAS flow, % TN removal, sludge volume index, effluent TSS	• Influent TSS, flow, COD • Primary effluent orthophosphate, TSS, ammonia, COD • Secondary scum flow, WAS flow, F/M ratio, MLSS, solids retention time, sludge volume index, effluent COD, ammonia, orthophosphate, pH • Total % COD removal

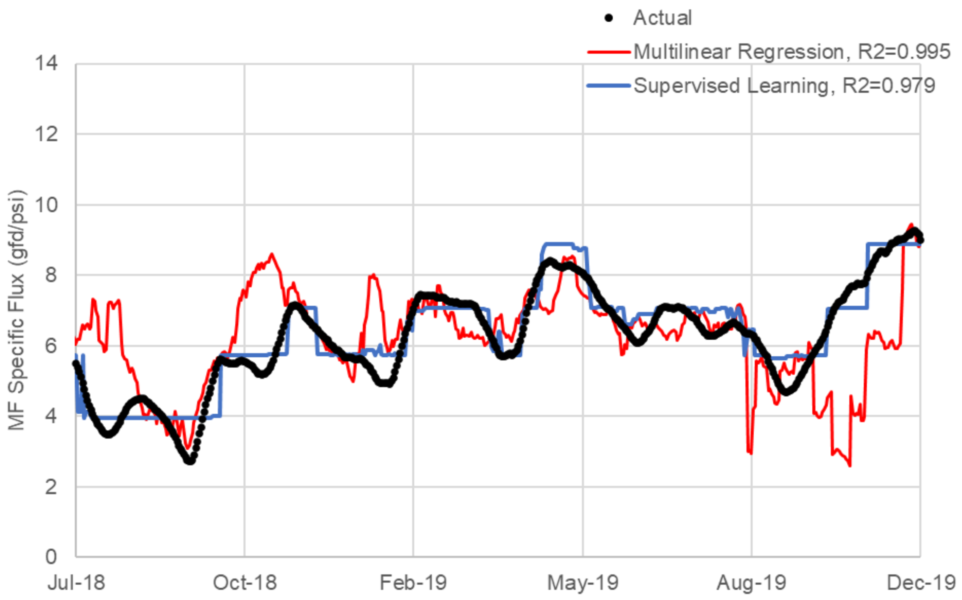


Figure 2-13. Utility No. 5 Microfiltration Specific Flux Compared to the Predictive Multilinear Regression Model and Supervised Learning Model.

2.3.6 Utility Commonalities and Insights

The utilities were cross compared to identify common WRRF parameters on AWT performance. This comparison was limited to utilities with similar AWT configurations and target parameters. Table 2-7 summarizes some of the commonalities observed across the utilities.

Table 2-7. Commonalities Across Utilities on AWT Performance.

AWT Interface Parameter	WRRF Parameters	Reference Utilities
GAC Effluent TKN	• Primary clarifier SOR, number in service • Digester HRT	Utility No. 1 Utility No. 4
GAC Effluent TP	• Primary clarifier SOR, number in service • Secondary clarifier alum use	Utility No. 3 Utility No. 4
GAC Effluent COD	• Primary solids flow • Bioreactor DO	Utility No. 3 Utility No. 4
MF Specific Flux	• Influent composition (e.g., COD, oil & grease) • Primary clarifier removal performance and operation (e.g., TSS removal, COD removal, orthophosphate removal, ferric dose) • Secondary clarifier blanket depth, operating performance • SVI	Utility No. 2 Utility No. 5
RO Specific Flux	• Raw influent composition (e.g., COD, TSS, oil & grease) • Primary clarifier removal performance and operation (e.g., TSS removal, COD removal, orthophosphate removal, ferric dose) • SRT, SVI, secondary clarifier blanket depth, effluent TSS	Utility No. 2 Utility No. 5

Several key takeaways as a result of this work:

- Utilizing time lag data helps increase the data richness and to identify trends across utilities. However, it is necessary to have a high enough frequency of sampling to generate meaningful time lags. Furthermore, it is possible that other WRRF parameters that exhibit impact on AWT performance were not identified due to a lack of data.
- This work analyzed large historical datasets for multiple utilities, with hundreds of monitored parameters. The results of this study provide a preliminary understanding of the interrelationship among WRRF parameters and key AWT performance. The analytical approaches used in this module identified several key parameters that appear to have an impact on AWT performance, and which to focus future efforts on to better understand. While some of the identified parameters may intuitively make sense (e.g., influent oil and grease impacts MF/RO specific flux), additional work is necessary to understand whether the other identified parameters have a direct or indirect impact on AWT performance.
- Several WRRF parameters that may be controlled by operations appear to have an influence on AWT performance (e.g., surface overflow rate, number of units in service, solids retention time, bioreactor DO). A sensitivity analysis should be performed to better elucidate the effect modifying these parameters may have on AWT performance, and to understand the cost/benefit of these modifications.
- The results of the multilinear regression models and supervised learning models do not specifically conclude whether the WRRF parameters identified have a causative effect. Rather, this work identified potential WRRF parameters that may influence AWT performance, either directly or indirectly. Additional work is needed to further understand the explanatory and mechanistic nature of these relationships.

CHAPTER 3

Module B: WRRF Effluent Impact on CBAT

3.1 Introduction

Conventional wastewater treatment processes are pretreatment processes for downstream ozone, BAF, and GAC-based AWT, or CBAT (Figure 3-1). The effluent quality from various wastewater treatment processes and how they are operated could impact the level of treatment needed within CBAT to produce water that is protective of public health and meets regulatory requirements. Furthermore, the water quality resulting from conventional wastewater treatment could impact the process selection and design, performance, maintenance, and economics of the downstream CBAT train. This chapter will address the following two challenges for the application of CBAT:

- What are the pass-through constituents for these systems that can potentially impact product water quality?
- What are potential interfering constituents that impact process operation and performance?

A pass-through constituent is defined as a constituent that was originally present in the wastewater effluent or is formed during CBAT and is still present at a level of human health concern in the product water of the AWT. An interfering constituent is defined as a constituent that is present in the wastewater effluent that interferes with the operation and optimal performance of ozonation, BAF and/or GAC treatment.

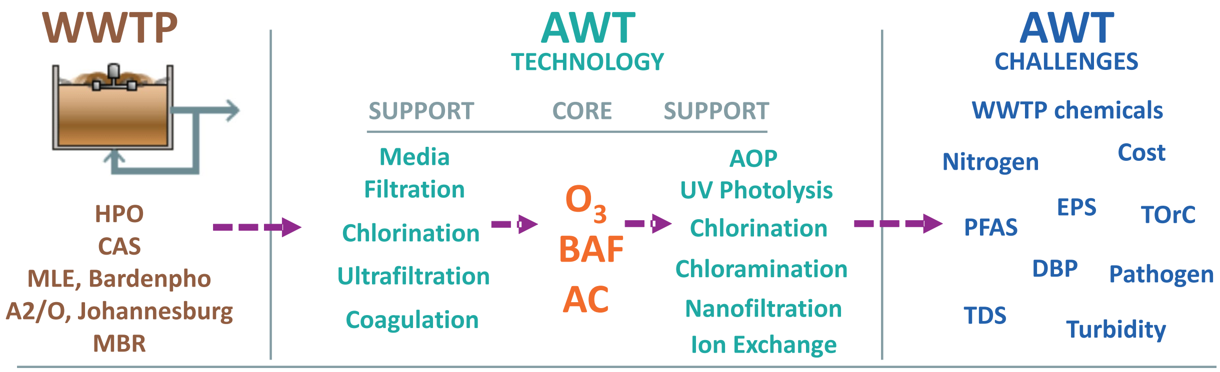
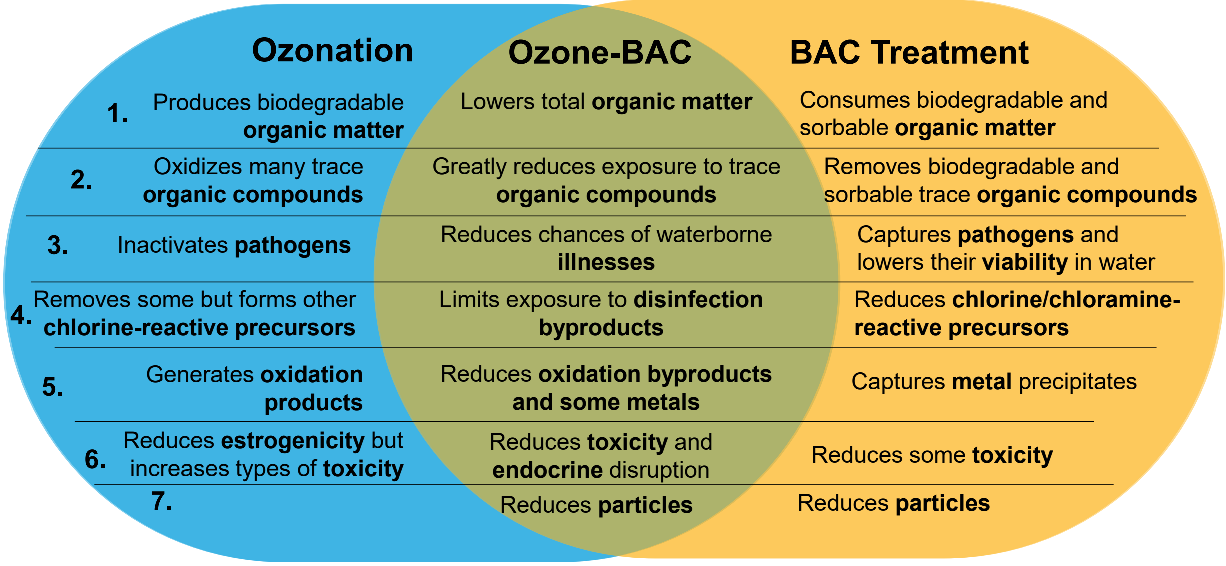


Figure 3-1. Conceptual Relationship Between Conventional Wastewater Treatment and CBAT.

3.2 Background

3.2.1 Ozone-BAC

Ozone with biological activated carbon (BAC) works synergistically to target multiple water quality concerns in potable reuse (Figure 3-2). Ozone is a powerful oxidant and by itself, ozone inactivates pathogens, increases the biodegradable organic matter (BOM) fraction, oxidizes inorganic compounds (i.e., iron/manganese), and removes some chlorine/chloramine-reactive disinfection byproduct (DBP) precursors. Ozone can also oxidize constituents of emerging concern (CECs), such as pharmaceuticals and personal care products (PPCPs) and steroid hormones, and thus reduce estrogenicity. Biological activity in BAC occurs when a disinfectant does not pass through a media filter, allowing microorganisms to proliferate and grow attached biomass on the media. BAC treatment can remove particles, metal precipitates, and pathogens via filtration. BAC can also biologically degrade organic matter (OM), such as biodegradable organic matter (BOM) and organic DBP precursors, ozone byproducts, and CECs. When applied synergistically, ozone and BAC can remove various classes of contaminants.



	Ozonation	Ozone-BAC	BAC Treatment
1.	Produces biodegradable **organic matter**	Lowers total **organic matter**	Consumes biodegradable and sorbable **organic matter**
2.	Oxidizes many trace **organic compounds**	Greatly reduces exposure to trace **organic compounds**	Removes biodegradable and sorbable trace **organic compounds**
3.	Inactivates **pathogens**	Reduces chances of waterborne **illnesses**	Captures **pathogens** and lowers their **viability** in water
4.	Removes some but forms other **chlorine-reactive precursors**	Limits exposure to **disinfection byproducts**	Reduces **chlorine/chloramine-reactive precursors**
5.	Generates **oxidation products**	Reduces **oxidation byproducts and some metals**	Captures **metal** precipitates
6.	Reduces **estrogenicity** but increases types of **toxicity**	Reduces **toxicity** and **endocrine** disruption	Reduces some **toxicity**
7.		Reduces **particles**	Reduces **particles**

Figure 3-2. Benefits of Ozonation/BAC-Based Treatment Systems.

Ozone-BAC relies primarily on three major removal mechanisms: 1) oxidation via the ozone process, 2) biotransformation, and 3) sorption/desorption to biofilm and/or media in BAC treatment (Figure 3-3). Ozone is selectively reactive with electron-rich moieties, such as phenols, anilines, olefins, reduced sulfur, and amine moieties (Lee et al., 2013). Therefore, ozone can oxidize various classes of CECs. CECs with an ozone second-order rate constant greater than 1×10^4 $M^{-1}s^{-1}$ can be effectively oxidized by molecular ozone at typical applied ozone doses (Dickenson et al., 2009; Gerrity et al., 2012; Hollender et al., 2009; Lee et al., 2013; Park et al., 2017). In addition to molecular ozone, secondary oxidants, such as hydroxyl radicals, are produced via chain reactions, which further contributes to the oxidation of CECs in waters (Staehelin and Hoigne, 1985). Ozone can work synergistically with biotransformation in BAC to transform CECs. For instance, phenol can be transformed into muconic acid and 2-hydroxymuconic semialdehyde that are further biotransformed through the Krebs cycle (Park et al., 2020a)

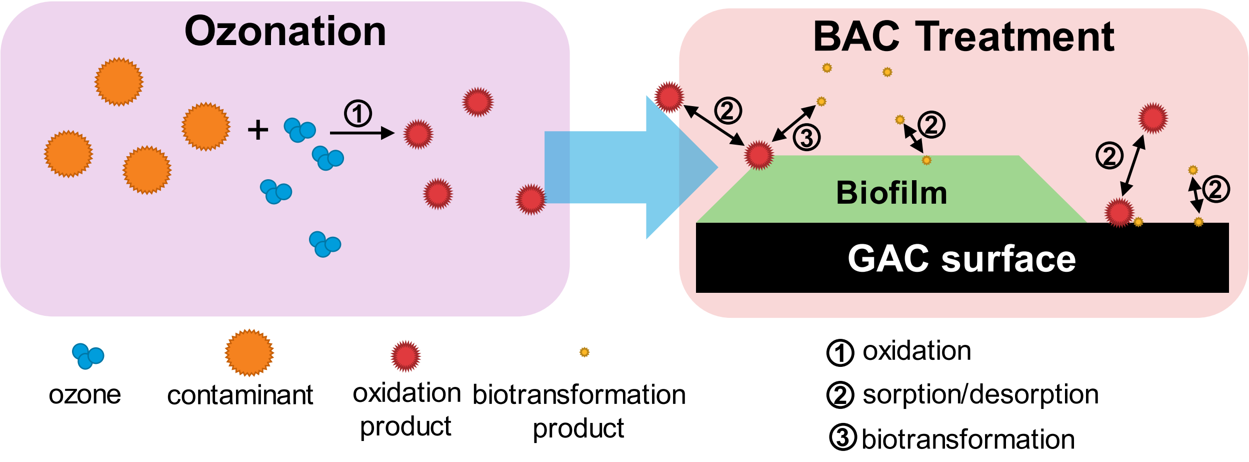


Figure 3-3. General Depiction of Ozone-BAC Treatment.

To have a biologically active filter, media such as granular activated carbon, sand, and anthracite, can be used to form attached biomass that can biotransform organic constituents. These constituents can be adsorbed by adsorptive media, such as GAC, until the exhaustion of adsorption capacity. In addition, surfaces of biofilm are also available for the adsorption of contaminants. Understanding the adsorption mechanisms in biofiltration may play a role in designing and optimizing ozone-BAF or ozone-BAC systems.

3.2.2 CBAT Configurations

In general, two configurations of CBAT have been considered and implemented: a) ozone followed by BAC (O_3-BAC) and b) ozone, biologically active filtration (BAF), followed by GAC treatment (O_3-BAF-GAC) (Figure 3-4). Here BAF can occur with inert media, such as anthracite, or with activated carbon with no regular changeouts and typically exhausted toward total organic carbon (TOC) adsorption. Both of these configurations rely on the three major removal mechanisms discussed in the section above: oxidation during ozonation, biotransformation during biofiltration, and adsorption onto adsorptive media. In configuration a) biotransformation and adsorption occur within the same BAC process and requires management of activated carbon changeouts without compromising biotransformation function. In configuration b) biotransformation and adsorption occur in separate processes. Separate operations can be deemed advantageous as biofiltration and adsorption processes can be isolated and thus be optimized per function. For example, ozone followed by biofiltration can expand the life span of post GAC treatment (Summers et al., 2020).

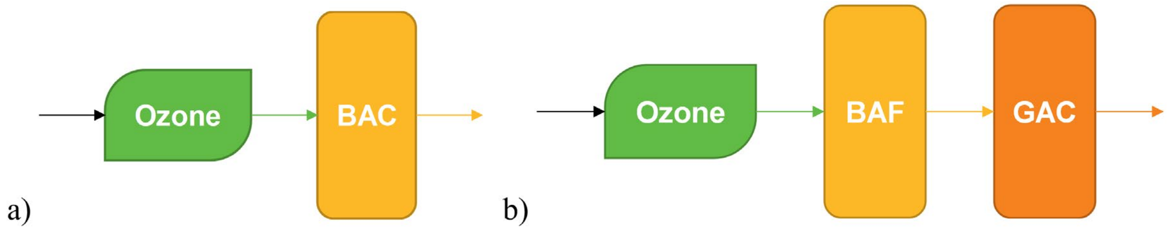


Figure 3-4. CBAT Configurations: a) Ozone Followed by BAC and b) Ozone in Series with BAF Followed by GAC.

3.2.3 Treatable Organic Constituents

As discussed, CBAT is an effective synergistic approach in reducing organic matter, and thus organic carbon concentrations, and has the potential to remove a variety of CECs and chlorine- or chloramine-reactive DBP precursors (Table 3-1). TOC is an important surrogate for bulk organic matter in potable reuse. For CBAT systems, TOC removal has been shown to correlate with CEC and DBP precursor removals (Schimmoller et al., 2020). Perhaps, and even more importantly, an increase in TOC breakthrough could indicate process failure, process exhaustion, or simultaneous breakthrough of a recalcitrant industrial contaminant (Marron, et al. 2019). To date, regulations addressing the organic content of purified water from potable reuse projects vary, with the U.S. Environmental Protection Agency (USEPA) recommending a TOC target of 2 mg/L for indirect potable reuse (IPR); and Florida requiring TOC limit of 3.0 mg/L for groundwater recharge (USEPA 2012, 2017). A recent study developed a framework for controlling organics in direct potable reuse (DPR) projects that do not incorporate RO because of the higher expected TOC concentrations (Schimmoller et al., 2020). They proposed comparing the TOC of the purified water from the AWT system with that of the local drinking water TOC. This was also recommended recently in guidelines for DPR in the state of Colorado (NWRI, 2019).

Ozone has a high oxidation potential, but it is not strong enough to mineralize organic carbon, therefore having relatively low TOC removal potential (< 10 percent at 0.5 mg O_3/mg TOC). However, downstream biofiltration can remove TOC partially, more so with ozone preceding, and GAC treatment can remove

TOC more effectively. Ozonation increases the biodegradable portion of organic carbon where changes in organic matter are observed, such as decrease in molecular weight and increase in the number of oxygenated functional groups (Terry and Summers, 2018). A recent comprehensive review evaluated TOC removal by biofiltration of wastewater effluents and higher TOC removal via biodegradation was achieved with pre-ozonation (O_3: TOC mass ratio > 0.6 mg/mg) at empty bed contact time (EBCT) greater than 8 minutes and the use of BAC (> 20,000 bed volumes [BVs]; lower adsorption influence); however only smaller impacts of increasing ozone dose were observed (**Figure 3-5**) (Peterson and Summers, 2021). Along with GAC treatment, good overall TOC removal can be achieved by CBAT, where such AWT systems can meet some of the treatment goals for TOC discussed above.

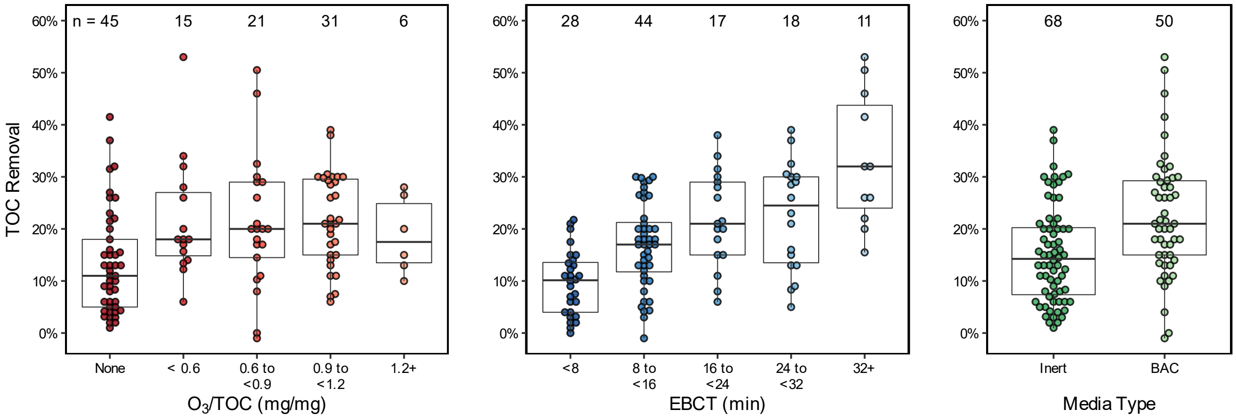


Figure 3-5. Distributions of TOC Removal Across Biofilter Operating Parameters.
Bins correspond to the pre-processing method (i.e., each source water is shown a maximum of once per bin). Each data point is shown once per panel (n = 118).
Source: Peterson and Summers (2021).

Summers et al. (2020) demonstrated CBAT can be used for nitrified wastewater effluent to control the formation of chlorinated DBPs (trihalomethanes [THMs] and haloacetic acids [HAAs]), where TOC can be used as a DBP precursor surrogate (Figure 3-6). They concluded a TOC target of 2 mg/L in treated effluents, which is in line with USEPA's recommended TOC limit for IPR and the recommendation proposed by Arnold et al. (2018).

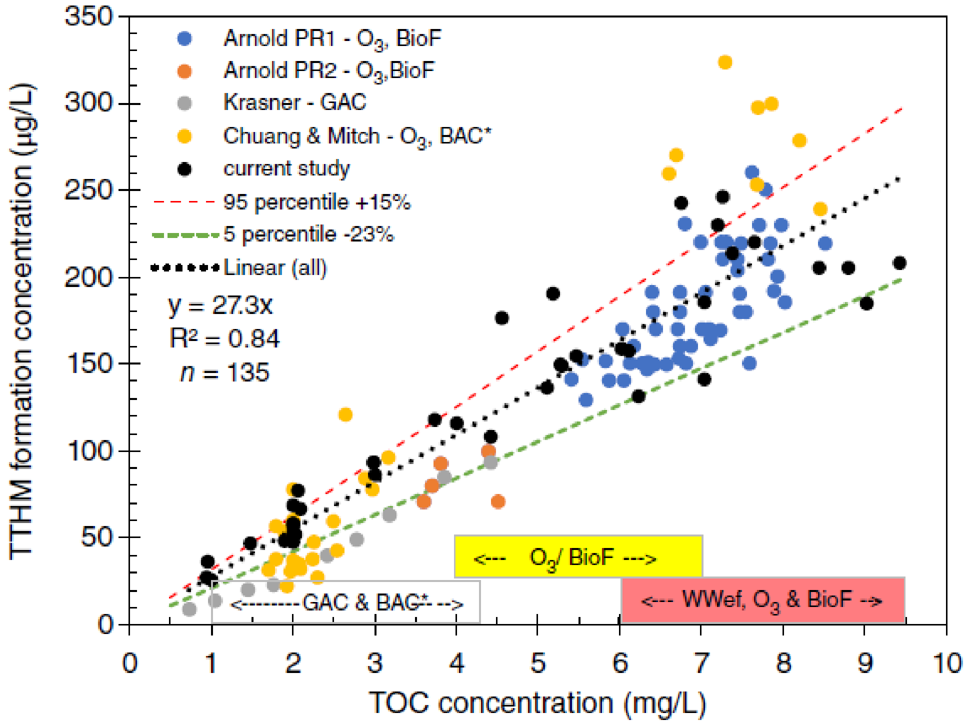


Figure 3-6. Total THM (TTHM) Formation Under Uniform Formation Conditions as a Function of TOC Concentration for Nine Secondary Wastewater Effluents.

Source: Summers et al. 2020.

Ozone can oxidize certain classes of CECs into lesser toxic products. Table 3-1 includes CECs with moderate or low reactivities with molecular ozone (i.e., the second-order rate constants, k, are below 100 $M^{-1}s^{-1}$). Compounds with k greater than 100 $M^{-1}s^{-1}$, including carbamazepine, diclofenac, diltiazem, propranolol, sulfamethoxazole, triclosan, and trimethoprim, were ruled out in Table 3-1 since their excellent removals are explicit. A recent review of ozone-biofiltration systems in reuse applications noted that CECs with high ozone reaction rates ($k_{O3} > 103$ $M^{-1}s^{-1}$) were removed well by ozonation (Sari et al., 2020). However, the degree of removal of these compounds may still be dependent on the initial concentration; O_3: TOC mass ratio; and the presence of scavengers, such as nitrite, carbonates, and ammonia. At ozone doses > 0.6 mg O_3/mg TOC in wastewater effluent, hydroxyl radicals can be produced and, thus, good removals of ozone-recalcitrant compounds, such as acesulfame, benzotriazole, N, N-diethyl-meta-toluamide (DEET), iopamidol, and primidone, can be expected (Thompson and Dickenson, 2020).

In addition to CECs, some organic DBP precursors that are reactive with chlorine or chloramine, such as those for N-nitrosodimethylamine (NDMA), THMs, and HAAs, can be attenuated by ozonation (Plummer and Edzwald, 2001). Although ozone can produce NDMA as an ozone byproduct in potable reuse, ozone reduces the overall NDMA formation potential if chloramines are used as a post disinfectant (Krasner et al., 2018).

Table 3-1. List of Classes of Constituents Potentially Treatable by CBAT.

Constituent	Description	Example	Concern	Removal			
				Ozone	Biofiltration	GAC	Overall
TOC	Purified water TOC ≤ Drinking Water TOC		DBP Precursors CEC Surrogate	Poor	Partial	Good	Target TOC Achieved
CEC	Oxidizable & Adsorptive	Primidone benzotriazole DEET	CEC Indicator [a]	Good	Partial	Good	Good
CEC	Oxidizable	Iopromide acesulfame iopamidol	CEC Indicator [a]	Good	Poor	Partial	Good
CEC	Partially-Oxidizable & Adsorptive	Meprobamate sucralose	CEC Indicator [a]	Partial	Partial	Good	Good
CEC	Adsorptive	TCEP	CEC Indicator [a]	Poor	Partial	Good	Good
Long-chain PFAS	Adsorptive	PFOA, PFOS	HAL [b] of 0.004 ng/L for PFOA and 0.02 ng/L PFOS	Poor	Poor	Good	< HAL
1,4-Dioxane	Oxidizable		CA-NL [c] of 1 µg/L	Partial	Poor	Poor	< CA NL
NDMA	Formed during ozonation Biodegradable		CA-NL of 10 ng/L	Poor	Good	Poor	< CA NL
NDMA Precursor	Chloramine-reactive precursor		CA-NL of 10 ng/L	Good	Partial [d]	Good	< CA NL
TTHM Precursor	Chlorine-reactive precursor		MCL [e] of 80 µg/L	Partial	Partial	Partial [f]	< MCL
HAA5 Precursor	Chlorine-reactive precursor		MCL of 60 µg/L	Partial	Partial	Partial [f]	< MCL
Other DBP Precursors	Chlorine or chloramine-reactive precursors	HNM, HK, HAN, HAM, HAL	Potential Health Concern	Partial	Partial	Good	Good

a. >75 percent: good removal, 25 percent-75 percent: partial removal, <25 percent: poor removal

b. U.S. EPA interim health advisory levels issued on June 15, 2022.

c. California notification level

d. NDMA formation has been reported (Li et al. 2017)

e. U.S. EPA maximum contaminant level

f. It is also important to note that GAC adsorption is an unsteady stead process, with high DBP precursor removal (i.e., >75%) at the beginning of service and partial removal (i.e., 25-75%) depending on GAC run time.

GAC treatment can effectively adsorb various CECs and chlorine- and chloramine-reactive DBP precursors. For example, GAC is effective towards CECs, such as meprobamate and sucralose, and long-chain per- and polyfluoroalkyl substances (PFAS) that are not effectively or partially removed during preceding ozone and BAF or BAC processes. However, GAC treatment is less effective for smaller, hydrophilic compounds, such as 1,4-dioxane and NDMA. However, upstream ozone and biofiltration can be potentially effective towards these specific compounds, where 1,4-dioxane can be partially attenuated during the ozone process via hydroxyl radical oxidation, while NDMA can be biotransformed during biofiltration (Table 3-1) (Sari et al. 2020).

3.2.4 Effluent Water Quality of Wastewater Treatment Processes

The influent water quality, such as turbidity, TOC, and inorganic nutrients, to a CBAT train can potentially impact process selection, operation, and performance. This influent water quality to the AWT system is reliant on the preceding raw wastewater quality, wastewater treatment type/configuration and its operation. The influent water quality to the AWT can change at a specific site due to diurnal, seasonal or episodic variability in the raw wastewater coming into the WRRF. Also, water quality changes could result in variable secondary treatment performance across seasons or due to an upset. The wastewater treatment type and configuration can also impact the effluent water quality.

A variety of secondary treatment processes are used in practice, but they can be generally categorized into four types. There are secondary activated-sludge treatment processes that: 1) just target biological oxygen demand (BOD) removal (e.g., high-rate aeration, high purity oxygen); 2) target both BOD and ammonia removals via nitrification (e.g., complete mix or conventional plug flow aerobic systems); 3) target nitrogen removal via nitrification/denitrification (e.g., Modified Ludzack-Ettinger [MLE], Bardenpho); or 4) target nitrogen and phosphorus removal via biological nutrient removal (e.g., A2/O, modified Bardenpho, Johannesburg). While some implications of nitrification/denitrification processes on broad effluent water quality parameters are apparent, such as reduced levels of turbidity, organic carbon, and nutrients (Table 3-2), others are less understood, such as removal of CECs and DBP precursors.

Table 3-2. Typical Range of Effluent Quality After Secondary or Tertiary-Filtration.

Source: (Asano et al. 2007, Metcalf et al. 1991).

Treatment Process	Turbidity	TOC[a]	VOCs	NH_3	Nitrate	Nitrite	P	CECs (ng/L)
	NTU	mg/L	ug/L	mg N/L	mg N/L	mg N/L	mg P/L	
Without Tertiary Filtration								
Activated sludge (BOD removal only)	<20	<30	10-40	15-25	0-trace	0-trace	4-10	***only highly biodegradable CEC*** >80% removal for caffeine, acetaminophen
Activated sludge/ nitrification	5-15	4-13	10-40	1-5	10-30	0-trace	4-10	***only highly and high biodegradable CEC*** >80% removal for naproxen, ibuprofen
Activated sludge/ nitrification-denitrification	5-15	4-9	10-20	1-2	<10	0-trace	4-10	***only highly, high and moderate biodegradable CEC*** >80% removal for DEET, gemfibrozil
Activated sludge/biological nitrogen and phosphorus removal	2-8	4-12	10-20	1-3	<10	0-trace	≤2	***only highly, high and moderate biodegradable CEC*** >80% removal for DEET, gemfibrozil
Without Tertiary Filtration								
Activated sludge (BOD Removal only) + granular media filtration	0.5-5	8-30	10-40	15-25	0-trace	0-trace	4-10	***only highly biodegradable CEC*** >80% removal for caffeine, acetaminophen
Activated sludge/ nitrification + granular media filtration	0.3-2	4-15	10-40	1-2	10-30	0-trace	≤1[b]-10	***only highly and high biodegradable CEC*** >80% removal for naproxen, ibuprofen
Activated sludge/ nitrification-denitrification + granular media filtration	0.3-2	4-8	10-20	1-2	<10	0-trace	≤1[b]-10	***only highly, high and moderate biodegradable CEC*** >80% removal for DEET, gemfibrozil
Activated sludge/biological nitrogen and phosphorus removal	0.3-2	4-8	10-20	≤2	<10	0-trace	≤1[b]-2	***only highly, high and moderate biodegradable CEC*** >80% removal for DEET, gemfibrozil

Treatment Process	Turbidity	TOC[a]	VOCs	NH_3	Nitrate	Nitrite	P	CECs (ng/L)
	NTU	mg/L	ug/L	mg N/L	mg N/L	mg N/L	mg P/L	
+ granular media filtration								
Membrane bioreactor/ nitrification-denitrification	≤1	1-8	10-20	<1-5	<10	0-trace	≤1[b]-10	***only highly, high and moderate biodegradable CEC*** >80% removal for DEET, gemfibrozil

a. TOC value was converted from COD (COD=7.25+2.99*TOC) (Dubber and Gray 2010)

b. with coagulant addition

Typically, shorter solids retention time (SRT) during activated sludge processes predominantly target BOD removal (SRT = 0.5-4 days), while longer SRTs are applied for nitrification (SRT = 3-15 days) and even longer for nitrification/denitrification (7-20 days) and biological-phosphorus-removal processes (SRT = 10-25 days). Generally, the organic carbon concentrations decrease in the secondary effluent with increasing SRT. Subsequent granular media filtration can further decrease organic carbon concentrations via biodegradation.

A number of studies have demonstrated the benefits of enhanced secondary biological treatment on effluent water quality and performance of downstream AWT processes. In particular, longer SRTs achieve lower concentrations of bulk organic matter and CECs, specifically those susceptible to biotransformation and/or adsorption (Achermann et al., 2018; Gerrity et al., 2013a). Building on this concept, Salveson et al. (2012) identified "threshold SRTs" achieving 80 percent CEC attenuation—as short as 2 days for susceptible compounds (e.g., acetaminophen, caffeine, ibuprofen, and naproxen) but up to 30 days for more recalcitrant compounds (e.g., trimethoprim). Despite observing similar water quality benefits, Gerrity and Neyestani (2019) found that longer SRTs are also associated with increased levels of antibiotic resistance (AR), although it is unclear whether this increased AR has any implications for public health. These relationships are summarized in Figure 3-7.

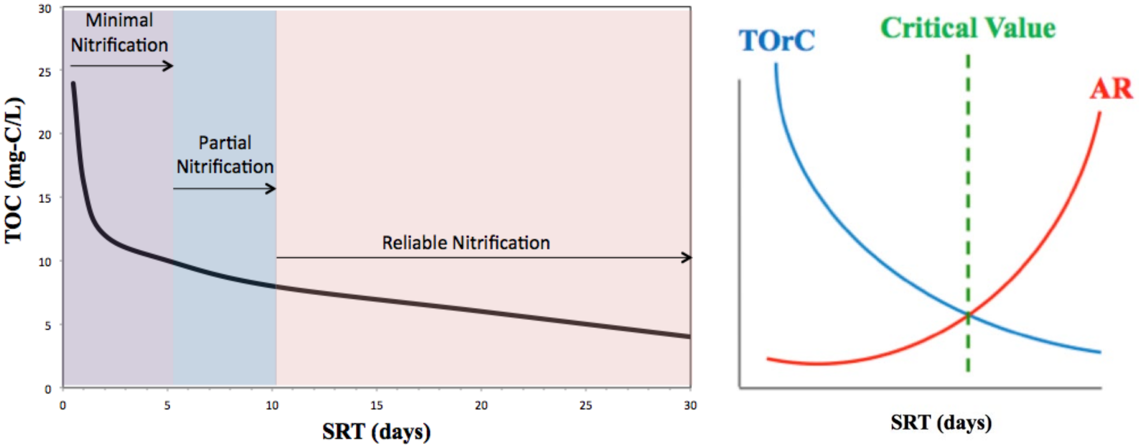


Figure 3-7. Conceptual Relationships Between SRT and Secondary Effluent TOC (Left) and Trace Organic Contaminant Concentration and Antibiotic Resistance (Right).

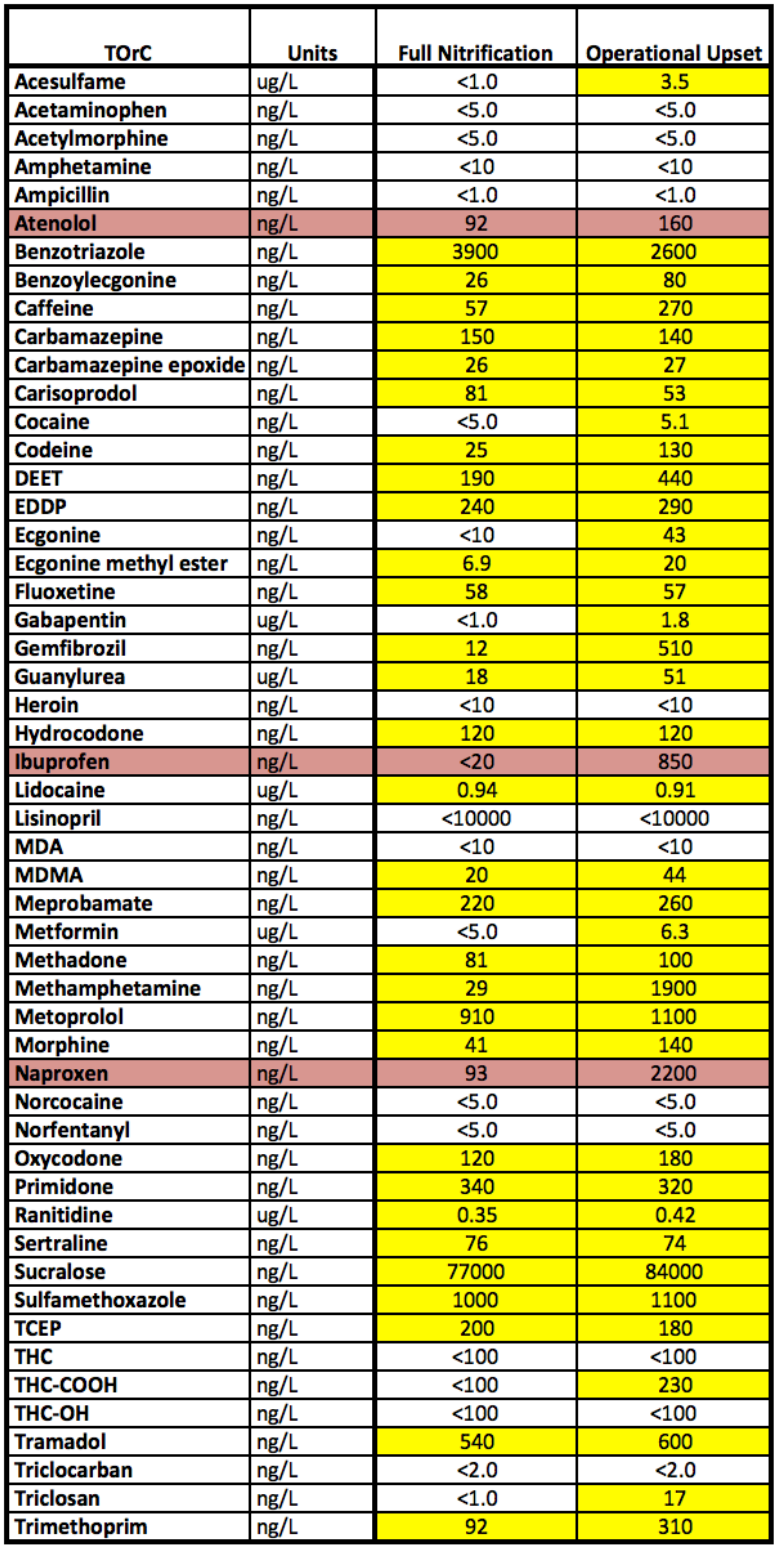
Short SRTs and low temperatures (e.g., <10 °C) (Gerrity and Neyestani, 2019) also impact nitrogen cycling and effluent water quality by inhibiting nitrification. From an operational perspective, non-nitrified secondary effluents have been linked to significant organic membrane fouling in potable reuse applications. Pre-ozonation has been successful in mitigating organic membrane fouling in bench-scale (Stanford et al., 2011) and full-scale applications (e.g., West Basin Municipal Water District), but pre-ozonation has also resulted in the formation of >100 ng/L of NDMA as byproduct in some non-nitrified secondary effluents (Gerrity et al., 2015). Significant ozone-induced NDMA formation has also been observed in fully nitrified systems (Gerrity et al., 2014), although this appears to be rare and likely linked to specific precursors that could potentially be addressed with enhanced source control. In potable reuse systems, these upstream treatment scenarios can have significant implications for the design and operation of downstream processes. For example, ozonation of a non-nitrified secondary effluent may require extensive UV photolysis to adequately attenuate high NDMA concentrations. Again, SRT optimization may be beneficial considering that biological treatment can reduce ambient concentrations of NDMA, and longer SRTs have been shown to reduce ozone-induced NDMA formation by up to 70 percent (Gerrity et al., 2015).

Table 3-3 provides another example of the relationship between the extent of biological treatment, specifically nitrification, and secondary effluent CEC concentrations. These samples were collected at a single wastewater treatment facility in Southern Nevada, with the first sample reflecting normal operational conditions achieving full nitrification, and the second sample reflecting an unexpected operational upset without nitrification. Consistent with the preceding discussion, common indicators of biological wastewater treatment (e.g., atenolol, ibuprofen, and naproxen) were observed at significantly higher concentrations during the operational upset—concentrations similar to those of a non-nitrified secondary effluent.

Although not shown here, other water quality parameters, notably ammonia and TOC, were also consistent with a non-nitrified secondary effluent during the operational upset. Beyond the direct effects on general water quality and CEC concentrations, operational upsets would also have indirect effects on effluent water quality and regulatory compliance due to reduced ozone efficacy (i.e., increase in TOC = lower O_3: TOC mass ratio) and reduced chlorine efficacy (i.e., increase in ammonia = lower free chlorine concentration × time, or CT), among other examples. These issues can potentially be mitigated with online monitoring of critical parameters, including TOC, nitrite, and ammonia, to detect and respond to changes in effluent quality that can impact operation and performance of AWT processes. For example, ozone dosing could be directly linked to secondary/tertiary effluent TOC and nitrite concentrations, with validation of process performance achieved with differential UV absorbance at 254 nm.

Table 3-3. Direct Comparison of Secondary Effluent CEC Concentrations During Normal Operation (i.e., Fully Nitrified) and During a Biological Upset (i.e., Non-Nitrified).

Source: Data courtesy of SNWA.



TOrC	Units	Full Nitrification	Operational Upset
Acesulfame	ug/L	<1.0	3.5
Acetaminophen	ng/L	<5.0	<5.0
Acetylmorphine	ng/L	<5.0	<5.0
Amphetamine	ng/L	<10	<10
Ampicillin	ng/L	<1.0	<1.0
Atenolol	ng/L	92	160
Benzotriazole	ng/L	3900	2600
Benzoylecgonine	ng/L	26	80
Caffeine	ng/L	57	270
Carbamazepine	ng/L	150	140
Carbamazepine epoxide	ng/L	26	27
Carisoprodol	ng/L	81	53
Cocaine	ng/L	<5.0	5.1
Codeine	ng/L	25	130
DEET	ng/L	190	440
EDDP	ng/L	240	290
Ecgonine	ng/L	<10	43
Ecgonine methyl ester	ng/L	6.9	20
Fluoxetine	ng/L	58	57
Gabapentin	ug/L	<1.0	1.8
Gemfibrozil	ng/L	12	510
Guanylurea	ug/L	18	51
Heroin	ng/L	<10	<10
Hydrocodone	ng/L	120	120
Ibuprofen	ng/L	<20	850
Lidocaine	ug/L	0.94	0.91
Lisinopril	ng/L	<10000	<10000
MDA	ng/L	<10	<10
MDMA	ng/L	20	44
Meprobamate	ng/L	220	260
Metformin	ug/L	<5.0	6.3
Methadone	ng/L	81	100
Methamphetamine	ng/L	29	1900
Metoprolol	ng/L	910	1100
Morphine	ng/L	41	140
Naproxen	ng/L	93	2200
Norcocaine	ng/L	<5.0	<5.0
Norfentanyl	ng/L	<5.0	<5.0
Oxycodone	ng/L	120	180
Primidone	ng/L	340	320
Ranitidine	ug/L	0.35	0.42
Sertraline	ng/L	76	74
Sucralose	ng/L	77000	84000
Sulfamethoxazole	ng/L	1000	1100
TCEP	ng/L	200	180
THC	ng/L	<100	<100
THC-COOH	ng/L	<100	230
THC-OH	ng/L	<100	<100
Tramadol	ng/L	540	600
Triclocarban	ng/L	<2.0	<2.0
Triclosan	ng/L	<1.0	17
Trimethoprim	ng/L	92	310

3.3 CBAT Case Studies

The tables in Appendix B summarize the individual treatment performances of ten (10) pilot- and full-scale CBAT systems for the removal of key organic and inorganic constituents. Each table reports the location of the facility, CBAT process train as well as the WRRF treatment configuration. General influent water quality for CBAT is listed. The purified water quality was characterized right after activated carbon treatment (BAC or GAC). Any post treatments (e.g., UV-H_2O_2) was excluded to allow for direct comparisons across sites. Indicator CEC removals were based on the AWT influent and BAC or GAC effluent. WRRF upsets (episodic or long-term) that impacted AWT operation or product water quality were noted. When the number of samples was specified, the reported values were averaged, or the median was used. Some values were estimated from graphs presented in the reference.

3.3.1 Summary

3.3.1.1 Finished Water Quality

Several sites (Altamonte Springs, City of Hollywood, Rio Rancho, Las Vegas, City of San Diego, Reno) demonstrated > 90 percent removal of indicator CECs, i.e., carbamazepine, sulfamethoxazole, primidone, DEET, meprobamate, sucralose, TCEP, where ozone and activated carbon treatments were the main barriers. A few of the CECs have been identified and recommended as possible process performance indicators for ozonation and GAC within a CBAT train (Thompson and Dickenson. 2020). Systems (El Paso, Los Angeles, Rio Rancho, City of San Diego) employing a low O_3: TOC mass ratio and/or aged BAC exhibited < 90 percent removal of the above indicator CECs. Some CECs, including sucralose and sometimes iohexal, that were well removed (>90 percent) were still detected in the GAC effluent, mainly due to high initial concentrations (1-10 µg/L) in the pilot feed.

The longer-chain PFAS, i.e., perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS), were usually removed more effectively by BAC/GAC than shorter-chain PFAS, such as perfluorobutanoic acid (PFBA), perfluoropentanoic acid (PFPnA) and perfluorohexanoic acid (PFHxA), though all the measured PFAS were typically below the most stringent state/federal MCLs or NLs.

In general, high ozone doses (O_3: TOC mass ratio > 1 mg/mg) may not be viable for waters with bromide concentrations > 100 µg/L (i.e., Rio Rancho, Los Angeles, Las Vegas, City of San Diego, Virginia Beach sites) due to potential bromate formation during ozonation without source control or a control strategy. The Rio Rancho case study employed hydrogen peroxide and the Virginia Beach case study employed chloramination to mitigate bromate formation due to high bromide concentrations. However, bromide was 55 µg/L at Altamonte Springs, and low bromate formation was observed at an O_3: TOC ratio of approximately 1 mg/mg.

For most of the sites, NDMA formed after ozonation, but was removed significantly (> 70 percent), often to non-detect or < 10 ng/L, after BAF or BAC treatment. However, NDMA was observed to reform during the end of a biofiltration column at the City of Hollywood site, which was hypothesized and attributed to a high ammonia level going into the biofilter and eventual denitrification conditions transpired in the later part of the biofilter.

NDMA formation after chloramination of GAC effluent typically remained below 2.9 ng/L (i.e., Las Vegas), indicating effective removal by chloramine-reactive precursors, mainly by the ozonation process.

A variable high concentration of acrylamide, several orders of magnitude higher than the regulatory “treatment goal” limit, occurred in the WRRF influent and was detected in the AWT product water at the Virginia Beach site. The source was identified as a chemical manufacturing company that produced concentrated acrylamide product, where a daily load limit was eventually enforced.

Typically, 1,4-dioxane levels were less than 1 µg/L post GAC, where partial removals were observed during ozonation. High levels can occur in WRRF effluents, such as at the Virginia Beach site. In one case, this site identified a landfill as a significant industrial contributor, and they are working with the landfill to employ two moving bed bioreactors to treat 1,4-dioxane onsite before discharging into the sewer.

HAA5 formation after chlorination of GAC effluent typically remained less than the federal MCL of 60 µg/L (i.e., Las Vegas; Summers et al. 2020). HAA9 formation, that includes more brominated HAAs, after chlorination of GAC effluent could be a concern considering USEPA's recent attention to this class of emerging DBPs in drinking water (i.e., Las Vegas; Summers et al. 2020).

TTHM formation after chlorination of GAC effluent can exceed the federal MCL of 80 µg/L (i.e., Las Vegas; Summers et al. 2020). Therefore, minimizing the GAC influent TOC would be necessary for the viability of GAC treatment. Source control and optimized biological treatment at WRRF, O_3-BAF, and/or pretreatment by enhanced coagulation might be necessary to remove dissolved effluent organic matter, particularly UV-absorbing organic compounds (details referred to pilot study in Appendix C).

Nitrate is not well removed by CBAT systems, but concentrations were typically < 10 mg/L as N post treatment, mainly due to secondary biological treatment employing nitrification with denitrification. For the Las Vegas and City of San Diego case studies, denitrification was not used or was partially used, thus nitrate levels were > 10 mg/L as N.

TDS are not well removed a by CBAT systems and concentrations were typically greater post treatment than the secondary drinking water MCL of 500 mg/L.

3.3.1.2 Water Quality Operational Impacts

Biological upsets during secondary treatment can cause high TOC levels in the wastewater effluent where the AWT system is unable to meet the finished water TOC target (i.e., Virginia Beach). During these times the AWT was taken offline.

Higher turbidity in the secondary treated wastewater as compared to tertiary-filtered wastewater caused more frequent backwashing of BAF and BAC for the Las Vegas case study (details referred to Appendix C).

A sudden increase in organic loading and TOC by Hurricane Irma increased the frequency of backwashing for the BAC in the City of Altamonte Springs case study.

Variable nitrite in the MBR filtrate caused increased ozone demand in the Rio Rancho case study. This was mitigated by improved nitrification during secondary treatment.

The chlorinated tertiary recycled water for Santa Clara Valley Water District pilot caused a lower TOC removal during O_3-BAF than the secondary unchlorinated effluent, possibly due to the total/free chlorine caused an ozone demand.

Bromide levels were high > 0.4 mg/L for the Virginia Beach system (HRSD). The bromide level was mitigated by source control where the disposal of landfill leachate was better controlled.

3.4 Pass-Through Constituents

A pass-through constituent is defined as a constituent that was originally present in the wastewater effluent or is formed during CBAT and is still present at a level of human health concern in the product water of the AWT. Potential pass-through constituents and degree of pass of through are listed in Table 3-4, along with potential mitigation strategies.

3.4.1 CECs

Generally, CBAT systems can mitigate various CECs. However, there are some CEC that are not or partially attenuated and can pass through and pose a regulatory concern (e.g., 1,4-iioxane) or indicate (CEC Indicator, short-chain PFAS, NMOR) the pass-through of other, unknown, similar CECs, but with potential and unknown health concern.

3.4.2 Indicator CECs

Artificial sweeteners, acesulfame and sucralose, and iodinated X-ray contrast media (ICM), iopromide, iopamidol and Iohexal, are classes of potentially recalcitrant compounds in CBAT. These compounds are not a health concern to humans and, thus are CEC indicators, indicating the pass-through of other similar compounds in terms of similar treatment behavior.

“Good” removal, >75 percent, but typically less than 90 percent, for acesulfame and sucralose were proposed for these compounds (Table 3-1), where these compounds can still be detected in the final effluent > 100 ng/L. The reason these compounds are still detected is because their levels in wastewater effluent are generally on the order of magnitude of 1,000-10,000 ng/L, much higher than most other CECs. However, “Good” removal is dependent on appropriate wastewater effluent characteristics and ozone (typically O_3: TOC mass ratio > 0.6) and GAC (change-out frequency) operations. If high O_3: TOC mass ratio cannot be achieved (e.g., contending with high bromate or NDMA formation potentials) and/or BAC/GAC treatment is operated with higher throughput, then more of these compounds will likely pass through and higher levels will be detected in the final effluent. Acesulfame (log $D_{ow,\ pH\ 7}$=-1.49 and log K_{ow} = -0.55, estimated using MarvinSketch 19.27, ChemAxon Ltd.) and sucralose (log $D_{ow,\ pH\ 7}$= log K_{ow} = -0.47) are both non-aromatic and hydrophilic, therefore they are challenging to oxidize during ozonation and remove by GAC treatment, thus, partial removals have been observed by these processes. According to Sari et al. (2020), acesulfame and sucralose are partially removed by ozone and fresh BAC and GAC treatments (Sari et al., 2020). As a means of mitigating the potential pass-through of acesulfame, and thus similar, unknown CECs, high dose UV or UV-advanced oxidation process (AOP) can be used (Thompson and Dickenson 2020). According to Yu et al., acesulfame is classified as a highly photolabile compound (Yu et al., 2019). The enone group of acesulfame would render its effective isomerization during direct photolysis (Turro, 1991). Also, hydroxylation of acesulfame has also been found as a major transformation product during direct photolysis (Scheurer et al., 2014). In contrast, direct photolysis is not a viable option for sucralose as it does not contain chemical moieties to absorb light efficiently (Yu et al., 2019). Sucralose can be effectively removed by nanofiltration.

Table 3-4. Constituents that can Potentially Pass Through CBAT.

Constituent	Description	Example	Concern	Removals				Potential Mitigation
				Ozone	BAF	GAC	Overall	
CEC Indicator	Present in reclaimed water	Iohexal Acesulfame Sucralose	Unknown Compounds	25-75%	<25%	25-75%	<90%	-UV photolysis/UV AOP -Nanofiltration
NMOR	Present in reclaimed water		Potential Health Concern	<25%	<25%	<25%	<25%	-Source control -UV photolysis
Short-chain PFAS	Present in reclaimed water or formed during activated sludge or ozone treatments	PFHxA PFPnA PFBA	Potential Health Concern	OBP	<25%	<25%	<25%	-Source control -Nanofiltration
1,4-Dioxane	Elevated levels Oxidizable		CA-NL of 1 μg/La	25-75%	<25%	<25%	> CA-NL	-Source control -Increase ozone dose -Additional AOP treatment
NDMA	High levels formed during ozonation Biodegradable		CA-NL of 10 ng/La	OBP	25-75%	<25%	> CA-NL	-Source control of precursors -Optimize activated sludge treatment -UV photolysis
Bromate	Elevated bromide levels Formed during ozonation		MCL of 10 μg/L[b]	OBP	<25%	<25%	> MCL	-Source control of bromide -Minimize bromate formation during ozonation (e.g., NH_3, H_2O_2, chloramine addition) -Anion exchange (AIX) treatment
Nitrate	Elevated levels in reclaimed water		MCL of 10 mg/L[b]	<25%	<25%	<25%	> MCL	-Use or optimize activated sludge denitrification -AIX treatment
TDS	Present in reclaimed water		MCL of 500 mg/L[b]	<25%	<25%	<25%	> MCL	-AIX treatment -Nanofiltration
Bromide, Iodide	Chlorine or chloramine-reactive precursors	Br/I-Organic DBP	Potential Health Concern	<25%	<25%	<25%	<25%	-Source control -AIX treatment

a. California notification level; b. U.S. EPA maximum contaminant level; OBP: ozone byproduct.

Also, “Good” removal was proposed for iopromide and iopamidol (Table 3-1). High levels of ICMs can also occur in wastewater effluent on the order of magnitude of 1,000 ng/L. Like the sweeteners, overall “Good” removal is dependent on appropriate wastewater effluent characteristics and appropriate high ozone doses and GAC operation, particularly for iopromide and iopamidol. ICMs are only partially removed by ozonation since they have low reactivities with oxidants. For instance, their reactivities with molecular ozone are low (Gerrity et al., 2012). In addition, they have low reactivities with hydroxyl radicals ($k < 5\times10^{9}$ $M^{-1}s^{-1}$) resulting in lower extents of reaction compared to other CECs frequently detected in wastewater effluents (Jeong et al., 2010; Park et al., 2017). Iodinated X-ray contrast media, such as iopromide (MW = 791 g/L; log D_{ow} = -0.44), iopamidol (MW = 777 g/mol; log D_{ow} = -0.74), and Iohexal (MW = 821 g/mol; log D_{ow} = -1.95), are hydrophilic (negatively charged) , and thus are not favorable for adsorption (Ziska et al., 2016). Fast GAC breakthrough was observed for iopromide (Stanford et al. 2017; Altmann et al. 2016; Kennedy et al., 2015). However, iohexal is expected to have faster breakthrough in GAC treatment given its lower log D_{ow} value. The ICMs are highly photolabile (Yu et al., 2015), so direct UV photolysis is a viable treatment option (Thompson and Dickenson, 2020).

3.4.2.1 NMOR

N-Nitrosomorpholine (NMOR) is a N-nitrosamine that is generally recalcitrant in CBAT. Although it is currently not regulated in the US, there exist guidelines or notification levels for NMOR. Germany has recommended a drinking water guideline of 10 ng/L (Planas et al., 2008) and Australia has set their Drinking Water Reuse Guideline at 1 ng/L (NHMRC, 2008) for NMOR. NMOR is a small (116.1 g/mol) and hydrophilic (-0.18 of log D_{ow} at pH 7) molecule that is not biodegradable. NMOR was reported to be the most recalcitrant N-nitrosamine in drinking water biofilters (Wang et al., 2015). While NMOR can be attenuated by GAC, the adsorption capacity for NMOR is rapidly exhausted; its breakthrough is before TOC. According to a study assessing pilot- and full-scale GAC adsorbers, a complete breakthrough of NMOR was observed less than 10,000 bed volumes (Glover et al., 2019). Therefore, source control or additional downstream treatment processes, such as UV photolysis, may be necessary to achieve an acceptable level of NMOR in final purified waters (Glover et al., 2019).

3.4.2.2 NDMA

The California Department of Public Health has established a 10 ng/L Notification Level for NDMA and other *N*-nitrosamines such as *N*-Nitrosodiethylamine (NDEA) and *N*-Nitrosodi-n-propylamine (NDPA) (CDPH, 2013). As discussed previously biofiltration is generally effective in removing NDMA (i.e., >75 percent) (Asami et al., 2009; Bacaro et al., 2019; Vaidya et al., 2021), however incoming NDMA could be formed too high from ozonation for effective post attenuation, or it could be potentially formed during biofiltration. One study observed poor removal (< 25 percent) likely due to the NDMA reformation (Li et al., 2017). The extent of denitrification in an anoxic zone in the biofilter, such as the nitrosation reaction may have contributed to NDMA reformation in biofiltration (Li et al., 2017). EBCT is also an important factor for biofilters for NDMA removal in that higher removal of NDMA correlated with higher EBCT, ≥10 min compared to 2 min (Bacaro et al., 2019; Vaidya et al., 2021); if aerobic conditions are maintained (Li et al. 2017). Vaidya et al. (2021) observed that nitrification (aerobic conditions) is a good indicator for NDMA biodegradation potential since nitrifying bacteria appear to flourish under similar BAF conditions although removal mechanisms for ammonia and NDMA are distinct.

3.4.2.3 Acrylamide

Acrylamide is produced industrially mainly as a precursor to polyacrylamides, which find many uses as water-soluble thickeners and flocculation agents. It is highly toxic, but its main derivative polyacrylamide is nontoxic. Acrylamide is an EPA regulated contaminant, but it is unique in that it does not have a listed MCL, rather it has a treatment technique goal. As there is acrylamide in polymer often used in water and wastewater treatment, the EPA allows for up to 1 mg/L of polymer dose with a maximum acrylamide concentration of 0.25 percent. Although, biological processes, such as secondary and biofiltration treatments, provide excellent removal of readily biodegradable contaminants like acrylamide, the magnitude of the influent concentration, and its variability, proved enough to break through where it was detected in product water of HRSD's CBAT system (SWIFT Research Center). A flocculation aid polymer was used at the AWT system that has a small acrylamide concentration and a polymer was added at the WRRF. However, HRSD measured a high concentration of acrylamide, several orders of magnitude higher than regulatory limit, in the WRRF influent. The acrylamide was coming from a chemical manufacturing company that produced concentrated acrylamide product. Therefore, HRSD applied a daily load limit for acrylamide for that industrial discharger and since then acrylamide has not exceeded the regulatory limit (i.e., source control).

3.4.2.4 1,4-Dioxane

The California Department of Public Health has established a 1 µg/L Notification Level for 1,4-dioxane. 1,4-dioxane is an industrial chemical that is mainly used for stabilizing chlorinated solvents, such as 1,1,1-trichloroethane (USEPA, 2017). As discussed previously, ozonation, via hydroxyl radical production, can be effective in reducing 1,4-dioxane levels, however incoming 1,4-dioxane could be too high for effective attenuation by ozonation. It is small (88.11 g/mol) and due to its miscible nature (-0.09 of log D_{ow} at pH 7, estimated using MarvinSketch 19.27, ChemAxon Ltd.), GAC adsorption is not a viable treatment option for 1,4-dioxane. The extent of biodegradation has also been reported to be low. About 15 percent of biodegradation of 1,4-dioxane was observed in a biofilter filled with GAC media (Vatankhah et al., 2019). While 1,4-dioxane is not photolabile, hydroxyl radicals produced during UV-AOP, as are produced during ozonation, can further remove 1,4-dioxane (Xu et al., 2019). Note the presence of monochloramine can jeopardize UV-H_2O_2 efficiency for 1,4-dioxane abatement (Patton et al., 2018). Interestingly, the UV-AOP with chlorine exhibited a similar efficacy for 1,4-dioxane removal on a cost-effectiveness basis (Zhang et al., 2019). Source control might be another effective means for mitigating 1,4-dioxane.

1,4-dioxane levels are high in most of HRSD's (Virginia Beach, VA) service areas, with typical values in the range of 0.8-1.3 µg/L. Their SWIFT program has an unregulated 1,4-dioxane goal of 1 µg/L. Their pilot system has a modest removal of 1,4-dioxane (mainly due to ozonation), but they are currently researching ways (e.g., UV-AOP) to optimize removal along with identifying significant industrial contributors. At another WRRF location, where full-scale CBAT will be employed, HRSD has identified an industrial user, a landfill, that contributes nearly 50 percent of the influent 1,4-dioxane. HRSD is working with the landfill to employ two moving bed bioreactors to treat 1,4-dioxane before discharging into the sewer.

3.4.2.5 PFAS

Short-chain per- and polyfluoroalkyl substances (PFAS) (molecular weight <400 g/mol), such as the following perfluoroalkyl carboxylic acids (PFCAs): perfluorobutanoic acid (PFBA, C4; MW = 214.039 g/mol), perfluoropentanoic acid (PFPeA, C5; MW = 264.05 g/mol) and perfluorohexanoic acid (PFHxA, C6; MW = 314.05 g/mol), are currently thought to be less toxic than their long-chain analogue, perfluorooctanoic acid (PFOA, C8). For example, PFHxA has a Michigan drinking water MCL of 400,000 ng/L, which is fifty thousand times greater compared to PFOA. Nevertheless, short-chain PFAS are still of concern because they are non-biodegradable and adverse health effects might be discovered later.

Short-chain PFAS are generally recalcitrant in ozone-BAF-AC-based AWT. Short-chain PFCA are recalcitrant chemically (i.e., resistant to both ozone and hydroxyl radical oxidation) and biologically due to the high bond energy of carbon and fluorine. In addition, they are less effectively adsorbed by GAC due to their hydrophilic nature (PFBA: log Dow at pH 7=-1.22) (Park et al., 2020b), while long-chain, more hydrophobic PFCA, such as PFOA is better adsorbed (Glover et al., 2018). Due to their resistance to chemical oxidation as well as UV photolysis, UV-AOP processes are not viable options. High-pressure membranes, such as nanofiltration (NF), can be a viable option for short-chain PFAS despite high energy consumption (Park and Snyder, 2020). However, NF is more energy-efficient than RO while rejecting PFAS effectively. A "loose "NF membrane (i.e., NF270, Dow Filmtec; MWCO = 326 Daltons) exhibited > 94 percent of PFBA, > 97 percent of PFPeA, and >95 percent of PFHxA (pH 6.7) indicating excellent PFAS rejection (Appleman et al., 2013). Reduced rejection of such small PFAS at a decreased pH (e.g., 3.4 from 7.4) suggests that electrostatic interactions play an important role in PFAS rejection in NF (Li et al., 2021). Source control can also be effective, where HRSD (Virginia Beach) has maintained a strict zero discharge policy towards aqueous film forming foam (AFFF) (PFAS-containing) since the mid-1970s, due to concerns that AFFF presence could inhibit effective settling within wastewater treatment plants (WWTPs). More recently, concerns over PFAS impacts on water reuse activities at HRSD have further supported this long-standing zero discharge policy (Gonzalez et al. 2020).

3.4.3 Inorganic Constituents

Overall, many inorganic constituents pass through CBAT, where TDS are not removed. The USEPA has set a secondary drinking water MCL for TDS at 500 mg/L. Above this level hardness, deposits, colored water, staining, and salty taste are issues of concern. Therefore, dominant inorganic ions, such as calcium, magnesium, sodium, chloride, and sulfate, pass through (Gerrity et al., 2013b). Nitrate is also not well removed, which has a primary drinking water MCL of 10 mg/L as N. This could be an issue for nitrifying systems. A denitrifying process following nitrification during secondary treatment would mitigate nitrate concentrations.

Halogen ions—particularly serving as a DBP precursor, such as bromide and iodide—may be of concern, particularly in ozone-based AWT or when chlorine or chloramines are applied as post disinfection. Bromide and iodide are not well attenuated (some bromide is consumed during ozonation). If chlorine or chloramine disinfection is applied on the product water, then there is the potential to form unregulated DBPs like brominated HAAs (i.e., HAA9), haloacetonitriles, haloacetamides and/or iodinated THMs (Verdugo et al., 2020) which are more toxic than the regulated DBPs (TTHM and HAA5) (Yang et al., 2014; Furst et al., 2021).

Also, ozone has the potential to react with bromide to form problematic levels of bromate (e.g., > 10 µg/L of MCL). Higher pH has been reported to produce a greater extent of bromate (Song et al., 1996). In certain cases (e.g., bromide concentration > 100 µg/L), in-situ bromate mitigation strategies, such as lowering pH and ammonia, chloramine, or hydrogen peroxide addition may be necessary (von Gunten, 2003b). Alternatively, anion exchange for the direct removal of bromide and/or bromate may be an effective control method that needs exploring. Source control can also be effective, where HRSD (Virginia Beach) has implemented it to mitigate high bromide levels for the Virginia Beach case study.

3.4.4 Summary

Some CECs, NMOR, iohexal, 1,4-dioxane, short-chain PFAS, can pass through CBAT. There could be potential health concerns for some of these compounds or similar types of unknown compounds that have yet to be discovered. To reduce these CECs, source control in the sewershed or additional advanced treatment, such as UV photolysis (NMOR, Iohexal), nanofiltration (short-chain PFAS, iohexal), and AOP (1,4-dioxane) may be required. Also, some ozone byproducts (OBPs) could pass through subsequent BAC/GAC treatment, such as NDMA and bromate. To reduce these OBPs, source control of their precursors (i.e., organic precursors for NDMA, bromide for bromate formation) or additional advanced treatment, such as UV photolysis (NDMA), in-situ chemical mitigation (bromate), or AIX (bromate) may be required. Additionally, some inorganic constituents, such as nitrate, TDS, bromide, and iodide, can pass-through and could be problematic. To reduce these inorganic constituents, they may require source control (bromide, iodide, acrylamide, 1,4-dioxane, PFAS), optimized secondary treatment for denitrification (nitrate) or additional advanced treatment, such as nanofiltration (TDS) and AIX (TDS, nitrate, bromide, iodide).

3.5 Interfering Constituents

An interfering constituent is defined as a constituent that is present in the wastewater effluent that interferes with the operation and/or optimal performance of ozone, biofiltration and/or activated carbon treatment. Potential process interfering constituents and potential mitigation strategies are listed in Table3-5.

3.5.1 Turbidity

Particulate matter—often characterized as turbidity and TSS—can adversely impact the operation of ozone and BAC. First, particulate matter consumes ozone, thereby increasing ozone demand. A recent study observed the elimination of particulate matter enhanced the attenuation of both fast-reacting compounds, such as sulfamethoxazole, diclofenac, and carbamazepine, and slow-reacting compounds, such as iopromide, Iohexal, and iopamidol (Zucker et al., 2015). Particulate matter can potentially interfere with the ozonation of CECs by two mechanisms. First, competition for ozone between particulate and dissolved matter can jeopardize the oxidation of trace organic compounds. However, another study saw the contrary, where 15 mg/L of TSS was spiked into a wastewater effluent and no substantial difference with the non-spiked effluent was observed, which suggests the effects of large particulate matter on ozonation of CECs are marginal (Huber et al., 2005). Little influence was likely due to the low specific surface area of the particles, which limits the diffusive transfer of ozone to particles (Huber et al., 2005). The second mechanism of reduced ozone efficacy for CEC abatement is the shielding effect. Particulate matter adsorbs CECs so that they are shielded by the particles. However, Zucker et al. concluded such a shielding effect is minimal (Zucker et al., 2015).

Particulate matter can block porous media and increases the hydraulic resistance, therefore increasing the operating cost and frequency of backwashing. Large particles (i.e., diameter>500 µm) are mainly removed at the top layer, whereas fine colloids are homogenously removed throughout the bed depth (Boller et al., 1997). In Boller et al.'s study, the progress of clogging with respect to the mass load of TSS increased the associated head loss until the porosity of the filter bed reached a critical value (e.g., 0.18-0.20) (Boller et al., 1997). Once the pores become smaller than a threshold value, the addition of TSS exponentially increased the head loss. Turbidity can be mitigated via pretreatment with tertiary filtration or by coagulation followed by filtration.

3.5.2 DOC

Natural organic matter (NOM) and effluent organic matter (EfOM) are the major pools of organic matter in reclaimed waters, and their dissolved forms constitute the major fractions of organic matter (Leenheer and Croué, 2003; Shon et al., 2006). Their adverse effects on ozone-BAF-AC-based AWT can be categorized into the following: ozone demand increase, head loss increase of biofilters, and rapid exhaustion of GAC adsorption capacity.

NOM and EfOM readily consume ozone. These organic constituents are quantified by total organic carbon (TOC) or dissolved organic carbon (DOC). In practice, the ozone:TOC (or ozone:DOC) ratio has been widely used as an operating parameter based on the postulation that ozone consumption per unit mass of organic carbon does not vary greatly in various water qualities. However, UV absorbance at

254 nm (UVA254) may be a better indicator of ozone dose due to its relationship with electron-donating capacity (EDC). Compounds with high EDC, such as phenols, react effectively with ozone. The change in EDC of dissolved organic matter (DOM) was correlated strongly with that in UVA254 (Chon et al., 2015; Önnby et al., 2018). DOC can also clog biofilters, but its impacts on filter clogging may be minor or negligible compared to particulate matter (Le Bihan and Lessard, 2000).

It is noteworthy that THM formation potential correlates with TOC (Summers et al., 2020) and TOC can negatively influence GAC adsorption. Lower GAC influent TOC concentrations are critical for extending the GAC run times. TOC will also potentially compete with CECs for adsorption sites. Hydrophobic compounds can be more effectively partitioned to the adsorbent surfaces. In some cases, dissolved organic matter can potentially promote certain CEC to have higher concentrations in the GAC effluent than influent, resulting in a net negative removal. Hydrophilic CEC will travel to and sorb to micropore surfaces and achieve local equilibrium. Subsequently, more hydrophobic compounds (e.g., aromatic DOM) can displace these hydrophilic compounds, which causes this phenomenon (Scheurer et al., 2010; Shih et al., 2005). Short-chain PFBA is an example exhibiting overshooting (Appleman et al 2013; Park et al., 2020b). Therefore, TOC removal can be achieved by optimized biological secondary and ozone/biofiltration pretreatments. Summers et al. (2020) demonstrated pretreatment by enhanced coagulation can also further lower TOC concentrations in the GAC influent. Hill et al. (2018) also demonstrated enhanced coagulation (40 mg/L of alum) was able to remove TOC and THM (20-50 percent) and HAA9 10-30 percent chorine-reactive precursors (less effective towards HAN4; <6 percent) for four different biological nutrient removal treated wastewaters.

If the TOC in the treated wastewater is too high the operation of the AWT could cease. For example, at HRSD (Virginia Beach), since AWT systems was put into operation in 2018, usually there are monthly upset events, where a slug of sewage high in nutrients and organics enters the WWTP for a 4-8 hour period. This brings the TOC value in the AWT influent up (15-20 mg/L) from typical values (~8 mg/L) and affects the WWTP performance for 24-48 hours. During these periods the SRC must be taken offline until the event has subsided as the process is unable to meet the finished water TOC target. The source of these events is being investigated.

3.5.3 Nitrite

During wastewater treatment, nitrite (NO2-) can be formed by the oxidation of ammonia. It can be formed for partly nitrifying secondary treatment, such as for the City of Hollywood case study, or for inefficient “full” nitrifying secondary treatment, such as for the episodic upset in the Rio Rancho case study, or it could occur during cold temperatures. Nitrite is reactive with molecular ozone (k_{O3}=3.7×10^5 $M^{-1}s^{-1}$) and its half-life is 0.1 s-1, therefore readily consuming ozone (von Gunten, 2003a). Approximately, 1 mg NO2- consumes 1.1 mg ozone (Wert et al., 2009). Therefore, a higher ozone dose is necessary at an elevated nitrite concentration. For the Rio Rancho case study, variable nitrite in the MBR filtrate caused increased ozone demand coming from nitrite.

3.5.4 Bromide

Bromide can interfere with the performance of ozonation by limiting the ozone dose, since ozone can readily oxidize bromide to bromate (von Gunten, 2003a). According to Pisarenko et al., less than 100 µg/L of bromide is insufficient to yield substantial formation of bromate (Pisarenko et al., 2012), as was observed for the City of Altamonte Springs case study. However, the ozone dose may need to be controlled if the bromide concentration in the wastewater effluent is higher to meet the drinking water MCL for bromate (i.e., 10 µg/L). To minimize bromate formation, in-situ bromate mitigation strategies, such as lowering pH and ammonia or chloramine addition, may be necessary (von Gunten, 2003b) or possibly bromate might be directly removed via anion exchange treatment. If bromide levels are really high, source control or direct removal of bromide (i.e., by AIX treatment) might be necessary. For example, bromide levels were high in many of HRSD's WWTPs, typically ranging between 0.4 and 1.2 mg/L. When HRSD started up its O3-BAF-GAC based treatment system in 2018 the bromate formation was higher than expected. HRSD was able to track down the source coming from one industrial user, a landfill. HRSD worked with the landfill to pump and haul their leachate to a different WWTP service area, so that a lower baseline influent bromide level could be established

3.5.5 Summary

The following interferences to AWT were identified: water quality that caused an increased ozone demand (turbidity, TOC, free chlorine, and nitrite), caused a head loss increase within BAF and thus shorter filtration run times (turbidity, TOC), caused rapid exhaustion of BAC/GAC adsorption capacity (SUVA, DOC), and interfered with optimal ozone performance (bromide). The pretreatment mitigation strategies included the following: enhanced source (sewershed) control (i.e., slugs of TOC, bromide), optimized secondary treatment (maybe with higher SRT) for DOC removal, enhanced coagulation for DOC and DBP precursor removals, optimized O3/BAF treatment for DOC removal (before GAC treatment), complete nitrification year-round for nitrite control, tertiary filtration with or without pre-coagulation for turbidity control, and avoid tertiary chlorination or use chloramines instead.

Table 3-5. Potential Interfering Constituents Present in Wastewater Effluent on Ozone, Biofiltration, GAC Treatment Operations.

	Ozone Operation		Biofiltration or GAC Operation		
	Effect	**Implication**	**Effect**	**Implication**	**Potential Mitigation to Avoid Process Impact**
Turbidity	Increased ozone demand	Increased O_3 dose	Shorter biofilter run times	Increased biofilter backwashing frequency	Upstream filtration Upstream Coagulation followed by filtration
DOC	Increased ozone demand	Increased O_3 dose	Shorter GAC bed-life for DBP precursor or CEC removal	More GAC bed change-outs	Source control of recalcitrant TOC Increase BOD/COD removal during secondary treatment Upstream enhanced coagulation
Nitrite	Increased ozone demand	Increased O_3 dose			Optimized secondary nitrification
Bromide	Limit Ozone Dose	Non optimized ozone performance			Source control of bromide AIX treatment of bromide Ignore bromide removal and minimize bromate formation during ozonation (e.g., NH_3, H_2O_2, chloramine addition)
Free Chlorine	Increased ozone demand	Increased O_3 dose			Use alternative disinfectant, i.e., chloramines Do not employ tertiary chlorination
Methanol Addition for Denitrification	Increased ozone demand	Increased O_3 dose	Shorter run times due to increased biomass growth	Increased backwashing frequency	Optimized organic substrate application; limit/control dose Use alternative organic substrate that is not an O_3 scavenger

3.6 A Conceptual Model

Optimization of effluent water quality can sometimes be achieved with operational adjustments in existing facilities. For example, higher ozone doses will achieve greater transformation of bulk and trace organics, which would lead to lower CEC and TOC concentrations in ozone and biofiltration effluents, respectively. To a lesser extent, ozone-induced NDMA formation could potentially be controlled with lower ozone doses, although correlations between NDMA formation and ozone dose are relatively weak (Pisarenko et al., 2012). On the other hand, major changes to secondary biological treatment, including longer SRTs, may be infeasible in full-scale applications. In the past, facilities have experimented with changes to their design SRT at full-scale (Gerrity et al., 2013a), but these considerations might be better suited for the design phase of a new facility or during a planned expansion. As such, the following conceptual analysis is intended as a basis for evaluating the effects of upstream treatment on water quality and cost for downstream ozone-biofiltration.

3.6.1 Basis of Conceptual Model

The conceptual model presented here is an assimilation of ozone-related research conducted by the project team over approximately 10 years. Therefore, the water quality, operational, and cost data are developed from a wide range of systems, some of which have unique attributes that may not be broadly applicable. Those attributes are noted to the extent possible in the following discussion. More importantly, the overall model has not been fully validated in a single system, so the analysis is meant to be conceptual in nature to provide an overview of how certain water quality or operational decisions might impact final effluent quality and cost. As will be described later, all of the cost calculations are based on Plumlee et al. (2014), which used a “conceptual-level Class 4” framework providing an accuracy of -30 percent to +50 percent (AACE, 2011). Although there are no specific confidence intervals for the model presented here, the intent of the effort is to provide a similar conceptual framework for evaluating certain design considerations.

Figure 3-8 illustrates the general scenarios considered for the conceptual model. The hypothetical treatment train included secondary/tertiary treatment, ozonation, and biofiltration with BAC and operated with a flow rate of 1, 10, or 100 million gallons per day (mgd). The secondary biological treatment process consisted of a 1) trickling filter, 2) a non-nitrified secondary effluent targeting removal of BOD only, 3) a nitrified secondary effluent, 4) a nitrified tertiary effluent with granular media filtration, 5) and an ‘extended SRT’ secondary effluent (e.g., SRT >10 days). Ozonation consisted of a moderate O3/DOC ratio of 0.5 and a high O3/DOC ratio of 1.5, with the higher dose being capable of achieving >0.5-log (69 percent) oxidation of 1,4-dioxane and 50 percent oxidation of sucralose. Finally, the EBCT of the BAC process was assumed to be 10 and 20 minutes.

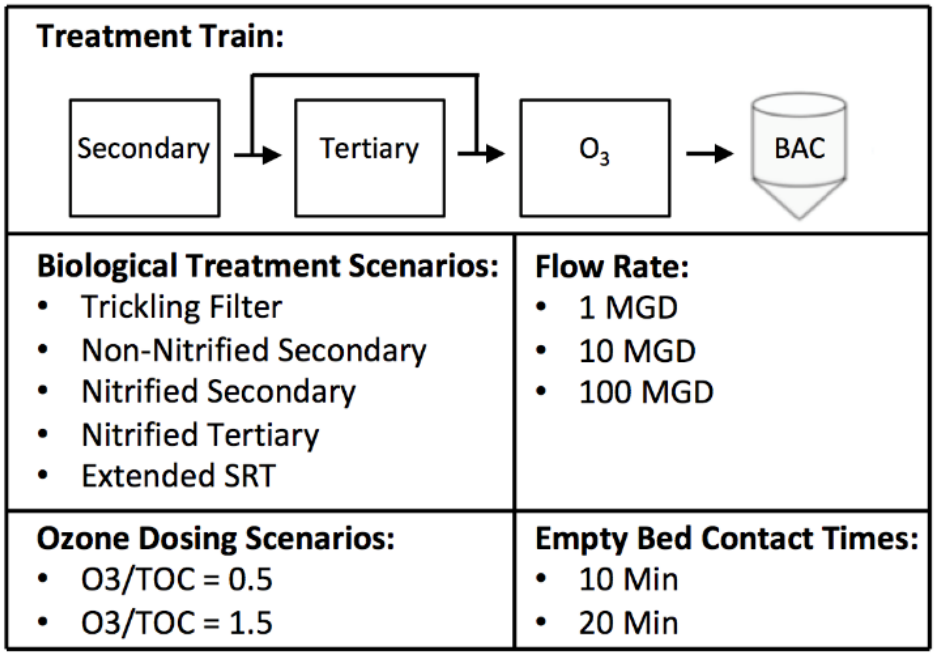


Figure 3-8. Conceptual Evaluation of Upstream Treatment on Ozone-Biofiltration.

3.6.2 Secondary/Tertiary Effluent Water Quality

Table 3-6 summarizes the secondary/tertiary effluent water quality for the different treatment scenarios considered in this evaluation. These values are adapted from WRF-08-05 (Snyder et al., 2014), which evaluated ozone efficacy for 10 different international wastewaters.

Table 3-6. Summary of General Water Quality as a Function of Upstream Treatment.

Source: Some Values are Taken Directly from WRF-08-05 (Snyder et al., 2014) and Some are Assumed (as noted).

Parameter	Trickling Filter	Non-Nitrified Secondary	Nitrified Secondary	Nitrified Tertiary	Extended SRT
Turbidity (NTU) [a]	20	20	5	0.5	5
DOC (milligrams of carbon [or organic carbon] per liter [mg-C/L])	26.4	15.0	7.0	6.0[a]	5.25 [a]
UV_{254} (cm^{-1})	0.410	0.268	0.146	0.125 [a]	0.110 [a]
Parameters relevant to OH scavenging:					
pH [b]	7.0	7.0	7.0	7.0	7.0
Alkalinity (mg/L $CaCO_3$)	295	332	123	123[c]	123[c]
NH_4^+/NH_3 (mg-N/L)	46.0	46.9	0.1	0.1 [c]	0.0
NO_3^- (mg-N/L)	0.2	0.1	14.0	14.0 [c]	14.0 [c]
NO_2^- (mg-N/L)	0.45	0.17	0.06	0.06 [c]	0.00 [a]
Br^- (mg/L)	0.140	0.409	0.174	0.174 [c]	0.174 [c]
$k_{\bullet OH,DOC}$ [$(mg/L)^{-1}$ s^{-1}] [d]	1.00×10^4	2.20×10^4	1.80×10^4	1.80×10^4 [c]	1.80×10^4 [c]
$k_{\bullet OH,Total}$ (s^{-1})[d]	3.19×10^5	3.95×10^5	1.50×10^5	1.32×10^5	1.18×10^5

[a]Generalized assumption (not available for given system); [b]Assumed to be the same regardless of treatment; [c]Assumed to be consistent with nitrified secondary; [d]See Lee et al. (2013) for additional details on •OH radical scavenging calculations.

For potable reuse systems employing ozone-biofiltration, the quantity and characteristics of EfOM) are critically important for a number of reasons. First, EfOM will affect the TOC concentration and UV transmissivity of the ozone-biofiltration effluent, which can have implications for regulatory compliance, disinfection byproduct formation potential, and/or the efficacy of downstream UV photolysis. As was shown in Figure 3-7 and summarized in Table 3-6, longer SRTs result in lower TOC concentrations, and those reductions are observed in 'regions' commonly associated with (1) protein-like, (2) fulvic-acid-like, and (3) humic-acid-like organic matter (Figure 3-9).

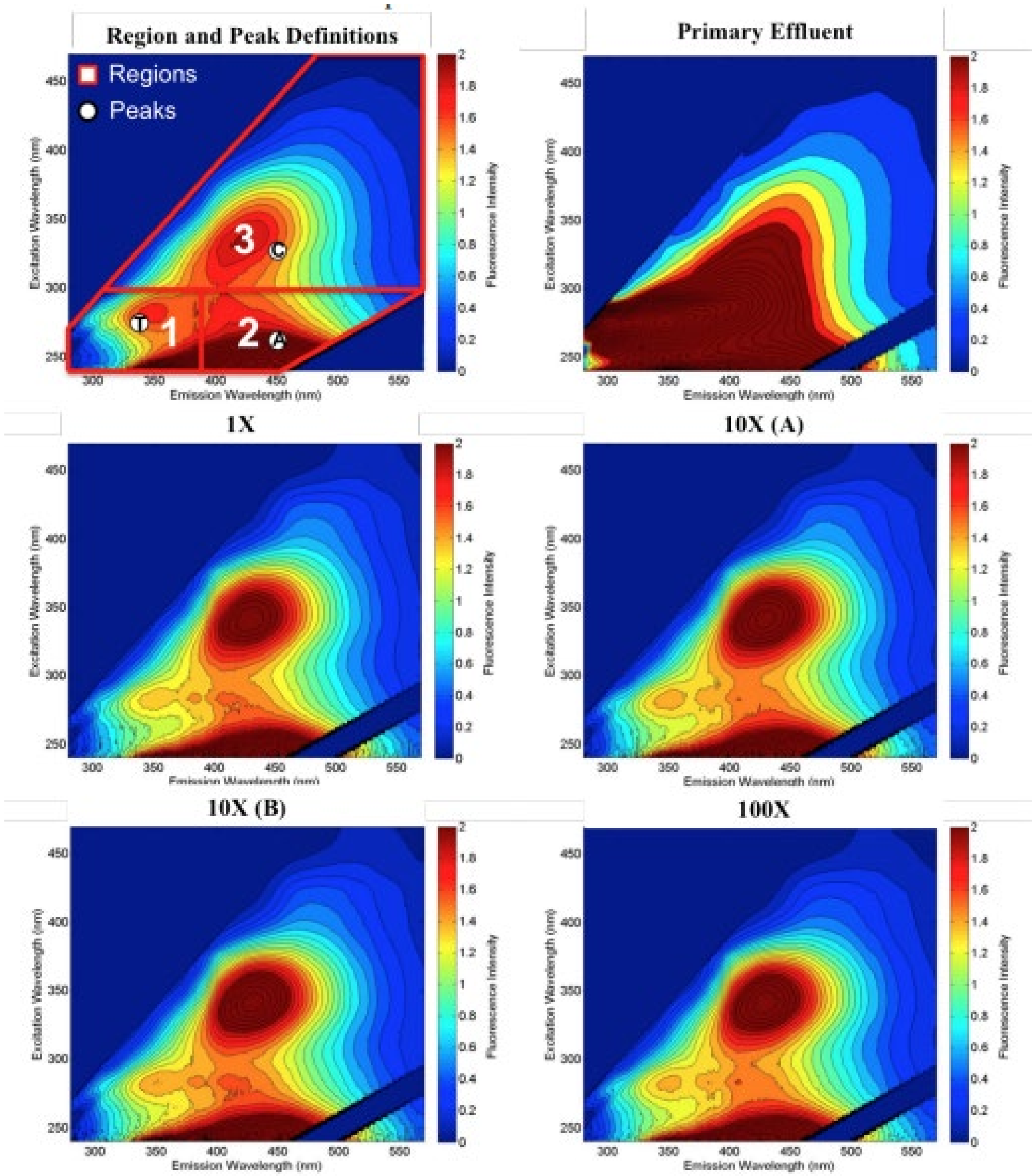


Figure 3-9. Effluent Organic Matter (EfOM) Characterization Based on Excitation Emission Matrices (EEMs) as a Function of SRT.

Source: Gerrity and Neyestani (2019).

EfOM is also the primary sink for •OH radicals generated during ozonation, or during UV-based advanced oxidation processes (AOPs) in the absence of reverse osmosis (RO) pretreatment. Based on Lee et al. (2013), Figure 3-10 illustrates the relative contributions of major scavengers to the overall •OH scavenging rate constant as a function of pretreatment. In all scenarios, EfOM (or DOC) is the primary hydroxyl radical scavenger, so the overall scavenging rate constant is essentially determined by the DOC concentration of the secondary/tertiary effluent in question. This is also the primary reason that ozone doses normalized to DOC concentration (i.e., O_3/DOC or O_3/TOC ratio) are so effective in achieving similar water quality objectives across diverse wastewater matrices. Bicarbonate, which is linked to the alkalinity of the wastewater, also has a significant, albeit lesser, effect on scavenging; all other scavengers are essentially negligible. Nitrite can be a notable scavenger for AOPs (Gerrity et al., 2016), but nitrite also reacts rapidly with dissolved ozone at a 1:1 mass-based ratio. Therefore, nitrite is consumed prior to impacting •OH oxidation of target constituents. That being said, reactions between ozone and nitrite have a significant impact on dosing and process efficacy, as will be described later.

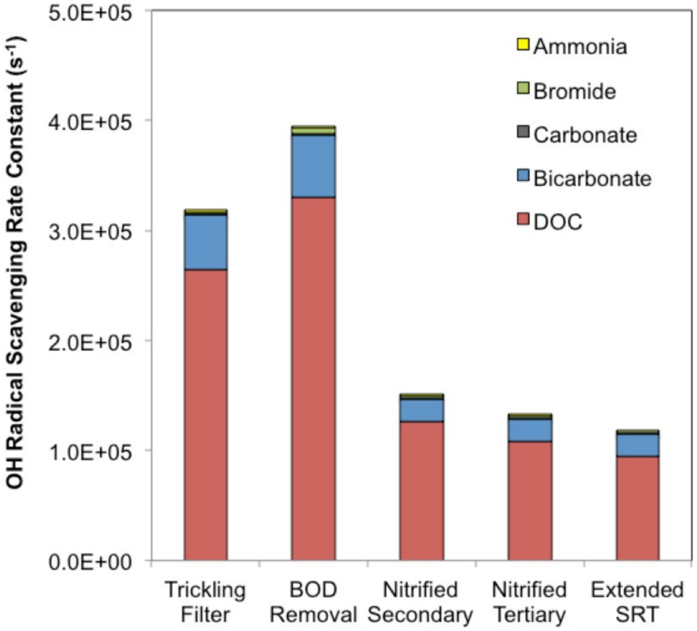


Figure 3-10. Relative Contributions to Hydroxyl Radical Scavenging During Ozonation as a Function of Pretreatment.

Even at concentrations typically observed in secondary effluent, the general consensus is that the vast majority of CECs pose a de minimis risk to public health in potable reuse applications (Trussell et al., 2016). Nevertheless, CEC attenuation is a common treatment objective and a principal justification for including ozonation in potable reuse treatment trains. Table 3-7 provides a summary of CEC concentrations that might be expected in various secondary/tertiary effluents as a function of biological treatment. Some of the reported differences in concentration are actually attributable to operational differences, with improved biological treatment and longer SRTs resulting in lower secondary effluent concentrations. For example, systems achieving full nitrification are likely to have low or non-detect concentrations of the most biodegradable compounds, such as naproxen and ibuprofen, while effluents with limited biological treatment may contain concentrations of naproxen and ibuprofen at the µg/L level. Naproxen and ibuprofen also have an important distinction in that naproxen is highly susceptible to ozone and ●OH oxidation whereas ibuprofen is moderately resistant to oxidation, hence their distinct 'groupings' in Table 3-7. Therefore, a system with poor biological treatment may have relatively high naproxen concentrations in the secondary effluent, but naproxen would likely be non-detect with only a moderate ozone dose. On the other hand, ibuprofen could still be present at the µg/L level even after ozonation, assuming poor upstream biological treatment. Table 3-7 also highlights the relationship between SRT and secondary effluent concentration for atenolol—a moderately biodegradable compound—with extended SRTs yielding up to 80 percent reductions in concentration (Gerrity and Neyestani, 2019). Atenolol can also be removed during biological filtration, which may at least partially explain the lower concentration for the nitrified tertiary vs. secondary. However, it is unclear whether the observed difference in atenolol concentration for the trickling filter vs. non-nitrified secondary is related to treatment or is simply a spatial/temporal artifact.

Table 3-7. Secondary/Tertiary Effluent Trace Organic Compound Concentrations (ng/L).
Groupings refer to compound susceptibility to ozone and •OH, as described later. Gray rows denote observed data from WRF-08-05 (Snyder et al., 2014) for compounds that are affected by differences in biological treatment. Any differences in concentration for the other compounds would likely be attributable only to spatial/geographic and temporal considerations. Therefore, constant concentrations have been assumed for those compounds for subsequent calculations.

Compound	Trickling Filter	Non-Nitrified Secondary	Nitrified Secondary	Nitrified Tertiary	Extended SRT
Group 1: Naproxen	2,700	320	<25	<25	<25 [a]
Group 2: Atenolol	1,300	2,100	421	120	93 [b]
Group 3A: Ibuprofen	9,500	47	<25	<25	<25 [a]
Group 3B: Phenytoin [c]	200	200	200	200	200
Group 4: Meprobamate [c]	200	200	200	200	200
Group 5: TCEP [c]	200	200	200	200	200
Sucralose [c]	50,000	50,000	50,000	50,000	50,000

[a] Assumed to be the same as nitrified secondary/tertiary

[b] Based on nitrified secondary and SRT benefit observed in Gerrity and Neyestani (2019)

[c] Assumed concentrations

The other compounds in Table 3-7 are biologically recalcitrant so their concentrations have no clear correlation with biological treatment. Instead, any observed differences in concentration are likely attributable to spatial/geographic or temporal considerations. For example, meprobamate is generally ubiquitous in U.S. wastewaters but was non-detect in the two Australian wastewaters in WRF-08-05 (Snyder et al., 2014), including the trickling filter effluent included in Table 3-7. To eliminate the confounding effects of location and time on subsequent calculations, a typical concentration of 200 ng/L was assumed for these compounds regardless of upstream treatment. Sucralose was not monitored in WRF-08-05 (Snyder et al., 2014) but is generally present in untreated and treated wastewater at concentrations ranging from 10-100 µg/L, hence an initial concentration of 50 µg/L (50,000 ng/L) was assumed for all treatment scenarios.

3.6.3 Ozone Dosing Considerations

As mentioned earlier, ozone dosing based on O_3/DOC or O_3/TOC is an effective strategy to achieve comparable effluent water quality across diverse wastewater matrices. This is because many ozone-reactive constituents are oxidized rapidly even at low ozone doses, and the remaining constituents rely on OH-based oxidation, for which DOC is the principal OH scavenger (Lee et al., 2013). A similar concept based on UV/DOC has even been demonstrated for UV AOP (Gerrity et al., 2016). Although effective, this dosing strategy has several key limitations: (1) it requires real-time monitoring and dose adaptation to feed water TOC concentrations and (2) it is inconsistent with historical disinfection frameworks that rely on ozone CT. The latter is not necessarily an issue when ozonation is applied primarily for CEC oxidation or bulk organic matter transformation upstream of biofiltration. Recent research has also identified alternatives to ozone CT (e.g., ΔUV_{254}) that could be implemented for validation of process efficacy (Gerrity et al., 2012).

This evaluation focuses on two ozone dose ratios (O_3/TOC = 0.5 and 1.5), with TOC and DOC assumed to be interchangeable for the remainder of the discussion. The applied ozone dose is first calculated as the product of the O_3/TOC ratio and the TOC of the wastewater as a function of upstream biological treatment. The first adjustment is based on the rapid reaction between molecular ozone and nitrite, for which 1 mole of ozone (48 g/mole) is consumed for every mole of nitrite (46 g/mole). Based on the molecular weight of each compound, this essentially represents a 1:1 mass-based ratio when nitrite is reported 'as NO_2' rather than 'as N'. In Table 3-8, this calculation results in the "adjusted ozone" dose, which subsequently allows for the calculation of the "actual O_3/TOC" ratio (i.e., as opposed to the applied O_3/TOC ratio of 0.5 or 1.5). The "actual O_3/TOC" ratio is then used to characterize ozone demand/decay kinetics. Using combined data from an evaluation of five different secondary effluents, Amoueyan et al. (2017) developed relationships between O_3/TOC ratio, instantaneous ozone demand (IOD), and the first order decay rate constant for dissolved ozone (k_{O3}) (Figure 3-11). The resulting dissolved ozone residuals as a function of time (i.e., ozone decay curves) are illustrated for each ozone dosing scenario in Figure 3-12.

Table 3-8. Ozone Dosing Summary.

Compound	Trickling Filter	Non-Nitrified Secondary	Nitrified Secondary	Nitrified Tertiary	Extended SRT
TOC (mg-C/L)	26.4	15.0	7.0	6.0	5.25
Nitrite (mg/L) [a]	1.48	0.56	0.20	0.20	0.00
O_3/TOC = 0.5					
Applied Ozone (mg/L)	13.20	7.50	3.50	3.00	2.63
Adjusted Ozone (mg/L)	11.72	6.94	3.30	2.80	2.63
Actual O_3/TOC	0.44	0.46	0.47	0.47	0.50
IOD [b] (mg/L)	9.25	5.40	2.55	2.17	1.99
k_{O3} (min^{-1})	9.73	5.17	2.34	2.04	1.60
Ozone CT (mg-min/L)	0.25	0.30	0.32	0.31	0.40
Ozone Exposure (M s)	3.18×10^{-4}	3.72×10^{-4}	4.00×10^{-4}	3.86×10^{-4}	4.96×10^{-4}
•OH Exposure (M s)	1.32×10^{-10}	1.39×10^{-10}	1.42×10^{-10}	1.41×10^{-10}	1.53×10^{-10}
O_3/TOC = 1.5					
Applied Ozone (mg/L)	39.60	22.50	10.50	9.00	7.88
Adjusted Ozone (mg/L)	38.12	21.94	10.30	8.80	7.88
Actual O_3/TOC	1.44	1.46	1.47	1.47	1.50
IOD[b] (mg/L)	20.33	11.65	5.46	4.67	4.15
k_{O3} (min^{-1})	1.47	0.82	0.38	0.32	0.27
Ozone CT (mg-min/L)	12.14	12.62	12.85	12.73	13.60
Ozone Exposure (M s)	1.52×10^{-2}	1.58×10^{-2}	1.61×10^{-2}	1.59×10^{-2}	1.70×10^{-2}
•OH Exposure (M s)	5.12×10^{-10}	5.19×10^{-10}	5.22×10^{-10}	5.21×10^{-10}	5.33×10^{-10}

[a] Note that the earlier nitrite concentration was presented "as N" while this is presented as "NO_2"

[b] IOD = instantaneous ozone demand.

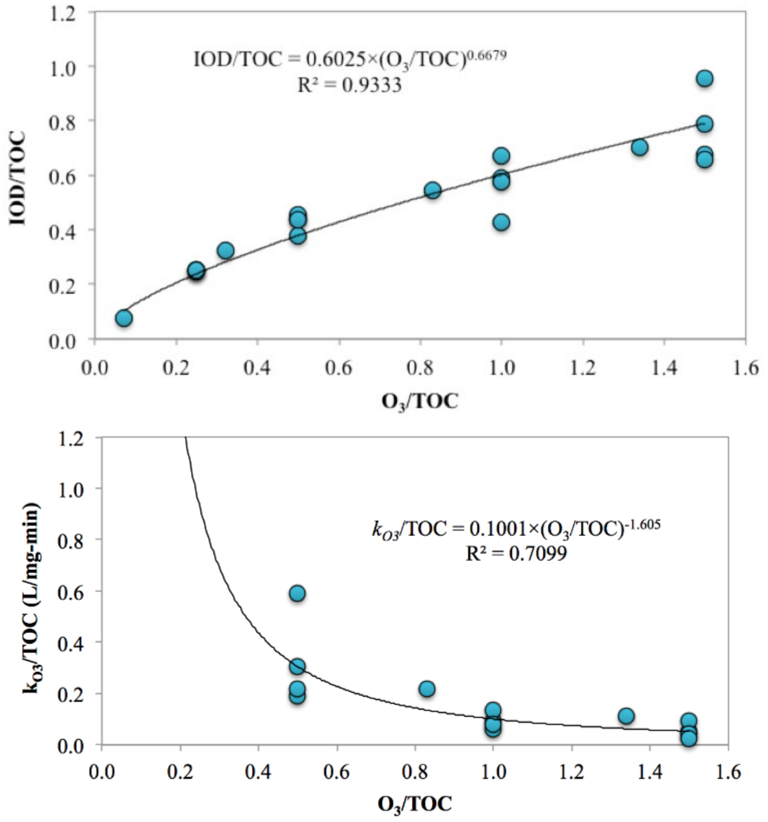


Figure 3-11. Relationship Between the TOC-Normalized Instantaneous Ozone Demand (IOD) and O_3/TOC Ratio (Top). Relationship Between the TOC-Normalized First Order Ozone Decay Rate Constant (k_{O3}) and O_3/TOC Ratio (Bottom).

Source: Amoueyan et al. (2017).

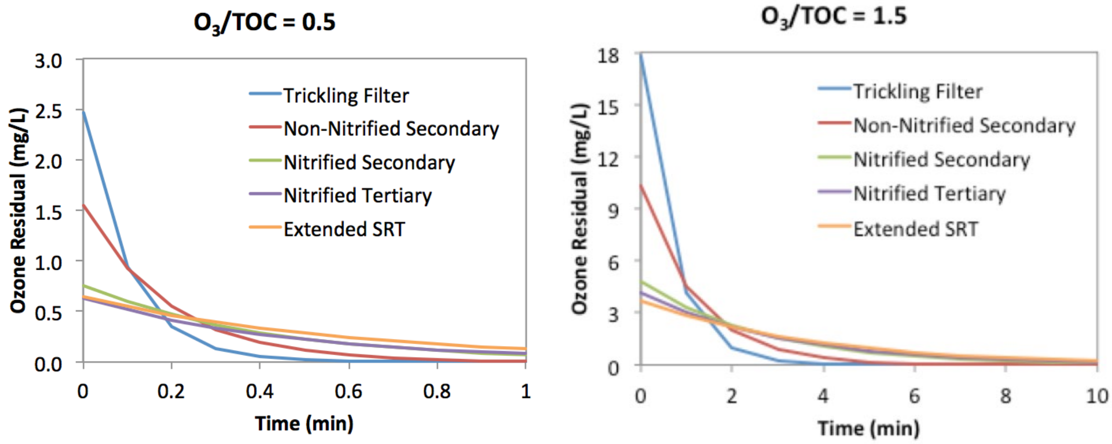


Figure 3-12. Ozone Decay Curves for the Secondary Biological Treatment Scenarios with Applied O_3/TOC = 0.5 (Left) and Applied O_3/TOC = 1.5 (Right).

The dissolved ozone residuals at time = 0 reflect the adjustments for the instantaneous ozone demands from nitrite and bulk organic matter.

These ozone demand/decay parameters were also used to calculate ozone CT values for each scenario using Equation 3-1. The ozone CT in units of mg-min/L is commonly used in the context of disinfection kinetics, but this value can also be converted to its molar equivalent in units of M-s for use in conjunction with second order rate constants describing the reactivity between dissolved ozone and target CECs. The overall kinetic relationship for estimating CEC oxidation based on reactions with dissolved ozone and •OH is described in Equation 3-2. For this evaluation, the overall •OH exposure for each scenario was determined using Equation 3-3 (Lee et al., 2013). Summaries of all water quality, ozone demand/decay, and oxidation kinetics parameters are provided in Table 3-8.

$$\mathrm{O_3\ CT\ (mg\text{-}min/L)} = \frac{\left[\left(\frac{\mathrm{O_3}}{\mathrm{TOC}}\right)\times\mathrm{TOC - IOD}\right]}{k_{\mathrm{O_3}}} \times \left(1 - e^{-k_{\mathrm{O_3}}t}\right) \qquad \text{(Equation 3-1)}$$

$$-ln\left(\frac{C}{C_0}\right) = k_{O_3,TOrC}\int[O_3]dt + k_{\cdot OH,TOrC}\int[\cdot OH]dt \qquad \text{(Equation 3-2)}$$

$$\int[\cdot\mathrm{OH}]\mathrm{dt\ (M\ s)} = 3.8\times10^{-10} \times \left(\frac{\mathrm{O_3}}{\mathrm{TOC}}\right) - 3.7\times10^{-11} \qquad \text{(Equation 3-3)}$$

3.6.4 Ozone Effluent Water Quality

There is now an abundance of peer-reviewed literature describing relationships between O_3/TOC ratios, contaminant oxidation (e.g., CECs), bulk organic matter transformation (e.g., UV absorbance and fluorescence), and even microbial inactivation. A subset of these relationships is summarized in Figure 3-13 and serve as the basis for the predicted effluent water quality data in this section (shown later in Tables 3-10 and 3-11).

An effective strategy for validating ozone process performance involves comparing observed vs. expected changes in UV_{254} absorbance. Based on the published relationship in Gerrity et al. (2012), applied O_3/TOC ratios of 0.5 and 1.5 would yield ΔUV_{254} values of 31-33 percent and 64-66 percent, respectively, after accounting for instantaneous ozone demand from nitrite and bulk organic matter. Although the ΔUV_{254} values would be comparable between the secondary/tertiary effluents, the absolute values would differ substantially because of the differences in feed water quality. Specifically, UV_{254} absorbance of the ozone effluents would range from 0.073-0.285 cm^{-1} and 0.037-0.146 cm^{-1} for O_3/TOC ratios of 0.5 and 1.5, respectively. UV transmittance (UVT) would then range from 52-71 percent for the ozonated trickling filter effluent to 84-92 percent for the ozonated secondary effluent with an extended SRT.

Beyond aesthetic water quality, these differences in UV transmissivity could have implications for downstream treatment, particularly if low pressure (germicidal) UV is employed for disinfection or photolysis. Table 3-9 summarizes the estimated energy consumption for a UV-based treatment process targeting a disinfection-based dose of 80 millijoules per square centimeter (mJ/cm^2) or a photolysis or AOP dose of 1,000 mJ/cm^2. Because of the aromaticity of the bulk organic matter in the wastewater, which absorbs a portion of the incident UV light, a considerable amount of energy would be required to achieve the target UV dose in a trickling filter effluent, particularly in the photolysis application (i.e., 0.87 Kilowatt hours per cubic meter [kWh/m^3]). However, the energy requirement could be reduced significantly with enhanced secondary/tertiary treatment and/or ozonation, down to 0.14 kWh/m^3 for the extended SRT and O_3/TOC of 1.5.

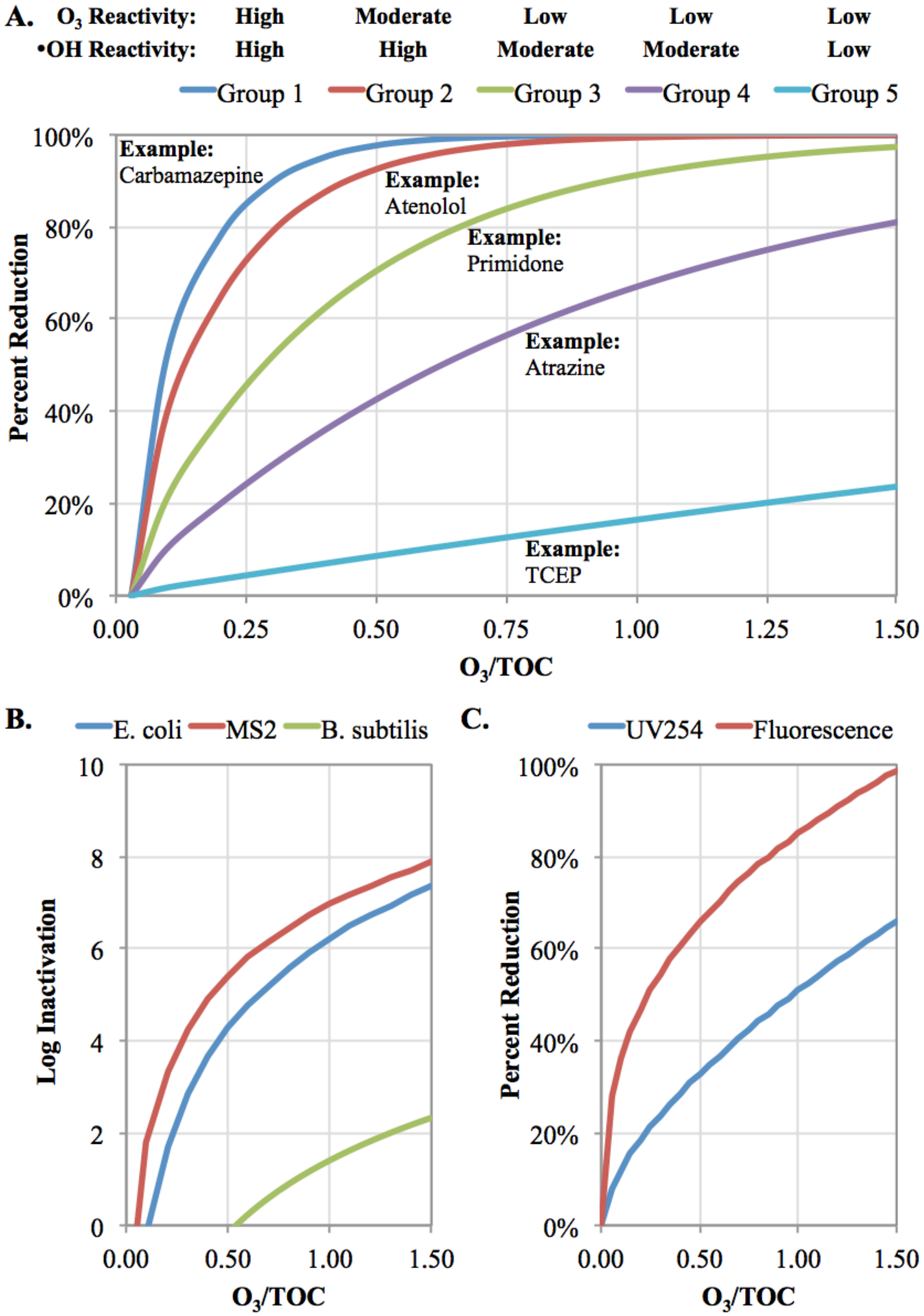


Figure 3-13. General Relationships Between O_3/TOC Ratio and CEC Oxidation (A) (Lee et al., 2013), Microbial Inactivation (B) (Gamage et al., 2013), and Bulk Organic Matter Transformation (C).
Data Source: Gerrity et al., 2012.

Table 3-9. Estimated Energy Consumption (kWh/m^3) for a Downstream UV Treatment Process as a Function of Ozone Dose, UV Dose, and Extent of Secondary/Tertiary Treatment.

UV Doses of 80 mJ/cm^2 and 1,000 mJ/cm^2 were Assumed for Disinfection and Photolysis Applications, respectively. Estimates are Based on UV Reactor Assumptions in Lee et al. (2016).

O_3/TOC	UV Dose (mJ/cm^2)	Trickling Filter	Non-Nitrified Secondary	Nitrified Secondary	Nitrified Tertiary	Extended SRT
0.0	80	0.07	0.05	0.03	0.02	0.02
	1,000	0.87	0.57	0.32	0.28	0.25
0.5	80	0.05	0.03	0.02	0.02	0.02
	1,000	0.61	0.40	0.24	0.21	0.19
1.5	80	0.03	0.02	0.01	0.01	0.01
	1,000	0.32	0.23	0.16	0.15	0.14

There are obviously trade-offs that must be balanced when making design and operational decisions. Table 3-9 demonstrates that there are substantial energy benefits for downstream UV disinfection or photolysis by employing enhanced secondary/tertiary treatment and/or high doses of ozone. However, the treatment upgrades required to achieve those energy benefits would have their own capital and O&M costs that would have to be considered. Moreover, higher doses of ozone could potentially lead to the formation of certain disinfection byproducts (DBPs), notably bromate and NDMA. For an O_3/TOC of 1.5 and no mitigation measures, Lee et al. (2016) reported bromate formation of up to 200 µg/L for a non-nitrified secondary effluent with a bromide concentration of 409 µg/L and up to 400 µg/L for a nitrified secondary effluent with a bromide concentration of 730 µg/L. There are some potential relationships between secondary/tertiary treatment and bromate formation potential, including reduced ozone CTs with higher ozone demands or reduced bromate formation in the presence of residual ammonia, but this was considered outside the scope of the current evaluation. Bromate mitigation is critically important for ozone-based treatment in potable reuse applications because there are few viable options for downstream removal other than high pressure membranes.

There is also a potential relationship between the extent of secondary treatment, ambient N-nitrosodimethylamine (NDMA) concentrations, and ozone-reactive NDMA precursors. WRF-08-05 (Snyder et al., 2014) and Gerrity et al. (2015) reported consistent formation of NDMA upon ozonation, with a non-nitrified secondary effluent reaching concentrations of up to 200 ng/L after ozonation. Unfortunately, NDMA formation was not monitored for the trickling filter effluent in WRF-08-05 (Snyder et al., 2014). Correlations between O_3/TOC and NDMA formation appear to be relatively weak, suggesting that NDMA formation is a rapid process even at low ozone doses. Therefore, the best strategies to control NDMA formation upon ozonation include enhanced biological treatment and source control to reduce concentrations of ozone-reactive NDMA precursors. In contrast with bromate, options for downstream NDMA mitigation include biofiltration (discussed later) and UV photolysis, hence the importance of UV transmissivity.

There are only a few instances in which CECs are directly or indirectly regulated in potable reuse applications. Several CECs have established U.S. EPA maximum contaminant levels (MCLs) (e.g., atrazine at 3 µg/L) or health advisory levels (e.g., PFOA/PFOS at 70 ng/L), and there are also compounds with state notification levels (e.g., 1,4-dioxane at 1 µg/L in California). In order to comply with "full advanced treatment" (FAT) requirements in California, potable reuse systems must satisfy specific criteria for the RO and AOP processes. While these requirements do not necessarily apply to upstream ozonation, they can still be used as a point of reference for ozone dosing and process validation. Specifically, the AOP criterion for FAT is 0.5-$\log_{10}$ (or 69 percent) destruction of 1,4-dioxane. This target constituent has potential public health implications when present in potable reuse systems, but it is more commonly considered a surrogate for other low molecular weight organics that might pass through RO. Similar to compounds like sucralose ($k_{\bullet OH,CEC} = 1.6\times10^9$ M^{-1} s^{-1}) and meprobamate ($k_{\bullet OH,CEC} = 3.7\times10^9$ M^{-1} s^{-1}), 1,4-dioxane ($k_{\bullet OH,CEC} = 2.4\times10^9$ M^{-1} s^{-1}) is highly resistant to ozone ($k_{O3,CEC} < 0.1$ M^{-1} s^{-1}) and slightly susceptible to OH, thereby requiring high ozone doses to achieve adequate OH exposures for attenuation.

Figure 3-3 (presented earlier) illustrates the expected percent reductions in CEC concentrations as a function of oxidant susceptibility. As summarized in Table 3-10 and Table 3-11, the O_3/TOC ratios of 0.5 and 1.5 are expected to achieve 0.14-0.16 $\log_{10}$ and 0.53-0.56 $\log_{10}$ destruction of 1,4-dioxane, respectively. Based on the previously assumed feed concentrations, the more recalcitrant CECs (e.g., meprobamate, sucralose, and TCEP) would be detectable even after an O_3/TOC of 1.5, but there would be considerable reductions in the more susceptible compounds, notably naproxen, atenolol, ibuprofen, and phenytoin. For the trickling filter effluent, ibuprofen would still be present at 3,573 ng/L and 186 ng/L in the two ozone effluents, respectively, because (1) it is present at high concentrations in untreated wastewater, (2) poor biological treatment would achieve limited removal of this otherwise highly biodegradable compound, and (3) it is only moderately susceptible to oxidation.

The final grouping in Figure 3-10 and Table 3-11 includes the microbial indicators/surrogates (*E. coli* and MS2 bacteriophage) and pathogens (*Giardia* and *Cryptosporidium*). Microbial inactivation was predicted based on ozone CT for MS2, *Giardia*, and *Cryptosporidium* using U.S. EPA's established CT relationships (Pecson et al., 2021) and ΔUV_{254} relationships for *E. coli* and MS2 using previously published relationships (Gamage et al., 2013; Gerrity et al., 2012). For an O_3/TOC of 0.5, *E. coli* and MS2 exhibited similar LRVs when MS2 inactivation was estimated based on ozone CT, with enhanced secondary/tertiary treatment providing up to 0.3-log and 1.3-log benefits for *E. coli* and MS2, respectively. However, the estimated LRVs for MS2 were considerably higher when based on ΔUV_{254}. This illustrates the potential regulatory 'gap' in certain ozone dosing scenarios, specifically when ozone is dosed near or below the IOD (e.g., $O_3/TOC<0.5$) or when supplemented with H_2O_2 to drive the AOP mechanism. In these scenarios, the ozone CT and corresponding LRV may be overly conservative compared to the observed inactivation of viruses (Wolf et al., 2019), which are inactivated rapidly even at very low CT values (Wolf et al., 2018). Due to a lack of data describing potential relationships between ΔUV_{254} and protozoa inactivation, these predictions relied on the conventional ozone CT framework, with *Giardia* LRVs ranging from 1.1-1.7 and *Cryptosporidium* LRVs essentially negligible for the lower ozone dose. For the O_3/TOC of 1.5, inactivation of *E. coli*, MS2, and *Giardia* reached the assumed maximum LRV of 6.0, while the estimated *Cryptosporidium* LRV ranged from 3.1-3.5 depending on the level of upstream treatment.

Table 3-10. Predicted Ozone Effluent Water Quality for an Applied O_3/TOC of 0.5.

Predicted CEC concentrations (ng/L) are based on initial concentrations in Table 2, CEC-specific second order rate constants from Lee et al. (2013), and dissolved ozone and •OH exposures from Table 4 of Lee et al. (2013).

Parameter	Trickling Filter	Non-Nitrified Secondary	Nitrified Secondary	Nitrified Tertiary	Extended SRT
Bulk Organic Matter					
ΔUV_{254}	31%	31%	32%	32%	33%
UV_{254} (cm^{-1})	0.285	0.184	0.100	0.086	0.073
UVT	52%	65%	80%	82%	84%
CEC Oxidation					
Δ1,4-Dioxane ($\log_{10}$)	0.14	0.14	0.15	0.15	0.16
Sucralose	40,498	40,038	39,817	39,931	39,141
Group 1: Naproxen	<MRL [a]	<MRL	<MRL	<MRL	<MRL
Group 2: Atenolol	<MRL	<MRL	<MRL	<MRL	<MRL
Group 3A: Ibuprofen	3,573	17	<MRL	<MRL	<MRL
Group 3B: Phenytoin [b]	87	83	82	82	76

Parameter	Trickling Filter	Non-Nitrified Secondary	Nitrified Secondary	Nitrified Tertiary	Extended SRT
Group 4: Meprobamate [b]	123	120	118	119	114
Group 5: TCEP [b]	186	185	185	185	184
Sucralose [b]	40,498	40,038	39,817	39,931	39,141
Disinfection [c]					
E. coli LRV (ΔUV_{254})	2.8	2.9	2.9	2.9	3.1
MS2 LRV (contact time [CT])	2.2	2.6	2.8	2.7	3.5
MS2 LRV (ΔUV_{254})	4.2	4.3	4.3	4.3	4.5
Giardia LRV (CT)	1.1	1.3	1.4	1.3	1.7
Cryptosporidium LRV (CT)	0.1	0.1	0.1	0.1	0.1

[a] The MRL was assumed to be 10 ng/L for all compounds for this summary

[b] Initial concentrations assumed to be 200 ng/L, or 50,000 ng/L for sucralose

[c] Parentheses indicate method of predicting LRV.

Table 3-11. Predicted Ozone Effluent Water Quality for an Applied O_3/TOC of 1.5.

Predicted CEC concentrations (ng/L) are based on initial concentrations in Table 17, CEC-specific second order rate constants from Lee et al. (2013), and dissolved ozone and •OH exposures from Table 19 of Lee et al. (2013).

Parameter	Trickling Filter	Non-Nitrified Secondary	Nitrified Secondary	Nitrified Tertiary	Extended SRT
Bulk Organic Matter					
ΔUV_{254}	64%	65%	65%	65%	66%
UV_{254} (cm^{-1})	0.146	0.094	0.051	0.044	0.037
UVT	71%	80%	89%	90%	92%
CEC Oxidation					
Δ1,4-Dioxane ($\log_{10}$)	0.53	0.54	0.55	0.54	0.56
Group 1: Naproxen	<MRL[a]	<MRL	<MRL	<MRL	<MRL
Group 2: Atenolol	<MRL	<MRL	<MRL	<MRL	<MRL
Group 3A: Ibuprofen	186	<MRL	<MRL	<MRL	<MRL
Group 3B: Phenytoin [b]	<MRL	<MRL	<MRL	<MRL	<MRL
Group 4: Meprobamate [b]	30	29	29	29	28
Group 5: TCEP [b]	150	149	149	149	148
Sucralose [b]	22,016	21,765	21,644	21,706	21,275
Disinfection [c]					
E. coli LRV (ΔUV_{254})	6.0[d]	6.0	6.0	6.0	6.0
MS2 LRV (CT)	6.0	6.0	6.0	6.0	6.0
MS2 LRV (ΔUV_{254})	6.0	6.0	6.0	6.0	6.0
Giardia LRV (CT)	6.0	6.0	6.0	6.0	6.0
Cryptosporidium LRV (CT)	3.1	3.2	3.3	3.3	3.5

[a] The maximum residue level (MRL) was assumed to be 10 ng/L for all compounds for this summary; [b] Initial concentrations assumed to be 200 ng/L, or 50,000 ng/L for sucralose; [c] Parentheses indicate method of predicting LRV; [d] Maximum LRV assumed to be 6.0.

3.6.5 BAC Effluent Water Quality

For potable reuse applications, the primary role of the biofiltration process (e.g., BAC) is the removal of biodegradable effluent organic matter, specifically the biodegradable transformation products (e.g., carboxylic acids and aldehydes) that form during upstream ozonation (Wert et al., 2007). This is important for mitigating increases in effluent toxicity that have previously been observed after ozonation (Stalter et al., 2010a, 2010b) and for overall reductions in TOC in the final product water, particularly if that water is eventually chlorinated for final disinfection (Arnold et al., 2018). Although reductions in CEC concentrations may be observed during biofiltration, this is generally not a principal objective, perhaps with the exception of NDMA (Bacaro et al., 2019) or 1,4-dioxane in specific applications. For example, Hampton Roads Sanitation District recently demonstrated enhanced 1,4-dioxane removal by specific chemicals (e.g., propane) to drive co-metabolism or upregulation of critically important genes. On the other hand, increased concentrations of some CECs have also been observed following biofiltration, presumably due to desorption of the compounds from the carbon media (Bacaro et al., 2019).

Biofiltration may offer 'polishing' of residual concentrations of biodegradable, oxidant-resistant compounds that might persist through poor secondary biological treatment and low-dose ozonation. For example, Table 3-10 and Table 3-11 predict residual concentrations of ibuprofen in the trickling filter and non-nitrified secondary effluents after ozonation. Downstream biofiltration would likely reduce these concentrations but not necessarily to the MRL. With the exception of specific biological treatment scenarios (e.g., trickling filters and non-nitrified secondary effluents) or operational upsets, there are very few compounds that are likely to be present in an ozonated secondary or tertiary effluent that would exhibit consistent/measurable removal during biofiltration. The compounds that would be susceptible to biofiltration are likely to be removed upstream during secondary biological treatment or during ozonation. This is why it is difficult to identify specific compounds that could serve as indicators of process efficacy for biofiltration.

Based on the discussion above, the subsequent analysis focuses on two objectives for the BAC process: (1) TOC removal and (2) NDMA removal (Table 3-12). The TOC removal was estimated by first calculating the amount of biodegradable dissolved organic carbon (BDOC) generated as a function of O_3/TOC ratio (Eq. 3-4), and then a kinetic relationship ($k_{\text{BDOC,BAC}}$ = 0.26 min^{-1}) was used to calculate the amount of BDOC removed as a function of empty bed contact time (EBCT) (Gifford et al., 2018). This change in BDOC was subtracted from the TOC of each ozone effluent to estimate the TOC concentration of the BAC effluent. A similar kinetic relationship was used to estimate NDMA removal as a function of EBCT ($k_{\text{NDMA,BAC}}$ = 0.20 min^{-1}) (Bacaro et al., 2019). Ozone effluent NDMA concentrations were based on WRF-08-05 (Snyder et al., 2014) and Gerrity et al. (2015), with reductions in NDMA formation assumed for longer SRTs and/or tertiary (bio)filtration. The NDMA concentrations were assumed to be independent of ozone dose.

$$\text{BDOC}_0\ (\text{mg-C/L}) = \text{TOC} \times \left(0.140 \times \left(\frac{\text{O}_3}{\text{TOC}}\right) + 0.146\right) \qquad \text{(Equation 3-4)}$$

As might be expected based on the secondary/tertiary effluent water quality, there were large differences in TOC concentration for the various ozone-BAC effluents. In terms of TOC removal, the effects of ozone dose (i.e., bulk organic matter transformation) were more pronounced than those of EBCT. In other words, there was little benefit in terms of TOC removal when the EBCT was doubled from 10 to 20 minutes. On the other hand, there was a significant benefit for NDMA removal from a regulatory compliance perspective with the longer EBCT (i.e., relative to the California notification level of 10 ng/L). For the trickling filter and non-nitrified secondary effluent, effluent NDMA decreased to 16 ng/L and 2 ng/L for EBCTs of 10 minutes and 20 minutes, respectively, and with enhanced secondary/tertiary treatment, effluent NDMA decreased to <10 ng/L and <MRL, respectively. In a potable reuse application, downstream UV disinfection/photolysis would likely be employed, which would provide an additional barrier for NDMA, so this should be taken into consideration when evaluating the potential benefits of longer EBCTs. Assuming a UV feed concentration of 16 ng/L and a first order photolysis rate constant of $4.5\times10^{-3}\ (\text{mJ/cm}^2)^{-1}$ (Gerrity et al., 2016), a disinfection-level dose of 80 mJ/cm^2 would achieve an NDMA concentration of 11 ng/L, which still exceeds the 10-ng/L

notification level. However, a photolysis or AOP-level dose of 1,000 mJ/cm^2 would reliably achieve the notification level and would even satisfy the 10^{-6} risk level of 0.69 ng/L.

Table 3-12. Predicted Ozone-BAC Effluent Water Quality as a Function of Upstream Secondary/Tertiary Treatment, O_3/TOC Ratio, and EBCT.

Parameter	Trickling Filter	Non-Nitrified Secondary	Nitrified Secondary	Nitrified Tertiary	Extended SRT
TOC (mg-C/L)	26.4	15.0	7.0	6.0	5.25
NDMA (ng/L) [a]	120	120	50	25	25
O_3/TOC = 0.5 and EBCT = 10 min					
Influent BDOC (mg-C/L)	5.50	3.16	1.48	1.27	1.13
Effluent BDOC (mg-C/L)	0.41	0.23	0.11	0.09	0.08
TOC Removal (mg-C/L)	5.09	2.93	1.37	1.17	1.05
Effluent TOC (mg-C/L)	21.31	12.07	5.63	4.83	4.20
Effluent NDMA (ng/L)	16	16	6.8	3.4	3.4
O_3/TOC = 0.5 and EBCT = 20 min					
Influent BDOC (mg-C/L)	5.50	3.16	1.48	1.27	1.13
Effluent BDOC (mg-C/L)	0.03	0.02	0.01	0.01	0.01
TOC Removal (mg-C/L)	5.47	3.14	1.48	1.26	1.13
Effluent TOC (mg-C/L)	20.93	11.86	5.52	4.74	4.12
Effluent NDMA (ng/L)	2.2	2.2	<MRL [b]	<MRL	<MRL
O_3/TOC = 1.5 and EBCT = 10 min					
Influent BDOC (mg-C/L)	9.19	5.26	2.46	2.11	1.87
Effluent BDOC (mg-C/L)	0.68	0.39	0.18	0.16	0.14
TOC Removal (mg-C/L)	8.51	4.87	2.28	1.95	1.73
Effluent TOC (mg-C/L)	17.89	10.13	4.72	4.05	3.52
Effluent NDMA (ng/L)	16	16	6.8	3.4	3.4
O_3/TOC = 1.5 and EBCT = 20 min					
Influent BDOC (mg-C/L)	9.19	5.26	2.46	2.11	1.87
Effluent BDOC (mg-C/L)	0.05	0.03	0.01	0.01	0.01
TOC Removal (mg-C/L)	9.14	5.23	2.45	2.10	1.86
Effluent TOC (mg-C/L)	17.26	9.77	4.55	3.90	3.39
Effluent NDMA (ng/L)	2.2	2.2	<MRL	<MRL	<MRL

[a] Assumed based on observations in WRF-08-05 (Snyder et al., 2014) and Gerrity et al. (2015)

[b] NDMA MRL assumed to be 1 ng/L.

For potable reuse, California has a wastewater-derived TOC benchmark of 0.5 mg/L, the U.S. EPA has a non-enforceable target of 2 mg/L, and Florida has a benchmark of 3 mg/L. Beyond these examples, there are few guidelines for effluent TOC concentration or TOC removal in potable reuse applications. One alternative for assessing ozone-BAC effluent water quality is based on expected DBP concentrations upon final chlorination (Arnold et al., 2018). Consistent with the TOC benchmarks for Florida and the U.S. EPA, Figure 3-14 indicates that reasonable targets are ~3 mg/L to achieve the TTHM MCL with minimal buffer, or 2 mg/L with a ~25 percent compliance buffer. Only the most extensive treatment scenario in this evaluation (i.e., extended SRT with O_3/TOC = 1.5 and EBCT = 20 minutes) approaches the 3 mg/L target, while all others would require additional treatment (e.g., upstream enhanced coagulation or downstream ion exchange or granular activated carbon) to even approach the high-end TOC benchmark.

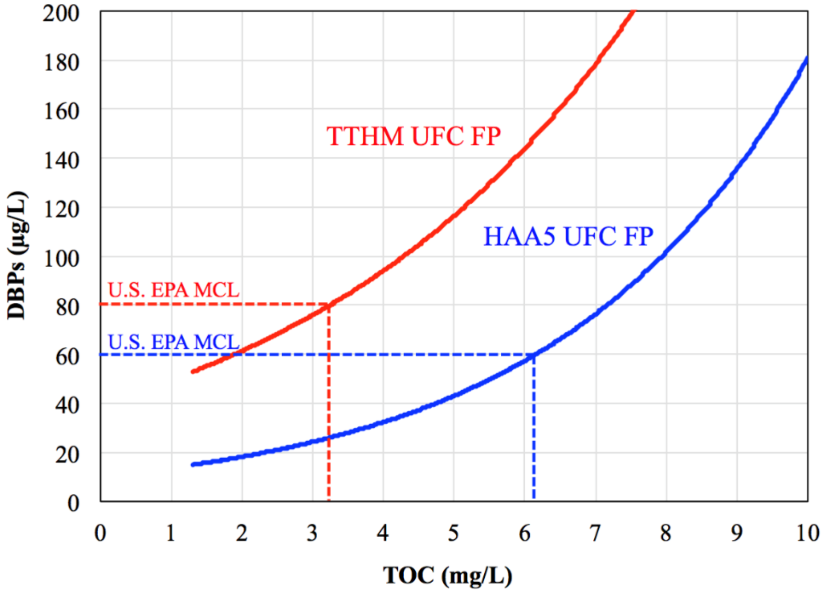


Figure 3-14. Generalized DBP Formation Potential, Specifically for Total TTHMs and the Five Regulated Haloacetic Acids (HAA5), as a Function of Total Organic Carbon (TOC) Concentration.
The DBP formation potential tests were performed using the uniform formation conditions (UFC) approach.
Source: Arnold et al. (2018).

One final operational consideration for BAC related to upstream treatment is backwash frequency. Turbidity is expected to vary as a function of secondary/tertiary treatment, with Table 3-6 assuming a value of 20 NTU for trickling filters and non-nitrified secondary effluents, 5 NTU for a fully-nitrified secondary effluent, and 0.5 NTU for a tertiary effluent. As noted earlier in this chapter, this project included a comparison of secondary and tertiary effluent as the feed to a pilot-scale ozone-biofiltration system. The operational data indicated that secondary effluent required daily backwashing, whereas the tertiary effluent required only weekly backwashing to maintain operational set points. As noted earlier in the chapter, using secondary effluent as the feed may also lead to more rapid breakthrough of GAC when used for adsorption downstream of ozone-BAC. Although not included in the cost analysis below, these issues would have implications for O&M that might justify enhanced upstream treatment.

3.6.6 Cost Considerations

The final component of this evaluation considers the cost implications for ozone-BAC in the context of variable upstream secondary/tertiary treatment. Although developed in 2011, the cost estimation approach detailed in Plumlee et al. (2014) may still provide a valuable basis for comparison. The models from that study were used to develop capital and O&M cost estimates for the ozone and BAC components of a hypothetical treatment train. The evaluation considered three different flow rates (1 mgd, 10 mgd, 100 mgd), two different ozone dose (O3/TOC = 0.5 and O3/TOC = 1.5), and two different EBCTs (10 minutes and 20 minutes). The various secondary/tertiary treatment scenarios were considered based on changes in ozone feed TOC concentration, which directly impacted the applied ozone dose. Plumlee et al. (2014) is primarily based on a default applied ozone dose of 3 mg/L, but the paper also provides a framework to consider other ozone doses. Therefore, the cost model can distinguish the higher ozone dose required for a trickling filter effluent with a TOC concentration of 26.4 mg-C/L versus the lower ozone dose required for an extended SRT secondary effluent with a TOC concentration of 5.25 mg-C/L. Separate BAC cost models are also provided for EBCTs of 10 minutes and 20 minutes and for flow rates ranging from 1-10 mgd and >10 mgd. For the current analysis, the baseline cost estimates were adjusted to 2021 U.S. dollars using the Engineering News Record (ENR) Construction Cost Indices (CCI) for September 2011 (9116) and December 2021 (12481).

Summaries for capital and O&M costs are provided in Table 3-13 and Table 3-14, respectively. It is important to note that these summaries do not account for any differences in cost specifically related to upstream secondary/tertiary treatment or for any downstream treatment processes needed for 'polishing' of the ozone-BAC effluent. Therefore, the potential ozone-BAC cost savings (up to $42 million in capital and $7 million in annual O&M) should be compared against the additional costs associated with the enhanced secondary/tertiary treatment required to achieve those savings. Furthermore, there may be additional costs associated with any post-treatment for the 'pass-through' constituents described earlier in this chapter, including PFAS and residual TOC (i.e., GAC adsorption), nitrosamines such as NDMA and NMOR (i.e., UV photolysis), total dissolved solids (i.e., NF or RO), and additional barriers for accruing pathogen log reduction values (LRVs). Despite these limitations, these summary tables provide an indication of how upstream treatment potentially impacts the costs of ozone and BAC.

Table 3-13. Summary of Estimated Capital Costs ($M) for the Various Secondary/Tertiary Treatment Scenarios.
All costs are based on a "Class 4" approach with an estimated accuracy of -30 percent to +50 percent.
Source: AACE, 2011; Plumlee et al., 2014.

Parameter	Trickling Filter	Non-Nitrified Secondary	Nitrified Secondary	Nitrified Tertiary	Extended SRT
Flow Rate = 1 mgd					
O_3/TOC=0.5 and EBCT=10 min	7.2	7.2	7.1	7.1	7.1
O_3/TOC=0.5 and EBCT=20 min	7.4	7.3	7.2	7.2	7.2
O_3/TOC=1.5 and EBCT=10 min	7.6	7.4	7.2	7.2	7.2
O_3/TOC=1.5 and EBCT=20 min	7.7	7.5	7.3	7.3	7.3
Flow Rate=10 mgd					
O_3/TOC=0.5 and EBCT=10 min	22	22	21	21	21
O_3/TOC=0.5 and EBCT=20 min	24	23	23	23	23
O_3/TOC=1.5 and EBCT=10 min	26	24	22	22	22
O_3/TOC=1.5 and EBCT=20 min	28	25	24	24	23
Flow Rate=100 mgd					
O_3/TOC=0.5 and EBCT=10 min	129	121	116	115	115
O_3/TOC=0.5 and EBCT=20 min	144	136	131	130	130
O_3/TOC=1.5 and EBCT=10 min	164	141	125	123	122
O_3/TOC=1.5 and EBCT=20 min	179	156	140	138	137

Table 3-14. Summary of Estimated O&M Costs ($M/year) for the Various Secondary/Tertiary Treatment Scenarios.

All costs are based on a "Class 4" approach with an estimated accuracy of -30 percent to +50 percent.
Source: (AACE, 2011; Plumlee et al., 2014).

Parameter		Trickling Filter	Non-Nitrified Secondary	Nitrified Secondary	Nitrified Tertiary	Extended SRT
	Flow Rate = 1 mgd					
O_3/TOC=0.5 and EBCT=10 min		0.1	0.1	0.1	0.1	0.1
O_3/TOC=0.5 and EBCT=20 min		0.2	0.1	0.1	0.1	0.1
O_3/TOC=1.5 and EBCT=10 min		0.2	0.2	0.1	0.1	0.1
O_3/TOC=1.5 and EBCT=20 min		0.2	0.2	0.1	0.1	0.1
	Flow Rate = 10 mgd					
O_3/TOC=0.5 and EBCT=10 min		1.0	0.8	0.8	0.7	0.7
O_3/TOC=0.5 and EBCT=20 min		1.1	1.0	0.9	0.9	0.9
O_3/TOC=1.5 and EBCT=10 min		1.6	1.2	0.9	0.9	0.9
O_3/TOC=1.5 and EBCT=20 min		1.7	1.3	1.1	1.0	1.0
	Flow Rate = 100 mgd					
O_3/TOC=0.5 and EBCT=10 min		9.7	8.4	7.5	7.3	7.3
O_3/TOC=0.5 and EBCT=20 min		11	9.9	9.0	8.9	8.8
O_3/TOC=1.5 and EBCT=10 min		16	12	9.0	8.7	8.4
O_3/TOC=1.5 and EBCT=20 min		17	13	11	10	10

CHAPTER 4

Module C: WRRF Effluent Impacts on MF/UF

4.1 Background

This module was tasked with understanding the interface parameters between the WRRF and AWT, i.e., the relationship between WRRF effluent water quality and the operations and performance of an AWT approach that starts with MF/UF. Design and operation of MF/UF systems for potable reuse is typically considered very site-specific, with on-site pilot studies and significant empirical iteration necessary to define the design flux and cleaning regimes for a future full-scale design. Some basic relationships are clear: WRRF effluents that are higher in solids and organics are more difficult to treat by MF/UF.

This module leverages pilot- and full-scale data from 12 facilities that include MF or UF membranes as the first step in AWT to provide a more semi-quantitative evaluation of what effluent water quality parameters affect MF/UF design and operation, and how. Specifically, the objective of this module was to assess the impacts of water quality and upstream water treatment processes on flux and translate these impacts to full-scale costs associated with MF/UF.

4.2 Approach

Existing utility data was compiled, and new data was requested, consisting of WRRF water quality parameters and AWT performance. Figure 4-1 shows the interface parameters that formed the basis of our utility data requests for this Module. This data was then analyzed as described in the following sections.

The interface relationships shown in Figure 4-1 were augmented through evaluation of the existing utility data as well. For example, upon close examination of data and operational challenges, presence of “macro” items such as fruit and vegetable stickers and insects (interface parameters) were identified as a potential problem ahead of MF/UF systems. The presence or absence and efficiency of tertiary filtration (WRRF parameter) has an impact on the collection of these stickers or insect larvae in pre-MF/UF strainers, which further influences the cleaning frequency, operational downtime, and labor cost. Another example is contribution of SRT and ammonia (WRRF parameters) to extracellular polymerase substances (EPS) (interface parameter) in the wastewater effluent, which in turn adversely affects operational membrane flux.

Additional data was generated using bench-scale MF/UF fouling tests to systematically evaluate the effects of various pretreatments on MF/UF fouling and permeate water quality and compare the proposed design flux to the corresponding operational flux at the pilot/ demo facility.

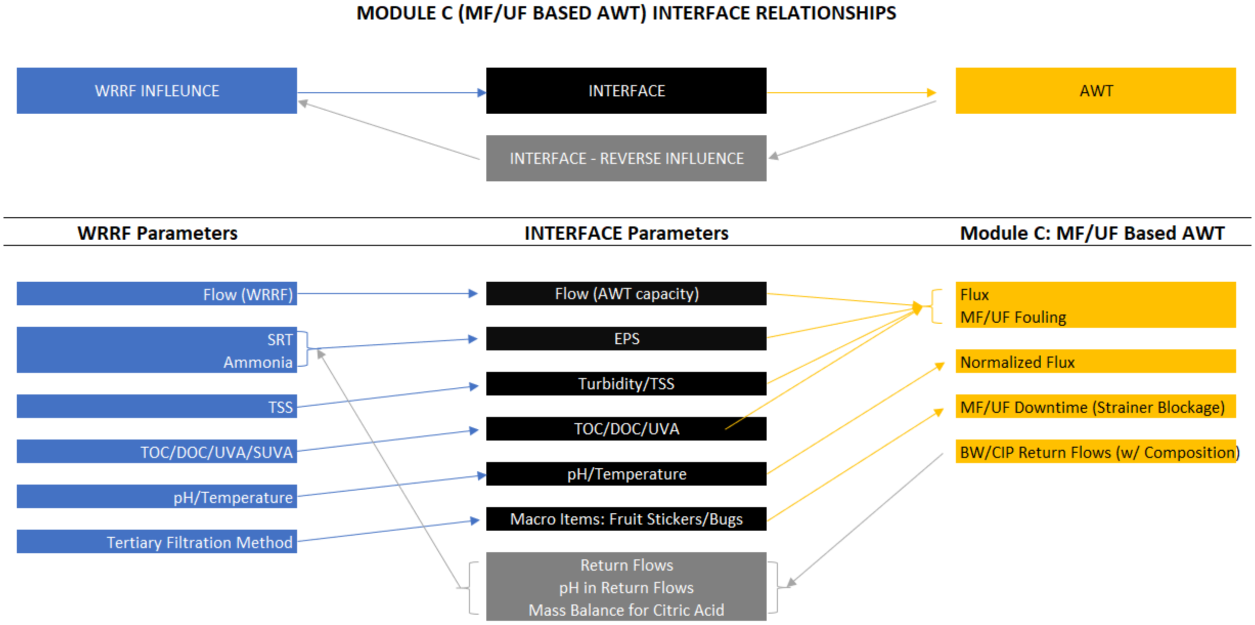


Figure 4-1. Module C Interface Relationships, which Serve as the Basis for Data Requests.

4.3 Utility Data Surveys

4.3.1 Utility Data Collection

Based on preliminary review of available data form Carollo-led pilot studies, a data request matrix specific to Module C was developed. Project team members met with Valley Water to explain the interface relationships (Figure 4-1) and aid with obtaining relevant data. Preliminary data received showed that when the interface parameters were paired with the directed data request, it was easier for the utility to fulfill the data request.

It often proved difficult to retrieve both WRRF and AWT data, as most sites operate independently and have minimal data sharing. Our experience retrieving data from different operator teams within our partner utilities highlights how siloed our treatment facilities still are between WRRF and AWT and point to the need for some institutional changes in addition to treatment optimization.

4.3.2 WRRF and AWT Correlations

WRRF and AWT operational and performance data was collected from partner utilities, grey literature, and Carollo's design group to evaluate interface parameters, particularly the effect of WRRF solids retention time (SRT) on MF/UF design flux. A summary of the utility partner datasets used for this effort is provided in Table 4-1. This was the focus because design flux is a key parameter that dictates MF/UF capital cost, which far outweighs operational costs on an annualized basis. As such, several water quality parameters (i.e., interface parameters) are related to the flux, including TOC, turbidity, TSS, ammonia, etc. These correlations were investigated to better understand the relationship between WRRF and AWT and how upstream treatment processes at WRRFs impact AWT.

Table 4-1. Module C - Technical Data Overview from Partner Utilities.

Location	Membranes Tested	Secondary Biological Process	Tertiary Filtration?	Additional Tertiary Treatment?
Daly City	• Toray HFU Type 2020N (UF) • Scinor SMT600-P80 (UF) • Dow SFD-2880XP (UF) • BASF Inge dizzer XL 0.9 MB 70WT (UF) • Nanostone CM-131 Ceramic (UF)	Low SRT Pure Ox activated sludge with BOD removal only	No	No
Palo Alto	• Dow IntegraFlux (UF) • Toray HFU Type 2020N (UF) • Hydranautics Hydracap Max 80 (UF)	Single-stage trickling filters followed by nitrified activated sludge	Yes, deep bed dual media filtration	Yes, low dose UV system for effluent discharge
Santa Cruz	• Toray HFU Type 2020N (UF) • Dow SFD-2880XP (UF)	Trickling filter solids contact process	No	No
Pismo Beach / IDE	• Pall UNA-620A (MF)	Denitrified secondary process	No	No
Las Virgenes MWD	• Pall UNA-620A (MF) • Toray HFU Type 2020AN (UF) • Dow SFD-2880XP (UF)	Nitrified secondary process	Yes, deep bed dual media filtration	Yes, chloramines with a minimum CT of 450 mg-min/L
El Paso	• Evoqua Memcor L40N/CP II (UF) • Pall UNA-620A (MF)	Intermittently nitrified	No	No
Valley Water	• Pall UNA-620A (MF)	Nitrified (but not denitrified)	No	No
OCWD	• Evoqua Memcor CS (UF) • Scinor SMT600-S60 Pilot Testing (UF)	Blend of effluents: nitrified and denitrified, trickling filter	No	No
West Basin	• Phase 4 Evoqua Memcor (UF) • Phase 5: Pall PVDF (MF)	Pure oxygen activated sludge for BOD removal only	No	No
Oxnard	• Pall UNA-620A (MF)	Non-nitrified secondary process	No	Chloramines
Post Falls	• Toray HFU-2020N (UF)	Nitrified and denitrified	No	Chloramines, floc / sed
Ventura	• Toray HFU-2020N (UF)	Nitrified and denitrified	Yes	Chloramines

The data in Figure 4-2 through Figure 4-4 show correlations between the proposed or actual MF/UF design flux as a function of WRRF SRT, effluent TOC, and effluent ammonia, respectively, for the same 13 WRRFs. Data are grouped and color coded by the type of upstream WRRF treatment. They are based on full-scale systems or pilot data being used to design full-scale systems. Only data at the actual or targeted (during pilot/demonstration tests) *design* flux is included, as AWT facilities have a wide range of variability in their operations and often deviate from the initial design. This variability was observed in full-scale data sets received from partner utilities that were compared to historical data sets used to design the respective facility. Whenever applicable, the full-scale data was excluded, and the corresponding design data was used. Data from facilities with enhanced tertiary treatment were excluded, such as chemical addition (e.g., coagulants) beyond typical chlorine or chloramine addition, ozonation, or biofiltration. We elected to not include these data in the correlations because these additional pretreatments occurred at the WRRF/AWT interface would sacrifice our ability to observe MF/UF performance strictly related to the secondary and/or tertiary wastewater treatment processes. Instead, the impacts of additional pretreatment were quantitatively evaluated through the bench-scale testing discussed below in Section 4.4.

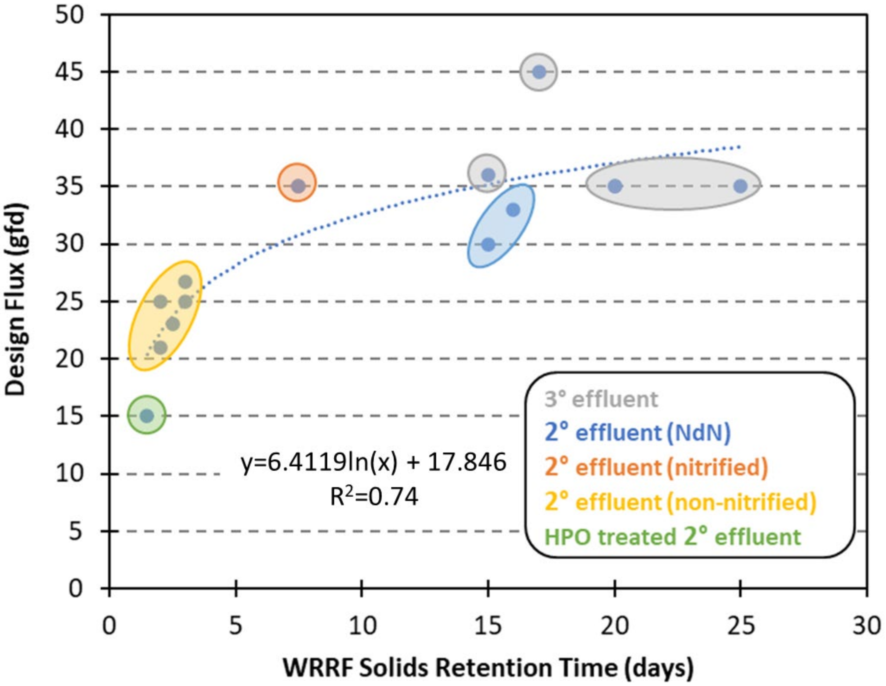


Figure 4-2. Correlation between WRRF Solids Retention Time and AWT MF/UF Design Flux.

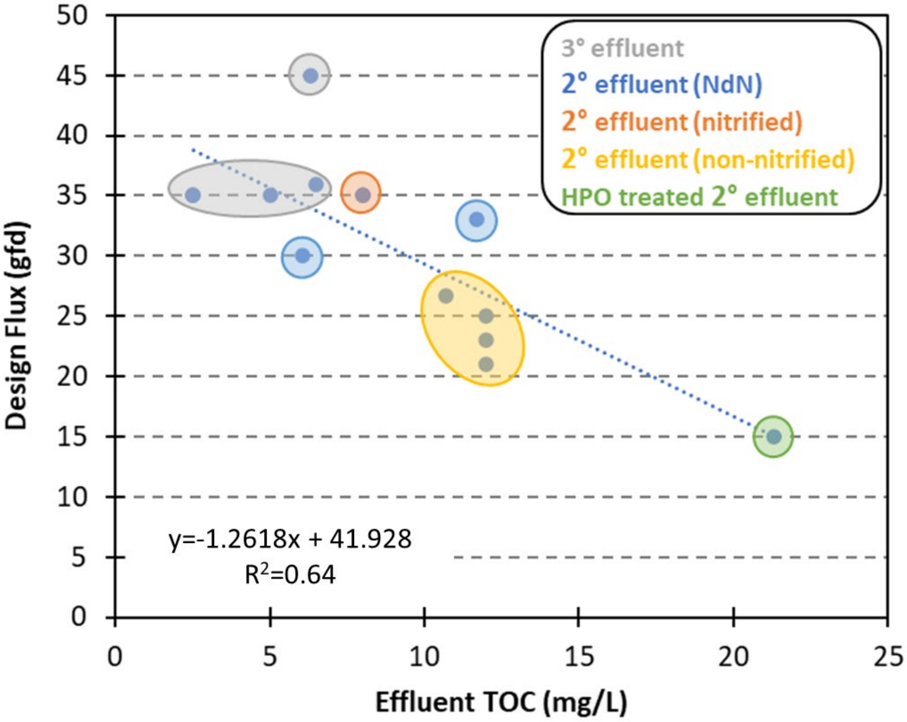


Figure 4-3. Correlation between WRRF Effluent TOC and MF/UF Design Flux.

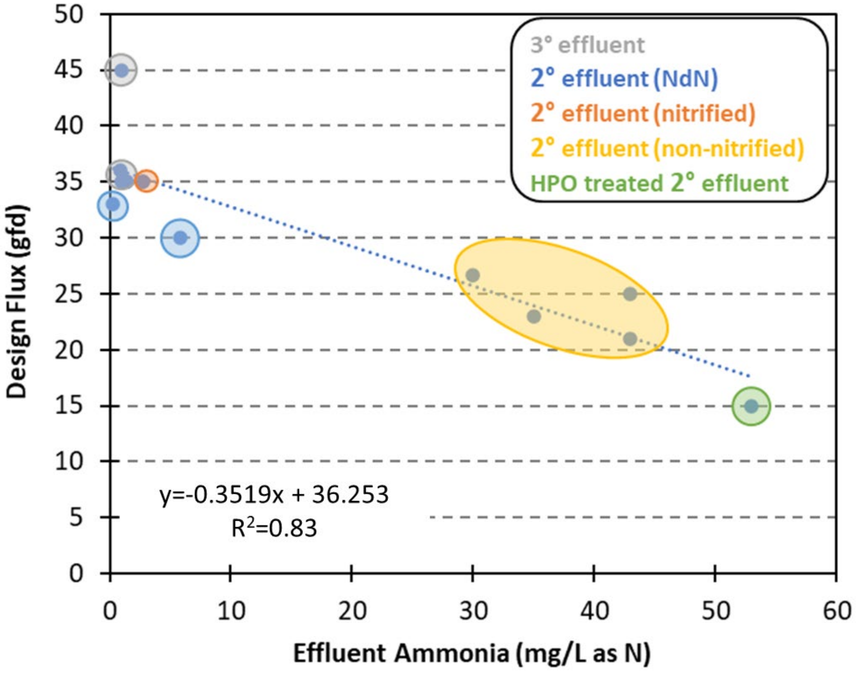


Figure 4-4. Correlation between WRRF Effluent Ammonia and MF/UF Design Flux.

Strong correlations were observed with respect to WRRF effluent quality and secondary treatment SRT. As expected, longer SRTs typically improved the effluent quality (e.g., reduced turbidity, lower ammonia, and TOC concentrations). Figure 4-2 demonstrates a log-linear relationship between MF/UF design flux and WRRF SRT ($y = 6.41\ln(x) + 17.8$ with $R^2 = 0.74$). WRRF pretreatment groupings indicate a trend of longer SRTs with more extensive secondary or tertiary treatment, suggesting that robust biological treatment often enables increased MF/UF design flux at the AWT. The high-purity oxygen (HPO) activated sludge facility has the lowest SRT of 1.5 days and the lowest MF/UF design flux of 15 gallons per square foot per day (GFD). AWT facilities receiving non-nitrified secondary effluent, with SRTs between 2 and 3 days achieved slightly higher fluxes of 21 to 26.7 GFD. Those with even longer SRTs (i.e., approximately 7.5 days) achieving nitrification and partial denitrification enabled design fluxes near 35 GFD. WRRFs with complete denitrification and SRTs around 15 days resulted in design fluxes near 30-33 GFD. Facilities with SRTs longer than 15 days tended to be those have tertiary filtration capacity. AWTs receiving tertiary effluent had design fluxes of about 35 GFD, with one facility reaching 45 GFD. While SRT in Figure 4-2 groups well by the degree of secondary or tertiary treatment applied, there is little difference in MF/UF design fluxes for AWT when SRT was over 15 days (with exception of the 45 GFD outlier), suggesting diminishing returns beyond this point. Additional data for WRRFs with nitrification/denitrification (NdN) and tertiary treatment capacities is needed to better understand the benefits or trade-offs between MF/UF fluxes and tertiary filtration.

The facility at 17 days SRT with a corresponding design flux of 45 GFD also demonstrates the high flux that may be achieved when robust biological treatment is maintained. This demonstration facility began UF operation at 30 GFD and systematically increased the flux to 45 GFD and greater without compromising filtration performance, cleaning regimes, or permeate water quality. While indicating the importance of WRRF treatment, this also shows the value in pushing flux or other design parameters during pilot and demonstration testing. Appropriately planned pilot testing that challenges the MF/UF system and typical fluxes may result in more refined design parameters that can save operational and capital costs at full-scale.

The data in Figure 4-3 demonstrate a negative linear correlation between AWT MF/UF design flux and WRRF effluent TOC (R^2=0.64). The relationship is skewed by the 45 GFD facility, but again shows some correlation between WRRF groupings, with the HPO facility containing the highest effluent TOC resulting in lowest flux, with the tertiary filtered effluent having the lowest TOC leading to highest flux. There is little difference between facilities achieving at least some extent of denitrification; however, more data would enable better distinction. Again, all facilities with non-nitrified secondary treatment were clustered with a TOC and flux falling between the HPO facilities and those with nitrification. Facilities with effluent TOC less than 7.5 mg/L all resulted in a design flux higher than 30 GFD, but lower effluent TOC did not necessarily relate to higher design flux.

MF/UF design flux as a function of effluent ammonia concentration is presented in Figure 4-4. Since nitrification oxidizes reduced nitrogen-containing compounds (primarily ammonia) to nitrite and nitrate, a clear distinction between facilities with and without nitrification capacity is observed. As expected, those with nitrification have low effluent ammonia concentrations, while facilities without nitrification have higher effluent ammonia concentrations. Higher ammonia correlates with lower design flux and includes WRRFs with lower SRTs. Ammonia does not enable us to distinguish nitrification from denitrification, so all WRRFs with secondary nitrification are clustered together with low effluent ammonia concentrations. In agreement with Figure 4-2 and Figure 4-3, more extensive wastewater treatment correlates with higher MF/UF design flux. Facilities with nitrification resulted in a design flux of 30-45 GFD, while non-nitrifying facilities with higher effluent ammonia concentrations generally led to a design flux less than 26 GFD. This trend suggests that a minimum level of wastewater treatment including secondary nitrification may be beneficial to enable higher MF/UF flux at the AWT, with a potential optimum SRT between 7.5 to 15 days (Figure 4-2) before diminishing returns of increasing SRT.

While SRT has an inherent degree of variability, due to difficulty in measuring and response to operational changes, the trends presented here show promising correlations between level of wastewater treatment (i.e., secondary and tertiary) and MF/UF design flux. While there is a noticeable advantage to higher level of wastewater treatment, there is potentially a point of diminishing returns in relation to MF/UF design flux. However, the effect of additional wastewater treatment (e.g., tertiary filtration, denitrification, etc.) on AWT performance beyond MF/UF flux was not evaluated in this module. It is likely that other process correlations may indicate advantageous capital or operational trade-offs associated with more extensive wastewater treatment. Pilot or demonstration testing can help WRRF/AWT facilities to better understand these trade-offs and the level of treatment needed at WRRFs to ensure effective and more economical AWT. In the case of the facility that operated MF/UF at a flux of 45 GFD in Figure 4-2, Figure 4-3, and Figure 4-4, pilot testing was critical and enabled the MF/UF system to be challenged for a better determination of an achievable flux and a better understanding of the operational ranges of the system.

4.4 Rapid Bench-Scale Screening Tests

Extensive pilot testing is typically required to design the appropriate MF/UF flux, whereas an acceptable bench-scale testing method that quickly informs design criteria is not yet available. Thus, the objective of the bench-scale testing was to develop a methodology that allows systematic evaluation of the impacts of various pretreatments on MF/UF performance as well as parallel comparison between the design flux and the operational flux at the *actual* utilities. While the project team believes that pilot testing will continue to be necessary to inform full-scale MF/UF system design, this bench-scale approach provides a tool to estimate MF/UF flux for projects that are in the planning or in conceptual design stages. For this module, it further highlights the impacts of different WRRF treatment processes and performance on effluent water quality and consequently, on membrane performance.

4.4.1 Methods

The bench-scale MF/UF system shown in
Figure 4-5 was used to conduct a series of fouling tests at Carollo's Water ARC® laboratory with effluent samples from three different WRRFs. The three WRRFs were strategically selected to cover a broad range of wastewater treatment processes and effluent water quality. In addition, because extensive pilot/demonstration studies were previously conducted at those sites, the obtained testing results could be compared across systems of different scales. Pretreatment processes, including coagulation, ozonation, and biofiltration, upstream of MF/UF were simulated at the bench to match those applied at the pilot or demonstration AWT facilities, from which the water samples were collected.

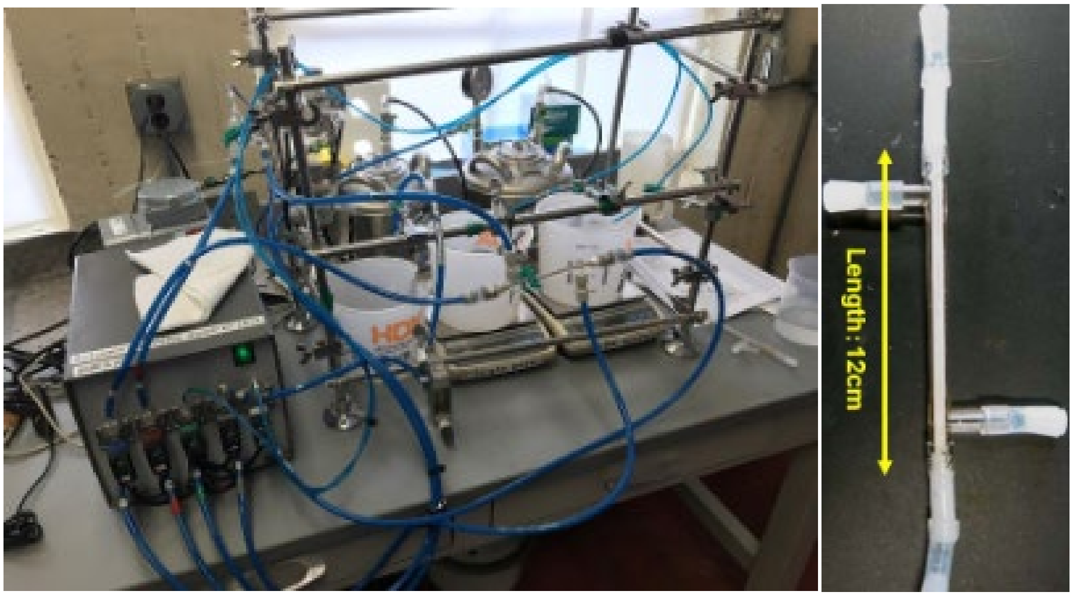


Figure 4-5. Bench-Scale MF/UF System Setup (left) and a UF Test Module (right).

4.4.1.1 WRRF Effluent

WRRF effluent (or AWT influent) samples were collected from Altamonte Springs pureALTA demonstration facility (Altamonte Springs, FL), Daly City (Daly City, CA), and Las Virgenes Municipal Water District (LVMWD; Calabasas, CA). Advanced treatment processes at each location are summarized below in Table 4-2. Two types of samples were collected from pureALTA, including tertiary effluent that feeds the pureALTA demonstration facility, and O_3-BAC effluent that feeds the UF system. A third UF feed was simulated by conducting O_3-BAC at the bench scale as described in Table 4-2. O_3-BAC operating conditions matched those applied at the demonstration facility. This was conducted to evaluate the scalability of bench testing results to demonstration testing results. Operating conditions are summarized in Table 4-2 and are discussed below in detail. Similarly, coagulant type and dose were the same as those applied at the Daly City pilot. This pilot is no longer in operation, and therefore a coagulated effluent sample was not available from the pilot. The tertiary filtered effluent from LVMWD was tested as is, with no additional bench-scale treatment at the Water ARC®.

Table 4-2. Summary of Samples for Bench-Scale MF/UF Fouling Tests.

Test	Site	Water Sample	Water ARC® pretreatment to UF	Treatment Processes
1	Altamonte	pureALTA feed	N/A	3° filtration/UF
2	Altamonte	pureALTA feed	BAC only (15 min EBCT)	3° filtration/BAC/UF
3	Altamonte	pureALTA feed	O_3-BAC (1: 1 mg/mg O_3: TOC and 15 min BAC EBCT)	3° filtration/O_3/BAC/UF
4	Altamonte	O_3-BAC effluent	N/A	3° filtration/O_3/BAC/UF
5	Daly City	2° Effluent	N/A	2° effluent/UF
6	Daly City	2° Effluent	Coagulation (5 mg/L of ACH)	2° effluent/coagulation/UF
7	LVMWD	MBR Effluent	N/A	MBR/UF

4.4.1.2 Bench-scale Test Conditions

BAF, O_3-BAF, and coagulation were conducted to the Altamonte Springs and Daly City WRRF effluent samples at the bench scale to evaluate the impacts of pretreatment on MF/UF performance and the scalability of bench testing results, as summarized in Table 4-2. The pureALTA feed sample was ozonated at an O_3: TOC ratio of 1 mg of O_3: 1 mg of C (TOC=7.4 mg/L, with non-detectable nitrite) using concentrated ozone stock solution that was prepared in distilled water. The ozonated and non-ozonated pureALTA feed was treated by biofiltration using BAC that had just finished service in a previous reuse pilot study but was not acclimated specifically to the pureALTA feed. The biofilters were operated in single-pass mode with an EBCT of 15 minutes, simulating the O_3-BAC system at the demonstration scale. The final BAC filtrate, with and without ozonation upstream, was collected and stored at 5 °C until the UF fouling tests commenced.

One batch of secondary effluent from Daly City WRRF was coagulated prior to the UF fouling tests. To simulate the pilot testing conditions, 5 mg/L of aluminum chlorohydrate (ACH) was dosed. Following rapid and slow mix, the settled effluent was collected and stored at 5 °C until subsequent UF fouling tests.

The same UF operating conditions were applied to all effluents. Miniature membrane modules of Toray HFU-2020N UF membranes were used (1.6×10^{-3} m^2 active surface area, 0.01 µm nominal pore size) and were replaced for each experiment. The system was operated at an ambient temperature of 20 °C and constant pressure (100 kPa), generating a very high flux and rapid fouling response. The fouling response was indicated by a decrease in permeate flux and was quantified by a fouling index. Each test was conducted for approximately 40 backwash/filtrate cycles, where each cycle produced 50 mL of permeate and 5 mL of backwash waste (backwashing at constant pressure of 150 kPa). At the end of each test, an air scour is added to the backwash to recover additional flux.

The data collected during the cycles is used to calculate three fouling indices (Figure 4-6):

1) δA [10^{12}/ m^2]: increasing rate of filtration resistance during a filtration cycle prior to backwashing (or between backwashes)
2) δBbw [10^{12}/ m^2]: increasing rate of filtration resistance following backwashing
3) $\delta Bair$ [10^{12}/ m^2]: increasing rate of filtration resistance from start to end of the test, including air scour (A/S)

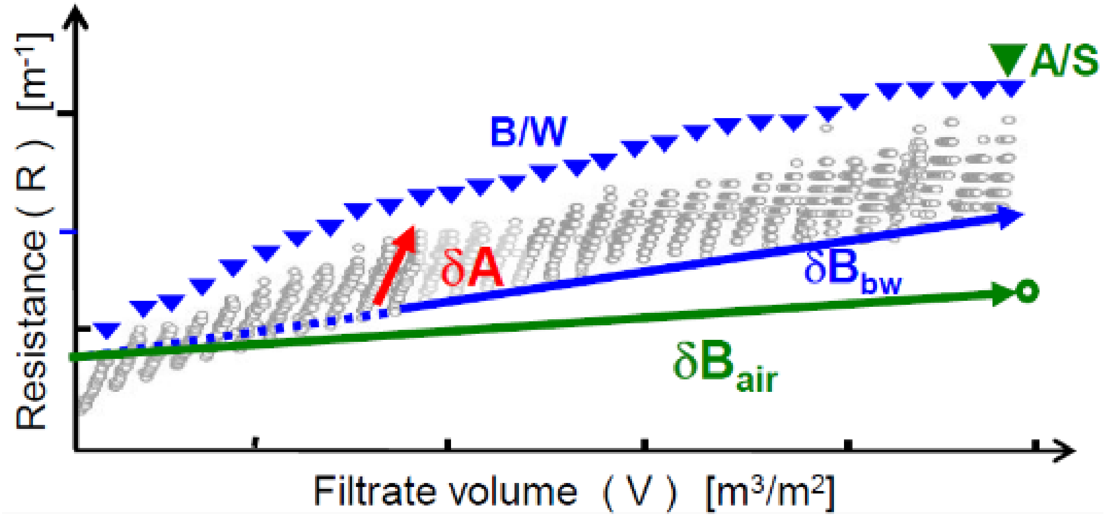


Figure 4-6. Filtration Resistance Parameters.

δA represents increasing rate of filtration resistance during a filtration cycle prior to backwashing (or between backwashes). δB_{bw} indicates increasing rate of filtration resistance following backwashing. δB_{air} is the increasing rate of filtration resistance from start to end of the test, including air scour (A/S).

4.4.1.3 Sampling and Water Analyses

All effluent samples were collected in 20 L carboys and were shipped and refrigerated at 5 °C until testing. Initial water quality characterization was conducted on all samples, which included pH, temperature, TOC, nitrate, nitrite, ammonia, turbidity, and zeta potential. Chlorine residual was also measured on the Altamonte Springs pureALTA feed prior to bench O_3-BAC treatment. The same constituents were analyzed following any pretreatment performed (e.g., coagulation, BAC, and O_3-BAC) and post UF.

Membrane performance parameters were monitored during all UF fouling tests, including flux and transmembrane pressure (TMP), based on which the rate of TMP increase, specific flux, and resistance were calculated for further comparison. The data generated were used to calculate fouling indices, which are essential to understand the extent to which pretreatment can mitigate membrane fouling and improve water quality. The fouling indices were also used to derive a suggested design flux for comparison to actual operational fluxes at each facility (e.g., Altamonte Springs, Daly City, LVMWD). The scalability of the testing results is crucial to the application of this bench-scale method as a potential design tool for MF/UF systems.

4.4.2 Results

The UF feed water quality of each water shipped to or generated at Water ARC® is provided in Table 4-3. Unfortunately, water quality for the lab-coagulated Daly City secondary effluent was not recorded.

Table 4-3. UF Feed Water Quality Summary.

	Units	pureALTA Feed	pureALTA O_3-BAC Effluent	pureALTA Feed + Lab O_3-BAC	Daly City Effluent	LVMWD UF Feed
Temperature	deg C	19.2	19.5	21.5	19.8	22
pH	SU	7.5	7.2	7.6	6.9	7.3
Alkalinity	mg/L as $CaCO_3$	114	111	92	312	123

Turbidity	NTU	0.402	0.392	0.690	8.03	0.664
Conductivity	µs/cm	502	502	501	1054	1107
UV254	cm^{-1}	0.149	0.073	0.054	0.357	0.097
TSS	g/L	0.0005	0.0005	0.0005	0.008	0.0005
ORP	millivolt (mV)	139	144	185	181	426
Hardness	mg/L	112	104	102	29	241
Total Ammonia	mg/L as N	0.047	0.04	0.01	73	1.3
COD	mg/L	141	112	11.8	92.6	16.2
TOC	mg/L	7.4	4.6	4.0	25.9	6.1
Total Chlorine	mg/L	0.033	0.02	0.01	0.11	1.45
Dissolved Oxygen	mg/L	6.58	14.6	8.45	7.04	7.84
Nitrite	mg/L	0.045	0.008	0.017	0.015	0.035
Nitrate	mV	5.68	6.25	4.88	0.274	6.73
Zeta Potential	mV	-11.4	-10.4	-12.1	-17.4	-14.3

The results from the UF fouling tests are shown in separate graphs for each facility: pureALTA (Figure 4-7), Daly City (Figure 4-8) and Las Virgenes (Figure 4-9), in addition to a direct comparison of UF feed water between pureALTA and Las Virgenes (Figure 4-10). In those figures, normalized resistance to flow (1/m) was shown as a function of area-normalized total filtrate volume produced (m^3/m^2). Fouling indices were also calculated for each water tested and compared to the design fluxes selected for each project (independent of this analysis). Results of the calculations are summarized below in Table 4-4.

The pureALTA data indicated that pretreatment with O_3-BAC significantly mitigated UF membrane fouling. Both bench- and demonstration-scale O_3-BAC (shown by gray and yellow symbols in Figure 4-7) provided significant reductions in filtration resistance compared to the pureALTA feed without O_3-BAC pretreatment (shown by the blue symbols in Figure 4-7). This is reflected also by the calculated fouling indices (Table 4-4), especially the δA, decreasing from over 20×10^{12} m^{-2} for untreated pureALTA feed to below 10×10^{12} m^{-2} for O_3-BAC-treated effluent at both bench- and demonstration-scale.

Treatment by BAC without ozonation (orange symbols) appeared to cause additional UF membrane fouling, although this was evidenced only by the gradual increase in fouling over time, and thus was captured in the tripled δBbw and δBbair values for the lab-BAC treated water in comparison to the pureALTA feed. Furthermore, the UF membrane performed significantly better with demonstration-scale O_3-BAC effluent compared to bench-scale O_3-BAC effluent, with values for all three fouling indices lower for the demonstration-scale O_3-BAF filtrate. Both of these effects may be related to a non-specifically acclimated BAC, which may have been sloughing biomass as it was exposed to a different feed.

The Daly City secondary effluent was difficult to filter. The 5 mg/L of ACH appeared to have little impact on fouling rates as shown in Figure 4-8. Higher coagulant doses tested during later pilot testing phases may have provided additional improvement in UF flux but additional ACH doses were not tested at the bench scale. Fouling rates were so high that it made calculation of fouling indices (δA) challenging. These results are consistent with the low flux of 15 GFD designed for this project.

Finally, the Las Virgenes UF feed resulted in similar filterability as the demonstration-scale O_3-BAC treated water from pureALTA. The similarities were evidenced by the filtration resistance shown in

Figure 4-10, the similar calculated fouling indices, and the design fluxes (Table 4-4). Beyond the somewhat but unremarkably similar quality of these two waters (Table 4-3), nothing specifically would have predicted how unproblematic the Las Virgenes effluent would be for downstream UF treatment. In fact, the Las Virgenes project team has been quite (pleasantly) surprised with their ability to push the UF flux to a very high level despite no particular pretreatment effort. While positive surprises can be nice, it is better to understand and be able to predict and thus take advantage of superior performance capacity. This bench-scale testing could have predicted the UF performance, at least qualitatively, before any permanent equipment was installed.

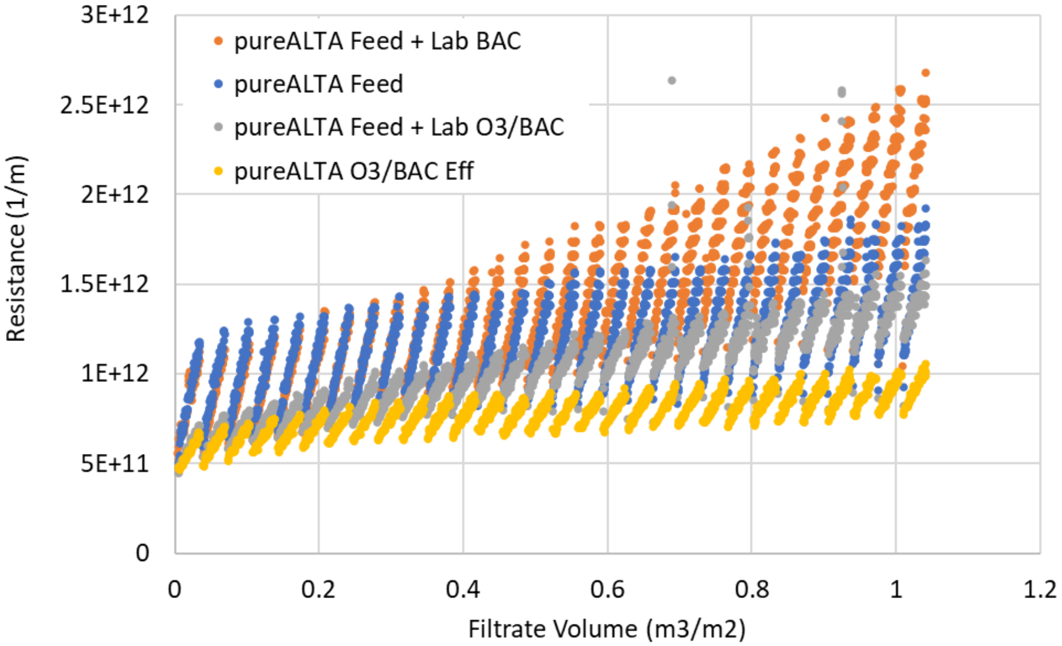


Figure 4-7. Filtration Resistance as a Function of Normalized Filtrate Volume for PureALTA Samples.

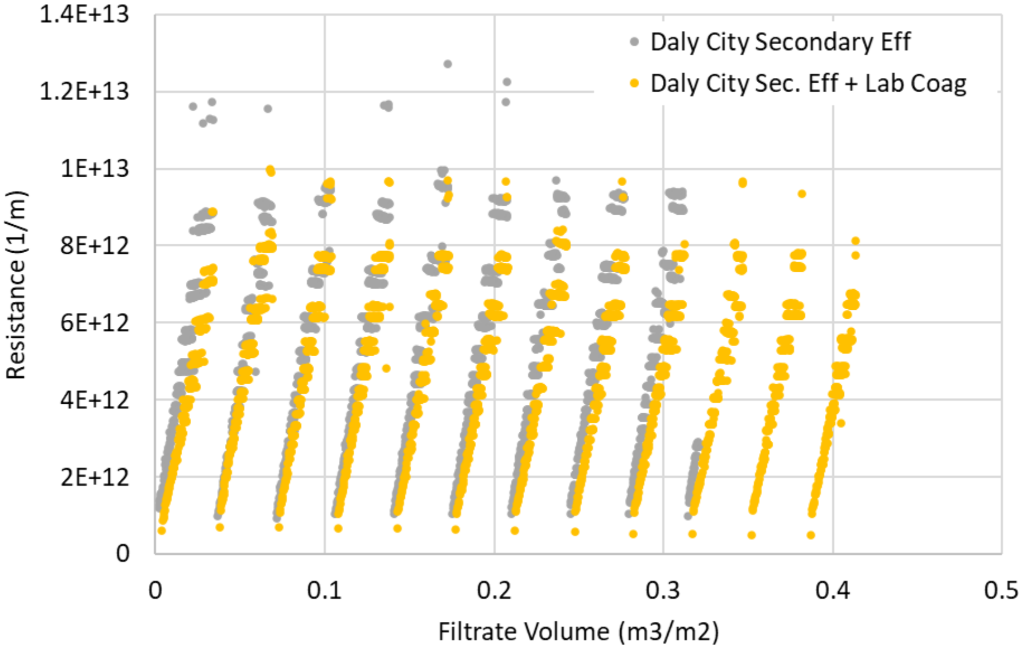


Figure 4-8. Filtration Resistance as a Function of Normalized Filtrate Volume for Daly City Samples.

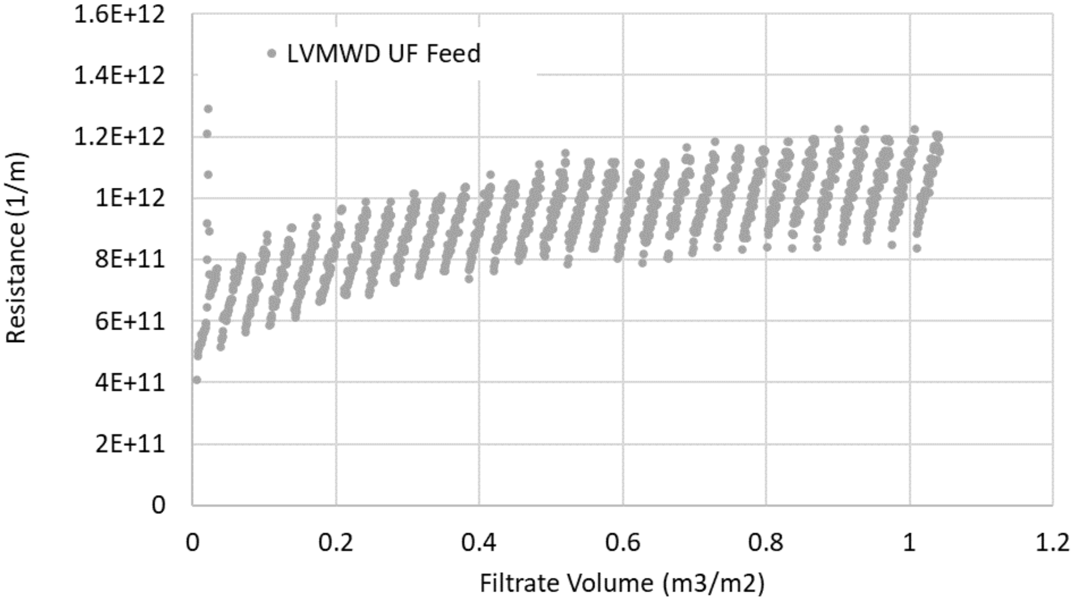


Figure 4-9. Filtration Resistance as a Function of Normalized Filtrate Volume for Las Virgenes Sample.

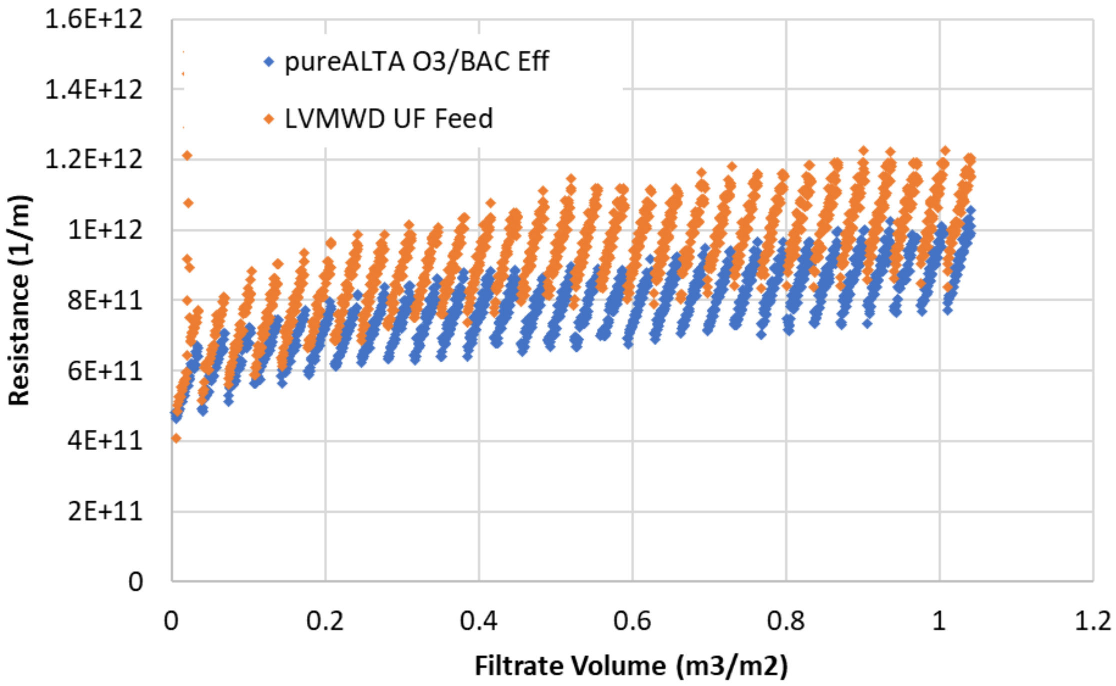


Figure 4-10. Filtration Resistance as a Function of Normalized Filtrate Volume for PureALTA and Las Virgenes UF Feed Water.

Table 4-4. Calculated Fouling Indices Compared to Design Flux for Each Location.

Water Tested	δA [$\times 10^{12}$ m^{-2}]	δB$_{bw}$ [$\times 10^{12}$ m^{-2}]	δB$_{air}$ [$\times 10^{12}$ m^{-2}]	Design Flux [gfd]
pureALTA Feed	20.14	0.41	0.42	NA[b]
pureALTA feed + lab BAC	22.96	1.16	1.20	NA[b]
pureALTA feed + lab O_3-BAC	8.98	0.58	0.58	NA[b]
pureALTA O_3-BAC	6.70	0.20	0.21	37.2[c]
Daly City Effluent	NA[a]	287	287	NA[b]
Daly City Coag. Effluent	NA[a]	-0.5	0.0	15
LVMWD UF Feed	8.74	0.2	0.2	45

[a] Fouling index δA could not be calculated.

[b] Design flux is only listed for the conditions most closely matching the UF feed at pilot or demonstration scale.

[c] The design flux at the pureALTA facility was dictated by a 20 gallon-per-minute feed flow treated with a single full-scale Toray HFU-202-N UF element. Based on the element’s current operation, which requires CIPs less than once per year, an optimal design flux may have been higher than 37.2 GFD.

CHAPTER 5

Module D: MBR Impact on Reverse Osmosis

5.1 Background

One of the key issues for MBR-based AWT is the pathogen reduction by MBR. These issues are summarized in depth as part of four projects, including WRF Projects 4997 and 4959 (Salveson et al. 2021, Branch et al. 2023). WRF 4997 provides an extensive literature review of pathogen removal by MBR, which is summarized herein along with the results from the other three relevant ongoing projects.

Module D focuses on the interaction between MBR and RO systems. In total, there are two primary areas of investigation. These are (1) MBR pathogen removal and (2) RO fouling and operation downstream of MBR. It is commonly acknowledged that an MF or UF system should be inserted between MBR and RO, to provide a verifiable barrier for pathogens and a robust pretreatment for RO. The data and information presented in this module suggest that both of these key functions of the stand-alone tertiary MF or UF membranes can also be achieved with an MBR in many cases and that MBR and RO can be successfully paired to reduce total project cost and footprint.

5.1.1 Pathogen Reduction by MBRs

There are at least five ongoing or recently completed efforts related to MBR pathogen removal. These five projects, which are summarized in the subsections, with some relevant support from the literature, are:

- WRF Project 4997, *Validation Protocols for Membrane Bioreactors and Ozone/Biologically Activated Carbon for Potable Reuse* (Salveson et al. 2021). This project is complete and published.
- WRF Project 4959, *Evaluation of a Validation Protocol for Membrane Bioreactors Based on a Correlated Surrogate to Achieve Pathogen Credit for Potable Reuse* (Branch et al. 2023).
- Metropolitan Water District Pure Water Southern California Demonstration Plant. The facility is constructed and has been operational since the fall of 2019. It is anticipated to continue operating and publishing results through 2022 or longer. Some results have been shared with this project.
- Hyperion MBR Demonstration. Three different membrane vendors will undergo WRF 4997 Tier 2 pre-commissioning validation testing throughout 2022 with results anticipated 2023.
- Kubota Membrane USA Corporation research at the Lake of the Pines Wastewater Treatment Plant in Auburn, California. Sampling for this project is complete but results have not yet been published.

5.1.1.1 WRF 4997 and 4959 Review

WRF has funded two projects to build upon the pathogen LRVs work done in Australia and documented by Branch and Le-Clech (2015) and WaterSecure (2017). These Australian documents developed a three-tier concept for MBR removal of pathogens, simplified follows:

- Under Tier 1, a wide-ranging review of MBR industry data and specific investigations of full-scale facilities resulted in conservative default LRVs for viruses, protozoa, and bacteria of 1.5, 2, and 4, respectively. These LRVs were determined to be applicable to submerged MBR systems that have nominal pore sizes of 0.04–0.1 µm. The listed LRV credits are assumed to be only applicable to MBR systems operated in accordance with design specifications and a specific operational range. Note that Branch and Le-Clech (2015) concluded that higher LRVs than listed by WaterSecure (2017) are appropriate for the smaller pore size MBRs.

- Under Tier 2, projects must conduct challenge testing under the most conservative operating conditions to determine the minimum expected LRVs. Ongoing performance monitoring is also required. Tier 2 LRVs are anticipated to be above default values from Tier 1. The system would then be confined to operate within the validated envelope at all times for the validated LRVs to remain applicable.
- Under Tier 3, which was conceptual only, challenge testing could be performed to demonstrate the correlation between online parameter(s) and the pathogen removal performance of the MBR. This allows critical limits to be established that are specific to and correlated with the LRVs claimed.

WRF Project 4997, *Validation Protocols for Membrane Bioreactors and Ozone/Biologically Activated Carbon for Potable Reuse*, includes Tier 1 and Tier 2 efforts. WRF Project 4997 is complete and published (Salveson et al. 2021). The key conclusions of the Tier 1 work for WRF 4997 are conservative virus and protozoa LRVs, as shown in Table 5-1 below.

Table 5-1. Recommended Tier 1[a] Default LRVs.

Turbidity 95% of the Time	Turbidity Maximum Allowable	Virus LRV	Protozoa LRV	Membrane Type	Operational Window
0.2 NTU	0.5 NTU	1.0	2.5	Hollow fiber and Flat Sheet	Operational window criteria not necessary if turbidity values maintained

[a] Based on the literature review and evaluation of raw data from Branch and Le-Clech (2015) and Salveson and Fontaine (2017).

Several other relevant conclusions in the Tier 1 analysis from WRF 4997 are:

- Somatic coliphage was recommended as a more conservative surrogate for virus LRV compared to all other studied virus (including MS2 and pathogenic viruses).
- *C. perfringens* was documented to be a conservative surrogate for protozoan LRV. Test results for *Giardia* indicated higher LRV compared to *C. perfringens*.
- Previous research has been challenged by poor analytical recovery in raw (screened) wastewater and high limits of detection (LOD). Low measured concentrations coupled with poor analytical recovery led to relatively small LRVs for *Cryptosporidium* (particularly).
- Data was analyzed using both a paired sampling analysis and a Monte Carlo analysis, in both cases using the lower 5th percentile LRV. The lower values of the two analyses were used for calculating the LRVs.
- After a thorough review of the literature, including both hollow fiber and flat sheet membranes, there were no studies suggesting that log removal values should be significantly below 1.0 for virus or below 2.5 for protozoa. The recommended LRVs are applicable to any hollow fiber or flat sheet membranes as long as MBR filtrate turbidity values are maintained at or below 0.2 NTU 95 percent of the time and that a turbidity of 0.5 NTU is not exceeded at any time, which is consistent with already established Title 22 regulations for recycled water. These values are applicable over a broad range of MBR operational conditions, and an operational range is not required.

WRF 4997 has also developed a Tier 2 test protocol (Protocol), which is also finalized. The Protocol details, which are already well reflected within the MWD and Kubota efforts and are not detailed here, include:

- Review of target pathogens and indicators
- Minimum sampling efforts (24 samples over a 3-month [or longer] period)

- Recommendations for sampling methods, volumes, and quality control
- Data analysis methods
- Long term monitoring requirements to verify Tier 2 LRVs

The important question for utilities that implement a Tier 2 program, is the trade-off between added LRV and added time, effort, and cost to document Tier 2 LRVs at startup and over the longer term of operation. For some systems, Tier 1 LRVs may be sufficient for both protozoa and virus. For others, additional protozoa and/or virus credits are needed, and justify the added expense and effort. *Evaluation of a Validation Protocol for Membrane Bioreactors Based on a Correlated Surrogate to Achieve Pathogen Credit for Potable Reuse*, explores the Tier 3 concept in much greater detail (Branch et al. 2023). The project is led by members of this WRF 4833 project team. The project is:

- Evaluating the latest correlations between turbidity with pathogen and surrogate LRVs within the literature and as part of ongoing parallel research
- Further developing the TSS-based correlations documented by Katz et al. (2018)
- Further developing Pressure Decay Test (PDT)-based monitoring systems and correlations with MBR LRV
- Considering novel approaches to real time MBR LRV performance monitoring, including side-stream high flux UF systems
- Developing a Test Protocol for various Tier 3 methods

At this time, it is not known if Tier 3 efforts will result in greater LRVs than Tier 2. However, a Tier 3 validation will provide a better (or even real-time) understanding of MBR performance, leading to greater water quality confidence and more stringent health risk management. It is possible that Tier 3 results will allow for a broader use higher LRV credits (similar to Tier 2) but be independent of MBR suppliers.

5.1.1.2 Metropolitan Water District of Southern California (Memcor and ZeeWeed MBRs)

The Metropolitan Water District of Southern California and the Los Angeles County Sanitation Districts (LACSD) are partnering on Pure Water Southern California (PWSC), a large-scale regional recycled water program. The PWSC Demonstration Plant at the Joint Water Pollution Control Plant in Carson, CA includes a 0.5-mgd demonstration-scale AWT facility to demonstrate pathogen removal by an MBR. Funding for this project with a tertiary MBR is provided in part by the U.S. Bureau of Reclamation through a Title XVI WaterSMART Water Reclamation and Reuse Research grant (Agreement No. R20AP00025) and project results are being provided to fulfill Metropolitan's in-kind contribution to WRF 4833. The MBR was operated as a tertiary MBR, fed with non-disinfected, non-nitrified secondary wastewater effluent. The tertiary MBR was operated to nitrify secondary effluent, remove pathogens, and provide high quality effluent for downstream RO treatment. The tertiary MBR evaluation concluded in the fall of 2021, transitioning in the winter of 2022 to a conventional "secondary" MBR operation where the MBR is fed with primary effluent. A flow schematic of the overall process train with a tertiary MBR is provided below in Figure 5-1.

The demonstration facility consists of two parallel MBR systems, both fed from a common biological reactor. The two systems are:

- MBR1 Veolia (formerly Suez/GE) –ZeeWeed 500d
  - a hollow fiber outside-in immersed membrane with a nominal pore size of 0.02 µm
- MBR2 DuPont (formerly Evoqua) – MEMCOR B40N
  - a hollow fiber outside-in immersed membrane with a nominal pore size of 0.04 µm

The demonstration facility tertiary MBR testing plan included pre-testing, baseline, and challenge phases. To demonstrate the removal of *Cryptosporidium* and *Giardia*, 10 L of non-disinfected secondary effluent and 10,000 L MBR filtrate samples were analyzed. Recovery of *Cryptosporidium* and *Giardia* was determined for every sample using ColorSeed spike organisms. This was particularly important for interpreting non-detects in large volume MBR filtrate samples. In addition to determining *Cryptosporidium* and *Giardia* LRVs, removal of infectious viruses by MBR and the utility of several potential microbial surrogates for pathogen LRV was also assessed.

The project effort was extensive, testing both MBRs under a range of conditions, including "baseline" performance and damaged fiber conditions. For this WRF 4833 project, key results are presented in this module from the "baseline" Veolia MBR operation:

- All 10 L secondary effluent samples had detectable levels of *Cryptosporidium* and *Giardia* with mean recoveries of 55 percent and 20 percent, respectively.
- Eight out of 20 10,000 L MBR filtrate samples had low levels of *Cryptosporidium* and *Giardia* (detection limit = < 0.00012 oocysts/L for *Cryptosporidium* and < 0.00012 cysts/L for *Giardia*), with mean recoveries of 51 percent for *Cryptosporidium* and 42 percent for *Giardia*.
- Based on these preliminary results, recovery-adjusted LRVs were 4.4 for *Cryptosporidium* and 5.8 for *Giardia*, well in excess of the Tier 1 values from WRF 4997 shown above.
- A suite of bacterial and coliphage indicator organisms was also monitored in secondary effluent and large volume MBR filtrate samples. All samples had detectable levels of total coliforms, *E. coli*, somatic coliphage, and aerobic endospores. One out of 24 samples was below detection for male-specific coliphage, and 19 out of 24 samples were below detection for *C. perfringens* endospores. Measured LRVs ranged from approximately 4.5 to 9.5 depending on the organism.

For reference, key process design criteria and configuration are summarized below in Table 5-2 and Table 5-3.

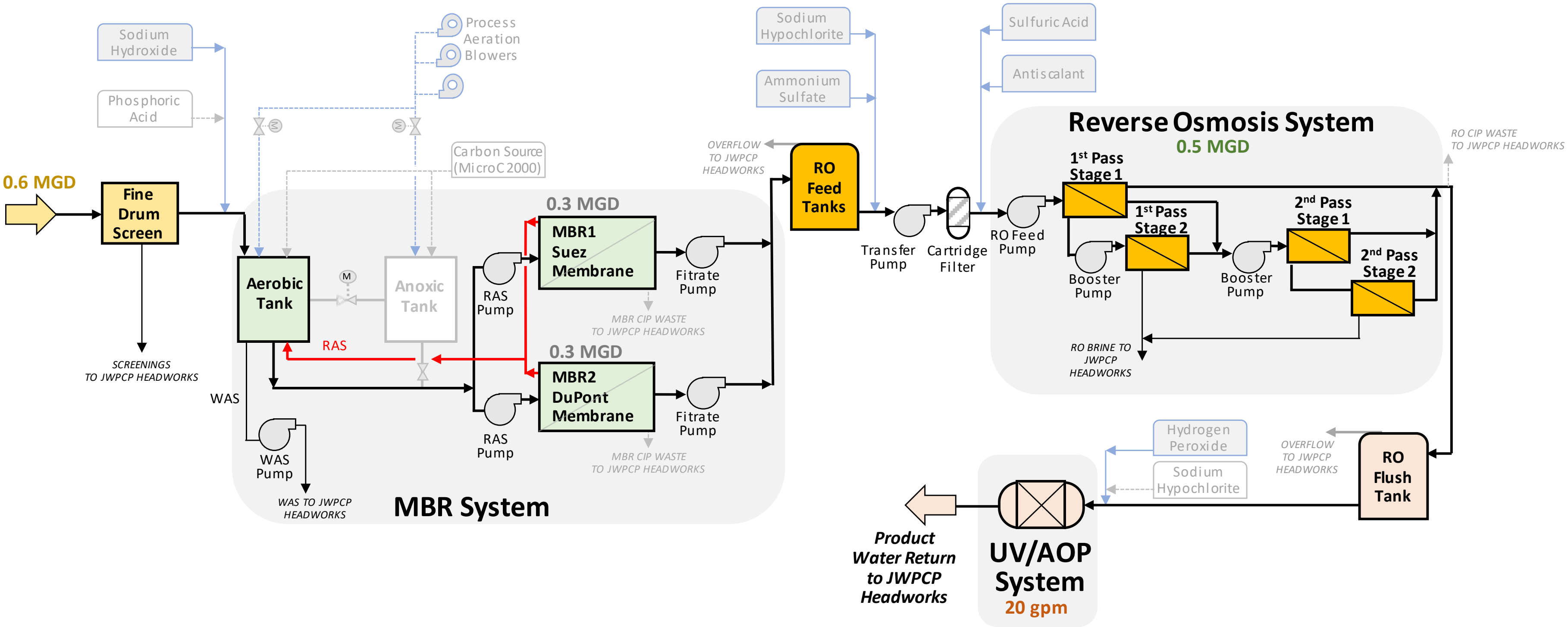


Figure 5-1. Flow Schematic of the Overall Process Including a Tertiary MBR at the Demonstration Plant.
The thickened lines show the active flow path in a nitrification-only (N-only) mode.
Greyed out equipment and processes are part of the demonstration facility but are not used or not used continuously during the tertiary MBR N-only testing configuration. Blue lines are supplemental chemicals and aeration flows.

5.1.1.3 MBR System Design Criteria

Key MBR system configuration and criteria are summarized Table 5-2.

Table 5-2. MBR System Design Criteria.

Membrane Bioreactor			
Fine Screen			
Type	-	Internally-Fed Drum Screen	
Size of Perforations	mm	1	
Number of Screens (Duty + Standby)	-	1 + 0	
Capacity	gpm at TSS	694 at 250 mg/L	
Bioreactor Basins			
Aerobic Tank			
Number of Basins	-	1	
Basin Length	ft	48.4	
Basin Width	ft	15	
Configuration	-	Tertiary MBR	Secondary MBR
Basin Volume (nominal)	gal	60,000	95,000
Side Water Depth	ft	11	17.5
HRT (Excluding Recycle Flow)	hours	2.3	3.6
Maximum MLSS Concentration	mg/L	10,000	
Mixing Energy Input, Minimum	hp/1000 ft^3	0.4	
Number of Mixers (Duty + Standby)	-	2 + 0	
Mixer Power, Each	hp	2.5	
Target SRT	days	10	
Number of Process Air Blowers, (Duty + Standby)	-	2 + 1	
Process Air Blower Capacity, Each	scfm	513 scfm @ 8 psig	
Process Air Blower Power, Each	hp	30	
Number of MLR Pumps (Duty + Standby)	-	1 + 0	
MLR Pump Capacity	gpm at psi	1,900 at 7.8	
MLR Pump Motor Power	hp	25	
Number of WAS Pumps (Duty + Standby)	-	1 + 0	
WAS Pump Capacity	gpm at psi	105 at 6.0 psi	
WAS Pump Motor Power	hp	1.34 (1.0 kW)	
Anoxic Tank			
Number of Basins	-	1	
Basin Length	Ft	32.2	
Basin Width	Ft	15	
Configuration	-	Tertiary MBR	Secondary MBR
Basin Volume (nominal)	gal	30,000	65,000
Side Water Depth	Ft	8.3	18
HRT (Excluding Recycle Flow)	hours	1.1	2.5
Maximum MLSS Concentration	mg/L	10,000	
Mixing Energy Input, Minimum	hp/1000 ft^3	0.4	
Number of Mixers	-	2	
Mixer Power, Each	hp	2.3	
Membrane System			
System	-	Veolia	DuPont

Type	-	Submerged Hollow-fiber	Submerged Hollow-fiber
Number of Basins, Each	-	1	1
Design Instantaneous Flux	GFD	11.64	12.3
Maximum Instantaneous Flux	GFD	13.85	13.7
Total Membrane Area Provided	ft^2	26,640	27,584
Number of Modules	-	72	64
Membrane Area per Module	ft^2	370	431
Membrane Air Blowers (Duty + Standby)	-	1 + 0	1 + 0
Membrane Air Blower Power, Each	hp	15.0	7.5
Filtrate Pumps (Duty + Standby)	-	1 + 0	1 + 0
Filtrate Pump Capacity	gpm at psi	500 at 19.5 psi	267 at 12.6 psi
Filtrate Pump Power	hp	15	7.5
Filtration Cycle Duration	min	12	12
Relaxation Duration	s	60	60
Number of RAS Pumps (Duty + Standby)	-	1 + 0	1 + 0
RAS Pump Capacity	gpm at psi	1,075 at 13.2 psi	1,075 at 7.2 psi
RAS Pump Motor Power	hp	15	10

5.1.1.4 RO System Design Criteria

Key RO system configuration and criteria are summarized in Table 5-3.

Table 5-3. RO System Design Criteria.

RO System Configuration			
Type	-	First Pass	Second Pass
Overall Feed Rate	gpm	298 – 400	60 – 80
Overall Flux	GFD	10.0 – 13.5	8 – 11.5
Permeate Recovery	%	75 – 85	88 – 92
Pressure Vessel Array (Stages 1: 2)	-	9:4	2:1
Total Elements per Vessel	-	7	7
Membrane Area per Module	ft^2	400	440
Stage 1			
Design Recovery (@ 85% overall first pass recovery)	%	65	
Recovery Range	%	53 – 65	
Front Permeate Share	%	60	
Design Flux (@ 11.7 GFD overall first pass flux)	GFD	13	8 – 9
Number of Vessels per Stage	-	9	2
Total Elements Provided	-	63	14
Booster Pump Capacity	gpm at psi	465 at 163	129 at 230
Booster Pump Motor Power	Hp	75	30
Stage 2			
Booster Pump Capacity	gpm at psi	218 at 34	--
Booster Motor Power	Hp	7.5	--
Design Recovery (@ 85% overall first pass recovery)	%	56	
Recovery Range	%	48 – 56	
Design Flux (@ 11.7 GFD overall first pass flux)	GFD	8.8	8 – 9
Number of Vessels per Stage	-	4	1
Total Elements Required	-	28	7

5.1.1.5 Lake of the Pines WWTP (Kubota Membrane)

Kubota membranes used in MBRs are a flat sheet configuration and typically have a reported nominal and maximum pore size of 0.2 and 0.4 µm, respectively. The larger pore size relative to some other competing membrane products (such as DuPont or Veolia) has resulted in a false perception that removal due to size exclusion will relatively be lower. In addition, the flat sheet configuration is not suitable for application of pressure decay testing (which can be effectively done by DuPont) to ensure membrane integrity, due to the risk of membrane damage at the required test pressures. The difficulty with integrity monitoring and perceived impact of a larger pore size have made it difficult for the industry, in the absence of robust data, to assign high LRVs to Kubota membrane products. Until this study, there is no data reporting *Cryptosporidium* and *Giardia* removal for Kubota membranes and only a sparing set of indicator microorganism data when compared to hollow fiber competitors. Also, previous sampling efforts on Kubota systems (and other projects) suffered from poor analytical recoveries and low sample volumes which capped the LRV able to be demonstrated.

The Lake of the Pines Wastewater Treatment Plant (WWTP) has a Kubota (flat sheet) MBR equipped with the RW400 submerged membrane. The WWTP has a capacity of 1.2 mgd with an A2O process, MBR, and UV disinfection. The 12+ month study, currently with >75 percent of sampling complete, is based on the proposed Tier 2 validation method currently under development for WRF Project 4997, *Validation Protocols for Membrane Bioreactors and Ozone/Biologically Activated Carbon for Potable Reuse*. In total, more than 20 samples were taken to enable robust statistical analysis of LRV distributions. To date, sampling has been conducted for human viruses (adenovirus, enterovirus, and noroviruses) and protozoa (*Cryptosporidium* and *Giardia*). 150 L filtrate samples have been concentrated using Envirochek filters. 300 L filtrate samples have been concentrated using NanoCeram electropositive cartridge filters for virus analysis. Pathogen and microbial indicator analyses were being performed by third-party laboratories utilizing EPA-approved methods. Samples were collected over the seasonal range for Auburn, CA and before and after membrane cleaning events.

The following conclusions and key points apply to this testing program:

- The key membrane aspects (pore size, membrane type, modes of operation) of Kubota membranes are identical for a range of MBR products, the difference being the size and configuration of the support structure of the flat sheet membranes.
- The Kubota membranes tested at the Lake of the Pines WWTP are more than 10 years old (past the normal lifetime), have been continuously operated, and have never been repaired.
- Turbidities for the installed system have continuously met Title 22 requirements for non-potable water reuse.
- Protozoa LRVs have ranged from >3.4-log for *Cryptosporidium* (range 3.4 to 5.4 LRV) and >5.4-log for *Giardia* (range 5.4 to 5.5 LRV).
- Protozoa LRVs for both *Giardia* and *Cryptosporidium* observed to date are much higher than the WRF 4997 Tier 1 values but lower than the Metropolitan Water District baseline testing results. It is critical to note that the Metropolitan Water District project is collecting 10,000 L of MBR filtrate samples as compared to the 150 L of samples at Lake of the Pines, a potential difference of almost 2-LRV.
- Results have shown virus LRVs that range from 4.3-log for total culturable virus, 6.8-log for adenovirus gene copies, >2.9-log for norovirus gene copies, and >4.1-log for enterovirus gene copies.
- In addition to pathogens, microbial surrogates that are being monitored include somatic and male-specific coliphages, *Clostridium perfringens* spores, and pepper mild mottle virus (PMMoV). Coliphage LRVs have ranged from >3.6-log for male-specific (range 3.6 to 4.6 LRV) and >2.1-log for

somatic (range 2.1 to 4.9 LRV). *Clostridium perfringens* LRVs have been >2.3-log (range 2.3 to 4.0 LRV) and PMMoV LRVs have been >5.7-log (range 5.7 to 6.6 LRV).
- The increase in observed values compared to the Tier 1 results from WRF 4997 are largely due to improved analytical methods and greater sample volumes allowing demonstration of higher LRVs.
- The results of this study suggest that in a well operated system, Kubota flat sheet membranes can continue to achieve significant LRVs beyond the typically expected life. No protozoa LRVs observed were below 3, which confirms that MBRs are appropriate as a replacement for direct microfiltration in membrane-based reuse schemes where over 12 log reduction of virus and 10 log reduction of *Cryptosporidium* and *Giardia* are required (SWRCB, 2018).
- TSS methods of Tier 3 analysis, performed in general accordance with Katz et al. (2018), show promise, but equally show challenges associated with the filter material and the level of effort required to run daily TSS tests. The value of this method as an ongoing monitoring technique remains to be determined.

5.1.2 MBR Impact on RO Fouling and Performance

5.1.2.1 Relevant Literature

Practitioners of RO design reasonably focus upon reduction of organics and solids in the feed to RO, which is typically and successfully done by tertiary MF or UF. Properly maintained MF and UF systems have minimal broken fibers and provide a reasonably constant feed water quality to downstream RO. MBR systems are subject to a harsh environment within the activated sludge process, and as a result, will have a reasonable number of broken fibers. The concern specific to MBR systems upstream of RO is if, and to what extent, do the broken fibers result in passage or more organic and/or particulate matter that may result in increased RO membrane fouling?

The research into MBR effluent quality as a feed to RO has examined turbidity, silt density index (SDI), TOC, DOC, ammonia, and nitrate concentrations. Higher effluent quality (e.g., lower organics, lower solids, and lower nutrients) is presumed to result in higher RO flux and lower RO fouling. However, conventional MF/RO systems have performed with a range of RO feed water quality, including high TOC (approximately 15 mg/L) and ammonia (30-35 mg/L as nitrogen) concentrations (Oxnard, 2018). For comparison, MBR systems are typically run at high SRTs, resulting in TOC concentrations of <10 mg/L, and have essentially no ammonia and small amounts of nitrate. One example is the Cabezon MBR system in Rio Rancho, New Mexico, a project partner on this grant, with TOC in the range of 5 to 8 mg/L, ammonia below detection, and nitrate in the range of 4 to 5 mg/L as nitrogen.

Pertaining to MBR followed by RO, we list two pioneering full-scale projects:

- Abilene Texas was an early adopter of MBR/RO on a large scale. Their Hamby Water Reclamation Facility has an average MBR flow of 10 to 14 mgd and a peak MBR flow of 19.5 mgd. The MBR filtrate splits between RO treatment (60 percent of AWT flow) and O_3-BAC treatment (40 percent of AWT flow) (Holton et al., 2018). SDI testing in the MBR effluent shows an SDI value ranging from 1 to 2, with an average of 1.5, and SDI values do not appear to be tied to MBR operational criteria (e.g., pre or post MBR cleaning conditions). Other than mineral fouling associated with phosphorus, which has subsequently been mitigated, RO fouling downstream of MBR has not been problematic (Holton et al., 2018).
- Singapore Public Utilities Board (PUB) has implemented MBR treatment at their Jurong and Changi NEWater plants used to augment surface water through indirect potable reuse. To date, the advanced treatment facilities used for potable reuse in Singapore do not have MBR directly ahead of RO, but PUB is now transitioning to MBR/RO systems to minimize cost and footprint (Lay et al., 2017). PUB runs MBR/RO demonstration (Tuas Demo) at the Ulu Pandan water reclamation plant,

with the demonstration conclusions summarized herein. The positive results have led PUB to implement MBR/RO at full scale to “Liquid Module 3” at the Changi water reclamation plant. From PUB’s perspective, the MBR provides “process robustness, superior filtrate quality, and compact footprint” (Lay et al., 2017), with MBR product water quality being equivalent to or better than UF product water (Tao et al., 2005). PUB researchers subsequently documented that the MBR/RO process combined provided greater removal of organics compared to conventional activated sludge processes followed by MF and RO. For example, TOC post MBR/RO was 24 to 33 µg/L whereas the conventional process train produced finished water TOC values in the range of 33 to 53 µg/L. Lastly, RO flux was higher post MBR than after conventional activated sludge and MF treatment (Qin et al. 2006). Additional details regarding PUB’s investigation into MBR/RO systems at the Tuas Demo (from Tao et al., 2008) include:

- Small capacity demonstration, with MBR sized at about 55 gpm and RO sized at about 5 gpm.
- Two different MBR systems, both hollow fiber membrane systems, with nominal pore sizes of 0.4 µm and 0.035 µm, respectively.
- 6-month demonstration
- SRT of 5 days
- The RO system, post MBR, was operated at a flux of 22 liters per square meter per hour (LMH; equivalent to 12.9 GFD), which was 30 percent higher than the 17 LMH (10 GFD) of the full-scale RO system preceded by conventional activated sludge and MF.
- No CIP was required on the RO system downstream of MBR over the 6-month demonstration.

5.1.2.2 Comparative RO Performance Metrics

MBR effluent COD and BOD in municipal wastewater treatment applications are typically low, <20 mg/L and <2 mg/L, respectively. At these concentrations, the impact on organic fouling of downstream RO is minimal. Further, the proven ability of MBR in removing total phosphorus (TP) to below detectable levels, reduces the potential for phosphorus-related scaling of the downstream RO membrane (Holton et al., 2018). From a practical sense, the fouling concerns, both biological and mineral, for RO downstream of MBR still require study and comparison over longer periods of time (years as opposed to months). The information in the Table 5-4 below is intended to provide perspective on “typical” RO performance in conventional activated sludge/MF/RO systems. Overall, Carollo’s position is to utilize the ASTM standard[1] for RO data normalization, which does not present readily in a table format.

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[1] ASTM D4516-00: Standard Practice for Standardizing Reverse Osmosis Performance Data

Table 5-4. RO Performance and Cleaning Goals.

Metric or Control Mechanism	Example Values and Ranges	OCWD (OCWD, 2020)	MWD PWSC Demonstration Plant (provided by project team members)
Flux	10 GFD to 14 GFD	12 GFD	11-12 GFD (Pass 1); 7-9 GFD (Pass 2)
Stages	2 or 3	3	2
Recovery	75% to 85%	75% to 85%	80 - 85% (Pass 1); 85-90% (Pass 2)
Temperature Corrected Specific Flux (for each stage)	0.08 to 0.14	Minimum of 0.1 GFD/psi, cleaning initiated at this value	Stage 1: 0.13 to 0.16 GFD/psi Stage 2: 0.085 to 0.12 GFD/psi
Reduction in Temperature Corrected Specific Flux (normalized to 20 degrees C)	0.5 to $1*10^{-5}$ GFD/psi/day Use of the ASTM data normalization method is recommended to best understand performance decay.	0.02 GFD/psi total drop over a cycle between CIPs (see below)	0.0004 to 0.002 GFD/psi/day (Pass 1, Stage 1) 0.0009 to 0.0014 GFD/psi/day (Pass 1, Stage 2) (No reduction observed in Pass 2) 0.01 to 0.03 GFD/psi total drop over a cycle between CIPs
Normalized Permeate Flow	Drop of 10% over 8-12 months of operation	Drop of 10% triggers a CIP, or 6-8 months, whichever is sooner	Drop of 10% triggers a CIP, or 6-8 months, whichever is sooner
Normalized salt passage	Increase of 5% over 8-12 months of operation	Increase of 5% triggers a CIP, or 6-8 months, whichever is sooner	Increase of 5-10% triggers a CIP, or 6-8 months, whichever is sooner
Normalized Pressure Drop (feed-concentrate)	Increase of 10% over 8-12 months of operation	Drop of 10% triggers a CIP, or 6-8 months, whichever is sooner	Drop of 10-15% triggers a CIP, or 6-8 months, whichever is sooner
Anticipated Performance Metrics After CIP Compared to Baseline	Use of the ASTM data normalization method is recommended to best understand performance decay and recovery. Individual metrics can be examined, including Recovery of Temperature Specific Flux, Recovery of Salt Rejection, and Recovery of Pressure Drop.	Temperature Specific Flux – 10-20% increase post CIP Salt Passage – 0.5-1.5% reduced performance compared to baseline post CIP Normalized Pressure Drop – 20% decrease in feed pressure post CIP	Temperature Specific Flux – 10-20% increase post CIP Salt Passage – 0.5-1.5% reduced performance compared to baseline post CIP Normalized Pressure Drop – 20% decrease in feed pressure post CIP

5.1.2.3 MWD Research Progress

As mentioned previously in this document regarding the operation of MWD's demonstration facility, a broad range of operational conditions of the MBR and RO systems has been completed. To ease results discussions, discrete periods of testing are summarized below in Table 5-5.

Process Targets and Performance per Testing Phase

MBR and RO system target operational conditions are summarized in Table 5-5 and Table 5-6 and discussed further below.

Table 5-5. MBR System Target Operational Conditions.

Parameter	Units	Pretesting Phase (NdN Mode)	Baseline and Challenge Testing Phase (N-only Mode)
Bioreactor pH	-	6.6 to 7.5	6.6 to 7.5
Bioreactor DO	mg/L	2.0	1.7
Bioreactor Temperature	ºC	22 to >30	22 to >30
SRT, Total	days	10	9
HRT	hours	3.4	2.5
Aerobic MLSS	mg/L	4,700	1,000-1,200
Instantaneous MBR Flux	GFD	14	14
MicroC 2000 Dose	mg/L	210	none
Nitrogen Removal	%	80	none
Phosphoric Acid Dose	mg/L	2.1-2.5	none
Mixed Liquor Flow Ratio	Times Q	3.5-4.0	1.6

Table 5-6. RO System Target Operational Conditions.

Parameter	Units	Baseline and Challenge Testing (N-only Mode)
Average Flux, First Pass	GFD	11.7
Average Flux, Second Pass	GFD	8.3
Recovery, First Pass	%	80-85
Recovery, Second Pass	%	85-90
Target RO Feed pH	-	6.4
Total Chlorine Residual	mg/L	1.0 mg/L
Antiscalant Dose	mg/L	3 mg/L

Preliminary Testing

Preliminary testing or "pretesting" of tertiary MBR performance began in October 2019 and continued through June 2020, wherein the tertiary MBR system, was run in a nitrification/denitrification (NdN) mode. The bioreactor was operated at total SRT and hydraulic retention time (HRT) of approximately 9-15 days and 4-5 hours, respectively, to achieve complete nitrification with aerobic tank mixed liquor suspended solids (MLSS) concentration of 4,000-7,000 mg/L. TOC concentrations in the combined MBR filtrate ranged from 4.1 to 8.8 mg/L, with a median of 7.5 mg/L. Preliminary testing examined pathogen removal, mostly by the MBR1 system (Veolia ZeeWeed), as well as RO system performance. Over the pretesting period, MBR membrane fouling was minimal, with average flux ranging from 10 to 11 GFD, and TMP typically well below the respective TMPs that would necessitate a clean-in-place (CIP) for either MBR system. Nonetheless, complete CIPs were performed in February 2020 (for MBR1) and May 2020 (for MBR2) per manufacturer recommendations. Filtrate turbidity was below 0.1 NTU from both MBR systems, except when following maintenance activities such as chemical maintenance cleans or extended membrane system downtime. These instances of elevated turbidity were mostly due to inaccuracies caused by inadequate MBR filtrate sample line flushing and/or air bubbles trapped in the sample line/cell, rather than actual elevated MBR filtrate turbidity upon system restart. Procedural adjustments were made to minimize turbidity meter inaccuracies following MBR membrane maintenance activities and extended downtimes.

While the tertiary MBR effluent was of high quality, the nitrogen removal performance in the NdN mode did not meet prescribed water quality targets. While MBR filtrate ammonia concentrations were consistently below 0.02 mg/L as N, median nitrate values were in the range of 15 to 20 mg/L as N. As such, target ammonia concentration in the MBR filtrate, denoted in the approved testing and monitoring plan of 10-12 mg/L as N, or approximately 80 percent total nitrogen removal, was not met, with actual performance ranging from 45 percent to 50 percent total inorganic nitrogen (TIN) reduction across the tertiary MBRs. The potential cause of the incomplete denitrification was associated with the use of glycerin-based carbon source, which promoted the growth of organisms that do not fully denitrify. Additional bench-scale testing will be conducted to assess alternative treatment options to achieve the target nitrogen removal in the NdN mode.

Baseline and Challenge Testing

Due to the incomplete denitrification observed, the demonstration facility was reconfigured to operate with a nitrification-only (N-only) tertiary MBR followed by a two-pass RO system to meet the project's overall TIN removal goal. From July 20, 2020 through the end of testing in November 2021, the bioreactor was operated at a total SRT and HRT of 9 days and 2.5 hours, respectively, and achieved consistent and complete nitrification. MLSS was approximately 1,200 mg/L in the aerobic tank. Median nitrate concentration in the MBR filtrate was 42 mg/L as N (33 to 53 mg/L as N), and median TOC and DOC concentrations were 8.3 mg/L (7.2 to 9.8 mg/L) and 8.2 mg/L, respectively.

During challenge testing, MBR1 system membrane fibers were intentionally damaged as part of an extensive effort to examine reduction in pathogen removal due to damaged fibers. Although no challenge testing of the MBR2 system was planned, unexpected membrane damage appeared to have occurred to the MBR2 system towards the end of baseline testing. The potential cause of unintentional damage that was evident in the MBR2 system may have been due to specific experimental conditions, and unanticipated snail growth and subsequent damage. The damaged membranes resulted in measurable increase in filtrate turbidity, particularly, for short periods of time after daily pressure decay testing (PDT). However, membrane performance with this unanticipated damage should not be used to make a general assessment of MBR2 system performance. Details about the impacts of damaged fiber on MBR filtrate turbidity as well as reduced pathogen removal are not presented here. The focus of this module is on the intentional and unintentional fouling impacts of the damaged MBR fibers on both the RO membrane and the cartridge filters.

Cartridge Filter Analysis

In addition to RO performance, it is important to note the performance of the cartridge filters that are installed upstream of RO to provide an additional barrier for the protection of the RO system. Fouling of the cartridge filters during baseline testing was minimal, based upon differential pressure observed across the cartridge filters. However, cartridge filter fouling was exacerbated during challenge testing as discussed below.

System Description

The cartridge filters are an integral part of the pretreatment system for RO. The RO system transfer pump delivers chloraminated MBR filtrate from the RO feed tank through the cartridge filters and to the RO system booster pump to be fed into the RO membrane array. A single cartridge filter vessel contains twenty-five (25) 5-µm rated filter cartridges, which removes suspended solids to protect the RO membranes. The cartridge filtration equipment is described below in Table 5-7.

Table 5-7. Cartridge Filter Equipment Summary.

Equipment	RO System No 1 Cartridge Filter
Number (Duty + Standby)	1 + 0
Equipment Number	05- CF-0230
Manufacturer	Fil-Trek Corporation
Model	S6GL16-025-3-4F-150
Design Flow Capacity, gpm	512

As the cartridge filters capture suspended solids on their surface, the differential pressure across the cartridge filter vessel increases. This increase in differential pressure tends to occur at an increased rate as filtration progresses, which is characteristic of a filtration process dominated by surface-removal.

Baseline Performance Trends

During baseline testing, MBR filtrate turbidity was generally low and the solids loading to the cartridge filters allowed for an average changeout interval of 24.5 days and an average pressure increase rate of 0.65 psi/day. Cartridge filter performance data during baseline testing are summarized in Table 5-8, and the differential pressure trend during this phase is shown in Figure 5-2. These trends are in alignment with the expected pressure increase patterns for surface removal.

In October 2020, snails (*Physa gyrina*) were detected in both the MBR1 and MBR2 tanks during maintenance. As noted, MBR2 membrane integrity was compromised likely due to experimental conditions, and the unanticipated snail growth, leading to elevated mixed liquor breakthrough, as well as to particle loading on the cartridge filter, including in the form of shell fragments. The accelerated differential pressure buildup observed in the latter part of baseline testing was likely due to the compromised conditions of the MBR2 fibers.

Table 5-8. Cartridge Filter Performance during Baseline Testing.

Lot No.	Date		Online Time	Differential Pressure (psi)		ΔP Accum (psi/day)
	New	Changeout	(day)	Start	End	
Lot 1	6/30/2020	8/7/2020	29.0	9.19	28.07	0.65
Lot 2	8/7/2020	9/17/2020	37.9	3.97	28.16	0.64
Lot 3	9/17/2020	10/5/2020	15.9	1.97	13.43	0.72
Lot 4	10/5/2020	10/26/2020	15.2	2.11	10.81	0.57
Baseline Average =			**24.5**			**0.65**

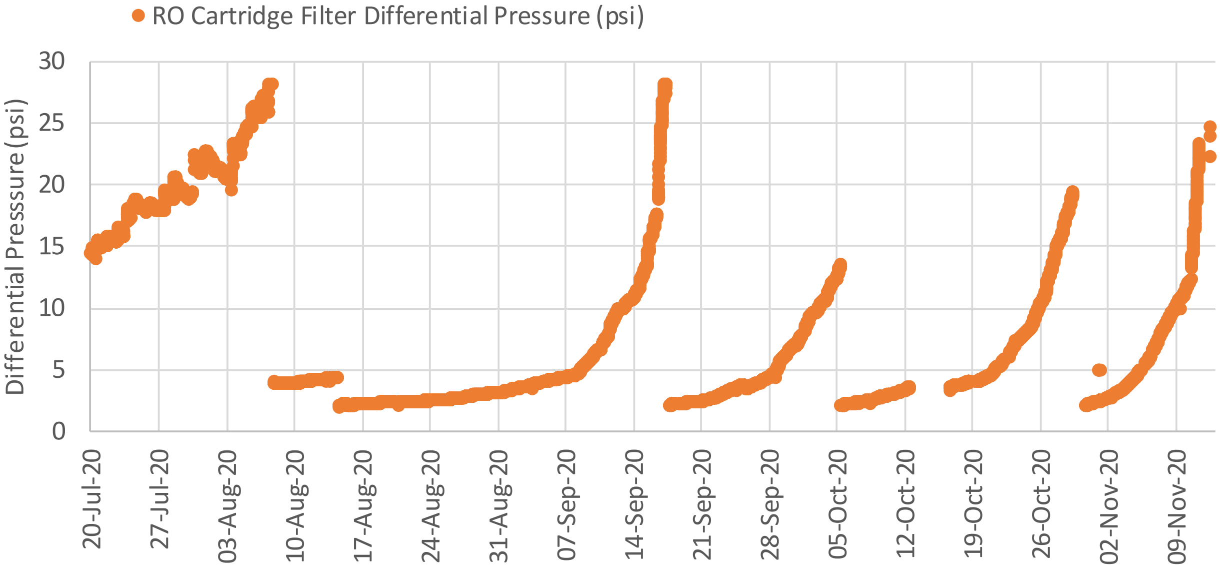


Figure 5-2. Typical Differential Pressure Across Cartridge Filters During Baseline Testing.

Challenge Testing Performance Trends

During challenge testing, increased solids loading occurred in the RO feed, primarily due to mixed liquor breakthrough from the MBR1 system as a result of fiber cutting events starting in November 2020, and from the MBR2 system due to the compromised membrane conditions associated with experimental conditions and snail damage. Although snail proliferation in the both the MBR1 and MBR2 tanks was being mitigated through more frequent chemical cleans, the presence of snails remained throughout the challenge testing phase. In addition, snails may have potentially continued to contribute to higher solids loading onto cartridge filters in the form of shell fragments.

All of these factors led to an increase in the rate of differential pressure accumulation in the cartridge filters. Steepening slopes of the cartridge filter differential pressure curves are shown in Figure 5-3, and the filter changeout interval, as summarized in Table 5-9, decreased to an average of 7.3 days (compared to the prior average of 24.5 days) after November 2020. Solids buildup and snail shells were noted on spent cartridge filters after changeouts as shown in Figure 5-4 through Figure 5-7. A reduction in the slope of cartridge filter differential pressure trends was observed when the damaged MBR2 membranes were replaced with new membranes in March 2021, as shown in Figure 5-3, such that the trends were once again comparable or better than those of baseline conditions.

It should be noted that the filtrates of the two MBR systems were combined in the RO feed tank, and the RO feed tank continuously overflowed due to excess flow available for operation, and hence, the loading on the RO system is based on the comingled filtrate quality of the two MBR systems. While the MBR systems generally produced filtrate with turbidity of less than 0.2 NTU, the frequent chemical cleans on the MBR2 system along with the persistence of snails led the to a continued degradation of MBR2 filtrate quality, such that RO feed would be starved without allowing filtrate of up to 0.5 NTU to be fed to the RO system. Beginning in late January 2021, the MBR2 system flux was temporarily halved to minimize solids loading onto the cartridge filters and the frequency of cartridge filter replacement. The impact of this change is evident in the lower rate of differential pressure buildup starting in February 2021 through mid-March 2021.

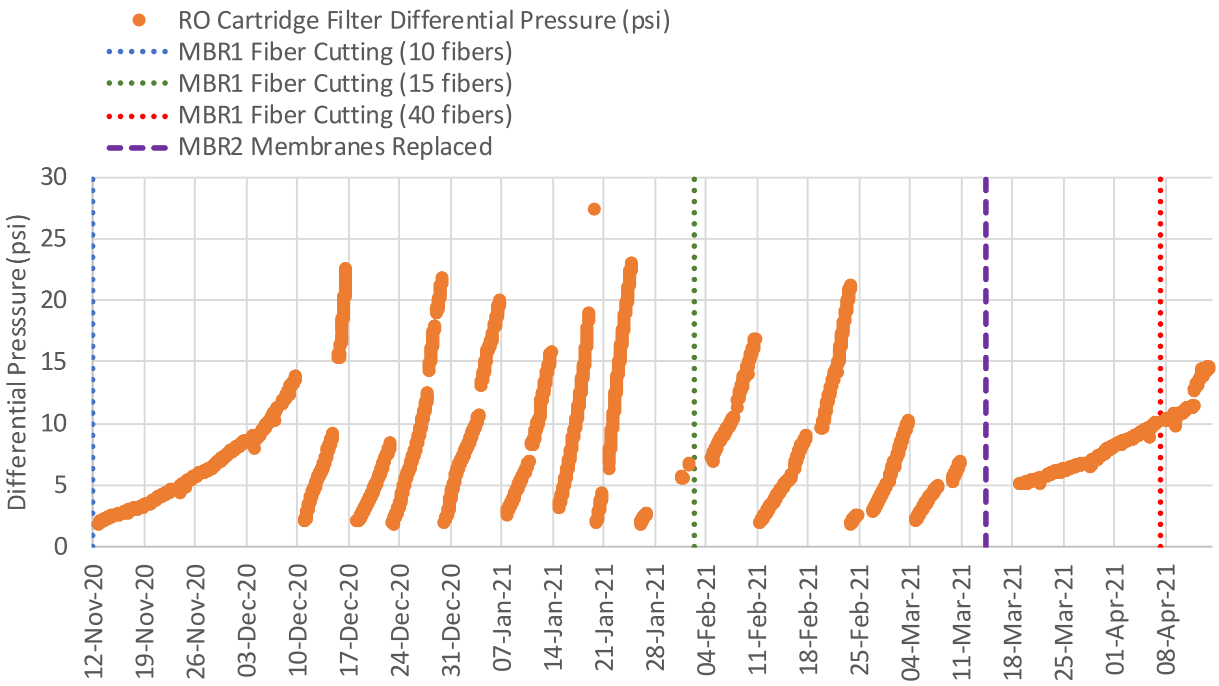


Figure 5-3. Typical Differential Pressure Across Cartridge Filters During Challenge Testing.

Table 5-9. Cartridge Filter Performance, Challenge Testing Phase.

Lot No.	**Date**		**Online Time**	**Differential Pressure (psi)**		**ΔP Accum**
	New	**Changeout**	**(day)**	**Start**	**End**	**(psi/day)**
Lot 5	10/30/2020	11/11/2020	10.9	1.76	23.40	1.99
Lot 6	11/13/2020	12/10/2020	21.5	2.03	13.88	0.55
Lot 7	12/11/2020	12/17/2020	4.6	1.93	22.60	4.46
Lot 8	12/18/2020	12/23/2020	4.3	1.81	8.29	1.51
Lot 9	12/23/2020	12/30/2020	6.1	1.91	21.78	3.24
Lot 10	12/30/2020	1/7/2021	6.9	1.94	19.94	2.61
Lot 11	1/8/2021	1/14/2021	5.5	2.77	15.73	2.34
Lot 12	1/15/2021	1/20/2021	4.1	2.99	28.29	6.12
Lot 13	1/20/2021	1/25/2021	3.8	2.00	22.79	5.50
Lot 14	1/26/2021	2/11/2021	6.2	1.72	16.85	2.44
Lot 15	2/12/2021	2/24/2021	9.5	1.92	21.22	2.04
Lot 16	2/24/2021	3/4/2021	5.2	1.82	10.30	1.63
Lot 17	3/5/2021	3/11/2021	3.8	2.10	6.93	1.27
Lot 18	3/19/2021	3/31/2021	10.3	4.94	7.88	0.29
Challenge Testing Average =			**7.3**			**2.6**

Figure 5-4. Cartridge Filters After Changeout on December 18, 2020.

Figure 5-5. Cartridge Filters After Changeout on October 29, 2020.

Figure 5-6. Cartridges After Changeout on January 28, 2021.

Figure 5-7. Cartridge Filters After Changeout on February 24, 2021.

RO Fouling Analysis

RO Normalized Flux

The normalized RO flux was calculated with a temperature correction factor based on water viscosity at 25°C to account for changes in feed water temperature. The net driving pressure (average feed-concentrate pressure minus permeate pressure) was also adjusted based on the estimated osmotic pressure, to account for minor changes in feed water salinity and concentrate strength. Normalized flux values were calculated based on continuously monitored flow, pressure, and conductivity data at a five-minute interval.

Average flux values were calculated for periods of time when the RO system was operated achieving 11 to 12 GFD permeate flux and 80-85 percent recovery, and at all times with a feed flow >200 gpm. Data collected in September 2020 were used to represent baseline conditions for comparisons of flux and salinity, because the RO system operation was stable during this month following control logic improvements. Prior to this month, RO flux at Pass 1 Stage 2 was highly variable as a result of set point adjustments and control valves operation.

The monthly average normalized RO fluxes during baseline and challenge testing phases are listed in Table 5-10 and plotted in Figure 5-8. A noticeable decrease in RO flux is observed starting in November 2020. RO flux notably increased at Stage 1 following a CIP cycle using both high-pH and low-pH solution, after which, continued flux decrease was observed with the sharpest decrease in February 2021.

Table 5-10. Monthly Average Normalized RO Flux in Baseline and Challenge Testing Phases.

Month	Time Online (hr)	Normalized Permeate Flux (GFD/psi)			
		Pass 1 Stage 1	Pass 1 Stage 2	Pass 2 Stage 1	Pass 2 Stage 2
July 2020	722	0.159	0.120	0.185	0.085
August 2020	691	0.163	0.117	0.192	0.085
September 2020 - Baseline	674	0.165	0.106	0.201	0.083
October 2020	584	0.161	0.101	0.205	0.083
November 2020 - Fiber Cutting	635	0.154	0.094	0.205	0.083
December 2020 - Pre-CIP	313	0.147	0.092	0.205	0.082
OVERALL - Pre-CIP		**-11%**	**-13%**		
December 2020 - Post-CIP	306	0.158	0.095	0.219	0.079
January 2021	694	0.146	0.091	0.215	0.079
February 2021	547	0.136	0.087	0.215	0.081
March 2021	333	0.133	0.085	0.212	0.082
OVERALL - Post-CIP		**-16%**	**-10%**		

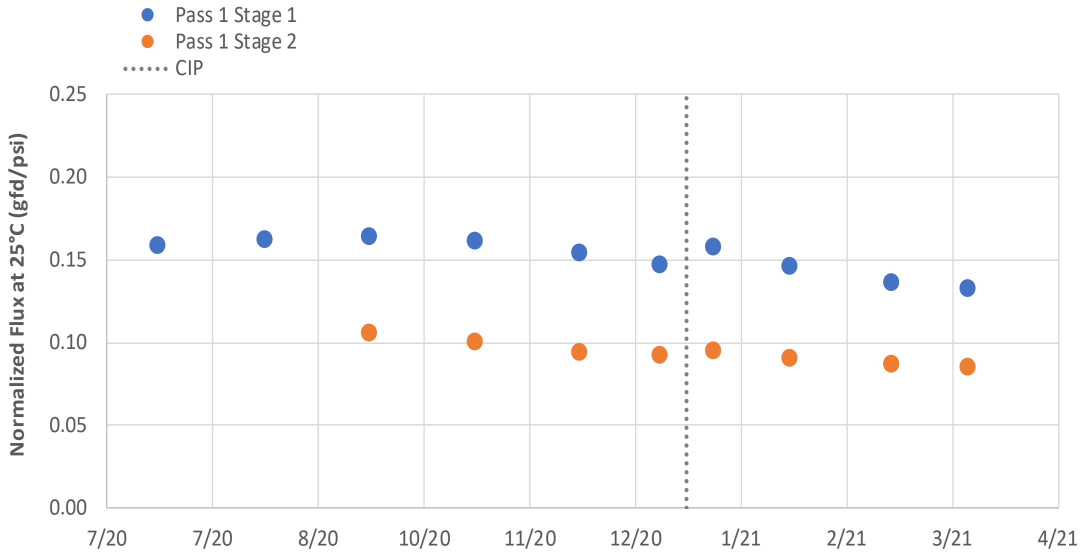


Figure 5-8. Monthly Average Normalized RO Flux During Baseline and Challenge Testing.

Observed RO Fouling

The cumulative decrease in RO flux and increase in salt passage are shown in Table 5-11, along with the average MBR filtrate turbidity for each month. In this table, cumulative decrease in flux was calculated using the September 2020 results as a benchmark, and a new benchmark following the December 2020 CIP. Increase in salt passage was calculated starting September 2020 using all available data. Fouling was observed at an increasing rate starting around October 2020, which coincided with the discovery of snails in the MBR tanks. Particularly for Stage 1 RO, the observed decrease in flux was consistent with an increase in organics and colloidal particles. During this time, the membranes remained good integrity, with no changes in salt passage at Pass 1 Stage 1 and slightly increased in Pass 1 Stage 2.

Table 5-11. RO Flux, Salt Passage, and MBR Filtrate Turbidity by Each Month.

Month	Flux (GFD/psi-day)		Salt Passage (%/yr)		Filtrate (NTU)	
	Pass 1 Stage 1	Pass 1 Stage 2	Pass 1 Stage 1	Pass 1 Stage 2	MBR-1	MBR-2
July 2020	N/A	N/A	N/A	N/A	0.028	0.031
August 2020	0.0000	N/A	N/A	N/A	0.030	0.034
September 2020 (Benchmark)	0.0000	N/A	N/A	N/A	0.029	0.042
October 2020	0.0004	0.0009	N/A	N/A	0.027	0.051
November 2020 (Fiber Cutting – 10)	0.0008	0.0014	N/A	N/A	0.024	0.068
December 2020 - Pre-CIP	0.0012	0.0014	N/A	N/A	0.025	0.138
December 2020 - Post-CIP					0.022	0.175
January 2021	0.0018	0.0011	N/A	0.03	0.028	0.191
February 2021 (Fiber Cutting – 15)	0.0022	0.0014	N/A	0.36	0.031	0.422
March 2021	0.0020	0.0013	N/A	0.00	0.024	0.155

N/A - not applicable

The observed decrease in flux, particularly in Pass 1 Stage 1, appeared to correlate to increasing turbidity in the MBR filtrate, particularly with the MBR2 system. The monthly average MBR filtrate turbidity for each system and the increase in differential pressure over the cartridge filters is plotted with time in Figure 5-9. As it was of interest to understand the source of the membrane foulant –

whether it was mineral scaling (e.g., phosphate, carbonate, or silica precipitates), colloidal fouling, organic fouling, biofouling, or some combination of these types of fouling, the MBR filtrate quality was compared with the RO specific flux decline to identify correlations. The temperature-corrected specific flux showed a somewhat positive correlation between MBR2 turbidity and fouling (higher flux decline), particularly for Pass 1 Stage 1 below approximately 0.1 NTU, as shown in Figure 5-10.

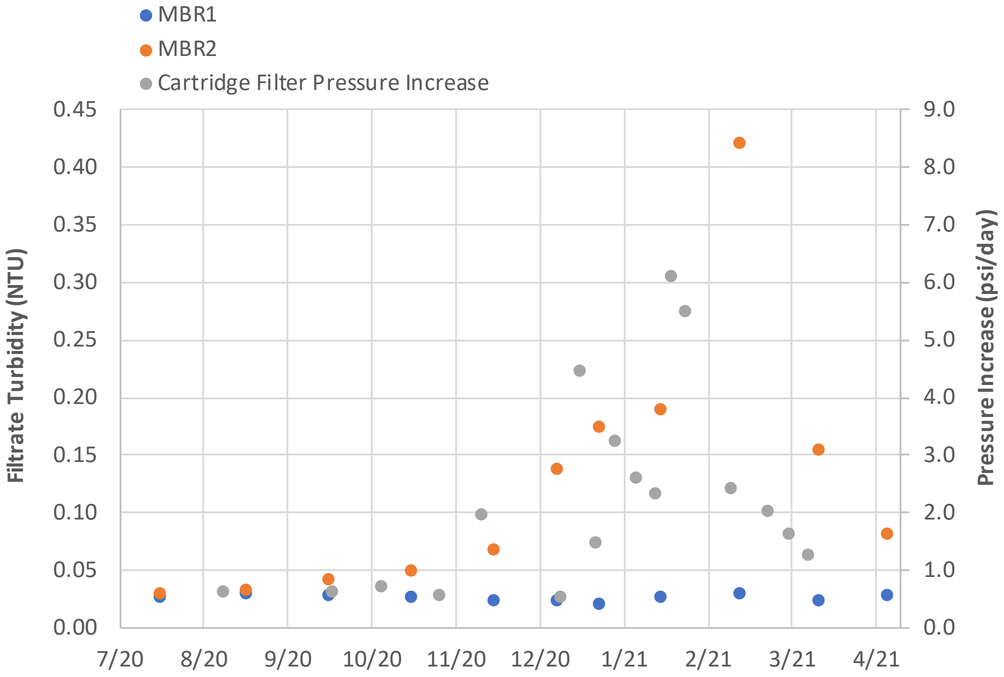


Figure 5-9. MBR Filtrate Turbidity (monthly average) Over Time During Baseline and Challenge Testing. Damage to the MBR-2 system and resulting performance decline was likely due experimental conditions, and unanticipated snail growth and subsequent damage.

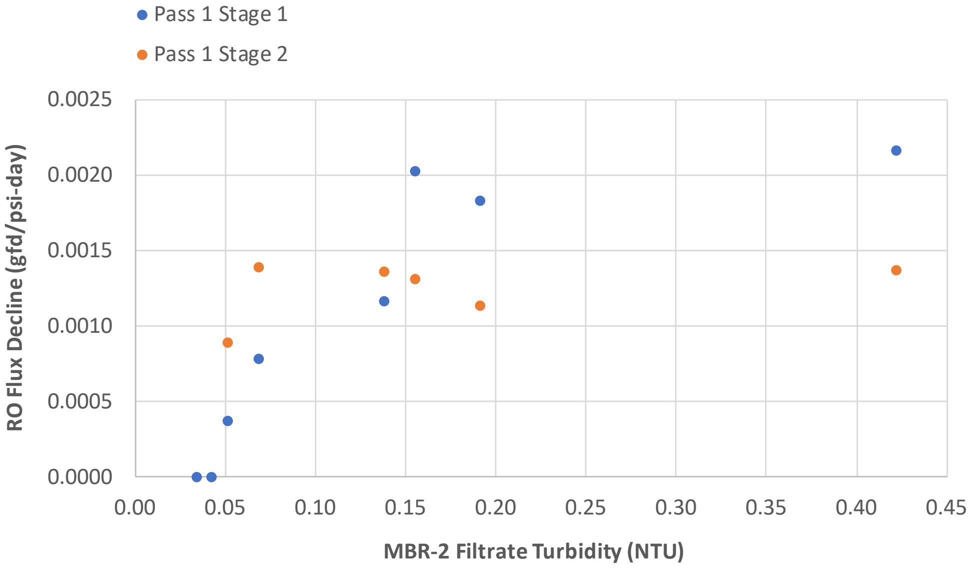


Figure 5-10. Correlation Between MBR-2 Filtrate Turbidity (monthly average) and Observed RO Flux Decline.

Colloidal and organic particle loading appears to correlate with the observed RO fouling based on membrane autopsy results, whereas the correlation between inorganic precipitates and RO flux is unclear. Results of the Avista Advisor^{TM} scaling modeling using major ion concentrations from baseline testing are summarized in Figure 5-11. Also shown in Figure 5-11 is that at an 85 percent RO recovery, and at the high end of the RO feed pH range, no inorganic scalants are expected to exceed their solubility limits in the RO concentrate. Calcium carbonate and silica are expected to govern scaling but are well within their limits for the Vitec 1400 antiscalant. Periodic excursions to higher recovery or interruptions to chemical flow could lead to RO membrane scaling, but this is not expected to be a severe risk in this case.

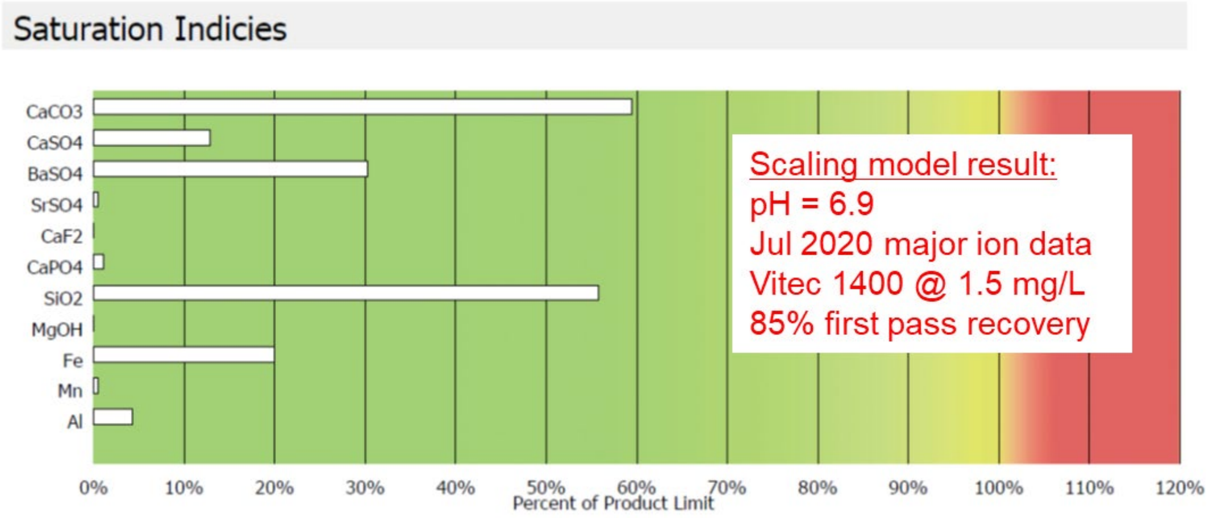
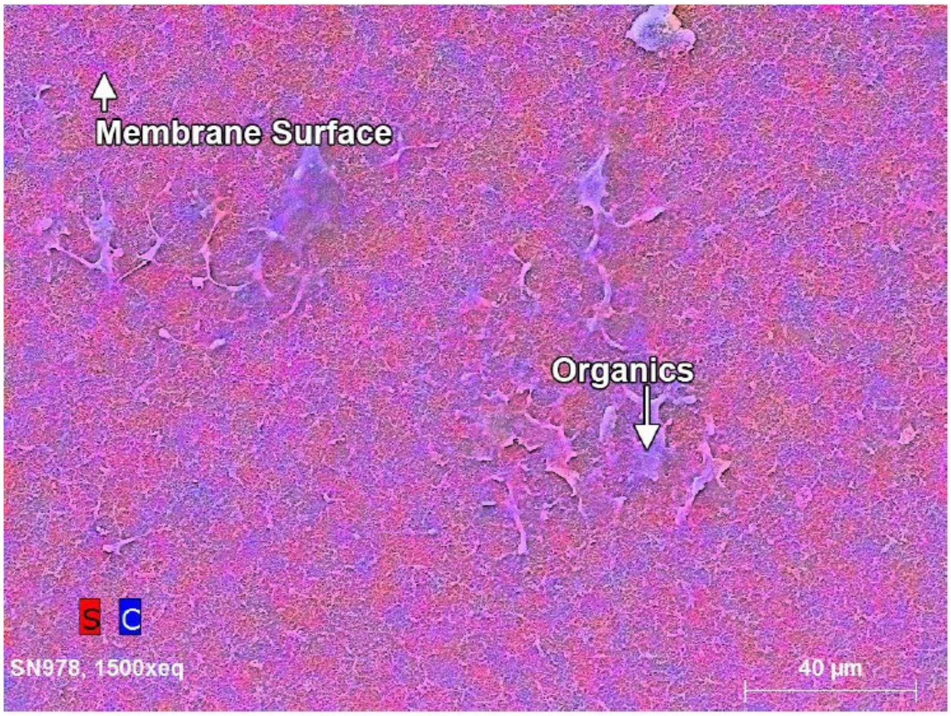


Figure 5-11. Avista Advisor Scaling Modeling Results.

Autopsy Results and Interpretation

One of the membrane elements was sampled from the lead position in a Pass 1 Stage 1 vessel prior to the CIP in December 2020, and was sent to Avista Technologies (San Marcos, California) for an autopsy analysis. The autopsy analysis revealed that the membrane element had normal salt passage but reduced flux, indicative of fouling. Organic material was observed visually on the membrane surface, and this was confirmed by analysis of the foulant composition. Imaging analysis (Figure 5-12) showed organic material, and elemental analysis showed the organic material consists of mostly carbon, oxygen, and nitrogen. Moreover, Fourier-transform infrared spectroscopy indicated biochemical molecules such as proteins and lipids are components of the organic material. A laboratory cleaning study effectively removed the foulants at high pH, which is the typical cleaning strategy to prevent organic and colloidal fouling.



CEI image (1500x) of the membrane surface with labels

Figure 5-12. Imaging Analysis of Membrane Surface from Avista Autopsy.

The operational data and autopsy results support the following overall observations:

- **Consistent fouling occurred in Pass 1** – this was supported by observed normalized flux decline trends and was confirmed in the autopsy results.
- **Organic and microbiological fouling appeared to govern** – this was supported by observed flux trends since fiber cutting; the correlation of flux decline to MBR turbidity; measurements of foulant composition; and the scaling model. There was no clear inorganic scale formation, and this was also observed with a second autopsy on a Pass 1 Stage 2 membrane element.
- **CIP required a high pH clean** – this was supported by field CIP results and the laboratory cleaning study, and consistent with the hypothesis that organic and colloidal fouling govern.
- **Membrane integrity was stable** – this was supported by observed salt passage and autopsy results.

CHAPTER 6

Module E: MBR Impact on CBAT

The content of this chapter consists of a summary of research activities conducted for this study in collaboration with and significant funding support from the City of Rio Rancho, New Mexico, at their CWRF and AWTF. A client report was produced as part of this work and is provided in its entirety as Appendix D to this final report.

6.1 Background

Rio Rancho Pure (Rio Rancho Water Utilities' or RRWU's potable reuse system) represents a critical first potable reuse project in New Mexico and the first O_3/BAC system nationally used for potable reuse via groundwater recharge. The AWT integrates an MBR at the Cabezon Water Reclamation Facility, followed by O_3/BAC treatment at Reservoir 3, which includes the groundwater recharge facilities. This MBR-O_3/BAC system provides multiple barriers for the control of pathogens and chemical contaminants and produces a product water that meets all New Mexico Environment Department (NMED) Standards. A process flow diagram for the CWRF and AWTF is shown in Figure 6-1. Note that the facilities are separated by 5.5 miles of pipeline and several storage tanks.

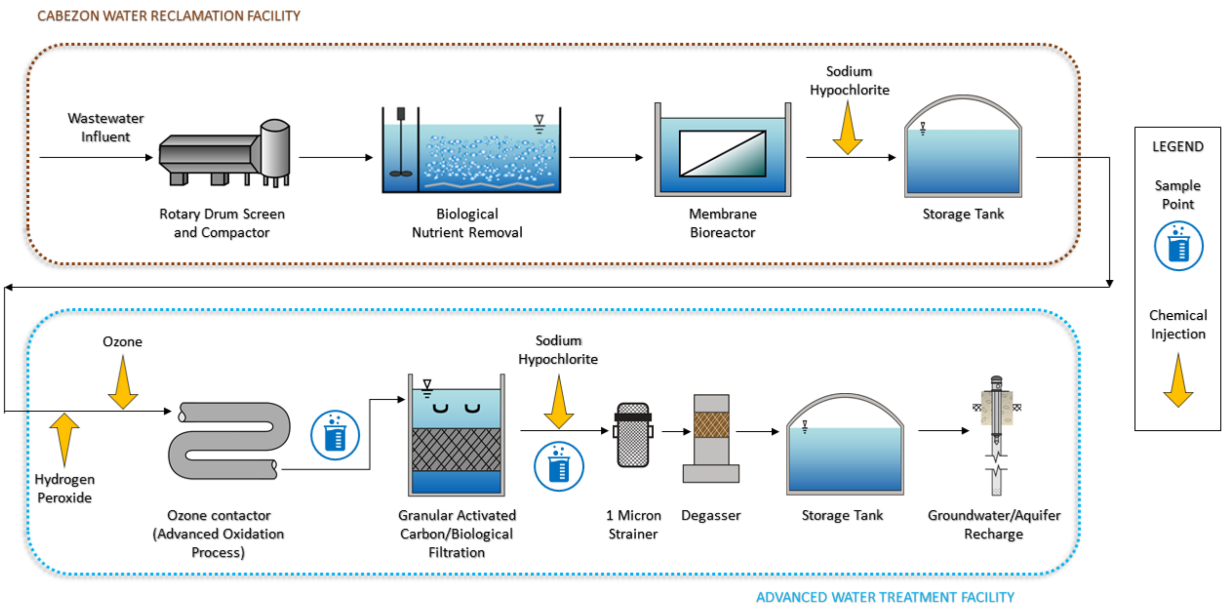


Figure 6-1. Process Flow Diagram Showing Cabezon WRF and the AWTF.

Since construction of this facility, the potable reuse industry has made large knowledge gains regarding optimization of O_3/BAC-based AWT systems, continuously tracking TOC concentrations in the feed to the system and controlling the transferred O_3 dose based upon a target O_3: TOC ratio.

6.1.1 The Ozone-to-TOC Ratio Dose Control Concept

Prior thinking on O_3 for wastewater disinfection focused upon the concentration × time (i.e., CT) concept, with the State of California Division of Drinking Water (DDW) granting 5-log LRV for virus disinfection by ozone based on a minimum CT of 1.0 mg × min/L (Ishida et al., 2008). WE&RF Project 11-02 (Trussell et al., 2016) documented similar virus inactivation LRV to Ishida et al. (2008) but defined virus log reduction dose/response as a function of transferred O_3 dose to TOC ratios (O_3: TOC). This finding was also detailed in Fontaine and Salveson (2014). This work consistently demonstrated 7+ LRV for seeded MS2 bacteriophage at O_3: TOC ratios of 1.0 and greater. Such LRV for MS2 bacteriophage is conservatively equivalent to 5 LRV for poliovirus and a broad range of other enteric virus (Ishida et al., 2008; Fontaine and Salveson, 2014). Recent work by Wolf et al. (2019) developed a correlation between O_3: DOC ratio and O_3 exposure. Wolf et al. (2019) also observed a strong correlation between O_3: DOC ratio and inactivation of both MS2 bacteriophage and coxsackievirus B5 in two surface waters and one secondary wastewater effluent. A strong correlation was also noticed between O_3: DOC ratio and log reduction of UV absorbance (UVA) at 254 nanometers (nm), and a predictive model was established to correlate UVA reduction and log virus inactivation (Wolf et al. 2019). An extensive ozone dosing ranges were validated for virus reduction in Fontaine and Salveson (2015), in which a broad range of O_3 dose, contact time, and O_3: TOC ratios were tested for virus reduction, with results matching the previously listed research projects, but also critically highlighting the potential impact of nitrite on O_3 demand (O_3: TOC ratio corrected for NO_2-N concentration).

These studies and others have demonstrated that O_3 performance is based upon the O_3: TOC ratio, with values in the range of 0.6 to 1.0 necessary for optimum disinfection and destruction of chemical contaminants. Nitrite in water also exerts high O_3 demand. Therefore, TOC and nitrite concentrations are critical in determining the O_3 dose.

6.2 Testing Conducted at Rio Rancho

6.2.1 Initial Testing

The first phase of work, completed in 2019, was an examination of water quality followed by bench-scale O_3 dose-response testing. Challenges were encountered regarding inconsistent nitrite occurrence at concentrations up to 4 mg/L as N, variable effluent TOC concentrations, and the impact of both on O_3 demand and performance. These challenges revealed the need to step back and fully understand the variation in TOC and NO_2 concentrations in the MBR effluent. For this reason, additional samples were collected at different locations and analyzed for ammonia, nitrite, and nitrate prior to feeding the AWTF. Samples were also split between laboratories to eliminate laboratory error as a potential confounding factor. This initial water quality characterization highlighted variable and abnormal water quality in the Cabezon MBR effluent. In response, plant staff at Cabezon evaluated and diagnosed MBR operational problems, including leaking air in the system and two malfunctioning anoxic zone mixers.

In addition to correcting the above operational problems, Rio Rancho also installed a new scan Spectro:Lyser ™ in a 3-million gallons (MG) effluent storage tank that is immediately downstream of the MBR. Spectro:Lyser ™ is an optical-based spectrophotometers that can measure UV wavelengths between 190 to 390 nm. The Spectro:Lyser ™ measures NO_2-N, TOC, NO_3-N, and UVA. Of these parameters, the NO_2, NO_3, and TOC are the most useful as they reflect the water quality of the Cabezon MBR effluent. Additional water quality sampling was conducted to understand whether grab sampling results match those data from the online sensor.

Once the operational problems were addressed, the MBR effluent quality has been improved in terms of both average concentrations and stability, as shown for TOC, nitrate, and nitrite in Figure 6-2 through Figure 6-4. In particular, online and grab sampling results confirmed that nitrite concentrations remained consistently below 0.1 mg/L as N in the MBR effluent. Details of this analysis are provided in Chapter 2 of Appendix D.

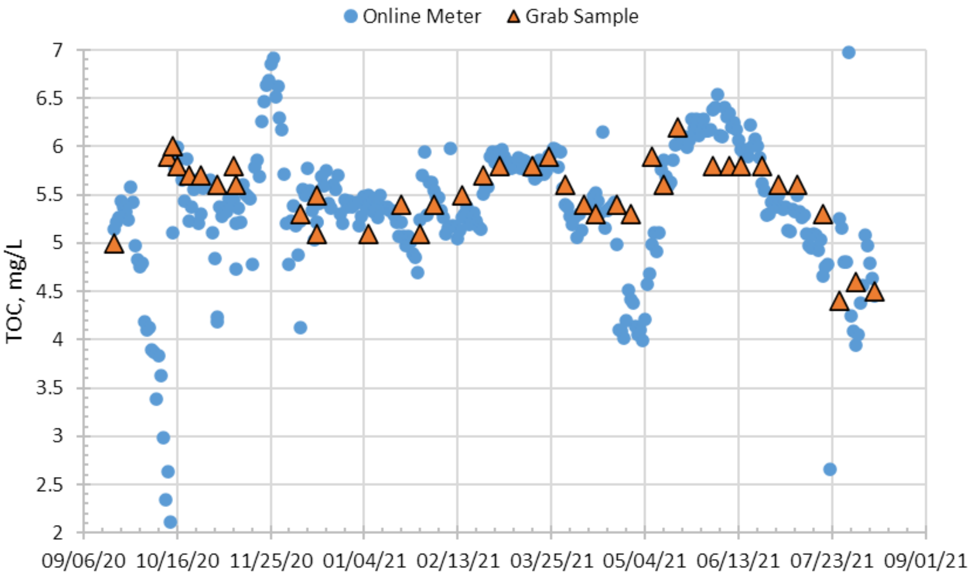


Figure 6-2. MBR Effluent Online and Grab Sample TOC Results After Improvements at the Cabezon WRRF.

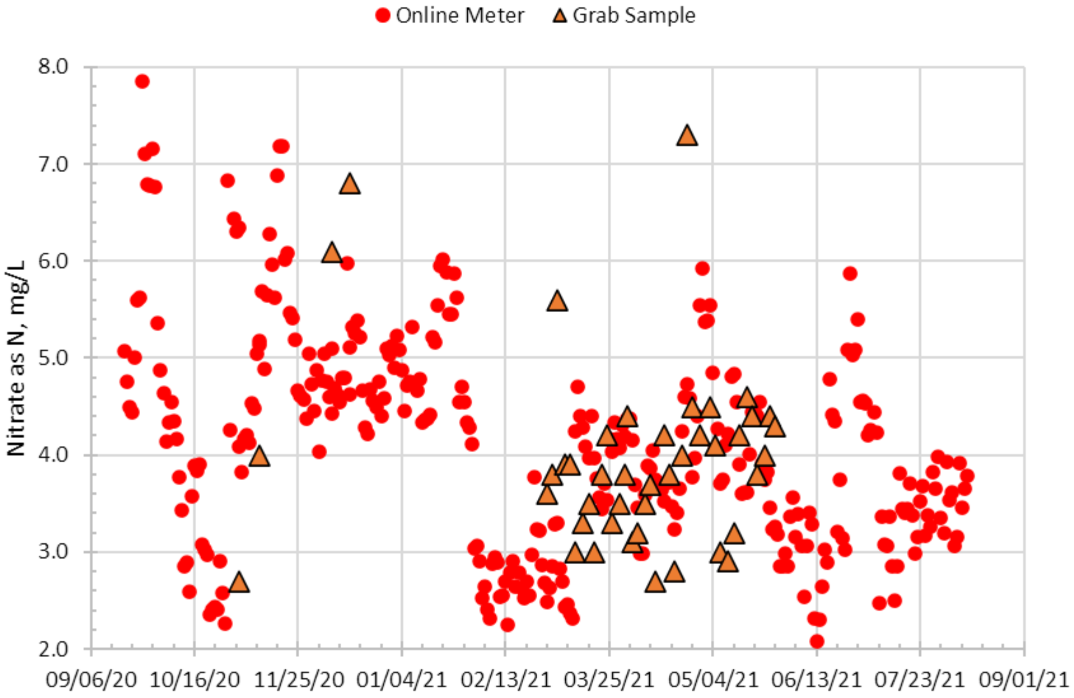


Figure 6-3. MBR Effluent Online and Grab Sample Nitrate Results After Improvements at the Cabezon WRRF.

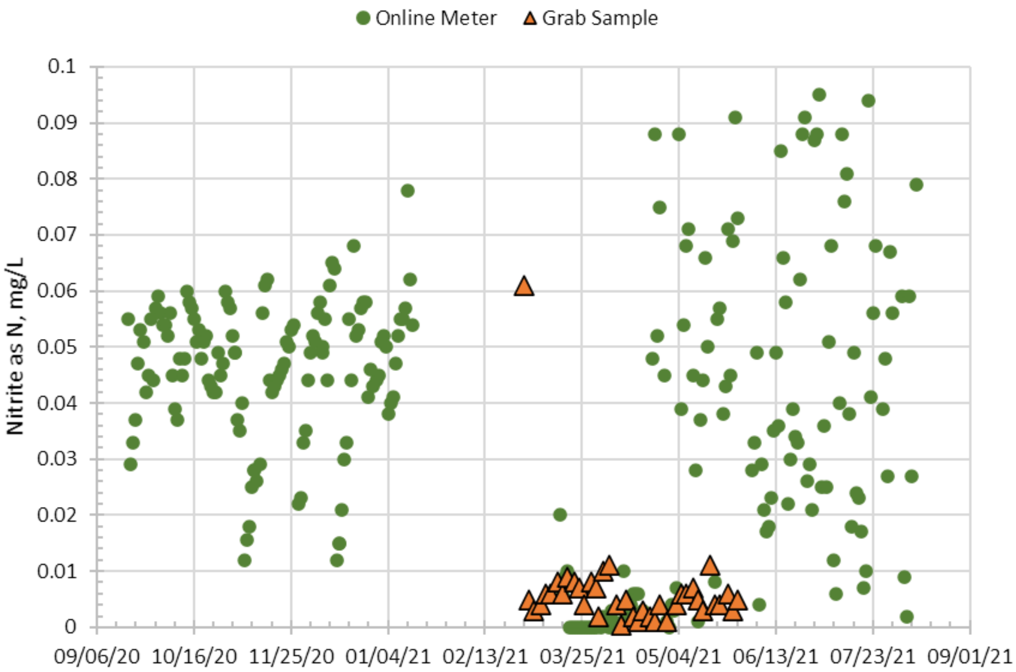


Figure 6-4. MBR Effluent Online and Grab Sample Nitrite Results After Improvements at the Cabezon WRRF.

One might dismiss these initial efforts in stabilizing the Cabezon MBR effluent water quality as mere troubleshooting exercise ahead of the “real” work associated with understanding the impacts of MBR on O_3/BAC performance discussed in the next section. However, for practitioners, this first phase of the team’s work at Rio Rancho represents a cautionary tale that applies not only to this particular WRRF/AWT combination, but to any utility contemplating AWT for potable reuse: **A well-operated, sensed and maintained WRRF – regardless of design – is an absolute prerequisite for good performance of AWT.**

6.2.2 Extended Testing

With the MBR effluent water quality at Cabezon improved and stabilized, and with better sensing capabilities to facilitate better data collection, additional testing was conducted to evaluate treatment performance that is specific to CBAT: control of bromate and halogenated DBP formation, CEC destruction, and pathogen inactivation. These topics were explored through:

1. Bench-scale ozone dose-response testing with and without hydrogen peroxide.
2. Full-scale AWTF baseline sampling for CECs and DBPs.
3. Full-scale AWTF sampling for CECs and DBPs after GAC change-out.
4. Full-Scale AWTF sampling for CECs and DBPs under modified operating conditions.
5. Bench-scale ozone dose-response testing with Cabezon effluent to evaluate virus inactivation with seeded MS2 bacteriophage.

Detailed result discussions from these testing efforts are provided in Chapter 3 of Appendix D.

6.2.2.1 Bench-scale Ozone Dose-response Testing for the Control of Bromate Formation and CEC Destruction

Four Cabezon MBR effluent samples were collected in November and December 2020 and were sent to Carollo’s Water ARC® laboratory for bench-scale O_3 dose-response testing. Tests with ozone alone, and with H_2O_2 addition at an ozone: H_2O_2 mass ratio of 1: 1.2 were performed for each of the four samples. CEC samples were collected and analyzed by the laboratory at SNWA.

As shown in Figure 6-5, no ozone residual was measurable until the ozone dose exceeded nitrite-corrected ozone: TOC mass ratio of 0.8: 1 (mg of O_3/mg of C). This ozone dose corresponded to the point at which significant amount of bromate was formed without hydrogen peroxide addition. As shown in Figure 6-6, significant bromate formation (exceeding MCL of 10 µg/L) occurred at ozone dose greater than ozone: TOC ratio of 0.8: 1. Bromate formation was effectively mitigated by the addition of hydrogen peroxide as described above, with no detectable (<1 µg/L) bromate formed in any of the samples with hydrogen peroxide addition (refer to Table 3.3 in Appendix D).

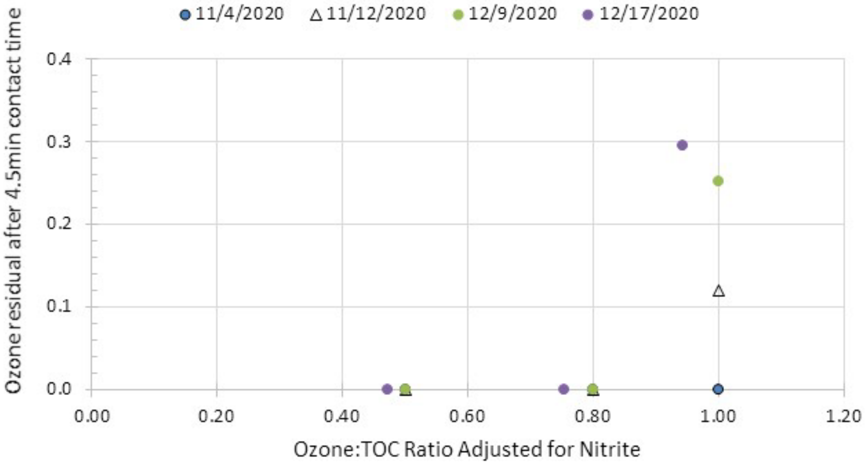


Figure 6-5. Ozone Residual as a Function of Nitrite-Adjusted Ozone: TOC Ratio.

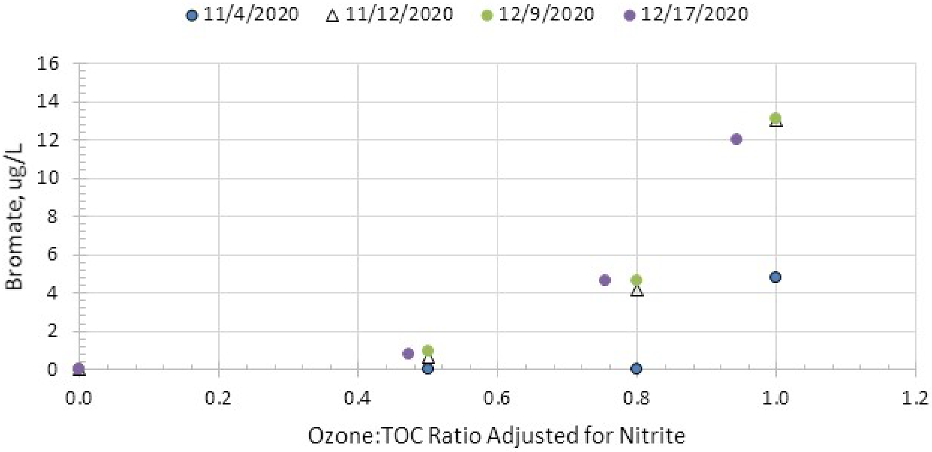


Figure 6-6. Bromate Formation at Different Nitrite-Adjusted Ozone: TOC Ratios without H_2O_2 Addition.

This is consistent with what was reported in previous studies and points to a potential goal of operating a CBAT system at sub-residual ozone doses to minimize bromate formation – if such ozone doses provide the desired level of disinfection and CEC destruction. Hydrogen peroxide addition was effective in mitigating bromate formation and may be a prudent backstop if ozone performance is unknown. While hindsight would suggest testing at a nitrite-adjusted O_3: TOC ratio of 0.8: 1 might have been more optimal, CEC destruction testing was conducted at nitrite-adjusted O_3: TOC ratio of 1.0: 1 to achieve high levels of CEC removal (refer to Table 3-4 in Appendix D for more details).

6.2.2.2 Full Scale AWTF Baseline Sampling and Post-GAC Changeout Testing

The carbon in the BAC system was replaced with fresh GAC in mid-November 2020. Prior to the GAC changeout, one sampling event across the CBAT train (pre-ozone, post ozone, post BAC) was conducted to benchmark baseline CBAT performance for a range of water quality parameters, including CECs and PFAS (analyzed at the SNWA laboratory). After new GAC was installed, the transition from GAC to BAC was monitored by similar sampling approach. Over a period of seven weeks, PFAS and CECs were characterized across the CBAT train over 5 sampling events. These five sampling events occurred from December 8, 2020, through January 19, 2021. Detailed PFAS and CEC sampling results are provided in Chapter 3 in Appendix D. The following section provides a brief overview of the sampling results:

As shown in Figure 6-7, TOC removal achieved through BAC clearly indicates GAC exhaustion over time. Within two months after GAC changeout, more than 50 percent of influent TOC had broken through.

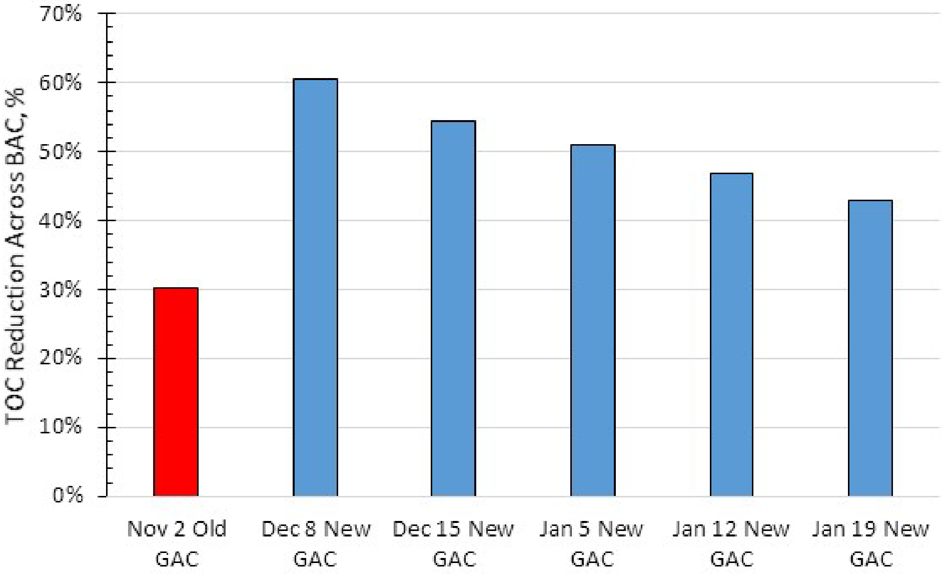


Figure 6-7. TOC Reduction through GAC Pre- and Post-Changeout.

High effluent nitrite concentrations were observed during the full-scale AWTF baseline sampling on November 2, prior to GAC changeout. The occurrence of high nitrite appeared to be a transitory event as MBR effluent nitrite concentrations were measured to be low during all subsequent sampling events.

Although ozone doses are reported herein as nitrite-corrected O_3: TOC ratios, the AWTF was not constructed to deliver ozone dose this way. With nitrite exerting a high ozone demand up to 6 mg/L during baseline sampling event, the corresponding nitrite-corrected O_3: TOC ratio was nearly zero. This resulted in several unanticipated results, including a low UVT reading post-BAC during the baseline sampling event, as shown in Figure 6-8. The increase in post-BAC UVT after GAC replacement was more in line with the higher TOC percent removal presented in Figure 6-7, as was the gradual decrease in UVT over time through the transition period from GAC to BAC.

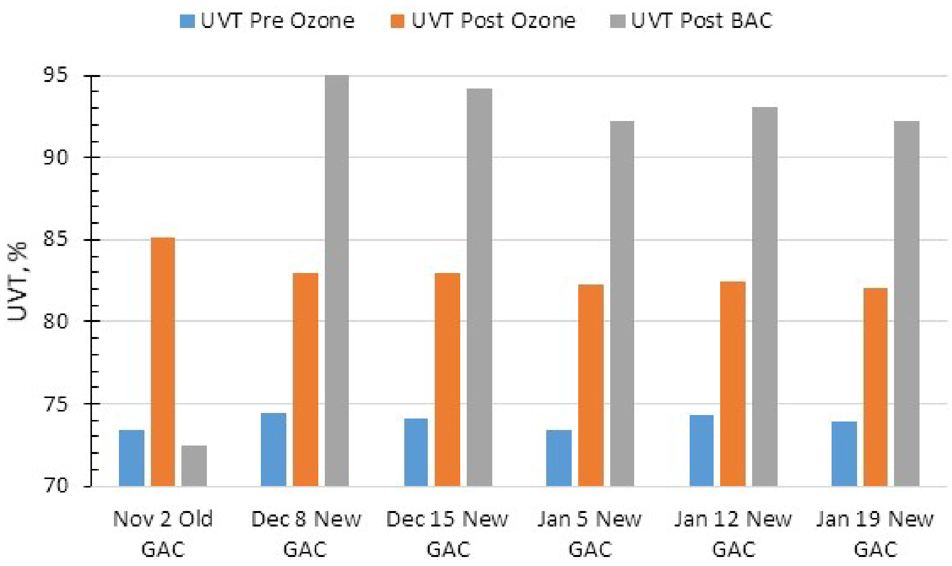


Figure 6-8. UVT Across Ozone/BAF Pre- and Post-Changeout.

Unsurprisingly, the CEC removals by ozone during AWTF baseline sampling were also significantly lower than the removal rates observed during bench-scale testing; however, the BAC still provided significant CEC removal. After GAC changeout, once MBR effluent nitrite concentrations had stabilized at low levels, the CEC removal through ozone returned to levels comparable to those from bench scale testing (refer to Table 3-13 of Appendix D for more details).

Although some studies have reported the formation of certain PFAS compounds by ozonation due to oxidation of their precursors (Rahman et al., 2014) that was generally not the case in this study, evidenced by the sampling results. As expected, no removal of shorter-chain PFAS compounds, and limited removal of PFOS and PFOA were achieved prior to GAC changeout. Post-changeout, PFAS removals were nearly complete initially, with rapid PFAS breakthrough over the transition period that was monitored. For example, removal of perfluorohexanoic acid (PFHxA) by GAC, a short-chain PFAS compound commonly present in wastewater effluent, which had a post-ozone concentration between 35 and 44 ng/L, decreased from 77 percent to 45 percent over the December 8 to January 19 GAC to BAC transition period (refer to Tables 3-15 and 3-16 in Appendix D for more details).

The Bottom Line: Effluent nitrite continued to be a challenge, but only periodically. Maintaining low nitrite concentrations in the MBR effluent is critical to efficient and effective performance of CBAT. PFAS presents a challenge, in particular after the carbon installed in the BAC contactors transitions from an adsorptive process to a biodegradation process. PFAS concentrations, as of the last sampling date, are below the United States Environmental Protection Agency (USEPA) Health Advisory Levels (HALs), but above regulated and advisory levels in other states.

6.2.2.3 Full-Scale System Modifications

Pertaining to ozonation and the control of bromate formation, the results documented above indicate a challenge to the existing O_3 oxidation system due to variable TOC and nitrite concentrations in the MBR effluent. TOC concentrations that exceeded 5 mg/L reduced O_3 oxidation effectiveness, whereas nitrite concentrations at any level reduced or even eliminated the oxidation potential of O_3 given its high ozone demand. With high effluent TOC concentration and measurable nitrite, high ozone dose required to break through the ozone demand resulted in increased bromate formation. In comparison, lower effluent TOC concentration and non-detectable nitrite required lower ozone dose. Sampling results further indicated that bromate formation was effectively mitigated when O_3: (TOC+ NO_2) ratio was maintained at 0.8 or below or an ozone dose that could control ozonated effluent UVT to be below 82 to 83 percent.

It is noteworthy that one of the goals of this project is to minimize or eliminate the use of hydrogen peroxide while controlling bromate formation as a result of ozonation. To evaluate the achievability of this goal, temporary modifications (i.e., a few hours per test) were made to the full-scale AWTF operation and water quality sampling was performed in September 2021 to understand the effectiveness of those operational changes.

Results of the full-scale system modification and sampling suggested that MBR could achieve high effluent quality, with TOC concentrations below 5 mg/L and nitrite below its method detection limit of 0.1 mg/L as N. An ozone dose at O_3: (TOC+ NO_2) ratio of 0.8 resulted in an increase in UVT of ozonated effluent from 77 percent to 81 percent and up to 83 percent, which was in alignment with the ozone dose suggested based on bench-scale testing that would provide sufficient disinfection and oxidation without exceeding bromate MCL of 10 µg/L. Bromate was non-detect (i.e., <5 µg/L) at O_3: (TOC+ NO_2) ratio ranging from 0.6 to 0.8. However, bromate formation was quantified to be 7.3 µg/L at an O_3: (TOC+ NO_2) ratio of 1.1. Moreover, ozone was effective in the destruction of CECs and higher the O_3: (TOC+ NO_2) ratio, greater the CEC removal. Notably, ozone was ineffective in destroying CECs including caffeine, sucralose, and TCEP. BAC continued to serve as a polishing step for CECs post ozonation, providing a strong barrier for CECs other than caffeine.

Overall, these full-scale AWT testing results suggested that a high and stable MBR effluent quality allowed for a more controlled ozone dose that would provide effective destruction of CECs and not result in bromate formation exceeding its MCL of 10 µg/L without the need for hydrogen peroxide addition. Furthermore, an ozone dose at O_3: (TOC+ NO_2) ratio of 0.8 was confirmed by both bench- and full-scale testing to be an optimal setpoint to conservatively control bromate formation.

6.2.2.4 Virus Challenge Testing

Parallel to full-scale AWTF operation modification and testing, MBR effluent was collected for bench-scale virus challenge testing. The challenge test used a non-pathogenic surrogate for viruses (i.e., MS2 bacteriophage) and MS2 was seeded to evaluate ozone dose-response at three different O_3: (TOC+ NO_2) ratios. Results of the virus challenge tests are shown below in Figure 6-9 and Figure 6-10 and confirmed high virus log reduction at nitrite-corrected O_3: TOC ratios from 0.5 to 1.0. With the prior work indicating non-detectable to limited bromate formation at an O_3: (TOC+ NO_2) ratio of 0.8 or less, these testing results demonstrated that 6-log virus reduction could be obtained without exceeding the bromate MCL without hydrogen peroxide addition.

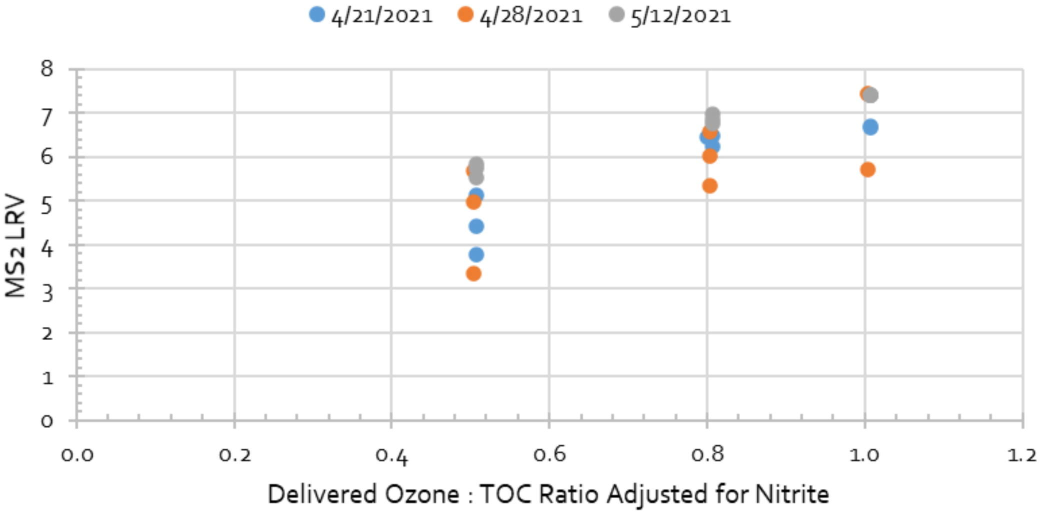


Figure 6-9. MS2 Log Reduction as a Function of Nitrite-Corrected O_3: TOC Ratio.

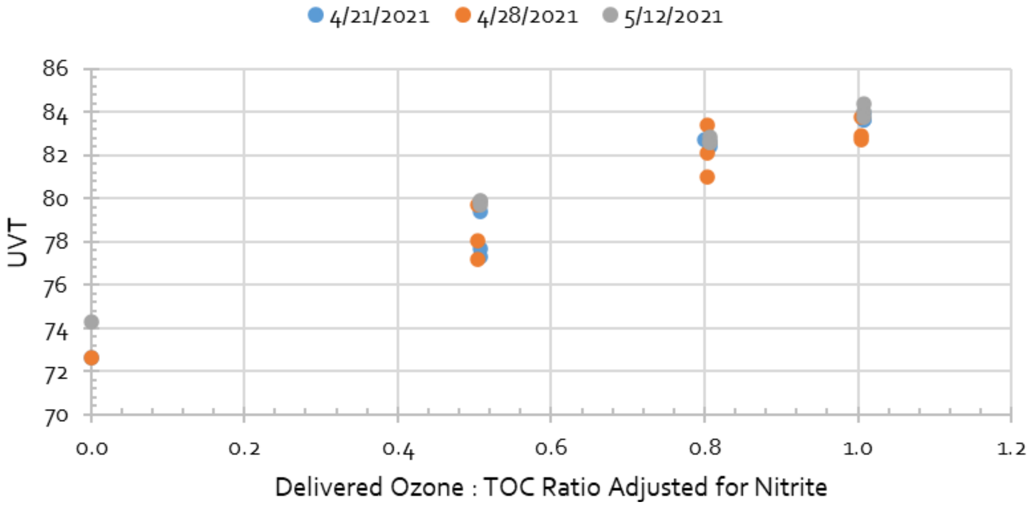


Figure 6-10. Ozone Effluent UVT as a Function of Nitrite-Corrected O_3: TOC Ratio.

CHAPTER 7

Cost Trade-Offs at the WRRF-AWT Interface

The purpose of this chapter is to present semi-quantitative cost trade-off evaluations that provide insight into what path to potable reuse might be most cost-effective for utilities with a range of WRRF treatment regimens and effluent water qualities. This has been done through a combination of cost curves, which are compelling in their simplicity and general applicability, but cannot capture important site-specific considerations and case studies, which are by definition tailored but perhaps not as generally applicable.

7.1 Cost Data and Decision Factors for WRRF/ AWT Processes

7.1.1 General Cost Factors

At the most general level, two factors will drive the decisions with respect to treatment optimization or upgrade at the WRRF/AWT interface for the purpose of potable reuse:

1. **Relative Flow:** In most potable reuse projects, existing and proposed, the flow being treated at the WRRF typically exceeds the total flow proposed for AWT and potable reuse. This has the benefit of providing a consistent flow to the AWT system while the existing WRRF outfall maintains the capacity to dispose of variable treated wastewater flows. This comes on top of the excess treatment capacity that must be provided at some WRRFs to address peak flows. In these scenarios, the cost of an upgrade to the WRRF will skew high compared to additional treatment at the AWT, simply because of the disparities in overall system scales.
2. **Regulatory Constraints:** Regulatory drivers in some states will preclude the design of a more cost-efficient AWT approach for potable reuse through a combination of prescriptive treatment technology requirements and treatment goals that far exceed those of other jurisdictions. Thus, two utilities with very similar WRRFs but located in different states may see a very different set of choices, and thus costs, for their WRRF/AWT upgrade evaluations. The cost impact of regulatory constraints was not explicitly considered within the scope of this project, but regulatory limitations are considered within the case study examples.

Focusing then on the potential trade-offs examined in the prior chapters, a few specific additional major cost factors must be quantified in order to provide even order-of-magnitude guidance on cost trade-offs. These include:

1. A generic rule-of-thumb cost assumption for constructing a new WRRF (without solids handling facilities) is $12-$14 per gpd annual weather dry flow (AWDF) capacity. This provides an important bookend to cost estimates for WRRF upgrades and may be close, for example, to the cost of converting a trickling filter plant to a biological nutrient removal facility.
2. A generic rule-of-thumb cost assumption for greenfield construction of MBRs (without solids handling facilities) is $17 per gpd at AWDF, and $10 per gpd at AWDF for MBR retrofits in existing basins.

7.1.2 Cost Trade-Offs Related to MF/UF and MBR

Important to evaluating cost trade-offs for many of the treatment scenarios evaluated, cost curves for MF/UF were developed based on varying plant flow and design flux. The cost curves in Figure 7-1 and Figure 7-2 were generated based on recent project data and equipment estimates, and assume a 2021 RS

Means location factor of 12054 (Southern California), building footprint allocated to MF or UF, but no electrical or control rooms, construction cost only (no engineering cost), and a power cost of \$0.15/kWh.

Both sets of curves illustrate a stark difference between the costs of MF/UF at low design flux (20 GFD) versus diminishing rates of return at increasing deign flux between 40 and 50 GFD. Moreover, these curves show important economies of scale. It is noteworthy that values at 1 mgd were also calculated for construction cost but are not shown herein to avoid the loss of resolution at other flow rates. Interestingly, the curves converge at 1 mgd (and \$4.2 million/mgd), indicating that at this low flow, the cost impact of design flux is dwarfed by the lost economy of scale.

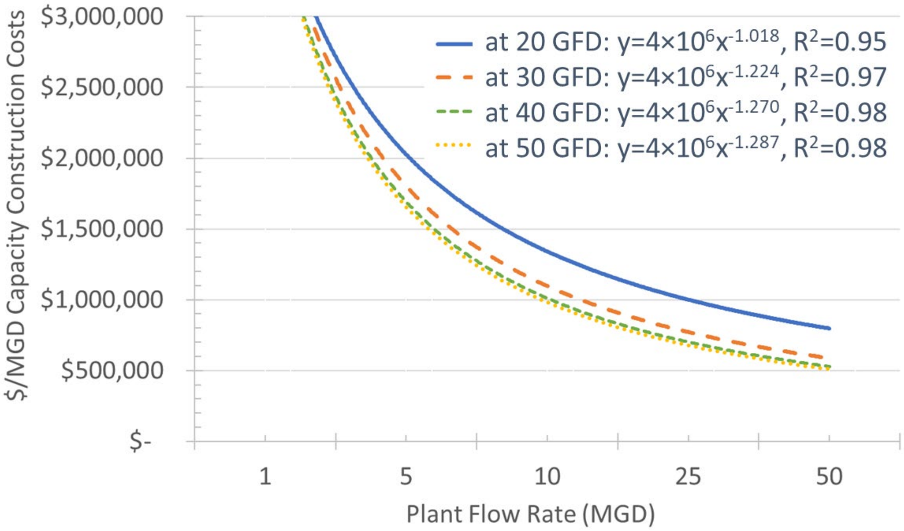


Figure 7-1. MF/UF Construction Cost as a Function of Total Flow (mgd) and Design Flux (GFD).

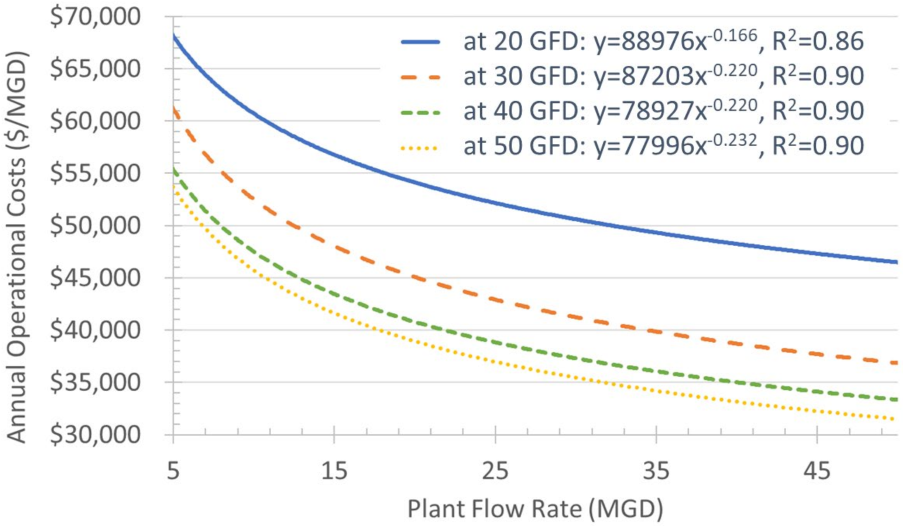


Figure 7-2. MF/UF Annual Operation and Maintenance Costs as a Function of Total Design Flow (mgd) and Design Flux (GFD).

7.1.2.1 MF/UF System Construction Cost as Function of WRRF SRT and Effluent Quality

A combination of the correlations shown in Figure 7-1 and Figure 4-2 through Figure 4-4 can provide a direct correlation between WRRF SRT, effluent ammonia, and effluent TOC and the estimated construction cost of the MF/UF system, respectively, needed to treat the WRRF effluent, as illustrated for two hypothetical MF/UF facilities with 25 mgd total flow:

- **Scenario 1:** The WRRF has SRT = 2 days, effluent ammonia = 30 mg/L as N, and effluent TOC = 20 mg/L. This would predict a design flux under 20 GFD, which translates to a cost of at least $1.0 million per mgd, or at least $25 million in construction cost.
- **Scenario 2:** The WRRF has SRT = 12 days, effluent ammonia < 1 mg/L as N, and effluent TOC = 5 mg/L. This would predict a design flux of approximately 30 GFD, which translates to a cost of about $800,000 per mgd, or about $20 million in construction cost, representing at least 20 percent savings over the cost of the MF/UF system designed to treat the lower quality effluent from Scenario 1.

7.1.2.2 Potential Savings through Elimination of MF/UF System Cost with MBR before AWT

Based on the results of the MBR studies summarized in Module D, MBR-based WRRFs may likely be able to forego altogether a tertiary MF/UF system ahead of RO with minimal capital cost impacts. Figure 7-1 and Figure 7-2 thus also represent the potential construction and O&M *cost savings,* respectively, provided by an MBR/RO based treatment approach. While the construction cost savings are likely applicable as-is, based on the data provided in Module D, operational impacts may exist related to potential increased cleaning frequencies and may reduce the total savings potential on an annual O&M basis. Even assuming a high flux (≥ 50 GFD) for the MF/UF system downstream of MBR, the construction cost savings associated with the elimination of an MF/UF in a 25 mgd AWTF under this scenario are around $19 million.

The additional benefit of this trade-off is that the key costs of eliminating the tertiary MF/UF downstream of MBR are related simply to confirming/validating the MBR's pathogen removal capacity through the tiered validation process described in Module D, rather than building additional treatment capacity – presuming that the WRRF already has an MBR in place.

A different trade-off exists if the WRRF itself is a lower-tech facility that currently produces lower-quality effluent. Now the cost savings from not building a tertiary MF/UF system may be higher (because a larger size MF/UF system would be designed at a lower flux to treat a lower-quality effluent); at 25 mgd, the construction cost of MF/UF might be close to the $25 million mark from "Scenario 1" above. However, the cost of retrofitting the WRRF for MBR is also substantial. Using the generic $10 per gpd rule-of-thumb cost for an MBR retrofit, this represents a $250 million investment compared to the $25 million in savings from avoiding the MF/UF construction – *even if* the AWT capacity is the same as the WRRF capacity (both of 25 mgd). This trade-off provides one illustration of the general trend throughout this project that major upgrades at the WRRF can generally not be justified for the sake of only the AWT alone.

In summary, if the WRRF already has an MBR, or is going to build one for reasons unrelated to an AWT for potable reuse, it will provide tangible benefits by saving the cost of a tertiary MF/UF system. On the other hand, if the WRRF does not have an MBR, and cannot justify building one based on significant benefits unrelated to an AWT for potable reuse, it more than likely will not pencil out to construct one.

7.1.3 Cost Evaluations Related to Effluent Quality and CBAT

CBAT cost differences for the ozone and BAC components with respect to differences in WRRF treatment scenarios and effluent water qualities were presented in Section 3.6.6 and Table 3-13 and Table 3-14 for capital and O&M cost impacts, respectively. For hypothetical CBAT facilities, the cost difference between treating an assumed high TOC trickling filter effluent and low TOC effluent from a well-operated conventional facility with extended SRT could be as high as $42 million in capital costs and $7 million in annual O&M costs at a scale of 100 mgd. These costs do not include potential impacts from pass-through constituents, such as nitrosamines, short-chain PFAS, etc., which may require "support treatment" that is specific to the constituents (e.g., anion exchange for PFAS, high dose UV photolysis for nitrosamines), depending on site-specific concentrations and regulatory circumstances.

For comparison purposes, when states on a *per mgd* basis, these maximal additional costs shrink dramatically, to $420,000/mgd in capital and $70,000 per mgd in O&M cost differences between a CBAT plant fed by a low-quality trickling filter effluent versus a high-quality long-SRT effluent. In comparison to the significant upgrades that would be needed on a similar per-mgd basis to transform a tricking filter facility to an extended SRT conventional treatment plant[2], the project team must conclude again, that even if the WRRF and AWT had identical design flows, it would be more sensible from a pure financial perspective, to invest in the AWT facility over investing the same dollars in upgrading the trickling filter WRRF, unless there would be the need for a lot of additional AWT "support treatment" processes beyond CBAT to address site-specific contaminants.

7.2 Cost Trade-off Case Studies

Case studies were developed for several utilities implementing AWT downstream of WRRFs. The purpose of these case studies is to provide examples of cost trade-offs of implementing upstream WRRF modifications to improve effluent quality (i.e., AWT feed water quality), and the corresponding cost impacts on the AWT facility. These case studies provide an overview of:

- Target AWT source water quality compared to the historical WRRF effluent quality.
- WRRF capital improvements and costs needed to meet AWT source water quality targets.
- AWT design and capital costs assuming (1) no WRRF improvements; and (2) implementation of upstream WRRF improvements to achieve influent AWT influent water quality targets to explore the cost trade-offs between WRRF modifications and desired AWT feed water quality.

The case studies cover a variation of WRRF and AWT configurations. Table 7-1 summarizes the utilities studied as part of this work.

Table 7-1. Summary of Case Study Utilities.

Case Study	WRRF Flow (mgd)	WRRF Train	AWT Flow (mgd)	AWT Train
No. 1	51.4	Primary, Secondary 5-stage BNR, Tertiary disk filters	0.8 - 1.6	MF/RO/UV-AOP/GAC/Cl_2
No. 2	3.6	Primary, Secondary Modified Ludzak-Ettinger, Tertiary Denitrification Filters	3.6	O_3/BAF/UF/GAC/UV
No. 3	400	Primary, Secondary High Purity Oxygen	180	RO/UV-AOP and MF/two-stage RO/UV-AOP

7.2.1 Case Study 1: Five-Stage Biological Nutrient Removal (BNR) WRRF

An activated sludge WRRF located in the Southwest region of the United States treats an average annual flow of 29 mgd municipal wastewater. The existing WRRF will be rehabilitated and expanded to meet 51.4 mgd average daily flow and the effluent quality requirements needed to feed the future downstream AWT for direct potable reuse application. Table 7-2 compares the WRRF historical effluent

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[2] The cost of upgrading a trickling filter plant to a conventional activated sludge based WRRF with extended SRT was not explicitly estimated but is assumed based on project experience to require multiple $ millions per mgd.

water quality to the AWT source water quality goals and the AWT water quality shutdown limits. Table 7-3 list the WRRF design effluent limits.

Table 7-2. WRRF Historical Effluent Quality in Comparison to AWT Source Water Quality Goals and AWT Shutdown Limits.

Parameter	Historical WRRF Effluent Quality	AWT Source Water Goals	Shutdown Limits (Minimum Requirements)
Disinfectant Residual	2.3 mg/L residual chlorine	UV preferred	Unchlorinated effluent
NH_3-N, mg/L	1.7	<0.5	Not defined
NO_3-N, mg/L	17.0	<10.0	<30
NO_2-N, mg/L	Not Monitored	< 0.03	<1.5
Turbidity, NTU	Not Monitored	<10	<10
cBOD5, mg/L	3.4	<15	Not defined
TSS, mg/L	7.5	Not defined	Not defined
pH	6.7	Not defined	Not defined
DO, mg/L	6.6	Not defined	Not defined

Table 7-3. WRRF Design Effluent Limits.

Parameter	Daily Average
cBOD5	20 mg/L
TSS	20 mg/L
NH_3-N	5 mg/L
E. coli	126 CFU
Total Chlorine Residual	1.0-4.0 mg/L
pH	6.0-9.0
DO	>4.0 mg/L

7.2.1.1 WRRF Improvements

Several alternatives were considered for the expansion of the WRRF to 51.4 mgd. The selected alternative included rehabilitation of the existing WRRF to provide 39 mgd of permitted capacity without compromising effluent quality, and expansion of the facility to provide an additional 22.4 mgd capacity to ensure future effluent flow and quality to meet the requirements set for the future AWT. The WRRF improvements included the following:

- Existing facility rehabilitation to meet 39 mgd permitted capacity:
    - Primary clarifier internal mechanism replacement. – larger influent ports, deeper center wells, sludge rakes, scum baffles, skimmer arms and collection system, replacement of mechanism drives and clarifier bridge repairs.
    - Aeration basin improvements – basin baffling to produce plug flow distribution, introducing swing zones with nitrified recycle (NRCY) lines and pumps, differ grid and air piping replacement and basin hydraulic improvements.
    - Secondary clarifier internal mechanism replacement. – replacement of center columns, smaller center wells, spiral sludge scrapers, scum baffles and effluent weirs, scum skimmer arms and collection system, replacement of mechanism drives and clarifier bridge repairs.
    - Hydraulic improvements in the existing primary clarifiers, aeration basins, and chlorine contact basin.
- New facility expansion to provide additional 22.4 mgd:
    - New 5-Stage BNR expansion with secondary clarifiers.

- New chlorine disinfection for surface water discharge.
- New disk filtration and UV disinfection for effluent pumped to the AWT.
- New primary sludge and WAS co-thickening.

Figures 7-3 and 7-4 show the process flow diagrams of the WRRF liquids and solids improvements. The colored icons represent the new facility expansion to provide an additional 22.4 mgd of flow and meet the future AWT requirements.

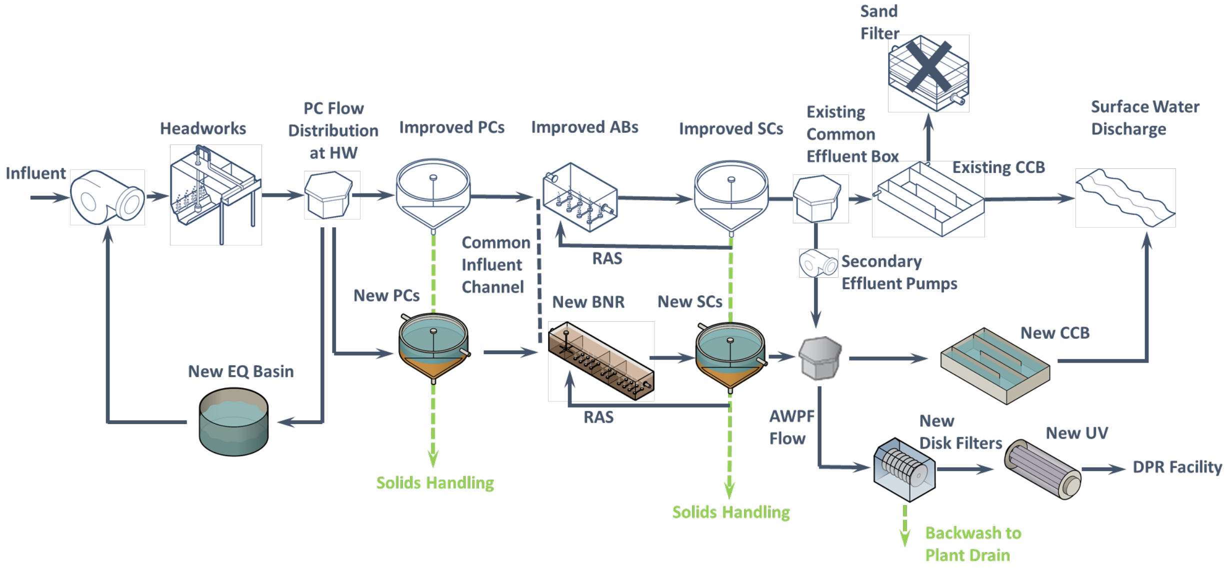
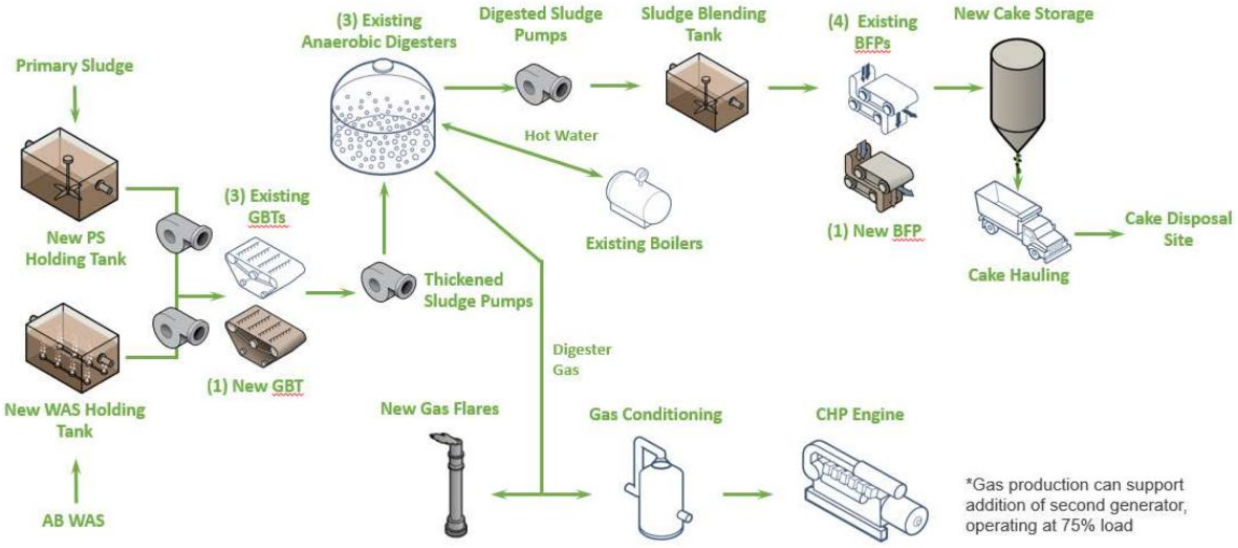


Figure 7-3. Process Flow Diagram of WRRF Liquids Improvements.



*Gas production can support addition of second generator, operating at 75% load

Figure 7-4. Process Flow Diagram of WRRF Solids Improvements.

Table 7-4 is a summary of capital costs for the WRRF Improvements for the existing facility rehabilitation to meet the current permitted capacity, and for the new facility expansion to meet the effluent quality requirements for the AWT facility.

Table 7-4. Summary of WRRF Capital Improvements.

Parameter	Existing Facility Rehabilitation	New Facility Expansion
Total Capital Cost ($M)	$77M to $167M	$116M to $248M
Design Flow Capacity (mgd)	39	22.4
Cost per mgd ($M/mgd)	$1.97 to $4.28	$5.18 to $11.1

7.2.1.2 AWT Improvements

The AWT in this case study is being designed to produce up to 12 mgd of advanced purified water for direct introduction into the City's drinking water distribution system post blending with some brackish groundwater. A conceptual process flow diagram for the AWT facility is shown in Figure 7-5. AWT processes include low-pressure membranes (MF/UF), RO, UV-AOP, GAC, and disinfection with free chlorine. The construction cost for the AWT facility is estimated to be approximately $80 million.

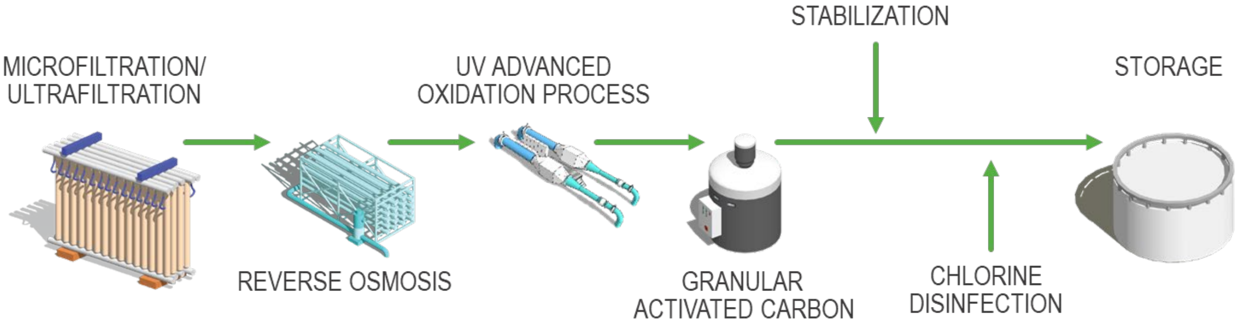


Figure 7-5. AWT Conceptual Process Flow Diagram.

The cost trade-offs for this case study are not straightforward, for two main reasons:

1. The expansion is necessary from a WRRF capacity perspective, irrespective of the plans for AWT and DPR. The effluent water quality goals for the expansion may have somewhat increased the cost relative to the need to meet only discharge standards; however, there is no comparison available, from which a "cost premium" related to AWT could be calculated. In any case, the estimated cost for the expansion facility is lower than the generic "greenfield" liquids-only construction cost assumed in Section 7.1.1 ($12-$14 per gpd AWDF). Thus, there does not appear to be an "excess cost" penalty associated with the WRRF expansion for the purpose of AWT and potable reuse.
2. The AWT system shown in Figure 7-5 must be capable of treating the existing effluent before the proposed WRRF upgrades are completed, and no reduction in treatment capacity is proposed once the new WRRF comes online. For these reasons, there is no cost savings on the AWT side with and without the WRRF modifications.

The only distinction between AWT treating the existing effluent versus higher quality effluent produced by the upgraded WRRF is the amount of system uptime achievable by the AWT facility and can be described as a "reliability penalty." Assume that a higher quality WRRF effluent will increase average AWT uptime from 80 percent to near 95 percent averaged over the life of the facility, this 15 percent loss in uptime could be equivalent to a reliability penalty of $12 million in construction costs. With no measurable cost for the proposed WRRF expansion that is directly attributable to AWT, it is not at all surprising that the utility has decided to pursue this option.

7.2.2 Case Study 2: Modified Ludzack-Ettinger (MLE) Filter WRRF

In the Western Region of the United States a potable reuse project was evaluated that would involve the design of a CBAT facility to produce advanced purified water to augment the region's groundwater supply. Two separate scenarios were contemplated for this project: the first would have required significant additional improvements to the WRRF to meet proposed AWT influent water quality targets, as described below. The other scenario required no WRRF upgrades but needed a pipeline to transport the AWT product water instead.

7.2.2.1 WRRF Improvements for Scenario 1

A key component of this scenario was to improve treatment performance at the upstream 3.6 mgd WRRF for additional nutrient removal. Table 7-5 compares the historical WRRF effluent quality to the AWT source water quality goals in terms of nutrient concentrations. A simplified process flow diagram of the existing WRRF is shown in Figure 7-6.

Table 7-5. Historical WRRF Effluent Quality and AWT Source Water Quality Goals in Terms of Nutrients.

Parameter	Historical WRRF Effluent Quality	AWT Source Water Goals
Total Nitrogen	13.5 mg/L as N	< 2 mg/L as N
Total Phosphorus	0.1 to 6 mg/L as P	< 0.1 mg/L as P

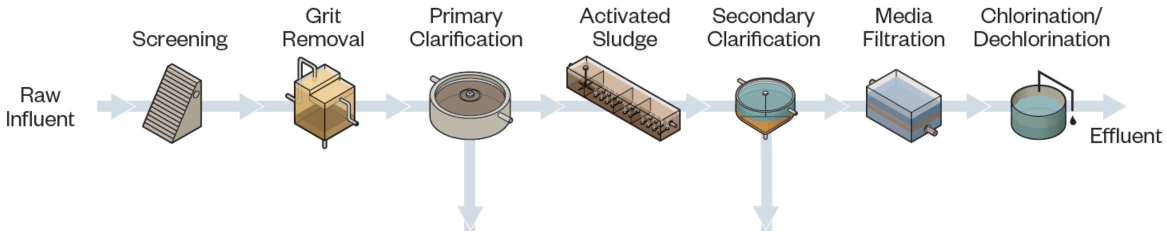


Figure 7-6. Process Flow Diagram of the Existing WRRF.

To achieve the level of nutrient reduction targeted at the WRRF, a combination of biological nutrient removal in the activated sludge system as well as upgrades to the tertiary filters are being considered:

- Convert the existing activated sludge system to a MLE process by adding internal recycle pumping to return nitrified mixed liquor to the first anoxic zone.
- Implementation of chemical phosphorus removal.
- Convert existing granular media filters to perform denitrification

Table 7-6 is a summary of capital costs for the WRRF improvements to meet the secondary effluent quality requirements for the advanced water purification facility.

Table 7-6. Summary of WRRF Capital Improvements.

Parameter	Value
Design Flow Capacity (mgd)	3.6
Capital Cost per mgd ($M/mgd)	$1.68 to $3.83

7.2.2.2 AWT Costs and other Decision Factors

Virtually identical CBAT systems were proposed for both scenarios; the nutrient removal requirements were related mainly to a discharge limitation for Scenario 1. Thus, the trade-off decision made by this utility included the relative costs of WRRF improvements at approximately $3 million per mgd versus the cost of the pipeline, which came to approximately $6 million per mgd. Ultimately, cost was not the deciding factor; rather permitting challenges drove the utility to choose the second scenario.

7.2.3 Case Study 3: High Purity Oxygen Plant Facility

A desktop evaluation was prepared by Stantec as part of the Nitrogen Management Study jointly with Metropolitan Water District of Southern California and the Sanitation Districts of Los Angeles County to explore the potential of building a 150 mgd AWT facility that will treat non-nitrified secondary effluent from the Sanitation Districts' Joint Water Pollution Control Plant (JWPCP) in Carson, CA (MWD 2018). The JWPCP is a 400 mgd HPOAS facility that discharges treated effluent to the ocean. Figure 7-7 is a process flow diagram of the existing JWPCP. The existing liquid treatment processes were not designed for nitrification/denitrification. For this reason, the JWPCP effluent had an average TN concentration of 46.9 mg/L as N historically. As shown in Table 7-7, a TN < 3.5 mg/L as N was previously established as the AWT water quality goal. As a result, nitrogen removal was determined to be crucial for potable reuse to meet the water quality objectives established for the AWT facility.

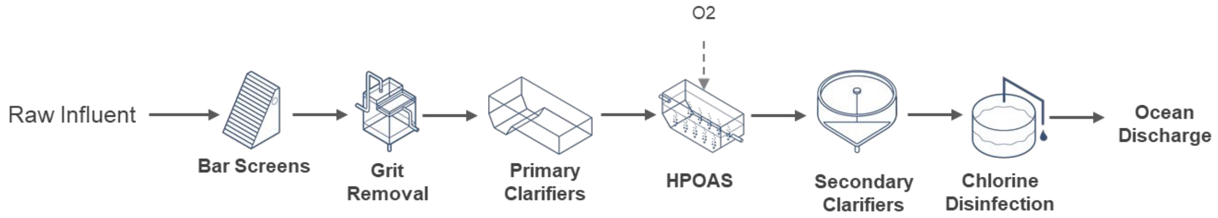


Figure 7-7. Existing JWPCP Liquids Process Flow Diagram.

Table 7-7. Historical JWPCP WRRF Effluent Quality and AWT Effluent Water Goals.

Parameter	Historical WRRF Effluent	AWT Water Quality Goals
TN, mg/L as N	46.8	<3.5

7.2.3.1 WRRF Improvements

Several alternatives were considered for improving JWPCP effluent quality to meet the feed water quality requirements set for the future AWT facility.

The selected JWPCP liquid process improvement includes the construction of a new secondary nitrification-denitrification MBR to treat 180 mgd of WRRF primary effluent flow. Figure 7-8 is a process flow diagram of the proposed JWPCP improvements. The colored icons indicate the addition of secondary nitrification-denitrification MBR to meet the future AWT facility source water quality requirements. Table 7-8 compares the projected secondary effluent water quality after MBR implementation to the historical WRRF effluent quality.

It should be noted that the feasibility of the secondary MBR concept has not been verified at the demonstration facility and thus no data have been generated to support the assumptions made for cost estimates. The cost estimates were prepared as part of the Nitrogen Management studies conducted jointly by Metropolitan Water District of Southern California and LACSD (MWD, 2018). These estimated were developed in 2018 at a Class V level solely for comparison purposes.

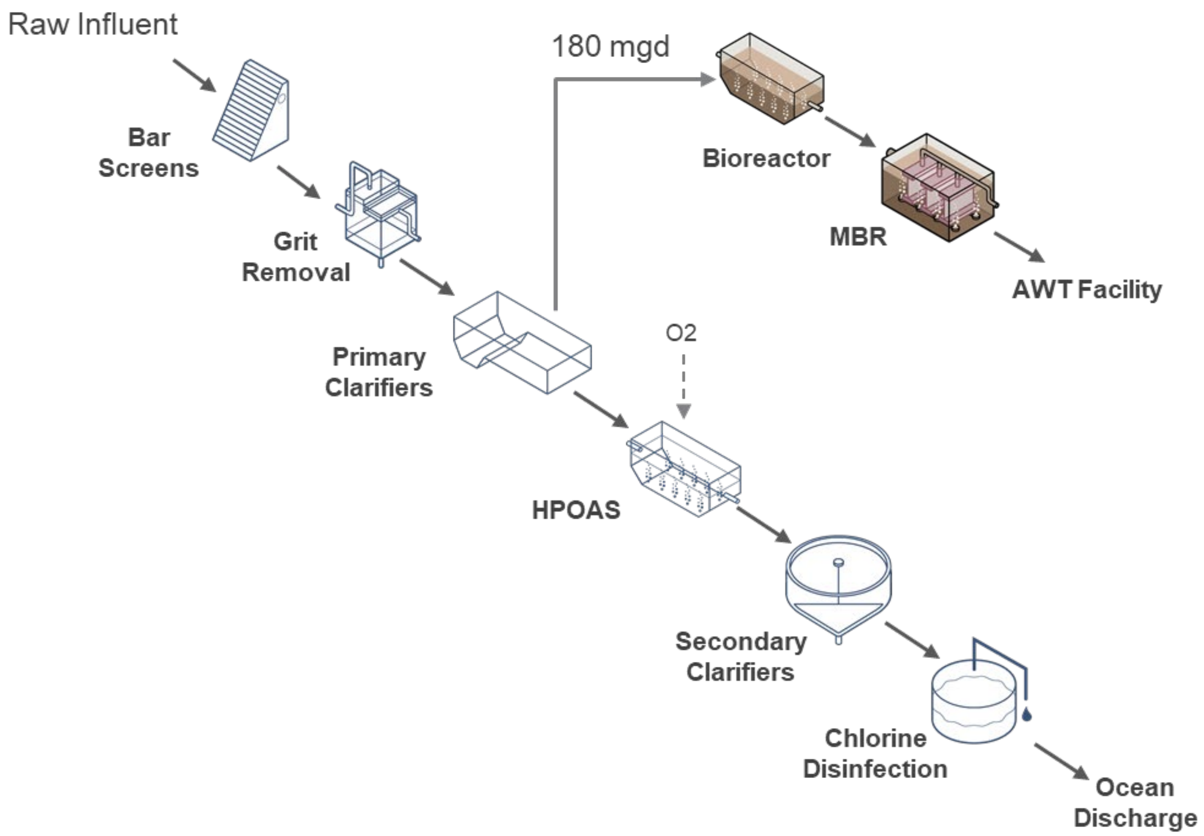


Figure 7-8. Proposed JWPCP Improvement with the Addition of Secondary MBR.

Table 7-8. Historical JWPCP Effluent Quality and Project WRRF Effluent Quality.

Parameter	Historical WRRF Effluent	Projected WRRF Effluent Quality
TN, mg/L as N	46.8	15
NO_3-N, mg/L	0.13	13
NH_3-N, mg/L	44.9	0

Table 7-9 summarizes capital costs for the proposed MBR facility.

Table 7-9. Summary Capital and O&M Cost Estimates for the MBR Facility.

Parameter	WRRF Improvements
Capital Costs ($M)	$502
Capital Cost ($M/mgd)	$3.35

7.2.3.2 AWT Improvements

Two AWT alternatives were evaluated and compared with and without the proposed WRRF improvement with MBR. Figure 7-9 and Figure 7-10 are process flow diagrams of the two AWT configurations:

- AWT Alternative No. 1 assumes that the secondary nitrification-denitrification MBR will be implemented upstream of the AWT facility. Effluent from the secondary MBR facility will be conveyed to the AWT facility. The AWT train will consist of a one-pass RO system, UV-AOP, and post stabilization.

- AWT Alternative No. 2 assumes that current secondary effluent post HPOAS from the JWPCP will be conveyed to the AWT facility without MBR. The corresponding AWT train will consist of MF/UF, two-pass RO, UV-AOP, and post stabilization.

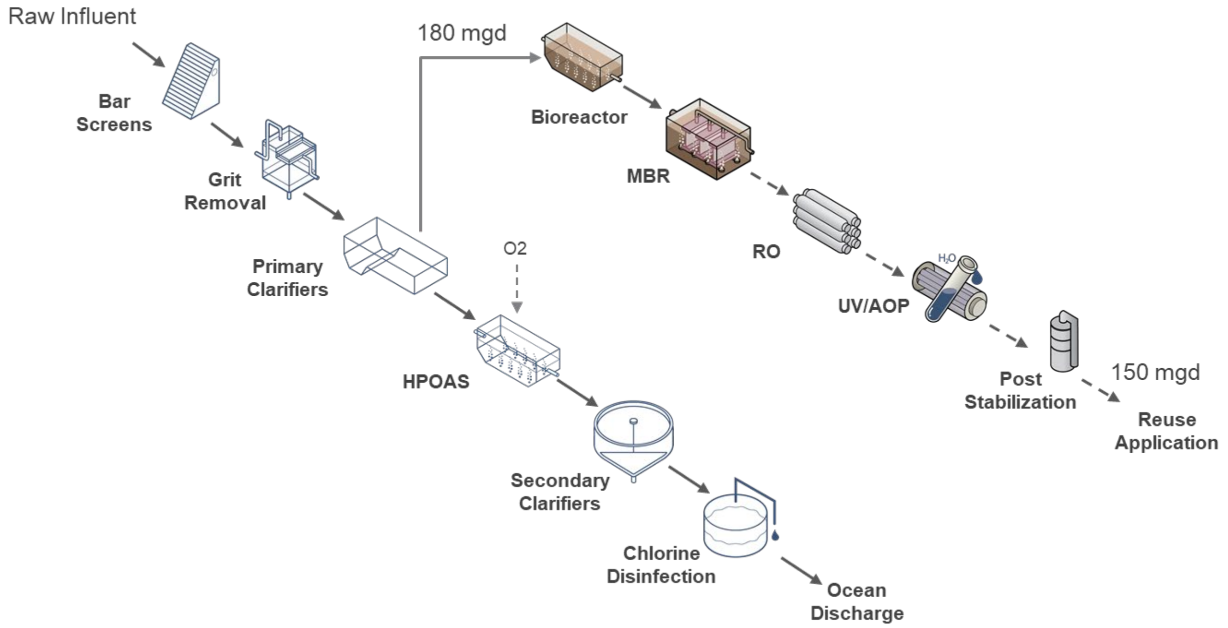


Figure 7-9. AWT Alternative No. 1 with MBR Implementation Upstream of ATW.

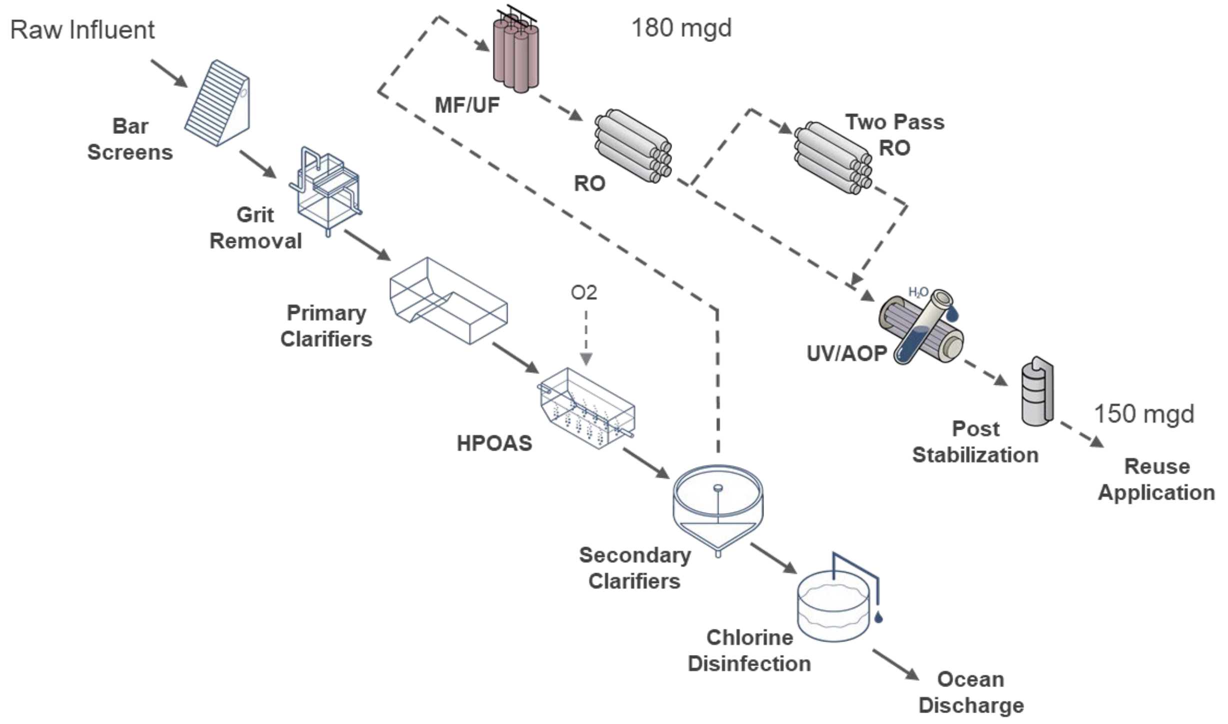


Figure 7-10. AWT Alternative No. 2 Treating Current Secondary Effluent without MBR.

Table 7-10 compares the estimated costs Class V cost estimates of the two AWT alternatives with and without the construction of secondary MBR. Although the total capital cost for Alternative No. 1 is greater than Alternative No. 2, it is expected that the total life cycle costs of Alternative No. 1 will be less than Alternative No. 2 due to the addition of MF/UF and the need for two-pass RO facility. The estimated capital costs for both alternatives is within 20 percent, indicating a negligible capital cost difference between the two alternatives. The utility elected to move forward with the configuration described in Alternative No. 1 for advanced treatment.

Table 7-10. Comparison of Estimated Costs for AWT Alternative No. 1 and No. 2.

	Alternative No. 1—with MBR	Alternative No. 2—without MBR
WRRF Improvements		
Capital Costs ($M)	$502M	$0
Capital Cost ($M/mgd)	$3.35	$0
AWT Costs		
Capital	$418M	$790M
Capital Cost ($M/mgd)	$2.79	$5.27
Total Costs		
Total Capital	$920M	$790M
Total Capital Cost per mgd ($M/mgd)	$6.13	$5.27

7.2.4 Case Study Conclusions

When viewed through the lens of specific projects, treatment decisions cannot be made on the basis of cost trade-offs related to AWT alone. In all three cases, other factors unrelated to AWT costs will ultimately dictate what project option is selected. More specifically, for case study No 1, it is AWT reliability; for case study No.2, it is an inability to dispose of RO concentrate, and for case study No. 3, the two alternatives examined are equivalent in estimated costs at a Level V cost estimation accuracy, so the selection of either AWT alternative will be made on the basis of other, external factors.

CHAPTER 8

Conclusions and Guidance Material

8.1 General Conclusions

The overarching goal of this research project is to help utilities decide the best path towards potable reuse with a given WRRF treatment configuration and effluent water quality. The five modules developed around common WRRF- AWT combinations systematically evaluated challenges, or “soft spots”, associated with each combination, and how to best address such operational or water quality challenges. Results from each module and specific case studies were reviewed to understand the cost trade-offs at the WRRF-AWT interface and inform where to prioritize the investment among WRRF upgrades, AWT facilities, or elsewhere.

Generally, the project identified and recommended responses to “soft spots” that are specific to each WRRF-AWT combination, as follows:

Conventional WRRF with downstream CBAT: Some specific water quality challenges associated with pass-through constituents (i.e., those that are not addressed by the O_3-BAF-GAC processes) suggest that the core treatment approach will often need to be supplemented by “supportive process(es)” and occasionally with contaminant-specific treatment (such as anion ion exchange treatment for nitrate or PFAS). Operational and cost trade-offs between WRRF and AWT were associated with effluent organic matter concentration, nitrite concentration, and solids loading versus AWT ozone dose and filter operation.

Conventional WRRF with downstream MF/UF (for RO-based advanced treatment, or RBAT): Differences in WRRF treatment (specifically, solids retention time) and effluent water quality (especially TOC and ammonia) can make up to a 20 percent difference in MF/UF capital cost. However, given the high cost associated with WRRF treatment improvements due to much higher flow relative to AWT, in the absence of other drivers, it is likely still more cost-effective to construct a lower-flux MF/UF system (greater in both size and costs) to treat lower-quality wastewater effluent than to implement additional treatment at the WRRF to improve effluent water quality.

MBR with downstream RBAT: MBR pathogen validation studies show good removal of protozoa and even virus, achieving equivalent log removal/reduction values to the existing credits awarded to the combination of conventional wastewater treatment and tertiary MF/UF. In this treatment scenario, MBR system is designed to replace conventional secondary treatment and tertiary MF/UF. Obtaining LRVs for this level of pathogen removal through MBRs will be possible once higher-tier validation protocols are approved. For jurisdictions that allow treatment goal development on the basis of a source water (i.e., effluent) characterization study, the low MBR filtrate pathogen concentrations will reduce the treatment requirements placed on the downstream AWT.

From an operational perspective, compared to RO systems operating on filtrate from tertiary MF/UF, some additional barriers (e.g., cartridge filters and/or more frequent RO cleaning) may be necessary if membrane breaches result in higher solids concentrations passing through the MBR. This does not preclude implementation of the MBR/RO approach as the cost of potential increased cleaning frequency is easily outweighed by the savings from eliminating the tertiary MF/UF system. However, based on a simple cost comparison, retrofitting a conventional WRRF into an MBR system would cost far more than the economic value of the benefits described above, so these benefits are really only applicable to systems with pre-existing MBRs or those projects where other factors (such as space constraints) drive the utility towards MBR-based WRRFs.

MBR with downstream CBAT: The work performed for this project in collaboration with the City of Rio Rancho provided a few important conclusions: First, it is imperative that the MBR process be well designed, instrumented, and controlled. Unanticipated effluent water quality fluctuations, especially with respect to ozone scavengers such as nitrite (and TOC) can significantly affect CBAT's performance with respect to both CEC removal and disinfection performance. However, a stable and high-quality MBR filtrate can provide significant advantages to CBAT, including lower solids loading and lower influent pathogen concentrations, which reduce the treatment burden on downstream processes.

Based on these evaluations, the project team has concluded that there is no prevalent WRRF treatment approach nor effluent water quality that cannot be used as an AWT source water for potable reuse. More challenging WRRF effluent simply requires more AWT barriers.

With respect to general observations about cost trade-offs between addressing water quality and/or operational challenges at the WRRF or AWT, the relatively higher design flows for WRRFs compared to AWTs, and the high cost of WRRF treatment improvements mean that it is almost always more cost-effective to close "treatment gaps" on the AWT side than to pursue retrofits at the WRRF. That said, real-world case studies indicated that non-monetary factors and factors unrelated to a potential reuse project often drove utilities to implement improvements at the WRRF.

8.1.1 Accessible Guidance Material

The results generated and compiled for this study have been summarized in two different ways to support dissemination of the content in a more accessible and graphically engaging way. Both sets of graphical summaries are intended to be useful not only as a supplement to this final report, but also as stand-alone materials that can support outreach and education on the topics covered in this project.

8.1.1.1 Graphical Treatment Scenario Case Studies

The project team developed a set of hypothetical "graphical case studies" illustrating the important considerations utilities must take into account when selecting certain treatment approaches for a given WRRF and effluent water quality starting point. These mirror the WRRF-AWT combinations evaluated in each of the project's modules and also discuss potential site-specific considerations and adaptations in a quick-to-read one-page format. These graphical case studies are provided in Appendix E.

8.1.1.2 Fact Sheets

As a second approach to disseminating the important take-aways from this project, the project team developed three two-page fact sheets. These fact sheets are designed for front-and-back printing on a single sheet and respectively cover the three over-arching treatment topics covered in this project: (i) reverse-osmosis based advanced treatment (or RBAT), (ii) carbon-based advanced treatment (or CBAT), and (iii) the benefits and important considerations associated with pursuing potable reuse with membrane bioreactor filtrate (MBR) as a starting point. These Fact Sheets are also provided in Appendix F.

APPENDIX A

Module A - Multilinear Regression and Supervised Learning Model Statistics

A.1 Utility No. 1 Model Results

A.1.1 Multilinear Regression Analysis

Table A-1. Utility No. 1 ozone effluent bromate multilinear regression results.

WRRF Process	WRRF Parameter	Coefficient	p-value
Raw	Influent Sulfate (mg/L)	0.0799	0.000
Raw	Influent COD (mg/L)	0.0011	0.001
Raw	Influent sCOD (mg/L)	0.0333	0.000
Raw	Influent %TVSS	-0.0741	0.000
Preliminary	Ferric Chloride Use (ppd)	-0.0013	0.000
Secondary	Secondary Clarifier SOR (gpd/sf)	-0.0022	0.000
Sidestream Phosphorus Recovery	TP Removal (%)	0.0075	0.000
Solids	Centrifuge Polymer Dose (ppd)	-0.0164	0.000
Solids	Digester Temp	0.0599	0.000
Solids	GBT Filtrate COD (mg/L)	-0.0084	0.000
Solids	GBT Polymer Use (ppd)	-0.003	0.015
R^2: 0.973 Adj. R^2: 0.973 F-statistic: 1112			

Table A-2. Utility No. 1 GAC effluent TKN multilinear regression results.

WRRF Process	WRRF Parameter	Coefficient	p-value
Secondary	Secondary Clarifier No. in Service	0.0861	0.00
Solids	Centrifuge Feed TS Load (ppd)	0.017	0.00
Solids	Digester Detention Time (days)	-0.0049	0.00
Primary	Primary CBOD Removal (%)	0.0025	0.00
R^2: 0.972 Adj. R^2: 0.972 F-statistic: 2877			

Table A-3. Utility No. 1 GAC effluent TOC multilinear regression results.

WRRF Process	WRRF Parameter	Coefficient	p-value
Odor Control	Scrubber NaOCl Chemical Dose per H2S	0.0313	0.000
Primary	Effluent %TVSS	0.0212	0.000
Secondary	F/M Reaction Rate (1/day)	8.9328	0.000
Secondary	Secondary Clarifier Operational Hours	0.1078	0.000
Primary	TSS Removal (%)	-0.3388	0.000
Solids	GBT Filtrate OP (mg/L)	0.0734	0.000
R^2: 0.912 Adj. R^2: 0.911 F-statistic: 587.6			

Table A-4. Utility No. 1 GAC effluent NDMA multilinear regression results.

WRRF Process	WRRF Parameter	Coefficient	p-value
Raw	Influent cBOD:TP	0.4125	0.000
Raw	Ferric Chloride Use (ppd)	0.0058	0.000
Primary	TSS Removal (%)	0.044	0.000
Sidestream Phosphorus Recovery	TP Removal (%)	-0.0716	0.000

WRRF Process	WRRF Parameter	Coefficient	p-value
Odor	Scrubber NaOCl Chemical Use (ppd)	-0.0027	0.045
R^2: 0.845 Adj. R^2: 0.842 F-statistic: 275.2			

Table A-5. Utility No. 1 AWT effluent 1,4-dioxane multilinear regression results.

WRRF Process	WRRF Parameter	Coefficient	p-value
Raw	Influent TSS Load (ppd)	-0.0001	0.000
Primary	Number of Clarifiers in Service	0.2145	0.000
Solids	Centrifuge Polymer Dose (ton/day)	0.0011	0.000
R^2: 0.974 Adj. R^2: 0.974 F-statistic: 3838			

A.1.2 Supervised Learning Analysis

Table A-6. Utility No. 1 ozone effluent bromate supervised learning results.

WRRF Process	WRRF Parameter	Mutual Information	p-value	Spearman Coefficient
Raw	Raw Influent Chemical Oxygen Demand (COD) (mg/L)	0.441	0.00%	0.630
Raw	Raw Influent OP (mg/L)	0.406	0.00%	0.441
Raw	Raw Influent Temperature (deg C)	0.379	0.00%	0.527
Raw	Raw Influent Soluble Chemical Oxygen Demand (sCOD) (mg/L)	0.372	0.00%	0.372
Raw	Raw Influent %TVSS	0.344	0.00%	-0.444
Raw	Raw Influent Soluble Total Kjeldahl Nitrogen (sTKN) (mg/L)	0.343	0.00%	0.191
Secondary	WAS Flow (gpm)	0.330	0.00%	0.418
Raw	Raw Influent Conductivity (mS/cm)	0.325	0.00%	0.668
Plantwide	Total %BOD Removal	0.310	0.00%	0.405
Raw	Raw Influent Chloride (mg/L)	0.300	0.00%	0.623
Solids	Digester Feed %TS	0.231	0.00%	0.562
Raw	Raw Influent Magnesium (g/L)	0.181	0.00%	0.294
Plantwide	Total %TP Removal	0.129	0.00%	0.114
ROC Index: 0.99 R: 0.905 R^2: 0.82 Overall Precision: 0.87				

Table A-7. GAC effluent TOC supervised learning results.

WRRF Process	WRRF Parameter	Mutual Information	p-value	Spearman Coefficient
Secondary	Secondary Clarifier Ferric Addition (ppd)	0.58	0.00%	0.441
Secondary	WAS Flow (mgd)	0.575	0.00%	-0.281
Solids	Digester Feed TVS Load (ppd)	0.546	0.00%	-0.153
Primary	No. of Primary Clarifiers in Service	0.496	0.00%	0.607
Disinfection	Disinfection Cl2 Dose (mg/L)	0.450	0.00%	-0.734

WRRF Process	WRRF Parameter	Mutual Information	p-value	Spearman Coefficient
Solids	Centrifuge Recycle TSS Load (ppd)	0.425	0.00%	0.675
Primary	Primary Clarifier %CBOD Removal	0.242	0.00%	-0.081
ROC Index: 99.9 R: 0.964 R^2: 0.929 Overall Precision: 0.927				

Table A-8. Utility No. 1 GAC effluent NDMA supervised learning results.

WRRF Process	WRRF Parameter	Mutual Information	p-value	Spearman Coefficient
Secondary	Aerobic HRT	0.854	0.00%	-0.599
Raw	Raw Influent OP (mg/L)	0.636	0.00%	0.615
Preliminary	Preliminary Ferric Addition (ppd)	0.488	0.00%	0.524
Plantwide	Total %BOD Removal	0.459	0.00%	0.671
Raw	Raw Influent CBOD:TP	0.412	0.00%	0.222
Raw	Raw Influent TS (mg/L)	0.314	0.00%	0.159
Primary	Primary Clarifier %TSS Removal	0.274	0.00%	0.488
Primary	Primary Clarifier Surface Overflow Rate (gpd/sf)	0.269	0.00%	-0.228
Raw	Raw Influent Conductivity (mS/cm)	0.264	0.00%	0.189
Secondary	CBOD F/M Aerobic Reaction Rate (1/day)	0.241	0.00%	0.252
ROC Index: 0.997 R: 0.941 R^2: 0.885 Overall Precision: 0.965				

Table A-9. Utility No. 1 GAC effluent TKN supervised learning results.

WRRF Process	WRRF Parameter	Mutual Information	p-value	Spearman Coefficient
Raw	Raw Influent Temp	0.426	0.00%	-0.284
Secondary	WAS Flow	0.323	0.00%	-0.267
Primary	No. of Primary Clarifiers in Service	0.297	0.00%	0.531
Raw	Raw Influent %TVSS	0.285	0.00%	0.202
Raw	Raw Influent Sulfate (mg/L)	0.251	0.00%	-0.251
Primary	Primary Clarifier %BOD Removal	0.230	0.00%	0.248
Raw	Raw Influent TDS	0.150	0.00%	-0.268
Preliminary	No. of Grit Tanks in Service	0.060	0.00%	0.114
ROC Index: 0.957 R: 0.899 R^2: 0.808 Overall Precision: 0.883				

Table A-10. Utility No. 1 AWT effluent 1,4-dioxane supervised learning results.

WRRF Process	WRRF Parameter	Mutual Information	p-value	Spearman Coefficient
Raw	Raw Influent sCOD (mg/L)	0.470	0.00%	0.461
Secondary	Aerobic SRT (days)	0.343	0.00%	0.065
Raw	Raw Influent pH	0.325	0.00%	-0.439
Solids	Centrifuge Cake %TS	0.324	0.00%	-0.324
Odor	Scrubber NaOCl Use (ppd)	0.276	0.00%	0.425
Final Effluent	Final Effluent BOD Load (ppd)	0.249	0.00%	0.351
Secondary	Secondary Clarifier Blanket Depth (ft)	0.215	0.00%	-0.268
Raw	Raw Influent Alkalinity (mg/L)	0.171	0.00%	-0.012
Solids	Digester Feed %TS	0.167	0.00%	0.013
ROC Index: 0.997 R: 0.922 R^2: 0.849 Overall Precision: 0.928				

A.2 Utility No. 2 Model Results

A.2.1 Multilinear Regression Analysis

Table A-11. Utility No. 2 microfiltration specific flux multilinear regression results.

WRRF Process	WRRF Parameter	Coefficient	p-value
Secondary	Secondary Clarifier HRT (hrs)	0.0365	0.000
Secondary	HPOA lb O2 per lb BOD	0.5752	0.000
Solids	Centrate Recycle Flow (mgd)	7.4166	0.000
R^2: 0.830 Adj. R^2: 0.830 F-statistic: 3316			

Table A-12. Utility No. 2 microfiltration transmembrane pressure multilinear regression results.

WRRF Process	WRRF Parameter	Coefficient	p-value
Primary	Recycle Flow (mgd)	-0.079	0.000
Secondary	RAS Load (ppd)	-0.0008	0.000
Secondary	HPOA lb O2 per lb BOD	2.2593	0.000
Secondary	HPOA Reactor HRT (hrs)	0.2682	0.000
Primary	Effluent TSS (mg/L)	0.0094	0.000
Solids	Dewatering Centrifuge Operational Hours (hrs)	1.0664	0.000
R^2: 0.744 Adj. R^2: 0.744 F-statistic: 988.7			

Table A-13. Utility No. 2 reverse osmosis flux multilinear regression results.

WRRF Process	WRRF Parameter	Coefficient	p-value
Secondary	HPOA Reactor HRT (hrs)	0.0009	0.000
Solids	Dewatering Centrifuge Diluted Polymer Flow (gpd)	0.0004	0.000
Solids	Dewatering Centrifuge Operating Hours (hrs)	0.0038	0.000
Secondary	Secondary Clarifier HRT (hrs)	0.0015	0.000
Secondary	HPOA lb O2 per lb BOD	0.0012	0.000
Secondary	MLSS SVI (mL/g)	0.0002	0.000
R^2: 0.874 Adj. R^2: 0.874 F-statistic: 2421			

Table A-14. Utility No. 2 reverse osmosis total recovery multilinear regression results.

WRRF Process	WRRF Parameter	Coefficient	p-value
Secondary	Scum Flow (mgd)	0.9103	0.000
Primary	Effluent TSS (mg/L)	0.001	0.001
Secondary	Secondary Clarifier HRT (hrs)	0.0044	0.000
Secondary	HPOA Reactor HRT (hrs)	0.0047	0.000
Secondary	HPOA lb O2 per lb BOD	0.0402	0.000
R^2: 0.930 Adj. R^2: 0.929 F-statistic: 5529			

A.2.2 Supervised Learning Analysis

Table A-15. Utility No. 2 microfiltration normalized transmembrane pressure supervised learning results.

WRRF Process	WRRF Parameter	Mutual Information	p-value	Spearman Coefficient
Raw	Oil & Grease (mg/L)	0.330	0.00%	0.561
Raw	Influent TSS Load (ppd)	0.306	0.00%	0.560
Preliminary	Ferric Chloride Concentration (%)	0.312	0.00%	0.543
Primary	Primary Influent Flow (mgd)	0.547	0.00%	-0.836
Primary	Primary Clarifier %BOD Removal	0.462	0.00%	-0.430
Secondary	HPOA Oxygen Purity (%O2)	0.627	0.00%	0.586
Secondary	HPOA Oxygen Pressure (in)	0.549	0.00%	0.440
Secondary	Secondary Influent BOD5 (mg/L)	0.540	0.00%	0.638
Solids	Digester Temp (deg F)	0.495	0.00%	0.608
Solids	Recycle Centrate TSS Load (ppd)	0.480	0.00%	-0.608
Solids	Digester TPS + TWAS Load (ppd)	0.388	0.00%	-0.422
Solids	Dewatering Polymer Dilution (%)	0.339	0.00%	-0.450
Solids	Dewatering Polymer Flow (gpm)	0.248	0.00%	0.462
ROC Index: 0.993 R: 0.95 R^2: 0.903 Overall Precision: 0.845				

Table A-16: Utility No. 2 microfiltration specific flux supervised learning results.

WRRF Process	WRRF Parameter	Mutual Information	p-value	Spearman Coefficient
Raw	Oil & Grease	0.401	0.00%	-0.491
Primary	Flow (mgd)	0.526	0.00%	0.711
Primary	Primary Effluent BOD Load (ppd)	0.382	0.00%	0.617
Secondary	Scum Flow (mgd)	0.521	0.00%	0.448
Secondary	Secondary Clarifier Solids Loading Rate (ppd/sf)	0.289	0.00%	0.459
Secondary	Solids Retention Time (days)	0.205	0.00%	-0.184
Secondary	No. of Anoxic Reactors in Service	0.134	0.00%	0.110
Solids	Digester TPS + TWAS Load (ppd)	0.288	0.00%	0.468
ROC Index: 0.936 R: 0.871 R^2: 0.759 Overall Precision: 0.739				

Table A-17. Utility No. 2 reverse osmosis total percent recovery supervised learning results.

WRRF Process	WRRF Parameter	Mutual Information	p-value	Spearman Coefficient
Primary	Primary Influent TSS (mg/L)	0.214	0.00%	-0.353
Primary	Primary Effluent TSS Load (ppd)	0.200	0.00%	-0.395
Secondary	WAS Yield (WAS Load/Inf BOD Load)	0.202	0.00%	-0.377
Solids	Digesters Primary Solids Bypass Flow (mgd)	0.223	0.00%	0.317
Solids	Digester Thickened Primary Solids Load (ppd)	0.193	0.00%	0.344
Solids	Recycle Centrate Flow (mgd)	0.141	0.00%	-0.349
ROC Index: 0.996 R: 0.752 R^2: 0.565 Overall Precision: 0.838				

Table A-18: Utility No. 2 reverse osmosis specific flux supervised learning results.

WRRF Process	WRRF Parameter	Mutual Information	p-value	Spearman Coefficient
Primary	Primary Clarifier %TSS Removal	0.149	0.00%	0.067
Secondary	RAS Load (ppd)	0.271	0.00%	0.336
Secondary	MLSS (mg/L)	0.259	0.00%	0.329
Secondary	HPOA Organic Loading Rate (lb BOD/d/KCF)	0.177	0.00%	0.121
Secondary	F/M (lb BOD/lb VSS/day)	0.087	0.00%	-0.106
Solids	Cake Production (DT/d)	0.169	0.00%	0.261
ROC Index: 0.982 R: 0.831 R^2: 0.690 Overall Precision: 0.724				

A.3 Utility No. 3 Model Results

A.3.1 Multilinear Regression Analysis

Table A-19. Utility No. 3 AWT effluent COD multilinear regression results.

WRRF Process	WRRF Parameter	Coefficient	p-value
Primary	Primary Clarifier TP Removal (%)	0.0772	0.000
Secondary	Bioreactor DO (mg/L)	0.7569	0.000
Secondary	Secondary Clarifier Alum Dose (mg/L)	0.1405	0.000
Solids	Rotary Drum Thickener Polymer Dose (lb active/DT)	0.017	0.000
R^2: 0.882 Adj. R^2: 0.882 F-statistic: 5953			

Table A-20. Utility No. 3 AWT effluent fecal coliform multilinear regression results.

WRRF Process	WRRF Parameter	Coefficient	p-value
Primary	Primary Clarifier TP Removal (%)	0.0341	0.000
Secondary	Secondary Clarifier Effluent NH4-N (mg/L)	3.1558	0.003
Solids	Rotary Drum Thickener Polymer Dose (lb active/DT)	0.0023	0.000
R^2: 0.223 Adj. R^2: 0.222 F-statistic: 306.5			

Table A-21. Utility No. 3 AWT effluent TP multilinear regression results.

WRRF Process	WRRF Parameter	Coefficient	p-value
Secondary	Bioreactor DO (mg/L)	0.0019	0.000
Secondary	Secondary Clarifier Alum Use (gpd)	2.30E-05	0.000
Solids	Centrifuge Feed Rate (gpm)	9.53E-05	0.000
R^2: 0.886 Adj. R^2: 0.886 F-statistic: 8325			

A.3.2 Supervised Learning Analysis

Table A-22. Utility No. 3 AWT effluent COD supervised learning results.

WRRF Process	WRRF Parameter	Mutual Information	p-value	Spearman Coefficient
Primary	No. of Clarifiers in Service	0.1543	0.00%	-0.206
Primary	Primary Solids Flow (mgd)	0.1226	0.00%	-0.275
Primary	Primary Clarifier Surface Overflow Rate (gpd/sf)	0.083	0.00%	0.235
Secondary	Daily Yield (ppd/MGD)	0.1388	0.00%	0.364
Secondary	Secondary Clarifier Alum Use (gpd)	0.1245	0.00%	0.22
Secondary	No. of Bioreactors Online	0.1233	0.00%	-0.293
Secondary	Secondary Clarifier Solids Loading Rate (ppd/sf)	0.0589	0.00%	0.086
ROC Index: 0.909 R: 0.7 R^2: 0.489 Overall Precision: 0.523				

Table A-23. Utility No. 3 AWT effluent fecal coliform supervised learning results.

WRRF Process	WRRF Parameter	Mutual Information	p-value	Spearman Coefficient
Raw	Influent pH	0.0332	0.00%	-0.266
Primary	Primary Clarifier Surface Overflow Rate (gpd/sf)	0.0786	0.00%	0.145
Primary	Primary Clarifier Blanket Depth (ft)	0.0562	0.00%	0.062
Secondary	No. of Bioreactors Online	0.0756	0.00%	-0.261
Secondary	Secondary Clarifier Alum Use (ppd)	0.0544	0.00%	0.357
Secondary	Bioreactor DO (mg/L)	0.0454	0.00%	0.191
Secondary	Secondary Clarifier Blanket Depth (ft)	0.0432	0.00%	0.134
Secondary	Bioreactor MLSS (mg/L)	0.0417	0.00%	0.252
Solids	Centrifuge Polymer Dose (lb/DT)	0.0545	0.00%	0.166
Solids	Centrifuge Feed Rate (gpm)	0.0378	0.00%	-0.356
ROC Index: 0.968 R: 0.649 R^2: 0.422 Overall Precision: 0.913				

Table A-24. Utility No. 3 AWT effluent TP supervised learning results.

WRRF Process	WRRF Parameter	Mutual Information	p-value	Spearman Coefficient
Secondary	Secondary Clarifier Alum Dose (mg/L)	0.3142	0.00%	0.586
Primary	No. of Primary Clarifiers in Service	0.2745	0.00%	-0.415
Secondary	MLSS (mg/L)	0.2128	0.00%	0.469
Raw	Influent Alkalinity Load (ppd)	0.2049	0.00%	-0.488
Secondary	Secondary Clarifier Surface Overflow Rate (gpd/sf)	0.1871	0.00%	-0.393
ROC Index: 0.891 R: 0.716 R^2: 0.512 Overall Precision: 0.601				

A.4 Utility No. 4 Model Results

A.4.1 Multilinear Regression Analysis

Table A-25: Utility No. 4 AWT effluent TN multilinear regression results.

WRRF Process	WRRF Parameter	Coefficient	p-value
Primary	mol Alum per mol OP	-0.333	0.001
Solids	Total Polymer Use	0.0731	0.000
Solids	Digester Gas (scf/lb TSR)	0.1806	0.000
R^2: 0.743 Adj. R^2: 0.742 F-statistic: 932.2			

Table A-26: Utility No. 4 AWT effluent COD multilinear regression results.

WRRF Process	WRRF Parameter	Coefficient	p-value
Raw	Influent NOx (mg/L)	0.8857	0.000
Raw	Equalization Flow	0.1213	0.000
Secondary	Bioreactor ORP	-0.0087	0.000
Secondary	Bioreactor DO (mg/L)	0.2208	0.000
Secondary	Bioreactor pH	0.0253	0.003
Tertiary	UVT/COD	0.007	0.000
Solids	Digester Gas Flow to Boiler	0.015	0.000
R^2: 0.796 Adj. R^2: 0.795 F-statistic: 538.3			

Table A-27: Utility No. 4 AWT effluent TP multilinear regression results.

WRRF Process	WRRF Parameter	Coefficient	p-value
Raw	Equalization Flow	0.0015	0.000
Raw	Septage Flow	0.4076	0.000
Raw	Rainfall (in)	0.0145	0.004
Primary	lb Alum per lb OP	0.0006	0.000
Raw	Influent NOx (mg/L)	0.0115	0.000
R^2: 0.636 Adj. R^2: 0.635 F-statistic: 337.4			

A.4.2 Supervised Learning Analysis

Table A-28. Utility No. 4 AWT effluent TN supervised learning results.

WRRF Process	WRRF Parameter	Mutual Information	p-value	Spearman Coefficient
Primary	Blanket Depth	0.1981	0.00%	-0.297
Primary	Solids Loading Rate (ppd/sf)	0.1969	0.00%	-0.249
Primary	Primary Solids %TS	0.1449	0.00%	0.209
Secondary	Bioreactor DO (mg/L)	0.1007	0.00%	-0.269
Solids	Primary Solids, TWAS %VS	0.1507	0.00%	0.247
Solids	Dewatering Polymer Use	0.1421	0.00%	0.131
Solids	Digester VFA (mg Ac/L)	0.1125	0.00%	-0.019
ROC Index: 0.854 R: 0.688 R2: 0.473 Overall Precision: 0.671 Mean Precision: 0.655				

Table A-29. Utility No. 4 AWT effluent COD supervised learning results.

WRRF Process	WRRF Parameter	Mutual Information	p-value	Spearman Coefficient
Raw	Influent sCOD (mg/L)	0.2045	0.00%	0.259
Raw	Influent NOx (mg/L)	0.1692	0.00%	0.127
Raw	Influent TP (mg/L)	0.1323	0.00%	-0.078
Raw	Septage Flow	0.1546	0.00%	-0.099
Raw	Plant Waste Recycles NH3	0.1272	0.00%	-0.215
Primary	Sodium Hypochlorite Use	0.1968	0.00%	0.103
Primary	Primary Solids Flow	0.178	0.00%	-0.248
Secondary	Bioreactor DO (mg/L)	0.1339	0.00%	-0.199
Solids	Digester VFA (mg Ac/L)	0.1938	0.00%	0.338
Solids	Digester Influent VS Load (ppd)	0.1865	0.00%	-0.290
Solids	Digester TS Load (lb/cf/day)	0.1156	0.00%	-0.061
Solids	Dewatered Cake VS (mg/L)	0.1853	0.00%	-0.158
ROC Index: 0.969 R: 0.925 R2: 0.855 Overall Precision: 0.833				

Table A-30. Utility No. 4 AWT effluent TP supervised learning results.

WRRF Process	WRRF Parameter	Mutual Information	p-value	Spearman Coefficient
Raw	Septage Flow	0.1584	0.00%	0.422
Raw	Influent TDS Load (ppd)	0.1518	0.00%	-0.134
Raw	Equalization Tank Level	0.0825	0.00%	-0.226
Raw	Raw Influent TP Load (ppd)	0.0243	0.00%	0.043
Raw	Equalization Flow	0.0241	0.00%	-0.021
Primary	Alum Use (gpd)	0.1317	0.00%	0.336
Primary	Primary Clarifier Surface Overflow Rate (gpd/sf)	0.0636	0.00%	-0.034
Primary	Primary Clarifier Blanket Depth	0.0286	0.00%	-0.083
Secondary	MBR Effluent OP	0.4729	0.00%	0.752
Secondary	MBR Effluent TP	0.3007	0.00%	0.596
Secondary	Unit RAS Flow (mgd/bioreactor)	0.1251	0.00%	-0.143
Secondary	Alum Use (gpd)	0.0733	0.00%	-0.203
Secondary	Influent Flow (mgd)	0.0513	0.00%	0.071
Tertiary	Effluent TP	0.432	0.00%	0.844
Solids	Digester Influent TS Load (ppd)	0.0916	0.00%	0.125
Solids	Dewatered Centrate TKN (mg/L)	0.0461	0.00%	0.120
Solids	Digester Gas (scf/lb VSR)	0.0339	0.00%	0.029
ROC Index: 0.931 R: 0.579 R2: 0.335 Overall Precision: 0.744				

A.5 Utility No. 5 Model Results

A.5.1 Multilinear Regression Analysis

Table A-31. Utility No. 5 microfiltration specific flux multilinear regression results.

WRRF Process	WRRF Parameter	Coefficient	p-value
Raw	Influent NH3-N (mg/L)	-0.0947	0.0000
Raw	Influent COD (mg/L)	0.0055	0.0000
Raw	Influent pH	-0.0013	0.0000
Primary	% TSS Removal	0.0833	0.0000
Secondary	SRT (days)	0.0288	0.0000
Secondary	Effluent TSS (mg/L)	-0.0237	0.0010
Secondary	SVI (mL/L)	-0.0512	0.0000
Secondary	WAS Flow (gpm)	-0.0355	0.0000
Secondary	Blanket Depth (ft)	0.6268	0.0000
R^2: 0.995 Adj. R^2: 0.995 F-statistic: 4574			

Table A-32. Utility No. 5 reverse osmosis specific flux multilinear regression results.

WRRF Process	WRRF Parameter	Coefficient	p-value
Raw	Influent NH3-N (mg/L)	0.0009	0.0010
Raw	Influent COD (mg/L)	-0.0002	0.0000
Raw	Influent TSS (mg/L)	0.0002	0.0000
Raw	Influent pH	-3.81E-05	0.0000
Primary	% TSS Removal	0.0008	0.0000
Secondary	SRT (days)	-0.0004	0.0000
Secondary	Effluent TSS (mg/L)	-0.0006	0.0000
Secondary	SVI (mL/L)	0.0007	0.0000
Secondary	WAS Flow (gpm)	0.0009	0.0000
Secondary	% TN Removal	-0.0004	0.0030
R^2: 0.979 Adj. R^2: 0.978 F-statistic: 1278			

A.5.2 Supervised Learning Analysis

Table A-33. Utility No. 5 microfiltration specific flux supervised learning results.

WRRF Process	WRRF Parameter	Mutual Information	p-value	Spearman Coefficient
Raw	Influent COD Load	0.2595	0.00%	-0.022
Raw	Influent Flow (mgd)	0.3713	0.00%	0.604
Primary	% COD Removal	0.3663	0.00%	-0.403
Primary	Effluent PO4-P (mg/L)	0.4393	0.00%	0.562
Secondary	% TN Removal	0.2542	0.00%	0.103
Secondary	Effluent Alkalinity (mg/L)	0.4381	0.00%	0.556
Secondary	Effluent COD (mg/L)	0.6179	0.00%	0.768
Secondary	Effluent NH3-N	0.3022	0.00%	0.369

WRRF Process	WRRF Parameter	Mutual Information	p-value	Spearman Coefficient
Secondary	Effluent NO3 (mg/L)	0.4819	0.00%	-0.538
Secondary	Effluent TDS (mg/L()	0.2213	0.00%	-0.052
Secondary	Effluent Turbidity (NTU)	0.3541	0.00%	0.047
Secondary	Scum Flow (gpd)	0.6134	0.00%	-0.429
Secondary	WAS Flow (gpd)	0.5241	0.00%	-0.442
Plantwide	% COD Removal	0.2981	0.00%	-0.430
Plantwide	% TSS Removal	0.0937	0.00%	-0.147
ROC Index: 0.997 R: 0.957 R^2: 0.916 Overall Precision: 0.905				

Table A-34. Utility No. 5 reverse osmosis specific flux supervised learning results.

WRRF Process	WRRF Parameter	Mutual Information	p-value	Spearman Coefficient
Raw	Influent TSS (mg/L)	0.1981	0.00%	0.058
Raw	Influent Flow (mgd)	0.1826	0.00%	-0.383
Raw	Influent COD Load (ppd)	0.1505	0.00%	-0.010
Primary	Effluent PO4-P (mg/L)	0.4634	0.00%	-0.134
Primary	Effluent TSS (mg/L)	0.4506	0.00%	-0.206
Primary	Effluent NH3-N (mg/L)	0.3945	0.00%	0.215
Primary	Effluent COD (mg/L)	0.3935	0.00%	0.272
Secondary	Scum Flow (gpd)	0.5039	0.00%	-0.182
Secondary	WAS Flow (gpd)	0.4568	0.00%	0.286
Secondary	Effluent COD (mg/L)	0.4514	0.00%	-0.516
Secondary	F/M Ratio	0.3727	0.00%	0.515
Secondary	Effluent NH3-N (mg/L)	0.3081	0.00%	-0.238
Secondary	MLSS (mg/L)	0.2648	0.00%	-0.416
Secondary	SRT	0.2545	0.00%	0.405
Secondary	Effluent PO4-P (mg/L)	0.2347	0.00%	0.147
Secondary	Effluent pH	0.1962	0.00%	-0.017
Secondary	SRT (days)	0.1576	0.00%	0.045
Secondary	5 min SVI (mL/L)	0.144	0.00%	0.135
Plantwide	% COD Removal	0.2069	0.00%	0.384
ROC Index: 0.997 R: 0.933 R^2: 0.870 Overall Precision: 0.975				

APPENDIX B

Module B - Carbon-based Advanced Treatment (CBAT) Case Studies

Table B-1. Summary of the City of Altamonte Springs's CBAT case study.

Location/Process Configuration/ Operational Parameters	Post GAC Water Quality	Interfering Constituents:
City of Altamonte Springs, FL Pilot: **O_3-BAC**-UF-**GAC**-UV/H_2O_2 O_3:TOC ~1.0 BAC age: 2+ years GAC: Calgon F300; 15 min EBCT; 56,000 BVs	**Indicator TOrC:** ≥ 92% Removal: Carbamazepine, Sulfamethoxazole, Primidone, DEET, Meprobamate, Sucralose, TCEP	**TOC**: Hurricane Irma increased the frequency of backwashing for the BAC. This might have been attributed to a sudden increase in organic loading.
WWTP Pretreatment Configuration: Primary-CAS (Nitrification)-Filtration-Re-aeration	**Short-Chain PFAS:** ≤ 25% Removal: PFPnA, PFHxA	
Pilot Influent Water Quality: Turbidity = 0.55 NTU (n=12)	PFOA + PFOS < 5 ng/L	
TOC = 6 mg/L (n=12) ------------------->	TOC = 2.5 mg/L (n=12)	
TDS = 304 mg/L (n=12) -------------->	TDS = 322 mg/L (n=12)	
Nitrate = 4.8 mg/L as N (n=12) -------->	Nitrate = 7.2 mg/L (n=12)	
Nitrite = 0.11 mg/L as N (n=12)	**Ozone Byproducts:**	
NH_3 = 0.02 mg/L (n=12)	NDMA < 2.9 ng/L	
Bromide = 55 µg/L (n=12)	Bromate = 1.3 µg/L (n=12)	
Reference: Carollo Engineers, Inc., City of Altamonte Springs: Potable Reuse Demonstration Pilot Project Report, 2018, Orlando, FL.		

Table B-2. Summary of the City of Hollywood's CBAT case study.

Location/Process Configuration/ Operational Parameters	Post BAC Water Quality	Interfering Constituents:
City of Hollywood, FL Pilot: Cl_2- Filtration-IX[b]-IX[c]-**O_3-BAC** O_3:TOC ~1.0 BAC: Norit H300, 20 min EBCT, 11 mo. (new GAC used)	**Indicator TOrC:** ≥ 95% Removal: Carbamazepine, Sulfamethoxazole, Meprobamate, Sucralose, TDCPP **Indicator TOrC:** ≥ 75% Removal: Iopromide	**Ammonia**: Nitrification (consumption of ammonia/DO) followed by denitrification during BAC possibly caused the formation of NDMA during BAC. NDMA formation decreased to below detection limits during the first 14 min (EBCT) of transit in BAC. However, there was an increase above influent concentrations by 20 min of EBCT.
WWTP Pretreatment Configuration: Primary-CAS (BOD Removal; Partly Nitrifying)	**Short-Chain PFAS:** ≤ 25% Removal: PFBA, PFPnA, PFHxA	
Pilot Influent Water Quality: Turbidity = 6.7 NTU (n=6)	PFOA + PFOS < 2.6 ng/L	
TOC = 5.9 mg/L (n=6) --------------------->	TOC = 1.2 mg/L (n=3)	
TDS = 3610 mg/L (n=1) -------------------->	TDS = 3050 mg/L	
Nitrate = 2.7 mg/L as N (n=6) ------------->	Nitrate = 6.6 mg/L as N (n=9)	
Nitrite = 1.3 mg/L as N (n=6) ------------>	Nitrite = 0.2 mg/L as N (n=7)	
NH_3 = 3.5 mg/L as N (n=6) -------------->	NH_3 = 0.2 mg/L as N (n=8)	
Bromide = NA	**Ozone Byproducts:** NDMA = 16 ng/L (n = 7) Bromate = NA[a]	
References: Stanford et al., Controlling Trace Organic Compounds Using Alternative, Non-FAT Technology for Potable Water Reuse, 2017, WE&RF, Reuse-13-10, Alexandria, VA.; Li et al. 2017.		

a. not available; b. Ion-exchange for DOC removal,; c. Ion-exchange for NH_4 removal

Table B-3. Summary of the City of Rio Rancho's CBAT case study.

Location/Process Configuration/ Operational Parameters	Post BAC Water Quality	Interfering Constituents:
Rio Rancho, NM Pilot: H_2O_2-**O_3**-**BAC**-Cl_2 O_3:TOC ~1; O_3: H_2O_2 (molar): 1:1.2 BAC: Calgon F300; 41 min EBCT Old BAC: ? mo. New BAC: >2 mo. >5,000 BV	**Indicator TOrC Removal: New BAC**: > 93% (n=6) & **Old BAC**: > 71% (n=1): Carbamazepine, Sulfamethoxazole, DEET, Meprobamate, Primidone, TCEP, Sucralose	**Nitrite:** Variable nitrite in the MBR filtrate caused increased ozone demand coming from the nitrite. **Bromide/Bromate:** H_2O_2 was used to mitigate bromate formation during ozonation.
WWTP Pretreatment Configuration: Primary-CAS (Nitrification/ Denitrification)-MBR	**Short-Chain PFAS Removal:** **New BAC**[c]: < 65% (n=3) & **Old BAC**: < 10% (n=1): PFHxA, PFPnA	
Influent Water Quality for O_3-BAC: Turbidity = 0.1 NTU (n=4)	PFOA = <9 ng/L, PFOS < 0.4 ng/L (n=4)	
TOC = ~5 mg/L (n=5) ----------------> Nitrate = ~7 mg-N/L (n=5) ----------> NH_3 = ND[b] (n=5) --------------------->	TOC = 3.7 mg/L Nitrate = 6.6 mg-N/L NH_3 = ND[b] (n=5)	
Nitrite = ~0.2 mg-N/L (n=5) Bromide = 120 ug/L (n=4)	**Ozone Byproducts:** Bromate = 1-2 µg/L (n=5) NDMA = NA[a]	
Reference: Carollo Engineers, Inc., Rio Rancho Water Utilities: Advanced Water Treatment Facility Efficiency Study, 2022.		

a. not available; b. non detect; c. PFAS was only analyzed for a BAC age of ~2 months.

Table B-4. Summary of the City of San Diego's CBAT case study.

Location/Process Configuration/ Operational Parameters	Post BAC Water Quality	Notes:
City of San Diego, CA Pilot: **O_3-BAC**-MF/UF-RO-UV-AOP O_3:TOC ~2-3 BAC: Preexhausted towards TOC, Clagon CMR MUNIF300 (Coal-based), 15-16 min EBCT	**Indicator TOrC:** > 90 % Removal: DEET, Carbamazepine, Acesulfame, Sulfamethoxazole, Primidone, Iohexol **Indicator TOrC:** > 50 % Removal: Sucralose, TCEP, PFOS	**Indicator TOrC:** DEET, Carbamazepine, Sucralose, Sulfamethoxazole, Primidone, Acesulfame, Iohexol were mostly removed by ozone. **BAC Age**: Stabilization of TOC removal after 8 months from commissioning indicated exhaustion of the GAC and conversion to BAC. This was supported by the low average removal of Indicator TOrC by GAC (i.e., PFOA, Primidone, Sucralose).
WWTP Pretreatment Configuration: Primary-CAS (Nitrifying/Partial Denitrification)-Filtration	**PFAS:** < 25% Removal: PFHxA, PFOA	
Pilot Influent Water Quality: Turbidity = NA[a]	PFOA + PFOS = 174 ng/L (n=5)	
TOC = 7.9 mg/L (n=23) -----------------> TDS = 1069 mg/L (n=12) -------------------> Nitrate = 15 mg/L as N (n=50) -------------> Nitrite = 0.07 mg/L as N (n=49) -----------> NH_3 = 0.3 mg/L (n=47) --------------------->	TOC = 4.7 mg/L (n=24) TDS = 1092 mg/L Nitrate = 14 mg/L as N (n=9) Nitrite = <0.005 mg/L as N (n=7) NH_3 = 0.03 mg/L as N (n=8)	
Bromide = 321 µg/L (n=7)	**Ozone Byproducts:** NDMA < 2 ng/L (n = 7) Bromate = 71 µg/L (n=13)	
References: Trussell et al., Demonstrating Redundancy and Monitoring to Achieve Reliable Potable Reuse, 2018, WRF, Reuse-14-12/4765, Alexandria, VA; Tackaert et al. (2019)		

a. not available

Table B-5. Summary of the El Paso's CBAT case study.

Location/Process Configuration/ Operational Parameters	Post BAC Water Quality	Notes:
El Paso, TX Full-Scale: **O$_3$-BAC**-Cl$_2$ O$_3$:TOC ~0.3 Aged-BAC: 16 min EBCT	**Indicator TOrC:** ≥ 95% Removal: Carbamazepine, Sulfamethoxazole **Indicator TOrC:** ≤ 60% Removal: Meprobamate, DEET, Iopamidol	This full-scale system was not used for potable purposes. **Low O$_3$:TOC ratio (~0.3)**: Less effective towards Indicator TOrCs **Aged-BAC**: Less adsorption capacity towards Indicator TOrCs. The BAC had only been completely replaced twice in 27 years of operation.
WWTP Pretreatment Configuration: Primary-CAS (Nitrified/ Denitrified/PAC)-Lime-Filtration (sand)	**TOrC:** ≤ 25% Removal: Sucralose, TCEP	
Influent Water Quality for O$_3$-BAC: Turbidity = NA[a]	PFOA = 12 ng/L, PFOS = 9 ng/L	
TOC = 3.9 mg/L (n=4) --------------------->	TOC = 2.6 mg/L (n=4)	
TDS = NA[a] ------------------------------->	TDS = NA[a]	
TN = 4.5 mg/L (nitrate) ------------------>	TN = 4.0 mg/L (nitrate)	
Nitrite = NA[a]	**Ozone Byproducts:**	
NH$_3$ = NA[a]	NDMA < 2 ng/L (n=3)	
Bromide = NA[a]	Bromate = 9.1 µg/L (n=4)	
Reference: Trussell et al., Equivalency of Advanced Treatment Trains for Potable Reuse, 2016, WE&RF, Reuse-11-02-4, Alexandria, VA.		

a. not available

Table B-6. Summary of the Los Angeles's CBAT case study.

Location/Process Configuration/ Operational Parameters	Post BAC Water Quality	Interfering Constituents:
Los Angeles, CA Pilot: **O$_3$-BAC**-O$_3$-LPUV O$_3$:TOC ~0.4–1.0 BAC: Calgon F300; 15 min EBCT	**Indicator TOrC:** ≥ 95% Removal: Carbamazepine, DEET, Sulfamethoxazole **Indicator TOrC:** ≤ 60% Removal: Iopromide, Sucralose	**O$_3$:TOC ratio**: The ratio varied from 0.4–1.0, thus TOrC removals varied.
WWTP Pretreatment Configuration: Primary-CAS (Nitrification)-Filtration-NH$_4$Cl$_2$-Cl$_2$	**TOrC:** ≤ 25% Removal: PFOS, PFOA, TCEP	
Influent Water Quality for O$_3$-BAC: Turbidity = 1.0 NTU (n=116)	PFOA = 26 ng/L, PFOS = 3.6 ng/L 1,4-Dioxane = 0.84 ug/L	
TOC = 7.8 mg/L (n=145) ------------------>	DOC = 6.1 mg/L (n=6)	
Conductivity = 964 µS/cm (n=89) ------>	Conductivity = NA[a]	
TN = 8.2 mg/L-N (n=9) (nitrate) -------->	Nitrate = 3.3 mg/L-N (n=5)	
Nitrite = <0.02 mg/L-N (n=11)	**Ozone Byproducts:**	
NH$_3$ = 0.12 mg/L-N (n=11)	NDMA = 32 ng/L (n=4)	
Bromide = 250 µg/L (n=14)	Bromate = NA[a]	
Reference: Brown and Caldwell and Trussell Tech., Los Angeles Sanitation and Los Angeles Department of Water and Power: Advanced Water Purification Facility Pilot Study Report, 2018.		

a. not available

Table B-7. Summary of the Las Vegas's CBAT case study with *tertiary* effluent.

Location/Process Configuration/ Operational Parameters	Post GAC Water Quality	Interfering Constituents:
Las Vegas, NV Pilot: **O_3-BAC-GAC** O_3:TOC ~0.8 BAC age: 13+ GAC: Calgon F400; 10 min EBCT; 23,000 BV	**Indicator TOrC:** ≥ 89% Removal: Carbamazepine, DEET, Meprobamate, Primidone, Sulfamethoxazole, TCEP, Sucralose	See Table 11 (below) for a comparison.
WWTP Pretreatment Configuration: Primary-CAS (Nitrification/P removal)-Filtration	**Short-Chain PFAS:** < 25% Removal: PFPeA, PFHxA	
Influent Water Quality for Pilot: Turbidity = 0.50 ± 0.1 NTU (n=39) SUVA = 1.5 ± 0.2 AU-L/m-mg (n=5)	PFOA < 2.5 ng/L, PFOS < 0.125 ng/L (n = 5) 1,4-Dioxane = 0.24 ± 10 µg/L (n =2) NMOR < 5.9 ng/L (n=5)	
DOC = 7.7 ± 0.7 mg/L (n=23) ------------> Conductivity = 1655 ± 21 uS (n=4) -----> Nitrate = 13.3 mg-N/L ± 0.9 (n=5) ----->	DOC = 4.7 mg/L (n=23) Conductivity = NA[a] Nitrate = NA[a]	
Nitrite = 0.02 (n=5) NH_3 = 0.023 ± 0.009 mg-N/L (n=5) Bromide = 176 ± 21 µg/L (n=5)	**Ozone Byproducts:** NDMA <2.9 ng/L (n=5) Bromate = 16.8 ± 8.5 µg/L (n=5)	
References: Unpublished. See Appendix B.		

a. not available

Table B-8. Summary of the Las Vegas's CBAT case study with *secondary* effluent.

Location/Process Configuration/ Operational Parameters	Post GAC Water Quality	Interfering Constituents:
Las Vegas, NV Pilot: **O_3-BAC-GAC** O_3:TOC ~0.8 BAC age: 13+ GAC: Calgon F400; 10 min EBCT; 10,000 BV	**Indicator TOrC:** > 90% Removal: Carbamazepine, DEET, Meprobamate, Primidone, Sulfamethoxazole, TCEP, Sucralose	**Turbidity**: Higher turbidity in the secondary treated wastewater caused more frequent backwashing. **SUVA:** Organic matter with higher SUVA caused faster break-through of organic constituents during GAC treatment.
WWTP Pretreatment Configuration: Primary-CAS (Nitrification/P removal)	**TOrC:** < 25% Removal: PFPnA, PFHxA, NMOR	
Influent Water Quality for Pilot: Turbidity = 2.9 ± 1.0 NTU (n=72) SUVA = 2.0 ± 0.1 AU-L/m-mg (n=5)	PFOA = 0.79 ng/L, PFOS < 0.25 ng/L (n=5) 1,4-Dioxane = 0.34 ug/L ± 0.09 (n=5) NMOR = 7.2 ng/L (n=5)	
DOC = 6.8 ± 0.5 mg/L (n=5) --------------> Conductivity = 1557 ± 18 uS (n=5) ----> Nitrate = 12.3 ± 0.6 mg-N/L (n=5) ------>	DOC = 4.7 mg/L (n=5) Conductivity = NA[a] Nitrate = NA[a]	
Nitrite = 0.05 ± 0.01 mg-N/L (n=5) NH_3 = 0.023 ± 0.009 mg-N/L (n=5) Bromide = 132 ± 6 µg/L (n=5)	**Ozone Byproducts:** NDMA < 2.9 ng/L (n=5) Bromate = 9.4 µg/L ± 5.6 (n=5)	
References: Unpublished. See Appendix B.		

a. not available

Table B-9. Summary of the Virginia Beach's (HRSD) CBAT case study.

Location/Process Configuration/ Operational Parameters	Post GAC Water Quality	Interfering Constituents/Notes:
Virginia Beach, VA Pilot: Floc/sed-NH_2Cl-**O_3-BAC-GAC**-UV O_3:TOC ~1^c, ~0.8^f BAC: Preexhausted towards TOC GAC: Calgon F400; 10/20 or 15/15 min EBCT^b; 20,000 BV (New GAC)^c; 26,000 BV (New GAC)^f	**Indicator TOrC:** ≥ 90% Removal^c: Carbamazepine, Sulfamethoxazole, Primidone, TCEP **Indicator TOrC:** > 75% Removal^f: Iohexal, Sucralose	**PFAS, Bromide, Acrylamide:** Mitigated by enhanced source control. **TOC:** Routine TOC loading and biological upsets led to increased TOC levels and pilot being offline. **MeOH Additive**: Dosage was optimized to minimize MeOH being an ozone demand. **Bromide/Bromate**: In-situ chloramination was used for bromate control. GAC (20 vs. 10 min EBCT) was needed to reduce **NDMA** below 10 ng/L
WWTP Pretreatment Configuration: Primary-Step Aeration-Methanol fed Denitrification	**Short-Chain PFAS:** < 25% Removal: PFPeA^e, PFHxA^e	
Influent Water Quality for Pilot: Turbidity = 1.7 NTU (n=1365)	PFOA + PFOS < 8 ng/L^c 1,4-Dioxane = 0.38 µg/L^f NMOR = 3-4 ng/L	
TOC = 8.03 mg/L (n=75) --------------->	DOC < 4 mg/L (regulatory limit)	
TDS = 542 mg/L -------------------------->	TDS = 599 ± 71.1 mg/L	
Nitrate = 0.91 mg-N/L ------------------>	Nitrate = NA^a	
Nitrite = 0.5 mg-N/L	**Ozone Byproducts:**	
NH_3 = 0.95 mg-N/L	NDMA <7 ng/L (n=20)	
Bromide = 433 µg/L	Bromate = 7 µg/L (n=157)	
References: c. Vaidya et al. (2019); d. Vaidya et al. (2021); e. Gonzalez et al. (2021); f. Hogard et al. (2021)		

a. not available; b. parallel GAC adsorbers

Table B-10. Summary of the Reno's CBAT case study.

Location/Process Configuration/ Operational Parameters	Post GAC Water Quality	Interfering Constituents/Notes:
Reno, NV Pilot: Coag/Floc/Sed-Fil-**O_3-BAC-GAC**-UV O_3:TOC ~0.9-1.5 BAC: Calgon F400; 26 min EBCT (9 mos) GAC: Jacobi AquaSorb CX; 30-40 min EBCT (5 mos)	**Indicator TOrC:** ≥ 90% Removal: Carbamazepine, Meprobamate, Sulfamethoxazole, Primidone, Iohexol, Sucralose, TCEP	**Arsenic** was detected in the finished water (~4 ug/L), but it was consistently below the MCL of 10 ug/L. No **bromate** mitigation strategy was employed for low bromate formation in the presence of relatively high bromide concentration and O3:TOC of 1. GAC treatment was effective of reducing **NMOR** from 5 to below 2 ng/L. **BAC** has some sorption capacity present for TOrCs
WWTP Pretreatment Configuration: Primary-CAS (Nitrification/ Denitrification)-Filtration	**Short-Chain PFAS:** < 50% Removal: PFHxA, PFPeA	
Influent Water Quality for Pilot: Turbidity = 0.7±0.4 NTU (n=6)	PFOA + PFOS < 2 ng/L 1,4-Dioxane = 0.36±0.03 µg/L (n=5) NMOR = <2 ng/L (n=5)	
TOC = 4.6 mg/L±0.2 (n=13) ------------>	TOC = 1.8±0.5 mg/L (n=8)	
TDS = 411±23 mg/L (n= 6) ------------>	TDS = 416±19 mg/L (n=6)	
Nitrate = 3.8±0.6 mg-N/L (n = 6) ----->	Nitrate = 4.7±1.4 mg/L (n=6)	
Nitrite = <0.2 mg-N/L (n=2)	**Ozone Byproducts:**	
NH_3 = NA^a	NDMA < 2 ng/L (n=121)	
Bromide = 166±44 µg/L (n=19)	Bromate = 3±1 µg/L (n=18)	
References: One Water Nevada, 2020. Reno Stead Water Reclamation Facility: Advanced Purified Water Demonstration Study, Reno, NV.		

a. not available

APPENDIX C

Module B - Impact of Treated Wastewater Quality on the Performance of an Ozone, Biofiltration, and Granular Activated Carbon Treatment System

Objective

The primary goal of this pilot study was to evaluate the difference ***between secondary and tertiary treated wastewaters*** on the performance of ozone (O_3) with biologically-active filtration (BAF) with aged, activated carbon or anthracite followed by granular activated carbon (GAC).

Pilot System

The SNWA pilot plant was located at a Las Vegas wastewater treatment plant and supplied with unchlorinated tertiary-filtered effluent for Phase 1 of the study (April – September 2019) and then with secondary effluent for Phase 2 (January – May 2021) as illustrated in Figure 1. The WWTP treats an average of approximately 380,000 m^3/day (100 mgd) with a modified Johannesburg Process focused on biological phosphorus removal with no mixed liquor return. Aluminum sulfate was added after the secondary clarifiers. Subsequently, the coagulated water was filtered by dual-media filtration. The ozone pilot (Pacific Ozone Technology, SGC 21; Benicia, CA) was operated at a flowrate of 6-8 GPM and ~0.8 mg-O_3/mg-DOC. The ozonated effluent passed to the biofiltration skid (Intuitech Inc., Module F300; Salt Lake City, UT) that consisted of four columns. Two columns were operated in parallel as biofilters (one with aged BAC, another with anthracite), which fed two subsequent column adsorbers filled with new GAC (Figure 1). The details of the column operations are listed in Table 1. The biofilters were backwashed using non-ozonated influent (secondary or tertiary-filtered effluent), while dechlorinated tap water was used to backwash the GAC adsorbers.

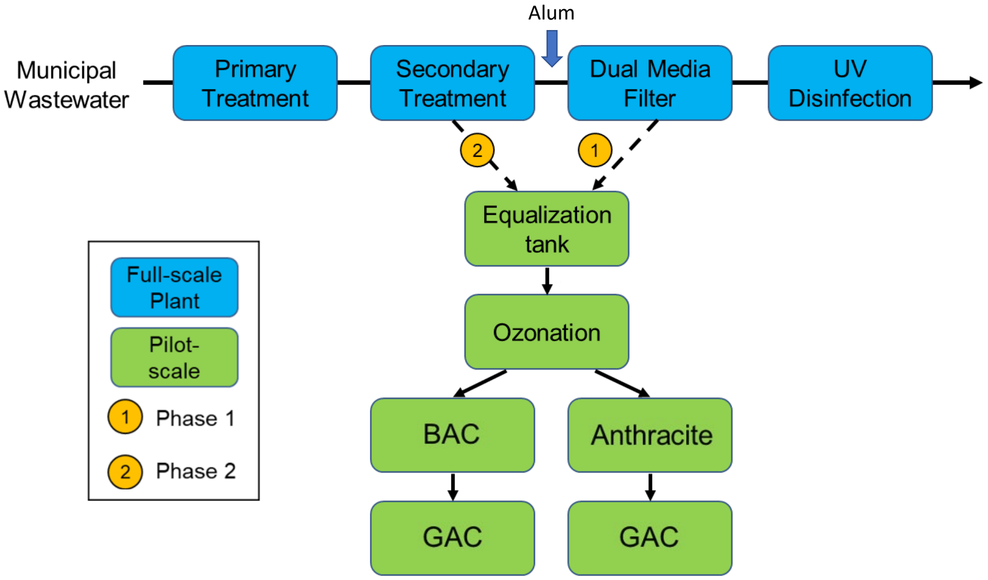


Figure 1. Process flow diagram of the full-scale treatment train at CCWRD and the SNWA O_3-BAF-GAC pilot plant. Study phases using different feed waters are indicated.

Table 1. Media configuration and operating parameters for the SNWA pilot columns.

Column	Media type	Age (years)	Media depth (in)	Flow rate (gpm)	Loading rate (gpm/ft^2)	EBCT (min)
BAC	GAC F816	+13	48	0.73	3.7	10
	Sand	+3	12			
BAF	Anthracite	+4	48	0.73	3.7	10
	Sand	+4	12			
GAC	GAC F400	0	39	0.62	3.2	10
	Sand	0	12			

Background Water Quality

Table 2 summarizes the water quality of the influents during Phases 1 and 2. In general, there were a few noticeable water quality differences observed between the secondary and tertiary effluents. The tertiary-filtered effluent exhibited a lower turbidity value (0.5 NTU) due to the filtration process, which impacted and reduced the frequency of backwashing for BAC and BAF columns. While weekly backwash frequency was sufficient to maintain below the threshold head pressure (i.e., 26 psi) of BAC and BAF with the tertiary-filtered effluent as the pilot feed, daily backwash was essential to maintain the operating pressure below the threshold value with the secondary effluent as the pilot feed (Turbidity = 3 NTU). The dissolved organic carbon (DOC) and bromide concentrations were lower and the SUVA was higher for the secondary treated pilot influent during Phase 2 than Phase 1. Note, the pilot influent bromide/DOC ratios for both Phases 1 and 2 were similar, ~20 ug/mg.

Table 2. Bulk water quality parameters of the pilot influents for Phases 1 and 2 ($n \geq 5$).

Parameter	Phase 1: Tertiary Effluent	Phase 2 Secondary Effluent
pH	7.0 ± 0.1	6.9 ± 0.1
Temperature (°C)	27 ± 2	24 ± 2
Turbidity (NTU)	0.50 ± 0.1	2.8 ± 0.8
Conductivity (uS)	1655 ± 21	1557 ± 18
Alkalinity (mg/L $CaCO_3$)	131 ± 5	120 ± 2
Bromide (Br) (µg/L)	176 ± 21	132 ± 6
Dissolved organic carbon (mg-C/L)	7.7 ± 0.7	6.8 ± 0.5
UV254 (AU/cm)	0.12 ± 0.004	0.13 ± 0.01
SUVA (AU-L/m-mg)	1.5 ± 0.2	2.0 ± 0.1
Total dissolved nitrogen (mg-N/L)	13.4 ± 0.9	12.4 ± 0.5
Nitrate (mg-N/L)	13.3 ± 0.9	12.3 ± 0.6
Nitrite (mg-N/L)	0.023 ± 0.002	0.05 ± 0.01
Ammonia (NH3) (mg-N/L)	0.034 ± 0.009	0.12 ± 0.03
Orthophosphate (mg-P/L)	0.03 ± 0.01	0.08 ± 0.02

It is important to note, Phase 2 occurred during the SARS-CoV-2 virus pandemic, whereas Phase 1 was pre-pandemic. Thus, the qualities of the raw wastewater and full-scale secondary treated wastewater could have been impacted due to changes in domestic (e.g., more remote working) and commercial (e.g., hotel shut-downs) water use in Las Vegas during the pandemic. Nitrate concentrations in both secondary and tertiary effluents were greater than federal drinking MCL of 10 mg/L because the secondary treatment was not optimized for denitrification as it had no mixed liquor return. Nitrate levels remained above the MCL after O_3-BAF-GAC treatment for both Phases.

Dissolved Organic Carbon

Prior to turning on the GAC filters for Phase 1, the BAC and anthracite biofilters were acclimated for 1 month with ozonated tertiary-filtered effluent. They were deemed “acclimated” when they reached steady-state DOC removal. A similar acclimation time was applied for the second phase of the project with ozonated secondary effluent as the feed. The DOC concentrations for the feeds and after each process for Phases 1 and 2 are presented in Figure 2. During Phase 1 the BAC biofilter averaged 16 ± 4% (23 samples) DOC removal, while the anthracite biofilter demonstrated slightly less removal at 12 ± 4%. This difference is statistically significant (p=0.00035, paired one-tailed t-test hereinafter unless specified). Two significant decreases in DOC of the tertiary-filtered influent were observed on days 75 and 161. This lower DOC then resulted in similarly reduced DOC concentrations following O3, BAF, and GAC treatment. The DOC breakthrough of the GAC filters was rapid, with ~35% breakthrough at onset and 50% breakthrough following 25 days (3,500 BV). Similarly, with the DOC removal in biofiltration, GAC following BAC exhibited a slightly higher, but statistically significant (p=0.0028), DOC removal than that following BAF. This was likely attributed to the lower DOC loading onto the GAC following BAC.

For Phase 2 using ozonated secondary effluent higher DOC removal percentages were observed across the both biofilters, compared to Phase 1, likely due to a higher initial biodegradable DOC present in the secondary effluent (Phase 2) than the tertiary-filtered effluent (the full-scale filter operates as a biofilter). The DOC was lower after both GAC treatments during Phase 2 than Phase 1, but this could be due to the initial DOC (Table 1) being lower in the feed during Phase 2 (Avg = 6.8 mg/l) than Phase 1 (Avg = 7.7 mg/L). During the Phase 1 study the DOC in the secondary effluent was measured at 9.4 mg/L (7/8/2019), which is higher than the average value measured during Phase 2. Thus, the secondary treated wastewater during Phase 2 would have been expected to have a higher DOC concentration, since it is less treated, but this was not the case. The full-scale tertiary-filtration (biofiltration) process at this plant partially removes DOC. Note, Phase 2 was during the COVID-19 pandemic, whereas, Phase 1 was pre-pandemic, thus the wastewater quality could have been impacted due to the pandemic. Another indicator of differing water quality was that the SUVA value for the secondary effluent was higher than the tertiary effluent (Figure 3). The full-scale dual-media filtration process was expected to increase the SUVA, since it is well known that biofilters are not expected to preferentially remove UV-absorbing compounds (more challenging to biodegrade aromatic compounds that typically reside in dissolved organic matter). This was observed for one sample point (7/8/2019) where the SUVA for the secondary effluent was 1.4 m-L/mg and increased to 1.7 m-L/mg after full-scale (bio)filtration. However, during Phase 2 the secondary effluent had a higher SUVA value than the tertiary-filtration effluent during Phase 1. Interestingly, for both Phases, the DOC removal and breakthrough profiles during GAC treatment were similar (Figure 4).

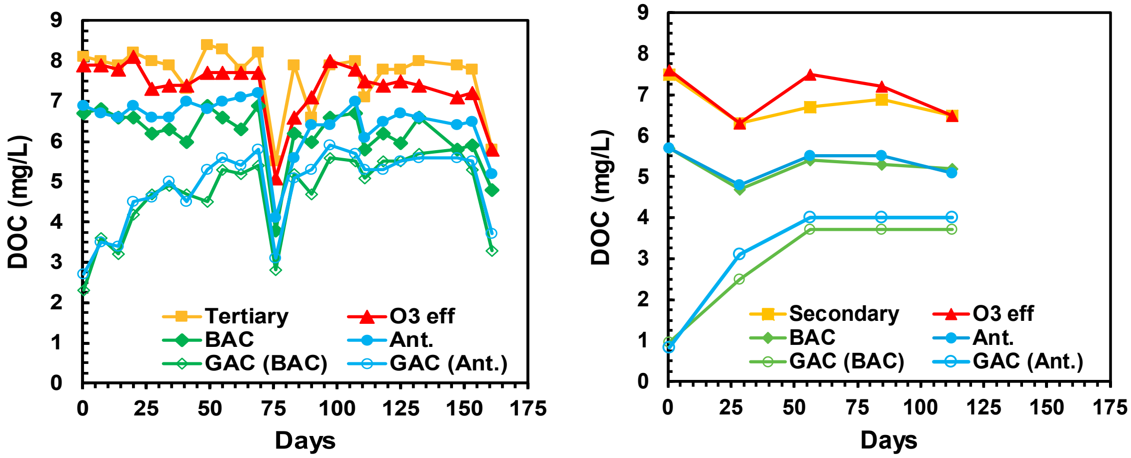


Figure 2. DOC as a function of time during O_3-BAF-GAC treatment of tertiary filtered effluent (left) and secondary effluent (right).

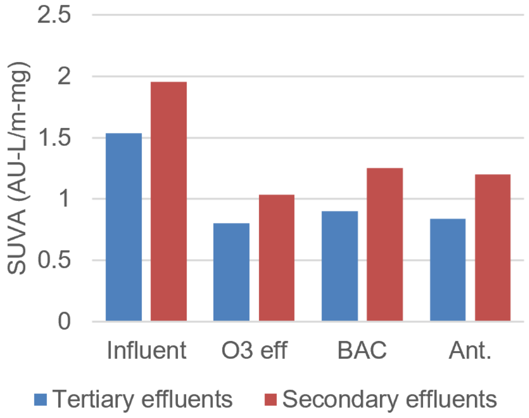


Figure 3. The mean SUVA values for the first phase (tertiary effluents) and the second phase (secondary effluents).

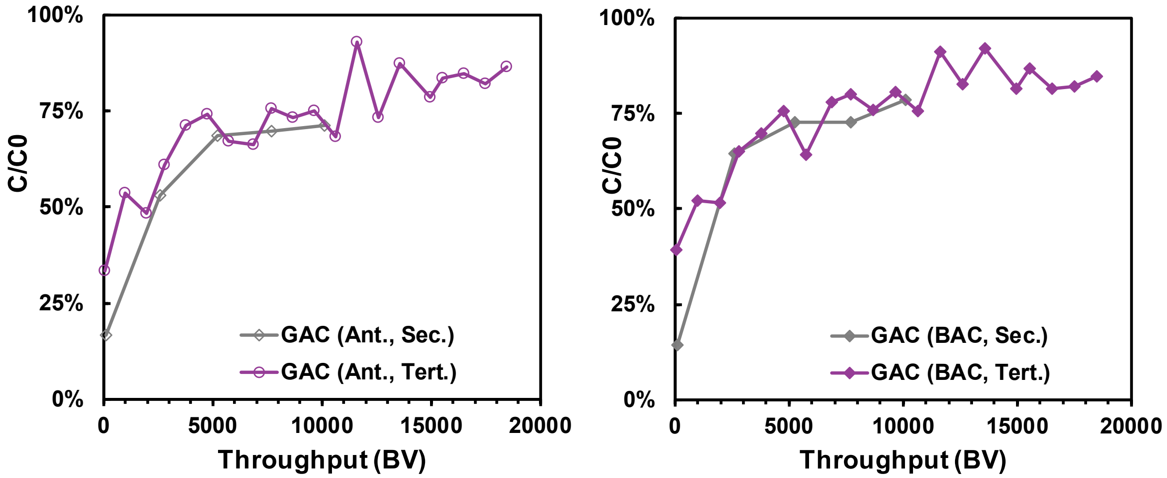


Figure 4. DOC breakthrough (C/C_0) of GAC with the influent of tertiary effluents (green symbols) and secondary effluents (blue symbols).

Trace Organic Compounds

Figure and 6 depict the average concentrations of 16 trace organic compounds (TOrCs) through the O_3-BAC-GAC for Phases 1 and 2, respectively. The results of O_3-BAF (anthracite)-GAC are not presented due to similar results. All the targeted TOrC were measurable in the tertiary-filtered wastewater (Phase 1) except for acetaminophen, caffeine, and ibuprofen (Figure 5). All the targeted TOrC were measurable in the secondary treated wastewater (Phase 2) except for acetaminophen (Figure 6). The lack of caffeine and ibuprofen in the tertiary-filtered wastewater, but their presence in the secondary effluent, is likely due to these compounds being biodegraded during full-scale filtration, acting as a biofilter. The following are the TOrCs that were detected above method reporting limits (MRLs) post GAC treatment: sucralose, 1,4-dioxane, DEET, meprobamate, primidone, sulfamethoxazole, and *N*-nitrosomorpholine (NMOR).

Ozonation was the main barrier for most of these TOrCs. The ozone process was able to oxidize the following compounds to below MRLs: atenolol, carbamazepine, fluoxetine, gemfibrozil, naproxen, triclocarban, triclosan, trimethoprim. Also, significant removal was observed for the following TOrCs: caffeine, DEET, ibuprofen, meprobamate, primidone and sulfamethoxazole. About half of sucralose, an artificial sweetener, was attenuated in ozonation, which is mainly attributed to the hydroxyl radicals produced during ozonation of treated wastewater. 1,4-dioxane, an industrial solvent, was also only partially removed (55-60%) during ozonation. TCEP, a flame retardant, was the only monitored TOrC that proved to be recalcitrant towards ozonation.

Biofiltration with anthracite was not effective towards any of the TOrCs detected after ozonation. BAC was not effective either and for some TOrCs their levels increased, such as atenolol, carbamazepine, fluoxetine, DEET, primidone, meprobamate, sucralose, trimethoprim, and sulfamethoxazole. This suggests that these TOrCs at one time adsorbed to this BAC and they were desorbing during the pilot testing. This is something to consider when using aged BAC and the TOrC exposure history of aged BAC.

GAC treatment was effective towards treating TOrCs detected after biofiltration. GAC had good removal of sucralose, although sucralose had the highest TOrC concentration in the GAC effluent, due to its very high initial concentrations. Sucralose had order of magnitudes higher concentrations (50,000-60,000 ng/L) in the tertiary or secondary effluents compared to the other measured TOrC. However, GAC was effective for TCEP, since TCEP is readily adsorbed due to its hydrophobicity (K_{ow}=1.63 estimated by the U.S. EPA EPISuite). GAC was also effective towards DEET, meprobamate, primidone and sulfamethoxazole, although low levels were detected post treatment. GAC was not effective towards 1,4 dioxane and NMOR, which are polar and smaller-sized compounds compared to the other TOrCs. While no federal MCL exists for 1,4-dioxane in drinking water and its concentration in the GAC treated water was below 1 µg/L (i.e., the notification level of the California State Water Resources Control Board), the persistency of 1,4-dioxane means the application of downstream processes, such as UV-advanced oxidation processes (UV-AOPs), might be necessary depending on the target treatment goal. NMOR was the most challenging TOrC to treat by O_3-BAF-GAC treatment. While this compound is not currently regulated in the United States, UV photolysis can be an effective removal strategy.

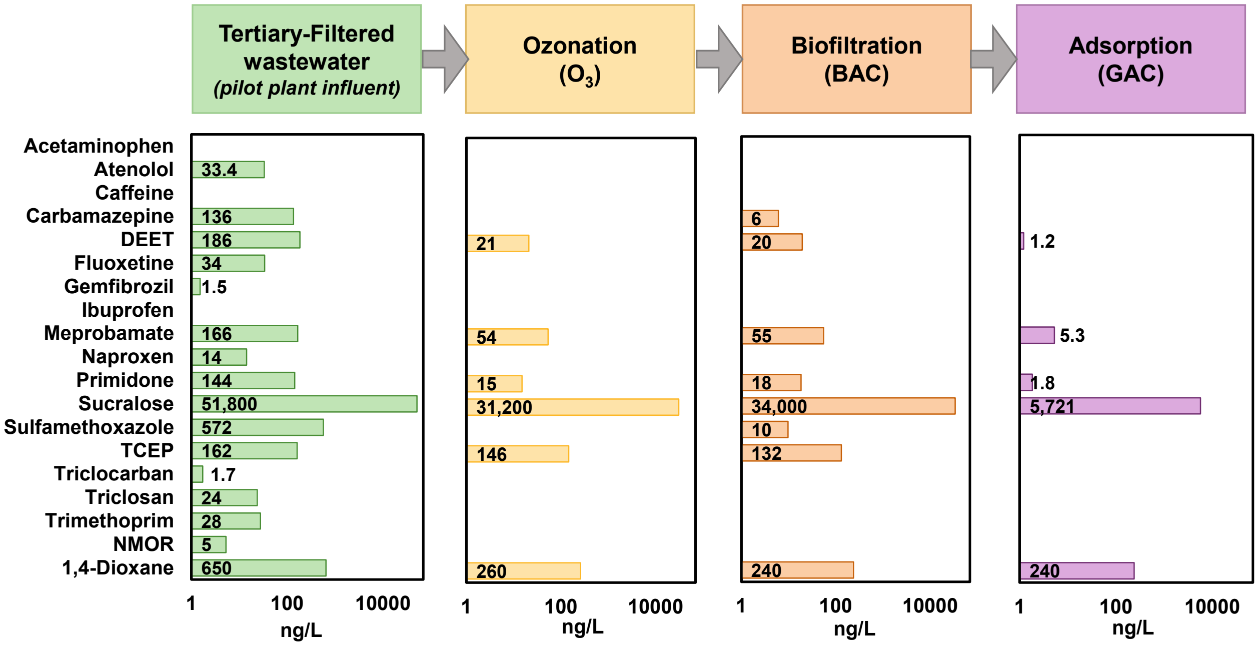


Figure 5. Average concentration of TOrCs in the O3-BAC-GAC pilot train fed tertiary-filtered wastewater (Phase 1).

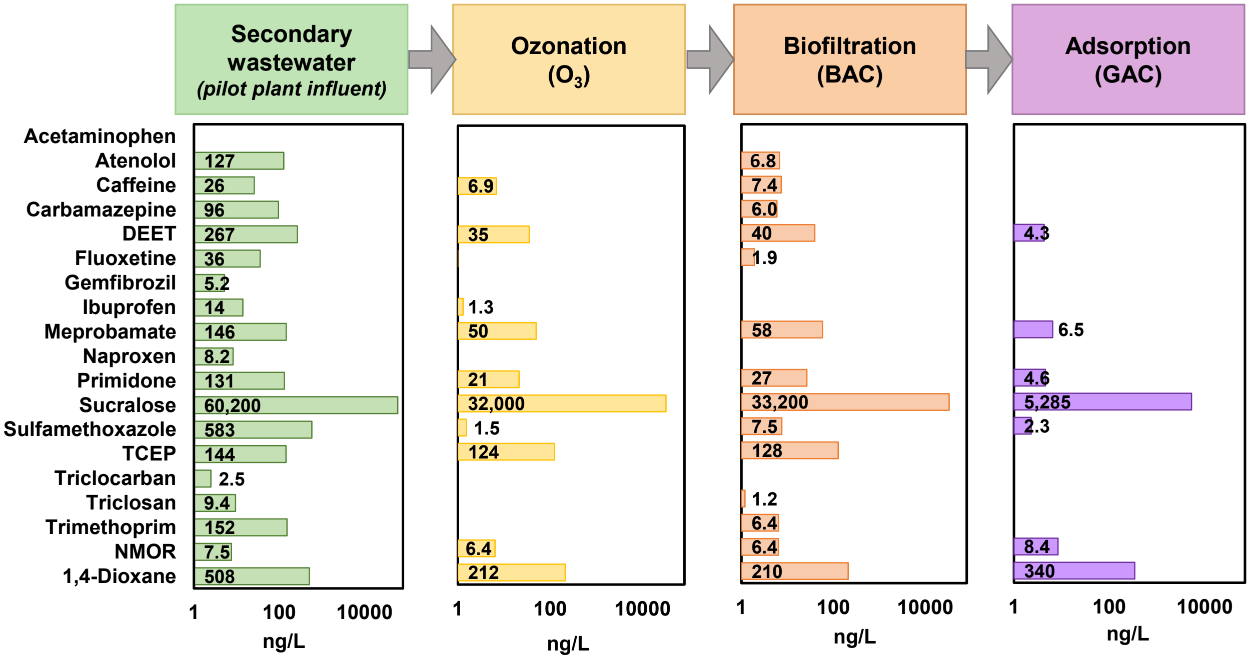


Figure 6. Average concentration TOrCs in the O3-BAC-GAC pilot train fed secondary treated wastewater (Phase 2).

During Phase 2 (secondary treated wastewater as the pilot train influent) the TOrC breakthroughs were faster than during Phase 1 (tertiary-filtered wastewater as the pilot train influent) (Figure 7). For instance, at around a throughput of ~10,000 bed volumes 30% of sucralose broke through (O_3-BAC-GAC train) for Phase 2, where twice the filtration volume was needed to achieve the same removal during Phase 1. This could be due greater competition between UV-absorbing dissolved organic matter and the TOrCs during Phase 2. The SUVA values for the biofilter effluents (GAC influents) were higher during Phase 2 than for Phase 1 (Figure 3), which likely attributed to a higher fraction of aromatic/hydrophobic organic matter that preferentially adsorbed to GAC and out competing the TOrC. There is caution in comparing the Phase 1 and 2 results since the dissolved organic matter for the tertiary-filtered and secondary treated wastewaters had unexpected DOC concentrations and SUVA values, as noted earlier, maybe caused by the SARS-CoV-2 virus pandemic.

In general, the TOrC breakthroughs were faster for GAC following BAF with anthracite than GAC following BAC (Figure 7). For example, ~40% breakthrough of meprobamate occurred at ~10,000 BV for GAC following BAF with anthracite, whereas ~20% breakthrough occurred at ~10,000 BV for GAC following BAC. Such a lower extent of breakthrough for GAC following BAC suggests that BAC is a more effective means of pre-treatment for GAC. This could be due to the DOC concentration being higher in the GAC influent from BAF with anthracite than the GAC influent from BAC, thus the potential for more organic matter to compete with TOrCs for sorption sites on the GAC (following BAF with anthracite). As noted earlier, BAF with anthracite removed less DOC than BAC, thus the higher concentration of DOC after BAF with anthracite.

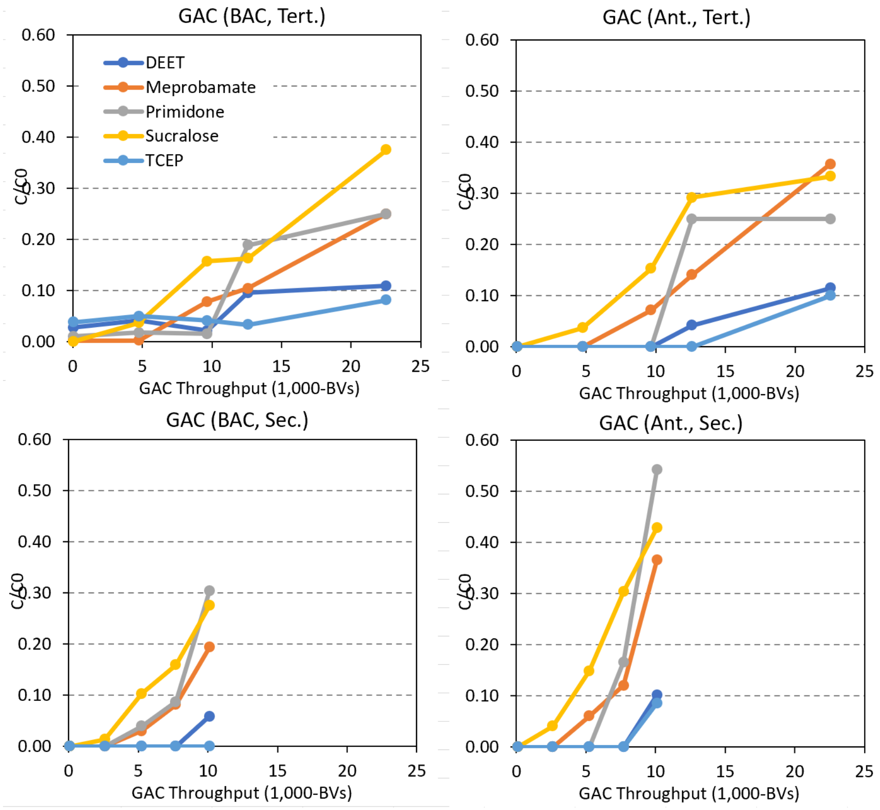


Figure 7. Breakthrough profiles of five selected TOrCs in GACs following BAC (left) and BAF (right), respectively, for Phase 1 operation (top) and Phase 2 operation (bottom).

Figure 8 shows the average concentration of perfluoroalkyl acids (PFAAs) following each treatment stage. Increases in the summed PFAA concentrations following ozonation and biofiltration were observed for Phase 1, whereas Phase 2 exhibited increased PFAA only following ozonation. Four PFAS, including PFHxS (C6), PFOS (C8), PFHxA (C6), and PFHpA (C7), in the ozone effluents for Phase 1 showed statistically higher concentrations than those in the ozone influents (*p*=0.049, 0.016, 0.0021, 0.00085, and 0.0045, respectively). The increase following ozonation is most likely due to the oxidation of PFAS precursors. Particularly, PFAA with C6 and C7 (PFHxA and PFHpA, respectively) were formed significantly for both Phases 1 and 2 (i.e., negative removal in Figure). Interestingly, BAF with anthracite in Phase 1 (tertiary effluent) did not show a statistically significant difference (*p*>0.05) for all the tested PFAS, while PFBS (C4), PFHxS (C6), PFHxA (C6), and PFNA (C9) are statistically greater in the effluent than the influent (*p*=0.0085, 0.050, 0.050, and 0.019, respectively), likely due to desorption from the biofilter media. Anthracite is inert; therefore, little adsorption and corresponding desorption are anticipated. However, the adsorbed PFAAs on BAC media of the biofilter can be desorbed by compounds with greater adsorption affinity, which may have caused the increased concentration of certain PFAAs in the BAC effluent.

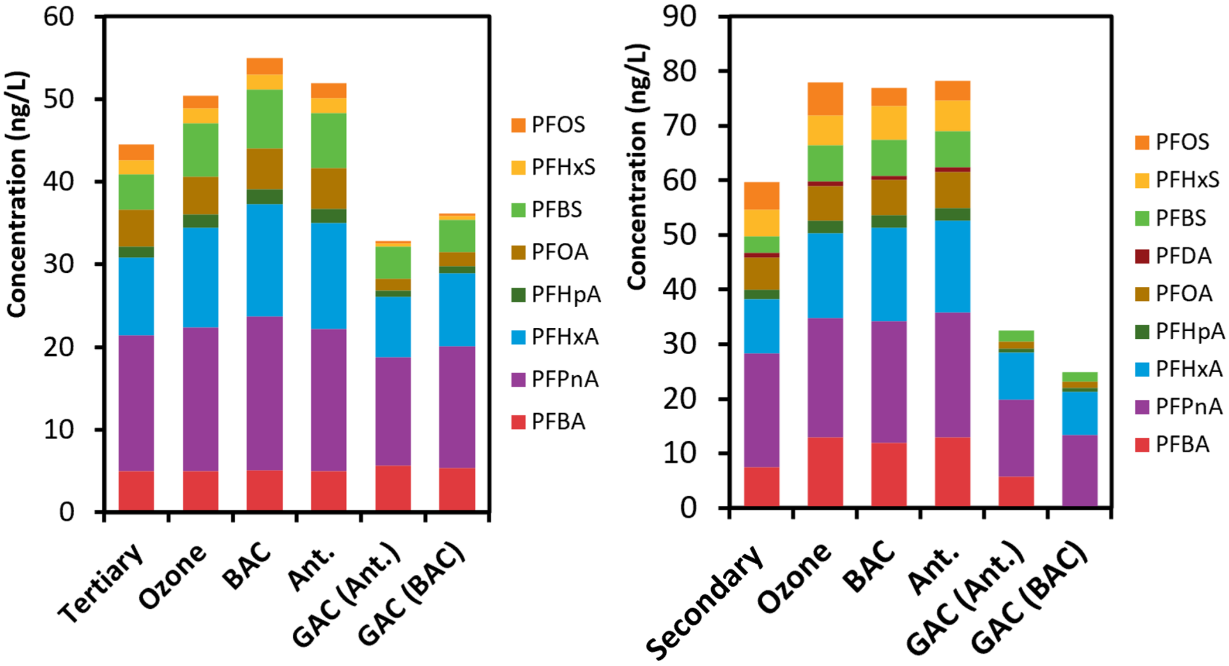


Figure 8. Average concentrations of PFCAs and PFSAs during Phase 1 (left, 22,500 BV) and Phase 2 (right, 10,100 BV) of pilot testing following each treatment stage.

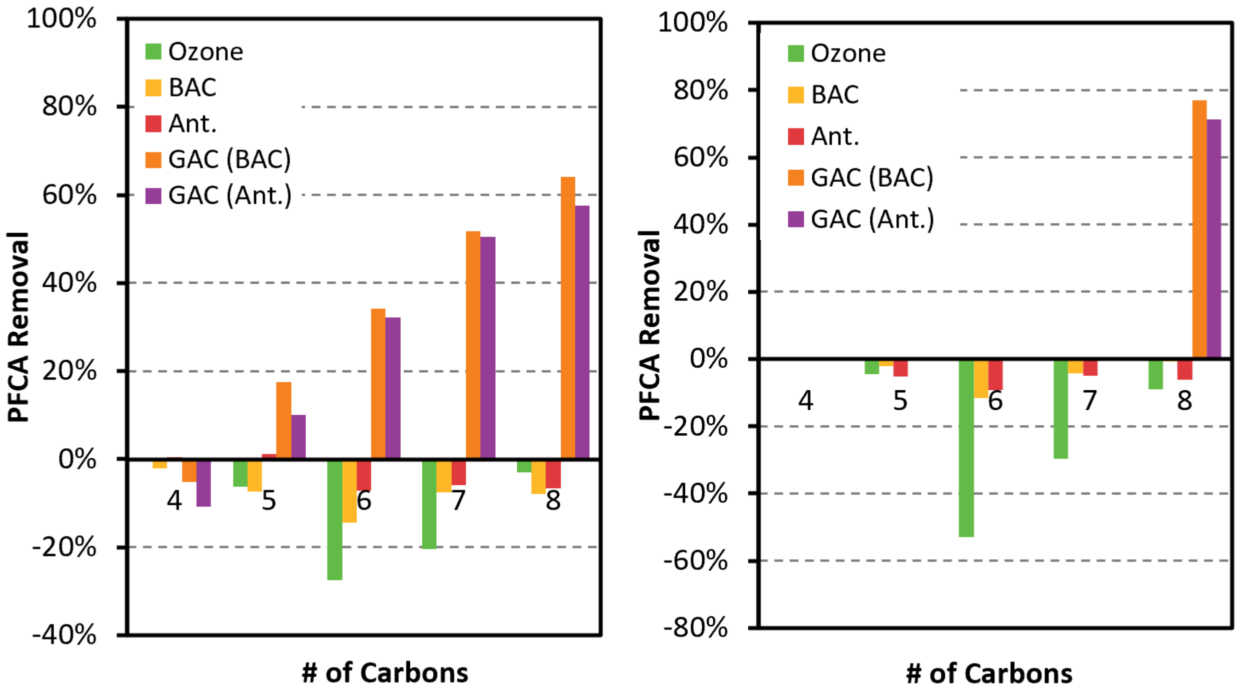


Figure 9. Average removal of PFCAs during Phase 1 (22500 BVs) and Phase 2 (10100 BV) by each treatment stage.

The longer chain PFAS was removed more effectively in GACs (Figure 10), whereas the shorter chain PFAS broke through faster, such as PFBA, PFPnA, PFHxA, and PFBS. The PFAS breakthrough trends in the GAC beds were different between Phases 1 and 2 and following differing biofilter types (Figure). For instance, during Phase 2 (using secondary treated wastewater as the pilot train influent) PFHpA and PFOA exhibited faster throughput than during Phase 1 (using tertiary-filtered wastewater as the pilot train influent) (Figure 11). Like the TOrC breakthrough behavior trends, this might be attributed to the greater aromaticity (i.e., higher SUVA) of the DOM in the GAC influent during Phase 2 (Figure 3) in secondary effluents, thus greater competition with PFAS for adsorption sites. DOM with a greater aromaticity could compete with PFAS adsorption to a greater extent than DOM with a lower aromaticity. Like the TOrC data, GAC following BAC exhibited a better removal of PFHxA, PFHpA and PFOA than GAC following anthracite during Phase 2, however less of difference was observed for Phase 1 (Figure 11).

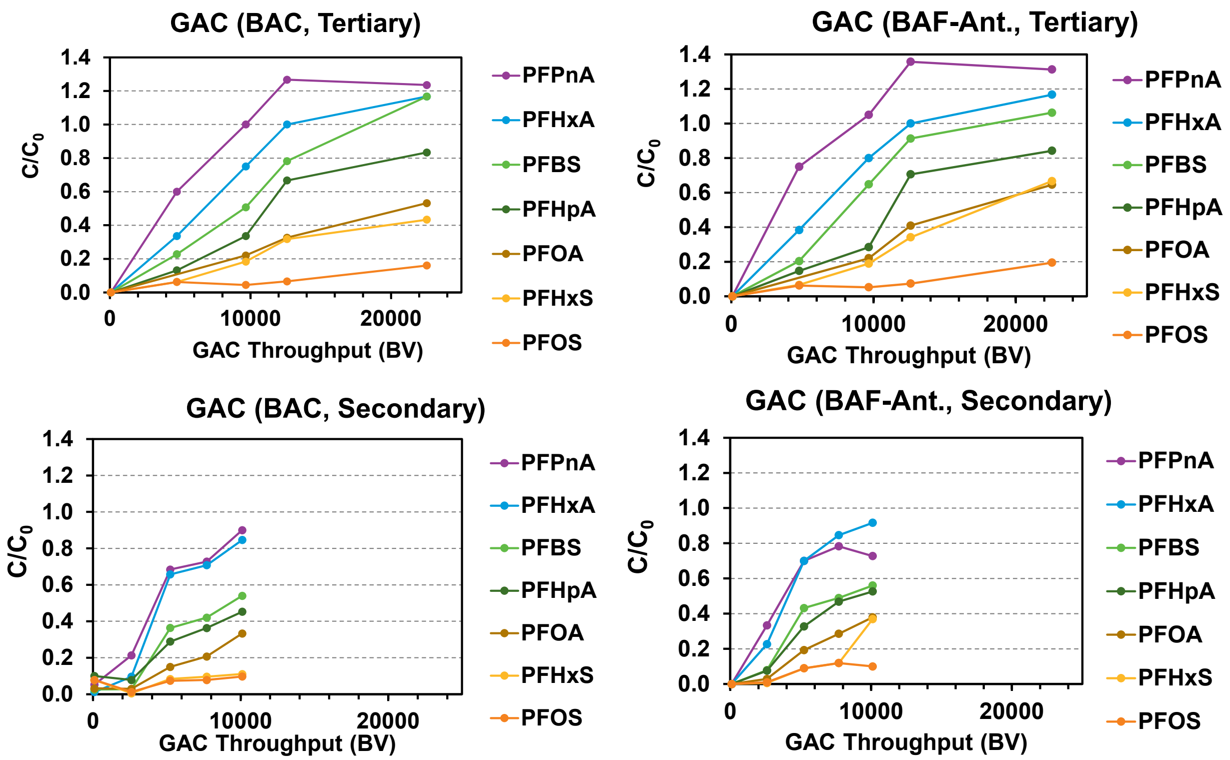


Figure 10. Breakthrough profiles of PFAS in GACs following BAC (left) and BAF (right), respectively for Phase 1 operation (top) and Phase 2 operation (bottom).

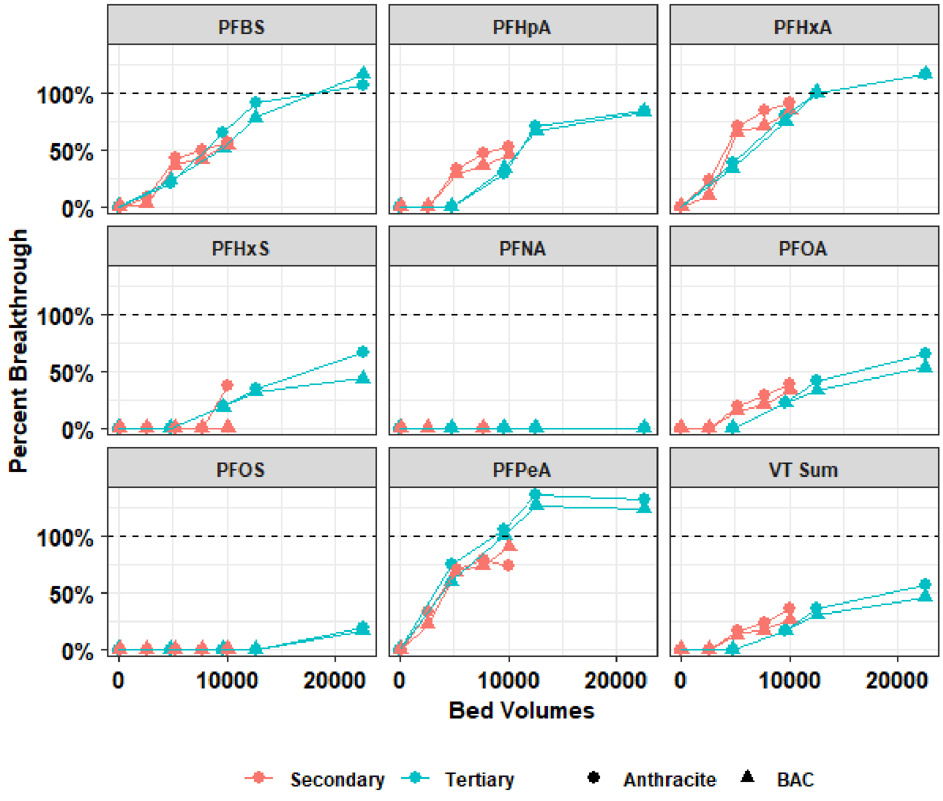


Figure 11. PFAS breakthroughs in GAC following BAC and BAF with anthracite.

Disinfection By-Products

Figure and 13 are the chlorinated HAA and THM precursor throughput profiles during GAC treatment for Phases 1 and 2, respectively. GAC effluents were chlorinated under UFC conditions. HAA5 remained under the EPA MCL of 60 µg/L throughout the study, while TTHM exceeded (Phase 1) or was near (Phase 2) 80 µg/L (MCL) for >10,000 bed volumes for GAC after BAF with anthracite and BAC treatments. Interestingly, despite the DOC being less in the GAC effluents during Phase 2 with secondary treated wastewater as the pilot influent the THM and HAA breakthroughs were faster and concentrations where higher for throughput up to 10,000 BVs during Phase 2. This could be due to the SUVA values in the GAC effluents during Phase 2 were higher (1.2 ± 0.1 L/m-mg) than in Phase 1 (0.7 ± 0.2 L/m-mg), where organic matter with higher UV-absorbing aromatic content yielding more THMs and HAAs being formed.

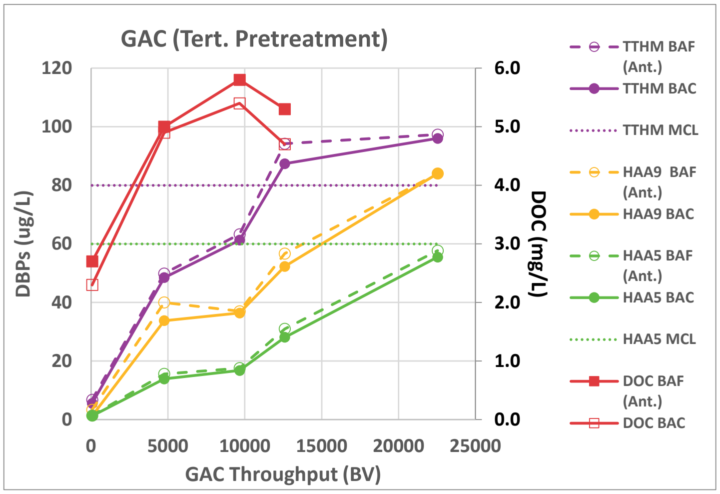


Figure 12. GAC throughput of DOC and chlorinated THM and HAA precursors during Phase 1 with tertiary-filtered effluent as the pilot influent.

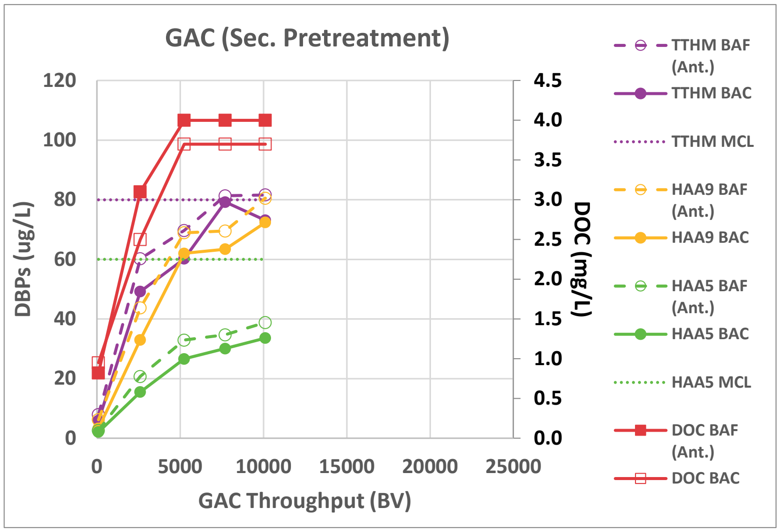


Figure 13. GAC throughput of DOC and chlorinated THM and HAA precursors during Phase 2 with secondary effluent as the pilot influent.

Figure 4 shows the concentrations of NDMA following each treatment stage. During the Phase 1 study using tertiary filtered effluent as the pilot feed, NDMA was below method reporting limit (< 2.9 ng/L) in the feed, while an average of 24.4 ng/L of NDMA was generated during ozonation. Following ozonation, NDMA was consistently removed by both the parallel BAC and anthracite biofilters to below the method reporting limit (< 2.9 ng/L). No NDMA was detected following GAC. This is also below California's 10 ng/L notification level. During the Phase 2 study using secondary effluent as the pilot feed, NDMA concentrations were higher after ozonation (55.2 ng/L on average) than Phase 1. Like Phase 1, the subsequent, parallel BAC and BAF with anthracite filters effectively reduced NDMA concentrations below 2.9 ng/L for BAC and 5 ng/L for the BAF with anthracite. Residual NDMA after the BAF with anthracite was not detected post GAC, most likely due to biodegradation, since NDMA is known to break through GAC readily. GAC effluent samples spiked with chloramine (targeting a 1.0 mg/L total chlorine residual after 3 days of exposure) under uniform formation conditions (UFC tests) remained below 2.9 ng/L, indicating chloramine-reactive precursors were removed during both pilot phase studies.

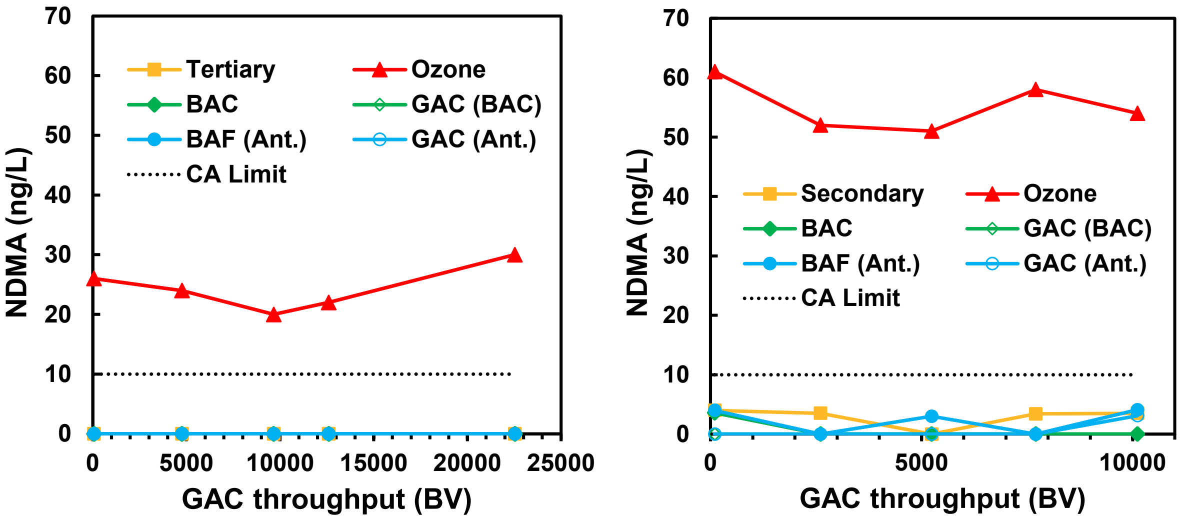


Figure 14. NDMA concentrations over time during O3/BAF/GAC treatment for Phase 1 (left) and Phase 2 (right).

Figure 5 shows the concentrations of bromate following ozone and GAC treatment stages. Following ozonation, bromate was formed as expected during Phases 1 (20-30 ug/L) and 2 (10-25 ug/L), more so during Phase 2, when the pilot used secondary effluent as the pilot feed. This correlated with Phase 2 having less incoming bromide (~132 ug/L) than during Phase 1 (~176 ug/L). This bromide discrepancy could be due to differences in raw wastewater qualities during pre and post pandemic time periods. As expected, bromate broke through quickly during GAC treatment near or above the federal drinking water MCL of 10 ug/L. Bromate formation mitigation strategies (i.e., in-situ hydrogen peroxide or chloramination before ozonation) would be necessary to minimize the formation of bromate during ozonation.

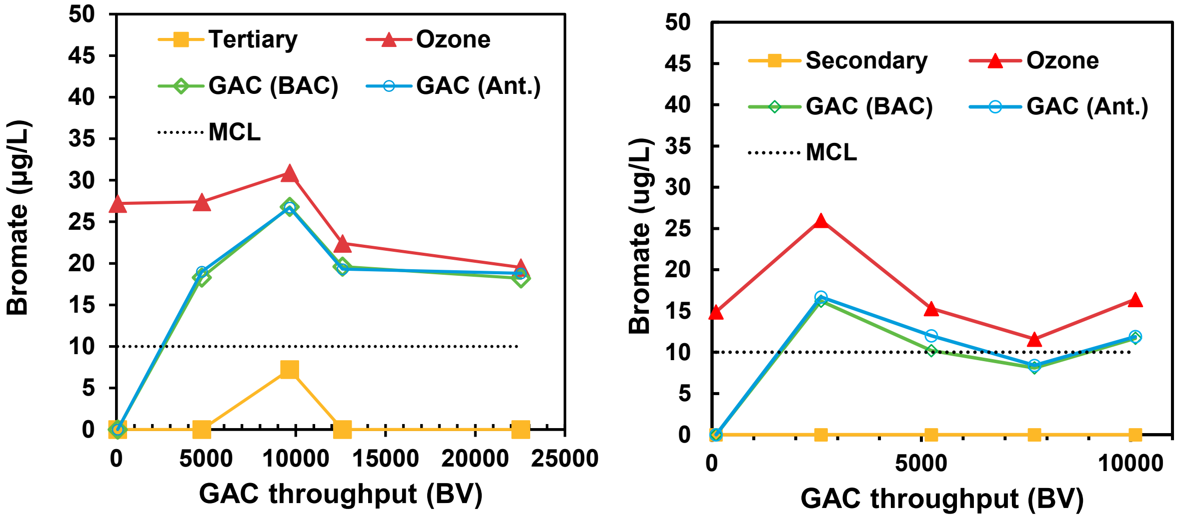


Figure 15. Bromate concentrations over time during O3/BAF/GAC treatment for Phase 1 (left) and Phase 2 (right).

Summary

- Note, Phase 2 was during the SARS-CoV-2 virus pandemic, whereas, Phase 1 was pre-pandemic, thus the raw wastewater and full-scale secondary treated wastewater qualities may have changed during the pandemic. For example, lower than expected DOC and bromide levels and higher than expected SUVA were observed in the pilot influent (secondary treated effluent) during Phase 2.

Finished Water Quality

- The ozonation process was the main barrier for most TOrCs.

- NDMA formed during ozonation was consistently removed by both parallel BAC and anthracite biofilters below California’s 10 ng/L notification level.

- GAC treatment was effective towards treating TOrCs detected after biofiltration (i.e., TCEP; Figure 16).
    - GAC had good removal of sucralose, although sucralose had the highest TOrC concentration in the GAC effluent, due to its comparably high initial concentrations, 50,000-60,000 ng/L, in the pilot feeds and GAC influents.
    - GAC was also effective towards DEET, meprobamate (Figure 16), primidone and sulfamethoxazole, although ***low*** levels were detected post GAC treatment.
    - The longer chain PFAS, i.e., PFOA (Figure 16) and PFOS, were removed more effectively by GAC than shorter chain PFAS, such as PFPnA (Figure 16) and PFHxA, though all the measured PFAS were below the most stringent U.S. state MCLs.

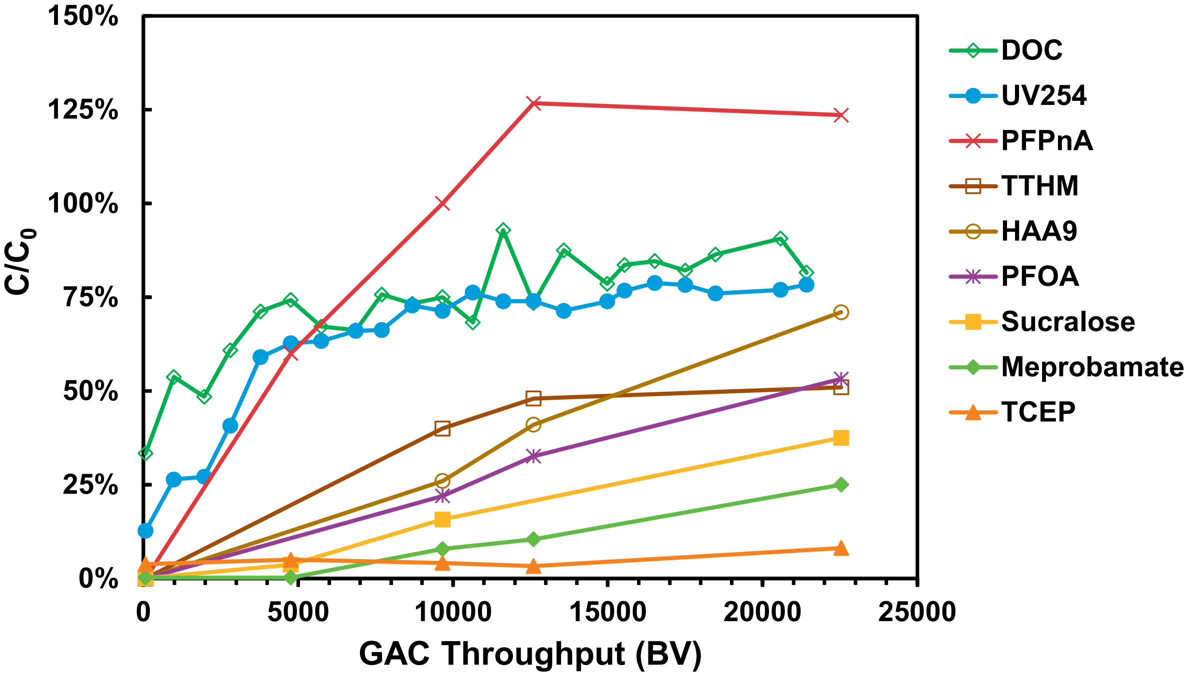


Figure 16. Comparison of breakthrough profiles of DOC, UV254, TTHM and HAA9 and TOrCs for the GAC following BAC for Phase 1.

- HAA5 formation after chlorination of GAC effluent remained less than the federal MCL of 60 µg/L for Phases 1 (<22, 000 BV) and 2 (<10,000 BV)

- NDMA formation after chloramination of GAC effluent remained below 2.9 ng/L, indicating chloramine-reactive precursors were removed during both pilot phase studies.

Potential Water Quality Concerns:

- GAC was less effective towards 1,4 dioxane and NMOR, polar and smaller sized organic compounds compared to the other TOrCs. The persistency of these compounds means the application of downstream processes, such as UV-advanced oxidation processes (UV-AOPs), might be necessary.

- Bromate formed during ozonation broke through quickly during GAC treatment near or above the federal drinking water MCL of 10 ug/L. Bromate formation mitigation strategies (i.e., in-situ hydrogen peroxide or chloramination before ozonation) might be necessary to minimize the formation of bromate during ozonation.

- TTHM formation after chlorination of GAC effluent exceeded the federal MCL of 80 µg/L after 10,000 BV during Phase 1 and it was near the MCL after 7,000 BV during Phase 2. Pretreatment with coagulation might be necessary to remove large molecular weight, UV-absorbing compounds within the effluent organic matter.

- HAA9 formation, that includes more brominated HAAs, after chlorination of GAC effluent could be a concern considering USEPA's recent attention to this class of emerging DBPs in drinking water.

- Nitrate concentrations in both secondary (Phase 2) and tertiary (Phase 1) effluents and the product water of the pilot trains were greater than the federal drinking MCL of 10 mg/L because the full-scale secondary treatment was not optimized for denitrification as it had no mixed liquor return.

Water Quality Operational Impacts

- The tertiary effluent exhibited a lower turbidity value (0.5 NTU) due to the full-scale filtration process, which reduced the frequency of backwashing for the BAC and BAF (with anthracite) filters.

- The SUVA values for the biofilter effluents (GAC influents) were higher during Phase 2 than for Phase 1 (Figure 3), which likely attributed to a higher fraction of aromatic/hydrophobic organic matter that preferentially adsorbed to GAC and out competing the TOrC (i.e., pharmaceuticals, PFAS) compared to Phase 1.

APPENDIX D

Rio Rancho Pure Advanced Water Treatment Facility Efficiency Study

Rio Rancho Water Utilities
Rio Rancho Pure

ADVANCED WATER TREATMENT FACILITY EFFICIENCY STUDY

FINAL | February 2022

RioRancho
City of Vision

Rio Rancho Water Utilities
Rio Rancho Pure

Advanced Water Treatment Facility Efficiency Study

FINAL | February 2022

ANDREW T. SALVESON

2/1/2022

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Tables

Figures

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Abbreviations

µg/L	micrograms per liter
abs	absorbance
AWTF	Advanced Water Treatment Facility
BAC	biologically activated carbon
Carollo	Carollo Engineers
CEC	contaminant of emerging concern
CWRF	Cabezon Water Reclamation Facility
DBP	disinfection byproduct
DDW	Division of Drinking Water
DOC	dissolved organic carbon
EBCT	empty bed contact time
G	grams
GAC	granular activated carbon
gpm	gallons per minute
gpm/sq ft	gallons per minute per square foot
H_2O_2	hydrogen peroxide
HAL	health advisory level
L	liter
LRV	log removal value
MBR	membrane bioreactor
MCL	maximum contaminant level
MG	million gallons
mg/L	milligrams per liter
mg-min/L	milligram - minute per liter
MRL	method reporting limit
N	nitrogen
ND	non-detect
ng/L	nanograms per liter
NH_3	ammonia
NL	notification level
nm	nanometers
NMED	New Mexico Environment Department
NO_2	nitrite
NO_3	nitrate
NTU	nephelometric turbidity unit
O_3	ozone

PFAS	per- and polyfluoroalkyl substances
PFCA	perfluorinated carboxylic acid
PFHxA	perfluorohexanoic acid
PFHxS	perfluorohexanesulfonic acid
PFNA	Perfluorononanoic acid
PFOA	perfluorooctanoic acid
PFOS	perfluorooctanyl sulfonate
PG/mL	picograms per milliliter
RRWU	Rio Rancho Water Utilities
TCEP	Tris(2-carboxyethyl)phospine
TOC	total organic carbon
USEPA	U.S. Environmental Protection Agency
UV	ultraviolet
UVA	ultraviolet absorbance
UVT	ultraviolet transmittance
WRF	Water Research Foundation
WWTP	wastewater treatment plant

EXECUTIVE SUMMARY

Rio Rancho Pure was a groundbreaking project in New Mexico (being the first and only potable reuse system in the state) and nationally due to the Advanced Water Treatment Facility (AWTF) use of membrane bioreactor (MBR), ozone (O_3) with hydrogen peroxide (H_2O_2), and biologically active carbon (BAC) filtration ahead of groundwater injection. Since construction of this facility, the engineering industry has made large knowledge gains regarding optimized control of O_3/BAC based purification systems, continuously tracking total organic carbon (TOC) concentrations in the feed to the system and controlling the transferred O_3 dose based upon a target O_3:TOC ratio. This new thinking results in robust virus disinfection, minimal bromate formation, less O_3 use, and no H_2O_2 use.

In 2019, Carollo Engineers (Carollo) was hired to evaluate the AWTF system, focusing upon the O_3 process but also examining the upstream (MBR) and downstream (BAC) processes. **The specific goals** were to optimize the O_3 dose and the O_3/BAC process in order to minimize formation of disinfection by-products (DBP), achieve significant reduction of contaminants of emerging concern (CEC) and provide robust removal of virus. An O_3:TOC based dose control approach must take into consideration other parameters that exert an initial O_3 demand. In particular, the O_3 demand of nitrite is about 3.43 grams-O_3 per gram of NO_2-N. Thus, the presence of nitrite can have a large impact on overall ozone dose control and efficiency.

The results of this study indicate:

- **Ozone Performance:**
  - Nitrite (NO_2) concentrations in the MBR effluent were high during the 2019 testing, dramatically impacting O_3 performance, essentially to the point eliminating the effectiveness of O_3.
  - Variable MBR water quality (TOC and NO_2) in 2019 were due to operational challenges at the Cabezon MBR, which was later remediated by staff. Both TOC and NO_2 values were low and stable in the 2020 and 2021 testing.
  - O_3 dose correlated with changes in ultraviolet transmittance (UVT, indicates water clarity) and changes in bromate formation, but must be adjusted for TOC and NO_2 concentrations to have reliable dose/response. Delivered O_3 dose alone does not predict bromate formation nor does it predict chemical or virus destruction capability.
  - The O_3:TOC ratio (after accounting for NO_2), referred to in this report as the "O_3:(TOC + NO_2) ratio", directly correlates with bromate formation, virus inactivation, UVT change, and chemical destruction.
  - Bromate formation begins at an O_3:(TOC + NO_2) ratio of ~0.5 but does not exceed the maximum contaminant level (MCL) of 10 micrograms per liter (µg/L) until the ratio exceeds 0.9 (based upon bench work)., However, full scale testing saw bromate rise to only 7.3 µg/L at an O_3:(TOC + NO_2) ratio of 1.1.

  - The addition of H_2O_2 fully mitigates bromate formation, which is well understood by AWTF staff. However, the work in this report documents that with proper control of O_3:(TOC + NO_2) ratio, H_2O_2 is not needed.
  - Destruction of trace chemicals (e.g., pharmaceuticals) is robust over the range of O_3:(TOC + NO_2) ratios, noting that higher ratios result in greater chemical destruction.
  - Monitoring UVT can be used to track system operation and anticipated performance.
  - **Bottom Line:** O_3 is a very effective oxidant for destruction of chemical pollutants, but variable concentrations of TOC and NO_2 substantially impact efficacy. Bromate formation can be mitigated through the use of the O_3:(TOC + NO_2) ratio eliminating the need for H_2O_2 addition and providing robust virus disinfection.
- **2020 Water Quality Monitoring Studies:**
  - The installation of online monitoring for TOC, nitrate (NO_3), and NO_2 in the MBR effluent provides for critical monitoring of the key water quality parameters that impact O_3. Continued focus upon calibration of these probes is important to gain best value from the data.
  - Grab sampling of water quality at the MBR effluent and at the AWTF (5 miles away) indicates:
    - There is little change in TOC and NO_3.
    - While one data set shows a measurable increase in NO_2 from the MBR to the AWTF, three other data show a small reduction of NO_2.
    - Ammonia (NH_3) appears to reduce from the MBR to the AWTF.
  - **Bottom Line:** Continued focus upon calibration of these probes is important to gain best value from the data. In particular, because of the outsized impact of NO_2 on O_3 performance, confidence in online NO_2 levels remains a critical item to address for the AWTF.
- **2020 & 2021 Full Scale AWTF Testing:**
  - Baseline Testing:
    - High NO_2 concentrations surfaced again during baseline testing, exerting an O_3 demand of almost 6 milligrams per liter (mg/L), which is essentially renders the O_3:(TOC + NO_2) ratio to close to zero and results in no oxidation or disinfection potential for O_3.
    - Reduction of TOC across the BAC is ~30 to ~40 percent, which is within expectations for BAC performance.
    - Reduction of trace chemical pollutants across the full-scale O_3 process is much reduced compared to bench scale testing where there was little to no NO_2. When NO_2 is not present, or when NO_2 is accounted for in dosing, full-scale performance is much improved.
    - Reduction of trace chemicals pollutants across the full-scale BAC is substantial, providing an important backup to O_3 performance.
    - Examination of per- and polyfluoroalkyl substances (PFAS) indicate:
      - Perfluorooctanoic acid (PFOA) and perfluorooctanyl sulfonate (PFOS) levels are below the 70 nanograms per liter (ng/L) U.S. Environmental Protection Agency (USEPA) health advisory limit (HAL);
      - PFOA levels **above** the California notification level (NL) of 5.1 ng/L and the Illinois HAL of 2 ng/L.

  - Testing with new granular activated carbon (GAC) installed in the full-scale BAC filters:
    - TOC reduction is initially much improved compared to the Baseline Testing but degrades with time as carbon adsorption sites are exhausted and the GAC transitions into BAC.
    - UVT increases across both the O_3 process and the BAC process, which is the anticipated result.
  - The data on trace chemical reduction, comparing the baseline with the new GAC data sets, indicates:
    - The baseline chemical oxidation performance was significantly worse compared to the other data, mostly likely due to the high NO_2 concentration in November 2020.
    - The last sampling event, 1/19/21, had a small concentration of NO_2, and some of the oxidation performance is reduced compared to the two sample dates with no NO_2.
    - The baseline chemical removal by the BAC is measurably less than seen by the new BAC, indicating the improved performance of the new BAC due to a combination of carbon adsorption and biodegradation.
    - There does not appear to be a reduction in BAC performance as the BAC transitions from adsorption to biodegradation.
  - PFAS data was also collected for the new GAC. This data indicates:
    - The old BAC had very little PFAS removal capability, presumably due to loss of all adsorption sites.
    - The new BAC provided robust removal of several PFAS, but that removal reduced with time. For example:
      - PFOA reduction values decreasing with time (95%, 90%, 75%)
      - Perfluorinated carboxylic acid (PFCA) reduction values decreasing with time (56%, 38%, 22%)
      - Perfluorohexanoic acid (PFHxA) reduction values decreasing with time (77%, 71%, 45%)
    - Related to regulatory guidance or regulated values:
      - PFOA and PFOS levels are below the 70 ng/L USEPA HAL;
      - PFOA levels **above** the California NL of 5.1 ng/L and the Illinois HAL of 2 ng/L for the last sampling date with the new GAC (1/19/21).
  - **Bottom Line:** NO_2 continues to be a challenge, but only periodically. Maintaining low NO_2 levels in the MBR effluent is critical to efficient and effective performance of the AWTF. PFAS presents a challenge, in particular after the carbon installed in the BAC contactors transitions from an adsorptive process to a biodegradation process. PFAS levels, as of the last sampling date, are below the USEPA HAL, but above regulated and advisory levels in other states.
- **2021 Full-scale Modifications Testing:**
  - A final series of chemical testing was completed at the full-scale, with the H_2O_2 system was **OFF** for all of the testing documented below. This work was intended to provide proof of O_3 treatment performance, including bromate minimization and trace chemical destruction at lower O_3:(TOC + NO_2) ratios with no H_2O_2 use, a more energy and chemically efficient approach to purification.

  - For the testing, MBR effluent was high quality with TOC values <5 mg/L and non-detect (ND) NO_2 (<0.1 mg/L).
  - O_3 increased UVT from ~77 to 81 to 83 precent, which is precisely within what was determined in bench-scale testing to be the proper range for disinfection and advanced oxidation without exceeding bromate MCL concentrations.
  - Bromate levels were ND (<5 µg/L) at O_3:(TOC + NO_2) ratios of ~0.6 and ~0.8 but was detected at 7.3 µg/L at a ratio of ~1.1. These results match bench-scale results (refer to Figure 3.7) and hypothesized results for full-scale.
  - O_3 continues to be very effective in the destruction of trace chemical pollutants, with increased performance as O_3:(TOC + NO_2) ratios increase. Notable exceptions where O_3 was not effective were for:
    - Caffeine
    - Sucralose
    - Tris(2-carboxyethyl)phospine (TCEP)
  - **Bottom Line:** With proper control and monitoring of an O_3:(TOC + NO_2) based control system, H_2O_2 can be turned off, allowing for robust chemical destruction while maintaining bromate less than the MCL. The potential O_3:(TOC + NO_2) ratio of 0.8 should be more repeatedly examined through more full-scale testing.
- **2021 Ozone Disinfection Testing**
  - MBR effluent samples were collected and tested with bench-scale O_3 equipment, demonstrating robust (5-log) virus reduction using the O_3:(TOC + NO_2) ratios.
  - Results match other research from around the US, documenting that robust disinfection of virus by O_3 can occur without an O_3 residual, which minimizes bromate formation.
  - **Bottom Line:** The O_3 system is a robust virus barrier **IF** TOC and NO_2 are properly accounted for in the dose/response control system. The current control system does not account for either of these parameters and during some water quality conditions virus disinfection is low.

Overall Conclusions

The extensive testing documented in this report demonstrate the robust chemical and disinfection performance of an O_3 and BAC treatment system, but also note significant vulnerabilities in performance of the O_3 system (due to spikes in TOC and NO_2) and the BAC (due to passage of PFAS). These results also show that, with proper control of the ozone system, and not using any H_2O_2, the O_3 process will provide robust destruction of trace chemical pollutants and virus inactivation and not exceed the 10 µg/L bromate MCL. To be clear, the "proper" control of the O_3 system is using O_3:(TOC+ NO_2) ratios in the 0.8 to 1.0 range, preferably in the 0.8 range until further data is generated. Further, such "proper" control relies heavily upon the online monitoring of both TOC and NO_2, and the accuracy of those two analyzers. These results also continue to show the benefit of BAC to water quality, working with the O_3 process to provide broad spectrum reduction of chemical pollutants. Last, these results demonstrate that BAC is not a robust barrier to PFAS, with a particular focus on PFOA and PFOS. GAC is a robust barrier to these two chemicals, which can be utilized downstream of BAC if deemed necessary by Rio Rancho.

Chapter 1

OVERVIEW

1.1 Rio Rancho Pure

Rio Rancho Pure (Rio Rancho Water Utilities', or RRWU's potable reuse system) represents a critical first potable reuse project in New Mexico and the first ozone/biologically activated carbon (O_3/BAC) system nationally used for purification and groundwater recharge. The Advanced Water Treatment Facility (AWTF) project utilizes a membrane bioreactor (MBR) at the Cabezon Water Reclamation Facility (CWRF), followed by O_3/BAC purification at Reservoir 3, which includes the groundwater recharge facilities. This system, MBR, O_3, BAC, provides for multiple barriers for pathogens and chemical pollutants and meets all New Mexico Environment Department (NMED) Standards. A process flow diagram for the CWRF and AWTF is shown in Figure 1.1. Note that the facilities are separated by 5.5 miles of pipeline and several storage tanks.

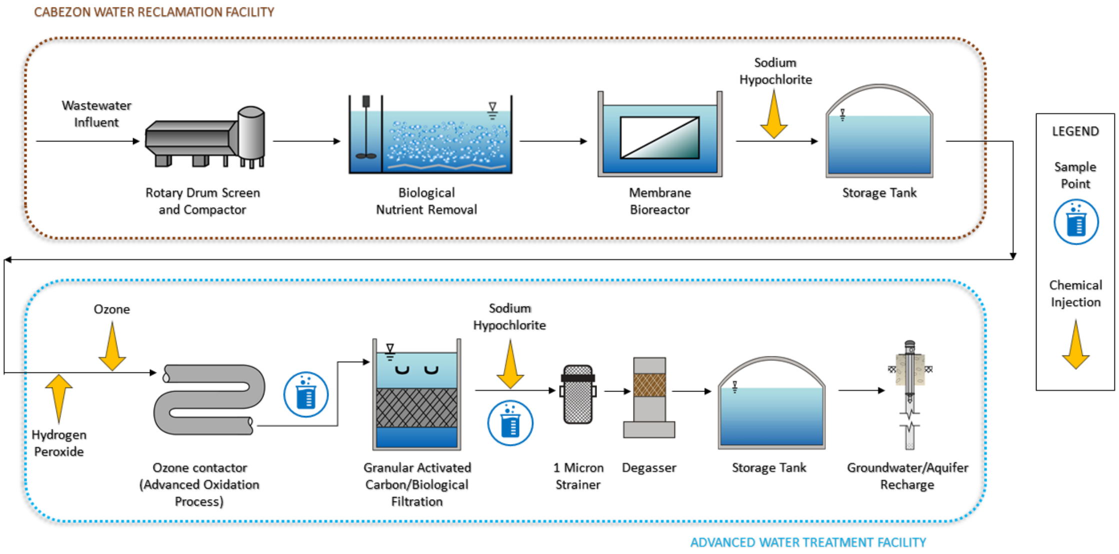

Figure 1.1 Process Flow Diagram showing Cabezon WRF and the AWTF

1.1.1 Project Goals

Since construction of this facility, the engineering industry has made large knowledge gains regarding optimized control of O_3/BAC based purification systems, continuously tracking total organic carbon (TOC) and nitrite (NO_2) concentrations in the feed to the system and controlling the transferred O_3 dose based upon a target O_3:(TOC+ NO_2) ratio.

The goal of this project is to optimize the O_3 dose and the O_3/BAC process such as to minimize formation of disinfection byproducts (DBP), achieve targeted concentration of contaminants of emerging concerns (CEC) and targeted log removals. Using the O_3:(TOC+ NO_2) ratio robust virus disinfection has been shown at ratios of 0.6-1.0 milligrams per liter (mg/L) O_3 per mg/L TOC (Salveson and Fontaine [2014] and Salveson and Fontaine [2015]). In order to develop an dose control approach, it is also important to understand other parameters that exert an initial O_3 demand. In particular, the O_3 demand of NO_2 is about 3.43 grams-O_3 per gram of NO_2-N. Thus, the presence of NO_2 can have a large impact on overall O_3 dose control.

1.1.2 Project Collaboration

This project began in 2019 as a directly funded effort by Rio Rancho, with the information to be shared with the Water Research Foundation (WRF) Project 4833 as an in-kind contribution. Project 4833 is an evaluation of the impacts of different types of wastewater treatment plant (WWTP) effluent quality on downstream advanced purification for potable reuse. One task within the project was to examine the combined performance of MBR with O_3 and BAC. Late in 2020, funding from Project 4833 was allocated to the Rio Rancho effort, substantially expanding the scope of work and overall project benefit.

Chapter 2

2019 RESULTS

For this analysis, it is important to fully understand the significant impact of TOC and NO_2 on O_3 performance. Prior thinking on O_3 for wastewater disinfection focused upon the CT concept, with the State of California Division of Drinking Water (DDW) granting 5 log removal value (LRV) of virus for O_3 disinfection based on a minimum CT of 1.0 milligram - minute per liter (mg-min/L) (Ishida et al., 2008). WE&RF Project 11-02 (Trussell et al., 2016) documented similar virus inactivation to Ishida et al., (2008) but defined virus dose/response as a function of transferred O_3 dose to TOC ratios (O_3:TOC). This finding is also detailed in Fontaine and Salveson (2014). This work consistently demonstrated 7+ LRV of seeded MS2 bacteriophage for O_3:TOC ratios of 1.0 and greater. Such LRV of MS2 bacteriophage is conservatively equivalent to 5 LRV of poliovirus and a broad range of other enteric virus (Ishida et al., 2008, Fontaine and Salveson, 2014). Recent work by Wolf et al (2019) found a relationship between O_3:dissolved organic carbon (DOC) ratio and O_3 exposure. Wolf et al. (2019) also found a strong correlation between O_3:DOC ratio and inactivation of both MS2 bacteriophage and coxsackievirus B5 in two surface waters and one secondary wastewater effluent. A strong correlation was also seen between O_3:DOC ratio and log abatement of ultraviolet absorbance (UVA) at 254 nanometers (nm), and a predictive relationship between UVA reduction and log virus inactivation was modeled (Wolf et al. 2019). An extensive ozone "validation" for virus reduction is found in Fontaine and Salveson (2015), in which a broad range of dose, contact time, and O_3:TOC ratios were tested for virus reduction, with results matching the previously listed research projects, but also critically noting the potential impact of nitrite (NO_2) on O_3 demand (the O_3 dose in the O_3:TOC ratio is a transferred O_3 dose and the ratio should be adjusted for NO_2 concentration).

The industry has now demonstrated that O_3 performance is based upon the O_3:TOC ratio, with ratios in the range of 0.6 to 1.0 necessary for optimum disinfection and chemical destruction performance. NO_2 in water also exerts an O_3 demand. Therefore, TOC and NO_2 are critical parameters in determining the O_3 dose.

2.1 Water Quality and Bench Scale Testing

The first phase of work, completed in 2019, was an examination of water quality followed by some bench-top dose/response testing. Challenges were encountered regarding inconsistent detection of NO_2, the variable TOC concentrations, and the impact of both of those on O_3 performance.

Initial bench-scale studies were conducted to evaluate the formation of bromate at varying O_3:(TOC+ NO_2) ratios, without the addition of hydrogen peroxide (H_2O_2).

- Samples were collected from a 2 million gallon (MG) concrete tank that gravity feeds into another tank right upstream of the AWTF.

- The concentration of O_3 required for bench scale study was determined by the formula Targeted Ratio[1]*TOC + 3.5*NO_2-N. In the first bench scale test, **NO_2 and TOC in the feed water was measured to be 2.15 mg/L-N and 5.89 mg/L** respectively.
- The concentration of NO_2 was higher than anticipated resulting in a higher O_3 dose delivered to obtain the targeted ratio. This resulted in bromate formation.
- A second bench scale test was conducted, and the feed water analysis showed elevated levels of **NO_2 and TOC, measured as 4.26 mg/L-N and 7.47 mg/L** respectively. Because of the high NO_2 and TOC values, a higher O_3 dose compared to the first bench scale test had to be delivered to the feed water. This resulted in bromate formation.

The 2019 results, presented in the figures and Table 2.1 below, suggest:

- NO_2 concentrations are significant and will impact O_3 performance. Variable NO_2 in the MBR effluent indicates some operational challenges with the upstream MBR;
- TOC levels are variable in the MBR filtrate, also indicative of variable secondary treatment performance;
- There is a linear and repeatable impact of O_3 dose on ultraviolet transmittance (UVT), which translates to a linear and repeatable impact of O_3 dose on dissolved organic matter in the water;
- Delivered O_3 dose alone does not predict bromate formation;
- O_3:(TOC+ NO_2) ratio has a linear and reliable impact on UVT;
- NO_2 reaction with O_3 was quantified, demonstrating the immediate demand on O_3; and
- O_3:(TOC+ NO_2) ratio and UVT post ozone both appear to correlate well with bromate formation.

Table 2.1 Key Water Quality Parameters for MBR Filtration During Initial Testing

Parameter	Test 1	Test 2
Nitrite, mg/L	2.18	3.74
Bromide, mg/L	140	150
TOC, mg/L	5.89	7.47
pH	6.92	7.39
Temp, degrees C	16.9	20.4

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[1] The Targeted Ratio is the targeted O_3:(TOC+ NO_2) ratio, which was varied over a broad range to best understand performance.

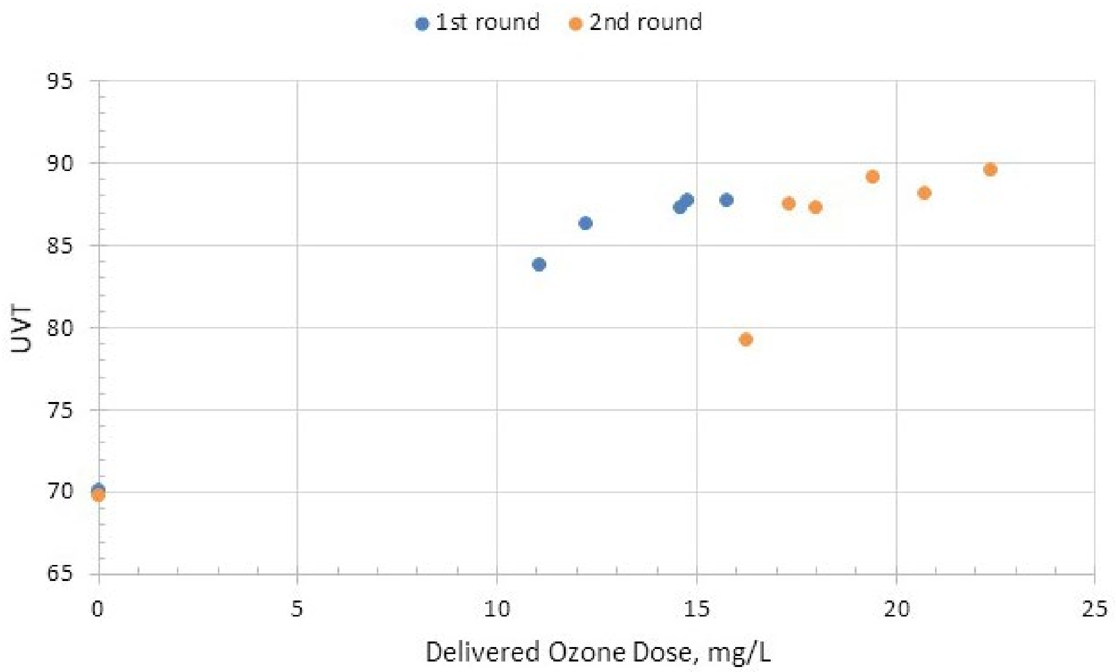

Figure 2.1 UVT as a Function of Delivered Ozone Dose

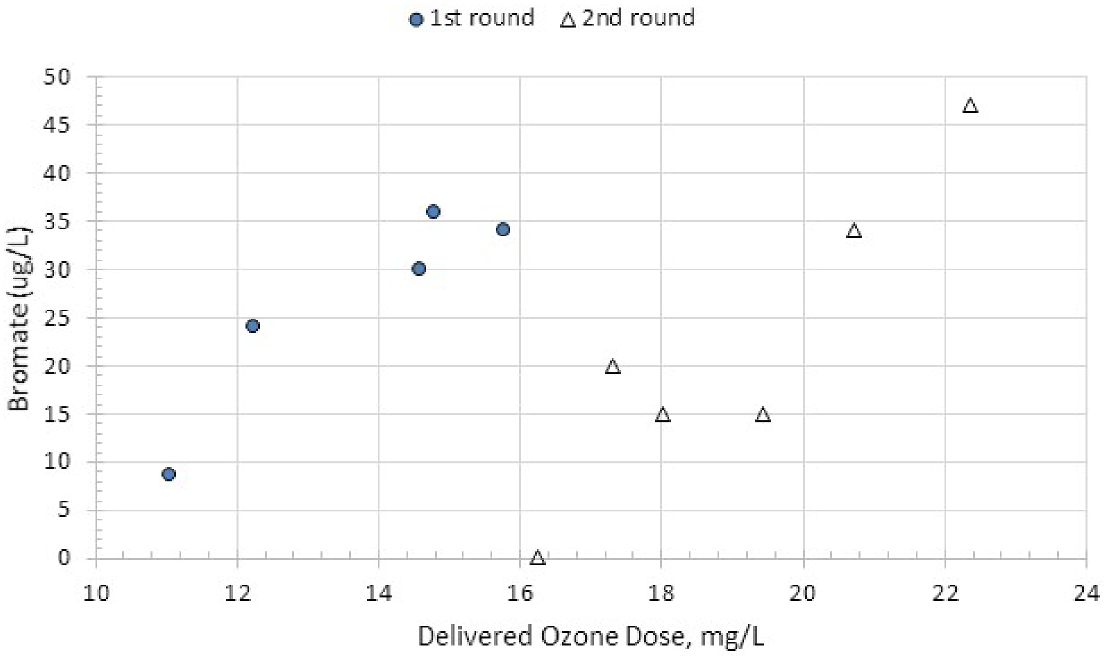

Figure 2.2 Bromate as a Function of Delivered Ozone Dose

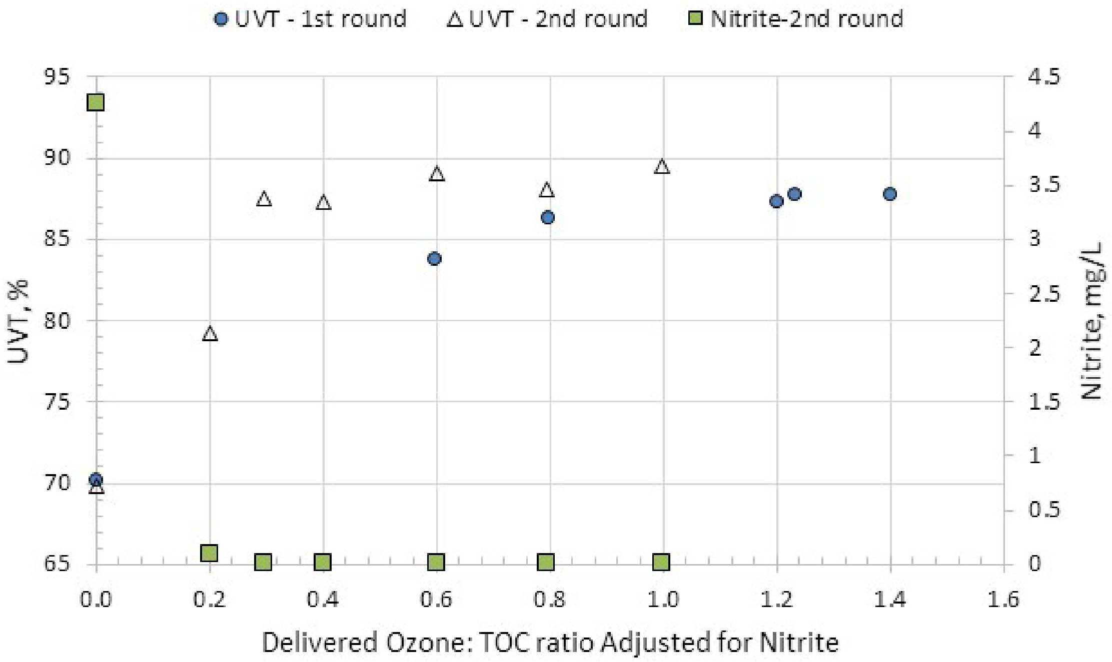

Figure 2.3 UVT and Nitrite as a Function of Delivered Ozone:TOC Ratio

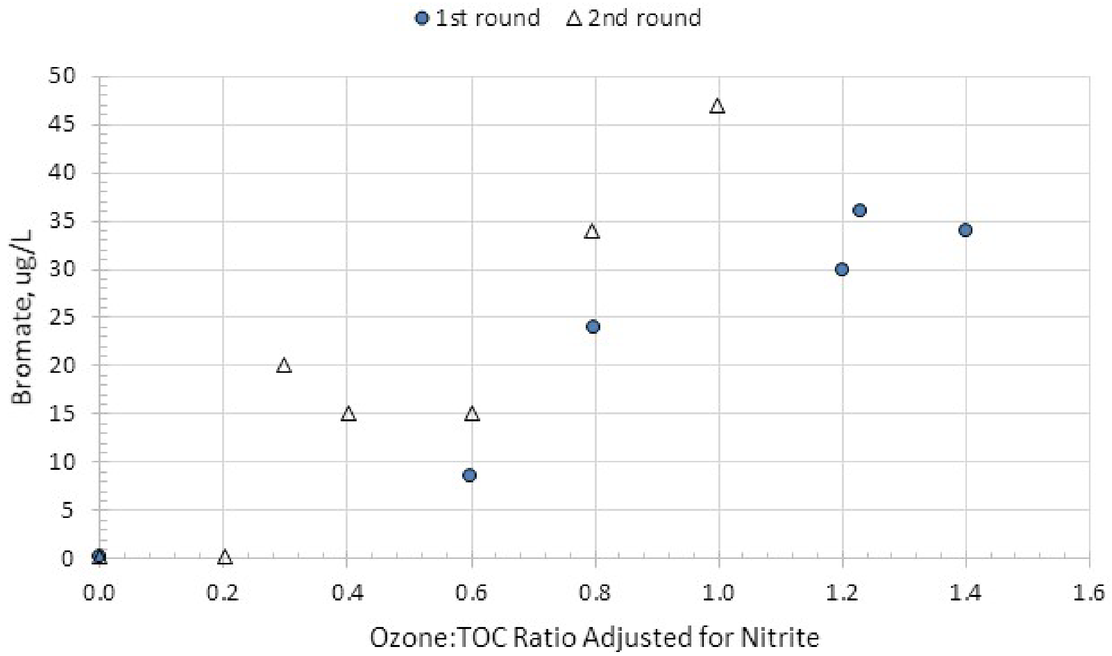

Figure 2.4 Bromate as a Function of Delivered Ozone:TOC Dose Ratio

2.2 Nitrite, TOC, and MBR Performance

The 2019 test results, though limited, pointed to the high and variable concentration of the two important constituents in the feed water (NO_2 and TOC) and their significant impact on the resulting O_3 residual and bromate. **These results demonstrated the need to step back and fully understand the variation in TOC and NO_2 in the MBR effluent**. To that end:

- Samples were collected and analyzed for ammonia (NH_3), NO_2, and nitrate (NO_3) at different locations prior to the AWTF feed.
- Effluent from the CWRF (Plant #6), effluent from a tank fed by CWRF effluent (Plant #6-booster station) and effluent from the tank directly feeding the AWTF (AWTF TI Tank) were sampled.
- Full results are displayed in Figure 2.5.
- Split samples were sent to two labs namely, Hall Environmental and California Laboratory and analyzed in house at the AWTF. Results from split sampling are shown in Figure 2.6. NO_2 was detected at 0.18 mg/L-N by one of the labs while it was ND at the two remaining labs. TOC was detected at 4.4 and 6.4 mg/L by two labs.

The work above, though limited, highlighted variable and abnormal water quality in the Cabezon MBR effluent. Plant staff at Cabezon subsequently evaluated and diagnosed operational problems, including leaking air in the system and two anoxic zone mixers that were not functioning. These problems have been corrected and the water quality is both improved and stable.

Rio Rancho installed a new s::can Spectro:Lyser[2] in the 3 MG tank that is immediately downstream of the Cabezon MBR. The Spectro:Lyser measures NO_2-N, TOC, NO_3-N, and UVA. Of these parameters, the NO_2, NO_3, and TOC are the most useful as they speak to the consistency of the water quality in the Cabezon MBR effluent. Details on the s::can probe are provided in Table 2.2.

Table 2.2 Detection Ranges of the Spectro:Lyser at the Cabezon MBR Effluent

Parameter	Spectro:Lyser Detection Range
Nitrate (NO_3-) as N, mg/L	0 - 50
Nitrite (NO_2-) as N, mg/L	0 - 10
Total Organic Carbon (TOC), mg/L	0 - 350

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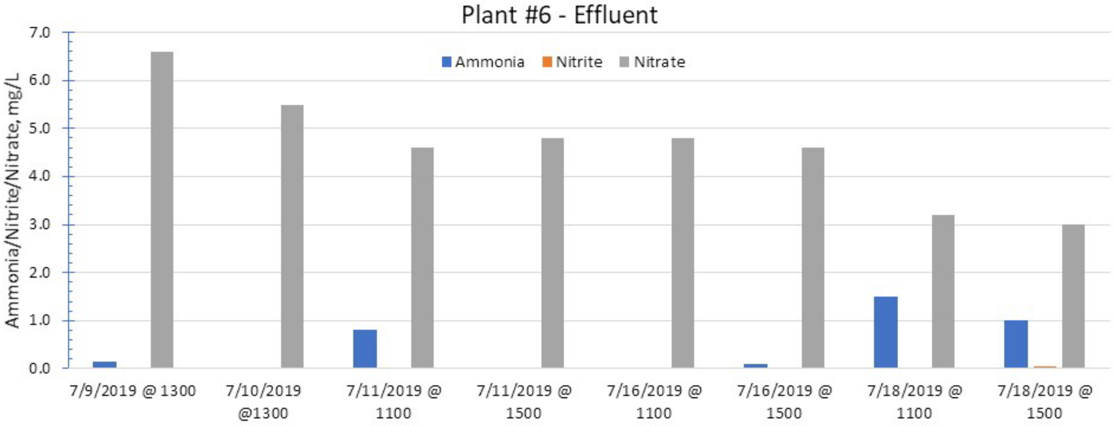
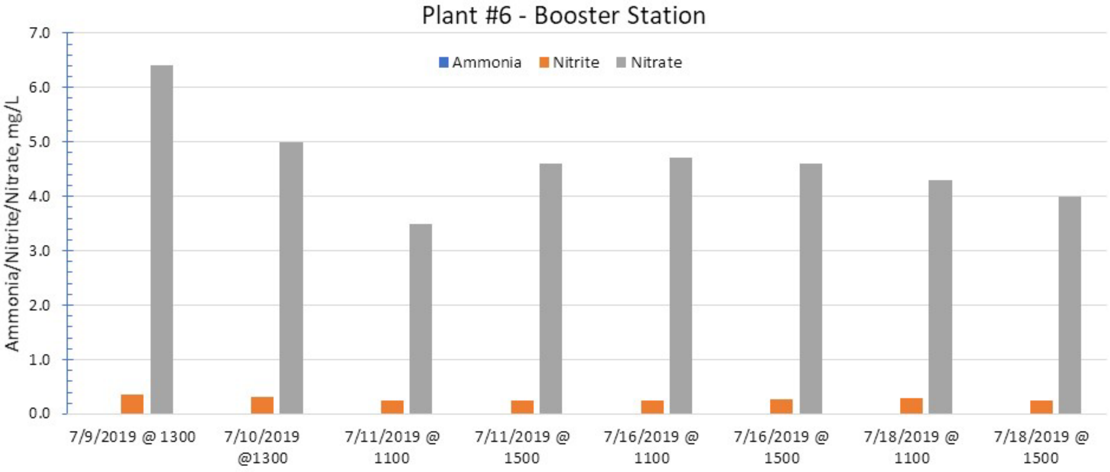
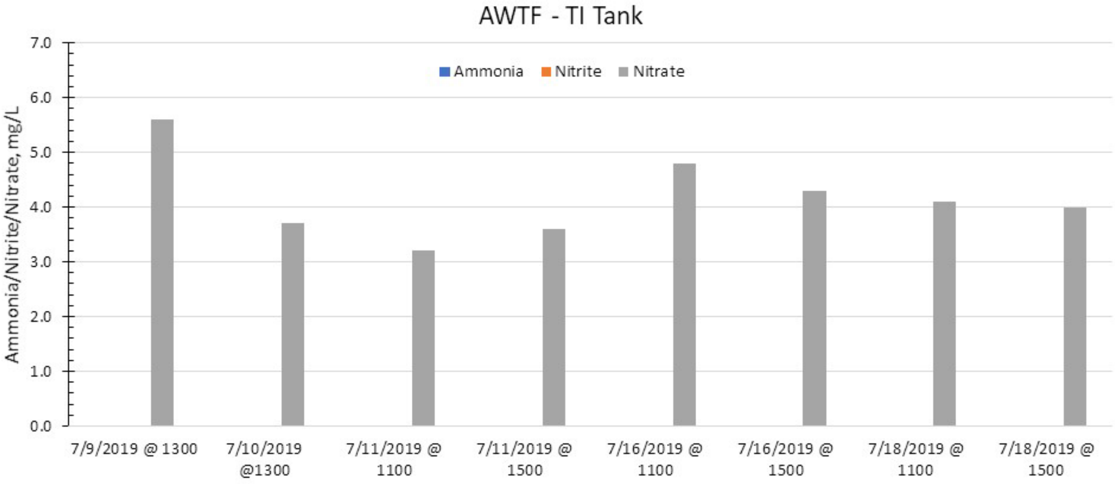
[2] Spectro:lyser^{TM} is an optical-based spectrophotometers that can measure wavelengths between 190 to 390 nm.



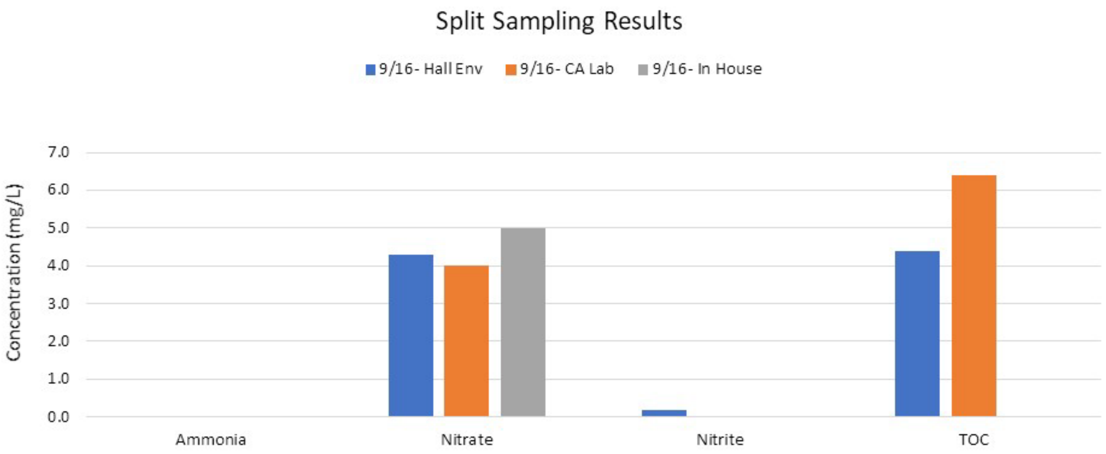


Note: This is Tank #3 Effluent. Booster station #6 pumps water 5.5 miles to Tank #2. Water from Tank #2 flows to AWTF Tank #1, as needed for injection. Water may sit in Tank #2 for up to another 3 days.



Note: Last tank into the AWTF - upstream of Ozone/BAC

Figure 2.5 Ammonia, Nitrite, and Nitrate Levels at Different Locations Prior to the AWTF



Note: Ammonia was analyzed as non-detect by all three labs
Nitrite was analyzed as non-detect by two labs
TOC was not analyzed in house

Figure 2.6 Results from Split Sampling for AWTF TI Tank Effluent

2.3 Online Monitoring Results

Figure 2.7, Figure 2.8, and Figure 2.9 contain a comparison of the Cabezon MBR effluent Spectro:Lyser data compared to samples analyzed by Hall Environmental Labs that were collected at the same time during each of the four sample events. The meter reading and the grab sample results were similar during the four sample events with the exception of NO_2. After discussions with s::can it appeared there may be a calibration issue or function check needed. This was corrected by Rio Rancho and s::can, and the latest data with those corrections is not included in this report.

Online data from September 2020 to August 10, 2021 of the Cabezon MBR effluent was compiled and evaluated, using a combination of Spectro:Lyser data at the Cabezon MBR and water quality sampling to evaluate the online meter accuracy. The online data was compiled based upon hourly average data. Four grab sampling events occurred at both locations as follows:

- Cabezon MBR Effluent at 3 MG Tank: sampling of TOC, NO_3, NO_2, UVT, and NH_3; and
- Feed to the AWTF sampled at the 2 MG feed tank at the AWTF site: sampling of TOC, NO_3, NO_2, UVT, and NH_3.

The four sample events occurred on November 2nd, November 10th, December 8th, and December 15, 2020. Figure 2.7, Figure 2.8, and Figure 2.9 contain the online data from September 2020 through August 2021. In October 2020 there were problems with the online meter drift. Before the meter was calibrated in October, the TOC reading was 2.63 mg/L and the grab sample analysis was 5.9 mg/L. Collection of grab samples and calibration of the meter were performed more frequently after that. During each subsequent calibration the meter was accurate within +/-19 percent of the grab sample with the majority of those samples being within +/-9 percent. In late November 2020 the data appears to indicate a process issue by the increase in TOC and NO_3, but plant staff checked performance and could not find a cause for this anomaly.

The online meter and calibration data suggests:

- The online TOC probe is reasonably accurate, and MBR effluent TOC values appear to be stable, averaging 5.3 mg/L.
- NO_3 values also appear stable, coinciding with the stability of the MBR effluent TOC. The online values match the trending of grab sample results but show some inaccuracy. Both online and grab sample results do indicate compliance well below the 10 mg/L (as N) NO_3 maximum contaminant level (MCL). Further improvements to probe accuracy through calibration are recommended.
- NO_2 values have some variability, and the accuracy compared to grab samples is poor. With that said, the NO_2 values are well below the MCL value of 1 mg/L (as N). Further improvements to probe accuracy through calibration are recommended. Last, the low level NO_2 concentration will impact available O_3, and Rio Rancho may want to consider how to adjust O_3 controls based upon an assumed low level NO_2 concentration.

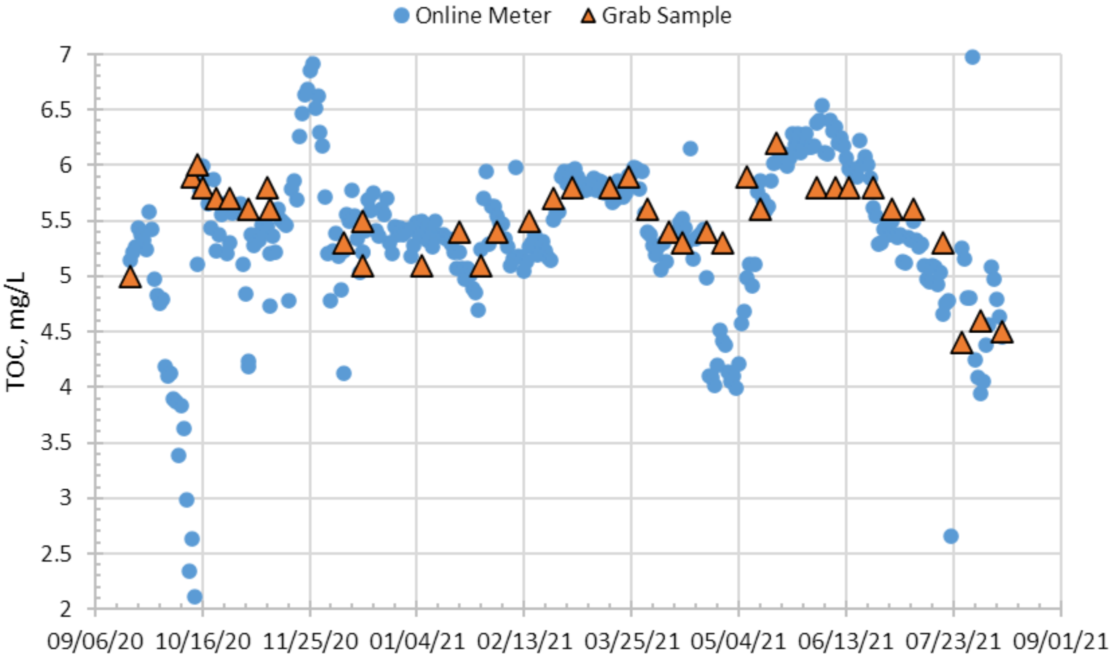


Figure 2.7 MBR Effluent Online TOC Data and Periodic Calibrations – September 2020 through August 2021

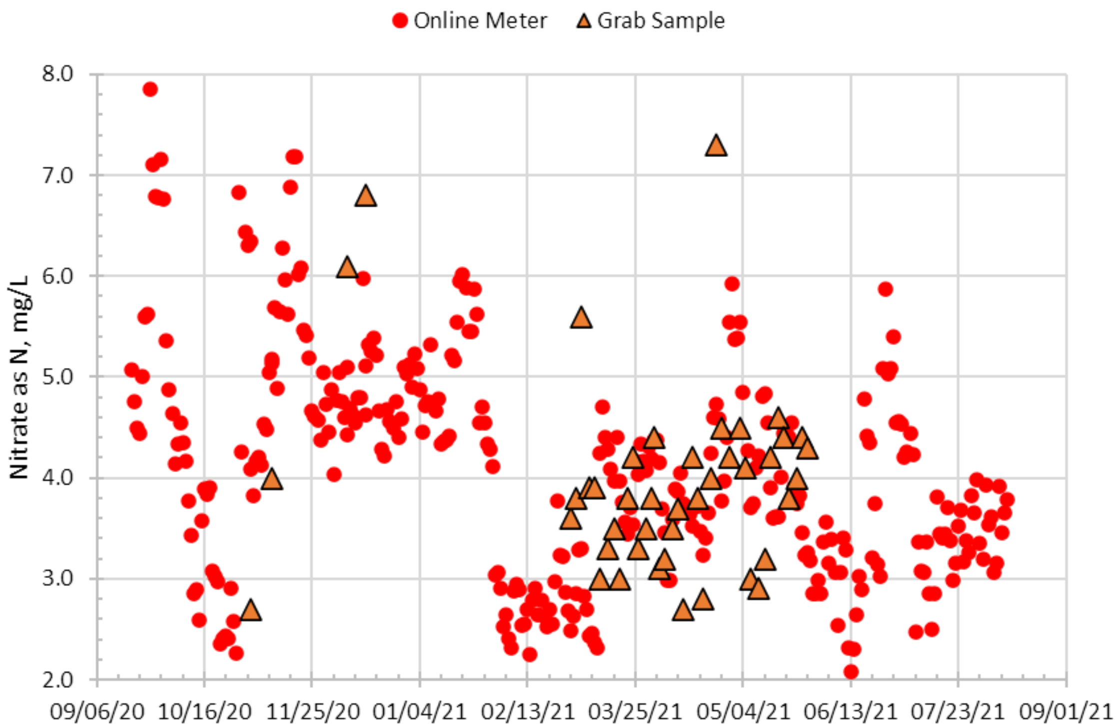


Figure 2.8 MBR Effluent Online Nitrate Data and Periodic Calibrations – September 2020 through August 2021

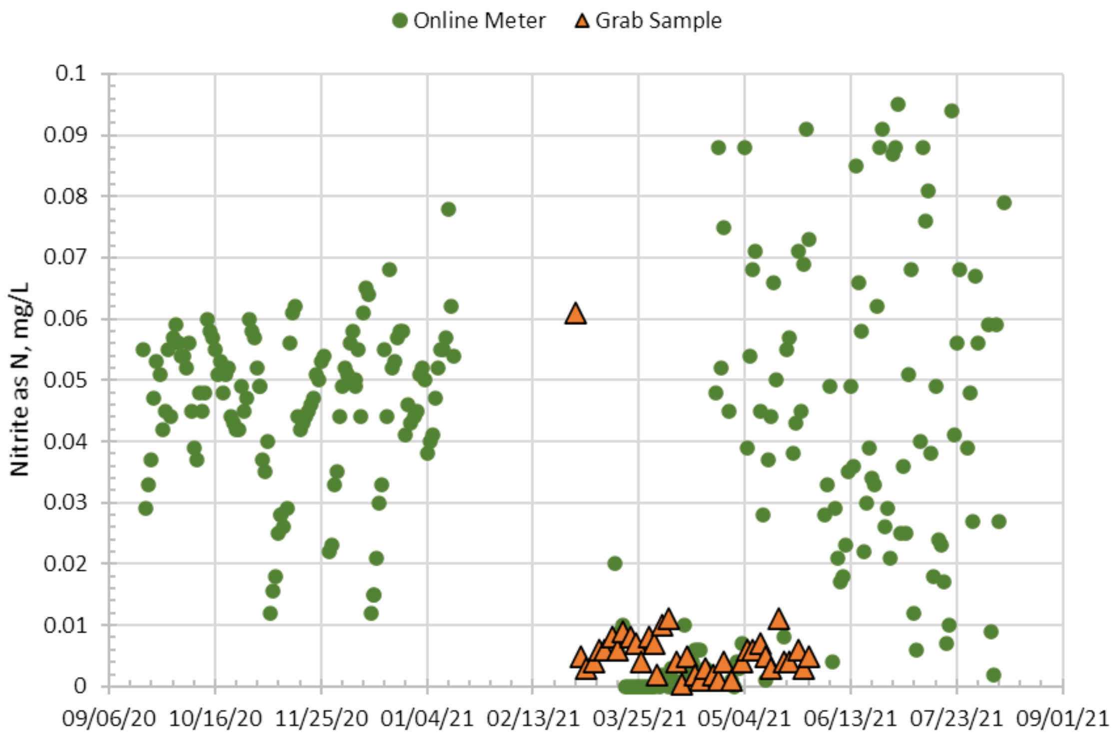


Figure 2.9 MBR Effluent Online Nitrite Data and Periodic Calibrations – September 2020 through August 2021

Figure 2.10 contains the online MBR turbidity from November 1, 2020 through January 24, 2021. The MBR process has three turbidimeters. Meter 6A measures the combined turbidity of the four oldest MBR trains, 6B measures the combined turbidity of four newer MBR trains, and 6C measures the turbidity of the single MBR expansion train.

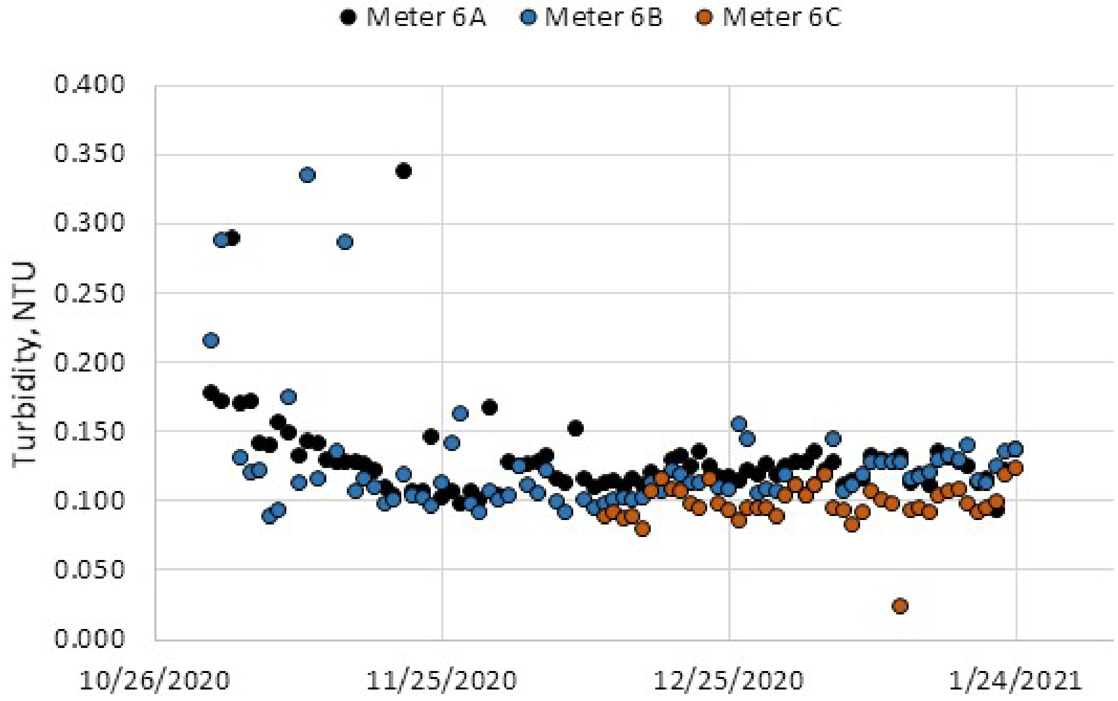


Figure 2.10 MBR Effluent Online Turbidity Data – November 2020 through January 2021

Further analysis was conducted to examine online measurements with contract and internal laboratory measurements. Two different locations were tested, one being at the Cabazon MBR and the other being 5 miles away at the AWTF. These different sample locations were evaluated to understand if there are water quality changes that happen during the 5-mile transport of water from the MBR to the AWTF (Figure 2.11 through Figure 2.14). The data indicates:

- There is little change in TOC and NO_3 during the 5-mile transport.
- While one data set shows a measurable increase in NO_2 from the MBR to the AWTF, three other data show a small reduction of NO_2.
- NH_3 appears to reduce from the MBR to the AWTF during the 5-mile transport.

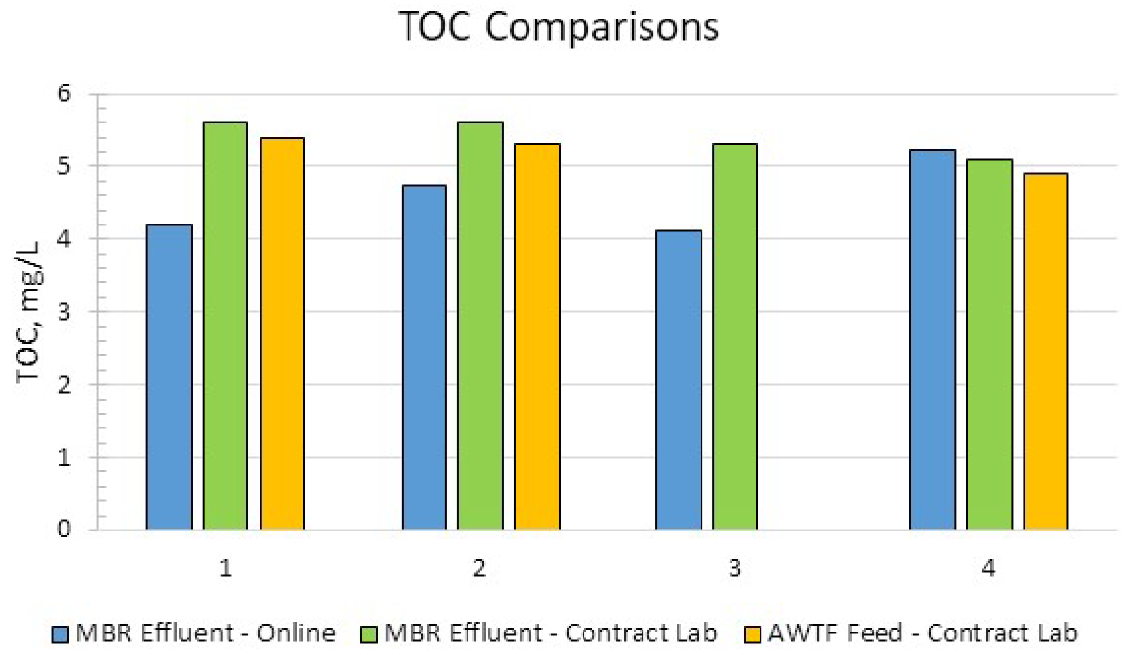


Figure 2.11 TOC Results Comparison Between Online and Grab Samples at Two Locations

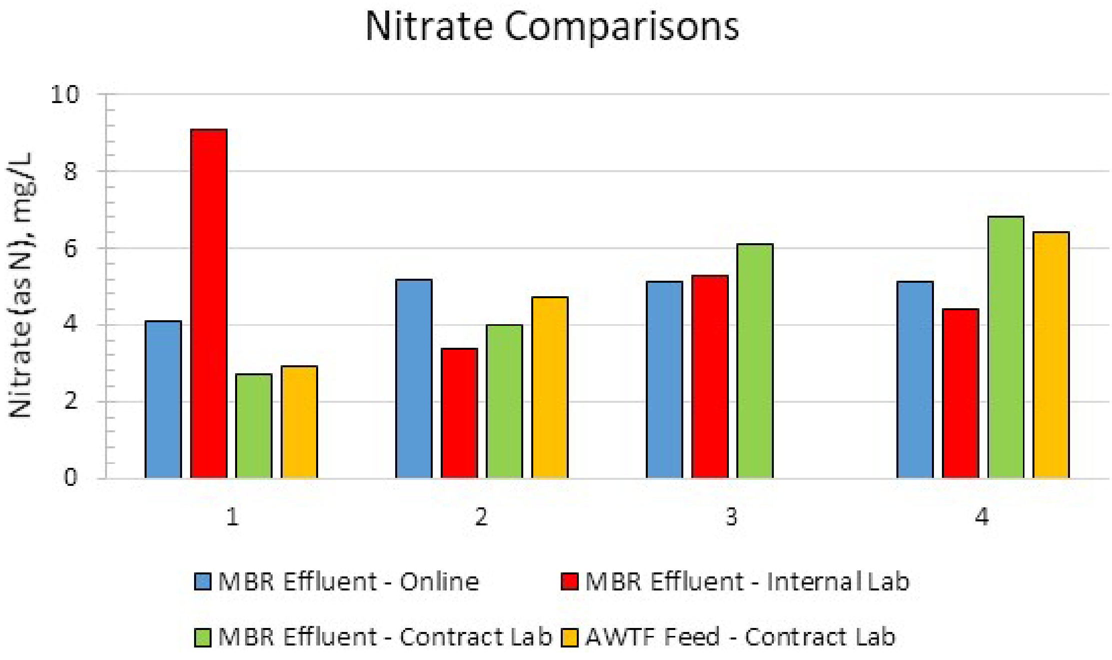


Figure 2.12 Nitrate Results Comparison Between Online and Grab Samples at Two Locations

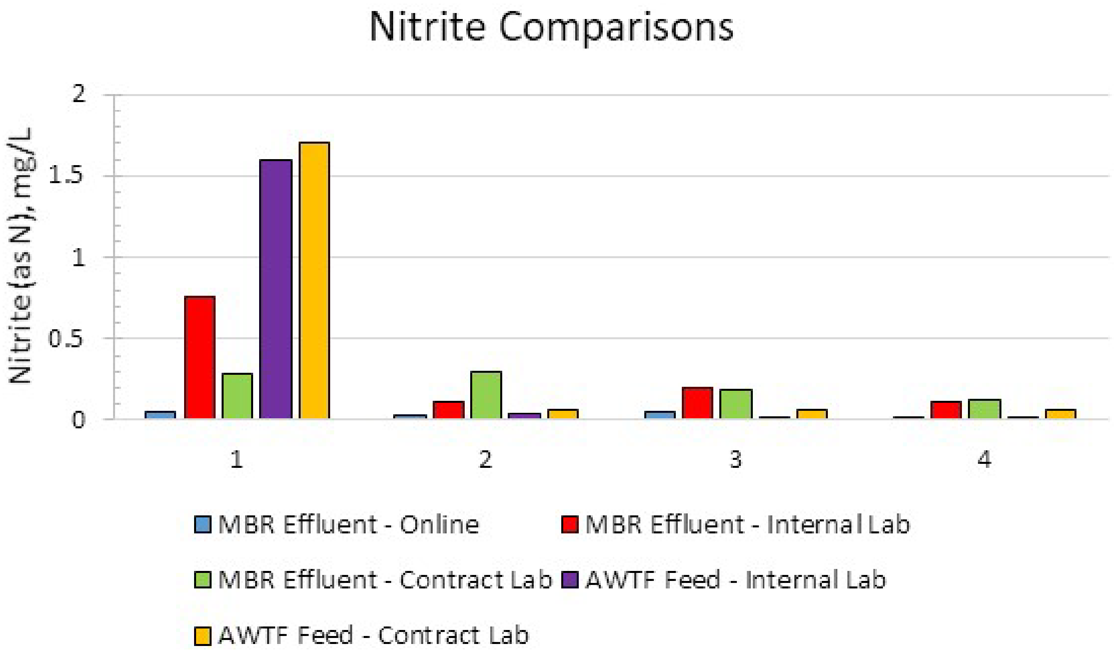


Figure 2.13 Nitrite Results Comparison Between Online and Grab Samples at Two Locations

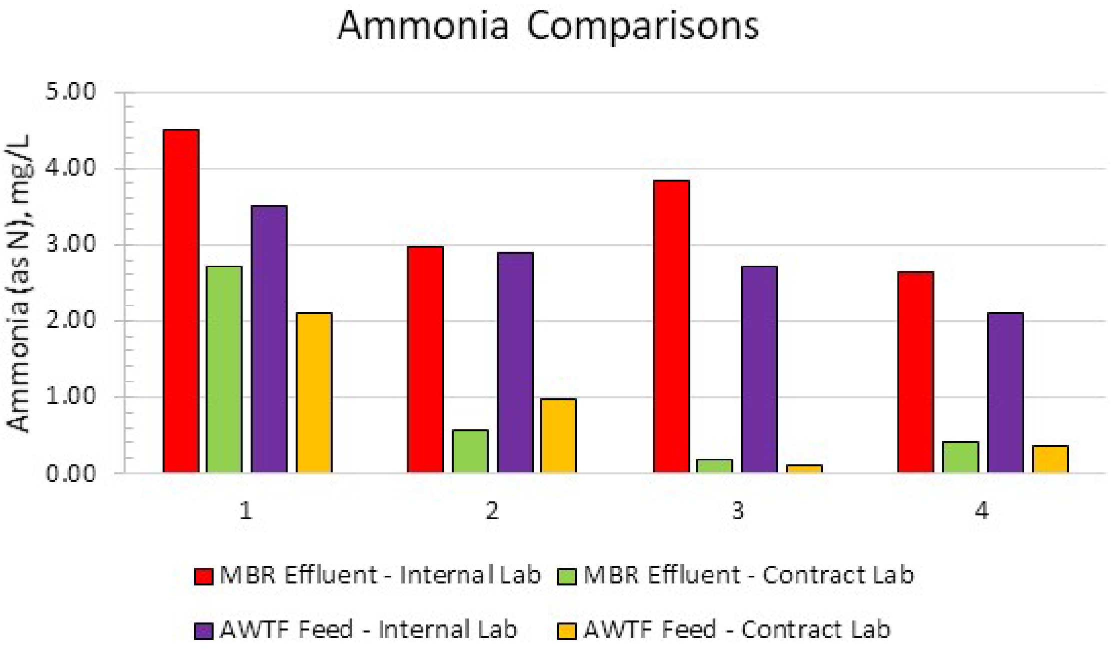


Figure 2.14 Ammonia Results Comparison Between Grab Samples at Two Locations

Chapter 3

2020 & 2021 EXTENDED TESTING

3.1 Overview

The final series of testing is intended to:

- **Bench Scale Ozone Testing:** O_3 dose/response testing to evaluate bromate formation and trace chemical destruction (e.g., hormones, pharmaceuticals), with and without hydrogen peroxide addition.
- **Full-Scale AWTF Baseline Testing:** Evaluation of the full-scale AWTF performance for various trace chemical pollutants and DBPs.
- **Full-Scale AWTF Testing with New Granular Activated Carbon (GAC):** The carbon used in the biofilters was replaced. Testing was repeated to document any changes as the result of new carbon in the biofilters.
- **Full-Scale AWTF System Modifications:** Based upon the collected data, short term modifications were recommended for full scale operation, resulting in another data set for chemicals and DBPs.
- **Bench Scale Virus Testing:** O_3 dose/response testing to evaluate virus disinfection (seeded MS2 bacteriophage).

3.2 Bench Scale Ozone Testing

Four samples were collected concurrently with the samples collected for evaluation of the online analyzer in November and December 2020. The four samples of Cabezon MBR effluent were sent to Carollo's Water ARC® laboratory for O_3 dose/response testing. Table 3.1 contains the testing matrix followed for each of the four samples. These results will be used to optimize operations and implement an O_3:(TOC+NO_2) based dose control approach to limit bromate formation *without H_2O_2 addition*, while maintaining targeted concentration of chemical pollutants and targeted virus reduction (by O_3). As mentioned previously, the delivered O_3 dose accounted for the TOC and NO_2 of the samples.

Unlike the previous testing in 2019 that had very high the TOC and NO_2 concentrations, the samples collected in November and December 2020 had very low NO_2 concentrations and lower TOC concentrations. Table 3.2 contains the water quality results for the four samples. NO_2 had little impact on demand and dosing during these experiments.

Table 3.1 Weekly Bench-Scale Ozone Testing Plan – November and December 2020

O_3/ TOC Ratio	O_3:H_2O_2 molar ratio	TOC	NO_3, NO_2, and NH_3	Bromide, Bromate	UVT	CECs
0	No H_2O_2	X	X	X	X	X
0.5	No H_2O_2	X	X	X	X	
0.8	No H_2O_2	X	X	X	X	
1.0	No H_2O_2	X	X	X	X	X
1.0	1:1.2	X	X	X	X	

Table 3.2 Water Quality Results for Cabezon MBR Effluent Prior to Bench-Scale Ozone Testing

Parameter	11-2-2020	11-10-2020	12-8-2020	12-15-2020
Total Organic Carbon (TOC), mg/L	5.91	5.59	5.67	5.35
Nitrate (NO_3-) as N, mg/L	2.8	4.2	ND	7.1
Nitrite (NO_2-) as N, mg/L	0.22	0.14	0.20	0.13
Turbidity, NTU	0.43	0.60	0.43	0.47
UV254, abs	0.143	0.139	0.140	0.144
pH	7.94	7.49	7.48	7.44
Ammonia (NH_3) as N, mg/L	3.1	0.24	0.04	0.06
Bromide, µg/L	140	180	100	91
Bromate, µg/L	ND	ND	ND	ND

Abbreviations:
NTU = nephelometric turbidity unit; abs = absorbance; µg/L = micrograms per liter; ND = non-detect

Figure 3.1 and Figure 3.2 present a comparison of the O_3 residual versus the delivered O_3 dose and the delivered O_3:(TOC+NO_2) ratio, respectively. An O_3 dose greater than 5 mg/L and an O_3:(TOC+NO_2) ratio greater than 0.9 was needed to maintain a residual in the samples after a 4.5 minute contact time.

Figure 3.3 presents the bromate formation compared to the O_3:(TOC+NO_2) ratio. The drinking water MCL for bromate is 0.010 mg/L (10 µg/L). A target O_3:(TOC+NO_2) ratio of 0.8 – 0.9 appears to be the optimal range for Rio Rancho to minimize bromate formation without peroxide.

Tests with H_2O_2 addition was included with each of the four rounds of testing, with details and results shown in the Table 3.3. Under the test conditions shown, addition of mitigates H_2O_2 bromate formation.

The O_3 destruction performance for a range of trace level chemical pollutants is shown in the Table 3.4. Robust performance (>75 percent) was shown, with the exception of sucralose (50 to 60 percent reduction), Tris(2-carboxyethyl)phospine (TCEP) (15 to 25 percent reduction), and meprobamate (56 to 80 percent reduction), and noting that triclosan removal estimates may be impacted by the very low concentrations near or below the method reporting limit (MRL).

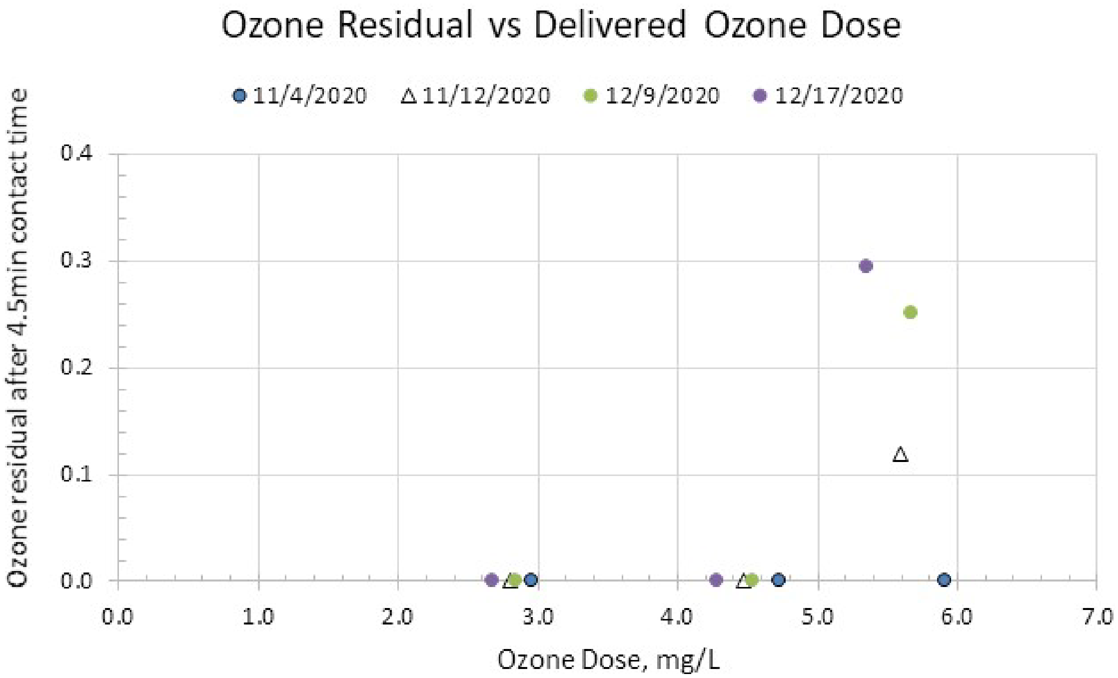


Figure 3.1 Comparison of O_3 Dose to O_3 Residual After 4.5 Minutes of Contact Time

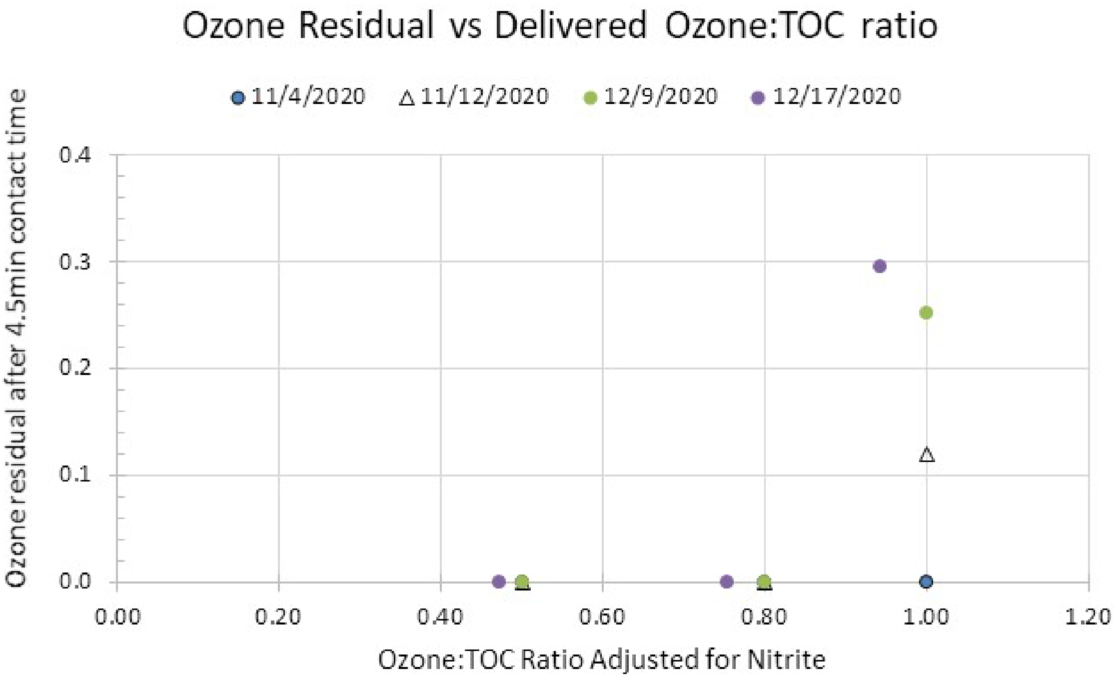


Figure 3.2 Comparison of O_3:(TOC+NO_2) Ratio to O_3 Residual After 4.5 Minutes of Contact Time

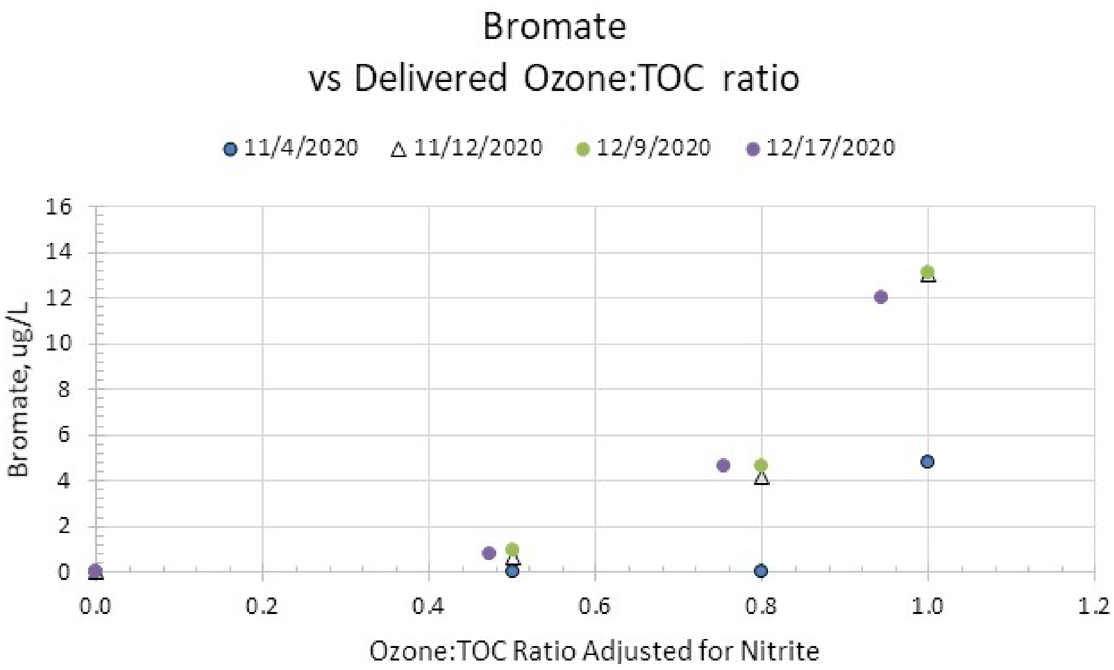


Figure 3.3 Bromate Formation at Various O_3:(TOC+NO_2) Ratios After 4.5 Minutes

Table 3.3 Bromate Formation Results for O_3/H_2O_2

O_3/TOC Ratio	$O_3:H_2O_2$ molar ratio	O_3:(TOC+NO_2) Mass Ratio	TOC (mg/L)	NO_2 (mg/L)	Bromate (µg/L)
1	1:1.2	1.0	5.91	ND(1)	ND(2)
2	1:1.2	1.0	5.59	ND	ND
3	1:1.2	1.0	5.67	ND	ND
4	1:1.2	0.94	5.35	ND	ND

Notes:
(1) Detection limit of nitrite method 0.070 mg/L.
(2) Detection limit of bromide method 1.0 µg/L.

Overall, these bench scale ozone testing results indicate:

- Both TOC and NO_2 values appear low and stable.
- O_3 residual is not seen until after an O_3:(TOC+NO_2) ratio of >0.8 is documented.
- Bromate formation begins at an O_3:(TOC+NO_2) ratio of ~0.5 but does not exceed the MCL of 10 µg/L until the ratio exceeds 0.9.
- The addition of H_2O_2 fully mitigates bromate formation.
- Destruction of trace chemicals (e.g., pharmaceuticals) is robust at an O_3:(TOC+NO_2) ratio of ~1, noting the lack of NO_2 in any of the tests.

Table 3.4 Reduction of Trace Chemical Pollutants by Ozone Bench Scale Testing

Parameter	Units	11/4/2020		11/12/2020		12/9/2020		12/17/2020	
		Zero Dose	1.0 O_3: $(TOC+NO_2)$ Mass Ratio	Zero Dose	1.0 O_3: $(TOC+NO_2)$ Mass Ratio	Zero Dose	1.0 O_3: $(TOC+NO_2)$ Mass Ratio	Zero Dose	1.0 O_3: $(TOC+NO_2)$ Mass Ratio
Acetaminophen	ng/L	<100	<5.0	<100	<5.0	<100	<5.0	<100	<5.0
Atenolol	ng/L	23	1.1	20	<1.0	38	<1.0	52	<1.0
Caffeine	ng/L	21	<5.0	12	<5.0	<100	<5.0	<100	<5.0
Carbamazepine	ng/L	520	<0.50	570	<0.50	390	<0.50	400	<0.50
DEET	ng/L	87	20	78	11	69	5.1	57	4.9
Fluoxetine	ng/L	43	0.79	46	<0.50	64	<0.50	60	7.2
Gemfibrozil	ng/L	250	0.39	98	0.68	81	<0.25	64	<0.25
Ibuprofen	ng/L	<20	<20	<20	<20	<20	<1.0	<20	<1.0
Meprobamate	ng/L	25	11	35	10	20	4	16	3.6
Naproxen	ng/L	56	<0.50	21	<0.50	51	<0.50	50	<0.50
Primidone	ng/L	510	120	530	66	480	32	600	36
Sucralose	ng/L	140,000	55,000	120,000	44,000	88,000	42,000	100,000	43,000
Sulfamethoxazole	ng/L	960	<5.0	650	<5.0	500	0.75	800	0.99
TCEP	ng/L	200	170	160	120	140	120	120	100
Triclocarban	ng/L	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0
Triclosan	ng/L	1.2	<1.0	<1.0	<1.0	<1.0	<1.0	1.2	<1.0
Trimethoprim	ng/L	30	<0.25	14	<0.25	10	<0.25	13	<0.25

Abbreviation:
ng/L = nanograms per liter

3.3 Full Scale AWTF Baseline Testing

There are two Calgon Modular Model 12 Carbon Adsorption Systems at the AWTF which function as biologically active carbon filters. Each system has two GAC filters. The design criteria of the filters are contained in Table 3.5. Figure 3.4 shows the layout of the BAC filters. During the testing only Filter 2B was being used.

Table 3.5 AWTF Biologically Activated Carbon Filters Design Criteria

Parameter	Value
Type	Calgon Modular Model 12
Number of Filter Vessels per Modular System	2
Total Number of Filter Vessels	4
Flowrate per Modular System	350 gpm
Flowrate per Vessel	175 gpm
Diameter	12-feet
Straight Side Height	7 feet, 9 inches
Carbon	Filtrasorb 300
Carbon per Vessel	20,000 pounds
Design Filter Loading Rate	1.55 gpm/sq ft
Design Empty Bed Contact Time	37.5 minutes

Abbreviations:
gpm = gallons per minute; gpm/sq ft = gallons per minute per square foot

The carbon in the BAC system was replaced in mid-November with new GAC, which impacts the performance as it transitions from GAC removal to BAC removal. Prior to that change-over, one sample event across the AWTF was conducted to document baseline treatment performance for a range of parameters. Samples were collected pre-ozone, post ozone, and at the BAC effluent. The baseline analysis sample was collected on November 2, 2020.

The operational parameters of the system on the day of testing were:

- O_3 dose – set point of 5.6 mg/L
- H_2O_2 Dose – set point of 1:1.2 O_3:H_2O_2 molar ratio
- Contact time – not applicable due to H_2O_2 Dose
- Flow - ~318 gallons per minute (gpm)
- BAC loading rate of ~1.4 gpm/sq ft
- BAC Empty Bed Contact Time (EBCT) of ~41 minutes

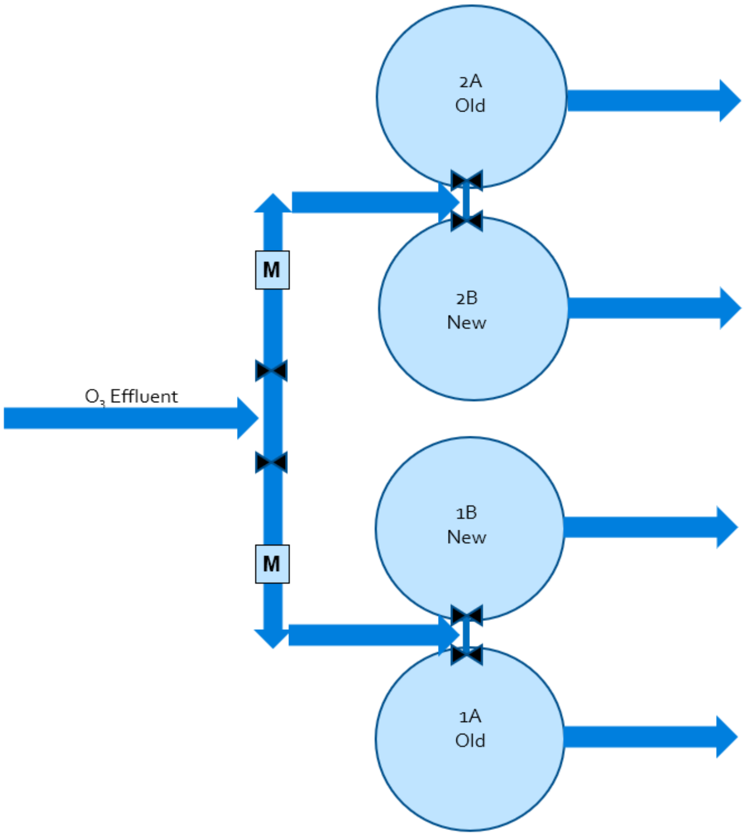


Figure 3.4 AWTF Biologically Activated Carbon Filter Layout

Water quality and trace chemical pollutant results are shown from pre-ozone, post ozone, and after the BAC in Table 3.6, Table 3.7, and Table 3.8. Field blanks for the sample date all came back below detection. These results suggest:

- High NO_2 concentrations exert an O_3 demand of almost 6 mg/L, which is assumed to render the O_3:(TOC+NO_2) ratio to close to zero.
- Reduction of TOC across the BAC is ~32 percent, which is within expectations.
- The drop in UVT across the BAC is surprising. Typically, UVT increases across BAC. After investigating the sample point it was discovered it was after chlorine dosing which explains the UVT.
- The reduction of NH_3 from 1.8 mg/L to below detection demonstrates nitrification across the BAC.
- Reduction of trace chemical pollutants across the full scale O_3 process is much reduced compared to bench scale testing.
- Reduction of trace chemical pollutants across the full scale BAC is substantial.

Table 3.6 November 2, 2020 Water Quality Results

Location	ATP (PG/mL)	TOC (mg/L)	Nitrate mg/L (as N)	Nitrite mg/L (as N)	UVT (%)	Ammonia mg/L (as N)	Bromate(3) (µg/L)
Pre-Ozone		5.4	2.8	1.7	73.5	2.0	<1.0
Post-Ozone	801	5.3	4.2	0.55	85.1	1.80	<1.0
BAC Effluent	811	3.7	6.6	ND(2)	72.4	ND(1)	<1.0

Notes:
(1) The ammonia detection limit is 0.36 mg/L.
(2) The nitrite detection limit is 0.070 mg/L.
(3) The bromate detection limit is 1.0 µg/L.
Abbreviation:
PG/mL = picograms per milliliter

Table 3.7 November 2, 2020 Trace Chemical Pollutants

Parameter	Units	Pre-Ozone	Post Ozone	Post BAC
Acetaminophen	ng/L	<100	<100	<100
Atenolol	ng/L	24	22	<1.0
Caffeine	ng/L	21	16	<5.0
Carbamazepine	ng/L	550	160	3.5
DEET	ng/L	130	110	16
Fluoxetine	ng/L	130	77	<0.50
Gemfibrozil	ng/L	270	190	13
Ibuprofen	ng/L	<20	<20	<20
Meprobamate	ng/L	34	32	10
Naproxen	ng/L	65	20	0.77
Primidone	ng/L	460	430	130
Sucralose	ng/L	160,000	130,000	28,000
Sulfamethoxazole	ng/L	990	310	32
TCEP	ng/L	170	200	25
Triclocarban	ng/L	<2.0	<2.2	<2.0
Triclosan	ng/L	4.7	<1.1	<1.0
Trimethoprim	ng/L	36	9.3	<0.25

Table 3.8 Percent Reduction of Trace Chemical Pollutants Under Different Ozone Demand Conditions

Parameter	Units	Bench(4) Test 1	Bench(4) Test 2	Bench(4) Test 3	Bench(4) Test 4	Full Scale Ozone(4)	Full Scale BAC(4)
Ozone Dose	mg/L	5.91	5.59	5.67(1)	5.35(1)	5.6	NA
TOC	mg/L	5.91	5.59	5.67	5.35	5.4	NA
Nitrite[5]	mg/L	ND	ND	ND	ND	2.8	NA
H_2O_2	Molar ratio	NA	NA	NA	NA	1:1.2 O_3:H_2O_2	NA
Acetaminophen		(2)	(2)	(2)	(2)	(2)	(2)
Atenolol		95%	>95%(3)	>97%(3)	>98%(3)	8%	>95%(3)
Caffeine		>76%(3)	>58%(3)	(2)	(2)	24%	>69%(3)
Carbamazepine		>99%(3)	>99%(3)	>99%(3)	>99%(3)	71%	98%
DEET		77%	86%	93%	91%	15%	85%
Fluoxetine		98%	>99%(3)	>99%(3)	88%	41%	>99%(3)
Gemfibrozil		>99%(3)	99%	>99%(3)	>99%(3)	30%	93%
Ibuprofen		(2)	(2)	(2)	(2)	(2)	(2)
Meprobamate		56%	71%	80%	78%	6%	69%
Naproxen		>99%(3)	>98%(3)	99%	>99%(3)	69%	96%
Primidone		76%	88%	93%	94%	7%	70%
Sucralose		61%	63%	52%	57%	19%	78%
Sulfamethoxazole		>99%(3)	>99%(3)	100%	100%	69%	90%
TCEP		15%	25%	14%	17%	-18%	88%
Triclocarban		(2)	(2)	(2)	(2)	(2)	
Triclosan		>17%(3)	(2)	(2)	>17%(3)	77%	(2)
Trimethoprim		>99%(3)	98%	>98%(3)	>98%(3)	74%	>97%(3)

Notes:

(1) Ozone dose set to match TOC dose on a mass basis.
(2) Both influent and effluent samples below detection.
(3) Effluent value is below detection.
(4) Bench scale test results from 11/4, 11/12, 12/9, and 12/17, all in 2020. Full-scale samples taken on 11/2/2020.
(5) The nitrite detection limit is 0.070 mg/L.

Testing was also conducted on November 2, 2020 for a broad range of per- and polyfluoroalkyl substances (PFAS), as shown in Table 3.9. The regulatory context of PFAS is important for consideration, with a broad range of regulated or health-based guidance nationally.

- Some states are setting very low requirements or targets for perfluorooctanoic acid (PFOA) and perfluorooctanyl sulfonate (PFOS), including:
  - California:
    - Notification levels (NL) for PFOA and PFOS of 5.1 and 6.5 ng/L; and
    - Response levels for PFOA and PFOS of 10 and 40 ng/L.
  - Illinois:
    - Health advisories for PFOA (<2 ng/L), perfluorohexanesulfonic acid (PFHxS) (<140 ng/L), PFBS (<140,000 ng/L), Perfluorohexanoic acid (PFHxA) (<560,000 ng/L)
  - New York:
    - MCLs for PFOA and PFOS at 10 ng/L each
  - New Jersey:
    - Perfluorononanoic acid (PFNA) (<13 ng/L), PFOA (<14 ng/L), and PFOS (<13 ng/L)
- U.S. Environmental Protection Agency (USEPA):
  - Federal Health Advisory Level (HAL) for PFOA+PFOS of 70 ng/L;
  - Current movement at USEPA is to formally regulate PFOA and PFOS, and the number may be less than the 70 ng/L level, potentially in the ~20 ng/L range;
  - Re-issued the proposed UCMR5 list, which contains monitoring requirements for 29 additional PFAS.

Results from the November 2, 2020 testing, compared to some of the regulations and guidelines, indicate:

- PFOA and PFOS levels below the 70 ng/L USEPA HAL;
- PFOA levels above the California NL of 5.1 ng/L and the Illinois HAL of 2 ng/L.

Table 3.9 November 2, 2020 Per- and Polyfluoroalkyl Substances (PFAS) (Note, carbon in the BAC filters was replaced AFTER this Sampling Event)

Parameter	Units	Pre-Ozone	Post Ozone	Post BAC
Gen X	ng/L	<0.56	<0.50	<0.50
N-EtFOSAA	ng/L	<0.28	<0.25	<0.25
N-MeFOSAA	ng/L	<0.28	<0.25	<0.25
Perfluorobutane sulfonate	ng/L	6.8	8.1	9.1
Perfluorobutanoic acid	ng/L	<100	<100	<100
Perfluorodecanoic acid	ng/L	1.4	1.3	0.51
Perfluoroheptanoic acid	ng/L	2.9	2.9	2.4
Perfluorohexane sulfonate (PFHxS)	ng/L	0.47	0.36	<0.25
Perfluorohexanoic acid (PFHxA)	ng/L	27	26	25
Perfluorononanoic acid (PFNA)	ng/L	<0.56	<0.50	<0.50
Perfluorooctane sulfonamide	ng/L	<0.28	<0.25	<0.25
Perfluorooctane sulfonate (PFOS)	ng/L	1	1	0.33
Perfluorooctanoic acid (PFOA)	ng/L	14	13	8.9
Perfluoropentanoic acid (PFCA)	ng/L	71	78	75

3.4 Full Scale AWTF Testing with New GAC

After new GAC was placed within the system the week of November 16, 2020, the transition of GAC based performance to BAC based performance was monitored. Over a period of seven weeks, data like the above work was collected across the AWTF (pre-ozone, post ozone, post BAC), with 50 percent of events having testing of PFAS and CECs. These five samples were collected from December 8, 2020 through January 19, 2021. For the five test dates, the operational conditions are shown in Table 3.10.

Table 3.10 Operational Conditions for Post GAC Replacement Full Scale Testing

Date	Location	Flow (gpm)	Estimated BAC Loading Rate (gpm/sq ft)	Estimated BAC Empty Bed Contact Time	BAC Bed Volumes Since GAC Replacement	Ozone Dose (mg/L)	O_3:H_2O_2 Molar Ratio
12/8/2020	Pre-O_3	320					
	Post- O_3	320	1.4	41		5.26	1:1.2
	BAC Eff	305			1540		
12/15/2020	Pre- O_3	305					
	Post- O_3	314	1.4	41		5.44	1:1.2
	BAC Eff	318			2030		
1/5/2021	Pre- O_3	304					
	Post- O_3	321	1.4	42		4.55	1:1.2
	BAC Eff	318			3501		
1/12/2021	Pre- O_3	314					
	Post- O_3	337	1.5	39		4.77	1:1.2
	BAC Eff	341			3991		
1/19/2021	Pre- O_3	314					
	Post- O_3	309	1.4	42		5.39	1:1.2
	BAC Eff	312			4481		

Water quality and trace chemical pollutant results are shown from pre-ozone, post ozone, and after the BAC in Table 3.11 through Table 3.14 and Figure 3.5, through Figure 3.8. Field blanks for the sample date all came back below detection. These results suggest:

- NO_2 levels are very low, which will improve O_3 oxidation performance for the set operational criteria.
- TOC reduction is initially much improved compared to the Baseline Testing but degrades with time as carbon adsorption sites are exhausted and the GAC transitions into BAC (Figure 3.5).
- UVT increases across both the O_3 process and the BAC process, which is the anticipated result. Data also suggests a small reduction in treatment of UV absorbing chemicals as the GAC transition to BAC with time (Figure 3.6).

- Bromate formation by O_3 is limited, noting that H_2O_2 is added for the full-scale operation. Interesting:
  - Bromate formation as a function of UVT appears to match with bench scale results from 2019, as shown combined with bench results and full-scale results collected in 2019, 2020, and 2021 (Figure 3.7).
  - Bromate formation as a function of O_3:(TOC+NO_2) is not fully defined, as the 2019 bench scale tests (with high TOC and high NO_2) do not match up with the 2020/2021 bench scale tests (with low TOC and low NO_2) (Figure 3.8).
- The data on trace chemical reduction, comparing the testing from November with three new data sets, indicates:
  - Regarding ozone oxidation
    - The November chemical oxidation performance was significantly worse compared to the other data, mostly likely due to the high nitrite concentration in the November event.
    - The last sampling event, 1/19/21, had a small concentration of NO_2, and some of the oxidation performance is reduced compared to the two sample dates with no NO_2.
  - Regarding BAC removal
    - The early November chemical removal by the BAC is measurably less than seen by the new BAC (replaced 11/16/21), indicating the improved performance of the new BAC due to a combination of carbon adsorption and biodegradation.
    - To date, there does not appear to be a reduction in BAC performance as the BAC transitions from adsorption to biodegradation.

Table 3.11 Water Quality Results for Post GAC Replacement Full Scale Testing

Date	Location	ATP (PG/mL)	TOC (mg/L Lab)	Nitrate (mg/L Lab)	Nitrite (mg/L Lab)$^{(1)}$	UVT (% Lab)	Ammonia (mg/L Lab)$^{(2)}$	Bromide (mg/L Lab)$^{(3)}$	Bromate (µg/L Lab)$^{(4)}$
12/8/2020	Pre- O_3		4.8	6.8	ND	74.5	0.11	ND	<1.0
	Post- O_3	627	4.8	6.8	ND	83.0	0.17	ND	3.4
	BAC Eff	678	1.9	6.9	0.098	95.1	0.11	ND	2.5
12/15/2020	Pre- O_3		4.7	7.2	ND	74.1	ND	ND	<1.0
	Post- O_3	941	4.6	7.0	0.014	83.0	ND	0.11	1.8
	BAC Eff	424	2.1	6.7	ND	94.2	ND	0.094	1.4
1/5/2021	Pre- O_3		4.8	7.4	ND	73.5	ND	ND	<1.0
	Post- O_3	1371	4.5	7.2	ND	82.2	ND	0.1	2.3
	BAC Eff	347	2.2	7.1	0.89	92.3	ND	0.091	2.4
1/12/2021	Pre- O_3		4.8	6.4	0.067	74.3	ND	0.1	<1.0
	Post- O_3	1477	4.7	6.6	ND	82.4	ND	0.11	1.2
	BAC Eff	617	2.5	6.7	ND	93.1	ND	ND	1.6
1/19/2021	Pre- O_3		5.0	6.7	0.29	74.0	0.11	ND	<1.0
	Post- O_3	833	4.9	6.8	ND	82.0	ND	0.12	1.4
	BAC Eff	412	2.8	7.0	ND	92.3	ND	ND	1.3

Notes:
(1) The nitrite detection limit is 0.070 mg/L.
(2) The ammonia detection limit is 0.36 mg/L.
(3) The bromide detection limit is 0.25 mg/L.
(4) The bromate detection limit is 1.0 µg/L.

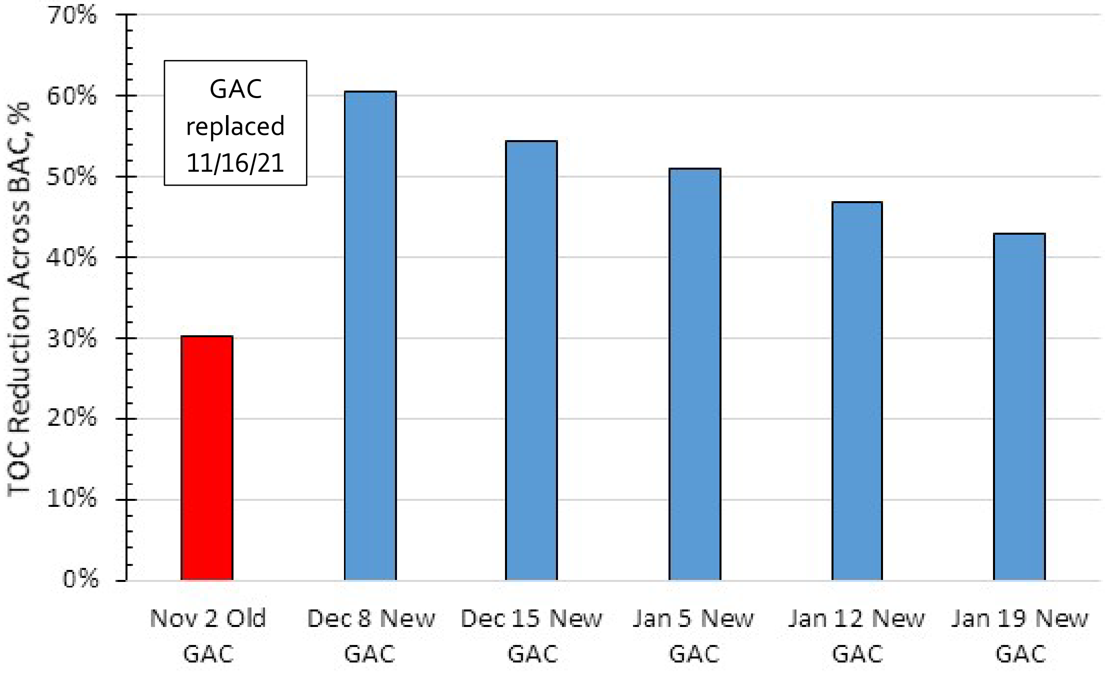


Figure 3.5 Reduction of TOC Across BAC with Old and New GAC

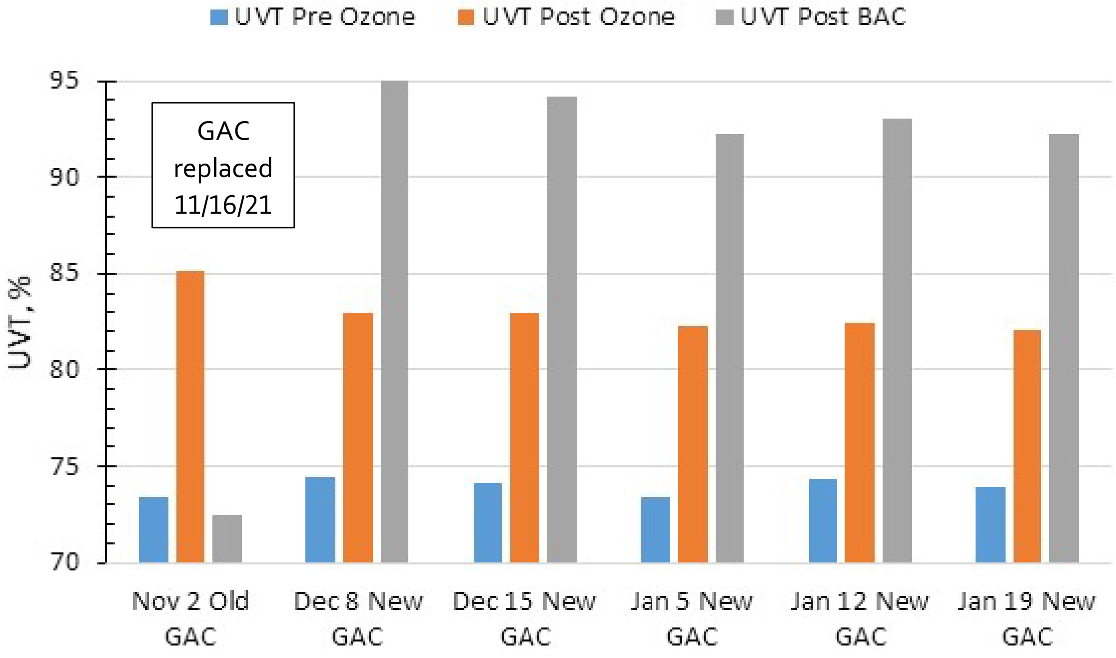


Figure 3.6 Increase in UVT Across Ozone and BAC with Old and New GAC

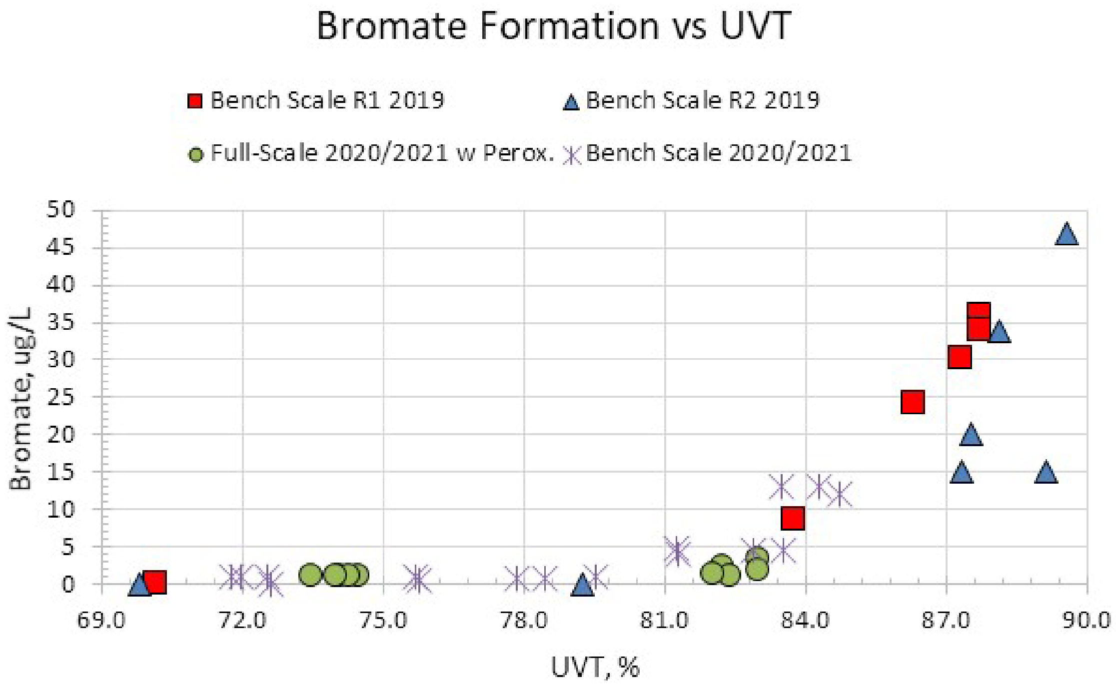


Figure 3.7 Bromate Formation as a Function of UVT

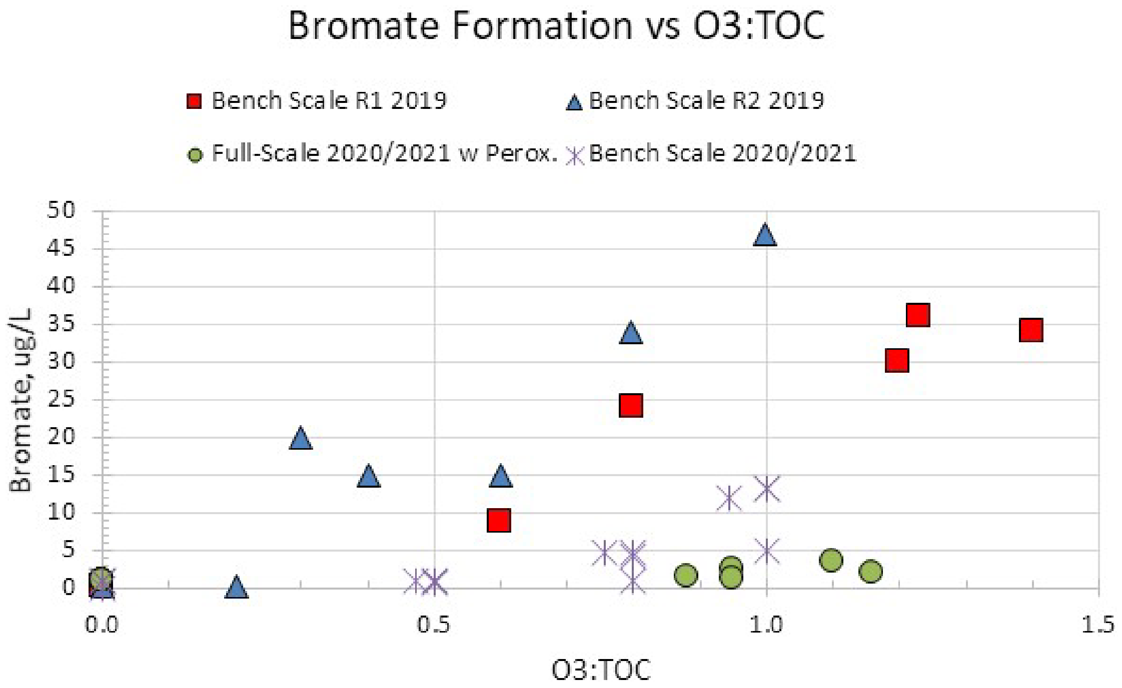


Figure 3.8 Bromate Formation as a Function of O_3:(TOC+NO_2)

Table 3.12 Trace Chemical Pollutant Analysis with New GAC

Parameter	Units	12/8/2020			1/5/2021			1/19/2021		
		Pre Ozone	Post Ozone	Post BAC	Pre Ozone	Post Ozone	Post BAC	Pre Ozone	Post Ozone	Post BAC
Acetaminophen	ng/L	<100	<100	<5.0	<100	<5.0	<5.0	<100	<5.0	<5.0
Atenolol	ng/L	37	<1.0	<1.0	56	<1.0	<1.0	110	<20	<1.0
Caffeine	ng/L	<100	<5.0	<5.0	<100	<5.0	<5.0	<100	<5.0	<5.0
Carbamazepine	ng/L	360	<0.50	<0.50	630	<0.50	<0.50	490	<0.50	<0.50
DEET	ng/L	85	<1.0	<1.0	63	<1.0	<1.0	290	5.7	<1.0
Fluoxetine	ng/L	77	<0.50	<0.50	71	1	<0.50	93	0.74	<0.50
Gemfibrozil	ng/L	77	<0.25	<0.25	62	<0.25	<0.25	74	<0.25	<0.25
Ibuprofen	ng/L	<20	<1.0	<1.0	<20	<1.0	<1.0	<20	<1.0	<1.0
Meprobamate	ng/L	22	1.2	<0.25	20	1	<0.25	34	3.5	<0.25
Naproxen	ng/L	52	<0.50	<0.50	58	<0.50	<0.50	120	<0.50	<0.50
Primidone	ng/L	550	5.6	<0.50	620	5.4	<0.50	580	13	<0.50
Sucralose	ng/L	77,000	21,000	270	110,000	20,000	250	120,000	36,000	1,600
Sulfamethoxazole	ng/L	750	2.5	<0.25	1300	2.1	<0.25	1200	3.9	<0.25
TCEP	ng/L	130	96	<10	140	110	<10	110	80	<10
Triclocarban	ng/L	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0
Triclosan	ng/L	1.8	<1.0	<1.0	2.6	<1.0	<1.0	2.9	<1.0	<1.0
Trimethoprim	ng/L	11	<0.25	<0.25	18	<0.25	<0.25	26	<0.25	<0.25

Table 3.13 Percent Reduction of Trace Chemical Pollutants by Ozone at Full Scale

Parameter	Units	11/2/20	12/8/20	1/5/21	1/19/21
Ozone Dose	mg/L	5.6	5.3	4.6	5.4
TOC	mg/L	5.4	4.8	4.8	5.0
Nitrite[4]	mg/L	2.8	ND	ND	0.29
H_2O_2	Molar ratio	1:1.2 O_3:H_2O_2	1:1.2 O_3:H_2O_2	1:1.2 O_3:H_2O_2	1:1.2 O_3:H_2O_2
Acetaminophen		(2)	(2)	(2)	(2)
Atenolol		8%	>97%(3)	>98%(3)	>82%(3)
Caffeine		24%	(2)	(2)	(2)
Carbamazepine		71%	>99%(3)	>99%(3)	>99%(3)
DEET		15%	>99%(3)	>98%(3)	98%
Fluoxetine		41%	>99%(3)	99%	99%
Gemfibrozil		30%	>99%(3)	>99%(3)	>99%(3)
Ibuprofen		(2)	(2)	(2)	(2)
Meprobamate		6%	95%	95%	90%
Naproxen		69%	>99%(3)	>99%(3)	>99%(3)
Primidone		7%	99%	99%	98%
Sucralose		19%	73%	82%	70%
Sulfamethoxazole		69%	99.7%	99.8%	99.7%
TCEP		-18%	26%	21%	27%
Triclocarban		(2)	(2)	(2)	(2)
Triclosan		77%	>44%(3)	>62%(3)	>66%(3)
Trimethoprim		74%	>98%(3)	>99%(3)	>98%(3)

Notes:
(1) Ozone dose set to match TOC dose on a mass basis.
(2) Both influent and effluent samples below detection.
(3) Effluent value is below detection.
(4) The nitrite detection limit is 0.070 mg/L.

Table 3.14 Percent Reduction of Trace Chemical Pollutants by BAC at Full Scale

Parameter	Old BAC 11/2/20	New BAC 12/8/20	New BAC 1/5/21	New BAC 1/19/21
Acetaminophen	(1)	(1)	(1)	(1)
Atenolol	>95%(2)	(1)	(1)	(1)
Caffeine	>69%(2)	(1)	(1)	(1)
Carbamazepine	98%	(1)	(1)	(1)
DEET	85%	(1)	(1)	(1)
Fluoxetine	>99%(2)	(1)	(1)	(1)
Gemfibrozil	93%	(1)	(1)	(1)
Ibuprofen	(1)	(1)	(1)	(1)
Meprobamate	69%	79%	75%	93%
Naproxen	96%	(1)	(1)	(1)
Primidone	70%	>91%(2)	>91%(2)	>96%(2)
Sucralose	78%	99%	99%	96%
Sulfamethoxazole	90%	>90%(2)	>88%(2)	>94%(2)
TCEP	88%	>90%(2)	>91%(2)	>88%(2)
Triclocarban	(1)	(1)	(1)	(1)
Triclosan	(1)	(1)	(1)	(1)
Trimethoprim	>97%(2)	(1)	(1)	(1)

Notes:
(1) Both influent and effluent samples below detection.
(2) Effluent value is below detection.

PFAS data was also collected for the new GAC, presented in the tables below. This data indicates:

- The old BAC had very little PFAS removal capability, presumably due to loss of all adsorption sites.
- The new BAC provided robust removal of a number of PFAS, but that removal reduced with time. For example:
  - PFOA reduction values decreasing with time (95%, 90%, 75%)
  - PFCA reduction values decreasing with time (56%, 38%, 22%)
  - PFHxA reduction values decreasing with time (77%, 71%, 45%)
- Related to regulatory guidance or regulated values:
  - PFOA and PFOS levels below the 70 ng/L USEPA HAL;
  - PFOA levels above the California NL of 5.1 ng/L and the Illinois HAL of 2 ng/L for the last sampling date with the new GAC (1/19/21).

Table 3.15 Per- and Polyfluoroalkyl Substances (PFAS) with New GAC

Parameter	Units	12/8/2020			1/5/2021			1/19/2021		
		Pre-Ozone	Post Ozone	Post BAC	Pre-Ozone	Post Ozone	Post BAC	Pre-Ozone	Post Ozone	Post BAC
Gen X	ng/L	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50
N-EtFOSAA	ng/L	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25
N-MeFOSAA	ng/L	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25
Perfluorobutane sulfonate	ng/L	24	16	1.9	15	15	2.5	12	16	6.3
Perfluorobutanoic acid	ng/L	<100	<100	<100	<100	<100	<100	5.7	9.8	9.9
Perfluorodecanoic acid	ng/L	1.6	1.8	<0.50	1.4	1.4	0.5	2.2	2	0.5
Perfluoroheptanoic acid	ng/L	3.3	3.6	<0.50	2.5	2.8	0.5	2.5	3.5	1.3
Perfluorohexane sulfonate (PFHxS)	ng/L	0.3	0.25	<0.25	0.31	0.26	0.25	0.31	0.36	0.25
Perfluorohexanoic acid (PFHxA)	ng/L	40	39	9	35	38	11	44	42	23
Perfluorononanoic acid (PFNA)	ng/L	0.77	0.86	<0.50	0.72	0.78	0.5	0.67	0.74	0.5
Perfluorooctane sulfonamide	ng/L	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25
Perfluorooctane sulfonate (PFOS)	ng/L	<0.25	<0.25	<0.25	0.41	0.5	0.25	0.44	0.63	0.25
Perfluorooctanoic acid (PFOA)	ng/L	33	32	1.6	18	16	1.6	34	33	8.1
Perfluoropentanoic acid (PFCA)	ng/L	89	84	37	77	71	44	87	76	59

Table 3.16 Percent Reduction of PFAS by BAC at Full Scale

Parameter	Old BAC 11/2/20	New BAC 12/8/20	New BAC 1/5/21	New BAC 1/19/21
Gen X	(1)	(1)	(1)	(1)
N-EtFOSAA	(1)	(1)	(1)	(1)
N-MeFOSAA	(1)	(1)	(1)	(1)
Perfluorobutane sulfonate	-12%	88%	83%	61%
Perfluorobutanoic acid	(1)	(1)	(1)	(1)
Perfluorodecanoic acid	61%	>72%(2)	>64%(2)	>75%(2)
Perfluoroheptanoic acid	17%	>86%(2)	>82%(2)	63%
Perfluorohexane sulfonate (PFHxS)	>31%(2)	(1)	>4%(2)	>31%(2)
Perfluorohexanoic acid (PFHxA)	4%	77%	71%(2)	45%
Perfluorononanoic acid (PFNA)	(1)	>42%(2)	>36%(2)	>32%(2)
Perfluorooctane sulfonamide	(1)	(1)	(1)	1
Perfluorooctane sulfonate (PFOS)	67%	(1)	>50%(2)	>60%(2)
Perfluorooctanoic acid (PFOA)	32%	95%	90%	75%
Perfluoropentanoic acid (PFCA)	4%	56%	38%	22%

Notes:
(1) Both influent and effluent samples below detection.
(2) Effluent value is below detection.

3.5 Full Scale System Modifications

Pertaining to ozone and bromate, the results documented above indicate the following:

- Variation in both MBR effluent TOC and NO_2 presents a challenge to the existing O_3 oxidation system. TOC concentrations much above 5 mg/L will reduce O_3 oxidation effectiveness whereas NO_2 concentrations at just about any level will reduce or eliminate the oxidation potential of O_3 all together.
  - Recent data suggests that TOC is maintaining at a low level, in the high 4 to low 5 mg/L range.
  - Recent data also suggests that NO_2 levels are being maintained at a low level.
- With high TOC and measurable NO_2, breaking through the high oxidant demand appears to correlate with increased bromate formation. With the lower TOC and little NO_2, the data indicates that bromate can be minimized by maintaining a O_3:(TOC+ NO_2) ratio of 0.8 or lower while also maintaining the post ozone UVT to below 82 to 83 percent.

Understanding that one of the goals of this work is to minimize or eliminate the use of H_2O_2 while confidently keeping bromate formation low, short term modifications to full scale operation was made as follows, with results documented further on:

1) Implement the modifications for a short duration, on the order of a few hours, instead of a longer duration (weeks) as planned.
2) Measure both TOC and NO_2 values, anticipated to be ~5 mg/L and ~0 mg/L, respectively.
3) Drop the O_3 dose point from the current value of 5.6 to ~4 mg/L, resulting in an O_3:(TOC+ NO_2) ratio of ~0.8.
4) Turn off the H_2O_2.
5) Measure the UVT post O_3, with a target value of 82 or 83 percent. If the UVT is higher than 83 percent, reduce the O_3 dose by 0.2 mg/L increments and retest the UVT.
6) Allow for 30 minutes of time to pass.
7) Perform the planned sampling for chemical pollutants across both O_3 and BAC.
8) After sampling is complete, return the ozone and H_2O_2 system to normal operation.
9) Repeat this testing effort for the selected setpoints.

Following the procedures listed above, full-scale operational testing was conducted in September of 2021. As noted, the H_2O_2 system was **OFF** for all of the testing documented below, unless otherwise noted. The results of the full-scale testing, based upon the data presented below, demonstrate:

- High water quality in the MBR effluent, with TOC values <5 mg/L and ND NO_2 (<0.1 mg/L);
- Ozone increased UVT from ~77 to 81 to 83 percent, which is precisely within what was determined in bench-scale testing to be the proper range for disinfection and advanced oxidation without exceeding bromate MCL concentrations;
- Bromate levels were ND (<5 µg/L) at O_3:(TOC+ NO_2) ratios of ~0.6 and ~0.8 but was detected at 7.3 µg/L at a ratio of ~1.1. These results match bench-scale results (refer back to Figure 3.8) and hypothesized results for full-scale;
- Ozone continues to be very effective in the destruction of trace chemical pollutants, with increased performance as O_3:(TOC+ NO_2) ratios increase. Notable exceptions where ozone was not effective were for:
  - Caffeine
  - Sucralose
  - TCEP
- BAC continues to work well to polish O_3 effluent, providing robust reduction of all trace chemicals in O_3 effluent other than caffeine.

Overall, these limited results are very promising, documenting that a control system that runs at an O_3:(TOC+ NO_2) ratios in the 0.8 to 1.0 range will provide robust destruction of trace chemical pollutants and not exceed the 10 µg/L bromate MCL. Operating at a ratio setpoint of ~0.8 appears to be a conservative value, with further full-scale testing recommended to better define the bromate safety factor. These results also continue to show the benefit of BAC to water quality, working with the O_3 process to provide broad spectrum reduction of chemical pollutants. We do note here that no PFAS work was conducted during this round of testing, and that prior work for this project has demonstrated that GAC, not BAC, is an effective tool for PFOA and PFOS reduction below the various regulatory targets in NM and nationally.

Table 3.17 Water Quality Results During Full-Scale Modifications at Three O_3:(TOC+NO_2) Ratios

Date	Location	O_3: (TOC+ NO_2)	TOC (mg/L Lab)	Nitrate (mg/L Lab)	Nitrite (mg/L Lab)(1)	UVT (% Lab)	Ammonia (mg/L Lab)(2)	Bromide (mg/L Lab)(3)	Bromate (µg/L Lab)(4)
9/7/2021	Pre-O_3	0.6	4.4	7.0	ND	77.6	ND	ND	-
	Post- O_3	-	-	7.0	ND	82.6	ND	-	ND
	BAC Eff	-	2.5	6.6	ND	90.8	ND	-	-
9/14/2021	Pre- O_3	0.8	4.5	6.7	ND	75.9	ND	ND	-
	Post- O_3	-	-	7.1	ND	82.6	ND	-	ND
	BAC Eff	-	2.8	6.9	ND	90.6	ND	-	-
9/21/2021	Pre- O_3	1.1	4.2	6.2	ND	77.6	ND	ND	-
	Post- O_3	-	-	6.2	ND	81.1	ND	-	7.3
	BAC Eff	-	2.5	6.5	ND	91.2	ND	-	-

Notes:
(1) The nitrite detection limit is 0.1 mg/L.
(2) The ammonia detection limit is 1.0 mg/L.
(3) The bromide detection limit is 0.50 mg/L.
(4) The bromate detection limit is 5 µg/L.

Table 3.18 Trace Chemical Pollutant Numerical Results During Full-Scale Modifications at Three O_3:(TOC+NO_2) Ratios

Parameter	Units	O_3:(TOC+NO_2) = 0.6 9/7/2021			O_3:(TOC+ NO_2) = 0.8 9/14/2021			O_3:(TOC+ NO_2) = 1.1 9/21/2021		
		Pre Ozone	Post Ozone	Post BAC	Pre Ozone	Post Ozone	Post BAC	Pre Ozone	Post Ozone	Post BAC
Acetaminophen	ng/L	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0	<100	<5.0	<5.0
Atenolol	ng/L	14	4	<1.0	<20	<20	<1.0	14	1.6	<1.0
Caffeine	ng/L	14	7.7	5.1	6.3	<5.0	12	12	7.2	<5.0
Carbamazepine	ng/L	390	19	<0.50	460	11	<0.50	440	12	<0.50
DEET	ng/L	90	35	<1.0	140	55	5.8	120	18	<1.0
Fluoxetine	ng/L	29	5.8	<0.50	33	1.9	<0.50	32	3.4	2.9
Gemfibrozil	ng/L	8.6	<0.25	<0.25	<0.25	2.4	<0.25	8.7	0.52	<0.25
Ibuprofen	ng/L	<20	<20	<1.0	<1.0	<1.0	<1.0	5.8	<1.0	<1.0
Meprobamate	ng/L	14	7.9	<0.25	16	9.7	<0.25	16	5.5	<0.25
Naproxen	ng/L	15	<0.50	<0.50	<0.50	3	<0.50	14	<0.50	<0.50
Primidone	ng/L	400	170	2.9	450	170	3.5	510	80	4.4
Sucralose	ng/L	94000	73000	4400	110000	77000	4200	120000	57000	5700
Sulfamethoxazole	ng/L	270	27	1.7	300	15	1.1	320	19	1.6
TCEP	ng/L	150	140	<10	140	130	<10	130	100	<10
Triclocarban	ng/L	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0
Triclosan	ng/L	4.3	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	2.1
Trimethoprim	ng/L	2	<0.25	<0.25	1.6	<0.25	<0.25	2.4	<0.25	<0.25

Table 3.19 Percent Reduction of Trace Chemical Pollutants by Ozone During Full-Scale Modifications at Three O_3:(TOC+NO_2) Ratios

Parameter	Units	9/7/2021	9/14/2021	9/21/2021
O_3:(TOC+NO_2)	Ratio	0.6	0.8	1.1
Ozone Dose(1)	mg/L	2.5	3.5	4.5
TOC	mg/L	4.4	4.5	4.2
Nitrite(4)	mg/L	ND	ND	ND
H_2O_2	Molar ratio	0	0	0
Acetaminophen	-	(2)	(2)	(2)
Atenolol	-	71%	(2)	89%
Caffeine	-	45%	>21%	40%
Carbamazepine	-	95%	98%	97%
DEET	-	61%	61%	85%
Fluoxetine	-	80%	94%	89%
Gemfibrozil	-	>97%	(3)	94%
Ibuprofen	-	(2)	(2)	>83%
Meprobamate	-	44%	39%	66%
Naproxen	-	>97%	(3)	>96%
Primidone	-	58%	62%	84%
Sucralose	-	22%	30%	53%
Sulfamethoxazole	-	90%	95%	94%
TCEP	-	7%	7%	23%
Triclocarban	-	(2)	(2)	(2)
Triclosan	-	77%	(2)	(2)
Trimethoprim	-	88%	84%	90%

Notes:
(1) Ozone dose set to achieve target ratio.
(2) Both influent and effluent samples below detection.
(3) Influent value is below detection.
(4) The nitrite detection limit is 0.1 mg/L.

Table 3.20 Percent Reduction of Trace Chemical Pollutants by BAC During Full-Scale Modifications at Three O_3:(TOC+NO_2) Ratios

Parameter	9/7/2021	9/14/2021	9/21/2021
Acetaminophen	(1)	(1)	(1)
Atenolol	>75%	(1)	>38%
Caffeine	34%	(3)	>31%
Carbamazepine	>97%	>95%	>96%
DEET	>97%	89%	>94%
Fluoxetine	>91%	>74%	15%
Gemfibrozil	(1)	>90%	>52%
Ibuprofen	(1)	(1)	(1)
Meprobamate	>97%	>97%	>95%
Naproxen	(1)	>83%	
Primidone	98%	98%	95%
Sucralose	94%	95%	90%
Sulfamethoxazole	94%	93%	92%
TCEP	>93%	>92%	>90%
Triclocarban	(1)	(1)	(1)
Triclosan	(1)	(1)	(1)
Trimethoprim	(1)	(1)	(1)

Notes:

(1) Both influent and effluent samples below detection.

(2) Effluent value is below detection.

(3) Influent value is below detection.

3.6 Virus Testing

MBR effluent was collected for bench-scale O_3 dose/response testing of virus. Results confirm prior published literature on virus disinfection as a function of O_3:(TOC+NO_2). The work includes:

- A challenge test using a non-pathogenic surrogate for viruses (MS2 bacteriophage)
- MS2 seeding at three different O_3:(TOC+NO_2) ratios (three different O_3 doses).

The work shown in Figure 3.9 and Figure 3.10 demonstrates robust virus disinfection at O_3:(TOC+NO_2) ratios of 0.5 to 1.0. With the prior work indicating no to limited bromate formation at a ratio of ~0.8, these results demonstrate that 6-log virus reduction (99.9999 percent) can be obtained without exceeding the bromate MCL (and without using H_2O_2).

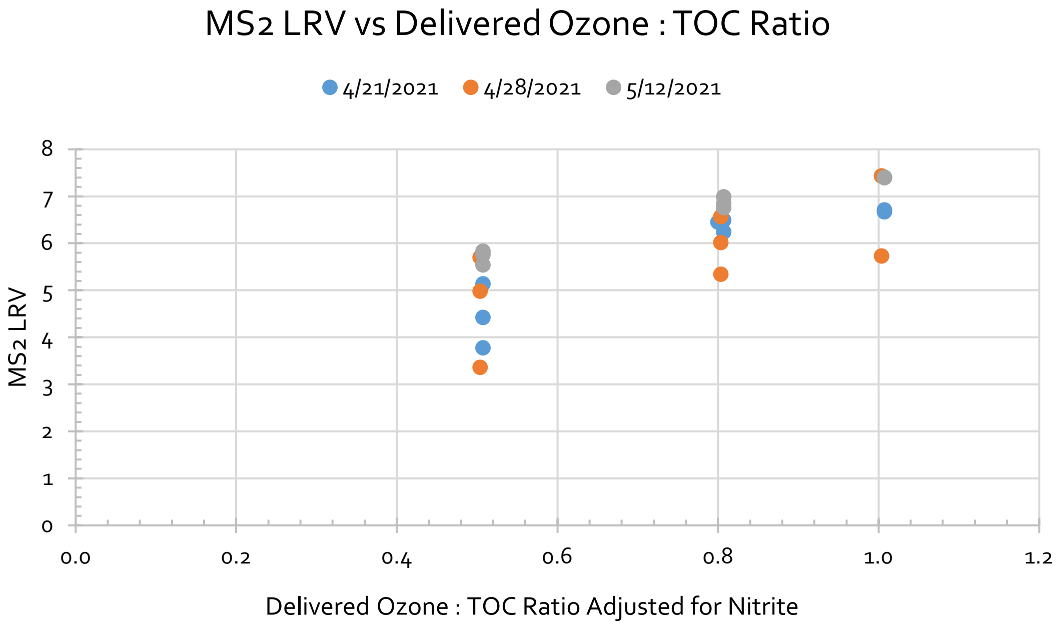


Figure 3.9 MS2 Log Reduction as a Function of O_3:(TOC+NO_2)

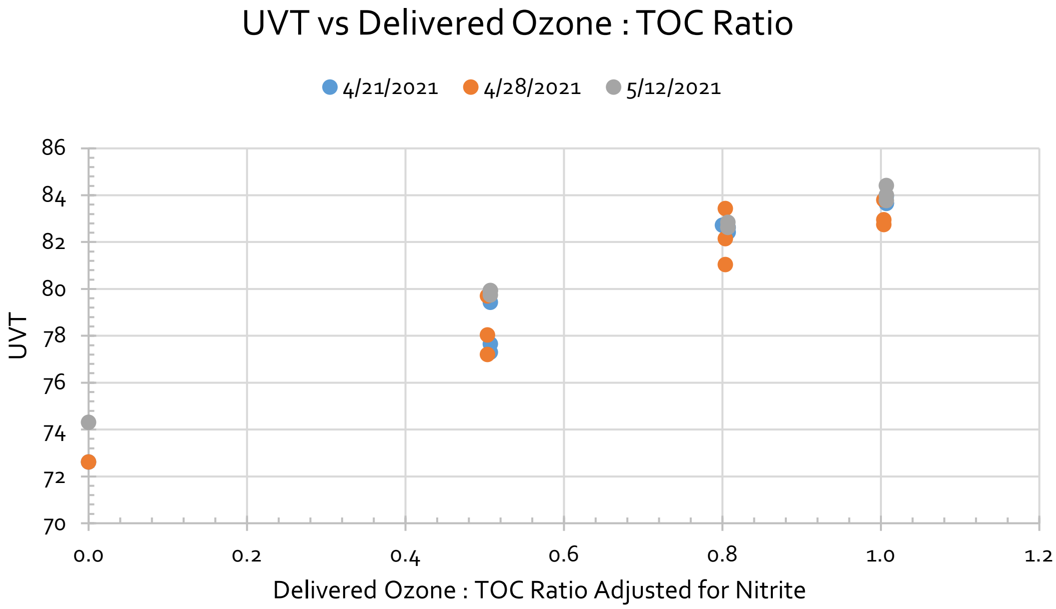


Figure 3.10 UVT as a Function of O_3:(TOC+NO_2)

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Chapter 4

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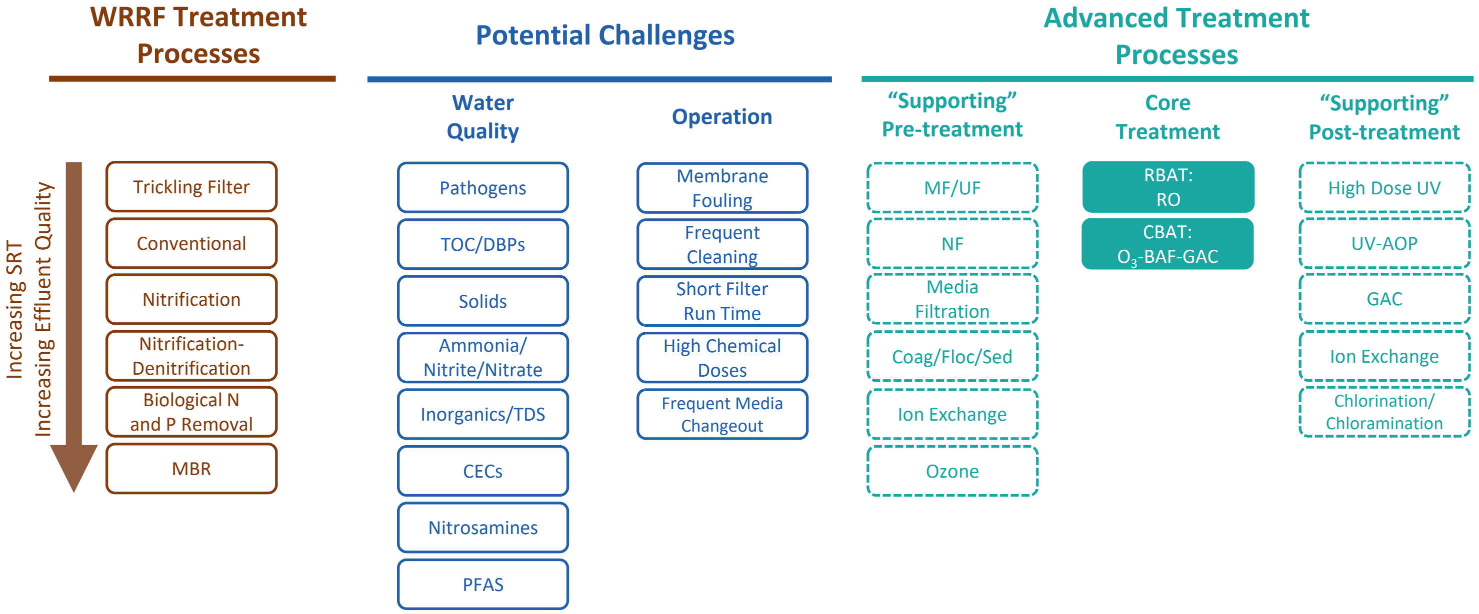
APPENDIX E

Graphical Treatment Scenario Case Studies

Graphical Treatment Scenario Case Studies

A set of hypothetical case studies was developed to illustrate the potential pathways and key considerations that utilities much consider in order to implement potable reuse with a given WRRF treatment process and effluent water quality starting point. The case studies mirror the WRRF-AWT combinations what were evaluated in each of the modules in this project.

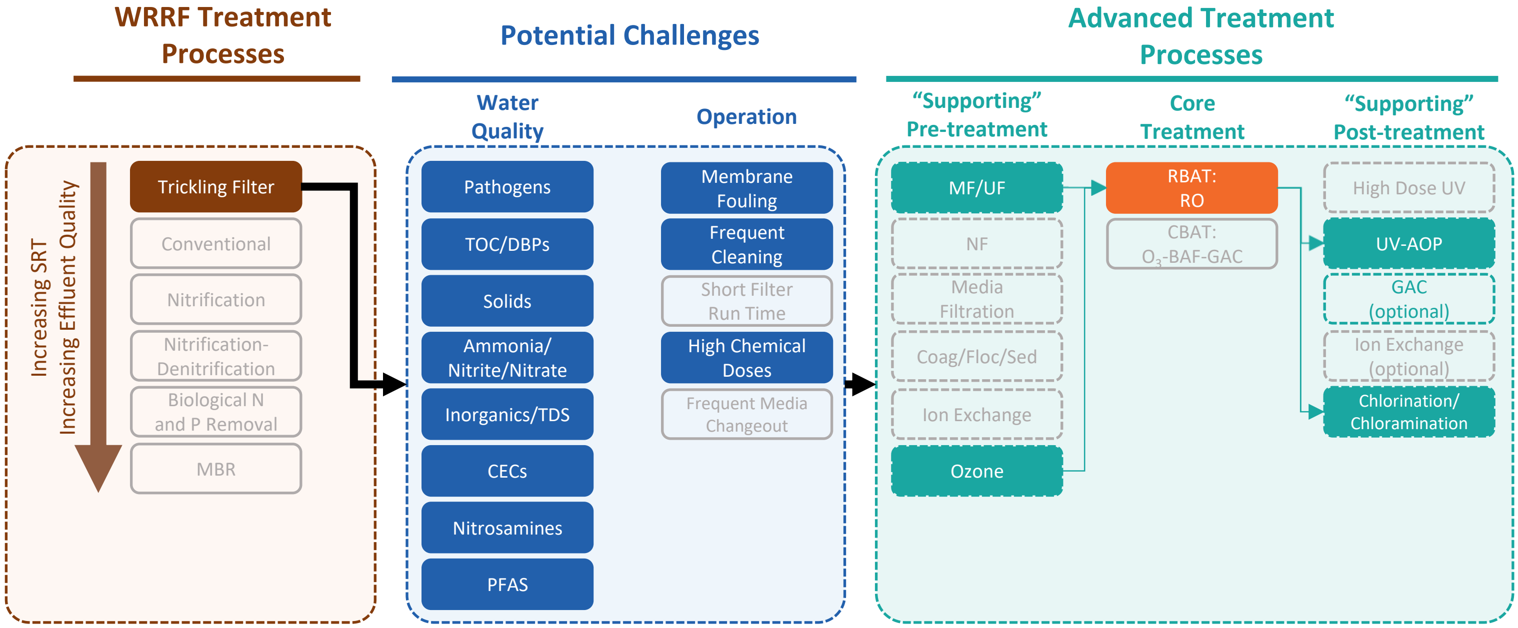


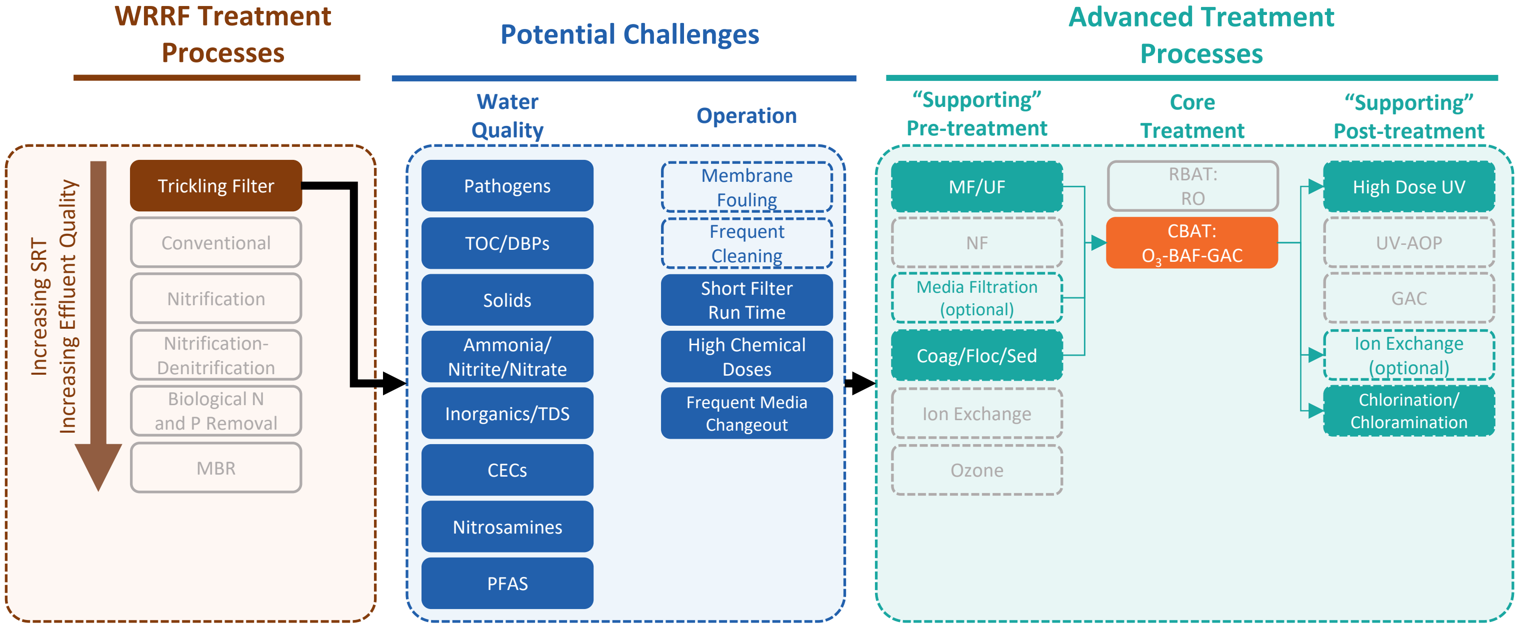
How to chart a course to potable reuse given your WRRF treatment type and starting effluent water quality?

1. Select the type of treatment at your WRRF. Effluent water quality is expected to improve with the level of treatment achieved at WRRF (from trickling filter to MBR). This starting point can reflect your current WRRF type and effluent quality or allow you to select a higher level of WRRF treatment and explore the impact of potential upgrades.
2. Based on the selected WRRT treatment type, these graphical case studies will highlight the anticipated water quality and operational challenges that are associated with the effluent water quality typical to the chosen wastewater treatment approach.
3. Each page provides two scenarios, one for each general AWT approach: RBAT (top) or CBAT (bottom) as noted by which of these is highlighted in orange.
4. Based on the selected WRRF-AWT combination, these graphical case studies highlight water quality challenges encountered with this combination, and the potential pre- and/or post-treatment processes that might be needed to supplement the core AWT processes in order to achieve an acceptable water quality. In general, the more primitive is the WRRF treatment approach, the lower is the effluent water quality, and the more "supporting" treatment barriers would be required to achieved the desired recycled water quality for potable reuse.
5. Twelve WRRF-AWT combinations were reviewed in this study and are shown below as examples.

Scenarios 1&2: **Trickling Filter Effluent in Combination with AWT by RBAT or CBAT**

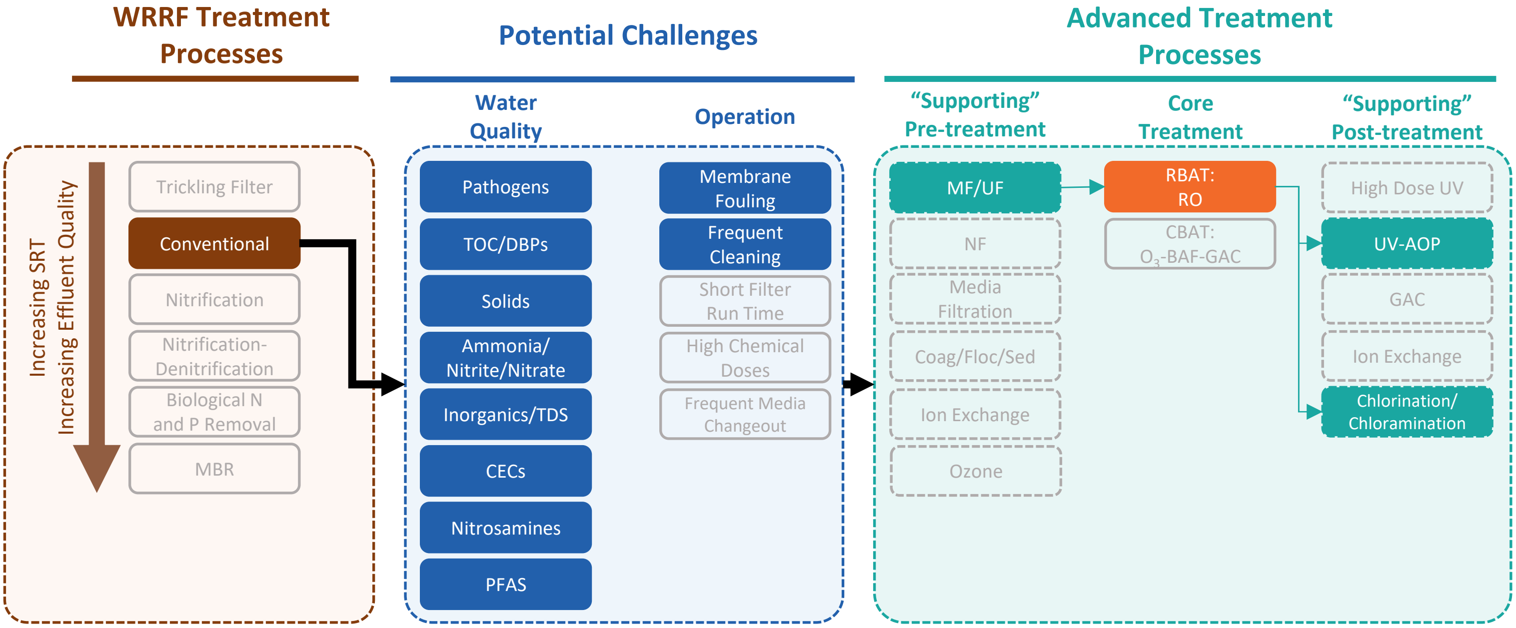
Starting with trickling filter effluent, there still is a pathway to potable reuse but multiple pre- and post- “supporting” treatment processes are needed to achieve the water quality standards for direct or indirect potable reuse.





Scenarios 3&4: Conventional Wastewater Treatment in Combination with AWT by RBAT or CBAT

Starting with conventional wastewater treatment, targeting biological oxygen demand (BOD) removal only.



WRRF Treatment Processes

Increasing SRT
Increasing Effluent Quality

- Trickling Filter
- Conventional
- Nitrification
- Nitrification-Denitrification
- Biological N and P Removal
- MBR

Potential Challenges

Water Quality
- Pathogens
- TOC/DBPs
- Solids
- Ammonia/Nitrite/Nitrate
- Inorganics/TDS
- CECs
- Nitrosamines
- PFAS

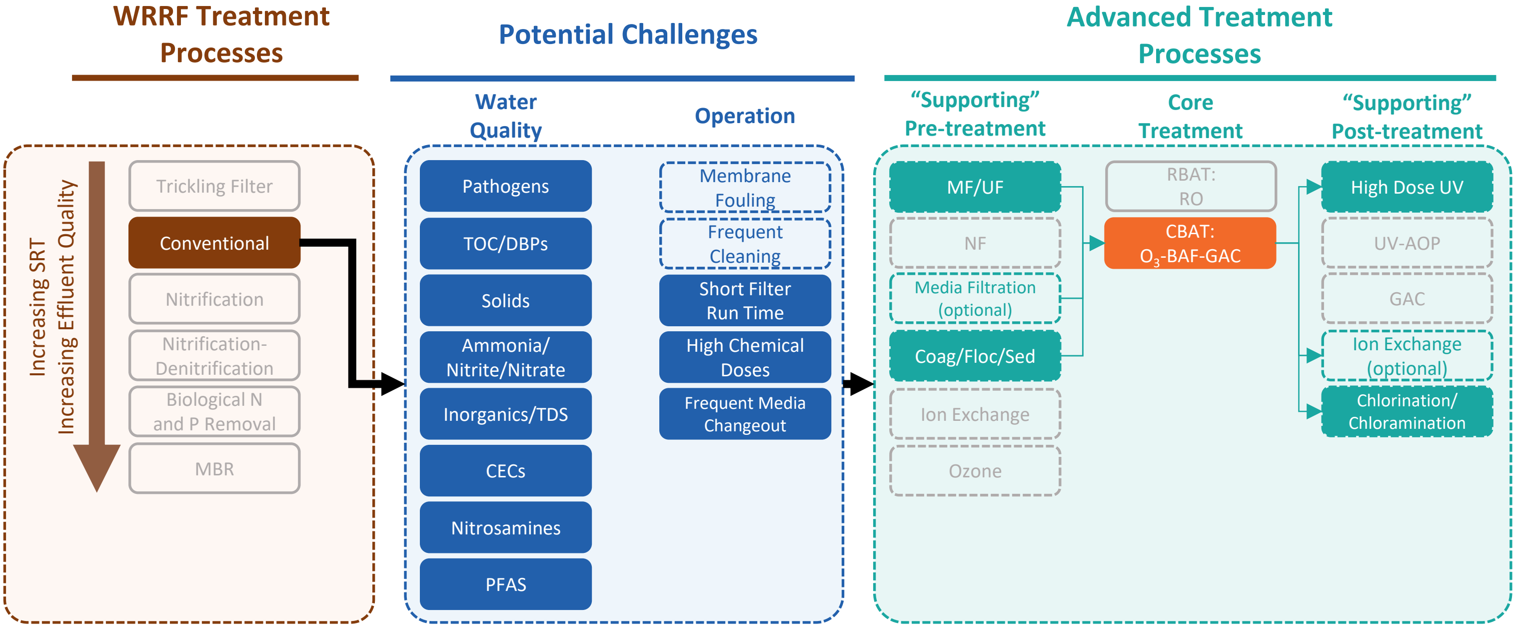
Operation
- Membrane Fouling
- Frequent Cleaning
- Short Filter Run Time
- High Chemical Doses
- Frequent Media Changeout

Advanced Treatment Processes

“Supporting” Pre-treatment
- MF/UF
- NF
- Media Filtration
- Coag/Floc/Sed
- Ion Exchange
- Ozone

Core Treatment
- RBAT: RO
- CBAT: O_3-BAF-GAC

“Supporting” Post-treatment
- High Dose UV
- UV-AOP
- GAC
- Ion Exchange
- Chlorination/Chloramination



WRRF Treatment Processes

Increasing SRT
Increasing Effluent Quality

- Trickling Filter
- Conventional
- Nitrification
- Nitrification-Denitrification
- Biological N and P Removal
- MBR

Potential Challenges

Water Quality
- Pathogens
- TOC/DBPs
- Solids
- Ammonia/Nitrite/Nitrate
- Inorganics/TDS
- CECs
- Nitrosamines
- PFAS

Operation
- Membrane Fouling
- Frequent Cleaning
- Short Filter Run Time
- High Chemical Doses
- Frequent Media Changeout

Advanced Treatment Processes

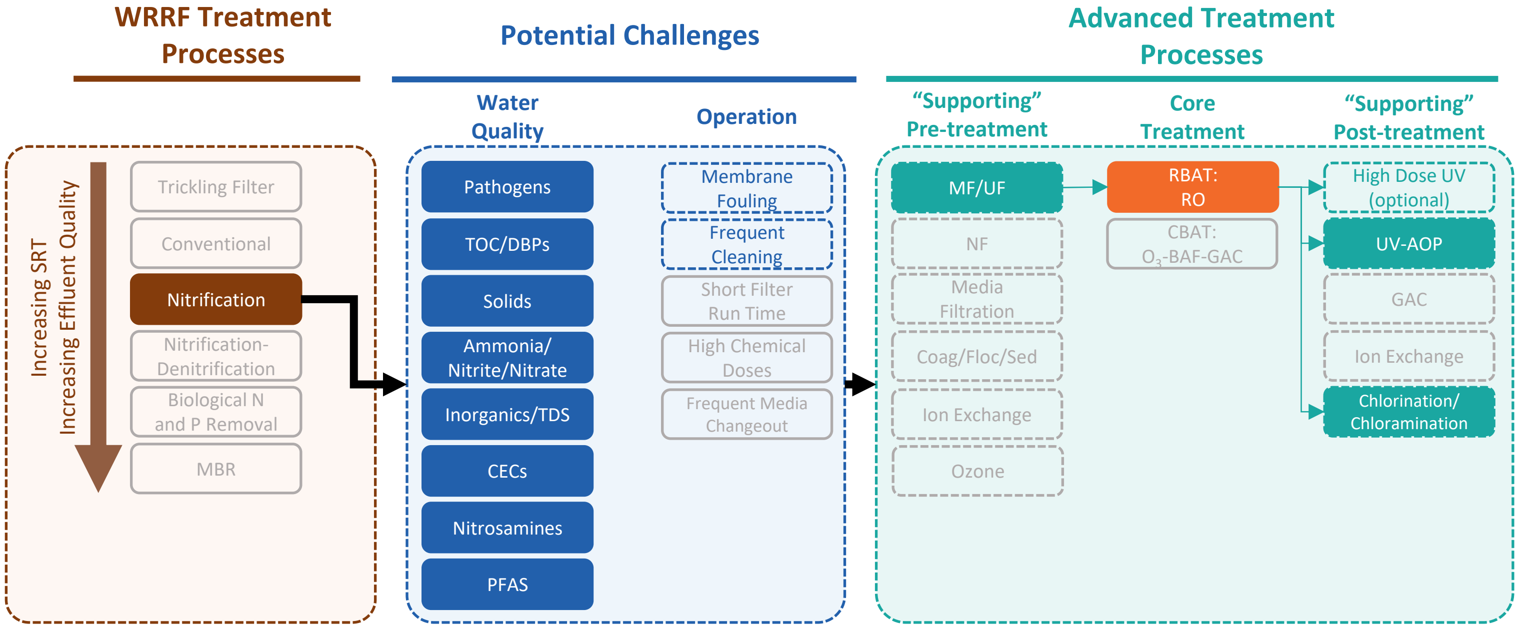
“Supporting” Pre-treatment
- MF/UF
- NF
- Media Filtration (optional)
- Coag/Floc/Sed
- Ion Exchange
- Ozone

Core Treatment
- RBAT: RO
- CBAT: O_3-BAF-GAC

“Supporting” Post-treatment
- High Dose UV
- UV-AOP
- GAC
- Ion Exchange (optional)
- Chlorination/Chloramination

Scenarios 5&6: Nitrified Effluent in Combination with AWT by RBAT or CBAT

Starting with wastewater treatment by activated sludge with nitrification.



WRRF Treatment Processes

Increasing SRT
Increasing Effluent Quality

Trickling Filter
Conventional
Nitrification
Nitrification-Denitrification
Biological N and P Removal
MBR

Potential Challenges

Water Quality

Pathogens
TOC/DBPs
Solids
Ammonia/ Nitrite/Nitrate
Inorganics/TDS
CECs
Nitrosamines
PFAS

Operation

Membrane Fouling
Frequent Cleaning
Short Filter Run Time
High Chemical Doses
Frequent Media Changeout

Advanced Treatment Processes

“Supporting” Pre-treatment

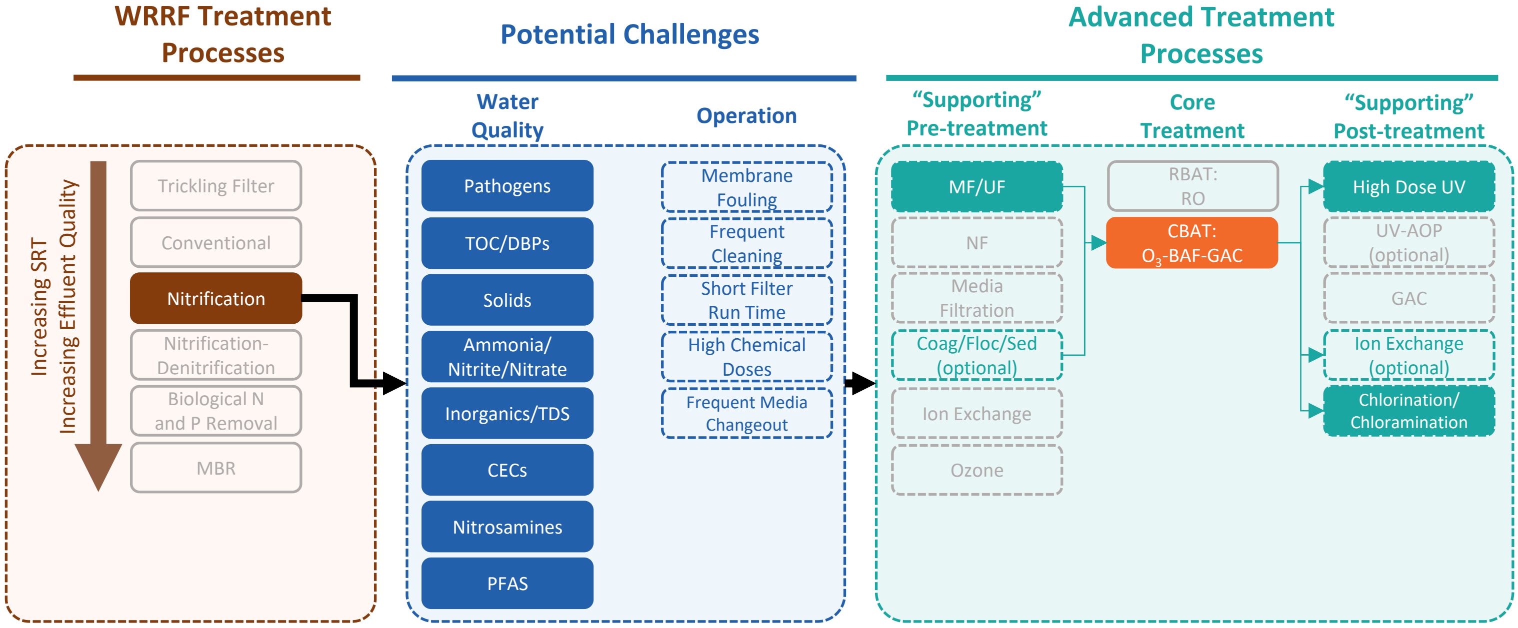
MF/UF
NF
Media Filtration
Coag/Floc/Sed
Ion Exchange
Ozone

Core Treatment

RBAT: RO
CBAT: O_3-BAF-GAC

“Supporting” Post-treatment

High Dose UV (optional)
UV-AOP
GAC
Ion Exchange
Chlorination/ Chloramination



WRRF Treatment Processes

Increasing SRT
Increasing Effluent Quality

Trickling Filter
Conventional
Nitrification
Nitrification-Denitrification
Biological N and P Removal
MBR

Potential Challenges

Water Quality

Pathogens
TOC/DBPs
Solids
Ammonia/ Nitrite/Nitrate
Inorganics/TDS
CECs
Nitrosamines
PFAS

Operation

Membrane Fouling
Frequent Cleaning
Short Filter Run Time
High Chemical Doses
Frequent Media Changeout

Advanced Treatment Processes

“Supporting” Pre-treatment

MF/UF
NF
Media Filtration
Coag/Floc/Sed (optional)
Ion Exchange
Ozone

Core Treatment

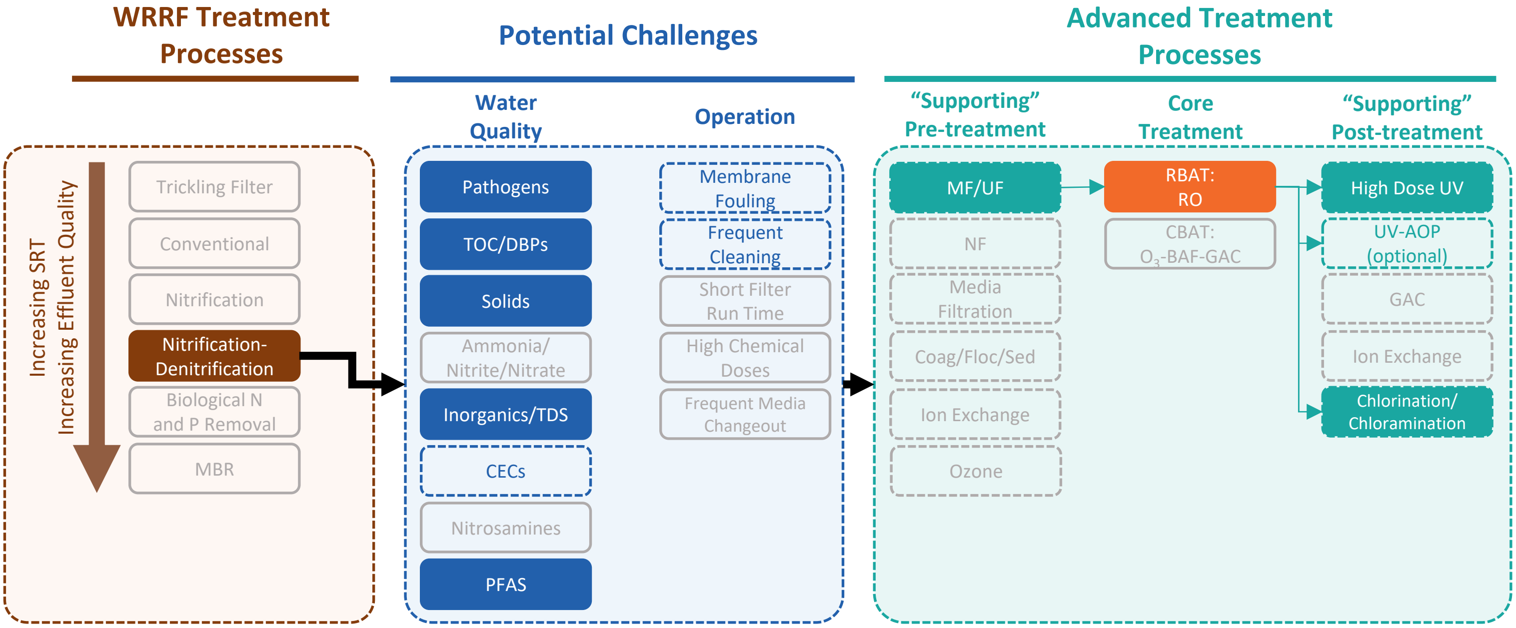
RBAT: RO
CBAT: O_3-BAF-GAC

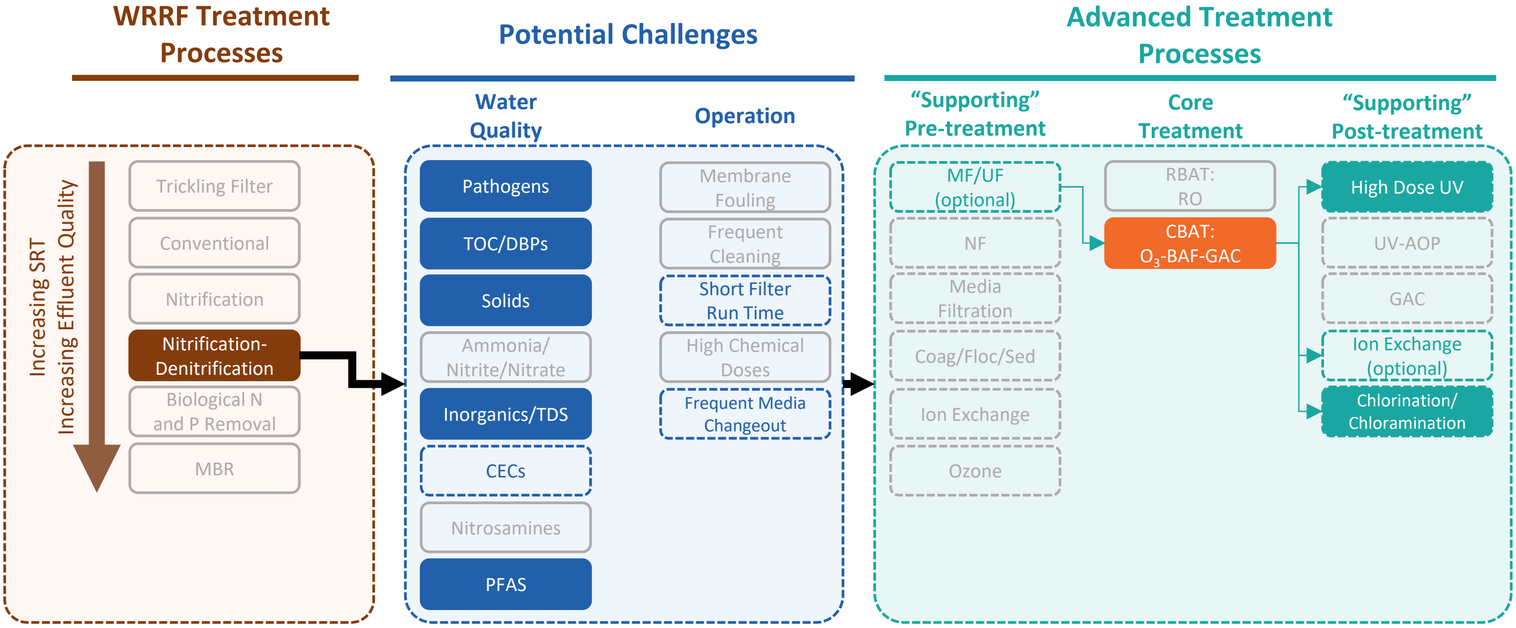
“Supporting” Post-treatment

High Dose UV
UV-AOP (optional)
GAC
Ion Exchange (optional)
Chlorination/ Chloramination

Scenarios 7&8: Denitrified Effluent in Combination with AWT by RBAT or CBAT

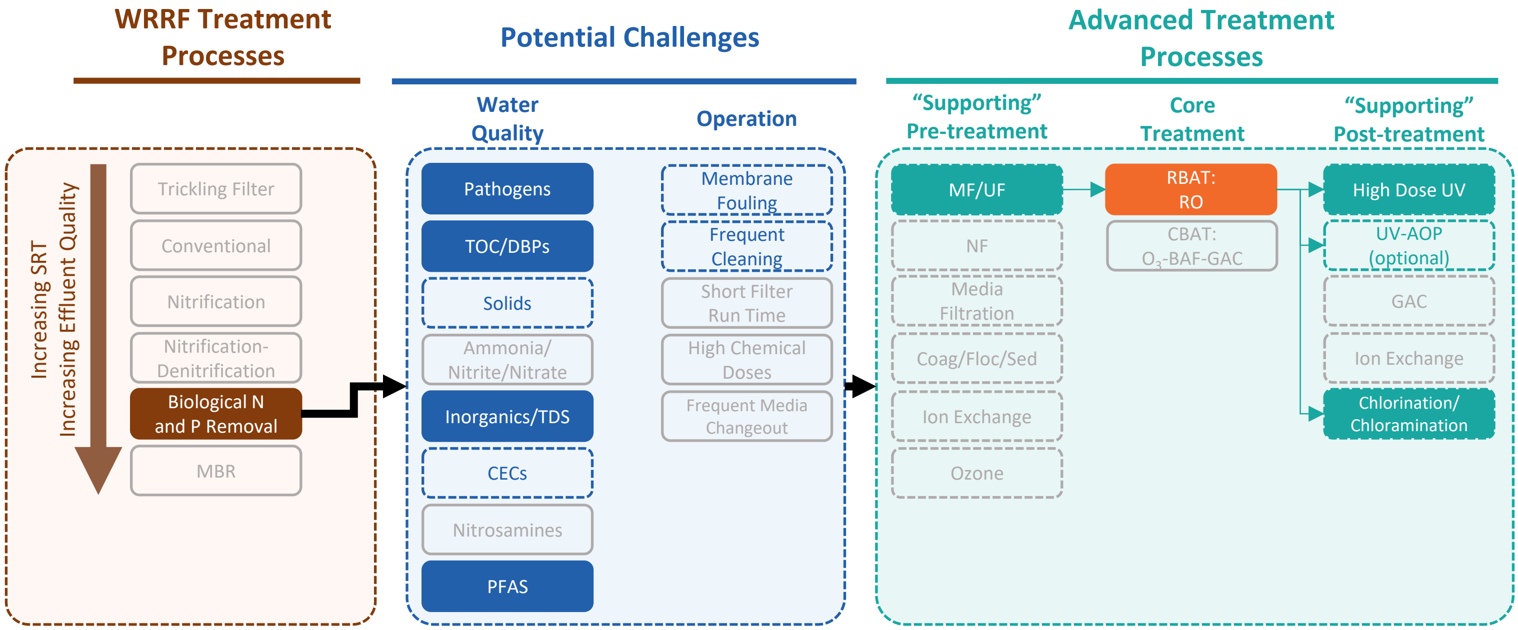
Starting with biological treatment with capacity for both nitrification and denitrification.

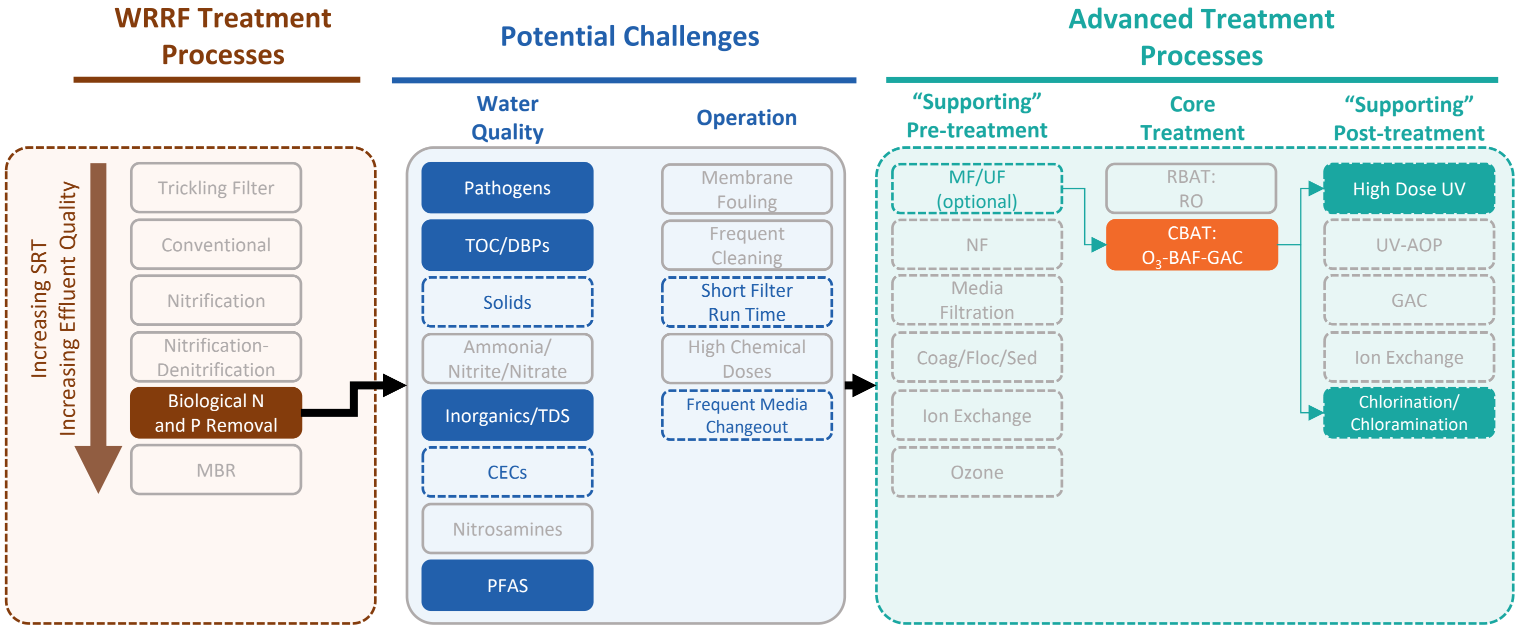




Scenarios 9&10: Biological Nutrient Removal Effluent in Combination with AWT by RBAT or CBAT

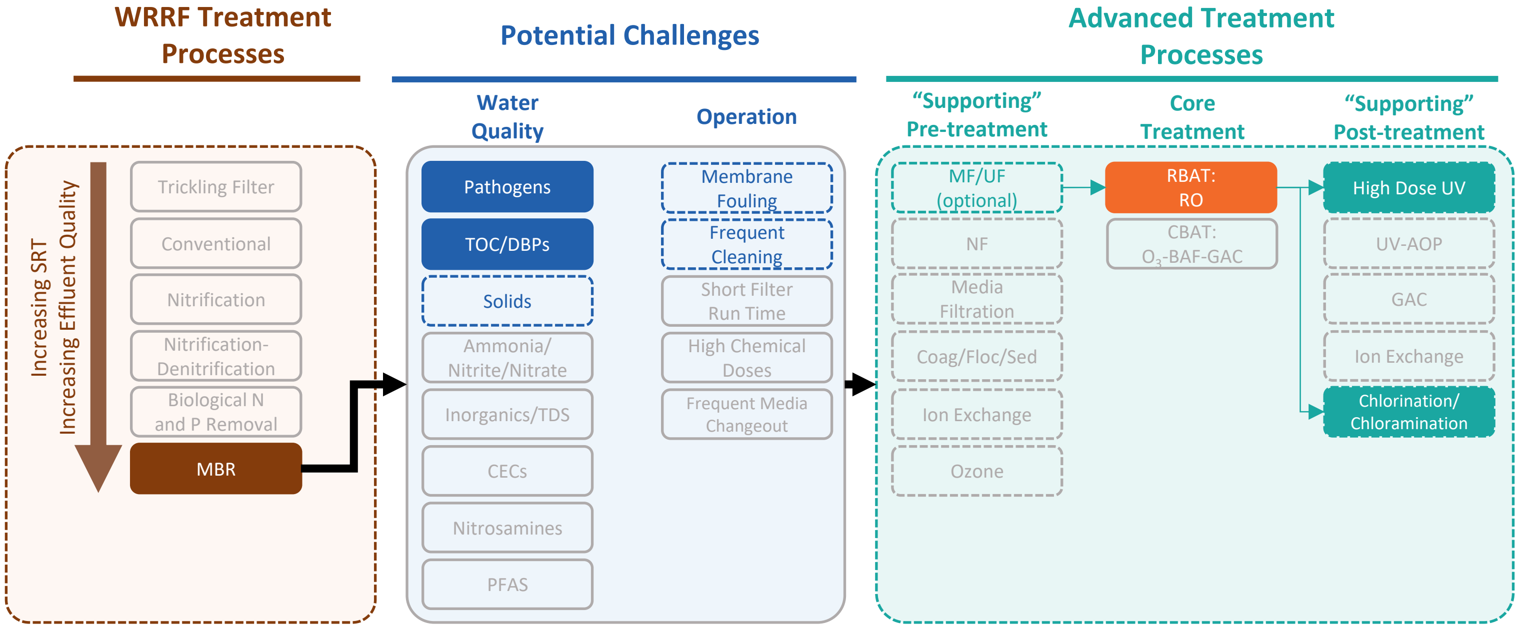
Starting with biological treatment with capacity for both nitrogen and phosphorus removal.

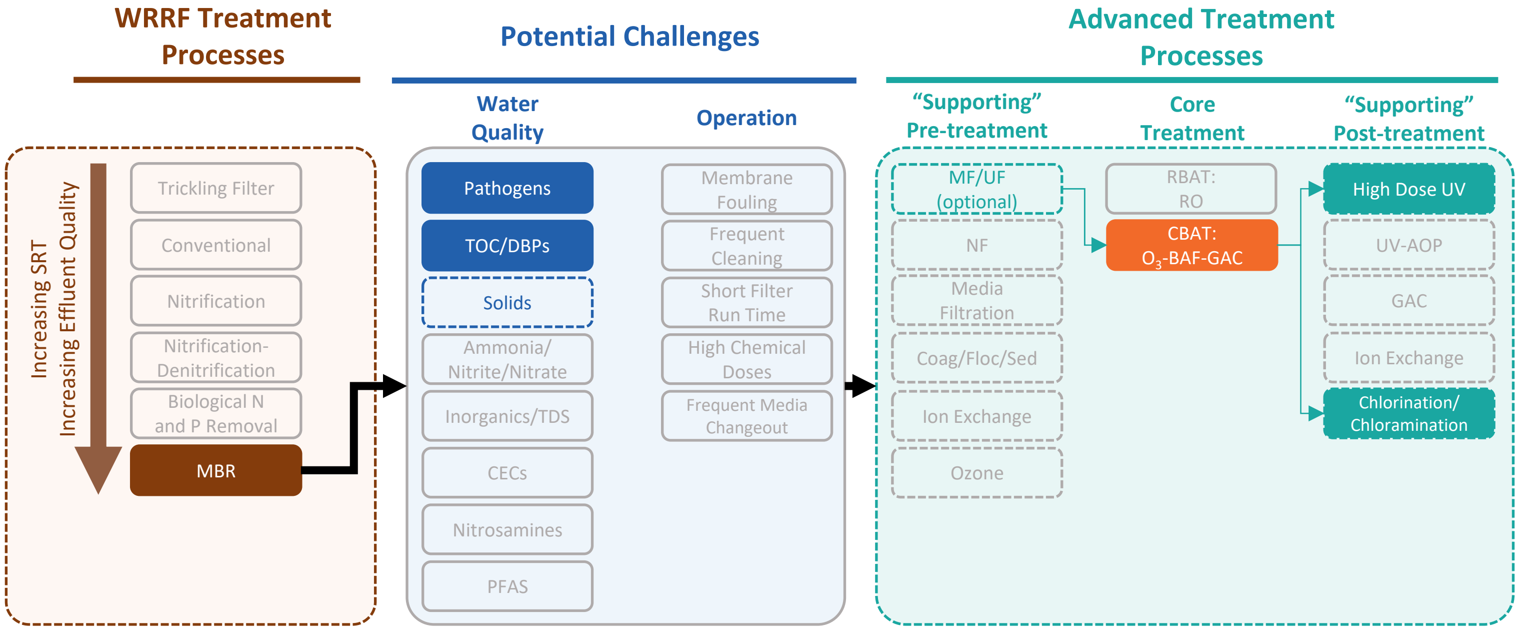




Scenarios 11&12: MBR Effluent in Combination with AWT by RBAT or CBAT

MBR produces high effluent quality and reduces the level of potential water quality and operational challenges for downstream AWT, and the extent of pre- and post-processes required to support RBAT and CBAT.





APPENDIX F

Factsheets

THE Water Research FOUNDATION

From the WRF 4833 Series: *Considering Potable Reuse?*

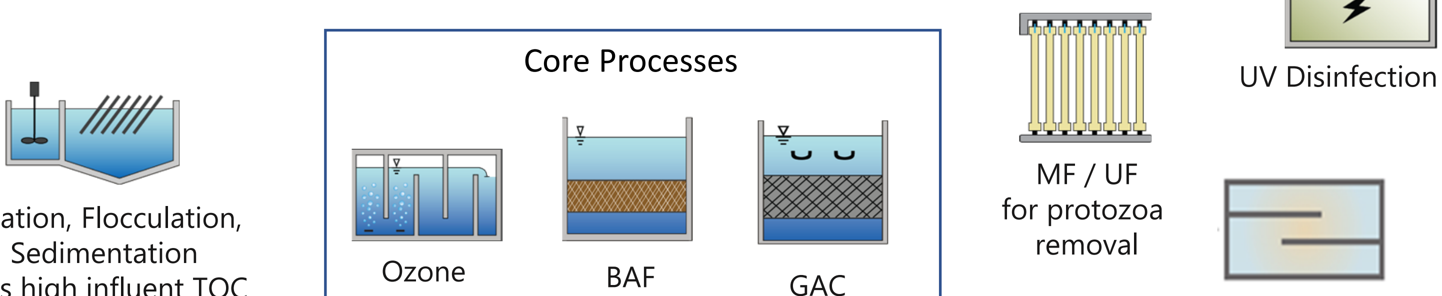
Carbon-Based Advanced Treatment

Is CBAT for potable reuse right for my utility?

Carbon based advanced treatment or CBAT uses core processes consisting of ozone, biofiltration (BAF) and granular activated carbon (GAC), and supporting processes, including disinfection (UV and chlorine), to address chemical and microbial contaminants of concern in potable reuse. Whether CBAT is right for your utility depends on several regulatory and technical factors. If CBAT does not face regulatory barriers in your state and your existing water resource recovery facility (WRRF) produces a high-quality, low salinity, and denitrified effluent, this approach can provide a safe, high-quality purified water at substantial cost savings over reverse osmosis-based treatment.

Even if your WRRF effluent quality is not as high, the core CBAT treatment approach can be augmented by any number of additional treatment steps that can improve water quality and provide additional pathogen barriers. The graphic below illustrates the core CBAT processes, and some additional processes that can help address potential water challenges.

CBAT Treatment: Core and Support Processes



Coagulation, Flocculation, and Sedimentation address high influent TOC

Core Processes

Ozone

BAF

GAC

MF / UF for protozoa removal

UV Disinfection

Chlorine Disinfection

CBAT at Scale

The 60 mgd F. Wayne Hill Water Resources Center in Gwinnett County, GA has been purifying wastewater with the CBAT approach for introduction into Lake Lanier since 2010.

Find out more at: vimeo.com/389473017

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From the WRF 4833 Series: *Considering Potable Reuse?*

Carbon-Based Advanced Treatment

This fact sheet was developed for Water Research Foundation Project #4833, which is a collaboration between Carollo Engineers, Hazen, Southern Nevada Water Authority, and Metropolitan Water District of Southern California, along with over 20 other partner utilities.

The overarching goal of this research project is to help utilities decide the best path towards potable reuse with a given water resource recovery facility (WRRF) treatment configuration and effluent water quality. Five inter-dependent modules were developed around common WRRF-advanced water treatment (AWT) combinations to systematically investigate identified challenges within each WRRF-AWT combination, and how best to address those. Cost trade-offs between investing in WRRF upgrades versus additional AWT were evaluated. While a pure cost perspective would typically drive utilities to make needed improvements to AWT rather than upgrade their WRRFs, case studies revealed that non-cost or non-AWT related factors often provide additional incentive to make improvements at the WRRF as well.

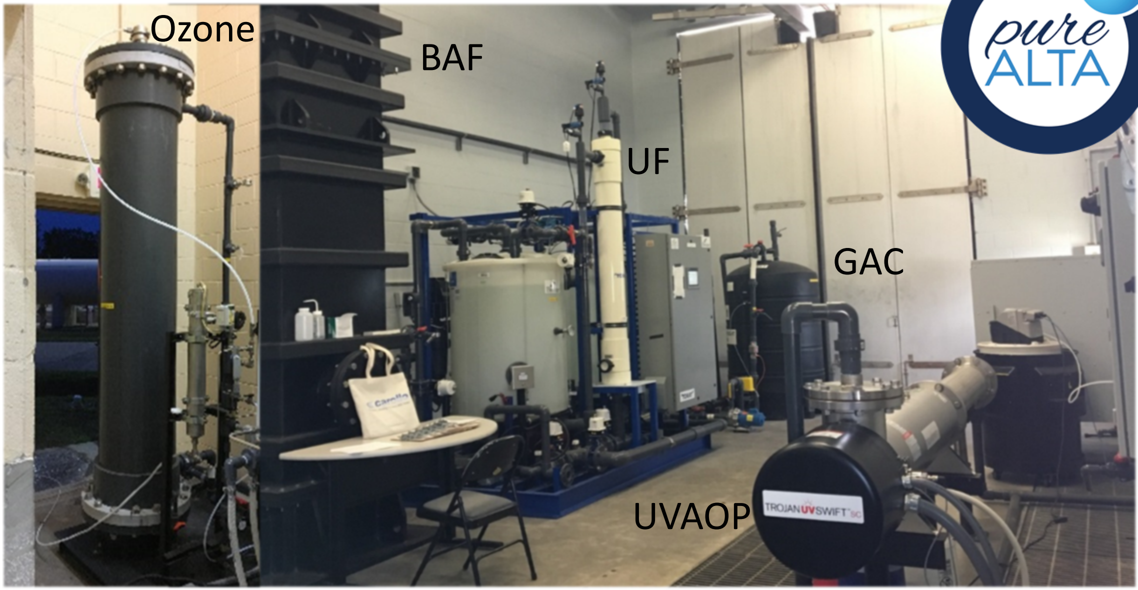
Myth:
"Only reverse osmosis (RO) can provide acceptable water quality for potable reuse."
Reality:
Carbon-based advanced treatment (CBAT), which does not include an RO treatment step, is practiced for potable reuse around the U.S. and the world. Building on many previous studies and projects, this report provides guidance on how to safely implement potable reuse without RO.

Myth:
"CBAT uses only carbon to treat water for potable reuse."
Reality
CBAT involves several treatment steps, typically including ozone, biofiltration (BAF) and granular active carbon (GAC) , and supplemental disinfection steps, such as UV or chlorine. It may also include additional steps micro- or ultrafiltration (UF), conventional treatment (coagulation, flocculation, and sedimentation), or ion exchange.

CBAT for Direct Potable Reuse

In 2017, the City of Altamonte Springs, FL implemented pureALTA, an award-winning direct potable reuse (DPR) demonstration facility using the CBAT approach.

Find out more at:
altamonte.org/754/pureALTA



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From the WRF 4833 Series: *Considering Potable Reuse?*

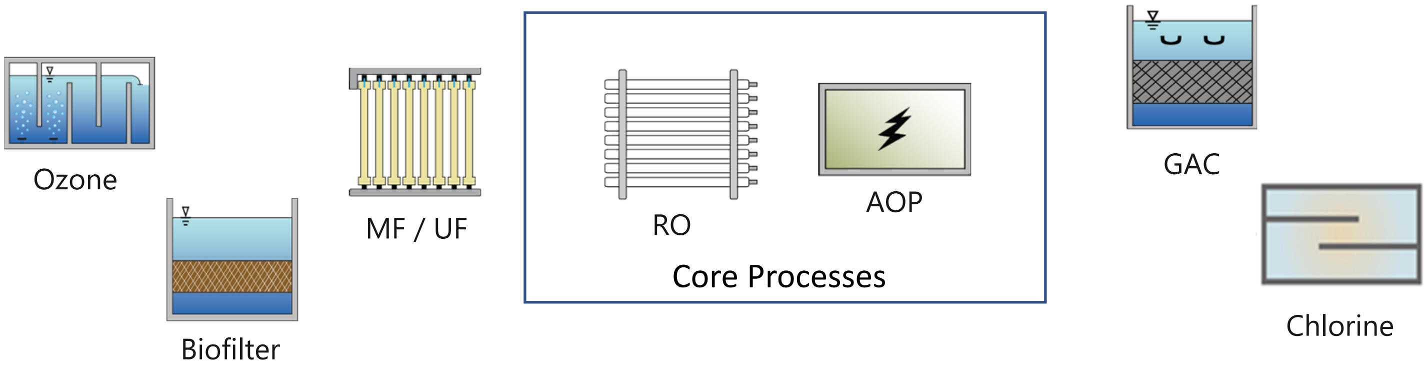
Reverse Osmosis-Based Advanced Treatment

Is RBAT for potable reuse right for my utility?

Reverse osmosis (RO) based advanced treatment or RBAT uses core processes consisting of RO and ultraviolet disinfection with advanced oxidation (UVAOP) along with supporting processes, including micro- or ultrafiltration (MF/UF), ozone, biofiltration (BAF), activated carbon (GAC), and chlorine to address chemical and microbial contaminants of concern in potable reuse. Whether RBAT is right for your utility depends on several regulatory and technical factors. To date, RBAT is the most common approach for potable reuse and may be required by state regulations, or necessary to address specific water quality challenges, such as high salinity.

One significant drawback of the RBAT treatment approach is the production of concentrate from the RO process. This constitutes 15-20% of the total feed flow to the RO process, and requires disposal through ocean discharge, deep well injection, or other costly measures. This means alternatives, such as carbon-based advanced treatment (CBAT), are worth evaluating.

RBAT Treatment: Core and Support Processes



RBAT at Scale

The Orange County Water District in California has been operating its Groundwater Replenishment System since 2008. The ultimate build-out of this MF, RO, UVAOP facility is currently under construction and will increase its capacity from 100 mgd to 120 mgd.

Find out more at: ocwd.com/gwrs

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From the WRF 4833 Series: *Considering Potable Reuse?*

Reverse Osmosis-Based Advanced Treatment

This fact sheet was developed for Water Research Foundation Project #4833, which is a collaboration between Carollo Engineers, Hazen, Southern Nevada Water Authority, and Metropolitan Water District of Southern California, along with over 20 other partner utilities.

The overarching goal of this research project is to help utilities decide the best path towards potable reuse with a given water resource recovery facility (WRRF) treatment configuration and effluent water quality. Five inter-dependent modules were developed around common WRRF-advanced water treatment (AWT) combinations to systematically investigate identified challenges within each WRRF-AWT combination, and how best to address those. Cost trade-offs between investing in WRRF upgrades versus additional AWT were evaluated. While a pure cost perspective would typically drive utilities to make needed improvements to AWT rather than upgrade their WRRFs, case studies revealed that non-cost or non-AWT related factors often provide additional incentive to make improvements at the WRRF as well.

Myth:
"Only reverse osmosis (RO) can provide acceptable water quality for potable reuse."
Reality:
RO membranes are the workhorse of the RBAT treatment approach and provide an excellent product water quality. Additional polishing through UVAOP and other treatment is typically also needed. That said, building on many previous studies and projects, this report also provides guidance on how to safely implement potable reuse without RO.

Myth:
"RO concentrate cannot be discharged except to the ocean."
Reality
RO concentrate is a waste stream produced by the RBAT approach that requires disposal. Many projects must deep well inject, discharge to the ocean, or turn to zero liquid discharge alternatives. But some potable reuse projects, including the example below, discharge their concentrate to inland receiving waters.

RBAT for Direct Potable Reuse

In 2013, the Colorado River Municipal Water District in Texas started operating the first DPR facility in the U.S. Their Raw Water Production Facility uses an RBAT approach consisting of MF, RO, and UVAOP.

Find out more at:
crmwd.org/water-sources/reuse

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From the WRF 4833 Series: *Considering Potable Reuse?*

How can I benefit from my Membrane Bioreactor?

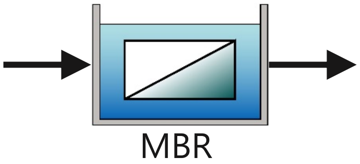
Considering Potable Reuse using MBR Filtrate as a Source?

You're in luck! Membrane bioreactor filtrate is an especially high-quality water source for potable reuse. MBRs provide an effluent that is low in solids and pathogen concentrations.

Benefits specific to reverse-osmosis based advanced treatment (RBAT) include the potential to forego tertiary micro- or ultrafiltration (MF/UF) ahead of the RO process, due to MBR filtrate's low solids content. Our study also summarized ongoing work demonstrating pathogen removal credit through MBRs, which is important if tertiary MF/UF is eliminated and more generally to establish MBRs as substantial pathogen barriers. MBRs with denitrification are especially beneficial for carbon-based advanced treatment (CBAT) as nitrate removal is a challenge for these trains. In all cases, these benefits are contingent upon the MBR system being well designed and operated.

The cost evaluations conducted in our study indicate it is does not make sense to implement MBR based wastewater treatment *only* for the purposes of potable reuse, as the benefits above alone typically do not outweigh the cost of an MBR retrofit.

Benefits of MBR Filtrate as a Source Water for Potable Reuse



1. Low solids (typically <0.2 NTU)
2. Low to non-detectable pathogens
3. Denitrification sometimes already in place

MBR for Potable Reuse in Operation

The Hamby Water Reclamation Facility in Texas uses biological nutrient removal and MBR to produce source water for 7 mgd of advanced treatment, of which 60% passes through RBAT (RO) and 40% passes through CBAT (ozone and biologically active carbon), before being discharged to Lake Fort Phantom Hill, the City of Abilene's drinking water supply.

Find out more at:
abilenetx.gov/455/Wastewater-Treatment

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Myth:
"You can't get pathogen credit for an MBR."
Reality:
MBRs provide pathogen removal through a combination of biological activity, adsorption to solids, and physical separation at the membrane surface. Whether you get credit for that removal depends on the validation requirements in your state. For states that allow you to establish site-specific treatment goals based on source water characterization, the MBR filtrate samples will contain very low pathogen concentrations, resulting in less downstream advanced treatment needed.

Myth:
"MBR filtrate is not suitable as an RO feed."
Reality
MBR filtrate is typically low in solids. Results described in our study show that it can be used as a source water for the RO process without an intermediate MF or UF step. Additional cartridge filter change-outs or RO cleaning may be needed if breaches in the MBR result in higher than usual solids passing through to the RO process.

MBR for Potable Reuse at Scale
The Metropolitan Water District of Southern California and the Sanitation Districts of Los Angeles County operate a Demonstration Project comprising MBR, RO, and UVAOP that will provide the basis for their potential future joint 150 mgd Regional Recycled Water Advanced Purification Center.

Find out more at: mwdh2o.com

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