



Guidelines for Direct Potable Reuse in Colorado

NWRI Independent Expert Advisory Panel Final Report

Prepared for:

WaterReuse Colorado
Denver, Colorado

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Disclaimer

This report was prepared by an Independent Expert Advisory Panel (Panel), which is administered by National Water Research Institute. Any opinions, findings, conclusions, or recommendations expressed in this report were prepared by the Panel. This report was published for informational purposes.

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Acronyms and Abbreviations

Board	Colorado Water Conservation Board
COC	Contaminant of concern
Commission	Colorado Water Quality Control Commission
CCP	Critical control point
CDPHE	Colorado Department of Public Health and Environment
CDPS	Colorado Discharge Permit System
CRMWD	Colorado River Municipal Water District
DPR	Direct potable reuse
DBPs	Disinfection byproducts
EBCT	Empty bed contact time
EPA	Environmental Protection Agency
GAC	Granular activated carbon
HAL	Health advisory level
IPR	Indirect potable reuse
LRV	Log reduction values
MCL	Maximum contaminant levels
NDMA	N-Nitrosodimethylamine
NPDES	National Pollutant Discharge Elimination System
NPP	National Pretreatment Program
NWRI	National Water Research Institute
Panel	Independent advisory panel



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PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctanesulfonic acid
WRCO	WaterReuse Colorado
QMRA	Quantitative microbial risk assessment
RO	Reverse osmosis
SDWA	Safe Drinking Water Act
SWCS	Source water characterization study
TOC	Total organic carbon
TOrC	Trace organic contaminant
WPF	Water purification facility
WQCD	Colorado Water Quality Control Division
WRF	Water reclamation facility



Terminology

Action limit. A limit provided at a critical control point that, when exceeded, triggers a response to prevent a potentially hazardous event.

Alert limit. A limit provided at a critical control point that, when exceeded, alerts an operator that a potential problem may require a response.

Barrier. A treatment process used to control microbial or chemical contaminants.

Blending. Intentional mixing of source waters to enhance treatability and/or quality.

Constituents of concern. Potentially harmful or difficult-to-treat chemicals.

Critical control point. A point in a treatment process designed to reduce, prevent, or eliminate a human health hazard.

Design report. A report prepared for review and approval by Colorado Department of Public Health and Environment (CDPHE) that describes the elements of the proposed direct potable reuse project and the proposed design, operation, and monitoring approaches to comply with CDPHE requirements for direct potable reuse.

Direct potable reuse. Placing purified water: 1. Into raw water conveyance to a drinking water treatment plant; 2. At a point after a drinking water treatment plant but before the potable water distribution system; or 3. Into the potable water distribution system.

Disinfection. Removing or inactivating pathogens and, thereby, preventing their ability to cause illness.

Disinfection byproducts. Chemicals formed when disinfectants such as chlorine or ozone react with organic or inorganic matter in treated water or wastewater.

Drinking water distribution system. Pipes, storage tanks, pumps, and other infrastructure that conveys treated drinking water to customers.

Engineered storage. A facility that stores purified water before it is introduced into the potable water treatment plant or potable water distribution system to: 1. confirm adequate water quality, and 2. hold water if it does not meet quality requirements.



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Enhanced Source Control. A source control program applied to a wastewater collection system that goes beyond traditional methods to minimize or eliminate local drinking water contaminant sources.

Guidance. Non-binding, recommended practices to assist and guide regulatory staff, regulated entities, or the public. Guidance documents are used to encourage or educate a targeted audience and may also provide background information or supporting details about a statute, regulation, or policy.

Guidance document. A non-binding practice recommendation intended to assist and guide actions of regulatory staff, regulated entities, or the public. Guidance documents are used to encourage or educate, and may provide background information or supporting details about a statute, regulation, or policy.

Indirect potable reuse. The introduction of advanced treated water to an environmental buffer such as a stream, reservoir, or groundwater basin before rediverting and further treating the water, if necessary, to ensure that it is safe for drinking.

Log reduction value. A reduction in the concentration of a contaminant or microorganism by a factor of 10. For example, 1 log reduction value (LRV) corresponds to a 90-percent reduction from the original concentration, and 2 LRVs correspond to a 99-percent reduction from the original concentration.

Maximum Contaminant Level. A maximum contaminant level is an enforceable numeric drinking water standard that is applicable to public water supplies and represents the highest concentration of the contaminant the EPA allows in drinking water.

Nitrification and denitrification. A combined biological treatment process at a water reclamation facility that removes ammonia and nitrate.

Online monitoring. Locating instruments directly in the process flow or sample line and monitoring water quality in real-time continuously or semi-continuously, with a sample time of 15 minutes or less.

Pathogen. A microorganism such as bacteria, virus, or protozoa that can cause human illness.



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Policy. Defines how CDPHE’s Water Quality Control Division (WQCD) interprets law or regulations or determines the appropriate approach to exercise flexibility in the law or regulations while making case specific decisions where the underlying applicable law or regulation is ambiguous or provides the implementation program with discretion.

Point of compliance. Locations at which water reclamation plant or drinking water plant water quality is evaluated by CDPHE to confirm compliance with water quality requirements described in Colorado regulations.

Potable water. Water suitable for drinking, cooking, and bathing. Potable water distributed by public drinking water systems in the United States must meet the standards within National Primary Drinking Water Regulations and may also be subject to additional state or local regulations for drinking water.

Potable water distribution system. See *Drinking water distribution system*.

Public health. According to the American Public Health Association, public health promotes and protects the health of people and communities where they live, learn, work, and play.

Public water system. A system that provides the public with water for human consumption, contact, or other uses through pipes or other constructed conveyances, if such system has at least 15 service connections or regularly serves at least 25 individuals at least 60 days per year. For details, see Regulation 11, Colorado Primary Drinking Water Regulations.

Purified water. Can be used interchangeably with “potable water” as described above but is used specifically in relation to DPR systems. It includes recycled wastewater that has been treated at a water purification facility to meet specific DPR requirements and all applicable drinking water regulatory standards using treatment processes specifically designed for this purpose. Purified water may include blending with other water, to reduce the concentration of contaminants.

Regulated contaminant. Any physical, chemical, biological, or radiological substance or matter that has been identified as a concern to public health if it is present in drinking water and is, therefore, regulated by the Environmental Protection Agency (EPA) or State of Colorado. The EPA and the State of Colorado sets regulatory limits as required by the Safe Drinking Water Act to limit certain contaminants in water provided by public water systems



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Regulation. Binding requirements that federal, state, or local regulatory agencies enact.

Risk. The probability that a person or organism of concern exposed to a specified hazard will experience an adverse response.

Source control. The elimination or control of the discharge of constituents of concern (COCs) into a wastewater collection system. Source control targets COCs that are difficult to treat and/or that may damage the water reclamation or purification facility.

Treatment technique. An enforceable procedure or level of technological performance that public water systems must follow to ensure the control of a contaminant.

Treatment train. A combination of treatment operations and processes used to produce water meeting specific water quality levels.

Unregulated contaminant. Term used by EPA for contaminants suspected to be in drinking water but not included in the National Primary Drinking Water Regulations or Colorado Primary Drinking Water Regulations.

Wastewater collection system. Network of conveyance that gathers used water from homes, businesses, and industries for delivery to a water reclamation plant. Sometimes referred to as a sanitary sewer, sewerage system, or sewershed.

Water purification facility. A utility or plant where recycled wastewater is treated to produce purified water to meet specific DPR requirements identified in this report.

Water reclamation facility. A publicly owned wastewater treatment plant which is designed to treat municipal sewage and industrial waste. Also may be referred to as wastewater treatment plant.



Project Background

National Water Research Institute (NWRI), with assistance from Western Resource Advocates, administered an Independent Advisory Panel (Panel) to support the safe and effective implementation of direct potable reuse (DPR) in Colorado. WaterReuse Colorado (WRCO) sponsored this effort to provide expert guidance to the Colorado Water Conservation Board (Board) and the Colorado Department of Public Health and Environment (CDPHE).

WRCO is the state section of the national WaterReuse Association. It comprises a broad group of reuse professionals, including municipal water providers, recycled water users, engineering consultants, regulators, and researchers. WRCO's primary objectives include advocating for legislation and regulations that promote safe and effective reuse throughout Colorado, and improving public understanding of water reuse.

Currently, no state regulations prohibit or govern DPR in Colorado, and the federal government does not regulate the practice. Colorado water regulators recognized that utilities are more likely to invest in potable reuse infrastructure if clear regulations, policies, and guidance are in place. To meet this end, the project stakeholders are soliciting expert advice on a regulatory framework for DPR.

What is DPR?

DPR is the planned introduction of purified water into one of three locations of a potable water system: into the raw water conveyance to a drinking water treatment plant, at a point after a drinking water treatment plant but before the potable water distribution system, or directly into the potable water distribution system. .

Communities throughout the western United States are increasingly turning to recycled water projects, including DPR, to meet their water supply needs. This trend will continue as water managers need to offset water shortages caused by drought and the overallocation of existing water sources.



Project Goals

WaterReuse Colorado began developing a proposal for how DPR could be regulated in Colorado in Phase 1 of this project, Advancing Direct Potable Reuse to Optimize Water Supplies and Meet Future Demands.

Technical Memorandum 1 from Phase 1 (WaterReuse Colorado 2018) outlined a detailed path forward for developing DPR regulations in Colorado, including a list of key regulatory categories that need to be developed before moving through the Colorado Water Quality Control Commission (Commission) rulemaking process. The memo recommended that the development of regulatory categories could be “led by technical experts outside of the Water Quality Control Division (WQCD) and would benefit from national and local expertise in public health, advanced treatment, pathogen removal, chemistry, and other states’ regulatory experience to date.”

During Phase 1 of the project, stakeholders identified the following goals:

- Define proposed DPR treatment techniques and develop monitoring and management policies that are protective of public health and enable sound investment in potable reuse infrastructure in Colorado. A treatment technique is an enforceable procedure or level of technological performance that public water systems must follow to ensure control of a contaminant.
- Write proposed regulations, policies, and guidance to enable safe and effective DPR with an emphasis on policy-level recommendations that CDPHE and the Commission can develop, implement, and enforce.
- Recommend allowed pollutant removal rates that are supported by scientific and technical literature on pathogen and chemical removal from municipal wastewater.
- Recommend language to communicate health effects as required by the Public Notification requirements within the Colorado Primary Drinking Water Regulations (Colorado Department of Public Health and Environment 2018). Address Tier 1, 2, or 3 notifications and the required health effects language for each regulatory requirement, including treatment goals such as removal of unregulated contaminants. A contaminant is any physical, chemical, biological, or radiological substance that may adversely affect human health or the environment.



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Project goals will be met by developing the regulations, policy, and guidance concepts necessary for each of the following categories that were defined in Phase 1:

- The First Barrier – Source Control
- Optimizing the Water Reclamation Facility
- The Water Purification Treatment Train
- Pathogen Disinfection/Removal and Monitoring
- Chemical Pollutant Removal and Monitoring
- Education and Outreach

Other categories that will be addressed by CDPHE, but are outside the scope of this project, are:

- Reporting
- Facility Operations/Certification Programs
- Technical/Managerial/Financial Capacity

NWRI Project Role and Approach

NWRI's scope of work included identifying and engaging technical expert panel members, planning and facilitating three meetings and one teleconference for the Panel and invited stakeholders, and editing and producing the final Panel consensus report. NWRI also facilitated disciplined peer review to ensure high-level process engagement by the Panel, stakeholders, and clients. These planning and facilitation methods are based on hundreds of similar facilitated groups that form the core of NWRI's service offerings over the past 20 years.

Panel Members

NWRI engaged six experts who work in disciplines relevant to potable reuse, including: advanced water treatment, wastewater treatment, analytical methods for microbiological and chemical water quality parameters, and public health and community outreach.



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The Panel has experience with water reuse practice and policy throughout the western United States, including Colorado, California, Nevada, and Texas. The Panel members are:

- Panel Chair: Larry Schimmoller, PE, Jacobs
- Christopher Bellona, PhD, Colorado School of Mines
- Richard Danielson, PhD, BioVir Laboratories
- Eric Dickenson, PhD, Southern Nevada Water Authority
- Ellen McDonald, PhD, PE, Plummer
- Kristina Mena, PhD, MSPH, University of Texas – Houston

See **Appendix A: Panel Biographies** for brief profiles of all Panel members.

Stakeholders and Meeting Contributors

Representatives from stakeholder organizations, including Colorado water and wastewater utilities, regulatory agencies, and water reuse consultants participated in three workshops that NWRI administered in Denver on July 26, 2018, November 29, 2018, and April 19, 2019. Stakeholders reviewed drafts of the report and provided written comments and requests for clarification. The Panel presented the draft report to the stakeholders during a conference call held November 12, 2019, and stakeholders submitted their final comments and questions the following week.

Project team members from NWRI and Western Resources Advocates facilitated and participated in all workshops.

Organization of the Report

Chapter 1 describes Colorado's Water Plan and the vision for water conservation and reuse in the state. Chapters 2 through 7 describe the specific categories that were defined in Phase 1, and include recommendations for regulations, policy, and guidance to help define the path toward DPR in Colorado.



Chapter 1: Colorado's Water Supply Challenges

Colorado is a semi-arid western state, with topography that ranges from plains in the east to the Rocky Mountains in the west half of the state. It is a headwater state where many major rivers originate and flow downstream to 18 states and Mexico. Colorado has a strong and diverse economy with thriving cities, productive agricultural communities, extensive environmental resources, and a booming recreational industry.

The state's population in 2015 was more than five million and is projected to nearly double by 2050. That growth will bring significant water supply challenges, complicated by the fact that about 85 percent of Colorado's population lives on the east slope of the Continental Divide, which runs north-south through the state, while roughly 85 percent of water supplies originate on the west slope. In the coming decades, climate change will result in a hotter and drier environment with more frequent and extreme droughts, floods, and wildfires.

Colorado's Water Plan and Water Reuse

To address these and other challenges, Colorado completed its first comprehensive Water Plan in late 2015 in response to the governor's executive order for a roadmap to a secure water supply future in the state. Colorado's Water Plan was developed collaboratively with input from diverse communities and stakeholders around the state. The plan recognized the importance of identifying water supply and demand management strategies, including: conservation, storage, land use planning, new methods of sharing water with agriculture (the largest water use in the state), and reuse. The plan established several water-related values, including:

- A productive economy that supports vibrant and sustainable cities, viable and productive agriculture, and a robust skiing, recreation, and tourism industry;
- Efficient and effective water infrastructure promoting smart land use; and
- A strong environment that includes healthy watersheds, rivers and streams, and wildlife.



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Colorado’s Water Plan recognized that, “Water conservation activities and water reuse will play an important role in balancing the need for additional water supply with strategies to lessen that need.” It also acknowledged that the “Widespread development of potable reuse will be an important facet of closing the future water supply–demand gap.” The plan set forth measurable objectives, goals, and actions by which Colorado will address its projected water needs and measure its progress.

One of the actions in the reuse section of Colorado’s Water Plan is to, “Clarify the regulatory environment: Over the next two years, the Board and the CDPHE will work with stakeholders to examine the application of water quality regulations to reuse water. The aim will be to identify potential change that fosters permanent growth in the reuse of limited water supplies, and that protects health and the environment.” The Water Plan also includes Critical Actions to “Evaluate regulations to foster reuse of water supplies while protecting health and the environment.” (Colorado Water Conservation Board 2015)

Water Reuse in Colorado

All water reuse in Colorado must comply with state water law that specifies which water supplies can be legally reused and, as a result, not every community has reusable water. In addition, Colorado water law is designed to avoid injury to other water rights. As a general rule, reuse cannot decrease historical return flows from native (in–basin) water supplies that other water rights holders rely on. Legally reusable or fully consumable water supplies include most trans–basin diversion water, transferred consumptive use supplies, non–tributary groundwater, and other supplies with decreed reuse.

Currently, Colorado has both non–potable and indirect potable reuse (IPR) projects in operation. IPR is the introduction of advanced treated water to an environmental buffer such as a stream, reservoir, or groundwater basin before rediverting and further treating the water, if necessary, to ensure that it is safe for drinking.

The Commission is the rulemaking authority within CDPHE that is responsible for developing water quality policies and regulations for surface water and groundwater in Colorado. The Commission adopts water quality classifications, standards, and regulations to achieve compliance and to protect beneficial uses of waters of the state while protecting public health. The WQCD is the administrative agency responsible for implementing water quality regulations and policies adopted by the Commission.



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Colorado's water quality regulatory framework includes the following:

- **Regulation.** Binding requirements that federal, state, or local regulatory agencies enact.
- **Policy.** While not legally binding, policies define how CDPHE's Water Quality Control Division (WQCD) interprets law or regulations or determines the appropriate approach to exercise flexibility in the law or regulations while making case specific decisions where the underlying applicable law or regulation is ambiguous or provides the implementation program with discretion.
- **Guidance.** Non-binding, recommended practices to assist and guide actions of regulatory staff, regulated entities, or the public. Guidance documents are used to encourage or educate a targeted audience and may also provide background information or supporting details about a statute, regulation, or policy.

As in many other states, interest in DPR is growing in Colorado. And because DPR is not regulated by the federal government, states are creating their own regulatory narratives and terminology.

For example, in Colorado, project stakeholders differentiated DPR from IPR for the purpose of developing proposed regulations. A typical IPR scheme includes an environmental buffer, such as a reservoir, to temporarily hold discharged water from a water reclamation plant before it is treated by a drinking water treatment plant and ultimately distributed to the drinking water distribution system, while DPR schemes do not. Specifically, DPR water, or purified water, is recycled wastewater that is treated to meet drinking water standards using prescribed treatment techniques, which may include blending with other water.

DPR Water Blending Scenarios

The expert panel used the following stakeholder definitions for DPR water blending scenarios or configurations when they developed recommendations for DPR regulations in Colorado.

Direct potable reuse is the intentional introduction of purified water:

- Into any system of conveyance that delivers purified water for blending with one or more approved raw source waters before treating the blended water at a drinking water treatment plant.



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- Downstream of a drinking water treatment plant and before distribution by a potable water distribution system.
- Into any potable water distribution system directly from a water purification facility.

These three options are defined and illustrated on the following pages. The points of compliance shown in these figures represent locations currently regulated by CDPHE for water reclamation facilities and drinking water treatment plants. For water reclamation plants, the point of compliance is the location specified in the National Pollutant Discharge Elimination System (NPDES) permit or Colorado Discharge Permit System (CDPS) permit for water quality compliance before it is discharged to a receiving body.

For drinking water treatment plants, the point of compliance is the “entry point” into the potable water distribution system as defined in CDPHE Regulation 11 – Colorado Primary Drinking Water Regulation. These points of compliance will not change with implementation of DPR. However, monitoring at the water purification facility (WPF) is required at various points within the WPF to confirm adequate removal of pathogens and chemicals as described in this report.

Raw Water Blending. Raw water blending is defined as adding purified water into any conveyance system that blends it with one or more approved sources of raw water before treating the blended water at a drinking water treatment plant, as shown in Figure 1.



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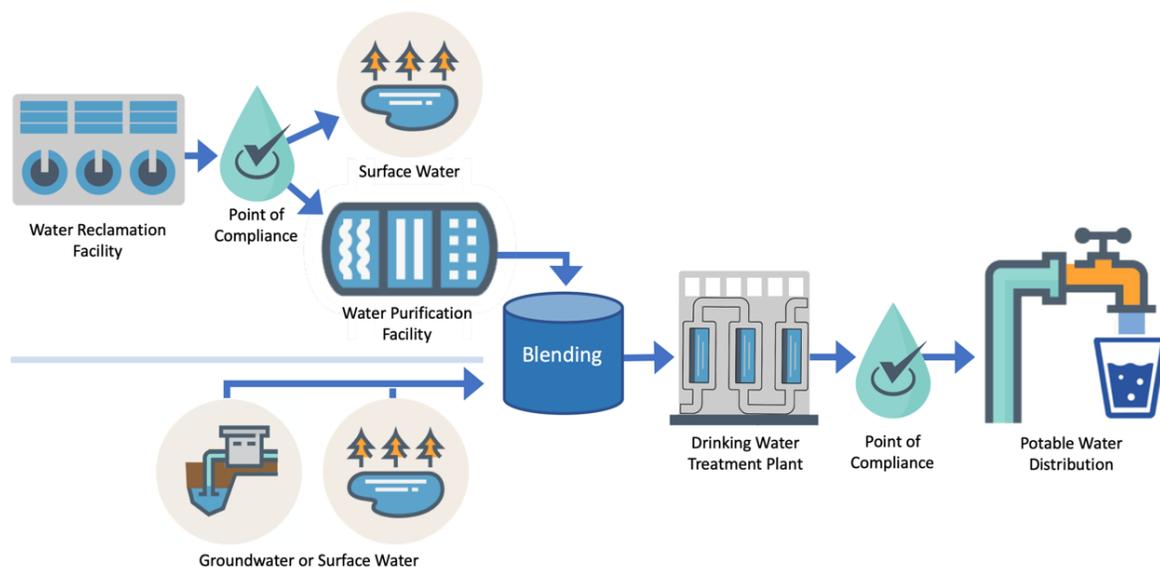


Figure 1. Blending purified water with approved source water before it goes to drinking water treatment.

Potable Water Blending. Potable water blending is the intentional blending of purified water downstream of a drinking water treatment plant and before distribution by a potable water distribution system, either before or after the disinfection process, as shown in Figure 2. The point of compliance for this scenario (i.e., entry point into the distribution) would be after blending of the two waters.

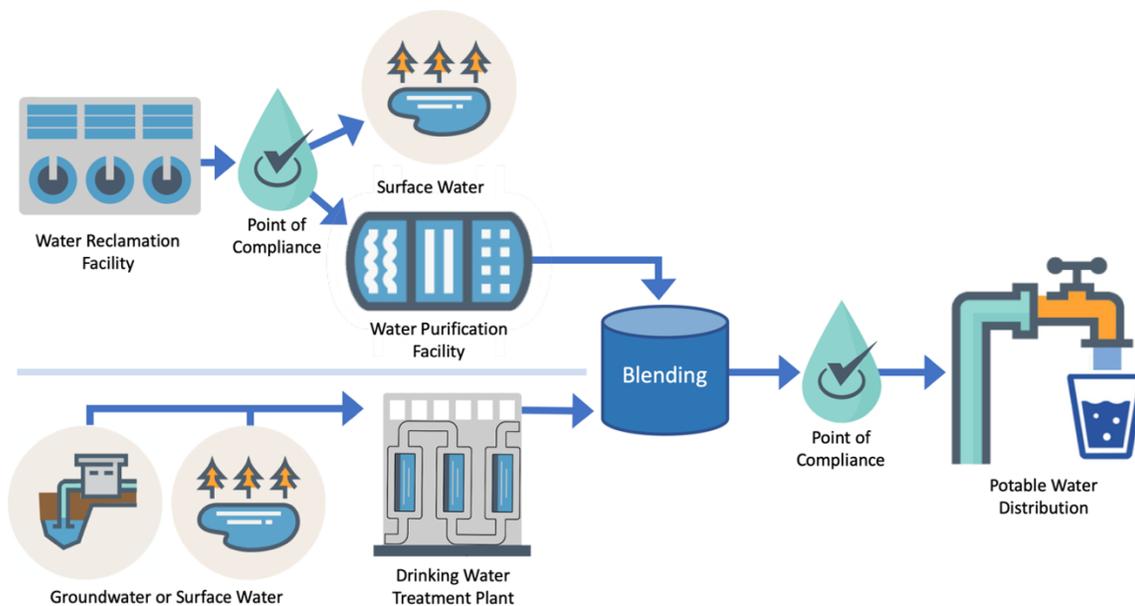


Figure 2. Blending purified water with water from the drinking water treatment plant before it goes to the potable water distribution system.

Potable Water Production. Potable water production is the intentional introduction of purified water into any potable water distribution system directly from a water purification facility, as shown in Figure 3. In this case, CDPHE would require the WPF to have its own Point of Compliance in addition to the DPR treatment and monitoring requirements outlined in this report.



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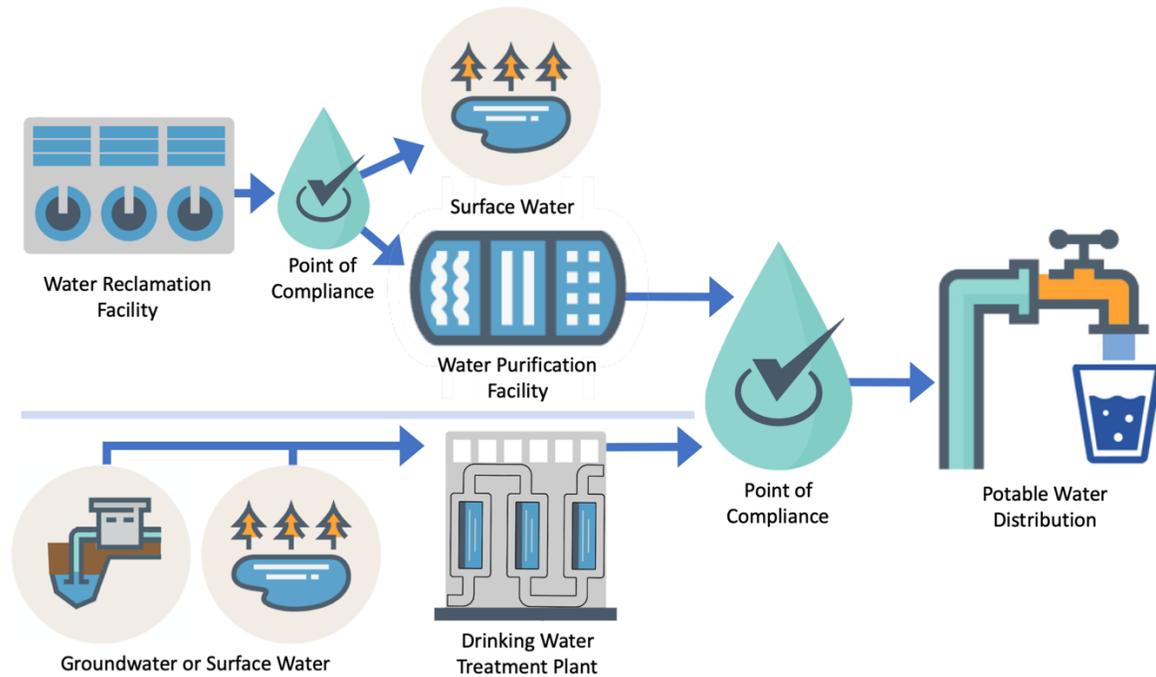


Figure 3. Production of potable water from the water purification facility to serve potable water distribution.

The industry best practice for designing and implementing any potable reuse project is to use multiple treatment barriers to remove specific contaminants so that if one barrier fails, performs inadequately, or is taken offline, the water purification facility will still perform effectively. These values are embodied in the “Four Rs” concept (reliable, redundant, robust, and resilient), which provides a framework to evaluate multi-barrier treatment trains (Pecson, et al. 2015). A train is a series of treatment processes designed to produce water that meets specific water quality levels. Any potable reuse project proposed in Colorado will be designed around these core values, as described in Chapter 4, The Water Purification Treatment Train.



Chapter 2: The First Barrier—Source Control

Wastewater generated by residential, commercial, institutional, and industrial sources is the source water for DPR projects. Given the diversity of these sources, the quality of the wastewater entering a water reclamation facility can vary significantly. Therefore, it is critical to develop and implement an enhanced source control program to protect public health and control or eliminate the discharge of COCs to the wastewater collection system and prevent them from entering the WPF. In the context of source control for DPR projects, COCs are potentially harmful or difficult-to-treat chemical constituents that must be managed.

Enhanced source control is the first of the multiple barriers recommended by the Panel for protection of public health. This barrier is intended to provide a source water to the DPR project that consistently meets community-specific DPR project source water specifications to maintain optimal operating conditions for the WPF.

Traditional source control, implemented by the US Environmental Protection Agency (EPA) under the National Pretreatment Program (NPP), provides a proven set of regulatory tools to control microbial and chemical contaminants entering a community's wastewater collection system through technical, operational, and managerial mechanisms. Enhanced source control, as described in this chapter, includes traditional source control combined with local regulations that minimize or eliminate sources of locally relevant drinking water contaminants.

Summary of Recommendations for Regulations

The Panel recommends that regulations for water reclamation facilities that serve DPR projects include the following:

- DPR projects in Colorado should be required to implement source control programs and pretreatment programs that comply with the NPP, including the adoption of a local sewer use ordinance and technically based local limits as described in the NPP. The Panel notes that conformance with the NPP may not sufficiently protect public health in some DPR scenarios.



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- Source control programs for DPR should be required to provide enhanced source control that goes beyond NPP regulations to protect public health and address DPR source water management challenges. Enhanced source control practices must be appropriate for the wastewater collection system and be compatible with selected treatment technologies.

Summary of Recommendations for Policy and Guidance

The Panel recommends the following policy and guidance related to enhanced source control for water reclamation facilities that serve DPR projects:

- Implement an approved NPP based traditional source control program.
- Implement a program to characterize the industrial dischargers for parameters relevant to drinking water and the AWT process.
- Implement a program to characterize the secondary effluent for parameters relevant to drinking water.
- Update the enhanced source control program periodically in concert with the NPDES permit cycle and whenever drinking water quality considerations warrant a change.
- Implement a program that eliminates or minimizes the discharge of COCs to the wastewater collection system from homes, businesses, industries, and health care facilities.
- Assure the quality of WPF source water through improved primary, secondary, and tertiary wastewater treatment (see Chapter 3).

Details and Rationale for Recommended Regulations, Policy, and Guidance

Protecting Public Health

In the consensus view of the Panel, effective source control is the first of the multiple public health protection barriers required of every DPR project in Colorado. Source control programs are implemented by water reclamation facilities to prevent hazardous substances, pollutants, or contaminants from entering the wastewater collection system or the environment and to reduce the impacts to public health and the environment associated with the release of these substances.



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For DPR projects, the traditional source control program must be enhanced to provide additional protection, because the water reclamation facility treats water that will be further purified for use as drinking water. Each DPR project must have an enhanced source control program designed to prevent or minimize the specific COCs entering the wastewater collection system and water reclamation facility.

Municipal wastewater contains discharges from homes, businesses, industries, hospitals, and other public and private institutions. Because every community's mix of discharge is different, the organic and inorganic constituents contained in its wastewater are also different. It is a best practice for a DPR project to reclaim mostly water from households rather than commercial and industrial flows, because the latter tend to contain more concentrated waste. However, with proper source control and treatment, DPR projects can reclaim water that contains commercial and industrial flows.

Source control and the pretreatment of municipal wastewater is authorized in Colorado under the Clean Water Act and the NPP. These federal regulations provide a comprehensive toolbox for Colorado communities to ensure that DPR source water consistently meets applicable public health standards.

The Panel finds that the top operational priority for enhanced source control programs serving a DPR project is to prevent COCs from any sources from entering the wastewater collection system, thereby keeping these contaminants out of the DPR project's source water. Therefore, in addition to successfully implementing an NPP-compliant traditional source control program, the Panel recommends policy or guidance supporting source control program enhancements that protect public health and DPR project source waters by:

- Focusing on contaminants that are relevant to drinking water as the ultimate product of a DPR project.
- Minimizing or eliminating the discharge of potentially harmful or difficult to treat chemical constituents to the wastewater collection system from homes, businesses, industries, and health care facilities.
- Assuring the quality of WPF source water through improved primary, secondary, and tertiary wastewater treatment. See Chapter 3, Optimizing the Water Reclamation Facility, for treatment and water quality requirements related to the water reclamation facility.



The National Pretreatment Program

The National Pretreatment Program (NPP) serves as a proven regulatory framework that has effectively protected people, infrastructure, the natural water environment and water recycling using risk-based analysis. Through established control and enforcement mechanisms, the NPP limits or prevents discharges of regulated or aesthetically offensive contaminants to the wastewater collection system from industrial sources.

The NPP provides the legal authority for local officials to regulate the discharge of contaminants to the wastewater collection system and the treatment facilities by requiring industrial users to:

- Protect the wastewater collection system and treatment facilities and the people who live and work in and around a water reclamation facility (WRF)¹.
- Prevent toxic contaminants from passing through or interfering with a WRF.
- Improve opportunities to reclaim municipal wastewater.

In a DPR project, one or more of the participating public agencies will be permitted to discharge highly treated effluent meeting federal secondary wastewater treatment standards under an approved NPDES permit issued by the United States Environmental Protection Agency (EPA) Region 8 Administrator as an alternative to providing source water to the DPR Project. The DPR project agency or agencies with NPDES permits will serve as the local Source Control Program Control Authority as described below.

Under the NPP, the CDPS permit is granted to a WRF for the purposes of:

- Preventing the pass-through of pollutants through a WRF;
- Preventing the interference of pollutants with the WRF treatment processes; and
- Regulating the discharge of pollutants to the environment

¹ CWA regulations define the term *pretreatment* as the pollutant control requirements for nondomestic sources or industrial users that discharge wastewater to publicly owned treatment works (POTW). In this document, the term water reclamation facility (WRF) is used as a synonym for POTW.



Enhanced Source Control to Support DPR in Colorado

Where a community has decided to move forward with DPR, the Panel recommends enhanced source control programming that (a) considers and addresses all potential inputs to a DPR wastewater collection system and (b) uses federal and state drinking water quality standards and other relevant health-based drinking water guidelines to select the most appropriate source control or pretreatment mechanisms. Enhanced source control requires a holistic, community-specific source identification and control scheme that reflects all the elements of the NPP plus additional locally relevant controls implemented primarily through technically based local limits.

Mechanisms of Enhanced Source Control

Source control and pretreatment mechanisms enhanced to support DPR are recommended as a set of rules, strategies, and best practices aimed at: eliminating or minimizing harmful pollutants entering the wastewater collection system; protecting public health; and providing the public with the confidence that the wastewater collection system is being managed with potable reuse in mind. Figure 4 shows how conventional source control programs are enhanced for DPR.

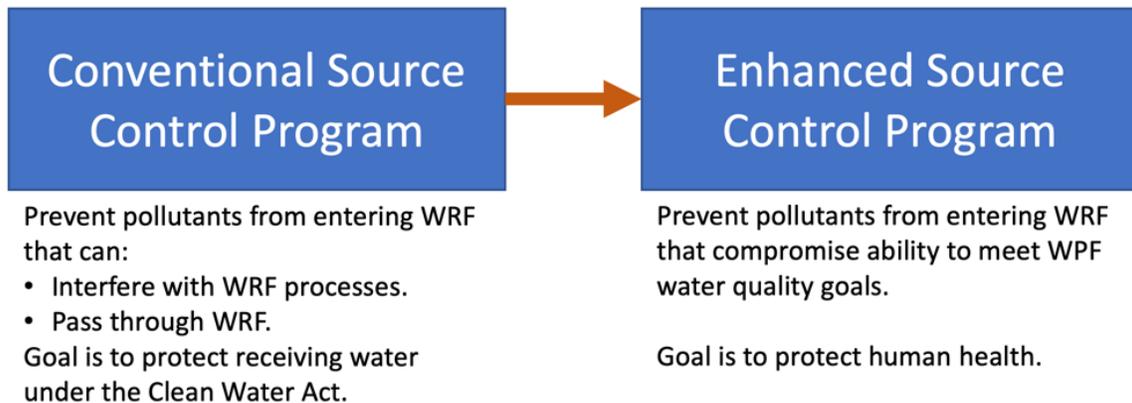


Figure 4. Enhanced source control for DPR (courtesy of Jacobs, 2018).

To accomplish these purposes, the NPP provides four regulatory foundations upon which both traditional and enhanced source control may be lawfully imposed and enforced:

1. **General Discharge Limitations** forbid the discharge of any pollutant that can pass through or interfere with the wastewater collection system delivering wastewater to a NPDES permitted WRF.



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2. **Specific Discharge Prohibitions** make it unlawful for anyone to discharge pollutants to the wastewater collection system, with or without a permit, that alone or in combination with other materials: create a fire or explosion hazard; obstruct pipelines; cause corrosion or other damage to infrastructure; interfere with biological water purification systems; or, create toxic gases or vapors.
3. **EPA Categorical Standards** provide effluent limitation guidelines prescribed for specific industry categories on a national basis via the NPP. These standards require the discharger to implement and maintain specific, technology-based or other pretreatment systems upstream of the discharger's connection to the wastewater collection system.
4. **Local Limits** are locally adopted regulations that address specific, locally relevant COCs. Local limits provide the key regulatory tool for enhanced source control. They are site-specific, can be numeric or narrative effluent discharge limits, and may include other alternative discharge control mechanisms accepted by the Approval Authority.

Six primary elements are recommended as part of an enhanced source control program for DPR and include:

1. Regulatory Authority
2. Characterize, Assess, and Monitor the DPR Project Sewershed
3. Source Investigations
4. Maintain Current Inventory of Chemicals and Constituents
5. Public Outreach
6. Response Plan for Specified Constituents

Table 1, which is adapted from *Framework for Direct Potable Reuse* (Tchobanoglous et al., 2015), provides details on these elements.



Table 1. Elements of an enhanced source control program

Enhanced Source Control Program Element 1	Regulatory Authority
Legal Authority	Ensure that the source control program has sufficient legal authority to develop and implement source control measures, including authority for oversight/inspection, as well as plan and review new connections to the collection system
Discharge Permits	Ensure that industrial wastewater discharge permits and other control mechanisms can effectively regulate and reduce the discharge of COCs.
Enforcement	Ensure that the enforcement response program can identify and respond rapidly to discharges of COCs.
Alternative Control Program	Consider alternative control mechanisms, such as best management practices or self-certification for zero discharge of pollutants, for classes of industries or commercial businesses.
Enhanced Source Control Program Element 2	Characterize, Assess, and Monitor the DPR Project Sewershed and WRF Effluent
Source Water Characterization Study	Identify all dischargers contributing to the DPR source water. Characterize discharges with respect to water volume and water quality.
Routine Monitoring	Monitor the secondary or tertiary WRF effluent sent to the WPF routinely for regulated constituents and other COCs that may be discharged into the wastewater collection system.
Constituent Prioritization	Identify and prioritize COCs using results from the routine monitoring program. Separate monitoring programs may be needed for the constituents of greatest concern.
Adoption of Technically Based Local Limits that Support DPR Project specifications.	Evaluate regulated constituents and other COCs for their potential to cause interference, pass through a WPF, or affect human and environmental health and safety. When developing local limits, consider including a spectrum of COCs, such as regulated and unregulated contaminants that are relevant for DPR (such as drinking water contaminants)
Enhanced Source Control Program Element 3	Source Investigations
Industrial, Commercial and Business Inventory	Develop and frequently update a comprehensive inventory of industries and businesses that may use products or chemicals containing COCs or generate intermediate COCs. For agencies with large service areas, multiple communities, or industrial flows coming from other wastewater entities, consider linking the inventory to a service area map such as a geographic information system network.
Joint Response Plan	Include a flow chart showing key responsibilities and decision points to either investigate or mitigate COCs being discharged into the collection system.
Enhanced Source Control Program Element 4	Maintain Current Inventory of Chemicals and Constituents
Chemical Inventory Program	Develop and maintain a database of the chemicals stored and inventory volumes used annually by industrial and commercial producers and manufacturers in the service area. Information sources include the industries themselves, State and Local Emergency Response Commissions, and local fire departments.



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Septage Hauler Monitoring Program	A program is needed to monitor and track discharges of septic wastes or other wastewater delivered to the collection system by truck. Haulers should be permitted and required to provide chemical inventory and discharge information to the wastewater treatment authority before being allowed to discharge. Consideration should be given to requiring waste haulers to deliver to a different treatment facility.
Chemical Fact Sheets	Maintain a database of fact sheets for COCs encountered within the service area.
Enhanced Source Control Program Element 5	Public Outreach
Industrial Discharges	Provide (1) public outreach information on DPR to industries; (2) source control practices; and (3) compliance assistance and permit assistance to support the DPR program. Develop a program that encourages commercial and industrial dischargers to partner to protect the wastewater collection system. An environmental stewardship programs or award programs can promote consistent compliance. Assist and encourage industries and businesses that use chemicals that contain COCs to identify alternative source control options, such as chemical substitution.
Service Area Pollution Protection Partnership Program	Develop a cooperative program with cities, counties, or other jurisdictions within the WRF service area to disseminate information to the public about COCs and acceptable discharges to the wastewater collection system.
Public Education and Outreach Program	Provide outreach to the public regarding the proper disposal of pharmaceuticals and household products containing chemicals that may be difficult to treat (for example, what to flush and not flush). Consider developing a household hazardous waste collection program.
Education Program	Develop school educational programs for grades 1 through 12 that address source control issues related to potable reuse.
Enhanced Source Control Program Element 6	Response Plan for Water Quality Deviations
Interagency Collaboration	Formalize roles and responsibilities. The success of a source control program will depend on strong interagency cooperation and responsiveness between the WRF and WPF. For DPR projects that receive industrial waste from outside the service area, ensure that the agreement to accept the waste is consistent with source control program requirements. In cases where the agency that operates the WPF does not administer the source control program, consider entering into a memorandum of understanding or other contractual agreement as needed to protect water quality.
Response to Water Quality Excursions	Develop an action plan for responding to water quality deviations. For example, if a specific chemical constituent is detected at the WPF, then review the operation and calibration records for online meters and any relevant analytical methods. If no problem is identified, then notify the WRF to initiate a review and inspection of the WRF for sources of the constituent. If no source is found at the WRF, then initiate a wastewater collection system sampling program. If a problem is identified, the action plan directs the operations staff to notify the source control staff to respond to and correct the issue and, if necessary, bypass and/or shut down the facility.

Notes: Table content adapted from Framework for Direct Potable Reuse, (Tchobanoglous et al, 2015).
COC = Contaminant of Concern



Source Water Characterization Study

Program Element 2, identified in Table 1, recommends a source water characterization study (SWCS) as part of an Enhanced Source Control Program. Proper identification and subsequent control of hazardous chemicals entering the wastewater collection system is critical to a safe DPR system. Therefore, the panel recommends that a comprehensive baseline SWCS be performed before project startup. The SWCS should identify all dischargers within the sewershed of each WRF contributing source water to the DPR project. Baseline monitoring of each significant industrial discharger should be performed to characterize the volume and quality of each discharge. In addition to parameters required to be analyzed through the NPP, COCs relevant to drinking water should be analyzed, including:

- Safe Drinking Water Act (SDWA) Maximum Contaminant Levels (MCLs) and Colorado Regulation 11 Parameters.
- Relevant unregulated chemicals of interest to DPR. These parameters will be determined by CDPHE and could include chemicals with EPA health advisory levels and/or state MCLs or notification limits. Example chemicals include N-Nitrosodimethylamine (NDMA), 1,4-dioxane, Perfluorooctanoic acid (PFOA), and Perfluorooctanesulfonic acid (PFOS).
- Other parameters deemed appropriate by CDPHE.

Where the loading of a COC from an industrial discharger results in exceedance of the health relevant value (for example, MCL, health advisory level [HAL], notification limit), an evaluation should be conducted to determine the removal efficacy by the WRF. For compounds not well removed below the health relevant value by the WRF, local limits should be applied to the industrial discharger. Where local limits are impractical, the WPF should be designed and operated for removal of the COC. The SWCS should be updated every three years, and also when significant changes occur in the sewershed, such as when a new service area is connected to the collection system.

Routine Monitoring of WRF Effluent

A routine monitoring program is important to characterize the quality of the WRF effluent and adopt appropriate source control measures to minimize the impacts of COCs on the WRF, the WPF, and ultimately the end product—drinking water.

The Panel recommends **monthly monitoring** of the effluent at all WRFs contributing source water to the DPR project during the initial planning phase and prior to



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submission of the Design Submittal to CDPHE for approval. Monthly monitoring should be performed for at least one year and include the following parameters:

- SDWA MCLs and Colorado Regulation 11 Parameters.
- Relevant unregulated chemicals of interest to DPR. These parameters will be determined by CDPHE and could include chemicals such as those having EPA health advisory levels and chemicals with state MCLs or notification limits. Example chemicals include NDMA, 1,4-dioxane, PFOA, and PFOS.
- Other parameters deemed appropriate by CDPHE.

Composite (24-hour) samples should be collected following secondary or tertiary treatment. In addition, implementation of local limits should be considered for COCs that are not well removed below health relevant values by the WRF or WPF.

After the initial baseline monitoring is complete, the frequency of routine sampling can be reduced, as justified by the variability of the monthly results. At a minimum, ongoing monitoring should be performed annually.

Figure 5 is an example of how Enhanced Source Control monitoring at industrial dischargers and WRF effluent affects establishing local limits, communication with industries, and WRF and WPF treatment requirements.

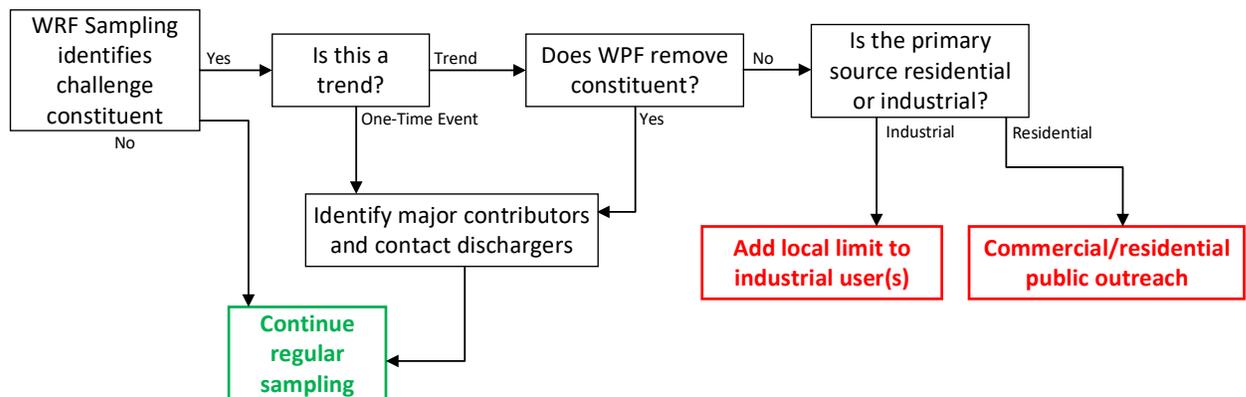


Figure 5. Example of a basic decision flow chart for identifying and controlling challenge constituents using an enhanced source control program (Figure courtesy of Jacobs, 2018).



Roles and Responsibilities

The NPP identifies three critically important roles related to the development and implementation of the NPP and enhanced source control: (1) the Approval Authority; (2) the Control Authority; and (3) Industrial Users. The Panel recommends that these roles be maintained in an enhanced source control program for DPR, as described below.

Roles and Responsibilities of the Approval Authority. The Approval Authority determines if a pretreatment program is required, and, if it is required, that the proposed pretreatment program for WRFs meets all applicable requirements for approval under the NPP. According to federal regulation, Approval Authority is designated as described in Table 2 below.

Table 2. Approval Authority Designation

State With Designated NPDES Authority	State With Designated NPP Authority	Approval Authority
Yes	Yes	Designated state agency head
Yes	No	EPA Region 8 Administrator
No	No	EPA Region 8 Administrator

The State of Colorado is not authorized by EPA to implement either the NPDES or the NPP. Therefore, until the state applies for and receives delegated EPA authority to implement both the NPDES and the NPP, the Approval Authority for all pretreatment programs in Colorado is the Regional Administrator for EPA Region 8.

The responsibilities of the Approval Authority include:

- Determine when and where a WRF pretreatment program needs to be developed.
- Set the schedule and requirements for a WRF to develop a pretreatment program, including the conditions of the NPDES permit or other control mechanisms.
- Review and approve requests for new or modified WRF pretreatment programs.
- Provide technical guidance to control authorities.
- Review and approve requests for site-specific variances to categorical pretreatment standards.



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- Review and receive the control authority’s annual pretreatment reports.
- Evaluate the WRF pretreatment program implementation by conducting compliance audits and inspections.
- Initiate enforcement actions against noncompliant WRFs or industries as appropriate.

For implementation of DPR, the Approval Authority would also be responsible for approving and enforcing required elements of enhanced source control programs.

Roles and Responsibilities of the Control Authority. The Control Authority locally administers and enforces both the traditional source control program and enhanced source control requirements for DPR, as mandated by the Approval Authority. Under the NPP, a WRF with an approved pretreatment program is the authorized Control Authority. Thus, because the Panel has recommended a policy that all DPR projects be conditioned upon the approval and implementation of an enhanced source control program, one or more of the local NPDES permit holders will serve in this critical role.

Currently, not all wastewater collection systems and treatment plants in Colorado operate with an NPP-compliant source control and pretreatment program. More specifically, implementation of an NPP-compliant pretreatment program is only required when:

- A water reclamation facility is designed to treat more than 5 million gallons per day.
- Regulated industrial pollutants are or could be discharged to the wastewater collection system or treatment plant.
- EPA Region 8 otherwise requires it.

The Panel recommends that all DPR projects be required to implement a source control program that is NPP-compliant and includes appropriate elements described in Table 1, regardless of whether the WRF was previously required to implement a pretreatment program. Therefore, the Panel recommends that each DPR project in Colorado have an NPP-compliant Control Authority whose responsibilities will include:

- Developing legal authority for their jurisdiction, local limits, standard operating procedures, and an enforcement response plan to establish and maintain an approved pretreatment program.



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- Regulating dischargers by: issuing control mechanisms, conducting monitoring and inspections, receiving and reviewing reports and notifications, reviewing requests for net/gross variances, evaluating compliance with program requirements, and taking appropriate enforcement action.
- Submitting regular reports to the Approval Authority to describe the implementation of the pretreatment program.

Roles and Responsibilities of Dischargers. Under the NPP, dischargers to the collection system are typically referred to as Industrial Users. Enhanced source control uses local limits and other control mechanisms to address all potential dischargers within a sewershed—not just the industrial users targeted by the NPP. Using the NPP permitting and control mechanisms well understood in the community of source control practice, the Panel recommends regulation to ensure dischargers to a DPR project are controlled by permits issued by the Control Authority, and are required by permit to comply with all applicable source control, pretreatment, monitoring and reporting standards and requirements set forth in the discharge permit. Some federal requirements apply to all dischargers while other requirements only apply to specific types of industrial users.

The Panel recommends policy to ensure each Discharger is required to notify the Control Authority before the following discharges or changes to existing discharge practices:

- Changes affecting potential for slug discharge. A slug discharge is any discharge including an accidental spill which has the potential to cause interference or that will pass through a water reclamation facility.
- Potential problems, including slug discharge.
- Changes in discharge characteristics.
- Changes in production processes, systems, or equipment.
- Bypass of the Discharger’s pretreatment system.

Dischargers should be subject to monitoring conducted by the WRF or required to monitor their own discharges; monitoring programs are based on the type of dischargers and any applicable limits and potential constituents of concern. In addition, as with the NPP, dischargers should be required to notify the WRF, the EPA,



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and CDPHE in writing if they discharge a substance into a WRF, which, if otherwise disposed of, would be defined by federal regulations as hazardous waste.

WRFs should monitor influent and effluent for toxic or hazardous pollutants if there is reason to suspect that they may be present. Information on some hazardous chemicals manufactured, processed, or otherwise used by specific industries and discharged to WRFs is available from the EPA's Toxics Release Inventory Program. The Toxics Release Inventory Program tracks the management of more than 650 chemicals that may pose a threat to human health and the environment.



Chapter 3: Optimizing the Water Reclamation Facility

This chapter outlines proposed regulations, policy, and guidance for water reclamation facilities that provide the source water for DPR projects.

Optimizing the water reclamation facility (WRF) is crucial to ensure that the water delivered to the WPF consistently meets quality targets and regulatory requirements (NWRI 2015). The Panel focused on providing guidance to ensure equalized and consistently high-quality effluent and NPDES compliance to support best management practices for DPR.

Online monitoring refers to instruments that are located directly in the process flow or sample line and that monitor water quality in real-time continuously or semi-continuously.

Summary of Recommendations for Regulations

The Panel recommends that regulations for WRFs that serve DPR projects include the following:

- Require WRFs used in DPR applications to comply with Colorado Regulation 22-5 CCR 1002-22, which describes the site location and design approval process for domestic wastewater treatment works.
- Require new and existing WRFs to consistently comply with NPDES permits and produce high-quality effluent for treatment at a WPF and eventual use as drinking water.

Details and rationale for these recommendations are provided later in this chapter.

Summary of Recommendations for Policy and Guidance

The Panel recommends that policy and guidance for WRFs that serve DPR projects include the following:



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- Use online monitoring to ensure the quality of WRF effluent. Monitoring parameters could include, at a minimum, ammonia, conductivity, nitrate, pH, temperature, and turbidity.
- Include the capability for automatic diversion of off-specification water during pre-defined WRF upset conditions for key parameters such as conductivity or turbidity. The design report for the DPR project must define upset conditions as they relate to online monitoring at the WRF.
- Use critical control points (CCPs) to detect upset conditions and define response levels including alert limits, action limits, and treatment targets for WRF effluent.
- Optimize performance of the water reclamation facility for DPR to provide stable water quality for downstream treatment at the WPF.
- Set goals for nitrogen control at the WRF. The Panel recommends a limit of 10 mg/L of total nitrogen in the WRF effluent. Potential exceptions to this recommendation are provided in more detail below.
- Evaluate the need for flow equalization based on diurnal water quality variation to optimize process performance and efficiency.
- Develop a disinfection byproduct management plan and include its description in the Design Report.
- Develop a list of options for increasing the level of treatment at the WPF to compensate for lower-quality WRF effluent.
- Create training goals for operators at WRFs that provide effluent to a WPF for DPR.
- Set minimum requirements for an emergency response plan to protect the quality of the WRF effluent.

Details and rationale for these recommendations are provided later in this chapter.

Recommended Regulations: Details and Rationale

This section provides the Panel's rationale for its recommended regulations for WRFs that serve DPR projects.

The Panel recommends that WRFs used in DPR applications must comply with Colorado Regulation 22-5 CCR 1002-22. This regulation describes the state's requirements for site location and design approval for WRFs including treatment plants, individual



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sewage disposal systems, lift (pumping) stations, and certain interceptor wastewater collection systems with a capacity of 2,000 gallons per day or greater, as well as certain facilities that produce reclaimed domestic wastewater. The regulation was last amended in 2009 and can be accessed online.

The Panel also recommends requiring WRFs that serve DPR projects to consistently comply with NPDES permits to produce high-quality effluent for use as a drinking water source water. This recommendation goes hand-in-hand with the recommendation in Chapter 2 (The First Barrier—Source Control) that every DPR project in Colorado implement an enhanced source control program that complies with the NPP. The Panel believes it is essential to start with the NPDES and NPP regulations because WRF staff and operators already understand and adhere to these requirements. In some cases, the existing NPDES permit may be sufficient to ensure optimal operation of the DPR project. In others, adjustments to water quality goals may be needed to address other contaminants.

Recommended Policy/Guidance: Details and Rationale

This section provides the Panel's rationale for its policy and guidance recommendations for WRFs that serve DPR projects.

- Use routine monitoring of the WRF effluent to ensure that high-quality water is being provided consistently to the water purification facility. Online monitoring parameters should include ammonia, conductivity, nitrate, pH, temperature, and turbidity. These parameters ensure the WRF is operating as designed to produce consistently high-quality effluent for WPF influent.
- Design a monitoring protocol to automatically divert off-specification water from discharging to the WPF. A single CCP at the point of discharge or conveyance to the WPF should be sufficient to ensure water quality. The design report should define the limits for each parameter that is monitored at the CCP, including the following:
 - **Alert limits** to inform operators that they may need to take action. For example, if the online turbidity measurement is one standard deviation above the mean, then the WRF operators would be alerted to investigate WRF operations to improve performance.



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- **Action limits** that will trigger a response action. For example, if the online turbidity measurement is two standard deviations above the mean, then the WRF effluent would be diverted away from the influent of the WPF.
- **Treatment targets** for WRF effluent and allowable deviations from each target value should be defined in the Design Report along with the specific response actions.

It is important to optimize the operation of the WRF to provide high-quality effluent for the influent of the WPF, as shown in Figure 6.

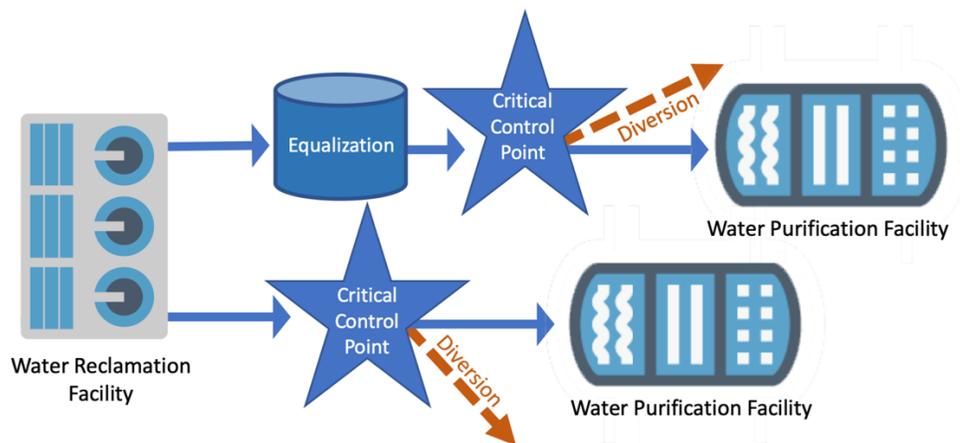


Figure 6. Water quality of the WRF effluent should be monitored using online instrumentation to protect the WPF. Alert Limits and Action Limits should be established for each parameter at this CCP.

Research demonstrates that increasing the levels of wastewater treatment removes more pathogens and chemical contaminants, and provides better operation and performance of downstream WPF processes.

The Panel recommends the following requirements to provide high-quality WRF effluent to the influent of the WPF:

- A WRF effluent total nitrogen concentration of 10 mg per liter (mg/L) or less as a conservative goal to ensure compliance with the EPA MCL for nitrate in drinking water. Research indicates that more types of organic contaminants are degraded by nitrification and denitrification at WRFs (Ekblad, et al. 2019, He, et al. 2018, Tran 2018).



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- Require nitrification (conversion of ammonium to nitrate) and denitrification (conversion of nitrate to nitrogen gas) at the WRF to consistently produce instantaneous total nitrogen concentrations below 10 mg/L.
 - Include the nitrification and denitrification requirement in the agreement between the WRF and the drinking water agency that implements DPR. The agreement should include guidance on nitrification and denitrification numerical performance goals, commonly observed diurnal variations, and blending to reduce nitrogen levels.
 - Diurnal influences on wastewater treatment and recycle streams can significantly increase total nitrogen concentrations on an instantaneous basis. The Design Report should identify how nitrogen will be controlled below 10 mg/L on an instantaneous basis while considering diurnal load impacts and recycle streams.
 - The DPR project proposer may justify a request for a higher total nitrogen limit by proving that blending water can be reliably used to achieve total nitrogen of 10 mg/L or less.
 - The WRF could justify allowing a higher nitrogen level if a downstream treatment process at the WPF targets removal of specific nitrogen species.
- Evaluate the need for flow equalization based on diurnal water quality variation to optimize process performance and efficiency. Evaluate how operations at the WRF could impact effluent quality and, ultimately, operations at the WPF. For example, equalization may be necessary if the WRF influent and effluent total nitrogen concentrations fluctuate significantly, or if it is difficult to keep WRF effluent ammonia and nitrate concentrations within EPA MCLs. Effluent organic matter can impact downstream processes such as ozone and biological activated carbon (O₃/BAC), membranes, and granular activated carbon (GAC), so equalization may be needed to maintain consistent WRF effluent quality. A utility may opt to use historical data or perform additional sampling and analysis to evaluate the need for flow equalization.
 - Develop a management plan to control disinfection byproduct (DBP) formation at the WPF. This management plan should be based on disinfection strategies at both the WRF and WPF, as well as advanced treatment processes at the WPF. For example, if the WRF uses chlorine disinfection, then the treatment process and/or disinfection may need to be optimized to mitigate halogenated DBPs in the influent of the WPF. Alternatively, to eliminate the formation of halogenated DBPs in WRF



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effluent being delivered to the WPF; WRF effluent could be diverted to the WPF before disinfection, although this may result in higher LRV requirements at the WPF as determined by the Quantitative Microbial Risk Assessment (QMRA, see Chapter 5). Minimum requirements of the DBP management plan should include:

- Types of chemical disinfectants used at the water reclamation facility and the water purification facility.
 - Disinfection process specifications including chemical doses, contact times, and relevant equipment information (for example, basin hydraulic information).
 - Disinfection strategies to account for observed or anticipated variations in WRF effluent quality including parameters such as ammonia and organic matter.
 - DBPs of potential concern and goals for byproduct mitigation (for example, total trihalomethane and haloacetic acid concentrations should be less than 80 and 60 µg/L in WRF effluent, respectively; NDMA formation potential should be less than 10 ng/L, unless treatment for these constituents is provided at the WPF). A rationale for numerical goals should be included in the plan.
 - Short-term and long-term routine monitoring strategies, including sampling locations and DBPs to be monitored.
- Develop a list of options for increasing treatment levels at the WPF to compensate for lower-quality WRF effluent. For example, if the WRF cannot meet effluent total nitrogen goals of 10 mg/L, then develop a list of potential nitrogen removal or mitigation strategies, such as ion-exchange, dilution, or reverse osmosis. The options should be based on data generated by the WRF that can be evaluated for short-term (diurnal) and long-term (seasonal) water quality fluctuations that could affect operations at the WPF.
 - Set operator training goals and opportunities for WRFs that provide effluent to a WPF. Training opportunities specific to operating WRFs and WPFs associated with potable reuse should be offered to operators. It is recommended to look to other states that have implemented Advanced Treatment Operator Certification Programs for appropriate training programs.
 - Set minimum requirements for an emergency response plan to protect WPF influent quality. Minimum requirements should include:
 - Procedures for deciding whether to divert the WRF effluent away from the influent of the WPF.



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- A response time goal and a plan for diverting the WRF effluent away from the WPF influent and a specific procedure for how the response time can be achieved.
- Detailed plans for the physical process that will be used to divert the WRF effluent away from the influent of the WPF within the defined response time, once the decision has been made.
- A backup water supply to meet WPF demand while the WRF effluent is being diverted, or an acknowledgement that the WPF will be shut down during this period.
- Detailed plans for responding to malevolent attacks or natural hazards, especially climate-related natural hazards.



Chapter 4: The Water Purification Treatment Train

Water purification consists of a series of steps, called a treatment train, which produces water that meets specific water quality levels. Water purification technologies for potable reuse often include: chemical coagulation and sedimentation, ion exchange, reverse osmosis, ultraviolet radiation for disinfection and photolysis, chemical disinfection, advanced oxidation, activated carbon adsorption, granular media filtration, biological filtration, and micro-, nano-, and ultrafiltration. These technologies are often used in combination with upstream mechanical and biological wastewater treatment to purify water to drinking water quality.

Summary of Recommendations for Regulations

The Panel recommends that regulations for water purification facilities that produce drinking water for DPR projects include the following:

- Mandate that purified water meet MCLs included in the SDWA for inorganic chemicals, organic chemicals, disinfectants and DBPs, and microbes, plus additional requirements for bulk and trace organics. An MCL is an enforceable numeric drinking water standard that is applicable to public water supplies and represents the highest concentration of the contaminant the EPA allows in drinking water.
- Require at least three different, independent pathogen barriers to achieve the required LRVs described in Chapter 5, Pathogen Removal Standards. Each pathogen barrier must be a barrier to one of the required pathogens (i.e., virus, *Giardia*, *Cryptosporidium*), but is not required to be a barrier to all three. An LRV is the reduction in the concentration of a contaminant or microorganism by a factor of 10.
- Require at least three independent chemical barriers to remove chemicals as described in Chapter 6, Chemical Removal Standards. Treatment processes may serve as both chemical and pathogen barriers, depending on the type of technology employed (for example, ozone).

Details and rationale for these recommendations are provided later in this chapter.



Summary of Recommendations for Policy and Guidance

The Panel recommends that policy and guidance for water purification facilities that serve DPR projects include the following:

- Establish CCPs at each pathogen and chemical barrier to verify the performance of the treatment process and monitor predicted removals. Online and periodic monitoring requirements at CCPs to confirm adequate treatment are described in Chapters 5 and 6.
- Pilot test the proposed water purification facility treatment train to ensure sustained compliance with the MCLs included in the SDWA, the pathogen and chemical removal requirements listed in this report, and other requirements determined by CDPHE.
- Consider the use of engineered storage after water purification to provide adequate response time to ensure that treated water meets all required standards before it is introduced into the drinking water treatment facility or distribution system.
- Design and equip the water purification facility to automatically shut down or divert water if CCP action limits are exceeded. Develop an emergency response plan that describes action to be taken.
- Require submission of a Design Report for review and approval by CDPHE.

Details and rationale for these recommendations are provided later in this chapter.

Key Issues for Water Purification Treatment Trains

The foundation of advanced treatment provided for DPR projects is a reliable treatment process that protects public health by consistently removing pathogens and chemicals. A reliable treatment process for DPR is achieved as described in *Achieving Reliability in Potable Reuse: The Four Rs* (Pecson et al., 2015).

The first R, reliability, is the fundamental goal of the Four Rs framework—to provide a reliable source of safe drinking water to consumers.

To achieve this goal of reliability, the remaining three Rs provide the foundation. Redundancy provides additional treatment or monitoring that goes beyond the minimum requirements to ensure treatment goals are more reliably met or that performance is more reliably demonstrated. Robustness provides the treatment train



with a variety of different treatment mechanisms, thus addressing a broad range of contaminants and providing resistance to failure. Resilience addresses the ability of the treatment train to recover from and/or respond to a treatment failure. In combination, these three Rs both prevent failures and properly respond to any that do occur. Through this foundation, reliability is achieved.

RO and Non-RO Treatment Trains

Purification of secondary effluent for potable reuse projects has varied significantly in the United States, depending on geographic location and local regulations. Treatment trains can be broadly sorted into those that include reverse osmosis (RO) and those that do not.

Treatment trains that include RO. RO is effective at removing pathogens, regulated inorganic and organic chemicals, dissolved minerals, and many unregulated contaminants. It is an effective and well-understood water purification method. In general, the feasibility of RO for a given project is determined by how much it will cost to dispose of the high-salinity concentrate that results from the process. It is often cheaper to manage RO concentrate in coastal areas where ocean discharge is allowed, and is more expensive if it must be disposed of using methods such as injection, evaporation, or zero-liquid discharge.

In California, indirect potable reuse via direct injection to groundwater requires an advanced treatment train that must include RO (California Code of Regulations, Title 22, §60320.201) (State of California 2019). RO has been implemented at several full-scale facilities in California including Orange County Water District's 100-mgd Groundwater Replenishment System and the 12-mgd Terminal Island facility in Los Angeles. California's Groundwater Recharge Regulations in Title 22 specify that RO membranes must meet stringent requirements for salt rejection and total organic carbon (TOC) removal (≤ 0.5 mg/L of TOC in treated water) (State of California 2019).

A 1.8-mgd DPR project in Big Spring, Texas, uses RO. The facility, which is operated by the Colorado River Municipal Water District (CRMWD) is about 500 miles from the Gulf Coast, so it is not feasible to discharge RO concentrate to the ocean. CRMWD leveraged existing regulations and infrastructure to make the project feasible by getting an industrial discharge permit to dispose of RO concentrate in a brackish creek that the City's water reclamation facility was already permitted to discharge to. CRMWD uses an evaporation reservoir that was already serving the creek, which also helped to manage



the cost of concentrate disposal (Steinle–Darling, et al. 2019; Subedi, Codru, et al. 2015).

Non–RO treatment trains. Treatment trains without RO have been used for potable reuse projects around the world and have been proven to reliably remove pathogens, regulated inorganic and organic chemicals, and many unregulated contaminants. For example the 5.5–mgd DPR plant in Windhoek, Namibia has operated safely since 1968 and provides 35 percent of the city’s drinking water supply. The project includes multiple treatment barriers to pathogens and chemicals. Examples of potable reuse projects in the United States without RO include the 54–mgd Upper Occoquan Services Authority plant that discharges to the Occoquan Reservoir, a major drinking water supply in Northern Virginia, and the 60–mgd potable reuse project in Gwinnett County, Georgia, which discharges to Lake Lanier, a major drinking water supply near Atlanta. Both projects use multiple advanced treatment barriers such as GAC, ultrafiltration, ozone, and biofiltration.

Using RO in Colorado

The pathogen and chemical removal requirements recommended in this report were developed based on the understanding that most proposed DPR projects in Colorado will require a non–RO treatment system because of the high cost of brine disposal. (Schimmoller and Kealy, *Fit for Purpose Water: The Cost of Overtreating Reclaimed Water* 2014).

Because salts accumulate in water that enters the wastewater collection system, and non–RO treatment trains typically do not remove dissolved salts, it is essential for DPR project designers to carefully evaluate the amount of blending water that is required to maintain acceptable salt concentrations in the drinking water. If insufficient blending water is available, full or side–stream RO may be required to prevent excessive salt buildup, and RO concentrate disposal approaches such as deep well injection, evaporation ponds, and/or mechanical evaporation can be used. Note that where RO is used, post–stabilization chemicals are typically applied to the RO permeate to avoid corrosion of downstream pipes and infrastructure caused by the highly aggressive RO water.



Regulation Details and Rationale

This section provides the Panel’s rationale for its recommended regulations for water purification processes that serve DPR projects. The proposed pathogen and chemical removal requirements in this report support innovation and flexibility when designing WPF treatment trains to address site-specific issues in Colorado and to meet water quality requirements.

Pathogens such as bacteria, viruses, and protozoa can cause acute illness in humans. Effluent from a water reclamation facility usually contains higher concentrations of pathogens than traditional water sources, so best practices call for multiple barriers to remove and inactivate pathogens. Similarly, chemicals in source water from a water reclamation facility are usually more concentrated than in traditional water sources. These chemicals may represent a chronic health risk to people. Therefore, the Panel recommends the following:

- Multiple pathogen and chemical barriers are needed for security and redundancy at the WPF to safely purify secondary effluent from the water reclamation facility. If one treatment process fails, another process will compensate, allowing the facility to continue to produce water that meets regulatory standards. Redundant barriers can remove some of the same compounds or pathogens and complement the removal of others (Schimmoller and Kealy, *Fit for Purpose Water: The Cost of Overtreating Reclaimed Water* 2014).
- Potable water produced at the WPF must comply with MCLs in the SDWA for inorganic chemicals, organic chemicals, and disinfectants and DBPs. Microbial limits listed in the SDWA apply, but are amended with additional requirements. Additional requirements for bulk and trace organics are also required, as described in this report.
- The WPF must provide at least three separate pathogen treatment barriers. The treatment barriers shall provide at least the minimum total log reduction requirements described in Chapter 5 for listed pathogens. Consistent with California’s potable reuse regulation for groundwater replenishment via direct injection (SWRCB 2015), each pathogen treatment barrier must provide a minimum of 1 LRV, and no treatment barrier can be awarded more than 6 LRVs. This requirement ensures multiple pathogen barriers and a diversity of treatment methods. For DPR scenarios where the purified water is treated by a downstream



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drinking water treatment plant, LRV credits achieved by the drinking water plant may be included when calculating the total log reduction credits provided.

- The WPF must provide a minimum of three separate chemical treatment barriers and must meet the requirements listed in Chapter 6. Treatment processes that remove bulk organics are important to ensure good chemical removal and to prevent disinfection byproducts.

Policy/Guidance Details and Rationale

This section provides the Panel’s rationale for its recommended policy and guidance for water purification processes that serve DPR projects. The Panel recommends the following:

- Establish CCPs at each pathogen and chemical barrier to verify and monitor predicted removals. As defined in WE&RF Project 13–03, “CCPs are points in the treatment process that are specifically designed to reduce, prevent, or eliminate a human health hazard and for which controls exist to ensure the proper performance of that process.”
- Where possible, use EPA guidance to verify log reduction credits. Table 3 lists relevant guidance for verifying log reduction credits for water purification processes. Where pathogen reduction guidance has not been provided by EPA (for example, for RO), other sources, including state regulatory agencies such as the Texas Commission on Environmental Quality or pilot testing, should be used by CDPHE to determine log reduction credits.



Table 3. References for determining pathogen log credits for treatment processes

Treatment Process	EPA Guidance Manual
Coagulation and sedimentation; Granular media filtration; Chlorine disinfection; Ozone disinfection	Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources (EPA 1991) Disinfection Profiling and Benchmarking Guidance Manual (EPA 1999) Long Term 2 Enhanced Surface Water Treatment Rule Toolbox Guidance Manual (EPA 2006)
Low-pressure membrane filtration (micro- and ultrafiltration)	Membrane Filtration Guidance Manual (EPA 2005)
UV Disinfection	Ultraviolet Disinfection Guidance Manual for the Final Long Term 2 Enhanced Surface Water Treatment Rule (EPA 2006) Innovative Approaches for Validation of Ultraviolet Disinfection Reactors for Drinking Water Systems (Adams 2016)

- Use barriers to bulk organics and chemicals, such as GAC adsorption, coagulation and sedimentation, chemical softening, ozone with biological filtration, UV/hydrogen-peroxide (H₂O₂) with biofiltration, high-dose UV photolysis and UV/hydrogen-peroxide, physical separation with high-pressure membranes, and UV advanced oxidation downstream of high-pressure membranes. Other treatment barriers may be considered by CDPHE on a case-by-case basis through pilot testing or other types of verification. Pilot tests should be conducted offline and sent to waste disposal. Design considerations for these treatment processes are included in Table 4.



Table 4. Treatment Process Design Considerations for Removing Chemicals and Bulk Organic Constituents

Treatment Process	Design Considerations
Coagulation and sedimentation	Recommended: Bench or pilot test metal-based coagulants to determine optimum dose and pH conditions for removing bulk organic constituents under a variety of secondary effluent water quality conditions that can occur seasonally or diurnally at WRFs. Coagulation, flocculation, and sedimentation treatment processes should be required to comply with the State of Colorado’s Design Criteria for Potable Water Systems (CDPHE 2013).
Chemical softening	Recommended: Bench or pilot test chemical softening to determine optimum dose and pH conditions for removing chemicals and bulk organic constituents under a variety of secondary effluent water quality conditions that can occur seasonally or diurnally at WRFs. Design chemical softening treatment process requirements should be in accordance with the State of Colorado’s Design Criteria for Potable Water Systems (CDPHE 2013).
Adsorption via granular activated carbon	Required: A minimum 15 minutes for empty bed contact time (EBCT) with at least two GAC contactors. Coal-based GAC medium is recommended over other products, such as coconut-based medium, because of superior chemical removal in DPR applications.
Ozone coupled with biological filtration	Provide biofiltration downstream of ozone oxidation to consume smaller chain organics produced by ozone oxidation. The ozone process should operate above an ozone to TOC ratio of 0.5 , after demand by nitrite (if present). An ozone residual is not required unless simultaneous disinfection is a target. Monitor bromate to comply with the bromate MCL. A minimum EBCT of 10 minutes is required for biofiltration. GAC or anthracite medium is recommended unless pilot testing supports alternative media. A fine sand layer below the GAC/coal media is recommended if the operation of the filter targets pathogen removal by producing low filter effluent turbidity. In this case, design the filter in accordance with the State of Colorado’s Design Criteria for Potable Water Systems (CDPHE 2013). The ozone system shall also be designed in accordance with the applicable sections of the State of Colorado’s Design Criteria for Potable Water Systems (CDPHE 2013).
High-dose UV Photolysis; UV/H ₂ O ₂ Advanced Oxidation; UV/H ₂ O ₂ with biological filtration	High-dose UV irradiation can be used to photolyze certain organic compounds such as NDMA and other nitrosamines. Advanced oxidation using high-dose UV (>500 mJ/cm ²) plus hydrogen peroxide upstream can be used to oxidize chemicals recalcitrant to photolysis. Implementation of biofiltration downstream of the UV/H ₂ O ₂ process should be considered to consume the smaller chain organics produced by advanced oxidation. Design the UV/H ₂ O ₂ process in accordance with requirements outlined in California’s water recycling criteria for Indirect Potable Reuse, Groundwater Replenishment, Subsurface Application (SWRCB 2015). Design UV reactors in accordance with the applicable sections of the State of Colorado’s Design Criteria for Potable Water Systems (CDPHE 2013).
Physical separation via high-pressure membranes	High pressure membranes, such as RO or nanofiltration membranes, can be used to remove chemicals and bulk organics. However, implementation of these technologies should be considered carefully because it is difficult to dispose of waste concentrate.

- Provide online and quarterly monitoring at the WPF, as described in Chapter 6, to confirm adequate removal of bulk and trace organics. Online monitoring of bulk organics, such as TOC, is important because changing TOC levels can alert



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operators to deteriorating water quality that may require a treatment operations adjustment. Quarterly monitoring is necessary to comply with MCLs for regulated chemicals and to confirm that treatment processes are adequately removing unregulated chemicals.

- Pilot test the proposed WPF treatment train to ensure sustained compliance with the requirements outlined in this report, including compliance with the MCLs in the SDWA and the pathogen and organic removal requirements listed in this report. Pilot testing of proposed advanced treatment processes is a critical part of most potable reuse projects for a variety of reasons. Pilot testing can: confirm that the proposed treatment train will reliably comply with regulations and water quality goals under varying influent water quality conditions; establish appropriate design criteria for the proposed treatment processes; determine treatment success under abnormal conditions; be used to train operations staff; and provide regulators exposure to unfamiliar technologies.
- Engineered storage after water purification treatment should be considered to confirm treatment process operation and finished water quality before releasing the DPR water. The use of engineered storage and the appropriate volume of water to store will vary between DPR projects depending on many factors, including the level and redundancy of online instrumentation, the sophistication and speed of automated alarm responses, and the availability of on-site operators and their response time.
- The design report should clearly state if engineered storage is being provided and the rationale for the specified volume. An appropriate criteria for specifying volume is the amount of water needed to contain finished water flow while diverting or shutting down the water purification plant operations, if necessary. See *Framework for Direct Potable Reuse* (WateReuse Research Foundation 2015) and Salveson, Snyder, and Macpherson (2016) for more information on the use of engineered storage for DPR projects.
- A design report detailing the proposed DPR project should be submitted to CDPHE for review and approval. The content should match that required by CDPHE in the Drinking Water Design Submittal Basis of Design Report (*State of Colorado Design Criteria for Potable Water Systems*, CDPHE). Additional content shall include descriptions of enhanced source control measures, pathogen and chemical barriers, CCPs and monitoring techniques, QMRA results and pathogen LRV requirements (if



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performed), emergency response procedures, engineered storage, and the communication approach between the WRF and WPF.

Example DPR Treatment

The Panel assumed that most projects in Colorado would not use RO because of the difficulty in disposing of RO concentrate. A treatment train that includes RO may be used, if feasible, if it complies with the requirements included in this report.

An example treatment train for the implementation of DPR in Colorado is shown in Figure 7. The figure illustrates five pathogen treatment barriers: ozone, direct filtration with coagulant, ultrafiltration; UV disinfection, and chlorine disinfection. Three chemical barriers are shown, including: ozone with biofiltration, GAC, and UV photolysis.

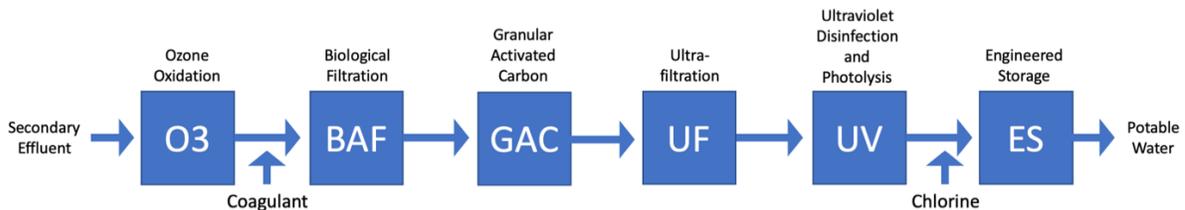


Figure 7: Example DPR treatment train

Details on complying with the specific pathogen and chemical requirements are described in Chapters 5 and 6.



Chapter 5: Pathogen Removal Standards

Significant removal of pathogens in DPR schemes is important because of the elevated pathogen concentrations typically present in wastewater sources. Pathogen reduction goals should be set using a risk-based approach and written with the entire treatment scenario in mind, from source water through distribution to customers.

The approach recommended by the Panel is consistent with approaches recommended by other states, such as California and Texas, which establish minimum pathogen log reduction requirements that must be provided by treatment. Log (base 10) reduction values (LRVs) represent the reduction in the concentration of a pathogen by a factor of ten. The following formula is used to calculate the LRV:

$$LRV = \log \left(\frac{\text{influent pathogen concentration}}{\text{effluent pathogen concentration}} \right)$$

A 90 percent reduction in pathogen concentration would correspond to 1 LRV and a 99 percent reduction would correspond to 2 LRVs. The Panel assumed that minimum LRV requirements would be established based on measured pathogen concentrations in the effluent from the water reclamation facility and that the WPF should provide sufficient treatment to meet these LRV requirements through LRV credits assigned to treatment processes. The Panel also assumed that the utility will outline an approach to achieving the LRV requirements in the Design Report.

Summary of Recommendations for Regulations

The Panel recommends that regulations for water purification facilities that produce drinking water for DPR projects include the following:

- Require at least three separate types of pathogen barriers in the water purification treatment process.
- Require online monitoring of critical control points that will shut down the water purification plant or divert water to a redundant system or to waste if out-of-specification water is produced.

Details and rationale for these recommendations are provided later in this chapter.



Summary of Recommendations for Policy and Guidance

The Panel recommends that policy and guidance for water reclamation facilities that serve DPR projects include the following:

- Allow the entity pursuing DPR to establish LRV requirements based on either: 1) Site-specific pathogen monitoring and QMRA or 2) Default LRV requirements.
 - Site-specific pathogen monitoring and QMRA: Site-specific LRV requirements for the WPF should be established based on the results of a QMRA and 12 months of biweekly sampling of the water reclamation facility effluent. The LRV requirements determined by the QMRA should be applied to the project unless they are less restrictive than the minimum required LRVs. The minimum required LRVs for viruses, Giardia, and Cryptosporidium are 8, 6, and 5.5, respectively, from water reclamation facility effluent to finished water, based on EPA guidance of 1 in 10,000 annual risk of infection. These LRVs are based on the minimum proposed by the Texas Commission on Environmental Quality (Texas Water Development Board 2015).
 - Default LRV Requirements: If the entity pursuing DPR elects not to conduct a site-specific QMRA, the minimum LRV requirements provided by the WPF, from water reclamation facility effluent to finished water, shall be 12, 10, and 10 for viruses, Giardia, and Cryptosporidium, respectively.
- Use current drinking water guidelines, such as the EPA Membrane Guidance Manual (EPA 2005) or EPA UV Guidance Manual (EPA 2006), to establish LRV credits for each treatment process.
- Allow flexibility to reduce LRV requirements if a wastewater treatment process provides more LRVs than typical secondary treatment at water reclamation plants (for example, membrane bioreactors or tertiary filtration). CDPHE will determine LRV requirements on a case-by-case basis.
- Use the Adenovirus method to determine the LRV requirement for viruses.

Details and rationale for these recommendations are provided later in this chapter.



Details and Rationale for Recommended Regulations, Policy, and Guidance

The Panel's recommendations include using a risk-based approach to identify the appropriate treatment technologies for each specific DPR project to provide sufficient pathogen removal.

Implementing a Risk-Based Approach

The Panel recommends allowing the entity pursuing DPR to establish LRV requirements for their specific DPR project based on either: 1) Site-specific pathogen monitoring and QMRA or 2) Default LRV requirements.

Site-specific pathogen monitoring

The current federal Surface Water Treatment Rule (40 CFR 141.70–141.75) includes goals for removing viruses, bacteria, and protozoa from surface water that is treated using filtration for drinking water supply. The goals are based on a minimum of 10^{-4} (1 in 10,000) annual risk of infection. The Panel recommends following the Surface Water Treatment Rule approach for pathogen reduction.

Annual infection risk levels are calculated based on the QMRA, which estimates the risk of contracting an infection from pathogens in DPR water. The process involves measuring known microbial pathogens or indicators and running a Monte Carlo simulation to estimate the risk of exposure. Using a dose-response model for the pathogen, the model can be used to estimate the probability of infection.

The Panel considered both the California regulation for direct groundwater recharge, which requires 12 LRV for viruses, 10 LRV for *Cryptosporidium*, and 10 LRV for *Giardia* from raw wastewater to finished water (after advanced treatment but before injection), along with the Texas Commission on Environmental Quality approach that requires a minimum of 8 LRV for viruses, 6 LRV for *Giardia*, and, 5.5 LRV for *Cryptosporidium* based on secondary effluent to finished water.

The Panel recommends adopting the Texas approach and that the 8 LRV, 6 LRV, and 5.5 LRV requirements for virus, *Giardia*, and *Cryptosporidium*, respectively, are the minimum values that must be achieved through the WPF. However, depending upon the actual pathogens measured in the water reclamation facility effluent and the subsequent QMRA, higher LRVs may be required. The QMRA should be based on the



outcome of the site-specific, 12-month, biweekly water reclamation facility sampling program. One of the DPR research projects currently being funded by the California State Water Resources Control Board, DPR-1 Plant Reliability and QMRA, will provide standard tools for conducting QMRA for DPR projects. These tools are expected to be available by the end of 2020 and should be considered for use on Colorado DPR projects. Other resources should also be reviewed, including information available from the Center for Advancing Microbial Risk Assessment (CAMRA, Michigan State University), which holds annual workshops on QMRA and provides reference material on this topic.

The recommended target pathogenic organisms are enteric viruses, *Cryptosporidium*, and *Giardia*.

Enteric virus. Due to the relatively high concentration of adenoviruses in wastewater, the Panel recommends using adenovirus tissue culture to represent enteric virus concentrations. There are no validated methods for quantifying viruses in secondary effluent or purified water, but EPA Method 1615, Measurement of Enterovirus and Norovirus Occurrence in Water by Culture and RT-qPCR, has been adopted for this purpose (EPA 600/R-10/181, January 2012). Method 1615 was designed for groundwater and has not been validated for complex matrices or for adenoviruses. However, the Panel recommends using Method 1615 for measuring adenovirus in water reclamation facility effluent, but modifications to the method may be necessary to accommodate the complexities of the wastewater matrix.

Protozoa. For protozoa, EPA Method 1693 outlines methods for determining *Giardia* and *Cryptosporidium* concentrations in water reclamation facility effluent (EPA 2014). Although not recommended by the Panel, if CDPHE considers applying LRV requirements using raw wastewater pathogen concentrations, there are no validated methods for quantifying protozoa in raw wastewater.

Programs are in place for auditing and certifying laboratories for protozoa analysis, however, no such programs exist for virus analysis. The Panel believes that this is important; as long as virus analysis will be part of the regulation, there must be validated methods and independent third-party evaluation of the laboratories conducting this analysis. Until nationally validated methods for viruses in these matrices are available, CDPHE may have to rely on third-party, independent auditing and accrediting organizations such as A2LA, the ANSI National Accreditation Board, or the International Organization for Standardization (ISO 2017). Costs for third-party



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auditing and accreditation are borne by the requesting laboratory. Alternatively, CDPHE may develop a program within the CDPHE Laboratory Certification Program to support this DPR regulation.

For ongoing monitoring, there are no options for real-time microbial monitoring. Regulatory microbial surrogates for water quality have, at best, an 18-hour turnaround time. Protozoa monitoring can be processed and reported within 12 hours, if tests are rushed. Near-real-time monitoring would require 24-hour access to certified laboratories. Tissue culture methods for viruses, especially adenoviruses, require three to four weeks to confirm a negative result, and it may take longer to reprocess samples that exhibit matrix effects. Therefore, because of these limitations, the use of critical control points for each pathogen barrier is required to confirm satisfactory performance, as described later in this report.

Default LRV Requirements

If the entity pursuing DPR elects not to conduct a site-specific QMRA, the minimum LRV requirements provided by the WPF, from water reclamation facility effluent to finished water, shall be 12, 10, and 10 for viruses, *Giardia*, and *Cryptosporidium*, respectively. These requirements are significantly more conservative than the minimum requirements established for entities that conduct site-specific pathogen monitoring and QMRA because of the lack of industry-wide pathogen data in raw wastewater and secondary effluent. CDPHE may elect to reduce (or increase) these default LRV requirements when more data is available that accurately represents pathogen concentrations under a variety of conditions (e.g., community size, WRF size and treatment type, seasonal impacts, community epidemics). One of the DPR research projects currently being funded by the California State Water Resources Control Board, DPR-2 Measure Pathogens in Wastewater, will provide valuable pathogen data in wastewater by 2021. CDPHE should revisit the proposed default LRV requirements when this data becomes available.



Advanced Treatment to Meet Pathogen LRV Requirements

The Panel recommends requiring at least three pathogen treatment barriers at the WPF to achieve the required LRVs. Each pathogen treatment barrier must provide a minimum of 1 LRV credit and no treatment barrier can be awarded more than 6 LRV credits, consistent with Article 5.2 of Title 22, California Code of Regulations (CCR §60320.208). This approach allows for a diversity of treatment for a variety of pathogenic microorganisms.

Each treatment process must have defined CCPs and an online monitoring system that will shut down the plant or divert water to a redundant system or to waste if out-of-specification water is produced.

Although the Panel recommends basing the pathogen LRV requirements on the measured pathogen concentration in the water reclamation facility effluent, CDPHE could elect to award credits toward the LRV requirements to water reclamation plants using advanced water reclamation technologies such as a membrane bioreactor or tertiary filtration. Credit awarded for treatment at the water reclamation facility would reduce the LRVs that the WPF needs to achieve. Site-specific studies measuring actual pathogen reduction across these more advanced WRF treatment processes are recommended to establish appropriate pathogen reduction credits.

Alternatively, CDPHE could use LRV credit recommendations developed by independent third-party agencies, such as those established for membrane bioreactors in the *WaterVal™ Membrane Bioreactor Validation Protocol* (Australian WaterSecure Innovations, 2017). A critical control point with online monitoring should be established for each treatment process where LRV credits will be granted to ensure proper operation.

LRV credits should to be determined following EPA guidance. Table 5 is an example of LRV credits for a treatment train that might be proposed at a WPF. An example treatment train is shown in Figure 7 (Chapter 4) and consists of ozone oxidation, coagulation, biologically active filtration, GAC adsorption, low-pressure membrane filtration (microfiltration or ultrafiltration), UV disinfection, and chlorine disinfection. Five pathogen treatment barriers in this example provide a total of 13, 13, and 12.5 LRV credits for viruses, *Giardia*, and *Cryptosporidium*, respectively.



Table 5. Example of LRV credits for a water purification treatment train

Treatment Process	Enteric Virus LRV	Giardia LRV	Crypto LRV
Ozone ¹	2	1	0
Coagulation + BAF ²	1	2	2.5
Granular Activated Carbon	0	0	0
Microfiltration/Ultrafiltration ³	0	4	4
UV ⁴	6	6	6
Chlorine ⁵	4	0	0
Total Achieved	13	13	12.5

1. Ozone LRVs per Equations 11-2 and 11-3 of the *Long Term 2 Enhanced Surface Water Treatment Rule Toolbox Guidance Manual* (EPA 2010, EPA 2010) at an ozone CT of 0.5 mg-min/L and a minimum temperature of 10 degrees Celsius (°C).
2. Direct filtration: 1-log removal of viruses and 2-log *Giardia* removal is granted per the *EPA Surface Water Treatment Rule Guidance Manual* (EPA 1991), section 5.5.2, for a direct filtration treatment plant. A 2.5-log *Cryptosporidium* removal is granted per the *Long Term 2 Enhanced Surface Water Treatment Rule Toolbox Guidance Manual* section 1.4.1 if the combined filter effluent (CFE) is less than 0.3 ntu 95 percent of the time and never greater than 1.0 ntu.
3. Four-log removal of *Cryptosporidium* has been assumed for microfiltration based on credit commonly granted by states for membranes passing daily membrane integrity tests in accordance with the *EPA Membrane Filtration Guidance Manual* (EPA 2005).
4. The UV LRVs based on the forthcoming EPA report *Innovative Approaches for Validation of Ultraviolet Disinfection Reactors for Drinking Water Systems* (Adams 2016).
5. Per the EPA Surface Water Treatment Rule Guidance Manual (EPA 1991), free chlorine provides 4-log virus disinfection at a contact time of 6 mg/L-min at a temperature of 10°C.



Chapter 6: Chemical Removal Standards

This chapter presents recommendations for chemical removal in DPR by utilities through regulation, policy, and guidelines.

Summary of Recommendations for Regulations

The Panel recommends that regulations for water purification facilities that produce drinking water for DPR projects include the following:

- Require at least three chemical treatment barriers at the WPF to remove chemicals.
- Require WPFs that produce drinking water from reclaimed water to monitor three levels of chemical contaminants: regulated chemicals, unregulated chemicals of special interest to DPR projects, and chemical indicators used to monitor treatment performance.
- Require monthly monitoring of target chemicals during the first year of operation. After one year of operation, CDPHE may adjust the monitoring frequency to quarterly, or more or less frequently, as needed.
- Require the purified water to meet the MCLs established by the SDWA or in the Code of Colorado Regulations as enforced by the CDPHE.

Summary of Recommendations for Policy and Guidance

The Panel recommends that policy and guidance for water reclamation facilities that serve DPR projects include the following:

- Use three chemical treatment barriers that have a unique mechanism to target different chemical groups or properties.
- Require that the median TOC concentration of the purified water, as measured by weekly grab samples, should not exceed the median TOC of the drinking water that was used by the customers within the area that will be served by the WPF. Corrective action should be planned and implemented when this limit is exceeded, but immediate action is not required. Comparison to the drinking water's 95th percentile TOC may be considered after sufficient data is collected on MCLs and



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unregulated contaminants demonstrating the safety of the DPR water at these TOC concentrations.

- Require that the TOC concentration of purified water, measured by online instruments, should not at any time exceed 1.5 times the 95th percentile TOC of the original drinking water that was used by the customers within the area to be served by the WPF. Immediate action should be taken when this limit is exceeded.
- Require redundant online TOC analyzers in the finished water to compare the TOC concentration in the DPR water to the drinking water TOC from which the DPR water was sourced. A substitute online analyzer, such as UV254, could be used if it is proven to provide sufficient correlation to TOC grab samples.
- Require that unregulated chemicals of special interest for DPR (Level 2 compounds) meet limits established by CDPHE.
- Require that the DPR train remove at least 75 percent of each Level 3 compound (i.e., treatment performance indicators) as measured from the WPF influent to the WPF effluent.
- Require CCPs at each chemical barrier to ensure proper performance of that treatment process.

Details and Rationale for Recommended Regulations, Policy, and Guidance

Chemicals in Reclaimed Water

Chemicals in reclaimed water occur at levels comparable to or greater than typical drinking water sources (Russell and Lux 2009, Marron, et al. 2019, Pecson, et al. 2015). Chemicals often found in reclaimed water include trace organic compounds, such as pharmaceuticals, per- and polyfluoroalkyl substances (PFAS) and hormones; DBPs and DBP precursors (such as trihalomethanes, NDMA, bromate); inorganics (including radionuclides, heavy metals, salinity); and nutrients (such as ammonia, nitrate, phosphate). Many of those compounds pose chronic health risks and prolonged exposure above regulations or guidelines could increase the risk of diseases such as cancer or reproductive problems.

A few of these compounds, such as nitrate, could potentially be present at high enough concentrations in reclaimed water to constitute an acute health risk and cause illness after short-term exposure. Regardless of the type of health risk, chemicals



should be removed to meet all regulations and guidelines for public health and to meet or exceed the overall quality of the local drinking water source to increase public acceptance of the DPR project.

Rationale for Chemical Removal Strategy

Similar to the pathogen removal guidelines in Chapter 5, the Panel recommends requiring at least three chemical treatment barriers. Chemical treatment barriers may coincide with the three pathogen treatment barriers or they may be separate, depending on the technology. For example, GAC removes chemicals but is not credited with pathogen removal, while ozonation removes both chemicals and pathogens. In general, the Panel recommends arranging chemical treatment barriers from most resilient to the background matrix to most susceptible to matrix effects.

Each chemical treatment barrier should have a unique mechanism that targets different chemical groups or properties. For example, powdered activated carbon (PAC) would remove only a small additional amount of chemicals if installed in series to follow GAC. Table 6 lists examples of distinct chemical removal mechanisms.

Table 6. Mechanisms of chemical removal from water.

Mechanism	Examples	Types of Chemicals Removed
Biological*	Biofiltration	Assimilable organic carbon
Advanced Oxidation	Ozone, UV/H ₂ O ₂	Aromatics, carbon-carbon double bonds, deprotonated amines (Dickenson, et al. 2009)
Adsorption	Granular activated carbon, powdered activated carbon	Hydrophobic (Westerhoff, et al. 2005)
High Pressure Membrane Treatment	Reverse Osmosis, Nanofiltration	High molecular weight (>200 Da), charged (Bellona, et al. 2004)
Coagulation*	Enhanced coagulation, electrocoagulation	High molecular weight (>1000 Da) (Wert, et al. 2011), high specific ultraviolet absorbance (Korak, Rosario-Ortiz and Scott Summers 2015, Korak, Rosario-Ortiz and Scott Summers 2015), certain heavy metals and radionuclides (WHO 2011)
Photolysis	Direct UV photolysis	Nitrosamines (Aqeel, Kim and Lim 2017), iodinated compounds (Yu, et al. 2015), nitro compounds (Dong, et al. 2017)
Ion Exchange	Anion exchange resins	Positively <i>or</i> negatively charged
Absorption	Air stripping	Volatile, semivolatile

**Not recommended for credit as a chemical treatment barrier but may still be important for DBP precursor control or pre- or post-treatment in combination with other pathogen or chemical treatment barriers.*

WPFs should not necessarily be limited to the technologies listed here. Rather, the Panel recommends that the policy framework be flexible enough to encourage innovation as water treatment technology continues to advance.



Biological treatment should not receive credit as one of the three chemical treatment barriers. Compounds that are highly susceptible to biological treatment will be mostly removed in the upstream water reclamation facility. For example, a study on ozone–biofiltration for bulk organic removal and disinfection byproduct mitigation in potable reuse applications found less than 10 percent TOC removal in reclaimed water biofiltration without ozonation (Arnold, et al. 2018). Nevertheless, biofiltration may be the best approach to remove assimilable organic carbon or DBPs generated by ozonation, especially NDMA (Dickenson, et al. 2018, van der Kooij 1992). Thus, ozonation and biofiltration are often considered a single water purification unit, process, or critical control point (Figure 7) and ozone followed by biofiltration could receive a single chemical contaminant barrier credit in the advanced oxidation category.

Like biofiltration, coagulation is not recommended for credit as a chemical contaminant barrier but may, nevertheless, be important in a DPR system. Coagulation does not remove most trace organic compounds effectively (Snyder, Wert, et al. 2007). However, coagulation may contribute to overall TOC and DBP precursor removal (Hill, et al. 2018). Furthermore, coagulation is a useful pretreatment to increase particle size before filtration (EPA and CDM Smith 2017), reduce membrane fouling (Shon, et al. 2004), and lower the required ozone dosage (Wert, et al. 2011).

Many advanced oxidation processes (AOP) include both exposure to UV radiation and the addition of an oxidant (UV/AOP). Among these, UV/H₂O₂ is most common in existing reuse systems but related processes such as UV/HOCl appear promising in recent pilot–scale research for low pH conditions (Trussell, et al. 2018). Since these processes simultaneously apply to two distinct chemical removal mechanisms, they may earn credit as two chemical treatment barriers. However, the UV dose required for direct photolysis of target compounds (direct UV photolysis) may be different than the UV dose required for radical generation (advanced oxidation process). Therefore, these processes should only receive credit as two chemical treatment barriers if the UV dose is selected considering both direct photolysis and radical generation. Furthermore, in this scenario, both chemical and pathogen removal should be considered when selecting the UV wavelength(s).

Bulk and Online Surrogates

Surrogates are quantifiable parameters in water that can be used as treatment process performance measures for contaminant removal (Yu, et al. 2015). Often, surrogates are



detected using optical or electrochemical parameters that can be monitored easily and frequently, ideally with an online instrument or probe. Online in this context refers to instruments that are located directly in the process flow or sample line and monitor water quality in real-time on a continuous or semi-continuous basis (sample time of 15 minutes or less). WPFs should use relatively rapid, low-cost surrogates to frequently ensure that chemical treatment barriers are functioning as designed.

TOC is an important bulk surrogate for DPR. When considering WPFs as a whole, TOC removal correlates with trace organic contaminant (TOrC) removal (Schimmoller and Lozier, 2019). TOrCs refers to an array of natural and manufactured substances including industrial chemicals, household chemicals, metabolites excreted by people, and by-products formed during water treatment processes (Hai, et al. 2014). Some TOrCs have high toxicity, such as NDMA and PFOA, while others are considered nontoxic, for example, sucralose. TOC removal also correlates with regulated DBP precursor removal (Hill, et al. 2018). Perhaps, and even more importantly, an increase in TOC breakthrough could indicate process failure, process exhaustion, or breakthrough of a recalcitrant industrial contaminant (Marron, et al. 2019).

When the TOC in the purified water is lower than TOC in the original drinking water source, the TOrC concentrations have been found to be lower as well (Schimmoller and Lozier, *How to Regulate and Control Organics in Potable Reuse Plans that Don't Use Reverse Osmosis* 2019). If the TOC is greater in the purified water than in the original drinking water source, it creates uncertainty about DBP formation and bacterial regrowth in the distribution system and presents a challenge for public acceptance.

The Panel recommends comparing the median TOC of the purified water with that of the original drinking water TOC, shown in Figure 8. The drinking water and the purified water may contain low levels of natural TOC only, while the wastewater will contain a higher TOC load, shown in Figure 9.



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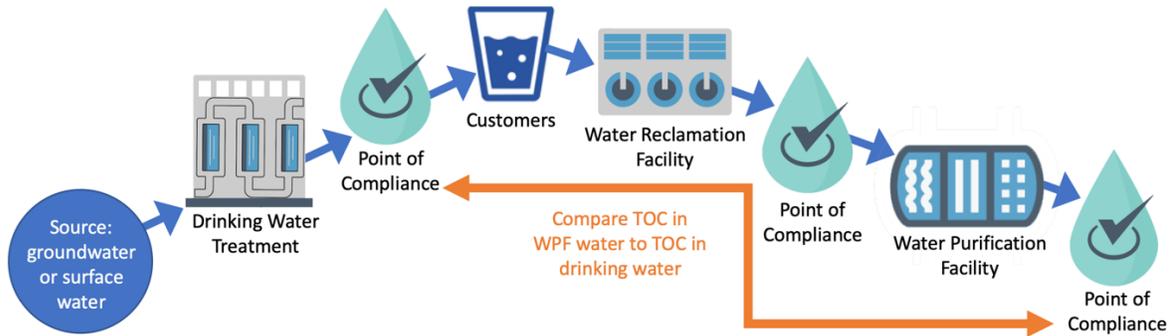


Figure 8: Comparing the median TOC concentrations in the purified water and the original drinking water is a useful surrogate for treatment performance.

If the median TOC of the purified water (rolling over the past month based on weekly grab samples) exceeds the median TOC of the drinking water (over the past year or more, at the discretion of CDPHE), then corrective action should be taken. Corrective action could include, for example, replacing the GAC bed or increasing the oxidant and coagulant doses.

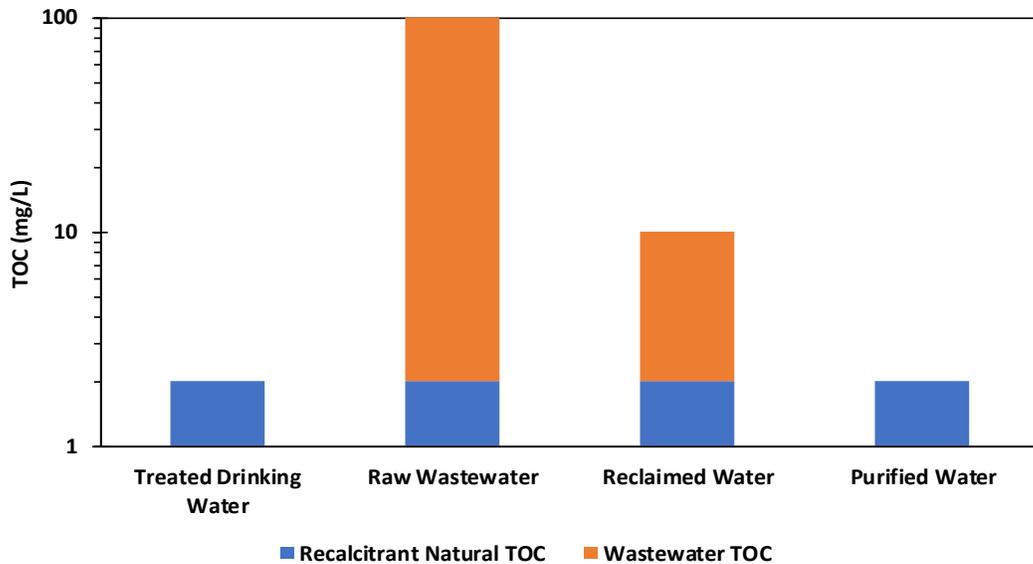


Figure 9. Hypothetical comparison of the a) sample locations and b) total organic carbon levels for the purified and original drinking water.

Immediate action, such as WPF shutdown or water diversion, is not necessary when this limit is exceeded. Comparison to the drinking water's 95th percentile TOC may be



considered after enough data is collected on MCLs and unregulated contaminants, and that data demonstrates the safety of the DPR water at the TOC concentrations.

The Panel also recommends that the TOC of the purified water should not exceed 1.5 times the 95th percentile TOC of the original drinking water. If the TOC exceeds this threshold as measured by online instrumentation, it should trigger an alarm leading to immediate facility shutdown or DPR water diversion.

DPR water with a TOC concentration higher than this value indicates potential treatment failure at either the WRF or WPF or significant chemical contamination of the wastewater through a discharge into the collection system, such as point source chemical dumping. Either of these conditions can create chemically unsafe water and require immediately stopping DPR water distribution and diverting the water to keep it from being introduced into the potable distribution system.

The Panel recommends redundant online instrumentation to minimize false alarms (Trussell, et al. 2018); in this case, the alarm would only be triggered if the TOC threshold was exceeded by both or all TOC instruments, as shown in Figure 10. CDPHE should consider alternative online instrumentation, such as UV absorbance analyzers, if they are shown to be adequate surrogates for online TOC analyzers.

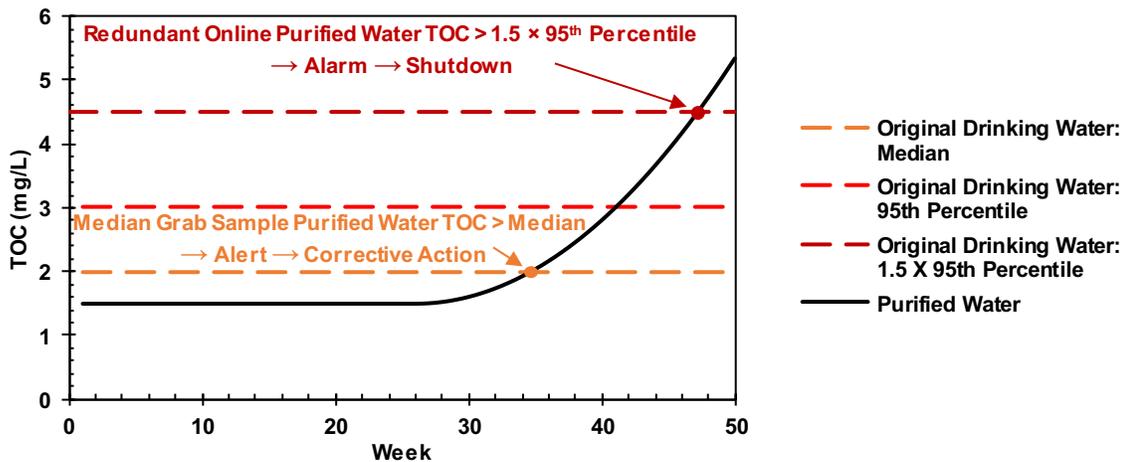


Figure 10. Recommended Action based on TOC Measurements in DPR Water

Specific Compounds

WPFs should monitor three levels of chemical contaminants. At startup, monitoring should be monthly for one year and then monitoring frequency may be changed to



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quarterly, or more or less frequently, at CDPHE’s discretion. The three levels are listed below and described in detail in the following sections:

- Level 1. SDWA MCLs and state requirements in the final purified water.
- Level 2. Unregulated chemicals of special interest to DPR (for example, PFAS, NDMA, 1,4-dioxane) in the final purified water.
- Level 3. Indicators to monitor treatment performance in the water reclamation facility effluent and final purified water.

Level 1 Compounds: Regulated

Level 1 compounds are all compounds with MCLs in the Code of Federal Regulations or in the Code of Colorado Regulations as enforced by the CDPHE. Tables listing these compounds and MCLs are in the Colorado Primary Drinking Water Regulations (Colorado Department of Public Health and Environment 2018). The Panel recommends that DPR regulations should require the purified water to meet these MCLs.

Level 2 Compounds: Special interest for DPR

Colorado’s reuse framework should include policy for unregulated chemicals of special interest for DPR. Chemicals in this category are not regulated under current SDWA or Colorado state-level regulations. Because the presence of these chemicals above certain levels could represent a health risk, plans need to be developed as to how to respond to exceedances of targets including operating changes and public notification. However, they are known to occur in reclaimed water at concentrations that could potentially approach or exceed safe levels if not controlled appropriately. Chemicals may fall into this category for either or both of the following reasons:

- **The compound or its toxicity is recently discovered.** The EPA has had insufficient time or has insufficient data to conclude whether nationwide regulation is justifiable. Nevertheless, recent toxicity studies on this compound, or toxicity studies on similar compounds, provide cause for concern about this compound.
- **The compound is common in reclaimed water but not surface water or groundwater.** Certain wastewater-associated potentially toxic compounds are diluted or naturally remediated in the environment to below detection limits or are far below plausible hazardous concentrations at conventional drinking water intakes. The prevalence of these compounds in natural water may not justify a nationwide drinking water standard. Nevertheless, these compounds may pose a



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chronic health risk in the context of DPR if they are not monitored and removed. Compounds that are recalcitrant to multiple treatment barriers (such as 1,4-dioxane or PFAS) or DBPs with wastewater-associated precursors that may form after or during early treatment steps (such as NDMA) merit greatest vigilance.

Compounds in Level 2 may be selected in consultation with CDPHE based on any or all of the following justifications (listed approximately in order of priority).

- Contaminants with EPA health advisory levels (HALs) but not yet MCLs, such as PFOA and PFOS or perchlorate.
- Contaminants with MCLs or equivalent by other states or countries, but not the US EPA, such as methyl-tert-butyl ether, which has an MCL in California (California State Water Resources Control Board 2018).
- Contaminants with notification levels or HALs or equivalent by other states or countries, but not the US EPA, such as 1,4-dioxane and NDMA.
- Contaminants that are present in reclaimed water at potentially hazardous or unpalatable concentrations in recent technical reports (such as reports by NWRI or The Water Research Foundation) or peer-reviewed journals, but with toxicity and prevalence not yet widely corroborated (Marron, et al. 2019, Khan, Fisher and Roser 2019).

Level 3 Compounds: Indicators

To confidently provide water that is equally or more safe than existing supplies, WPFs must demonstrate high removal of a wide variety of chemicals, not just known toxins. The DPR train should be required to remove at least 75 percent of each Level 3 compound as measured from the WPF influent to the WPF effluent. This goal is important for:

- **Public acceptance.** The idea that some compounds have entered the drinking water supply from human waste prevents people from accepting DPR. Public resistance may take hold even if the compounds are proven to be nontoxic and all Level 1 and Level 2 compounds have been completely removed. Public acceptance is crucial for DPR projects as described in Chapter 7.
- **Uncertain toxicity.** Many compounds that occur in reclaimed water but are thought to be safe or have not yet been thoroughly tested for toxicity. Future scientific studies may reveal toxicity for some of these compounds.



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- **Unidentified compounds.** Hundreds of manmade chemicals have been detected in reclaimed water, including at least 70 pharmaceuticals (Petrie, Barden and Kasprzyk–Hordern 2015) and over 20 per- and polyfluoroalkyl substances (Scott, et al. 2010 , Glover, Quinones and Dickenson 2018, Subedi, Codru, et al. 2015, Pisarenko, et al. 2015, Sinclair and Kannan 2006, Sedlak, et al. 2017). Thousands more are likely present at some level based on industrial registries, and new chemicals are invented every day. Furthermore, over 600 DBPs have been discovered after chlorine or chloramine water disinfection (Stanford, et al. 2018). Advances in analytical chemistry are accelerating the rate at which new compounds are detected in water (Strynar, et al. 2015).
- **Synergistic toxicity.** Certain compounds interact in such a way that their combined toxicity is greater than their individual toxicity (Chen, et al. 2015). It is impossible to assess the toxicity of all possible combinations of chemicals in reclaimed water.

Routinely monitoring all chemicals in reclaimed water is impossible. However, strategically selecting indicator compounds can demonstrate that all reuse treatment processes are properly functioning and are collectively removing virtually any chemical compound.

Indicator compounds are not necessarily toxic. Rather, indicator compounds have chemical properties that make them removable by some treatment processes but recalcitrant to others. For example, several artificial sweeteners that are approved for human consumption are useful indicators because of their recalcitrance to biological treatment (Jmaiff Blackstock, et al. 2019).

Monitoring a rigorously selected set of indicators should be included in regulation. However, because of site-specific factors and rapidly evolving state-of-the-science, the Panel recommends flexibility about *which* compounds are selected. The indicator selection process should be thorough and strategic; it should follow established steps and criteria, and should be conducted in partnership and consultation with CDPHE. Therefore, this selection process constitutes Policy.

Indicator selection should be site specific and be based on a number of factors that allow regular and accurate measurement of the selected chemicals to confirm good treatment process removal. Appendix C provides criteria and guidance for properly selecting Level 3 chemicals and presents a hypothetical case study of indicator selection for a WPF using Ozone, GAC, and UV treatment technologies as chemical barriers.



Critical Control Points and Sampling Locations

As described in Chapter 4, CCPs are required at each chemical barrier to ensure proper performance of that treatment process. At each chemical treatment barrier, a chemical hazard exists; in other words, Level 1 or Level 2 compounds are above or potentially above regulations or health advisory levels.

Figure 11 shows a representative DPR treatment train, the proposed three chemical barriers (ozone, GAC, and UV photolysis), and the recommended chemical indicator sampling at these CCPs to confirm proper performance of these treatment processes. The Level 3 indicator compounds shown in this example, primidone, perfluoroheptanoic acid (PFHpA), iohexol, and sucralose, are well-studied in the technical and scientific literature and would be good candidates for an indicator selection processes. However, the final indicator selection should be based on site-specific considerations and data. These measurements and locations are intended only for monitoring successful chemical removal; additional surrogates or sampling locations may be required for pathogen monitoring. Indicator compounds should be sampled at the WPF influent to calculate percent removals. This sample should be collected first; subsequent samples should be collected based on the hydraulic residence time of the system, such that each indicator sample is collected from approximately the same water as the upstream sample. Ozone indicators such as primidone may require sampling between ozonation and other downstream processes. However, UV indicators (such as iohexol), UV-resistant GAC indicators (such as PFHpA), and the system indicator (such as sucralose) should all be sampled in the finished water.



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Online monitoring of the chemical barriers is also required to ensure proper performance of the treatment processes and representative parameters are shown in Figure 11.

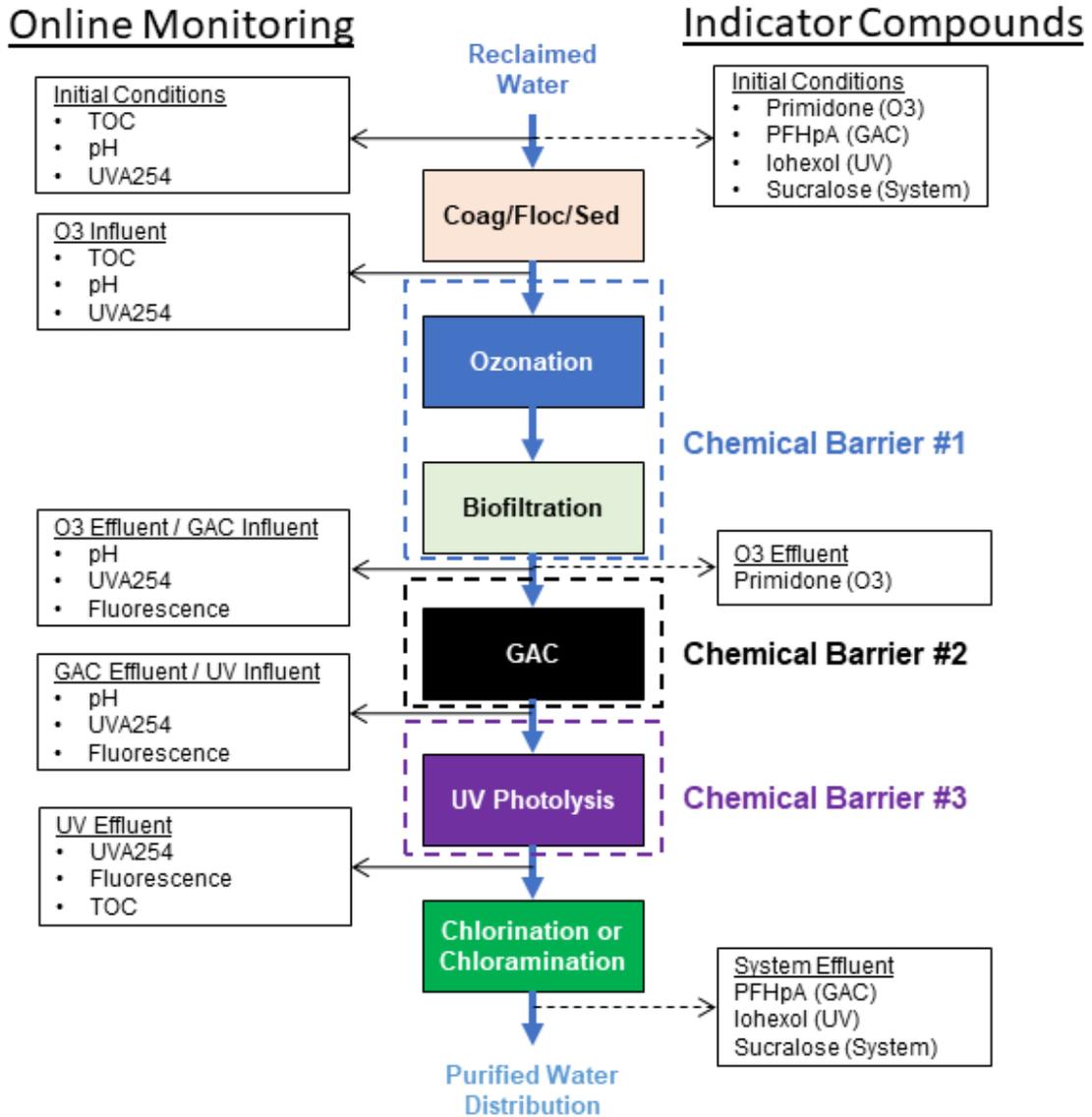


Figure 11. Hypothetical non-RO DPR system for indicator selection case study. Recommended surrogates for online monitoring are shown to the left and recommended indicator compounds for quarterly sampling are shown to the right.

If coagulation is used to contribute to DBP precursor removal or to reduce the required ozone dose, TOC and UVA254 online monitoring should occur before and after



coagulant is added. Regardless, online monitoring of TOC should occur before ozonation to calculate the required ozone dose. UVA254 should be monitored before and after ozonation because its removal correlates with TOC removal by ozone and can be used to estimate ozone dose (Dickenson, et al. 2009). UVA254 should be monitored before and after GAC and UV photolysis because its removal correlates well with TOC removal (Yu, et al. 2015, Anumol, et al. 2015, Sgroi, et al. 2018). Online instruments for specific fluorescence excitation–emission pairs or combinations thereof could also be used to monitor process performance if found to correlate with contaminant removal better than UVA254 during pilot testing (Sgroi, et al. 2018). The pH should be monitored throughout the system because it is important for all of these treatment processes, especially for chemical compounds with an acid dissociation constant (pKa) near neutral (Dong, et al. 2017, Snyder, Gunten, et al. 2014, Nam, et al. 2014, Edwards 1997). An online TOC analyzer is required in the finished water to compare the TOC concentration in the DPR water to the drinking water TOC from which the DPR water was sourced, as described earlier in this chapter. A substitute online analyzer, such as UV254, could be used if proven to provide sufficient correlation to TOC.

If operating as designed, the chemical contaminant barriers would be capable of and necessary to remove a wide variety of chemical hazards to below safety targets. Each process can be adjusted to improve removal, if needed. For example, the ozone dose can be increased, the GAC could be replaced or the empty bed contact time (EBCT) increased, and the UV dose could be increased by adding lamps or increasing contact time. Furthermore, ancillary processes that assist in overall treatment but do not receive chemical removal credit, such as coagulation and biofiltration, could be adjusted to increase downstream performance.



Chapter 7: Engaging the Community

When proposing DPR, partnering with the public and key decision makers is vital. During Phase 1 of this project, WateReuse Colorado developed a communications and outreach plan and initial materials to help foster public understanding and acceptance of DPR in Colorado. The Communications and Outreach plan in Technical Memorandum 2 from Phase 1 (WateReuse Colorado 2018), provides a framework for raising awareness and educating a broad range of stakeholders about the safety and value of DPR. This includes strategies at both the statewide and local level.

The communications and outreach plan provides the initial elements of the approach recommended by Patricia Tennyson and Kristina Ray (Journal of the American Water Works Association, January 2005), which are summarized in these seven steps:

- Identify goals and objectives
- Identify audiences
- Establish messaging
- Develop strategies and tactics
- Prioritize strategies and tactics
- Draft an implementation timeline
- Develop a method for evaluation.

Also during Phase 1, stakeholders identified key messages and audiences with targeted delivery mechanisms and strategies for each. The Plan is one of the primary accomplishments of the WateReuse Colorado Phase 1 DPR project and should be used in any outreach efforts along with the additional information and references provided below.

Access to quality drinking water is considered a basic human right, and the idea of creating drinking water by treating wastewater can trigger emotional responses and prevent people from adopting the new technology. The public needs to understand how water reuse benefits their community, and the specific reasons why water resource managers consider DPR an important piece of the water supply portfolio.



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Engaging the public during the planning stage fosters acceptance and makes implementation easier. Engaged community members can offer insights and will contribute to solutions should problems arise (Penn State College of Agricultural Sciences, 2019). Community partnerships build trust as people are empowered during the decision-making process. And through community input, an effective outreach program can be developed and implemented. The media should also be approached at the outset with clear, consistent messaging (AWWA 2016).

The overall objective of community engagement is to create opportunities that foster open dialog. Public engagement is the process of communicating with, educating, and informing the public on options and proposed plans for implementing potable reuse projects and includes soliciting and receiving input from the public, including questions and concerns from the community. Successful public engagement involves learning the values, knowledge, perceptions and concerns of community members to understand how they view recycled water and its potential health risks. That understanding helps identify relevant ways to talk to people about water reuse (Penn State College of Agricultural Sciences 2019). Such conversations create partnerships that lead to trust and acceptance; this process is diagrammed in Figure 12.

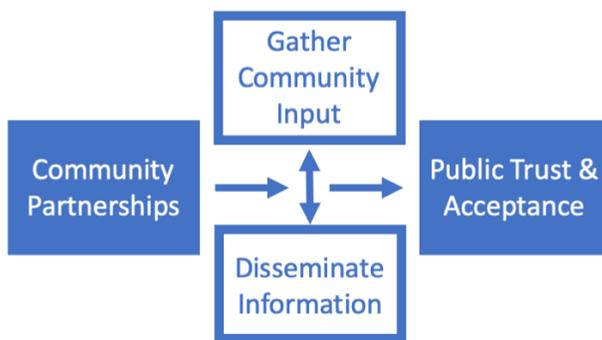


Figure 12. Community Engagement Model

Identifying the best ways to engage the public when implementing direct potable reuse is community-dependent. Specifically, understanding what is important to the community helps to customize outreach. Community stakeholders should represent a wide range of people with diverse viewpoints (EPA 2018). Languages spoken within the community and language preference of the participants should be considered.

Focus groups and surveys can help gather input from community stakeholders (Coxon, et al. 2016). Focus groups typically involve eight to ten people in a guided discussion.



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Including a third party such as a communications expert to moderate the focus group may be beneficial (EPA 2018). The focus group process may begin with broad, open-ended questions such as, “What concerns do you have, in general, about drinking water sources?” and “What does the term ‘recycled water’ mean to you?”

The latter question will indicate how your community defines water reuse and may identify better terminology to use in a survey. As participants respond, the discussion should progress to more specific questions such as, “What health risks do you think are associated with drinking recycled/reused/reclaimed water?” and should include questions that address complex, technological issues such as, “What level of oversight or monitoring do you think a potable reuse facility should have?” Information from focus groups can then be used to develop a survey that reaches a larger number of people in the community.

Surveys are also valuable tools for community engagement and may be more flexible than focus groups because they can be administered as a written questionnaire or over the telephone and don’t require an in-person meeting. As with the focus groups, language preference of the participants should be considered when designing the survey. Survey questions can seek demographic and socioeconomic information that can be related to responses about water reuse.

Both focus group and survey questions may ask how to best disseminate community information about DPR. Table 7 includes sample questions and topics to address in focus groups and/or surveys.



Table 7. Possible focus group/survey questions about water reuse

<p>Focus Group Questions</p>	<p>Where do you get your drinking water?</p> <p>What concerns do you have about sources of your drinking water?</p> <p>What do the terms recycled, reused, or reclaimed water mean to you?</p> <p>How do you perceive the terms processed, treated, potable, or purified water?</p> <p>What health risks do you think are associated with drinking recycled, reused, or reclaimed water?</p> <p>What level of oversight and monitoring do you think a potable reuse facility should have?</p> <p>Are you concerned about drinking water from a potable reuse facility?</p> <p>Why or why not?</p> <p>Are you concerned about your community’s future water supply?</p> <p>Would you support having a direct potable reuse facility in your community?</p> <p>Why or why not?</p> <p>What are best practices for disseminating information about a water reuse facility within your community?</p> <p>What is your preferred mode of communication for updates regarding your water supply (e-mail, bill insert, social media, text, newsletter, website, etc.)?</p>
<p>Survey Questions</p>	<p>What is your preferred mode of communication in the event of a compromised water supply?</p> <p><u>Related to:</u></p> <p>Demographics (age, gender, race, ethnicity)</p> <p>Socioeconomics (income, zip code)</p> <p>Current local water supply (source, quantity, quality)</p> <p>Knowledge/perceptions of water reuse</p> <p>Understanding of water treatment</p> <p>Support/Oppose water reuse</p> <p>Source of trusted information (utility, government official, media)</p> <p>Preferred method of information (flyer, television/radio messaging, mailer)</p>

Relevant community information obtained from the focus groups and surveys will provide critical insight into the knowledge and attitudes about water reuse that may



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influence support and acceptance. It may help to form a community advisory panel with a diverse (and perhaps rotating) membership that will foster continued conversations.

Focus groups and surveys also offer the opportunity to share information about water reuse and how it can benefit the community, such as providing a much-needed additional source of drinking water. Finally, after gathering baseline information that reflects residents' knowledge and perceptions about water reuse, outreach materials can be developed to enhance communication. Feedback on these materials will ensure that the public outreach strategy is effective and evolving.

Successful community outreach programs often include elements such as public tours of advanced treatment pilot or demonstration systems, purified water tasting events, educational programs targeted at the water cycle and water reuse, and dedicated water reuse visitor centers. Engagement of respected local community leaders, such as medical and academic professionals (including community health workers), strengthens public outreach programs. Use of proper terminology is also critical to avoid negative reaction from the public through use of terms that are unknown or elicit negative responses. Industry-accepted best management practices and reference documents include:

- WateReuse Foundation: Marketing Nonpotable Recycled Water.
- WateReuse Colorado: Technical Memorandum 1, Development of DPR Regulations in Colorado (see page 19)
- WateReuse Foundation: Model Communication Plans
- WateReuse California (2010). Public and Political Acceptance of Direct Potable Reuse. Sacramento, CA: Millan, M. and Nellor, M.H.
- WateReuse Foundation (2015b). Model Communication Plans for Increasing Awareness and Fostering Acceptance of Direct Potable Reuse. Millan, M., Tennyson, P. & Snyder, S.



Appendix A: Panel Biographies

Larry Schimmoller, MS, PE, (Panel Chair), is Global Technology Leader for Water Reuse at Jacobs. His experience includes planning, piloting, process selection, design, and construction of water treatment and water reuse projects throughout the country and abroad. He has served as principal investigator on numerous Water Research Foundation projects related to potable reuse, specifically focusing on research related to advanced treatment approaches for potable reuse that don't use reverse osmosis. Schimmoller has a BS in Civil Engineering from Clarkson University and an MS in Environmental Engineering from the University of Illinois at Urbana-Champaign.

Christopher Bellona, PhD, is Assistant Professor of Civil and Environmental Engineering at Colorado School of Mines, where he teaches courses in aquatic chemistry, chemodynamics, hazardous waste management, and physio-chemical treatment processes. His research focuses on technologies for water and wastewater treatment, water reuse, and remediation, including potable reuse and the use of advanced water treatment processes to remove organic contaminants. His interests include advanced oxidation processes, anaerobic membrane bioreactor systems for the treatment of mixed wastes, and the recovery of valuable constituents from various waste streams. Bellona received a BS in Environmental Science from Western Washington University and an MS and a PhD in Environmental Science and Engineering from Colorado School of Mines.

Richard Danielson, PhD, is Vice President and Laboratory Director at BioVir Laboratories, where his research focuses on environmental health microbiology. His expertise is in biotechnology, microbial risk assessment, environmental virology, parasitology, and emerging contaminants in water, including identifying constituents of concern, determining analytical methods, and evaluating potential effects on human health. He served as chief of the Environmental Microbial Diseases Section of the California Department of Health Services for five years and as a lecturer in public health microbiology at University of California Berkeley School of Public Health for more than ten years. Danielson received a BA in Biology from University of San Diego, an MA in Biology from California State University at Fullerton, and a PhD in Microbiology from University of California, Berkeley.



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Eric Dickenson, Ph.D., is the Research and Development Project Manager at the Southern Nevada Water Authority. Dr. Dickenson has more than 18 years of experience in drinking water, wastewater and potable reuse treatment of traditional and emerging chemical contaminants, such as disinfection byproducts, pharmaceuticals, nitrosamines, microplastics and poly- and perfluoroalkyl substances. His recent research has focused on the application of non-membrane-based potable reuse treatment systems. He serves on the WaterReuse Nevada Section committee. Dickenson received a B.S. in Chemical Engineering from University of California, Davis, and an M.S. and Ph.D. in Civil Engineering from the University of Colorado, Boulder.

Ellen McDonald, PhD, PE, is a Principal at Alan Plummer Associates, where she leads the water resources group. She has more than 20 years of experience in water resources planning, water reuse, water quality modeling, and water and wastewater system planning. McDonald has assisted several Texas cities and water districts with developing and implementing water reuse projects. She co-authored the *Direct Potable Reuse Resource Document*, prepared in 2015 for the Texas Water Development Board. McDonald received a BS in Civil Engineering from Bucknell University and an MS and PhD in Water Resources Engineering from Stanford University.

Kristina Mena, PhD, MSPH, is the Regional Dean of the El Paso Campus of UTHealth School of Public Health at Houston, where she is also Associate Professor and Program Head of Environmental and Occupational Health Sciences for the Department of Epidemiology, Human Genetics and Environmental Sciences. Mena just completed second terms on both the USEPA Chartered Science Advisory Board and the Drinking Water Committee where she provides expertise on public health and environmental issues. Her research focuses on environmental risk assessment related to water quality and food safety, and the environment's impact on health for various populations. Mena received a BA from Franklin College of Indiana, an MSPH from the University of South Florida, and a PhD from The University of Arizona.



Appendix B: Project Funding and Stakeholder Participation

Phase I (past work)

- Colorado Department of Public Health and Environment
- Colorado Water Conservation Board
- Basin Roundtables: Colorado, Metro, North Platte, and South Platte
- WaterReuse Colorado
- Denver Water
- City of Aurora
- Centennial Water and Sanitation District
- WaterReuse Research Foundation
- South Metro Water Supply Authority
- Western Resource Advocates
- Town of Castle Rock
- Plum Creek Water Reclamation Authority
- Colorado Springs Utilities

Phase II (this Project)

- Colorado Department of Public Health and Environment
- Colorado Water Conservation Board
- WaterReuse Colorado
- City of Aurora
- Carollo Engineers
- Denver Water



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- Town of Castle Rock
- South Metro Water Supply Authority
- Jacobs
- MSK Consulting
- Stantec
- Plum Creek Water Reclamation Authority
- Colorado Springs Utilities



Appendix C: Hypothetical Indicator Selection Case Study

This appendix describes a case study for a hypothetical Colorado utility that is planning a WPF. The TOrC concentrations and matrix interferences were assumed typical relative to studies using real reclaimed water in scientific literature or technical reports. The hypothetical system uses Coagulation/Flocculation/Sedimentation, Ozone, Biofiltration, GAC, and UV photolysis, a similar treatment train as the Sustainable Water Initiative for Tomorrow (SWIFT) demonstration facility operated by the Hampton Roads Sanitation District in Virginia. These chemical removal processes should be considered as examples and not necessarily prescriptive.

Indicator Criteria

Selection of Level 3 chemical indicators should be site-specific. Compounds prevalent in one community's reclaimed water might not be prevalent in another's. For example, medical professionals in different cities might choose to use different iodinated contrast media. Compounds that have been identified as potential indicators in the literature may be banned, phased out, or substituted with new chemicals over time (for example, triclosan, PFOA, and PFOS). The initial candidate list for indicator screening should take into account expected chemical emissions from local industry. Furthermore, indicators should target the treatment processes used at the specific WPF. Some criteria for selecting indicators include the following:

1. **Concentration.** The indicator should have a median concentration at least five times greater than its Method Reporting Limit (MRL). Otherwise, a high percentage of removal cannot be demonstrated.
2. **Prevalence.** The indicator should have a detection frequency greater than 80 percent in the site-specific reclaimed water. Otherwise, its absence may be random or seasonal and may not reflect treatment efficacy. For example, sunscreen UV blockers or allergy medications follow a seasonal occurrence pattern in reclaimed water (Petrie, Barden and Kasprzyk-Hordern 2015).
3. **Measurability.** Sufficiently precise and sensitive analytical methods for the compound are necessary to meet the above two criteria. Analytical methods should be well established in the scientific literature and approved by the EPA or CDPHE.



7. **Specificity.** The indicator compound should be removable by the process(es) it is intended to monitor. It should be sufficiently recalcitrant to any upstream processes—or at such high concentration in the reclaimed water—that it meets the concentration and prevalence criteria at the influent of the targeted treatment process. Ideally, the indicator compound should be recalcitrant to downstream processes, as well. If all indicators meet this criterion, then all indicators could be monitored at just two sampling locations (WPF influent and final effluent). This criterion is based on convenience and operational efficiency.
4. **Sensitivity.** The indicator should be moderately removable by the targeted process, such that 75 percent removal is feasible only when the process is functioning as designed. For example, ozone doses in reuse systems are typically around $CT_{10} = 4\text{--}11 \text{ mg}\cdot\text{min}/\text{L}$ to balance chemical and pathogen removal against bromate formation (Dickenson, et al. 2009). Some compounds such as hydrocodone are so sensitive to oxidation that they are more than 90 percent removed even when the operationally defined ozone exposure is $0 \text{ mg}\cdot\text{min}/\text{L}$ (Dickenson, et al. 2009). Hydrocodone would be a poor indicator for ozonation, since it can be removed below its MRL even if an ozone generator is malfunctioning and dosing less ozone than intended. On the other hand, ozonation removes chemicals such as chloroform and tris(2-chloroethyl) phosphate by less than 25 percent under typical conditions (Dickenson, et al. 2009). Removing more than 75 percent of these compounds with ozone would be cost prohibitive or physically impossible, and would likely cause the bromate concentration to exceed regulation. Moderately oxidizable compounds such as DEET or iopromide would serve as better ozonation indicators because they are more than 75 percent removed under typical conditions but mostly pass through at lower ozone exposure (Dickenson, et al. 2009).
5. **Diversity.** There should be at least one indicator that specifically monitors each chemical treatment barrier. Furthermore, there should be at least one indicator that is partially removed by each treatment barrier, but only removed to a target of at least 75 percent if all treatment barriers are functioning as intended—a system indicator.

To determine which compounds meet criteria 3 through 5, chemicals can be organized into groups based on their expected removal by each treatment process. Preliminary screening and organization of proposed indicators can be conducted using chemical properties that correlate with removal (for example, molecular weight, logD), bench-scale experiments under controlled, standardized conditions (for example, Rapid Small



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Scale Column Test), or published pilot-scale data. However, water treatment efficacy depends on site-specific factors such as pH and competition for adsorption sites. Therefore, the final indicator selection should use site-specific pilot study data.

By following these criteria, the ability of a WPF to remove virtually any chemical can be demonstrated with just four indicators: three for individual chemical contaminants removed by each of the required three chemical treatment barriers and one for the system as a whole. The number of additional compounds required for Level 3 monitoring could be fewer than four, if compounds are selected that meet the criteria for both Level 1 or Level 2 and Level 3. However, in this case, the selection of a Level 1 or 2 compound as an indicator compound should be clearly and specifically communicated to CDPHE. Such a compound should be monitored with the sampling frequency and locations assigned for both Levels. Furthermore, prevention of the compound through source control, DBP precursor removal, or upgrades to the water reclamation facility should be prioritized over maintaining the Level 1 or Level 2 compounds as an indicator.



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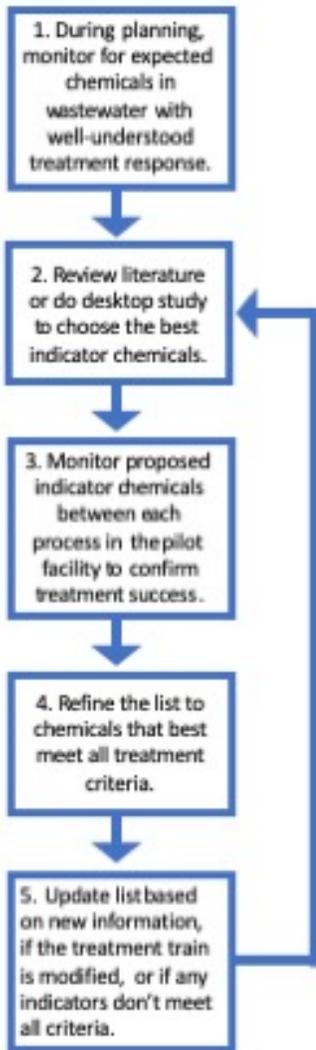


Figure C-1. Indicator selection and revision process.

The selected indicators in this case study were primidone for ozone, perfluoroheptanoic acid for GAC, iohexol for UV photolysis, and sucralose for the system as a whole. These compounds are examples and should not be interpreted as policy or regulation. Indicator selection should be site-specific, following the criteria and process described in this appendix. Notwithstanding, it would be advisable to include these compounds in a utility's initial indicator candidate list.

Removal of each compound by each process was categorized as Excellent, Good, Partial, or Negligible as defined in Table C-1. Details of how thresholds of chemical



properties were determined for each technology and removal category are explained in the sections below.

Table C-1. Treatment level definitions and chemical property thresholds for determining indicator groups.

Removal Category	Expected Removal	kO ₃ (1/M/s) at pH 7 ^a	logD at pH 7 ^b	φ×ε at 254nm (L/E/cm) ^c
Excellent	>99 percent	>103	> 1.5	>1200
Good	75–99 percent	1 to 103	0.5 to 1.5	300 to 1200
Partial	25–75 percent	<1	-0.5 to 0.5	40 to 300
Negligible	<25 percent	<1	< -0.5	<40

a. Partial and negligible removal distinguished based on pilot- or full-scale data.

c. Excluding heterocyclic N and positively charged compounds. Assuming 15 min EBCT and biannual replacement.

d. Assuming 800 mJ/cm².

Initial Indicator Candidate List

A list of over twenty compounds that have established analytical methods and well-documented occurrence and treatment behavior in reclaimed water were selected. Compounds highlighted as potential indicators in reuse studies and reports were focused on. The literature on the occurrence of these compounds in reclaimed water and their removal by ozonation, GAC, and UV were reviewed with findings recorded in Table C-2. Compounds were then grouped based on expected removal by each process.



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Groups were defined based on thresholds of fundamental chemical properties that related to expected removal (Table C-2). Expected removals were also verified based on pilot- or full-scale data where available.

Table C-2. Recommended Indicator Groups based on theoretical case study.

Indicator Group	kO ₃ at pH 7 (1/M/s)	LogD at pH 7	$\phi \times \epsilon$ at 254nm (L/cm/E)	Ozone Removal	GAC Removal	UV Removal	Example(s)
Ideal Ozone Indicator	$1 < k < 10^3$	< 0.5	< 300	Good	Negligible to Partial	Negligible to Partial	?
Potential Ozone Indicator (If concentration $> 100 \times$ MRL)	10^3 to 10^5	< 0.5	< 300	Excellent	Negligible to Partial	Negligible to Partial	Atenolol (Yu, et al. 2015, Gerrity, et al. 2012)
Potential Ozone Indicator (would require sampling before UV)	$1 < k < 10^3$	< 0.5	> 300	Good	Negligible to Partial	Good to Excellent	Iopromide (Yu, et al. 2015, Ning and Graham 2008)
Potential Ozone Indicator (would require sampling before GAC)	$1 < k < 10^3$	> 0.5		Good	Good to Excellent		Primidone, Benzotriazole, Galaxolide, Benzophenone, Ibuprofen, DEET (Dickenson, et al. 2009, Snyder, Gunten, et al. 2014, Gerrity, et al. 2012)
GAC Indicator	< 1	0.5 to 1.5	< 300	Negligible to Partial	Good	Negligible to Partial	PFHpA (Pisarenko, et al. 2015)
System Indicator (O ₃ + GAC + UV)	< 1	-0.5 to 0.5	40 to 300	Partial	Partial	Partial	Sucralose (Salveson, Dickenson, et al., Pathogen Risk Evaluation of Treatment and Monitoring System Performance for Potable Reuse 2018, Pepper and Snyder 2016, Bourgin, et al. 2017, Dickenson, et al. 2009)
UV Indicator	< 1	< 0.5	300 to 1200	Negligible to Partial	Negligible to Partial	Good	Iohexol (Yu, et al. 2015, Snyder, Gunten, et al. 2014)
Non-Conservative	$> 10^5$			Excellent			Acetaminophen (Javier Rivas, et al. 2011), Carbamazepine (Gerrity, et al. 2012), Trimethoprim (Gerrity, et al. 2012), Sulfamethoxazole (Snyder, Gunten, et al. 2014), Naproxen (Gerrity, et al. 2012)
Non-Conservative	< 1	> 1.5			Excellent		TCP, TCEP (Snyder, Gunten, et al. 2014)
Non-Conservative			> 1200			Excellent	Diclofenac (Yu, et al. 2015)

^a ϕ unknown, but partial UV removal reported by Pepper and Snyder (201



Ozone

First, candidate indicators were screened for ozonation. The assumed ozone dose was in the range 0.6 to 1.0 mgO₃:mgTOC, which is typical for pilot- and full-scale drinking water and reuse systems (Dickenson, et al. 2009). Chloramine injection to reduce bromate formation may be necessary at this ozone dose (Hogard, et al. 2019).

Full-scale ozonation removal is directly related to the compound's molar reaction rate with ozone (kO₃ (1/M/s)) (Dickenson, et al. 2009). Compounds with kO₃ greater than 10⁵ or greater than 10³ tend to have ozonation removal greater than 99 percent or greater than 90 percent, respectively, under realistic ozone doses (Dickenson, et al. 2009). Generally, these compounds could be considered non-conservative as indicators. That is, they may have removal to below the MRL even if the ozone dose is less than intended.

Ideal ozone indicators have kO₃ in the range 10⁰ to 10³ 1/M/s. Compounds on the high end of this range tend to be alkyl aromatics, and compounds on the low end of this range tend to be saturated aliphatics (Dickenson, et al. 2009). These compounds have greater than 75 percent removal with ozone doses greater than 4 mg-min/L (in other words, O₃:TOC ratios between 0.6–1.0 mg/mg) but less than 75 percent removal at lower ozone doses (Dickenson, et al. 2009). Thus, these are “sweet spot” compounds that are only well-removed by ozonation when the ozone dose is optimal. Many compounds fit this criterion, including primidone, benzotriazole, galaxolide, benzophenone, ibuprofen, and DEET (Dickenson, et al. 2009, Snyder, Gunten, et al. 2014, Gerrity, et al. 2012). However, all of the aforementioned compounds have logD greater than 0.5, indicating good removal by GAC, so they would require sampling before GAC (Appendix C). Iopromide has good ozonation removal with a kO₃ of 14 1/M/s and low GAC removal with a logD of -0.44 (Ning and Graham 2008). However, iopromide has effective removal by direct UV photolysis, so it would require sampling before UV.¹¹

Atenolol may be a viable ozone indicator if its concentration is consistently much higher than its MRL. It has a kO₃ of 2,000 1/M/s, placing it in the low end of the excellent removal group. Its logD is -2.14, indicating negligible GAC removal, and it has negligible UV removal (Figure C-2) (Yu, et al. 2015). Thus, assuming consistent high concentration and prevalence, atenolol could be an ozone indicator with a sampling point in the finished water. This situation would be plausible based on the atenolol MRL and mean concentration reported by Kostich, et al. (Kostich, Batt and Lazorchak 2014).



In this case study, no compounds were found that would fully meet all required and preferred criteria for ozone indicators. Therefore, more research is justified to quantify and characterize potential DPR indicators. Indicator criteria 5 (Sensitivity) is based on public health protection, while criteria 4c (recalcitrance to downstream processes) is based on operational convenience. Therefore, criteria 5 is a higher priority and for this case we would recommend sampling for compounds such as iopromide, meprobamate, or primidone as the ozone indicator upstream of the GAC treatment process.

Granular Activated Carbon

Compounds expected to pass significantly through ozonation were further investigated regarding GAC removal. With enough replacement frequency, GAC can remove virtually any organic compound. However, for the purposes of this case study, replacement frequency of no greater than twice per year was considered economically realistic. Assuming an empty bed contact time of 15 minutes, 25 percent breakthrough no sooner than 17,000 bed volumes would be considered good removal.

More hydrophobic compounds are generally better removed by GAC (Ling, et al. 2019). The octanol–water coefficient (also called K_{ow} , partition coefficient, or $\log P$) is a measure of the hydrophobicity of a compound and has been found to correlate well with the removal by activated carbon in certain cases (Westerhoff, et al. 2005). However, the octanol–water coefficient is conventionally reported for the neutral state of a compound. In fact, many trace organics (for example, conjugate acids or bases) are present as ionic compounds at neutral pH. Negatively charged compounds are generally less hydrophobic than the neutral states and therefore less well adsorbed.

$\log D$ is the octanol–water coefficient of a compound taking into account its ionic state(s) at a given pH. As such, it correlates with GAC removal better than the unadjusted octanol–water coefficient, especially for anionic compounds (Snyder, Wert, et al. 2007). Therefore, $\log D$ is a useful screening tool for estimating compounds' GAC removal and their usefulness as indicators.

Nevertheless, $\log D$ is not a perfect predictor of GAC removal and expected GAC removals should be verified with site–specific, pilot–scale data. $\log D$ is often predicted based on quantitative structure–activity relationships (QSARs) rather than experimentally determined. For example, caffeine is much better removed by GAC than would be expected based on $\log D$ (Figure C–2). This may be because the QSARs predicting $\log D$ are inaccurate for heterocyclic nitrogen–containing compounds⁵ or due to polar attraction between tertiary amines and



corresponding sites on the GAC. Other factors besides hydrophobicity also play a role in GAC removal, including molecular weight, molecular shape, and charge (Ling, et al. 2019). Positive compounds like fluoxetine are better removed by negatively charged GACs (and vice versa) than would be predicted by logD due to electrostatic interactions (Figure C-2). Low molecular weight (MW), semi-volatile compound such as those typically measured by gas chromatography mass spectrometry (GC-MS) may have lower activated carbon removal than indicated by logD (Westerhoff, et al. 2005). For example, NDMA (MW = 74 Da) and NMOR (MW = 116 Da) both have logD suggesting partial GAC removal but broke through pilot-scale GAC in reclaimed water in less than 2500 bed volumes (Salveson, Dickenson, et al., Pathogen Risk Evaluation of Treatment and Monitoring System Performance for Potable Reuse 2018).

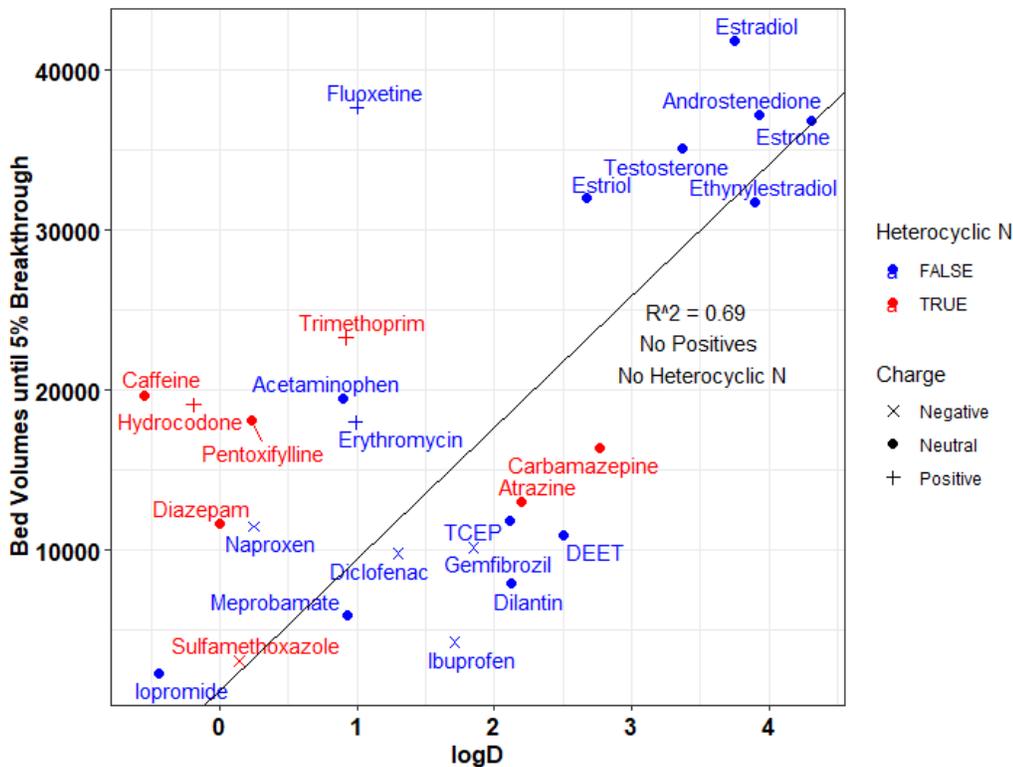


Figure C-2. GAC rapid small-scale column test (RSSCT) breakthrough vs logD. The RSSCT was conducted using surface water and the GAC was Hydrodarco 4000. Breakthrough data is from Removal of EDCs and Pharmaceuticals in Drinking and Reuse Treatment Processes (Snyder, Wert, et al. 2007), and logD and charge at pH 7 are according to Chemaxon.com. A low percentage breakthrough was selected for this figure so breakthrough of high logD compounds would be quantifiable. The linear correlation between logD and bed volumes until breakthrough had an R² of 0.69 but only when excluding compounds with heterocyclic nitrogen or positive charge.

Compounds were grouped based on expected GAC removal based on logD and the other factors discussed above. For consistency, all logDs reported here are according to the



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Chemicalize feature on Chemaxon.com. Compounds with logD greater than 1.5 were predicted to have excellent GAC removal and would be non-conservative indicators (They are easily removed even after a year or more of carbon age). Positively charged compounds like fluoxetine and neutral, heterocyclic nitrogen-containing compounds like caffeine were excluded as indicators because their GAC removal is also usually excellent.

Compounds with logD between 0.5 and 1.5 were considered to have good GAC removal (In other words, they have high removal for at least six months but potentially some breakthrough thereafter). These compounds would be ideal GAC indicators, provided high enough concentrations after ozonation. An example compound in this group would be perfluoroheptanoic acid (PFHpA). Compounds with logD between -0.5 and 0.5 are expected to have only partial GAC removal. The system as a whole could reliably remove these compounds by greater than 75 percent if they are also at least partially removed by ozonation or UV. An example compound in this group would be sucralose (Salveson, Dickenson, et al., Pathogen Risk Evaluation of Treatment and Monitoring System Performance for Potable Reuse 2018). Compounds with logD below -0.5 (such as PFBA, PFPeA, iopamidol, iohexol) tend to have negligible GAC removal or would require expensive GAC replacement frequency (Inyang and Dickenson 2017, Stanford, et al. 2017).

UV

Compounds expected to be above their MRL after both ozonation and GAC were further investigated for removal by direct UV photolysis. Typical UV doses for disinfection are in the range 20 to 100 mJ/cm² but few compounds are significantly removed at those levels (Yu, et al. 2015, Mofidi, et al. 2002, Estrada-Arriaga, et al. 2016). A UV dose of 800 mJ/cm² has been applied for UV/AOP at pilot-scale (Miklos, et al. 2018). Direct UV photolysis has been studied less than UV/AOP at pilot- and full-scale, but presumably UV doses at least as high would be economically competitive without the additional expense of oxidant injection. Therefore, a UV dose of 800 mJ/cm² was assumed for this case study, but somewhat higher UV doses such as 1000 mJ/cm² may also be realistic. The assumed wavelength was 254 nm, which is typical of low-pressure UV systems (Yu, et al. 2015).

The photodegradability of a compound is proportional both to its capacity to absorb light at a certain wavelength (its molar absorption coefficient, ϵ , 1/M/cm) and its transformation efficiency when light energy has been absorbed (quantum yield, ϕ , mol/Einstein). Thus, the photodegradability of a compound can be expressed as the product $\epsilon \times \phi$ (L/cm/E) (Yu, et al. 2015). Removal by direct UV photolysis is clearly a function of this product (Figure C-3).



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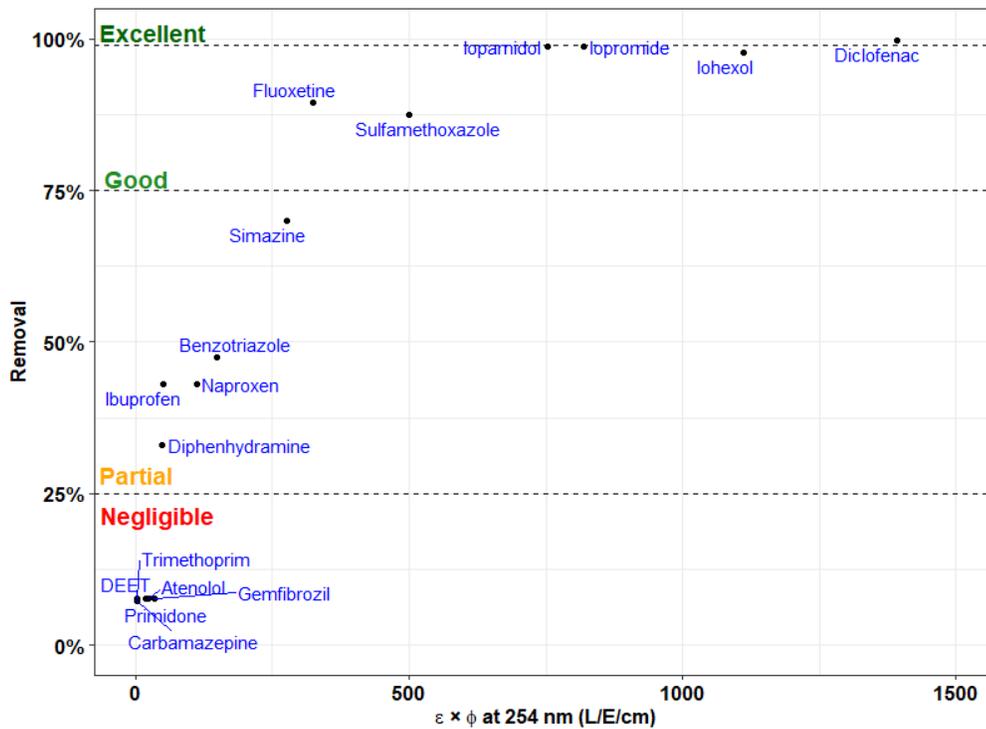


Figure C-3. Direct UV Photolysis removal vs the product of molar absorption coefficient (ϵ) and quantum yield (ϕ). Data is adapted from Yu, et al. ¹¹.

Compounds with $\epsilon \times \phi$ greater than 1200 L/cm/E would be non-conservative as indicators. For example, diclofenac, with $\epsilon \times \phi$ of 1393 L/cm/E, would still be greater than 90 percent removed even if the UV dose fell by 50 percent to 400 mJ/cm² (Yu, et al. 2015). Compounds with $\epsilon \times \phi$ between 300 to 1200 L/cm/E would be good indicators with expected removal between 75 and 99 percent. lohexol would be an ideal UV indicator because it is recalcitrant to ozonation and GAC and has $\epsilon \times \phi$ of 1112 L/cm/E (Yu, et al. 2015, Stanford, et al. 2017). Compounds with $\epsilon \times \phi$ between 3 to 300 L/cm/E would have partial removal, 25 to 75 percent. These compounds would be candidates for system indicators if their ozonation and GAC removal are partial as well. A compound fitting these criteria would be sucralose.

System Indicators

Sucralose is the ideal overall system indicator for a WPF with ozonation, GAC, and direct UV photolysis. Sucralose is a non-toxic, non-nutritive artificial sweetener that is widely used and is stable over time (Jmaiff Blackstock, et al. 2019). Sucralose has slow biodegradation in water reclamation facilities and the environment (Jmaiff Blackstock, et al. 2019). It is one of the most high-concentration and prevalent TOrCs in reclaimed water. For example, Subedi and Kannan (2014) reported an average sucralose concentration of 30,000 ng/L in New York



state, over one thousand times higher than its MRL (Salveson, Dickenson, et al., Operational, Monitoring, and Response Data from Unit Processes in Full-Scale Water Treatment, IPR, and DPR 2018). Sucralose was partially removed (46 percent) in pilot-scale reclaimed water ozonation (Dickenson, et al. 2018). Sucralose has a logD of -0.47 , indicating partial GAC removal; it had 25 percent breakthrough after about 12,000 bed volumes or 125 days in ozonated reclaimed water (Salveson, Dickenson, et al., Pathogen Risk Evaluation of Treatment and Monitoring System Performance for Potable Reuse 2018). Sucralose also has only partial removal by direct UV photolysis, with approximately 60 percent removal by 800 mJ/cm^2 at 254 nm (Pepper and Snyder 2016). Therefore, it would take all three chemical barriers working optimally and in concert to reliably remove sucralose by over 75 percent. Due to its high concentration to MRL ratio, sucralose would still be quantifiable even after a high degree of removal. Hence, its removal can be tracked with high precision to detect even slight drops in system performance.

Other Considerations

Thresholds between indicator groups should be considered flexible. References may differ somewhat on the values of properties for a given compound. For example, Huber, et al. (Huber, et al. 2003) and Ning and Graham (Ning and Graham 2008) disagree on the kO_3 of iopromide. Rather than being experimentally determined, the chemical property may be calculated based on QSARs. Different QSARs may provide slightly different estimates. For example, many QSARs disagreed on the physicochemical properties of polyfluorinated compounds (Rayne and Forest 2009). Furthermore, the chemical property may be highly sensitive to pH, especially if the pKa of the compound is near 7. For example, atenolol has a pKa of 9.6, and its kO_3 varies an order of magnitude between pH 7 and 8 (Snyder, Gunten, et al. 2014). Sulfamethoxazole has pKa of 6.2, and its activated carbon sorption is lower at higher pH (Nam, et al. 2014). Thus, indicator screening should be conducted based on the anticipated pH of the site-specific reclaimed water.

Furthermore, the degree of removal and therefore the range of chemical properties considered acceptable for an indicator compound depends in part on the initial concentration and the MRL of the compound. In particular, the boundary between “Good” removal (ideal indicator) and “Excellent” removal (non-conservative indicator) would depend in part on the ratio between the compound’s concentration and MRL. For example, if a compound is consistently 99.9 percent removed by the first chemical barrier but it has a concentration over 1000 times its MRL, it may still serve as an indicator because a change from 99.9 to 99 percent removal would suggest suboptimal process performance. When multiple compounds meet all criteria as indicators for a given process, the compound with the highest



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concentration to MRL ratio is recommended because its removal can be most precisely quantified.

An important class of chemicals that could potentially pass through the hypothetical system described above would be the very short-chain perfluorocarboxylic acids PFBA, PFPeA, and PFHxA. These compounds are considered less bioaccumulative and less toxic than PFOA or PFOS (Eriksen, et al. 2010, Gomis, et al. 2018). Nevertheless, if these compounds are included as Level 2 chemicals, they would need to be removed or controlled to certain targets.

The simplest approach for meeting Level 2 targets for these short-chain PFAS could be enhanced source control. Known sources of PFAS include air force bases, airports, landfills, textile mills, carpet factories, and metal plating (Hu, et al. 2016, Lang, et al. 2017, Zhang, et al. 2016, Konwick, et al. 2008). These industries could be required to implement industrial wastewater treatment for PFAS or banned from discharging to the municipal wastewater collection system. Another approach would be to reduce the logD threshold for GAC indicators, select a more recalcitrant GAC indicator (such as PFBA), and replace the GAC bed more frequently (for example, quarterly). A third potential solution could be substituting conventional ozonation with ozofractionation, a combined ozonation and air stripping technology that has successfully removed PFAS from groundwater at pilot-scale in Australia (Horst, et al. 2018). Failing the above, a last resort may be installing a fourth chemical barrier such as anion exchange or nanofiltration after GAC (Appleman, et al. 2013, Zaggia, et al. 2016). Additional innovative technologies are being investigated for PFAS removal (such as electrocoagulation (Liu, et al. 2018), electrochemical oxidation (Liao and Farrell 2009) fluorinated sorbents (Xiao, et al. 2017), and advanced reduction processes⁷²), but the economic viability of these technologies for short-chain PFAS has not yet been demonstrated at pilot-scale for reclaimed water.

Ozone or GAC only partially remove 1,4-dioxane, and it is negligibly removed with direct UV photolysis (Trussell, et al. 2018, Carrera, et al. 2019). If 1,4-dioxane exceeds its standard as a Level 2 compound, potential solutions would be industrial source control; increasing the ozone dose and selecting a more stringent ozonation indicator; or substituting an alternative AOP with greater hydroxyl radical production (Trussell, et al. 2018). While 1,4-dioxane is an important and challenging Level 2 compound, it would likely not meet the criteria as an indicator because its concentration is generally low relative to its MRL (Trussell, et al. 2018, Simonich, et al. 2013). Thus, a measurement of 1,4-dioxane below the MRL could be due to random chance or successful source control rather than high percentage removal. Similarly,



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NMOR has good removal by UV photolysis and low removal by ozonation and GAC but might not qualify as an indicator due to low concentration.



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