THE METROPOLITAN WATER DISTRICT OF SOUTHERN CALIFORNIA

Potential Regional Recycled Water Program
Task Order 10 –Direct Potable Reuse Support Services
Agreement No. 183184

Considerations for Direct Potable Reuse Downstream of the Groundwater Recharge Advanced Water Treatment Facility

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1. Introduction and Background

The Metropolitan Water District of Southern California (Metropolitan) and Sanitation Districts of Los Angeles County (Sanitation Districts) are partnering to consider the implementation of a potential Regional Recycled Water Program (Program) to provide a drought-resistant new water source for Metropolitan's member agencies. The potential Program will comply with regulatory requirements for the groundwater recharge (GWR) form of indirect potable reuse (IPR), including an advanced water treatment facility (AWTF) with an anticipated maximum capacity of 150 million gallons per day (MGD) to purify secondary effluent from the Sanitation Districts' Joint Water Pollution Control Plant (JWPCP) located in Carson, California. The proposed GWR AWTF includes a treatment train comprised of membrane bioreactor (MBR), reverse osmosis (RO), and ultraviolet light/advanced oxidation process (UV/AOP).

Metropolitan has also expressed interest in pursuing a form of direct potable reuse (DPR), namely, raw water augmentation (RWA). The 2018 technical memorandum (TM), "Considerations for the Potential Future Integration of Raw Water Augmentation into the Regional Recycled Water Program," discussed the anticipated regulatory and design considerations for pursuing an RWA project. The TM covered various project elements that would likely need to be added or enhanced to move from GWR to RWA including source control, monitoring, blending, and treatment at both the JWPCP and the AWTF. The approach assumed that the GWR treatment train would be enhanced with additional unit processes to augment treatment redundancy and robustness, and that the AWTF product water could be sent directly to either the Weymouth or Diemer Water Treatment Plant (WTP) where it would undergo additional treatment before entering Metropolitan's drinking water distribution system.

While the 2018 TM assumed the additional treatment processes would be placed *prior* to RO and would treat the full flow to DPR standards at the Carson facility, Metropolitan is also considering locating the additional treatment at a *downstream* satellite AWTF (hereby referred to as the DPR AWTF) that would receive a portion of the GWR AWTF product water as a feedwater. Providing treatment for DPR downstream of the GWR AWTF may allow for potential savings because only a portion of the flow would be treated to DPR standards. However, this configuration poses additional challenges that the potable reuse industry has not yet considered in either a design framework or a regulatory framework. In this TM, the following topics will be discussed for a DPR AWTF downstream of a GWR AWTF:

- Potable Reuse Perspective
- Challenges When Using RO Permeate as a Feedwater
- Treatment Options
- Blending
- Considerations for RWA with a Small Reservoir
- Coordination with Other Potable Reuse Projects
- Summary and Next Steps

2. Potable Reuse Perspective

2.1 Forms of Potable Reuse

California has developed regulations for three forms of IPR via groundwater recharge and surface water augmentation (Figure 1, left). While the State Water Resources Control Board (State Board) distinguishes between two forms of DPR—raw water augmentation and treated water augmentation (TWA)—they have recently stated that they will create a single regulatory package that covers all forms of DPR rather than sequential regulations for RWA and then TWA (Figure 1, right) (State Water

Resources Control Board 2019). The State Board intends to complete the DPR regulatory package by December 31, 2023, i.e., in the timeline specified by California Assembly Bill 574 (AB574). While Metropolitan has extensive facilities that would support RWA or TWA, this TM focuses on Metropolitan's implementation of RWA.

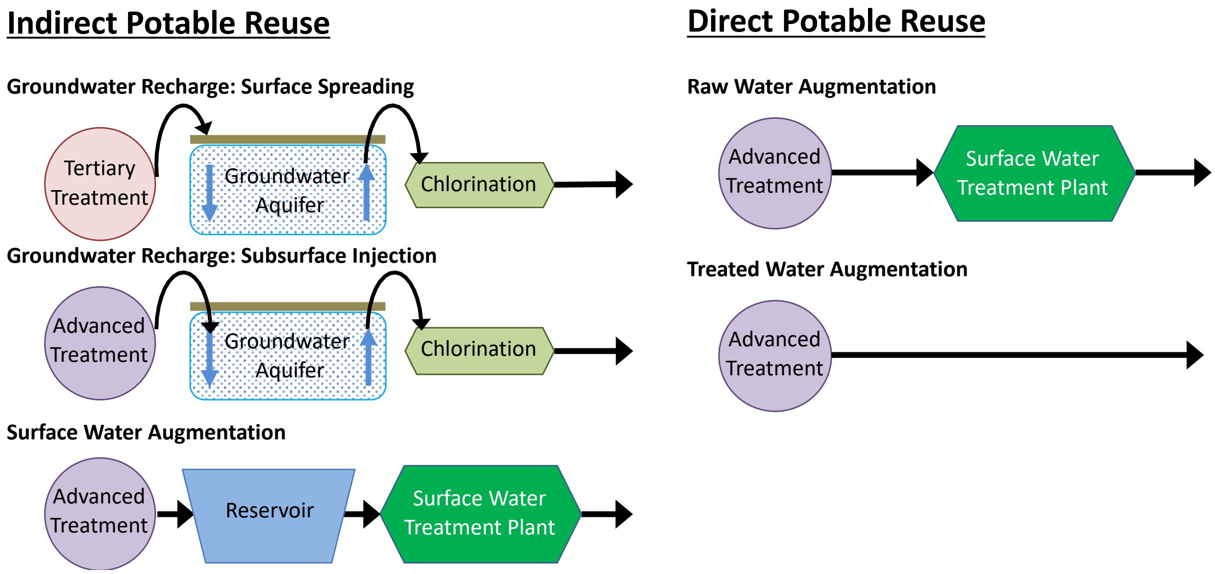


Figure 1. Existing and Anticipated Forms of Potable Reuse in California.

2.2 Considerations for DPR

As potable reuse becomes more direct, the requirements for certain public health elements (e.g., treatment, monitoring, source control) have become more stringent to account for the lost benefits of the environmental buffer, including the lost *time* to respond to any failures in the system. The logic for this shift is that as the proximity between the source and the consumer increases, the tolerance for fluctuations in risk decreases. This is evident, for example, in the increasingly strict requirements for pathogen reduction for each of the forms of potable reuse (Figure 2). This trend is consistent with the precautionary principle, which argues for the use of preventive action in the face of uncertainty (Harremöes et al. 2001).

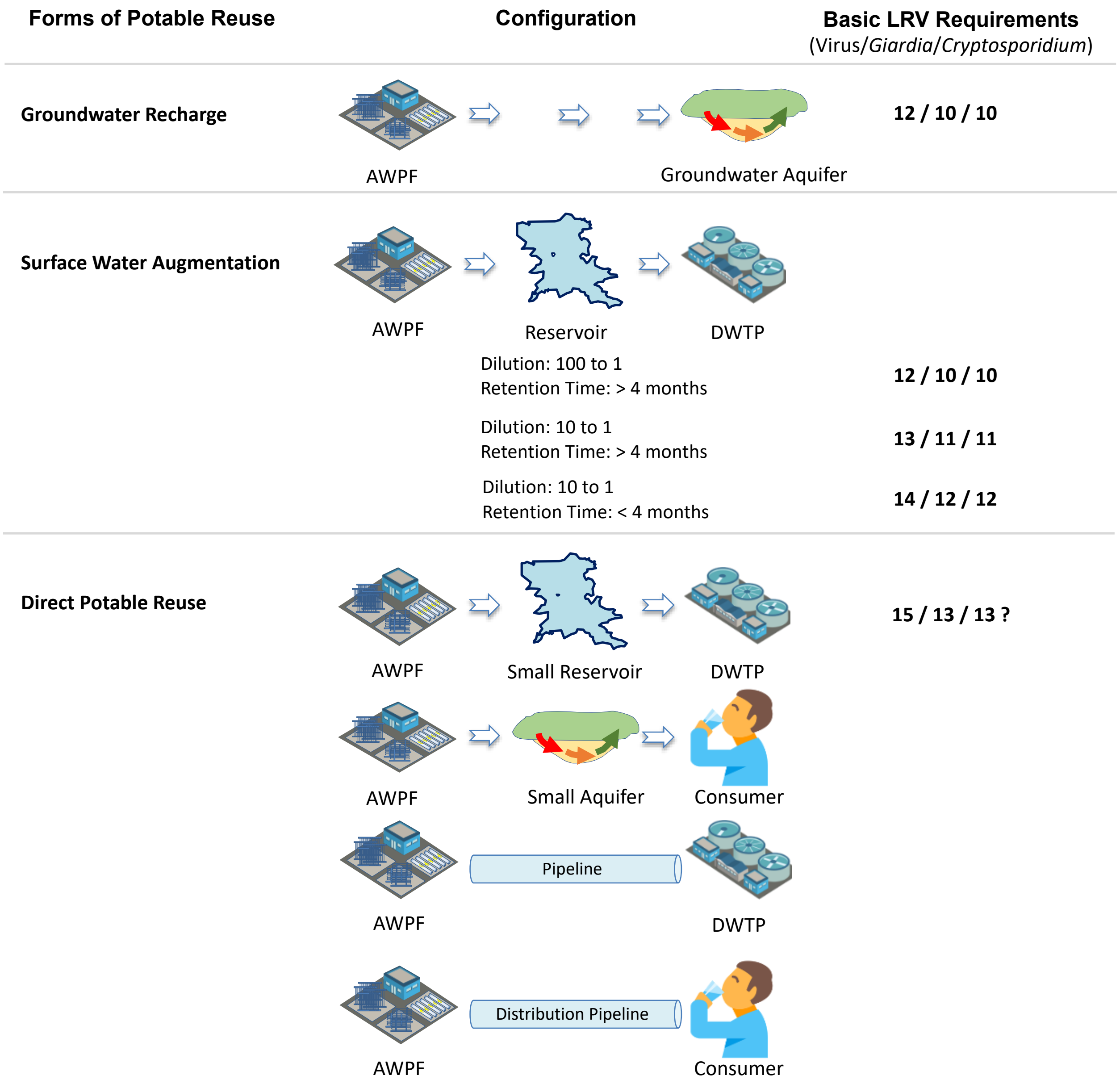


Figure 2. Pathogen Removal Requirements and Predicted Requirements for DPR

Due to the lack of experience with DPR in California, the State Board will likely require that DPR systems address “all” of the possible contaminants, meaning both known and unknown contaminants, in both the chemical and pathogen domains. Additional treatment beyond what is required for IPR will improve water quality and will be important for protecting public health and reducing risks. At some point, however, if additional treatment is *not* improving the robustness and reliability of a system and is realistically only providing minimal additional protection, requirements for investing in additional treatment may not make sense.

Yet, additional treatment is not the *only* way to protect public health in a DPR system. It is crucial that both regulators and water reuse programs look beyond treatment for ways to improve DPR systems.

The benefits of enhanced source control, improved monitoring, blending, diversions, small reservoirs, and storage buffers can all be used to promote public health protection (Figure 3). Multiple, different combinations of these elements can be balanced to provide the same degree of public health protection, such that the lack of one element (e.g., retention time) can be balanced by another element (e.g., monitoring). This flexibility provides project sponsors the option to balance these elements to suit their specific conditions. While this TM provides an in-depth discussion of *treatment* options for a satellite DPR AWTF, it will also provide context for some of the non-treatment or management barriers that can also be leveraged in DPR settings. The State Board's Division of Drinking Water (DDW) emphasizes the importance of management barriers in both the first and second editions of their DPR Regulatory Framework document (State Water Resources Control Board 2018, 2019).

Source Control	Benefits • Reduce concentration of toxic chemicals • Reduce frequency of chemical spikes
Treatment	Benefits • Reduce concentrations of pathogens and toxic chemicals
Diversions	Benefits • Ability to reroute off-spec water prior to reaching consumers
Small Reservoir	Benefits • Significant attenuation of contaminant peaks • Significant time to respond to the production of off-spec water
Engineered Storage Buffer	Benefits • Some attenuation of contaminant peaks • Additional time to respond to the production of off-spec water
Monitoring	Benefits • Confirm effectiveness of treatment barriers • Provides detection of off-spec water events

Figure 3. Potable Reuse Project Elements and their Benefits

These framework documents also provide insight into other considerations and potential requirements for DPR projects. Two particular items should be noted at this time:

- **Aesthetic Considerations for DPR.** In particular, they note the importance of ensuring that the temperature of the advanced treated effluent is similar to existing sources.
- **Water Treatment Plant Impacts.** Because WTPs were not designed to treat RO permeate, DDW has raised two concerns. The first is related to the performance of the WTP and how a purified water may impact WTP Operations (e.g., impact coagulations/flocculation processes). DDW will require site-specific treatability studies to demonstrate that the plant can treat blends of RO permeate with other waters. The second is related to pathogen credits, and how to (or if it is appropriate) credit WTP processes for treatment of purified water. DDW's new framework for the role of WTPs will require more rigorous validation of the treatment processes at the WTP—similar to what is required at AWTFs—to receive pathogen reduction credits.

2.3 Regulatory Timeline for DPR

The State has been considering the development of DPR regulations for many years. In 2010, DPR was formally defined by Senate Bill (SB) 918 and in 2013, SB322 mandated the investigation of the feasibility for developing DPR criteria. In 2016, the State's Expert Panel concluded that it was feasible to develop uniform criteria for DPR and identified six priority DPR research topics. Subsequently, DDW also concluded that it was feasible to develop uniform criteria for DPR. In 2017, Assembly Bill (AB) 574 mandated regulatory development for DPR. In 2018, DDW published the first edition of their proposed framework for regulating DPR, and in 2019, they updated the proposed framework with a second edition. In this second edition, they stated that they intend to develop one set of DPR regulations (for both RWA and TWA) by 2023. A summary of this timeline is shown in Figure 4.

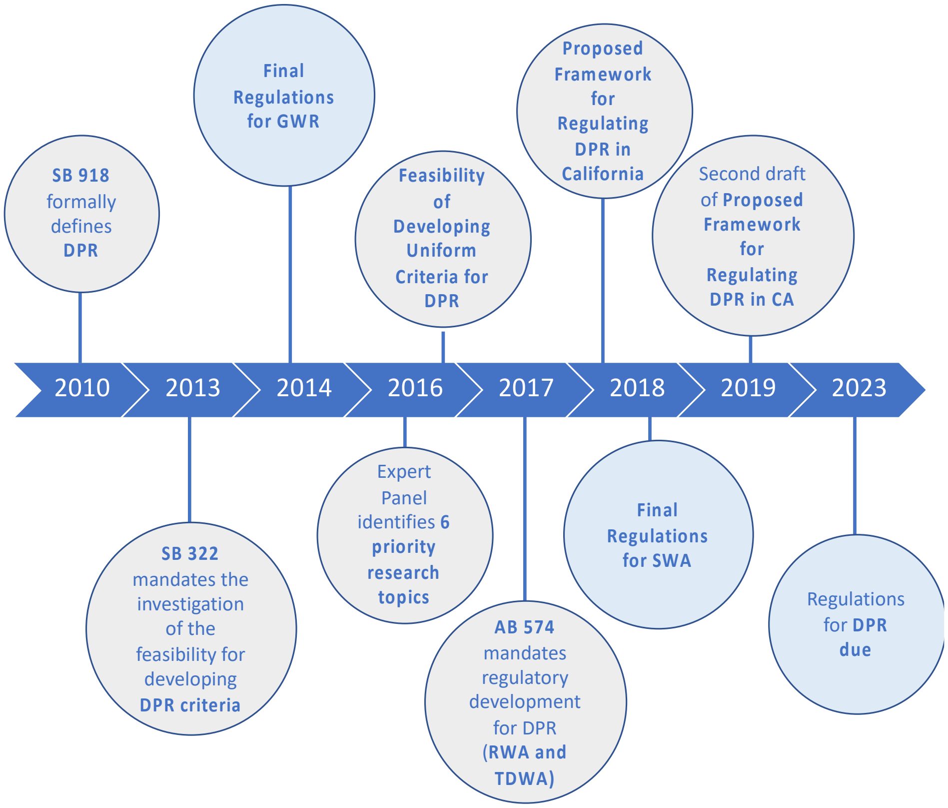


Figure 4. Timeline for DPR Regulations

While DDW was developing the proposed framework for regulating DPR, the six priority research projects recommended by the State Expert Panel started in 2018. The Water Research Foundation (WRF) is leading the research initiative for five of the six research topics:

- **DPR-1: Probabilistic Analysis of Treatment Train Performance and Quantitative Microbial Risk Assessment.** This project is developing tools to assist DDW in their assessment of treatment criteria and public health risk. The project will be completed in 2021.
- **DPR-2: Pathogen Monitoring in Raw Wastewater.** This project has developed methods for analyzing pathogens in raw wastewater and has started a sampling campaign to collect data about the concentrations of pathogens in raw wastewater. This project is ongoing and will be completed in 2021.

- **DPR-3: Collecting Pathogens in Wastewater during Outbreaks.** This project is investigating the feasibility of collecting raw wastewater pathogen concentration data associated with community outbreaks of disease. This project is ongoing and will be completed in 2021.
- **DPR-4: Treatment Processes for Averaging Chemical Peaks.** This project aimed to identify suitable treatment options for final treatment processes that can provide "averaging" with respect to potential chemical peaks. This project evaluated options beyond treatment as well such as source control and blending. This project will be completed in 2021.
- **DPR-5: Low Molecular Weight Unknown Compounds**. This project aimed to evaluate potential analytical methods for assessing unknown contaminants, such as non-targeted analysis (NTA), to identify contaminants not presently detected by current monitoring approaches, particularly low molecular weight compounds that may occur in wastewater and may not be removed by advanced treatment. This project has been completed.

The final research topic, source control, has been addressed by a panel of experts assembled by the National Water Research Institute (NWRI). The panel developed a report with recommendations for how source control can be a protective element for DPR projects. The panel report has been completed.

With the research projects wrapping up, the next steps for DPR regulation development are to assemble an Expert Panel that will assist DDW in the development of the regulations. The State is in the process of assembling the Expert Panel and is expected to begin engaging the Panel in 2021. It is expected that draft regulations will be released in 2022 and final regulations developed by the end of 2023.

3. Challenges When Using RO Permeate as a Feedwater

Metropolitan and the Sanitation Districts have proposed utilizing MBR-RO-UV/AOP for pursuing GWR and are now considering sending a portion of this effluent through a transmission system to a DPR AWTF. In this configuration, additional unit processes would be required to treat this unique water source—an AOP-treated RO permeate. Before discussing treatment schemes, it is important to understand the challenges associated with using RO permeate as a feedwater, particularly given the traditional placement of RO near the end of potable reuse treatment trains. This section provides perspective on the industry's experience in this setting and the anticipated treatment and monitoring challenges.

3.1 Industry Experience

Historically, municipal drinking water treatment has not included the use of RO—or other high-pressure membrane processes like nanofiltration—except for the desalting of high TDS groundwater or the removal of color and DBP precursors from waters with very high TOC. When RO is used in these applications, the only additional treatment provided is typically some form of disinfection to maintain a residual during distribution. With the pursuit of potable reuse, however, RO has become a staple for treating municipal wastewaters to meet the public health standards for potable uses.

RO is a powerful process that can remove a large suite of contaminants that are otherwise difficult to remove such as pharmaceuticals, personal care products, household chemicals, and others. RO typically receives a membrane-filtered feedwater, as membrane filtration (MF) pre-treatment has been shown to improve RO performance and reduce the fouling of the RO membranes. These two processes provide excellent protection against pathogens, particulates, TOC, and pharmaceuticals, though certain chemical compounds have been shown to pass through.

For example, in 2002, 1,4-dioxane was detected in the product water of the Orange County Water District's (OCWD's) Groundwater Replenishment System (GWRS) above the California Department of Public Health's (CDPH, now DDW) action level. The molecular weight of 1,4-dioxane is 88 g/mol, which makes it small enough to partially pass through RO (Drewes et al. 2006). OCWD also found problems with NDMA passing through RO, another small (74 g/mol), uncharged compound, as well. As a result of these findings, the GWR regulations were modified to include requirements for AOP that effectively introduced two additional mechanisms of contaminant control, namely, photolysis and advanced oxidation. The experience with NDMA and 1,4-dioxane had two lasting outcomes: (1) it further reinforced the benefits of treatment robustness (i.e., the use of a *diversity* of mechanisms to reduce contaminants) and (2) it highlighted the importance of also considering the chemicals that are not the focus of existing regulations, i.e., the new, emerging, or "unknown" contaminants.

The industry continues to focus on and gain new understanding about the types of chemicals that may be poorly removed through the full advanced treatment (FAT) train (MF-RO-UV/AOP). For example, an acetone spike was detected in the OCWD product water in 2013 (OCWD 2013), and additional investigations have shown that RO provides incomplete protection against pulses of formaldehyde and other small, uncharged compounds (Tackaert et al. 2019). Water Research Foundation (WRF) Project 14-19 further characterized the compounds of interest as those with halogenated substituents and carbon-carbon double bonds (such as disinfection byproducts and industrial compounds) that are not well removed by RO (Howe et al. 2019). In brief, there are compounds that are poorly rejected by RO and can persist even through UV/AOP processes, particularly if they enter the AWTF in spike events. Without the benefits of an environmental buffer that can dampen and attenuate contaminants, DPR treatment trains will be required to provide additional barriers (either treatment or management barriers or both) against chemicals that pass through the FAT train. This protection is as important for the compounds that are known to pass through as for those unknown compounds that may be identified in the future. The benefits of different treatment options in the control of these contaminants are discussed in Section 4.

To deal with treatment issues and the challenges of more direct forms of reuse, the industry has already begun evaluating modifications to the standard MF-RO-UV/AOP treatment train. Additional treatment has been included to mitigate source water challenges and to increase the redundancy and robustness that is required when moving to more direct forms of reuse. In each case, however, the additional treatment barriers have been added prior to RO. For example, Monterey One Water and West Basin Municipal Water District use ozone pre-treatment prior to membrane filtration to control fouling of the MF and improve removal of constituents of emerging concern (CECs). This application is particularly effective when using challenging secondary effluents. The City of San Diego's 34 MGD North City AWTF treats tertiary filtered water with ozone/biologically activated carbon (BAC) prior to membrane filtration to enhance treatment as follows: (1) additional pathogen reduction through ozone, (2) improved performance of downstream membrane processes (both MF and RO), and (3) improved reduction of low-molecular weight compounds such as acetone and formaldehyde (Tackaert et al. 2019).

Including these additional treatment barriers prior to RO has been the industry standard. The philosophy is to (1) reduce particulates, TOC, pathogens, and any challenging low-molecular weight chemicals as much as possible prior to RO, (2) use RO as the workhorse to effectively reduce the great majority of organic contaminants, and (3) use UV/AOP as a final polishing step. The reuse industry has little experience including additional treatment to address contaminants downstream of the RO process.

While the municipal water and wastewater industries have limited experience with treatment after RO, there are a handful of applications where such treatment is applied. Groundwaters that are contaminated with toxic compounds are sometimes treated by both RO and additional polishing steps. For example, granular activated carbon (GAC) has been used downstream of RO to provide additional protection against 1,2,3-TCP at groundwater sites where this compound is consistently detected at levels above health thresholds. Two other industries require “ultrapure” water that requires treatment beyond RO: the pharmaceutical industry and the semiconductor/microchip fabrication (or FAB) industry. Both of these industries require water in its purest form to create their products. While these industries have experience further treating RO permeate, the water quality standards these industries require result in water that would actually be considered a solvent and would be unsafe to drink (Fishman 2011). While municipal water and wastewater industry may be able to tap into some of the research that has been done by these industries to better understand the process of further treating RO permeate, the source water for these facilities is typically supplied from a municipal drinking water system, not a municipal wastewater system, so the challenges faced in a potable reuse setting would likely be different.

3.2 Water Quality Challenges

Due to the municipal reuse industry’s inexperience using RO permeate as a feedwater, there will likely be unique water quality and treatment challenges that will require additional research and potentially new design concepts. This section highlights potential challenges related to the monitoring of treatment performance, the design of processes treating RO permeate, and the potential deterioration of water quality as the effluent is transmitted from the GWR AWTF to the DPR AWTF.

3.2.1 Monitoring Treatment Performance

One of the most challenging aspects of treating RO permeate is determining how to continuously monitor unit process performance in a water that is essentially void of many traditional surrogates used for monitoring. This is a key concern because regulations often require that unit processes be continuously monitored to ensure they are performing at the intended design level. This type of monitoring requirement is anticipated for DPR as well (Olivieri et al. 2016), particularly for dealing with the acute public health threat from pathogens, but also for toxic chemicals.

3.2.1.1 Monitoring for Pathogen Reduction Crediting

Continuous monitoring is required to quantify the pathogen protection that is provided by each credited unit process. Rather than continuously measure pathogen reduction directly (an approach that remains technically infeasible), water quality parameters such as turbidity and conductivity are used as surrogates. These surrogates are correlated with pathogen reduction using frameworks that have been established by various regulatory bodies including the US EPA and the California Division of Drinking Water. These crediting frameworks have been developed assuming the use of municipal wastewater as the AWTF source water, i.e., a water containing high levels of numerous constituents that can be used in surrogate crediting frameworks. At a DPR AWTF fed with RO permeate, however, the options for surrogates are limited due to the extremely low levels of any kind of colloidal, particulate, and dissolved constituents in the water.

Table 1 shows the surrogates that are typically used to demonstrate pathogen reduction for common AWTF unit processes. For the disinfection processes—UV, ozone, chlorine—the traditional pathogen crediting schemes using CT or UV dose would still be viable options at the DPR AWTF. The filtration processes, however, would require a different approach. Traditional surrogates like turbidity, conductivity, total organic carbon (TOC), and strontium would no longer be present in concentrations high enough to detect using standard online monitors and methods. In lieu of these traditional approaches, additional research would be required to understand what new parameters or higher-sensitivity instrumentation could be used.

Table 1. Comparison of available surrogates for pathogen monitoring with municipal wastewater or RO permeate as a source water

Unit Process	**Surrogates available if source water is *municipal wastewater***	**Surrogates available if source water is *RO permeate***
Disinfection and Oxidation Processes		
UV/AOP	UV Dose UVT	UV Dose UVT
Ozone	Ozone CT	Ozone CT
Chlorine	Chlorine CT	Chlorine CT
Filtration Processes		
Membrane filtration	Indirect Integrity: Turbidity Direct Integrity: Pressure Decay Test	Indirect Integrity: n/a Direct Integrity: Pressure Decay Test
Reverse osmosis	Conductivity Total Organic Carbon Strontium	Research needed. Conductivity measurements may still be possible, or potentially an added marker or tracer such as TRASAR or sugar.
Activated Carbon-Based Processes[a]		
GAC	n/a	n/a
BAC	n/a	n/a

[a] There is no pathogen crediting framework for GAC or BAC in California.

3.2.1.2 Monitoring for Chemical Control

DPR facilities will also be required to monitor the removal of chemical constituents of concern, trace organics, and chemical peaks that may breakthrough (State Water Resources Control Board 2018, Olivieri et al. 2016). Rather than sample for every chemical or constituent of concern, indicator compounds and surrogates are monitored (Drewes et al. 2018). The indirect potable reuse regulations (groundwater recharge and reservoir augmentation) require monthly and quarterly sampling for specific indicator compounds, as well as the continuous monitoring of TOC or another surrogate to verify the performance of RO and the removal of trace organics.

This type of surrogate monitoring presents a challenge for treatment processes at the DPR AWTF due to the use of RO permeate as the feedwater. The typical surrogates, TOC and conductivity, would not be present at concentrations high enough in the feedwater to allow demonstration of meaningful reduction across a process without the use of exceptionally sensitive analyzers. Such analyzers are not currently utilized at potable reuse facilities, and additional research would be needed to understand if there are instruments sensitive enough to serve in a post-RO application.

There are several parameters that may be viable surrogates, but research would be required to show that the surrogates can be detected in both the feedwater and product water of the various treatment processes. Some emerging detection techniques to consider include fluorescence, ATP, flow cytometry, and particle counts. That said, the use of any new parameter would require a significant degree of testing and research to ensure that analyzers are capable of providing reliable detection in the influent and effluent of a treatment process or treatment train, and that benchmarks can be established that would confirm whether treatment goals are met.

3.2.2 Treatment Design Challenges

As new sources of water have been used to produce potable waters, the industry has evolved design standards adapted to each new source water. For example, membrane filter design varies significantly depending on whether they receive surface water, groundwater, or treated wastewater effluents as their feedwaters. The lack of experience treating RO permeate suggests that testing would be needed to guide the selection, design, and optimization of unit processes in this application. One of the major challenges of treating RO permeate will be the selection of a treatment train that provides both value and effectiveness. When starting with such a pure feedwater, it will be difficult to determine how to properly size, operate, and design some processes:

- What is the basis for sizing and design?
- What does proper operation and maintenance look like?
- What chemical feed doses will be required?
- Are the additional processes enhancing robustness in a cost-effective manner?

For example, the use of granular activated carbon is often considered as a final polishing step for DPR AWTFs. However, there are no criteria for how to size this process or how to assess and monitor its performance in this application. Pilot testing would provide valuable information on many of these issues, including the empty bed contact time (EBCT) needed, the rate of contaminant breakthrough, and the change-out frequency in this water quality matrix. Surrogates and indicators would also need to be identified in order to track performance. This situation departs from other post-RO applications—such as the use of GAC to remove groundwater contaminants after RO—because there may not be a constant, high level of a known contaminant (such as 1,2,3-TCP) to assess performance and change-out frequency. Some of the design challenges for the proposed treatment options are discussed in Section 4. Given the lack of experience using RO permeate as feedwater, treatment and design assumptions would need to be evaluated through testing or designed with a high degree of conservatism.

3.2.3 Challenges in the Transmission Line

After the GWR AWTF, the product water would travel through a transmission pipeline to the DPR AWTF where it would receive further treatment. While this may seem straightforward, there are several challenges to consider as this water travels and becomes the source water for the DPR AWTF.

3.2.3.1 Reformation of Nitrosamines

One of the challenges to consider is the potential for nitrosamine reformation within the transmission line, particularly NDMA. NDMA is reduced by 20% to 60% through RO, but is not completely rejected due to its polarity and low molecular weight (Fujioka et al. 2012, Plumlee et al. 2008). However, NDMA is highly photosensitive, and is well-removed through UV/AOP (Sharpless and Linden 2003, Stefan and Bolton 2002, Plumlee et al. 2008). While NDMA is expected to consistently be less than the notification level (10 ng/L) in the GWR AWTF product water, there is the potential for NDMA to *reform* in the transmission pipeline to the DPR AWTF.

There are three components that lead to NDMA reformation: (1) the presence of NDMA precursors, (2) the presence of dichloramine, and (3) elevated pH. NDMA precursors are comprised of a wide range of compounds with different chemical properties (Krasner et al. 2013), and research has shown that these precursors are not fully removed through RO and UV/AOP (Roback, Ishida, and Plumlee 2019). When these NDMA precursors react with dichloramine in an aerobic environment, NDMA reformation can occur (Schreiber and Mitch 2006). Dichloramine is often present in RO permeate due to the application of chloramines (principally monochloramines) to prevent biofouling of RO membranes. While monochloramines are the dominant species in the RO feed, the RO process drops the pH of the water to 5.5 to 5.8, a condition that favors the conversion of monochloramine to dichloramine. This formation is subsequently halted when the pH is elevated during post-treatment, i.e., when the product water is stabilized to minimize corrosion in the transmission pipeline. While arresting dichloramine conversion, the elevated pH also converts amine-based NDMA precursors into more reactive forms. The product water then contains dichloramine and the reactive NDMA precursors at elevated pH—the three conditions needed for NDMA reformation (McCurry et al. 2017). Figure 5, from McCurry et al. (2017) shows the mechanism for NDMA reformation through RO with NDMA concentration in blue, pH in black, and dichloramine ($NHCl_2$) in red.

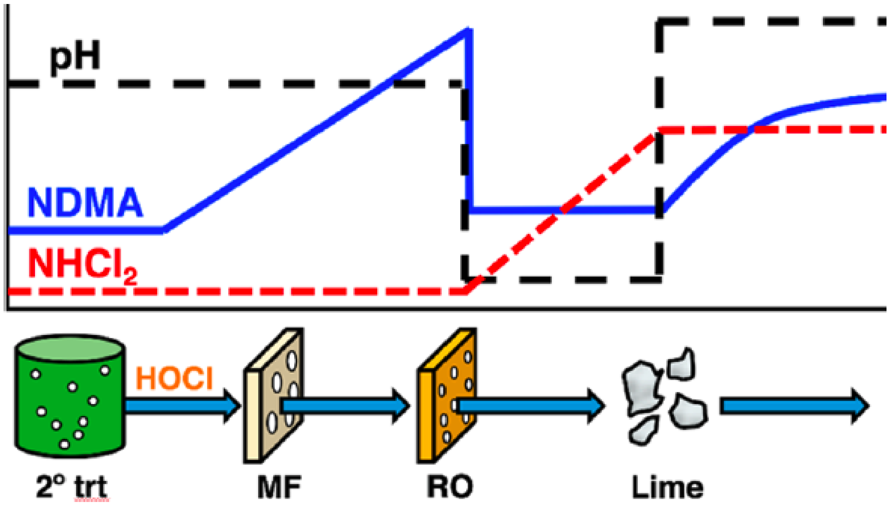


Figure 5. NDMA reformation mechanism from McCurry et al. (2017)

Full-scale potable water reuse facilities have observed NDMA reformation in transmission pipelines, with reported NDMA formation rates averaging approximately 0.7 ng/L/hr in the transmission lines (Roback, Ishida, and Plumlee 2019). This implies that if water has a long travel time (several hours) in the transmission pipeline from the GWR AWTF to the DPR AWTF, NDMA could rebound to levels that would require additional removal at the DPR AWTF to meet the 10 ng/L NDMA notification level (NL). Based on the growing body of literature on this topic, it is anticipated that NDMA reformation may occur in the product water of the JWPCP-fed GWR AWTF.

3.2.3.2 Biofilm Growth

Another water quality challenge to consider is the stability and growth of microorganisms and biofilms within the transmission pipeline. Microorganisms are well-known for surviving and establishing niches in even the most nutrient-deficient environments. Organisms have evolved special enzymes to pull in trace compounds in nutrient-deficient environments like the ocean (Bundy et al. 2018), and are notorious for growing in and contaminating the ultrapure water used in the semiconductor, pharmaceutical, and food and beverage industries (Kulakov et al. 2002). This knowledge has prompted current research to understand the stability of biofilms in pipelines following advanced treatment processes (Miller, Nelson, and Rodriguez 2017). While more research needs to be done to understand the prevalence and types of biofilms that can form following an RO-UV/AOP treatment train, it is anticipated that even in this high-quality, nutrient-poor water, biofilms will form on the transmission line. To address this concern, either (1) research needs to be done to understand how to control biofilm growth and minimize biofilm sloughing, or (2) the downstream DPR AWTF needs to be equipped with a treatment process, such as membrane filtration, that can remove any organisms that are present in the source water. If a disinfectant was applied or maintained through the transmission pipeline to control biofilm growth, this could impact NMDA reformation, and the downstream treatment processes would need to be designed to account for any increase in NDMA concentrations that may occur in the pipeline.

Another consideration is the presence of antibiotic-resistant bacteria (ARB) and antibiotic-resistant genes (ARGs) in the GWR AWTF effluent. There has been increasing attention on ARB and ARGs, and there is a call within the industry to understand the removal of ARB and ARGs through advanced water treatment processes (Olivieri et al. 2016). If ARB and ARGs are able to pass through an MF-RO-UV/AOP treatment train, their impact within the transmission pipeline will need to be fully understood. While chlorination within the pipeline may be sufficient to control ARB and ARGs, there is some debate on the ability of ARB to regrow and ARG transfer to proceed in the presence of chlorine (Hong et al. 2018).

3.2.3.3 Interaction with Pipe Surface

The inside of most water transmission mains is lined with cement mortar, part of which is lime (calcium hydroxide) that is soluble in water (Mindess, Young, and Darwin 2003). The leaching of the lime from the cement mortar impacts both water quality and the integrity of the cement mortar lining (CML) itself. Consequently, another consideration within the transmission pipeline is how to condition the GWR AWTF effluent in order to prevent deterioration of the transmission pipeline's CML while still maintaining feedwater quality goals for the DPR AWTF. Without proper conditioning, the CML is susceptible to deterioration due to exposure to the low-TDS AWTF effluent. Deterioration of the CML can introduce deposits into the water and could result in the exposure and corrosion of the metal pipeline. For example, OCWD experienced deterioration of the CML of their transmission line carrying AWTF effluent at rates greatly exceeding those of other pipelines exposed to similar soft, low alkalinity water quality such as the San Francisco Hetch Hetchy and the East Bay Municipal Utility District's Mokelumne Aqueducts (Plumlee and Hokanson 2019). Water Reuse Foundation Project 16-01 is investigating why the AWTF effluent deteriorated the CML at a higher rate than other traditional soft, low alkalinity waters.

Typically, to reduce the rate of deterioration of CML, the pH and alkalinity are increased to achieve a positive value on the Langelier Saturation Index (LSI). While this may seem like an obvious solution, an increase in pH can also aggravate NDMA reformation (see Section 3.2.3.1). Since the water traveling through the transmission line will act as the feedwater for the DPR AWTF, the water quality goals at the GWR AWTF will need to be optimized and controlled to prevent CML deterioration and pipeline corrosion while simultaneously minimizing NDMA reformation.

4. Treatment Options

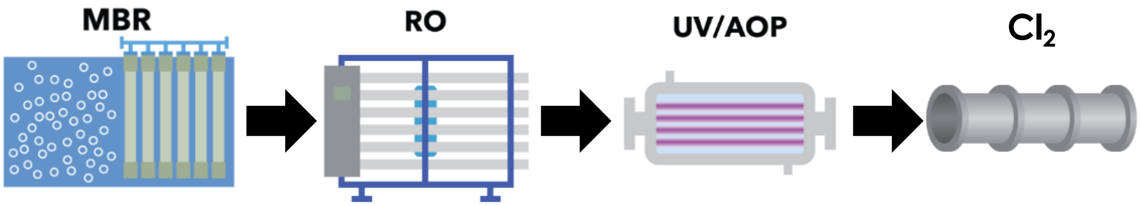
To be protective of public health, potable reuse projects must ensure protection against pathogens and toxic chemical compounds. The GWR AWTF will feature an MBR-RO-UV/AOP treatment train to meet regulatory requirements for groundwater recharge. Finished water from the GWR facility will then be transported to the DPR AWTF for additional treatment that satisfies the stricter regulatory requirements for DPR. While treatment is a major aspect of the DPR system, the degree of treatment required will also depend on the additional protections provided by the DPR system such as enhanced source control, blending with traditional supplies, the capability for separate disposal of off-spec water, and the use of reservoirs for peak attenuation.

As discussed in Section 2, the State Board has required increasingly higher degrees of pathogen control (i.e., log reduction requirements) as projects move from large, significant environmental barriers to smaller ones (Figure 2). In the GWR regulations, potable reuse systems must provide 12/10/10-log reductions for virus, *Giardia*, and *Cryptosporidium*, respectively through treatment and retention time in the ground. In the surface water augmentation regulations, projects that reduce the reservoir benefits to the minimum allowable levels (i.e., 10-to-1 dilution with 2-month theoretical retention times) must provide additional protection with no less than 14/12/12-log reductions coming from the AWTF (10/9/10) and the WTP (4/3/2). While the pathogen log reduction value (LRV) requirements have not been established for DPR, it is likely that LRV requirements may be higher than IPR (e.g., 15/13/13) to ensure public health reliability (State Water Resources Control Board 2019).

As discussed briefly in Section 2.2, the second edition of the DPR Regulatory Framework provides an update on how DDW will consider crediting the WTP in DPR settings. In this edition, DDW states that the WTP will be viewed as a series of unit processes that can each be credited. This is an important shift because the Surface Water Treatment Rule (SWTR) generally assigns credits for a *combination* of processes (e.g., coagulation, sedimentation and filtration) without the explicit quantification of each individual barrier. In making this shift, DDW brings WTP crediting into alignment with the AWTF—which has historically been credited on a process-by-process basis—but represents an important new challenge for monitoring and demonstrating the performance of WTP processes. DDW's rationale for this shift is that the WTP credits are no longer guaranteed for the purified water entering the plant. The details of these requirements remain unclear, though this shift places doubt on how many credits the purified water will receive at the WTP.

In Metropolitan's case, if the pathogen removal achieved through the GWR AWTF train is 12.5/10/10 (Figure 6), a minimum of an additional 2.5/3/3 will be required to achieve the anticipated DPR LRV requirements of 15/13/13. While some of the additional pathogen credits for DPR could be achieved at the WTP, it is uncertain how many credits DDW would approve at the WTP. Additional treatment will likely be needed to ensure that the anticipated 15/13/13 LRV requirements can reliably be met.

These additional credits could be achieved at the GWR AWTF, a downstream DPR AWTF, or at the WTP. As mentioned above, the pathogen removal credits assigned to WTPs through the SWTR, Enhanced SWTR, and the Long Term 2 Enhanced SWTR include credits for a combination of processes; specifically, 2.5/2/2 for the conventional treatment employed at Weymouth WTP and Diemer WTP. These regulations use performance in turbidity removal as the surrogate for confirming that this removal has been achieved. The basis of these treatment credits is from extensive studies that often used *Giardia* cysts and *Cryptosporidium* oocysts as a seed to understand removal of *Giardia* and *Cryptosporidium* through the treatment processes using conventional surface water supplies like State Project Water and Colorado River Water (Patania et al. 1995). However, none of these studies have been conducted with RO permeate or blends with RO permeate as the source water. In a recent presentation, DDW indicated that if the source water to the WTP contained blends of RO permeate, to receive pathogen removal credits, validating studies would need to be performed to meet requirements equivalent to those recently conducted in Australia (Bernados 2020; WaterVal 2015).



Pathogen	WRF	MBR	RO	UV/AOP	Cl_2[c]	Total
Virus	–[a]	0[b]	1.5	6	5	12.5
Giardia	–[a]	2.5[b]	1.5	6	0	10
Cryptosporidium	–[a]	2.5[b]	1.5	6	0	10

[a] WRF pathogen credit possible, though may require site-specific testing as stated in previous TM
[b] Based on current minimum MBR crediting being pursued for GWR project
[c] Recent research suggests that up to 6-log virus and 3-log *Giardia* may be possible

Figure 6. Pathogen Log Removal Values of the Current Groundwater Recharge Train

Beyond pathogen control, it is anticipated that additional requirements for the control of chemicals will also be included in the DPR regulations. DPR treatment trains will need to protect against at least three major categories of chemicals: (1) "known" chemicals including both those that are regulated and those that are unregulated, (2) "unknown," or emerging chemicals, and (3) peaks of chemicals including both known and unknown compounds.

Known Chemicals

For California potable reuse projects, the product water is subject to numerous federal and state regulatory limits like those included in the primary maximum contaminant levels (pMCLs), secondary maximum contaminant levels (sMCLs), notification level, and the State Board's Recycled Water Policy. Depending on the form of potable reuse pursued, other requirements may also be applicable including those contained in Basin Plans (groundwater projects) and the California Toxics Rule (CTR), the latter of which would be relevant for RWA projects using a small reservoir but not for hard-piped projects. This group comprises the known chemicals.

Unknown Chemicals

Chemical contaminants are challenging to address because they exhibit a large variety of physical-chemical properties in terms of molecular weights (i.e. size), charge, biodegradability, hydrophilicity/ hydrophobicity, polarity, etc. Given this diversity, there is no single treatment process that can adequately treat all groups of chemicals. Therefore, diversity of treatment mechanisms in a treatment train, or robustness, is important to adequately control the broad spectrum of chemical compounds (Pecson et al. 2015). The anticipated requirement for greater treatment robustness likely stems from the California regulators' experience with toxic chemical control, and the need to provide an additional level of safety for projects that do not benefit from significant environmental buffers. Greater robustness provides further protection against known contaminants, and proactively guards against future "unknown" contaminants.

Chemical Peaks

A project must also provide protection against chemical spike events when concentrations exceed the typical loading that is expected into the AWTF. This protection is relevant for all types of chemicals, both known and unknown. Because the environmental barrier is so effective at attenuating chemical peaks, DDW has stated that additional considerations will be needed to deal with them in DPR settings. Increasing the diversity of treatment is one approach to attenuate chemical peaks and will be one of the main considerations for selecting treatment processes to include at the DPR AWTF.

To better anticipate treatment needs for known problematic compounds at the DPR AWTF, water quality results from the 2010-2012 pilot study performed at the JWPCP in 2010-2012 were reviewed. The pilot study compared two treatment trains—UF-RO-UV/H_2O_2 and MBR-RO-UV/H_2O_2—to evaluate the feasibility of a regional potable reuse program and whether the product water could meet or exceed the applicable regulatory limits. Review of the water quality results from the pilot study revealed a selection of compounds in the UV/H_2O_2 effluent of the MBR-RO-UV/H_2O_2 train that may be of concern (Table 2). Removing or limiting the formation of these compounds will likely be needed at the future DPR AWTF.

Table 2. Compounds Exceeding Regulatory Limits

Analyte	Highest observed concentrations	Reason for concern
Bromide	0.140 mg/L in UV/H_2O_2 effluent	May form bromate above the 0.010 mg/L MCL
Bromoform	2.4 ug/L in UV/H_2O_2 effluent	Close to CTR limit of 4.3 ug/L.
Chlorodibromomethane	<0.5 μg/L in UV/H_2O_2 effluent	CTR limit is 0.401 ug/L limit. Results must always be non-detect, essentially.
Bromodichloromethane	1.3 μg/L in UV/H_2O_2 effluent	Exceeds CTR limit of 0.56 ug/L.
Chloroform	1.4 μg/L in UV/H_2O_2 effluent	Exceeds CTR limit of 0.56 ug/L.
Formaldehyde	0.063 mg/L in UV/H_2O_2 effluent	Results did not exceed 0.1 mg/L Notification Level but must be careful not to form additional formaldehyde at the DPR AWTF
N-Nitrosodimethylamine (NDMA)	4.4 ng/L in UV/H_2O_2 effluent	Exceeds CTR limit of 0.69 ng/L.
N-Nitrosdiethylamine (NDEA)	19 ng/L in UV/H_2O_2 effluent	Exceeds Notification Level of 10 ng/L.

The following subsections identify potential unit processes that could be implemented at the DPR AWTF and summarize the benefits and challenges associated with each process. The lens through which the processes are evaluated is based on whether they can help address the treatment challenges that have been laid out thus far in Sections 3 and 4:

- Reduces pathogen concentrations
- Increases robustness against chemicals
- Attenuates chemical peaks
- Addresses water quality issues related to transmission system

The evaluation also looks at whether sufficient information is currently known to design and monitor process performance in these unique, RO permeate conditions.

4.1 Membrane Filtration

Membrane filtration (MF) in the form of microfiltration and ultrafiltration is commonly used to remove turbidity and solids and is also an effective barrier for protozoa and bacteria through physical removal. MF and UF systems may provide pathogen log removal credits of up to 4 for *Cryptosporidium* and *Giardia*. No pathogen removal credit, however, is granted for virus. Inclusion of MF or UF at the DPR AWTF would increase the cumulative pathogen LRVs to 12.5/14/14. Although *Giardia* and *Cryptosporidium* pathogen LRV requirements will be met, (an) additional pathogen barrier(s) would need to be included to satisfy the anticipated 15-log virus removal criterion. The process would not be effective at providing additional control against chemicals, and it does not increase treatment robustness since the MBR provides a similar removal mechanism at the GWR AWTF. MF could help to deal with transmission system issues, however, including the control of bio-sloughing and ARBs.

The main challenge associated with the inclusion of a MF or UF system is how the system will continuously demonstrate membrane integrity. MF and UF systems are required to demonstrate integrity via both a direct integrity test and an indirect integrity test. The most common direct integrity test is the pressure decay test (PDT) that uses the loss of pressure within the system to determine if there are breaches compromising its ability to remove pathogens. This PDT must be performed daily to demonstrate direct integrity. At the DPR AWTF, PDTs would be possible even with RO feedwater.

The indirect integrity test involves continuous monitoring of the filtrate turbidity. While not as sensitive as the PDT, its major benefit is that it provides an on-going measurement of any gross failures. Turbidity spikes greater than 0.15 NTU in the filtrate for two consecutive 15-minute period readings suggest possible membrane breaches and trigger an immediate, additional PDT (EPA 2005). A membrane system must pass both the direct and indirect integrity test to demonstrate membrane integrity. While the direct integrity test could be performed at the DPR AWTF, there will be significant challenges implementing the indirect integrity test. Turbidity will be very low in the feed water to the MF system, since the system will be downstream of RO. Therefore, it is anticipated that in the event of an integrity breach at the DPR AWTF, the filtrate turbidity will not exceed the 0.15 NTU criteria since the feed turbidity is already below that.

Pathogen credit is unlikely to be granted without additional research to satisfy the requirement for continuous demonstration. Research on other monitoring methods sensitive enough to measure changes in water quality that will be indicative of membrane breaches, such as continuous particle counting, must be conducted. One plausible solution is to consider increasing the frequency of direct integrity tests in addition to researching other developing technology, such as high frequency flow cytometry. Approval from DDW will be needed so engagement with DDW during research is highly recommended.

Figure 7 summarizes the considerations for including membrane filtration at the DPR AWTF.

MF 	Benefits • 4-log pathogen credit for *Giardia* and *Cryptosporidium* • Provides control against bio-sloughing and ARBs present in the transmission system
Removal Mechanism Physical removal	Challenges • Requires research on acceptable indirect integrity monitoring • Provides no virus reduction credit • Provides no chemical control • Does not increase treatment robustness

Figure 7. Summary of MF benefits and challenges

4.2 Ozone for Disinfection

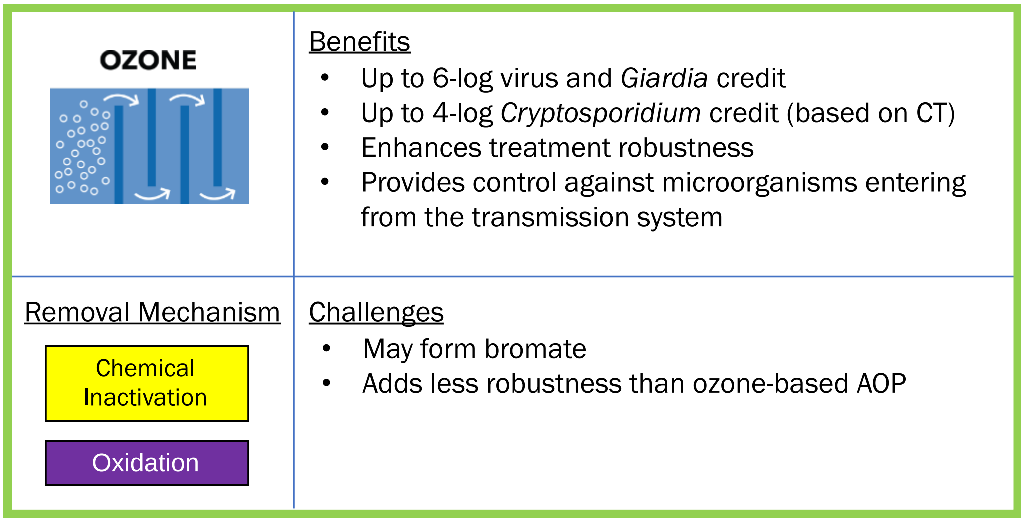
Ozone is a powerful oxidant that is used for both disinfection of pathogens and the oxidation of chemical compounds. It exerts these effects by either directly reacting with pathogens and chemicals, or indirectly through the formation of highly-reactive hydroxyl radicals. The latter reaction is commonly mediated through the presence of natural organic matter, which will be at negligible levels in the RO permeate. Consequently, another chemical—such as hydrogen peroxide (H_2O_2)—would need to be added to drive the advanced oxidation reactions (AOP using ozone is discussed in further detail in Section 4.4). This section focuses on direct reactions for disinfection.

The disinfection performance of the ozone system is impacted by the water quality conditions, which are, in turn, impacted by upstream treatment decisions. For example, the selection of the UV/AOP at the GWR AWTF could impact ozone dosing since the presence of peroxide and chlorine can exert demand and increase dosing requirements. Ozone disinfection is optimally conducted in low pH, low alkalinity water to minimize the rate of ozone decay. This is relevant because the RO permeate from the GWR AWTF will undergo post-treatment to stabilize the water by raising both pH and alkalinity. Benchtop testing may be required to evaluate the optimum pH and alkalinity for ozone disinfection at the DPR AWTF, and to explore strategies like carbon dioxide dissolution for adjusting the pH and alkalinity. The low levels of organics present in the process water are not anticipated to exert significant ozone demand. Provided a low or neutral pH is maintained, ozone would be an effective option for disinfection. Removal credit of up to 6 log is achievable for both virus and *Giardia*. *Cryptosporidium,* however, is more difficult to inactivate and requires larger ozone doses to achieve the higher CTs. For example, at 15˚C, EPA's CT tables require CTs of 0.5, 0.95, and 19 mg-min/L for a 3-log reduction of viruses, *Giardia*, and *Cryptosporidium*, respectively (EPA 1991; EPA 2006). The maximum ozone dose may be limited, however, by the formation of oxidation byproducts (including regulated compounds bromate and formaldehyde) and may not be sufficient to provide the required removal credit for *Cryptosporidium* on its own. Another pathogen barrier in addition to ozone may be necessary to meet the 15/13/13 pathogen log removal criteria. Optimizing the ozone dose and resulting pathogen removal credits is recommended to evaluate the level of disinfection that is feasible.

The control of DBPs is an important consideration in ozone design. Formaldehyde is formed in the ozone process during the oxidation of large molecular weight organic compounds (Wert et al. 2007). Since the concentration of organic matter is expected to be low after RO, the level of aldehyde formation is expected to be low enough to not violate regulatory limits, but will require confirmation.

Of greater concern with ozone for disinfection is bromate, which is formed from reactions with ozone and bromide. While RO substantially reduces the concentration of bromide, even low permeate concentrations can lead to issues with bromate control. For example, only 0.005 mg/L of bromide is needed to reach the bromate MCL of 0.01 mg/L. There have been limited studies exploring the ozone-driven formation of bromate in RO permeate, but bromate has formed in a downstream UV-AOP due to elevated bromide concentrations. Because the bromide concentrations in the RO permeate from this project are anticipated to be 0.1 to 0.2 mg/L, studies should be done to evaluate the formation and control of bromate. If bromate formation is confirmed as an issue, control strategies would need to be investigated. Likely control strategies will be those used by the drinking water industry, reducing the pH (Krasner et al. 1993), the chlorine/ammonia process (Neemann et al. 2004), or ammonia/chlorine (Yun et al. 2009).

In summary, ozone can provide additional pathogen credits while also increasing the robustness of the treatment system through the addition of a new oxidation mechanism. Greater robustness could be achieved if ozone were designed to leverage both its direct and indirect (i.e., advanced oxidation) mechanisms (further discussed in the AOP section below). Ozone would also be effective at disinfecting any microorganisms that enter the DPR AWTF through the transmission line. Figure 8 summarizes the considerations for including membrane filtration at the DPR AWTF. Because disinfection with ozone alone and oxidation via hydroxyl radicals are optimized at different pHs, it may be appropriate to segregate the disinfection and AOP steps in ozonation to maximize performance for a given dose.



OZONE

Benefits
- Up to 6-log virus and *Giardia* credit
- Up to 4-log *Cryptosporidium* credit (based on CT)
- Enhances treatment robustness
- Provides control against microorganisms entering from the transmission system

Removal Mechanism

Chemical Inactivation

Oxidation

Challenges
- May form bromate
- Adds less robustness than ozone-based AOP

Figure 8. Summary of ozone benefits and challenges

4.3 Ultraviolet Light for Disinfection

Ultraviolet (UV) light is a powerful disinfectant that inactivates a broad spectrum of pathogens through damage to the microorganisms' genetic material (i.e., DNA and RNA). Because up to 6-log of credit is achievable for virus, *Giardia*, and *Cryptosporidium*, the 15/13/13 pathogen log removal criteria could be easily met with the addition of a UV system.

To drive photolysis and AOP processes, significantly higher UV doses are required compared to those needed for disinfection alone. A UV/AOP option (such as UV/H_2O_2 and UV/HOCl discussed further in Section 4.4) would provide both the pathogen removal credits and an additional barrier against known chemicals, unknown chemicals, and chemical peaks. UV photolysis—for the control of NDMA and other compounds—would be particularly effective in the RO-treated water because of its high UVT and low absorbance.

One major challenge for implementing UV is scaling of quartz sleeves in UV reactors caused by calcium carbonate saturation added during post-treatment at the GWR facility. The efficacy of UV treatment is dependent on efficient transfer of UV light into the process water; scaling of the quartz sleeves will need to be controlled for process to remain effective. A UV or UV/AOP process would not, however, add robustness to the overall treatment train since UV/AOP is already utilized at the GWR facility. Though it does not provide additional robustness, the inclusion of UV may be worthwhile since it is a powerful pathogen barrier and provides attenuation of NDMA, which may form in the transmission line (see Section 3.2.3.1). A summary of benefits and challenges associated with UV are identified in Figure 9.

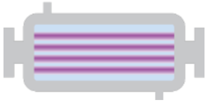
UV 	Benefits • 6-log credit for virus, *Giardia*, and *Cryptosporidium* • Reduces NDMA concentrations • Provides control against microorganisms entering from the transmission system
Removal Mechanism Physical Degradation Inactivation by UV Light	Challenges • No additional robustness due to use at GWR AWTF • Requires high doses for control of chemicals • Scaling may be an issue due to GWR post-treatment

Figure 9. Summary of UV system benefits and challenges

4.4 Advanced Oxidation Processes

Advanced oxidation processes are powerful barriers that provide protection against a diverse range of chemical compounds. The AOP dose needed to satisfy the regulatory requirements (i.e., 0.5 log removal of 1,4-dioxane) is effective at controlling a wide range of trace organics. This is because 1,4-dioxane is a relatively recalcitrant compound, meaning that most compounds will experience significantly greater than 0.5-log reduction as illustrated in Figure 10 (Hokanson et. al 2016). Though an AOP will already be included at the GWR AWTF (either UV/HOCl or UV/H_2O_2), repeating an AOP at the DPR AWTF may still be beneficial given its effectiveness against such a diversity of compounds. Selecting an AOP different than the one used at the GWR facility would increase the overall robustness of the treatment train for removing chemicals and chemical peaks. This section identifies and describes several AOP processes that may be considered for inclusion at the DPR AWTF.

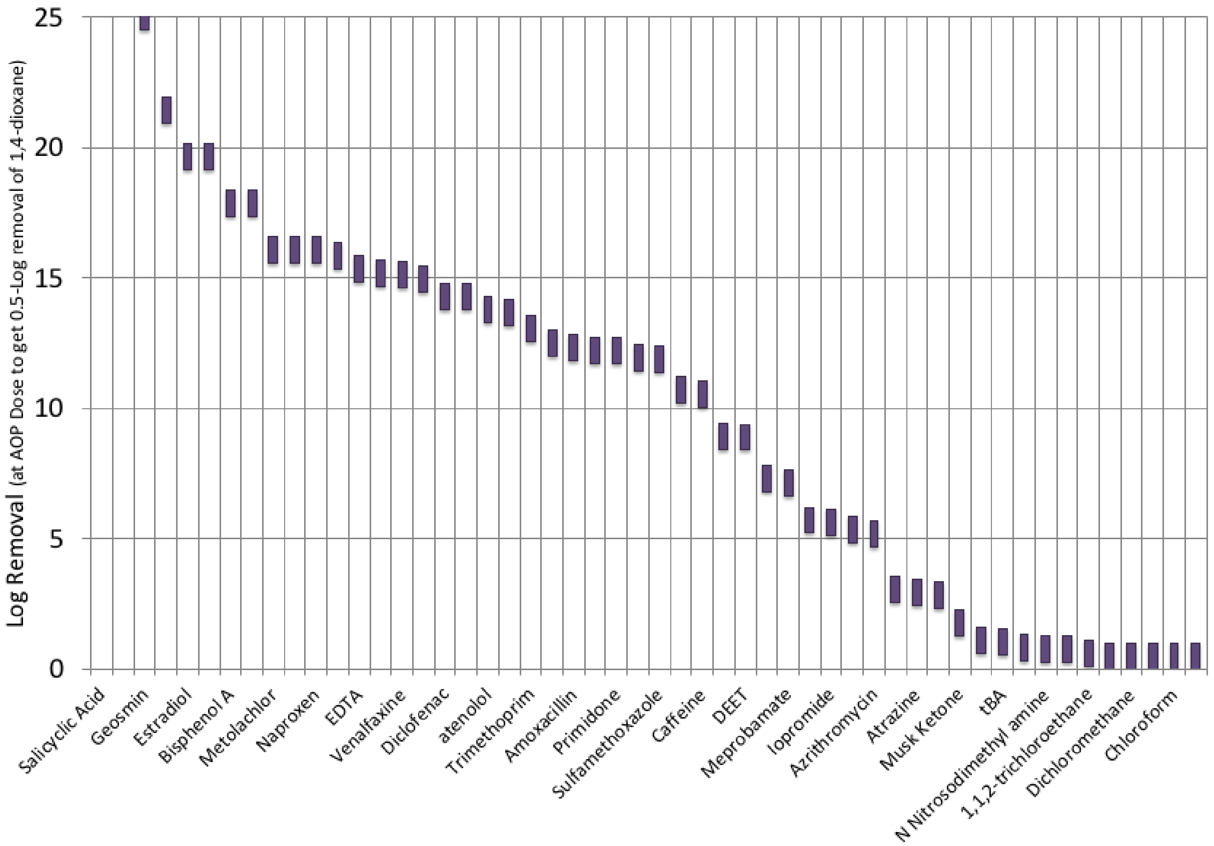


Figure 10. Removal of trace organics at the AOP dose needed to achieve 0.5-log removal of 1,4-Dioxane (adapted from Hokanson et. al 2016)

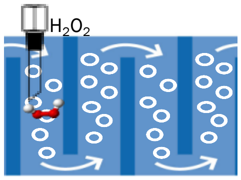
Ozone / Peroxide AOP

As discussed in Section 4.2, ozone dosed to RO permeate alone will not generate significant hydroxyl radicals due to the lack of natural organic matter in RO permeate. Hydrogen peroxide may be added to initiate reactions that transform ozone into hydroxyl radicals (von Gunten and Hoigne 1994, Ferguson et al. 1990). The generation of sufficient hydroxyl radicals would allow the ozone/peroxide process to meet the treatment requirements for AOP. This process may also serve as a pathogen barrier by granting contact time with ozone for disinfection before transformation to an AOP process through addition of hydrogen peroxide. Alkalinity added during post treatment, however, acts as a free radical scavenger, substantially reducing the effectiveness of hydroxyl radicals produced.

The efficacy of ozone/peroxide for removing target compounds may be estimated using rate constants between hydroxyl radicals and target organic compounds. This analysis was done for the application of ozone/peroxide in RO permeate for the removal of NDMA, 1,4-dioxane, and TCEP. Calculations estimated high degrees of chemical reduction (1.2 log NDMA, 3.6 log 1,4-dioxane, and 1.5 log TCEP) using reasonable design conditions (2 minutes of detention time, 1 mg/L of ozone, and 1 mg/L hydrogen peroxide) after post-treatment of RO (pH = 8 and alkalinity = 14 mg/L as $CaCO_3$) (Thompson et al. 2009). A more sophisticated model for evaluating ozone/peroxide performance was developed by Professor John Crittenden to estimate the reduction of additional chemical compounds like PCE and MtBE. Testing of this model would be useful in developing design criteria for this treatment process.

The main challenges with implementing ozone/peroxide would be (1) the scavenging of hydroxyl radicals by carbonate species, (2) the formation of NDMA, and (3) the formation of bromate. The presence of NDMA precursors and bromide will lead to the formation of NDMA and bromate, respectively. As discussed in Section 4.2, the formation of NDMA and bromate during ozonation of RO permeate should be studied at pilot-scale since the resolution of these issues will be site- and water quality-specific. Despite the challenges, O_3/peroxide provides a significant increase in the robustness of the overall treatment train. A full summary of benefits and challenges of including O_3/peroxide are identified in Figure 11.

OZONE/H_2O_2



Benefits

- Up to 6-log virus and *Giardia* credit
- Up to 4-log *Cryptosporidium* credit (based on CT)
- Enhances treatment robustness
- Provides control against microorganisms entering from the transmission system

Removal Mechanism

Chemical Inactivation

Oxidation

Challenges

- Formation of bromate
- Formation of NDMA
- Scavenging of hydroxyl radicals by alkalinity

Figure 11. Summary of O_3/peroxide benefits and challenges

UV/Hydrogen Peroxide and UV/Chlorine

UV/H_2O_2 is considered the gold standard for AOP processes in FAT trains, though the use of UV/HOCl has increased in the past decade. Both are effective AOP processes for removing 1,4-dioxane, NDMA, and attenuating a wide range of trace organic compounds. Like O_3/peroxide, both will be somewhat compromised by the alkalinity in the DPR AWTF feedwater. The GWR facility will employ either UV/H_2O_2 or UV/HOCl, depending on results generated from the Advanced Purification Center (APC) Demonstration plant at the JWPCP. Since UV/AOP will be incorporated to the GWR AWTF, a repeated application of these processes at the DPR AWTF will not enhance the overall robustness.

Once the oxidant is selected for the UV/AOP process at the GWR, however, additional work will need to be performed to evaluate the formation potential of NDMA after UV/AOP. Studies have been done to evaluate the removal efficacy of NDMA precursors through UV/AOP. Differences in performance, though, have been reported. NDMA precursors comprise a wide range of compounds with a wide spectrum of chemical properties (Krasner et al. 2013). As such, the effectiveness of the UV/AOP process depends on the specific precursors present in the process water. Therefore, it would be prudent to evaluate if there are differences in NDMA precursor removal between UV/H_2O_2 and UV/HOCl by performing formation potential tests on the product water resulting from these two AOPs.

Other Advanced Oxidation Processes

While UV/H_2O_2, UV/HOCl, and O_3/H_2O_2 are the most common AOPs, other options could also be evaluated. For example, titanium dioxide (TiO_2) photocatalysis is an AOP process that has demonstrated effective removal for a broad range of chemicals. TiO_2 is a photoreactive substance that can be added as a slurry that stimulates AOP when irradiated with UV light. While effective against a wide range of organic compounds and pathogens, its major limitation is that it has not yet been designed at a significant scale. While additional studies would be needed to optimize design and operation, depending on the scale of the satellite facility, this process may be a good AOP option when using RO permeate as feedwater.

4.5 GAC

Granular activated carbon (GAC) is an adsorption process that is effective at removing dissolved organics, particularly uncharged, hydrophobic compounds. Consequently, it is likely to be effective at removing some chemicals that are not well removed by RO and UV/AOP, such as THMs. Inclusion of GAC at the DPR AWTF would introduce a new mechanism into the treatment train and increase the overall robustness. Application of GAC after RO permeate, however, is not well understood and there is a strong possibility that most compounds that adsorb well are already well-removed by RO itself. Pilot testing would need to be undertaken to better understand the empty bed contact time (EBCT) needed, rate of contaminant breakthrough, and change-out frequency in this water quality matrix.

An additional concern is the potential for biogrowth in GAC filters. Though RO permeate is nutrient deficient, studies have shown that biological growth in GAC persists even after RO (Kantor, Miller, and Nelson 2019) and sloughing from GAC filters after RO permeate may result in high HPC and total coliform results (Idica 2012). Biogrowth in GAC may be mitigated by carrying a disinfectant residual through filtration (though this will oxidize the carbon and significantly reduce bed life); sloughing or contamination issues may be remedied with a disinfection or membrane filtration step after GAC. Though GAC would not get credit for pathogen removal, GAC increases the overall robustness of the treatment train with the adsorption treatment mechanism. Increasing the diversity of treatment mechanisms better equips the treatment train to be protective of more groups of chemicals. The benefits and challenges of GAC are summarized in Figure 12.

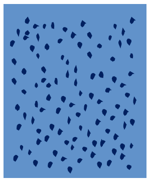
GAC 	<u>Benefits</u> - Increases robustness of treatment train - Controls chemicals known to pass through RO and UV/AOP treatment
<u>Removal Mechanism</u> Adsorption Physical removal	<u>Challenges</u> - Rate of breakthrough and media change-out frequency unknown in RO permeate matrix - Does not provide pathogen removal - Biogrowth in GAC will require a disinfectant residual or a pathogen barrier downstream

Figure 12. Summary of GAC Benefits and Challenges

4.6 Hybrid Powder Activated Carbon Membrane Filtration Processes

Similar to GAC, powdered activated carbon (PAC) may be used to remove dissolved organics and DBPs through adsorption. PAC is ideal for treatment of RO permeate since higher molecular weight compounds that may block adsorption sites in smaller pores are already removed in the RO process. Remaining contaminants in the water will likely consist of micropollutants not well removed by RO, which may then be removed by the PAC. However, one of the issues with PAC use is the high consumption of PAC and the fact that the process is less efficient than GAC as it operates in a co-current mode rather than counter-current (i.e., the fresh carbon sees the highest concentration of contaminants and the most exhausted carbon is present at the last stage of treatment vs. the opposite with GAC). Hybrid PAC membrane processes, however, present a solution to this problem by placing the PAC media in an immersed MF or UF processes. The media cannot pass through the membranes, which keeps the PAC media in suspension in the membrane tank. The buildup of cake on the membrane surface effectively replicates the countercurrent effect, and the process takes advantage of the greater available surface area of PAC compared to GAC.

This hybrid system combines two treatment objectives—adsorption for organic chemicals and pathogen removal credit for *Giardia* and *Cryptosporidium* through the membrane filtration process. This combination largely resolves many of the disadvantages of having separate adsorption and membrane filtration processes. Membrane filtration is an effective pathogen barrier and resolves the issues of contamination due to biogrowth in GAC processes. Though membrane filtration is a strong pathogen barrier, it provides no attenuation of chemical contaminants on its own. There are several installations of PAC/UF systems in full-scale drinking water treatment plants in Europe, mainly designed for the removal of NOM. Removal of micropollutants, though less documented, has been reported and show great promise including greater than 90% removal for certain hormones and pharmaceuticals (Markarian et al. 2010, Savaria and Frimmel 2008) and greater than 50% removal for atrazine (Campos et al. 1998). One benefit of the addition of PAC is that it would allow for the use of turbidity as an indirect measure of MF system performance for pathogen removal.

While showing promise, the effectiveness of the hybrid system would need to be confirmed in RO permeate. Optimization of cleaning frequency to control fouling, PAC dose, frequency of PAC media change-out to control biofilm development, and potential abrasion to membranes from media are among several topics worth evaluating during testing. It is likely that these problems would be manageable in RO treated product water. PAC/MF is a promising alternative since it provides control of pathogens and chemicals and adds robustness to the treatment train. A summary of benefits and challenges associated with the PAC/MF process are summarized in Figure 13.

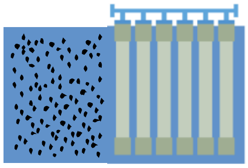
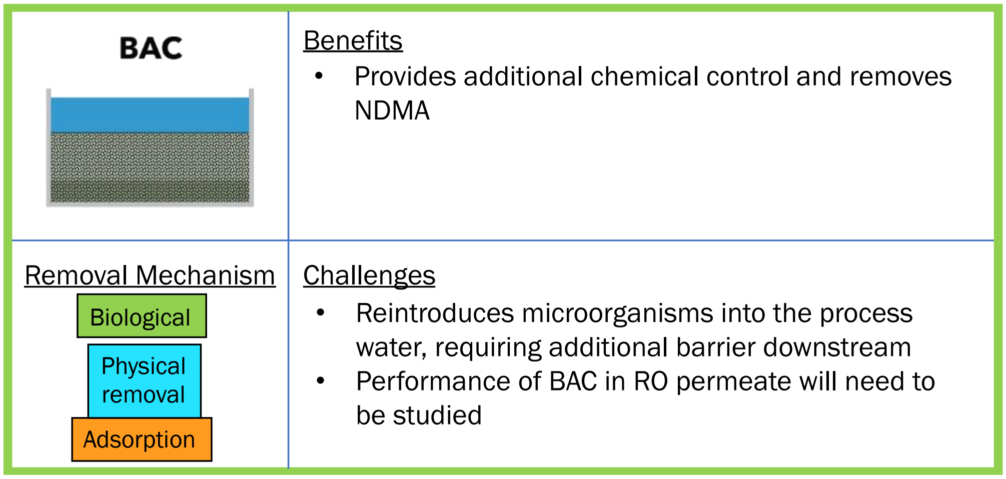
PAC/MF 	Benefits • 4-log credit for *Giardia* and *Cryptosporidium* • Adds robustness for chemical control • Indirect integrity monitoring may be possible • Provides control against bio-sloughing and ARBs present in the transmission system
Removal Mechanisms Physical removal Adsorption	Challenges • PAC may be abrasive to membranes • Operational challenges due to fouling need to be better understood • Optimization of PAC dose for micropollutant removal will need to be evaluated

Figure 13. Summary of PAC/MF benefits and challenges

4.7 BAC

Biological activated carbon (BAC) utilizes exhausted GAC as a substrate for biofilm development, shifting the predominant treatment mechanism from adsorption to biological degradation. This treatment process has gained prominence in the reuse setting due to its ability to remove bulk organic matter, oxidation byproducts, and trace organic chemicals. BAC has also been shown to be effective for removal of NDMA, which will likely be present in the feed water to the DPR AWTF due to reformation in the transmission lines.

BAC is frequently paired with ozone to take advantage of the synergistic effects of increased biodegradability resulting from ozone's oxidation of the high molecular weight organics present in wastewater. The performance of a BAC system treating RO permeate, however, is not known. Biofilms are likely to form on GAC even after treatment with RO (see Section 4.5). It is unknown whether BAC that has been acclimated on RO permeate will demonstrate comparable biodegradation as BAC acclimated on wastewater because many of the trace organics removed in BAC are removed through co-metabolism. Pilot testing of an RO-acclimated BAC process would help fill this knowledge gap. If BAC were used at the DPR AWTF, a disinfection or membrane filtration step would be required to remove or inactivate microorganisms introduced during the BAC process. A summary of benefits and challenges associated with the BAC process is presented in Figure 14.



Benefits

- Provides additional chemical control and removes NDMA

Challenges

- Reintroduces microorganisms into the process water, requiring additional barrier downstream
- Performance of BAC in RO permeate will need to be studied

Figure 14. Summary of BAC Benefits and Challenges

4.8 Air Stripping

Air stripping is a treatment process that is effective for removing volatile organic compounds (VOCs). Because of their lower molecular weight, VOCs are often not well-removed by RO. Air stripping promotes the contact between air and water, increasing the mass transfer of VOCs out of the aqueous and into the gaseous phase. The rate of VOC removal is a function of the air-to water ratio, hydraulic loading rate, Henry's constant of the VOC, the temperature of the water and air, and the packing efficiency (if packed column design). Both towers and aerators may be used. Towers are typically used for applications in which a high degree of removal is desired. Aerators are typically sufficient for moderate to low levels of removal and are generally more effective if the target compound has a low Henry's constant.

Of the specific compounds of concern identified in Table 2, air stripping would be most effective for controlling the concentration of bromoform, chlorodibromomethane, bromodichloromethane, and chloroform present in the finished water. The air stripping process would remove these compounds whether they had been formed in the upstream GWR AWTF or the downstream DPR AWTF. One major drawback, however, is that this process exposes the water to the atmosphere—presenting an opportunity for both chemical and pathogen contamination. In addition, the air stripping process may cause scouring and sloughing of biogrowth in the basins or towers. Therefore, disinfection must be included downstream of the air-stripping process.

Air stripping provides control of chemical compounds, removes DBPs, and introduces a new treatment mechanism to the treatment train, which increases the overall robustness of the train. However, air stripping would need to be complemented by another unit process since it alone cannot control pathogens. Air stripping would still be a positive addition to the train, though, due to its ability to remove chemical compounds. Additionally, air stripping is one of the least expensive process alternatives, both from the standpoint of capital costs and operations and maintenance costs. A summary of the benefits and challenges associated with air stripping is presented in Figure 15.

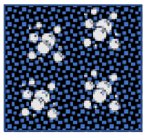
Air Stripping 	Benefits • Removes volatile compounds • Effective for removal of most THMs
Removal Mechanism Volatilization	Challenges • Exposes process water to atmosphere which might reintroduce contaminants to water • May lead to the sloughing of biological growth

Figure 15. Summary of Air Stripping Benefits and Challenges

4.9 Potential Treatment Trains for the DPR AWTF

With the various treatment options available, it is difficult to put together a treatment train that meets all of the treatment goals while avoiding any challenges. The benefits and challenges of two preliminary DPR AWTF treatment trains are presented in the following sections.

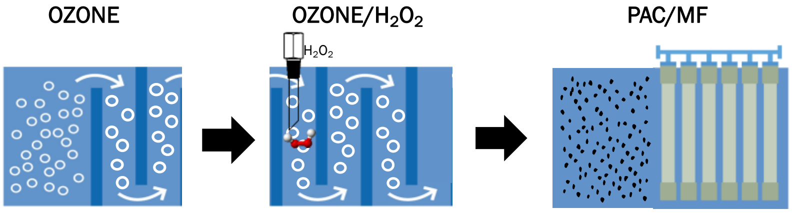
4.9.1 Treatment Train A

The first treatment train consists of Ozone-Ozone/Hydrogen Peroxide-PAC/MF (Figure 16). The initial step, ozone disinfection, provides additional pathogen reduction credits and chemical control. By using a new mechanism of oxidation it also adds robustness. With RO permeate as a feedwater, a relatively short ozone CT could provide up to 6-log virus and *Giardia* reduction, and with additional testing, *Cryptosporidium* reduction credits may also be achievable. Ozone residual and CT would be used to monitor the performance of this process. One challenge with ozone is the formation of bromate as discussed in Section 4.2. To control the formation of bromate, various control strategies—such as reducing the pH, using chlorine/ammonia, or ammonia/chlorine—could be evaluated.

Following ozone disinfection, the elevation of pH and the addition of hydrogen peroxide could be used to convert the ozone residual into hydroxyl radicals for advanced oxidation. The combination of ozone and hydrogen peroxide provides additional robustness since the process will include reactions with both hydroxyl radicals and ozone. As discussed in Section 4.4, this process can provide robust control of a wide suite of chemicals. To monitor process performance, ozone residual and peroxide concentrations could be measured at the influent and effluent of the process. However, some of the challenges associated with this process include (1) the scavenging of hydroxyl radicals by alkalinity in the water, (2) the formation of NDMA, and (3) the formation of bromate. The presence of NDMA precursors and bromide will lead to the formation of NDMA and bromate, respectively. These issues will need to be studied in a pilot-scale setting since they are water quality dependent.

After ozone/hydrogen peroxide, a PAC and MF hybrid process would be used to remove dissolved organics and DBPs through adsorption and provide additional pathogen reduction. Remaining contaminants in the water will likely consist of micropollutants not well removed by RO, which may then be removed by the PAC. The use of an adsorption process improves the robustness of the system. While the membrane filtration step does not add robustness, it will be necessary to remove the PAC from the water and provides a barrier for any microorganisms that may be present due to biofilm growth in the transmission line or on the PAC itself. To monitor this process, reduction of the added PAC across the membranes could be used as indirect integrity and PDTs could be used for direct integrity testing. However, some of the challenges associated with this hybrid process include optimization of cleaning frequency to control fouling, PAC dose, frequency of PAC media change-out to control biofilm development, and potential abrasion to membrane from media. These challenges are likely manageable, but will require pilot-testing.

A summary of this treatment train is provided in Figure 16. While pilot testing would be required to determine design criteria, and optimize and demonstrate performance, this treatment train provides robustness with new treatment mechanisms, provides additional pathogen reduction credits, and provides new chemical control mechanisms that would protect against unknown chemicals and chemical peaks.



Pathogen Credits				Total
Virus	6-log	n/a	n/a	6-log
Giardia	3-log[a]	n/a	4-log	7-log[a]
Crypto	TBD[b]	n/a	4-log	≥4-log[b]
Performance Monitoring	Ozone CT	Ozone residual H_2O_2 concentration	Indirect Integrity: Turbidity Direct Integrity: PDT	
Rationale	New mechanism for pathogen and chemical control	New AOP mechanism Chemical control	New chemical control mechanism Pathogen/microorganism control	
Considerations	NDMA/bromate formation	NDMA/bromate formation Hydroxyl radical scavenging	Biofilm growth Change-out frequency Membrane fouling	

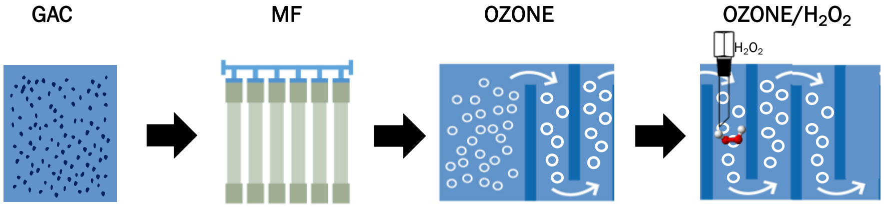
[a] 3-log *Giardia* credit achievable with low ozone CT (0.72 mg-min/L at 20˚C); up to 6-log credit may be sought with higher CTs.
[b] *Cryptosporidium* requires higher ozone CTs (~4 to 12 mg-min/L for 1- to 3-log credit) that may be limited by bromate formation.

Figure 16. Summary of Treatment Train A

4.9.2 Treatment Train B

Another potential treatment train is GAC-MF-Ozone-Ozone/Hydrogen Peroxide. This is similar to Treatment Train A, but GAC and MF are placed ahead of the ozone and ozone/hydrogen peroxide process. GAC is effective for removing dissolved organics, DBPs, and certain chemicals not well-removed by RO and UV/AOP. It may also be effective at removing NDMA precursors. In this train, GAC adds robustness with a new treatment mechanism. It is likely that there would be some biogrowth on the GAC filters. This could be mitigated by carrying a disinfectant residual through MF. With the MF step after GAC, a surrogate parameter would need to be identified to measure the indirect integrity of the membrane process. While Treatment Train A utilizes a hybrid PAC/MF system instead of a combination of GAC and MF, these two options should be viewed as roughly equivalent, interchangeable options. The major distinction between Treatment Trains A and B is the placement of the activated carbon and membrane filter either upstream or downstream of the ozone-based processes.

A summary of this treatment train is provided in Figure 17. While pilot testing would be required to determine design criteria, and optimize and demonstrate performance, this treatment train also provides robustness with new treatment mechanisms, provides additional pathogen reduction credits, and provides new chemical control mechanisms that would protect against unknown chemicals and chemical peaks.



Pathogen Credits Virus *Giardia* *Crypto*	n/a n/a n/a	n/a 4-log 4-log	6-log 3-log[a] TBD[b]	n/a n/a n/a	Total 6-log 7-log[a] ≥4-log[b]
Performance Monitoring	TBD	Indirect Integrity: TBD Direct Integrity: PDT	Ozone CT	Ozone residual H_2O_2 concentration	
Rationale	New chemical control mechanism NDMA precursor removal	Pathogen control	New mechanism for pathogen/chemical control	New AOP mechanism Chemical control	
Considerations	Biofilm growth Change-out frequency	Membrane fouling	NDMA/bromate formation	NDMA/bromate formation Hydroxyl radical scavenging	

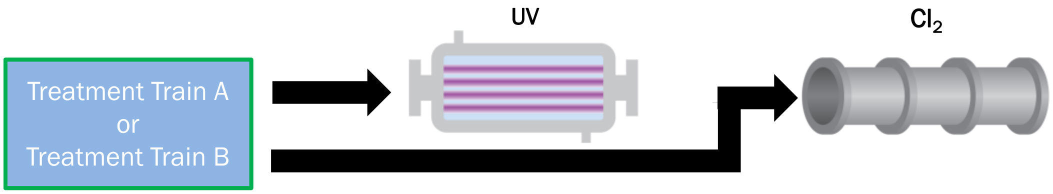
[a] 3-log *Giardia* credit achievable with low ozone CT (0.72 mg-min/L at 20˚C); up to 6-log credit may be sought with higher CTs.
[b] *Cryptosporidium* requires higher ozone CTs (~4 to 12 mg-min/L for 1- to 3-log credit) that may be limited by bromate formation.

Figure 17. Summary of Treatment Train B

4.9.3 Other Considerations

Other treatment processes that would complement these treatment trains and warrant additional consideration are UV and chlorine. UV can serve a number of functions ranging from pathogen control to NDMA control. At lower design doses (30-40 mJ/cm^2), UV can provide robust 6-log protection against *Giardia* and *Cryptosporidium*; moderate doses (186-300 mJ/cm^2) are required for 4- to 6-log virus credit. Higher doses of UV can also provide protection against NDMA. As discussed, NDMA formation may occur either in the transmission line (as a result of reformation) or in the DPR AWTF treatment train itself. Additional studies would be required to assess what degree of NDMA formation occurs, and, therefore, what UV doses would be required for NDMA control.

Chlorine could also be used at the end of the proposed treatment train to provide additional pathogen control. In particular, it provides a high degree of virus control (up to 6-log) at relatively low CTs. New chlorine crediting frameworks that the State Board is evaluating would provide 6-log virus credit for CTs as low as 10 mg-min/L. An added benefit of chlorine addition is that it could serve as the secondary disinfectant residual as the water travels to the downstream WTP. While neither process would increase robustness, an overview of the benefits of these two complementary processes—UV and chlorine—is presented in Figure 18.



Pathogen Credits		
Virus	Up to 4-log	Up to 6-log
Giardia	Up to 6-log	Up to 3-log
Crypto	Up to 6-log	n/a
Performance Monitoring	UV Dose UVT	Free chlorine CT
Rationale	Low-dose for pathogen control Moderate- to high-dose for NDMA control	Pathogen control Maintain residual to WTP
Considerations	Effectiveness of NDMA destruction at different UV doses	DBP formation

Figure 18. Summary of complementary treatment processes

5. Blending

In the first edition of the DPR Regulatory Framework, the State Board indicated that raw water augmentation projects will be defined as ones where "recycled water is mixed with raw water in the conveyance to a drinking water treatment plant such that the blend provides *a meaningful public health benefit*." In the second edition of the DPR Regulatory Framework, as DDW has moved to a single regulatory package for all forms of DPR, this language defining RWA was removed. However, it provides insight into how the State Board may view the value of blending in DPR scenarios. We can gain additional insight from the documents supporting the State Board's development of the 2018 surface water augmentation regulations. In a presentation to the State Expert Panel in July, 2014, the State Board presented their rationale for the preliminary criteria for surface water augmentation, stating that they believed that a 10:1 mixing ratio (i.e., 10-fold dilution) would be sufficient for mitigating trace organic compounds (Hultquist 2014). On the other hand, dilutions of 10- to 100-fold (i.e., 1- to 2-log reductions) would be needed to control failures impacting pathogens. Ultimately, these criteria were maintained through the final regulation, which includes two options: a) a minimum 100-fold dilution option and b) a minimum 10-fold dilution option that is coupled with additional pathogen removal requirements (DDW 2018).

Given this information, it appears that the State Board should consider blending that achieves a 10-fold dilution of the AWTF effluent to provide a meaningful public health benefit. If a project could achieve

10-fold dilution through blending (i.e., a blend of 10% advanced treated water and 90% traditional source water), there may be significant advantages in terms of both pathogen and chemical control. However, as stated in the previous DPR memo, it is not realistic to assume that many projects will be able to achieve such high degrees of blending of the advanced treated effluent. If the DPR regulations contain a restriction on the degree of blending that may be required, it would severely impact the adoption of DPR, particularly in light of on-going efforts to aggressively reduce wastewater discharges by 50 to 95% in the next 10- to 20-year timeframe. Consequently, the dilution requirements from the surface water augmentation will likely *not* be an appropriate metric for determining blending requirements in raw water augmentation.

The question becomes whether there continue to be benefits at blending ratios less than 10-to-1. To answer this, it is worthwhile to consider the different types of contaminants and the potential scenarios that would trigger a need for blending. The four principle categories are:

- Pathogens
- Chemicals consistently present in the AWTF effluent
- Peaks of chemicals
- Unknown chemical contaminants

5.1 Pathogens

Pathogens are frequently cited as the most important public health contaminant in potable reuse due to their ability to cause an infection in as little as a single exposure event (NRC 2012, Pecson et al. 2017). The risk-based pathogen reduction targets specified in California's potable reuse regulations require high log reductions for pathogens, with no less than 12/10/10 specified for virus, *Giardia*, and *Cryptosporidium*. To achieve these goals, project sponsors must utilize multiple barriers, but any treatment barrier that is seeking credit toward these goals must achieve at least 1.0-log reduction of one or more of the target organisms. Achieving this minimum 1-log pathogen reduction through blending would require that the AWTF water comprise no more than 10% of the total blended flow. In other words, *blending AWTF effluents at 10% or less would likely provide a meaningful public health benefit in terms of pathogen control*.

In the 2018 DPR memo, three- to four-fold dilutions were considered reasonable potential blending scenarios for the Weymouth and Diemer WTPs (corresponding to AWTF contributions of 33% and 25%, respectively). In such cases, the benefit of a 25%, 33%, and 50% blending ratio would respectively be 0.6-, 0.5-, and 0.3-log reductions in pathogen concentrations, i.e., below the 1-log minimum threshold currently specified for treatment. Since then, Metropolitan has discussed an alternative blending strategy that would allow for as much as 10-to-1 dilution of AWTF effluent with other source waters: approximately 50 MGD of AWTF effluent combining with up to 450 MGD of other traditional water sources depending on the demand of the Weymouth and Diemer WTPs. Under this regime, a more straightforward argument could be made for a significant pathogen barrier since it would provide the equivalent of a 1-log reduction.

If these high degrees of blending cannot be provided, alternative strategies could be pursued to provide similar public health benefits. The SWA regulations allow for the substitution of dilution for additional treatment in a 1-to-1 ratio, i.e., a 10-fold loss in dilution can be balanced by an additional log of treatment. This substitution of dilution-for-treatment may be needed for RWA projects that pursue

>10% AWTF contributions in their blended raw water supplies. Additional options are discussed below in Section 6.

5.2 Chemicals Consistently Present in the AWTF Effluent

The first category of chemicals to consider in the blending discussion are those that are consistently present at or near threshold levels in the AWTF effluent. As reported by various panels, the concentrations of many toxic organic chemicals are orders of magnitude below levels of health significance (Anderson et al. 2010, NRC 2012, Drewes et al. 2018). The high margin of safety for these compounds is often a combination of multiple factors including low levels of occurrence in wastewater, effective removal through the wastewater treatment plant, and further reductions through the advanced treatment processes. In fact, the State Board's Advisory Panel on Chemicals of Emerging Concern (CECs) recently reconvened in 2018 to update their monitoring recommendations. Their process included comparing the concentrations of 489 CECs in potable reuse applications against their health-based thresholds. Their conclusion was that more than 99% of the compounds did not merit routine monitoring because their levels are consistently one or more orders of magnitude below the *de minimis* health thresholds.

A handful of compounds, however, may be present at or near these thresholds a small fraction of the time[1]. The three compounds that the 2018 CEC Panel selected for monitoring in potable reuse applications include two disinfection byproducts—including NDMA and N-nitrosomorpholine (NMOR)—and the chemical stabilizing agent 1,4-dioxane. This recommendation is in line with the 2012 National Research Council's (NRC) report that showed wide margins of safety for most chemicals, with the exception of certain DBPs and other low molecular weight compounds that are less effectively removed by RO.

It is important to emphasize that many of these chemicals that may be present near health-thresholds are already identified as public health concerns and many have either MCLs (e.g., the trihalomethanes) or notification levels (NLs), such as NDMA and 1,4-dioxane. Other compounds are considered emerging contaminants (e.g., NMOR) that are also being evaluated for future regulations. As such, treatment systems are being expressly designed to control these compounds to acceptable levels. Consequently, when these compounds exceed the MCLs, NLs, or other health thresholds, it is often fractional increases above the limit and not order of magnitude exceedances. It would be rare for THMs and NDMA to exceed their limits by more than two-fold.

For the compounds that are consistently present at or near health-thresholds, blending can provide a meaningful public health benefit even at low blending ratios. Even a 50% reduction in THMs and NDMA (corresponding to a 1-to-1 ratio of AWTF-to-other source water) would frequently be sufficient to reduce exceedances in DBPs to concentrations below the MCLs and NLs. AWTF contributions of 25-33% would therefore also benefit from blending to help control this contaminant group to acceptable levels.

5.3 Chemical Peaks

Six topics were identified by the State Expert Panel as priority items to support the development of DPR regulations. One of these topics was additional understanding of what requirements should be included to help control the passage of peak concentrations of chemicals that might enter an AWTF due to a

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[1] The CEC Panel collected the measured effluent concentrations (MECs) from water reuse facilities across California and utilized the 90th percentile value as a conservative estimate for their comparison.

chemical spill. The State Board adopted all of the Expert Panel's six research recommendations but elevated their importance by stating that these topics needed to be understood *before* DPR regulations could be developed. To support this research, the State Board created a Technical Work Group (TWG) to help evaluate the topic of controlling chemical peaks—the findings from this TWG will be available in the summer of 2020.

As previously discussed, the SWA regulation and DDW's public comments have implied that they believe a 10-fold decrease (1-log reduction) to be sufficient to dampen out the impact of a failure to control trace organic compounds (TOrCs). It is possible, therefore, that a blending approach that achieves a 10-to-1 dilution of the AWTF effluent may be sufficient alone to address chemical peaks. Meeting such blend ratios would reduce (or potentially eliminate) the project's need for additional treatment processes and monitoring designed to control such peaks.

Lower blending ratios—such as those that achieve 25% to 33% AWTF contributions—would provide at least half of the overall 1-log reduction (0.5- and 0.6-log reduction, respectively), which may be sufficient to be viewed as a significant contributor towards this goal. Clearly however, such a blending strategy would need to be accompanied by another mechanism for controlling chemical peaks. One approach would be to implement a treatment mechanism for chemical control, as discussed in Section 4, though other options are also discussed in Section 6. This discussion again highlights the fact that RWA projects may rely on multiple public health elements, and that different combinations of these elements may be acceptable for achieving appropriate degrees of protection. An approach that relies on high blending may not require the same degree of treatment at the AWTF and vice-versa.

5.4 Unknown Chemical Contaminants

The final group of contaminants are the unknown and emerging chemical contaminants. Historically, the industry's principle strategy for dealing with this group has been to couple improved source control with a greater diversity of removal mechanisms in the treatment train. Because treatment robustness is the primary engineering barrier to unknown contaminants, the State Board has stated that it will require greater robustness for DPR (State Water Resources Control Board 2018).

Blending can also help to further control unknown and emerging chemical contaminants that may be present in the AWTF effluent. Blending with another source water stream would provide protection against all such contaminants (assuming they were not present in the other source water) with the level of protection proportional to the degree of blending. In line with the State Board's previous statements, blending ratios of 10:1 and higher should satisfy the need for the control of such unknown contaminants.

Whether lower blending ratios would also provide a meaningful barrier would depend on how close the AWTF effluent concentrations were to the health threshold. If they were present at or near health thresholds, then even 1:1 dilution may be sufficient per the previous discussion. With ratios less than 10:1, blending should be viewed as a complement to the principle mode of protection: robust treatment.

5.5 Other Considerations

While blending will provide varying degrees of protection against pathogens and toxic chemicals, it can provide important benefits in promoting the "treatability" of the water entering the downstream surface water treatment plant. One concern expressed by the regulators relates to their reluctance to grant the default Surface Water Treatment Rule pathogen reduction credits (4/3/2 for virus, *Giardia*, and *Cryptosporidium*) if the source water is comprised entirely or principally of AWTF effluent, i.e., essentially void of colloidal and suspended particles. As discussed previously, in August 2019, the State Board released the second edition of their DPR Regulatory Framework that provided an updated perspective on how they will credit WTPs. Because WTPs were not designed to treat RO permeate, the State Board states that they will require site-specific treatability studies to demonstrate that the plant can treat blends of RO permeate with other waters.

This new crediting framework appears reasonable for WTPs receiving 100% AWTF effluents or blends with percentages of AWTF effluent high enough that the effectiveness of treatment processes employed at the WTP might be affected. At sufficiently high blending ratios, however, this consideration should be negligible particularly if the introduction of the AWTF effluent does not shift the blended water quality outside of the range of water qualities already observed due to seasonal variations. In such cases, site-specific treatability studies may not be merited. A high blending ratio—such as the 10:1 ratio that is being considered—would appear to fall into this category of scenarios that should be exempt from such studies. For nearly all water quality parameters, a 10:1 blend would lead to a maximum 10% shift in their values. It is likely that a shift of this small magnitude would be essentially negligible compared to other sources of variability.

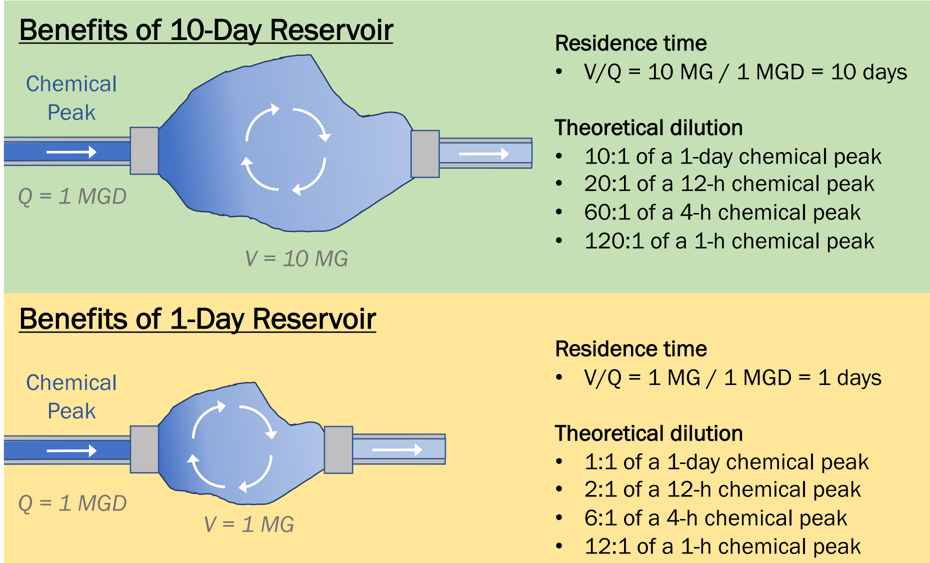
This delineation becomes less clear as blending ratios are increased. Nevertheless, blending of an AWTF effluent with another surface water—even at 1:1 ratios of each—may greatly improve the treatability of the RO permeate by rendering the water more similar to the surface waters for which the WTPs were designed.

6. Considerations for RWA With a Small Reservoir

This section further explores how RWA projects with and without small reservoirs may differ, and the potential rationale for these differences.

6.1 Pathogen and Chemical Peaks

As discussed above, blending will likely only provide significant additional protection against pathogens, at blending ratios greater than or equal to 10:1 assuming that a 1-log reduction is the threshold for significance. In a reservoir setting, however, a pulse of off-spec water can be attenuated if that pulse mixes with the existing on-spec water that makes up the remaining volume of the reservoir. The existing SWA regulations require theoretical reservoir retention times of no less than 60 days, as well as minimum levels of dilution of 10- to 100-fold. In an ideal case in which the reservoir is completely mixed, a 60-day retention time would provide a 60-fold dilution of a 1-day pulse of off-spec water. Along these lines, a small reservoir would only need to provide 10 days of retention time to achieve a 10-fold dilution of a one-day pulse assuming it was perfectly-mixed. The shorter the pulse of off-spec water, the greater the dilution achieved in the reservoir; a pulse of off-spec water lasting one hour would experience a 120-fold reduction in the same 10-day reservoir (Figure 19).



Residence time

- V/Q = 10 MG / 1 MGD = 10 days

Theoretical dilution

- 10:1 of a 1-day chemical peak
- 20:1 of a 12-h chemical peak
- 60:1 of a 4-h chemical peak
- 120:1 of a 1-h chemical peak

Residence time

- V/Q = 1 MG / 1 MGD = 1 days

Theoretical dilution

- 1:1 of a 1-day chemical peak
- 2:1 of a 12-h chemical peak
- 6:1 of a 4-h chemical peak
- 12:1 of a 1-h chemical peak

Figure 19. Theoretical dilution achieved by small reservoirs (10- and 1-day retention times) receiving pulses of off-spec water.

At some point, however, the retention time provided by a small reservoir becomes too small to provide a significant reduction. For example, a 1-day reservoir would only provide a 10-fold reduction in a pulse of off-spec water if the pulse had a duration less than approximately 2.5 hours. A 1-day off-spec pulse would only experience a 1:1 reduction in the peak—too little to be of significant protection against pathogens. This example shows that the reservoir benefits are also tightly linked to the time needed to detect and respond to a failure. The quicker the response time, the greater the degree of peak attenuation provided by a given reservoir. Increasing monitoring and operations to rapidly respond to treatment issues therefore is another strategy for preventing peaks from passing through the system.

The same discussion holds true for the reduction of *chemical* peaks as well. It should be emphasized, however, that the risk associated with a pathogen peak is of a very different nature than a chemical peak. Pathogens can initiate an infection after a single exposure event meaning that control of pathogens must be continuous to prevent an *acute* public health event. Most chemicals are present in wastewater at such low concentrations that they do not cause an acute impact on human health. Instead, the chemical contaminants must be consumed over long periods to impact public health. The *chronic* exposure required for such effects means that day-to-day variability is less important than the long-term, lifetime exposure levels. Nevertheless, the State Board has signaled that the control of chemical peaks will be an additional element that must be considered for DPR (DDW Reg Framework 2018). Clearly, a 10-day reservoir will provide sufficient control of a chemical peak to achieve the minimum 10-fold reduction that DDW has previously stated is sufficient for toxic organic compounds. As the reservoir retention time drops to 1-day, these peak reduction benefits become progressively smaller meaning that the reservoir *alone* is inadequate to provide control.

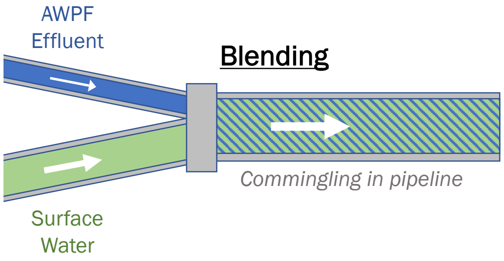
This discussion highlights that the benefits of the reservoir exist over a *spectrum* that is directly related to the retention time that it provides. This spectrum means that a reservoir can be used to varying degrees to satisfy the treatment requirements of DPR. For example, a reservoir providing 10 days of retention time may *alone* be able to satisfy future DPR requirements for peak attenuation. In such a case, additional treatment barriers at the DPR AWTF may not be needed. A smaller reservoir would provide *some but not all* of the minimum peak attenuation, and so may need to be supplemented by some degree of additional treatment at the DPR AWTF. In a hard-piped RWA scenario with no reservoir, all of the peak attenuation would need to occur at the DPR AWTF. In short, public health protection can be achieved through the balance of multiple elements, with small reservoirs being one of those elements.

6.2 Chemicals Consistently Present in AWTF Effluent

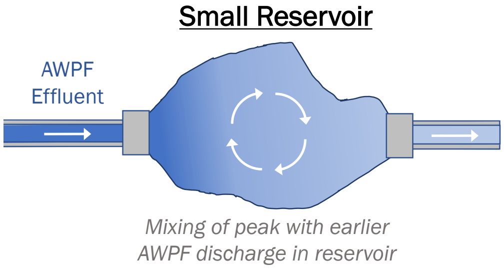
While small reservoirs provide benefits for peak attenuation (due to the mixing of off-spec pulses with larger volumes of on-spec water), they do not provide the same benefits in terms of reducing the concentrations of chemicals that are consistently present near health thresholds in the AWTF effluents. For example, if the AWTF effluent consistently contained THMs at levels equivalent to 80% of the MCL, there would not be a benefit to passing this water through a small reservoir, since the reservoir water would also contain the same background concentrations (assuming there was not significant environmental attenuation of the THMs in the reservoir). In this regard, *blending* with another source water provides better protection than the small reservoir in that even a 1:1 blend of AWTF effluent with the alternate source water would decrease the THM concentration by a factor of two. Decreasing the THM concentrations from 80% down to 40% of the MCL would provide a significant benefit. Other compounds that would benefit from even moderate levels of blending—i.e., those that are commonly present near their threshold values—include nitrate, boron, and the DBPs.

6.3 Unknown Chemical Contaminants

The ability of a small reservoir to provide protection against unknown chemical contaminants depends on the concentration and variability of the compound in the AWTF effluent. If the compound is typically controlled well below the threshold levels, but at times may be present as a high-concentration pulse, then the small reservoir will provide the benefits described in Section 6.1. If, however, the unknown contaminant is consistently present at or near the threshold levels, then the small reservoir would not provide a significant form of control (per Section 6.2). The opposite situation holds for blending, which is better at controlling consistently present unknown contaminants, but less effective at attenuating pulse inputs. The advantages and disadvantages of blending and small reservoirs is provided in Figure 20.



Pathogen Peak	Chemical Peak	"Consistent" Chemical	Unknown Chemical
✗	✗	✓	✓/✗



Pathogen Peak	Chemical Peak	"Consistent" Chemical	Unknown Chemical
✓	✓	✗	✓/✗

Figure 20. Overview of the benefits of blending and small reservoirs in the control of pathogens and chemical contaminants.

6.4 Summary

The inclusion of small reservoirs into RWA projects offers a number of advantages compared to hard-piped RWA projects. From a permitting perspective, DDW has indicated that it views these projects as having different (assumedly, lower) risk profiles given that the small reservoir provides public health benefits that hard-piped RWA and TWA cannot provide. Consequently, the use of small reservoirs may allow for an easier permitting process, particularly for the "early adopters" of RWA. Through the analysis in Section 6, it is clear that the mixing and dilution that occurs in reservoirs can satisfy a number of the anticipated treatment requirements for DPR projects, particularly the control of peaks of contaminants that may pass through the AWTF. This control would be effective for pathogens as well as pulses of both known and unknown contaminants. The inclusion of a small reservoir could greatly reduce (and likely eliminate) the need for additional engineered treatment barriers for the control of peak contaminants.

The major limitation of the small reservoir is its inability to provide significant protection against compounds that may be present at or near their threshold levels in the AWPF effluent. As discussed in Section 5.2, however, even modest degrees of blending (i.e., 1:1 blends of alternate source waters and AWTF effluents) can be useful for the control of this group of contaminants. Consequently, the use of small reservoirs with some degree of blending may be sufficient to provide the necessary protection without the need for additional unit treatment processes at the AWTF.

The benefits of small reservoirs scales with both their size and the speed with which operators respond to treatment issues—through this analysis it was shown that a reservoir providing a 10-day retention time can still provide significant protection against pathogens and chemicals. As the size is reduced to provide a retention time of only one day, many of the benefits become negligible unless coupled with rapid response times. For these reasons, engineered storage buffers that provide only hours of retention time will likely not satisfy future DPR requirements for additional protection against pathogens, chemical peaks, and unknown contaminants.

7. Coordination with Other Potable Reuse Projects

The previous discussion has assumed that Metropolitan's satellite DPR AWTF would receive its feedwater from a single source: Metropolitan's GWR AWTF. One option to expand the capacity of the system is to interface with the Los Angeles Department of Water and Power's (LADWP) potable reuse project. In this scenario, both the GWR AWTF and LADWP's AWTF would produce FAT-treated water that would commingle prior to treatment at the satellite DPR AWTF. This section describes how this alternative scenario would impact the considerations previously discussed.

7.1 Increasing project complexity

All of the existing potable reuse projects in California utilize a single AWTF to provide source water for a given end use—either a groundwater aquifer or a surface water reservoir. While there is no prohibition in the IPR regulations that limits the number of AWTFs contributing to a given potable reuse application, this scenario will further increase the complexity of the project due to the need to monitor, control, and ensure the reliability of separate AWTFs. The first item to coordinate would be the oversight and potential integration of source control programs. As the first barrier to contaminants, DPR source control requirements will be enhanced compared to the existing IPR programs. The coordination of source control programs for both the Sanitation Districts (overseeing the GWR AWTF) and LADWP (overseeing the LADWP AWTF) will require an additional effort to clarify roles and responsibilities, and to establish procedures to respond to failures of either system. As this configuration does not have precedents in California, additional discussion among the project sponsors and with the State Board is recommended to understand the requirements for source control.

Multiple source water AWTFs also doubles the amount of monitoring and control required for the project. Because the DPR AWTF is dependent on the quality of both feedwaters, operations staff at the DPR AWTF will need to establish clear protocols to rapidly respond to treatment issues at either source water AWTF. The design of the source water AWTFs will also need to be coordinated to ensure that both can meet the water quality requirements of the DPR AWTF.

7.2 Technical, Managerial, and Financial Capacity

Per the DPR Regulatory Framework, systems with higher degrees of complexity require higher degrees of technical, managerial, and financial (TMF) capacity. The State Board states that they will evaluate system complexity and sophistication based on the number and types of treatment processes, monitoring methods, and control points, and that they anticipate this to increase moving from IPR to DPR. A scenario that includes a DPR AWTF being sourced by separate AWTFs will increase the complexity of the system, and is anticipated to have stricter requirements for TMF capacity. Given this unique configuration, TMF requirements should also be discussed with the State Board.

7.3 Blending

Combining the flows of the GWR AWTF and the LADWP AWTF may decrease the amount of blending available for RWA. As discussed in Section 5, one option currently considered is to provide a 10:1 blend ratio with the DPR AWTF comprising 10% of the source water to the downstream WTPs. At these ratios, a relatively straightforward argument could be made regarding blending's benefits toward:

- Pathogen control
- Control of chemical peaks
- Control of unknown chemical contaminants
- Treatability of the blended water at the WTP

Increasing the capacity of the DPR AWTF through the commingling of multiple source water AWTFs will reduce the blend ratios and may impact these benefits. Some of these benefits may be replaceable with other elements (e.g., additional pathogen control barriers at one of the AWTFs). The loss of other benefits may have larger impacts, such as if lower blending ratios trigger the need for site-specific treatability studies at the WTPs. Additional discussion with the State Board is recommended to understand the impact of blending on the project's requirements.

While this TM assumes treatment for DPR would occur at a satellite DPR AWTF, as discussed in the 2018 TM, Metropolitan could include additional treatment for DPR at the GWR AWTF. In this case, if Metropolitan and LADWP were to comingle their AWTF effluents, both would need to meet DPR requirements prior to blending.

8. Summary and Next Steps

8.1 Summary

Metropolitan and the Sanitation Districts are considering RWA through treatment of GWR AWTF product water at a satellite DPR AWTF that would feed either the Weymouth or Diemer WTP. The primary concerns in DPR systems are controlling pathogens and controlling chemicals. To control pathogens, regulations will likely require additional pathogen log reduction. Chemical control will likely necessitate the ability to deal with spikes of chemicals, and the robustness in treatment mechanisms to deal with both known and unknown chemicals that may pose a threat to public health. Treatment at the DPR AWTF must provide both redundancy in the form of additional pathogen control, and robustness with treatment processes that add new mechanisms of removal.

With little industry experience treating RO permeate, there are design and monitoring challenges to overcome. Traditional surrogates for monitoring treatment performance may not be present in the feedwater to the DPR AWTF, so research will need to be done to develop new surrogates or find analyzers that are sensitive enough to capture valuable surrogate data. Two treatment trains have been proposed in the TM that may be viable options for a DPR AWTF. However, pilot testing will be required to develop design criteria for the proposed treatment processes and demonstrate performance.

As potable reuse moves to more direct forms, recycled water programs will need to utilize all aspects of their systems from enhanced source control, to treatment, to the use of small reservoirs or other engineered storage buffers. DPR systems will include many means for protecting public health, and while regulations are not yet in place for DPR, it is anticipated that requirements may be placed on some of these project aspects (e.g. enhanced source control). One of the elements of DPR systems that can provide an effective barrier for many of the concerns in a DPR system is the use of a small reservoir. A small reservoir can provide control of peaks of contaminants (pathogens and both known and unknown chemicals) that may pass through the AWTF and provide additional time to detect and respond to treatment issues.

8.2 Next Steps

As Metropolitan and the Sanitation Districts move forward, they should consider the following next steps:

- **Develop a White Paper on the Role of Metropolitan's WTPs in a DPR Project.** The White Paper should address how Metropolitan's WTPs can provide protection through dilution of certain chemicals. The White Paper should also address how the WTPs can preserve their current pathogen log-reduction credits.
- **Develop a DPR Concept Proposal.** Metropolitan should develop a concept proposal that outlines their proposed DPR project and how the project will protect public health. The Proposal should be reviewed by the IAP and submitted to DDW. The goal of the Concept Proposal is to receive DDW's approval of the proposed DPR project concept.
- **Engage the IAP.** The IAP can provide valuable feedback on the different potential DPR projects and what the challenges of each option might be.
- **Consider a Small Environmental Buffer.** Whether a small reservoir or a small groundwater basin, the use of an environmental buffer can provide valuable response time and additional protections for DPR such as dilution, or in the case of an aquifer, soil aquifer treatment.
- **Perform Treatability Studies for the WTPs.** Metropolitan should perform treatability studies to understand how advanced treated water would impact the performance of the WTP treatment processes at different blending ratios.
- **Model the Impact of Different Blending Ratios.** In addition to treatability studies, Metropolitan should conduct modeling to demonstrate the benefits of blending to DDW.
- **Develop a Pilot Testing Plan.** A pilot testing plan should be developed to evaluate the proposed treatment trains and any additional treatment trains that may be viable options for DPR.

- **Engage DDW.** Metropolitan should continue to meet with DDW. Engaging the regulators is an important aspect of developing a permittable project.
- **Clarify Treatment Requirements for Partnership with LADWP.** If the advanced treated water from LADWP’s AWTF will be introduced into Metropolitan’s system, both parties must put water of equivalent quality (e.g. GWR vs. DPR) for the intended downstream uses.

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