WATER ENVIRONMENT & REUSE FOUNDATION

Final Report

Potable Reuse Research Compilation: Synthesis of Findings

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Submitted by:

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Fountain Valley, California USA
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2016

WATER ENVIRONMENT & REUSE FOUNDATION
WE&RF

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

The Water Environment & Reuse Foundation (WE&RF) is a 501c3 charitable corporation seeking to identify, support, and disseminate research that enhances the quality and reliability of water for natural systems and communities with an integrated approach to resource recovery and reuse; while facilitating interaction among practitioners, educators, researchers, decision makers, and the public. WE&RF subscribers include municipal and regional water and water resource recovery facilities, industrial corporations, environmental engineering firms, and others that share a commitment to cost-effective water quality solutions. WE&RF is dedicated to advancing science and technology addressing water quality issues as they impact water resources, the atmosphere, the lands, and quality of life.

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Library of Congress Catalog Card Number: 2016960993
WE&RF ISBN: 978-1-94124-263-6
WE&RF Project Number: WRRF-15-01 (or Reuse-15-01)

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The Water Environment & Reuse Foundation (WE&RF) is a 501c3 charitable corporation seeking to identify, support, and disseminate research that enhances the quality and reliability of water for natural systems and communities with an integrated approach to resource recovery and reuse, while facilitating interaction among practitioners, educators, researchers, decision makers, and the public. Our research represents a portfolio of more than $200 million in water quality research.

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[1] Refers to the Expert Panel on the Feasibility of Developing Uniform Water Recycling Criteria for Direct Potable Reuse, sponsored by the Division of Drinking Water of the California State Water Resources Control Board and administered by the National Water Research Institute.

Abstract and Benefits

Abstract:

The Water Environment & Reuse Foundation (WE&RF) (formerly, the WateReuse Research Foundation) invested in a research portfolio valued at over $24 million to investigate different aspects of the technical feasibility of implementing direct potable reuse (DPR) projects. The purpose of this report is to summarize and synthesize key issues and findings from this research, as well as the results of complementary research, to provide a clear understanding of the state-of-the-art and state-of-the-science on DPR and to identify unknowns that may require further research.

The topics addressed in this report include: source control, treatment trains, surrogates and log reduction credits for pathogens, pathogen monitoring, constituents of emerging concern, critical control points to monitor DPR systems, operation and maintenance of DPR facilities, operator training and certification, the resilience of DPR systems, and reliable and redundant treatment train performance.

Benefits:

- Serve as an accessible resource to communities and decision-makers seeking more information on potable reuse, particularly DPR.
- Provide practical information to utilities and municipalities interested in implementing DPR projects.
- Inspire continued advancements and innovation in DPR research and technology.
- Promote a better understanding of the value, needs, and challenges associated with using DPR to provide a safe, reliable source of drinking water.

Keywords: Water reuse, direct potable reuse, advanced water treatment facility, advanced treated water, finished water, and research synthesis.

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Acronyms

AOP	Advanced oxidation process
ATP	Adenosine triphosphate
AWTF	Advanced water treatment facility
BAC	Biologically activate carbon
BOD	Biochemical oxygen demand
CCP	Critical control point
CEC	Constituent of emerging concern (also known as “chemical of emerging concern” or “contaminant of emerging concern”)
COD	Chemical oxygen demand
COP	Critical operating point
CT	Residual disinfectant concentration, C (in milligrams per liter), multiplied by the contact time, T (in minutes)
DBP	Disinfection byproduct
ddPCR	Digital droplet polymerase chain reaction
DDW	Division of Drinking Water of the State Water Resources Control Board (California)
DPR	Direct potable reuse
DWTF	Drinking water treatment facility
EBCT	Empty bed contact time
EC	Electrical conductivity
EDC	Endocrine disrupting compound
EEO	Electric energy per order of magnitude
efoM	Effluent organic matter
ELISA	Enzyme linked immunosorbent assay
ESB	Engineered storage buffer
FRT	Failure response time
GAC	Granular activated carbon
GWR	Groundwater recharge
GWRS	Groundwater Replenishment System (in Orange County, California)
HAA	Haloacetic acids
HACCP	Hazard Analysis and Critical Control Point
HUS	Hemolyric Uremic Syndrome
I/I	Inflow and infiltration
IPR	Indirect potable reuse
MALS	Multi-angle light scattering
MBR	Membrane bioreactor
MF	Microfiltration

NASBA	Nucleic acid sequence based amplification
NDMA	N-nitrosodimethylamine
NF	Nanofiltration
NGS	Next-generation sequencing
NOM	Natural organic matter
NPDES	National Pollutant Discharge Elimination System
NPP	National Pretreatment Program
NTA	Non-targeted analysis
NWRI	National Water Research Institute
O_3	Ozone
O&M	Operation and maintenance
OOC	Office of Operator Certification of the State Water Resources Control Board (California)
PAC	Project Advisory Committee (for WRRF-15-01)
PCR	Polymerase chain reaction
PDT	Pressure decay test
PML	Progressive multifocal leukoencephalopathy
POTW	Publicly owned treatment work
qPCR	Quantitative polymerase chain reaction
RO	Reverse osmosis
RRT	Response retention time
RWPF	Raw Water Production Facility (in Big Spring, Texas)
SCADA	Supervisory Control and Data Acquisition
SDWA	Safe Drinking Water Act
SNT	Serum neutralization test
SWA	Surface water augmentation
SWMOA	Southwest Membrane Operator Association
TCEQ	Texas Commission on Environmental Quality
TDS	Total dissolved solids
TOC	Total organic carbon
TrOC	Trace organic compound
UER	Upper end reduction
UF	Ultrafiltration
USEPA	United States Environmental Protection Agency
UV	Ultraviolet light
UV/AOP	Ultraviolet disinfection with advanced oxidation processes
UVT	Ultraviolet transmittance
WE&RF	Water Environment & Reuse Foundation
WEF	Water Environment Federation

WRRF	WateReuse Research Foundation (now called WE&RF)
WRF	Water Research Foundation
WWTP	Wastewater treatment plant

Abbreviations for Units of Measure

CFU	Colony forming unit
g	Gram (1 g = 10^3 mg = 10^6 µg = 10^9 ng = 10^{12} pg)
mg	Milligram
mg/L	Milligram per liter
mgd	Million gallons per day
mJ/cm^2	Millijoules per square centimeter
mL	Milliliter
mL/d	Milliliter per day
MPN	Most probable number
mW/cm^2	Milliwatts per square centimeter
ng	Nanogram
ng/L	Nanogram per liter
mg O_3/mg TOC	Milligram of ozone per milligram of total organic carbon
pg/mL	Picogram per milliliter
µg/L	Micrograms per liter

Terminology

Term	Definition
Advanced treated water	Water produced from an advanced water treatment facility for direct and indirect potable reuse applications.
Advanced water treatment	A general term used to describe the overall process and procedures involved in the treatment of wastewater beyond secondary wastewater treatment to produce advanced treated water.
Advanced water treatment facility	The treatment facility where advanced treated water is produced. The specific combination of treatment technologies employed will depend on the quality of the treated wastewater and the type of potable reuse (i.e., indirect potable reuse or direct potable reuse).
Barrier	A measure implemented to control microbial or chemical constituents in advanced treated water. A barrier can be technical, operational, or managerial in nature. Log reduction credits are assigned only for technical barriers.
Close-coupled processes	Two or more processes in series where the performance of the first process can affect the performance of the subsequent process or processes.
Concentrate	A liquid waste stream containing elevated concentrations of total dissolved solids and other constituents.
Constituent	Any physical, chemical, biological, or radiological substance or matter found in water and wastewater.
Constituent of emerging concern	Chemicals or compounds not regulated in drinking water or advanced treated water. They may be candidates for future regulation depending on their ecological toxicity, potential human health effects, public perception, and frequency of occurrence.
Contaminant	Any physical, chemical, biological, or radiological substance or matter that has an adverse effect on air, water, or soil. The term "constituent" could be used in place of "contaminant."
Critical control point	A point in advanced water treatment where control can be applied to an individual unit process to reduce, prevent, or eliminate process failure and where monitoring is conducted to confirm that the control point is functioning correctly. The goal is to reduce the risk from pathogen and chemical constituents.
De facto potable reuse	The downstream use of surface water as a source of drinking water that is subject to upstream wastewater discharges (also referred to as "unplanned potable reuse").

Term	Definition
Direct potable reuse	There are two forms of direct potable reuse. In the first form, advanced treated water is introduced into the raw water supply upstream of a drinking water treatment facility. In the second form, finished drinking water from an advanced water treatment facility permitted as a drinking water treatment facility is introduced directly into a potable water supply distribution system. The second form of direct potable reuse is not considered in detail in this document.
Disinfection byproducts	Chemicals formed by the reaction of a disinfectant (e.g., chlorine or ozone) with organic or inorganic matter found in treated water or wastewater.
Drinking water	Water that is supplied to a community for potable uses (including drinking, cooking, bathing, and other household uses) that meets the standards prescribed by the National Primary Water Regulations (40 CFR Part 141) of the U.S. Environmental Protection Agency and any applicable state or local regulations.
Engineered storage buffer	A storage facility used to provide retention time – before advanced treated water is introduced into the drinking water treatment facility or distribution system – to (1) conduct testing to evaluate water quality or (2) hold the water in the event that it does not meet specifications.
Environmental buffer	A groundwater aquifer or surface water reservoir, lake, or river into which advanced treated water is introduced before being withdrawn for potable reuse. In some cases, environmental buffers allow for (1) response time in the event that the advanced treated water does not meet specifications and (2) time for natural processes to affect water quality. Where tertiary effluent is applied by spreading, the environmental buffer provides both treatment and storage.
Finished water	Water produced by an advanced water treatment facility that also meets all federal, state, and local regulatory requirements for a drinking water treatment facility. Finished water can be introduced directly into a water supply distribution system.
Inactivation	Killing microorganisms or rendering them incapable of reproducing, thereby preventing their ability to cause illness.
Indirect potable reuse	The introduction of advanced treated water into an environmental buffer (e.g., groundwater aquifer, surface water reservoir) before being withdrawn for potable purposes (see also "*de facto* potable reuse"). Indirect potable reuse also can be accomplished with tertiary effluent when applied by spreading (i.e., groundwater recharge) to take advantage of soil aquifer treatment.

Term	Definition
Log (base 10) reduction	Log reduction corresponds to a reduction in the concentration of a constituent or microorganism by a factor of 10. For example, a 1-log reduction would correspond to a reduction of 90 percent from the original concentration. A 2-log reduction corresponds to a reduction of 99 percent from the original concentration.
Log (base 10) reduction credit	The number of credits assigned to a specific treatment process (e.g., microfiltration, chlorine disinfection, or ultraviolet disinfection), expressed in log units, for the inactivation or removal of a specific microorganism or group of microorganisms. A reduction of 90 percent would correspond to 1-log credit of reduction, whereas a reduction of 99 percent would correspond to 2-log credits of reduction.
Nonpotable reuse	A general term for all water reuse applications except those related to potable reuse.
Pathogen	A microorganism (e.g., bacteria, virus, *Giardia*, or *Cryptosporidium*) capable of causing illness in humans.
Public outreach	The process of communicating with and educating/informing the public on options and proposed plans for implementing potable reuse projects, as well as receiving input from the public, including questions and concerns that need to be addressed.
Public water system	A system used to provide the public with water for human consumption through pipes or other constructed conveyances, if such a system has at least 15 service connections or regularly serves at least 25 individuals; see Section 1401(4)(A) of the Safe Drinking Water Act.
Purified water	Some municipalities use the term "purified water" to refer to advanced treated water or finished water, especially in outreach and communication activities.
Redundancy	The use of multiple treatment barriers to attenuate the same type of constituent so that if one barrier fails, performs inadequately, or is taken offline for maintenance, the overall system still will perform effectively and risk is reduced.
Relative risk	Estimating the risks associated with a particular event for different groups of people.
Residuals	Waste streams and semisolids produced by wastewater treatment, advanced water treatment, and drinking water treatment processes.
Resilience	The ability to adapt successfully or restore performance rapidly in the face of treatment failures.
Risk	In risk assessment, the probability that something will cause injury combined with the potential severity of that injury.

Term	Definition
Robustness	The use of a combination of treatment technologies to address a broad variety of constituents and changes in concentrations in source water.
Safety	Practical certainty that a substance will not cause injury under carefully defined circumstances of use and concentration.
Source control	The elimination or control of the discharge of constituents into a wastewater collection system that can impact wastewater treatment, are difficult to treat, and can impair the final quality of the secondary-treated wastewater effluent entering the advanced water treatment facility.
Treatment reliability	The ability of a treatment process or treatment train to consistently achieve the desired degree of treatment, based on its inherent redundancy, robustness, and resilience.
Treatment train	A grouping of treatment technologies or processes to achieve a specific treatment or water quality goal or objective.
Wastewater characteristics	General classes of wastewater constituents, such as physical, chemical, and biological constituents.

Preface

P.1 Interest in Direct Potable Reuse

Planned potable reuse is a strategy used to augment public water supplies with highly treated municipal wastewater (or “advanced treated water”). One form of planned potable reuse is indirect potable reuse (IPR), in which treated wastewater is introduced into an environmental buffer (e.g., a groundwater basin or reservoir) before being withdrawn and used as a water supply. In the State of California, for example, IPR has been practiced for over 50 years. A second form of planned potable reuse is direct potable reuse (DPR), where advanced treated water is added directly into a water distribution system or into a raw water supply immediately upstream of a drinking water treatment facility. In water-scarce states like California, Arizona, New Mexico, and Texas, interest exists in implementing DPR projects to meet current and projected water demands and to develop sustainable, reliable local supplies of water.

Evaluation of Direct Potable Reuse for the State of California

In 2010, the California State Legislature signed into law SB 918, which required the State Water Resources Control Board (State Water Board) to report to the Legislature by December 31, 2016, on the feasibility of developing uniform water quality criteria for DPR. The legislative mandate is detailed in Sections 13560-13569 of the California Water Code.

Per the mandate, twelve water industry experts were appointed to an independent, third-party Expert Panel to provide advice and guidance to the State Water Board on the following:

- Public health issues and scientific and technical matters regarding the development of criteria for IPR using surface water augmentation.
- Public health issues and scientific and technical matters regarding the feasibility of developing criteria for DPR.
- What, if any, additional areas of research are needed for establishing criteria for DPR.

The Expert Panel on DPR was administered by the National Water Research Institute on behalf of the State Water Board. To fulfill its charge, the Expert Panel would need the most up-to-date information on current research and activities pertaining to DPR in the United States.

Direct Potable Reuse Research Initiative

The Water Environment & Reuse Foundation (WE&RF) (formerly, the WateReuse Research Foundation) and WateReuse California launched the DPR Research Initiative in 2012 to assist the State Water Board and its Expert Panel in fulfilling the legislative mandate to investigate the feasibility of developing uniform water quality criteria for DPR. For this effort, WE&RF invested in portfolio of research projects valued at over $24 million to investigate technical, operational, and managerial approaches and challenges as related to DPR.

Direct Potable Reuse Research Compilation (WRRF-15-01)

By 2015, a significant body of research information was available as a result of the DPR Research Initiative and other similar research efforts; however, the information was spread among them. Project WRRF-15-01, titled "DPR Research Compilation: Synthesis of Findings from DPR Initiative Projects," was undertaken in 2016 to summarize and synthesize the key issues and findings from this research to provide – in one comprehensive document – a clear understanding of the state-of-the-art and state-of-the-science on DPR and to identify unknowns that may require further research.

There specific goals for WRRF-15-01 included:

- Summarize and synthesize the key issues and findings from the research funded under the DPR Research Initiative, as well as the results of complementary research, to provide in a single, comprehensive document a clear understanding of the state-of-the-art and state-of-the-science on DPR and to identify unknowns that may require further research.
- Provide this information to the DPR Expert Panel sponsored by the State Water Board to evaluate the feasibility of developing uniform water recycling criteria for DPR in the State of California. Notably, the summarized information was presented to the Expert Panel prior to the Expert Panel submitting in August 2016 its report on the feasibility of developing uniform water quality criteria for DPR.[2]
- Make this information accessible to utilities and regulators in the United States and abroad interested in implementing DPR as a source of water supply.

Authors were selected to prepare nine synthesis papers for WRRF-15-01, which were prepared in time to provide input to the Expert Panel. The nine synthesis papers then were finalized and compiled into one report, which represents the final product of WRRF-15-01.

Conclusion of the Expert Panel on Direct Potable Reuse

Based on information provided by the DPR Research Initiative and many other resources, the Expert Panel concluded in its final report:

> "After a yearlong investigation, the Expert Panel finds it is feasible for the State of California to develop and implement a uniform set of water recycling criteria for DPR that would incorporate a level of public health protection as good as or better than what is currently provided in California by conventional drinking water supplies, indirect potable reuse (IPR) systems using groundwater replenishment, and proposed IPR projects using surface water augmentation" (Olivieri et al., 2016).

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[2] Olivieri, A.W., J. Crook, M.A. Anderson, R.J. Bull, J.E. Drewes, C.N. Haas, W. Jakubowski, P.L. McCarty, K.L. Nelson, J.B. Rose, D.L. Sedlak, and T.J. Wade (2016). *Expert Panel Final Report: Evaluation of the Feasibility of Developing Uniform Water Recycling Criteria for Direct Potable Reuse*. Submitted August 2016 by the National Water Research Institute for the State Water Resources Control Board, Sacramento, CA. http://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/rw_dpr_criteria.shtml (accessed 9/9/2016)

P.2 Development of this Report

This report represents a collection of "synthesis papers" that were written, edited, and peer reviewed by national experts and compiled into one document to address particular research topics or areas as related to DPR. The projects that were reviewed, the technical approach used to prepare the synthesis papers, and the organization of this report are described in this section.

Projects Reviewed

The projects reviewed for the preparation of this report, as summarized in **Table P-1,** cover a range of topics, including the reliability of treatment trains, microbial and chemical water quality, monitoring, and operations. WE&RF and/or the Water Research Foundation (WRF) provided funding for these projects.

Technical Approach

The National Water Research Institute (NWRI) provided administrative and editorial management of this effort, with assistance from Dr. George Tchobanoglous, who served as the technical lead and co-editor of the report. The approach used by NWRI and Dr. Tchobanoglous – with oversight from the Project Advisory Committee (PAC) and staff at WE&RF – to develop the synthesis papers and final report is described as follows.

Define the Topics of the Synthesis Papers

Based on the subject matter of the 34 projects, NWRI developed a draft list of topics to consider as the focus of the synthesis papers. This list was reviewed by the PAC and finalized to include the following:

- Source Control
- Evaluation of Potential Direct Potable Reuse Treatment Trains
- Pathogens (Surrogates and Credits)
- Pathogens (Rapid Continuous Monitoring)
- Risks and Removal of Constituents of Emerging Concern
- Critical Control Points
- Operation and Maintenance and Operator Training and Certification
- Failure and Resiliency
- Demonstration of Reliable, Redundant Treatment Performance

Table P-1: List of Research Projects Supported by the Water Environment & Reuse Foundation through the WateReuse Direct Potable Reuse Research Initiative

Project No.	Project Title	Principal Investigator(s)
WRRF-11-01	Monitoring for Reliability and Process Control of Potable Reuse Applications	Ian Pepper, University of Arizona
WRRF-11-02	Equivalency of Advanced Treatment Trains for Potable Reuse	R. Rhodes Trussell, Trussell Technologies, Inc.
WRRF-11-05	Demonstrating the Benefits of Engineered Direct Potable Reuse versus Unintentional Indirect Potable Reuse Systems	Glen Boyd, The Cadmus Group, Inc.
WRRF-11-10	Risk Reduction Principles for Direct Potable Reuse	Andrew Salveson, Carollo Engineers
WRRF-12-06	Guidelines for Engineered Storage for Direct Potable Reuse	Andrew Salveson, Carollo Engineers
WRRF-12-07	Methods for Integrity Testing of Nanofiltration and Reverse Osmosis Membranes	Joseph Jacangelo, MWH
WRRF-13-02	Model Public Communication Plan for Advancing Direct Potable Reuse Acceptance	Mark Millan, Data Instincts
WRRF-13-03	Critical Control Point Assessment to Quantify Robustness and Reliability of Multiple Treatment Barriers of Direct Potable Reuse Scheme	Troy Walker, Hazen & Sawyer
WRRF-13-12	Evaluation of Source Water Control Options and the Impact of Selected Strategies on Direct Potable Reuse	Alan Rimer, Black & Veatch
WRRF-13-13	Development of Operation and Maintenance Plan and Training and Certification Framework for Direct Potable Reuse Systems	Troy Walker, Hazen & Sawyer
WRRF-13-14 (WRF4508)	Assessment of Techniques to Evaluate and Demonstrate the Safety of Water from Direct Potable Reuse Treatment Facilities	Channah Rock, University of Arizona
WRRF-13-15 (WRF4536)	Blending Requirements for Water from Direct Potable Reuse Treatment Facilities	Andrew Salveson, Carollo Engineers
WRRF-14-01	Integrated Management of Sensor Data for Real Time Decision Making and Response	Jeff Neeman, Black & Veatch
WRRF-14-02	Establishing Additional Log Reduction Credits for Wastewater Treatment Plants	Zia Bukhari, American Water
WRRF-14-03	Develop Methodology of Comprehensive (Fiscal/Triple Bottom Line) Analysis of Alternative Water Supply Projects Compared to Direct Potable Reuse	Ben Stanford, Hazen & Sawyer
WRRF-14-08	Economics of Direct Potable Reuse	Robert Raucher, Stratus Consulting
WRRF-14-10	Enhanced Pathogen and Pollutant Monitoring of the Colorado River Municipal Water District Raw Water Production Facility at Big Spring, Texas	Eva Steinle-Darling, Carollo Engineers
WRRF-14-12	Demonstrating Redundancy and Monitoring to Achieve Reliable	R. Shane Trussell,

Project No.	Project Title	Principal Investigator(s)
	Potable Reuse	Trussell Technologies, Inc.
WRRF-14-13	From Sewershed to Tap: Resiliency of Treatment Processes for Direct Potable Reuse	Sharon Waller, Sustainable Systems, LLC.
WRRF-14-14	Framework for Public Health Monitoring: Workshop	Jeffrey Soller, Soller Environmental, LLC
WRRF-14-15	Application of Bioanalytical Tools to Assess Biological Responses Associated with Water at Direct Potable Reuse Facilities	To Be Determined
WRRF-14-16	Operational, Monitoring, and Response Data from Unit Processes in Full-Scale Water Treatment, Indirect Potable Reuse, and Direct Potable Reuse	Andrew Salveson, Carollo Engineers
WRRF-14-17	White Paper on the Application of Molecular Methods for Pathogens for Potable Reuse	Krista Wigginton, University of Michigan
WRRF-14-18	Ensuring Stable Microbial Water Quality in Direct Potable Reuse Distribution Systems	WRRF Workshop
WRRF-14-19	Predicting Reverse Osmosis Removal of Toxicologically Relevant Unique Organics	Kerry Howe, University of New Mexico
WRRF-14-20 (WRA-14-01)	Developing Direct Potable Reuse Guidelines	Jeffrey Mosher, National Water Research Institute
WRRF-15-01	Direct Potable Reuse Research Compilation: Synthesis of Findings from Direct Potable Reuse Initiative Projects	Jeffrey Mosher, National Water Research Institute
WRRF-15-02	Creating a Roadmap for Bioassay Implementation in Reuse Waters: A Cross Disciplinary Workshop	WRRF Workshop
WRRF-15-04	Characterization and Treatability of Total Organic Carbon from Direct Potable Reuse Processes Compared to Surface Water Supplies	Larry Schimmoller, CH2M
WRRF-15-05	Developing Curriculum and Content for Direct Potable Reuse Operator Training	Ben Stanford, Hazen & Sawyer
WRRF-15-07	Molecular Methods for Measuring Pathogen Viability/Infectivity	To Be Determined
WRRF-15-10	Optimization of Ozone/Biologically Activated Carbon Treatment Processes for Potable Reuse Applications	Zia Bukhari, American Water
WRRF-15-11	Demonstration of High Quality Drinking Water Production Using Multi-Stage Ozone-Biological Filtration: A Comparison of Direct Potable Reuse with Existing Indirect Potable Reuse Practice	Kati Bell, CDM Smith, and Denise Funk, Gwinnett County Department of Water Resources
WRRF-15-13	N-Nitrosodimethylamine (NDMA) Precursor Control Strategies for Direct Potable Reuse	Roshanak Aflaki, Los Angeles Sanitation

Select Lead Authors

Potential lead authors for each topic were identified based on a number of factors, including expertise, availability, and the balance and diversity of authors. Where possible, the Principal Investigators of the 34 projects were not selected as lead authors of topics where they would be reviewing their own research projects. The final list of lead authors selected by NWRI (as listed in **Table P-2**) was based on input from the PAC and WE&RF.

Table P-2: List of Authors for WRRF-15-01 by Topic

No.	Topic	Lead Author	Co-Authors
1	Source Control	Robert W. Emerick	
2	Evaluation of Treatment Trains	Larry Schimmoller	Jim Lozier Ufuk Erdal
3	Surrogates and Log Reduction Credits	Philip Brandhuber	
4	Pathogen Monitoring	Channah M. Rock	Daniel Gerrity Dametreea Carr
5	Constituents of Emerging Concern	Jean Debroux	Laura Kennedy Megan H. Plumlee
6	Monitoring DPR Systems and Critical Control Points	Andrew Salveson	Eva Steinle Darling
7	Operation and Maintenance, and Operator Training and Certification	Debra L. Burris	
8	Resilience in Potable Reuse	Brian Pecson	Sarah Triolo
9	Reliable, Redundant Treatment Performance	Ben Stanford	

Provide a Format for the Synthesis Papers

To guide the authors in their efforts, NWRI's editorial team developed a standardized format for the synthesis papers. The standardized format also included input from the PAC and consideration of the format of prior WE&RF reports. To provide the reader with a consistent overview of a particular topic, each synthesis paper opens with the same two headings:

- Principal issues.
- Findings presented in two parts: (1) what is known and (2) what is unknown.

Prepare the Draft Synthesis Papers

Drafts of the synthesis papers were prepared by the authors in time to provide input into the DPR Expert Panel, which was engaged in completing its own report to the Division of Drinking Water of the State Water Board by August 2016.

Prepare the Final Report

This report, prepared by NWRI's editorial team, represents a compilation of the individual synthesis papers. Its organization is described in this section.

Report Organization

To make the results of the synthesis papers readily accessible to interested readers, this report is divided into two parts:

- **Part I** is an extended executive summary addressing all nine synthesis papers. Each paper is summarized individually, providing a brief introduction followed by the principal issues and findings. The intent is to provide a comprehensive overview so that readers can readily compare and contrast the state-of-science for each topic.
- **Part II** contains the full text of each synthesis paper, along with references to the WE&RF and WRF projects reviewed and other literature cited.

Notably, the chapter numbers in **Part I** are consistent with the chapter numbers in **Part II** to make it easier to cross-reference the summaries with their corresponding synthesis papers.

Overall Goal

The goal of this report is to serve as an accessible resource to communities and decision-makers seeking more information on DPR, provide practical information to utilities and municipalities implementing DPR projects, inspire continued advancements and innovation in DPR research and technology, and promote a better understanding of the value, needs, and challenges associated with using DPR to provide a safe, reliable source of drinking water.

Part I: Extended Executive Summary

Because the issues and findings of the nine synthesis papers cover a wide range of topics, it is not possible to prepare a conventional executive summary in which a select number of key items are highlighted. Rather, an extended summary format is used in **Part I** in which each synthesis paper is summarized individually. The summary includes a brief introduction of the topic addressed, followed by the principal issues and findings. The full text for each synthesis paper, with corresponding chapter numbers, is presented in **Part II**.

ES-1. Source Control Program

Prepared by Robert W. Emerick, Ph.D., P.E., Robert Emerick Associates

The primary sources of chemical contaminants in wastewater include: (1) discharges from residences, businesses, and industries; (2) corrosion within the potable water distribution system; (3) the potable water supply; (4) stormwater; and (5) treatment processes for drinking water and wastewater. Because of the diversity of these sources, the organic and inorganic constituents found in wastewater can vary. Keeping constituents of concern out of the wastewater system through a robust source control program can be the most beneficial, efficient, and cost-effective strategy for managing and treating industrial, commercial, and other contributions to the wastewater supply; therefore, when pursuing and planning for direct potable reuse (DPR), it is crucial to implement a rigorous source control program in conjunction with other applicable programs, such as the National Pretreatment Program (NPP), to eliminate or control the discharge of constituents that might impact the production of advanced treated water.

The NPP was established as part of the Clean Water Act to control and regulate the discharge of pollutants to surface water by commercial and industrial dischargers of wastewater. Although the NPP has reduced the discharge of many constituents that are difficult to manage from a treatment and environmental standpoint, it has not eliminated the discharge of such constituents. To date, the NPP is directly applicable only to effluents discharged to surface waters. For wastewater agencies not subject to the NPP, local, state, or federal permitting authorities may not, in some cases, require a publicly owned treatment works to implement an approved pretreatment program or a program that meets all federal requirements; however, any wastewater agency that intends to operate a DPR project should develop a source control program as the first barrier to protect the quality of advanced treated water, even if it is not a permit requirement.

Identified key issues and a summary of principal findings related to the implementation of source control for DPR are presented below. The full text, including all reference materials, is presented in **Chapter 1** of **Part II**.

1.1 Identification of Key Issues

Key issues that should be considered in the development of source control programs for DPR include:

- Identifying sources of toxic compounds entering the sewershed from point sources that can be managed readily.
- Identifying and inventorying contaminant sources (e.g., stormwater and potable water supply chemical quality) in addition to those from commercial businesses and industries located within the sewershed.
- Identifying contaminants [e.g., corrosion, salinity, metals, N-nitrosodimethylamine (NDMA) or its precursors, Bis(2-ethylhexyl) phthalate, bromate, and other disinfection byproducts (DBPs) or their precursors] that may be formed within the potable water system or wastewater system or as part of treatment.

- Determining the most cost-effective means (e.g., source control, treatment) for removing each specific contaminant.

1.2 Summary of Principal Findings

The following principal findings are derived from a review of national and state regulations, as well as the experience of ongoing source control programs. Each topic area is considered in detail in **Chapter 1** of **Part II**.

1.2.1 What Is Known?

- The NPP has been successful when applied to its target objective: medium-sized to large-sized wastewater treatment plants (WWTPs) discharging to surface water. The NPP also has improved opportunities to recycle and reclaim municipal and industrial wastewaters and biosolids.

- Contaminant sources that exist beyond direct discharges by commercial businesses and industries can be controlled directly by the NPP.

- Considerable experience and knowledge has been developed and is available on the implementation of effective source control programs in a variety of settings, including municipalities and special sanitary districts.

- Although beneficial, the NPP has not eliminated pollutant loadings from industrial sources. Nor was it developed with the intent to regulate at trace levels. If a surface water discharge is not the aim of the treatment facility (e.g., protecting groundwater is a State-regulated responsibility and outside the jurisdiction of the Clean Water Act), the NPP may not be statutorily applicable. The NPP should be a key element of any DPR project and may require modifications to address the regulation of trace contaminants associated with DPR projects.

- Regional discharges of wastewater and stormwater – to both surface water and groundwater – require regulation in a holistic manner. Ultimately, wastewater that is disposed into the environment may impact potable water supplies that are downstream (with regards to surface water) or downgradient (with respect to groundwater).

- In many regions of the United States, DPR projects (i.e., the development of new potable water supplies) may be needed to sustain economic output. The most advantageous and cost-effective methods should be considered to eliminate contaminants. It may be more advantageous and cost effective to prevent the introduction of or treat specific contaminants at the source rather than dilute those contaminants through discharge into a collection system. Conversely, it might be more cost effective to construct more robust treatment at a downstream or downgradient central location, taking advantage of economies of scale.

1.2.2 What Is Unknown?

Although much is known about the implementation of source control programs, as the adoption of DPR becomes more widespread, additional benefits can be derived from research investigations to: (1) identify key regulatory indicators and develop corresponding cost-allocation approaches; (2) develop anti-degradation and pollutant trading options; and (3) optimize treatment process development.

- Consideration should be given to develop additional indicators and regulations to address concerns related directly to trace concentrations of contaminants applicable to DPR projects. Commercial businesses and industries are regulated routinely on items such as biochemical oxygen demand (BOD), total suspended solids, flow, and sulfate on a financial basis to fund centralized collection and/or treatment needs or to prevent corrosion-based deterioration. This approach encourages businesses and industries to evaluate whether a discharge to the wastewater system is more or less cost effective than preventing a discharge at the source. Likely, a similar approach would be effective for trace contaminants applicable to DPR projects.

- Regulations should be developed and implemented to account for the impacts that discharges can have on far downstream (or downgradient) water-short regions. Regions that make use of DPR projects, by definition, are water short, and their potable water supplies often originate far from the community generating the wastewater that will be the source of a DPR project. For example, water that is “discharged to land” is regulated; therefore, it undergoes treatment far differently than water that is percolated to groundwater as part of indirect potable reuse (IPR), although both treatment requirements are intended to protect the beneficial uses of potable water.

- Research is needed to quantify the specific process modifications appropriate for DPR projects. These modifications should account for the eventual need to implement DPR projects. Often, treatment systems for producing water suitable for DPR are modified treatment systems originally intended for wastewater discharge to land or surface water dispersal facilities. Because regulatory requirements associated with dispersal systems can differ markedly from DPR treatment systems, the chemicals used as part of treatment – and even the treatment process itself – can impact source water quality. Salinity, NDMA, aluminum, recalcitrant organic nitrogen, bromate, and other DBPs have been found to increase in concentration owing to the use of specific treatment processes.

ES-2. Evaluation of Potential Direct Potable Reuse Treatment Trains

Prepared by Larry Schimmoller, P.E., Jim Lozier, P.E., and Ufuk Erdal, Ph.D., P.E., CH2M

Many advanced water treatment processes that have been investigated and applied at full-scale IPR projects will be appropriate for DPR projects. Currently, a number of IPR plants in California employ advanced water treatment facilities (AWTFs) that include the following treatment barriers: microfiltration (MF), reverse osmosis (RO), and ultraviolet (UV) disinfection with advanced oxidation processes (AOPs). Although most full-scale potable reuse projects have provided multiple barriers to pathogens and organics, the specific treatment technologies employed at each treatment plant vary depending on local regulations and site-specific requirements. For example, California's IPR regulations for subsurface injection require the use of RO and limit the concentration of total organic carbon (TOC) in advanced treated water to 0.5 milligrams per liter (mg/L). Conversely, the chemical oxygen demand (COD) limits for projects in Virginia and Georgia have resulted in non-RO based treatment trains, which can be more suitable for inland locations.

Although potable reuse guidelines have been developed by the U.S. Environmental Protection Agency (USEPA) and were updated in 2012, no federal regulations currently exist for DPR. At present, the 2012 guidelines are being revised, with an expected publication date of late 2016 or early 2017. Potable reuse regulations, which have been developed by only a handful of states and only for IPR, vary in specific requirements. Typically, the selection of treatment processes is driven by several common regulatory requirements: (1) low bulk organic limits (e.g., TOC, COD); (2) requirements for pathogen log reduction; and (3) the use of multiple treatment barriers to control pathogens and chemicals, including trace organics. Regulatory requirements in California that have driven the selection of treatment processes include the following: 12-log reduction for enteric viruses, 10-log reduction of *Cryptosporidium*, and 9-log reduction of total coliform bacteria, measured from raw wastewater to finished water suitable for drinking. An Expert Panel that was convened to assess the feasibility of DPR concluded in 2016 that these criteria would ensure the advanced treated water would be free of pathogenic microorganisms and, therefore, could be used safely for potable purposes.

Identified key issues and a summary of principal findings related to the evaluation of potential DPR treatment trains are presented below. The full text, including all reference materials, is presented in **Chapter 2** of **Part II**.

2.1 Identification of Key Issues

Treatment processes appropriate to the specific DPR project must be evaluated and selected to ensure the production of water quality that is protective of public health. Identifying the appropriate treatment train is a complex task that involves:

- Full characterization of the source water (i.e., raw wastewater), including diurnal variations in flows and loads, as well as an evaluation of the source water control program.

- Evaluation of the design and operation of the WWTP, including conditions that can cause a plant upset and degradation of feedwater quality at the AWTF.

- Identification of finished water quality goals, including specific regulatory requirements for DPR and site-specific aesthetic requirements [e.g., total dissolved solids (TDS), hardness, color].

- Identification of multiple treatment barriers to pathogens and bulk and trace organics to meet regulatory requirements and specific finished water quality goals.

- Determination of treatment process reliability criteria, including the ability of treatment processes to properly treat upsets at the WWTP.

- Identification of waste disposal constraints, including site-specific limitations that may exist for the disposal of waste streams with elevated salinity (i.e., RO concentrate).

- Determination of space constraints for the construction of treatment processes.

- Estimation of capital and operating costs, as well as other triple bottom line factors.

Though all these issues can significantly influence the design and construction of an AWTF, regulatory requirements, source water quality, and the need for multiple treatment barriers to pathogens and organics have the largest impact on the selection of treatment processes for potable reuse.

2.2 Summary of Principal Findings

The following discussion of what is known and unknown about DPR treatment technology is based on regulatory considerations, selection of DPR treatment trains, pathogen removal, trace organics and chemical contaminant removal, and other water quality considerations affecting treatment. Each topic area is considered in detail in **Chapter 2** of **Part II**.

2.2.1 What Is Known?

- In the United States and abroad, most full-scale potable reuse projects provide multiple barriers to pathogens and organics.

- Specific treatment technologies employed at AWTFs vary depending on local regulations and site-specific requirements.

- At present, meeting low regulatory limits (or customer-dictated limits) for TOC (e.g., <0.5 mg/L) will require the use of RO. Alternative technologies, such as ozone/biological activated carbon (BAC) or granular activated carbon (GAC), often can be used at locations with higher limits for TOC (e.g., 2 to 3 mg/L).

- Non-RO based AWTFs are more suitable for inland locations where the disposal of RO concentrate is expensive and environmentally challenging.

- Because the analysis time for biological tests is long, engineered storage buffers (ESBs) of sufficient retention time may be needed to directly confirm suitable microbial quality.

- California's pathogen log reduction requirements for potable reuse are based on conservative maximum values in raw wastewater, derived from a review of the literature, with limited removal credited for wastewater treatment.

2.2.2 What Is Unknown?

- Can improved testing techniques for RO integrity be developed to demonstrate and, ultimately, make it possible to receive higher log reduction credits for RO, which could result in fewer treatment processes or modified operating and monitoring requirements?
- Can the need for MF or ultrafiltration (UF) treatment be eliminated if proper membrane integrity testing can be developed and demonstrated for membrane bioreactors (MBRs)? With MBRs, tertiary MF or UF membranes (which often are employed as pretreatment upstream of RO at AWTFs) may be unnecessary if suitable integrity testing methods can be developed and demonstrated for MBR systems.
- Can the need for an ESB be eliminated by providing additional log reduction credits through the use of additional treatment processes?
- Can standardized techniques be developed to establish log reduction credits for advanced water treatment processes?
- Can advanced techniques (e.g., TRASAR® technology,[3] high-resolution online particle counting, real-time detection through multi-angle light scattering) be developed to obtain higher log reduction credits for potable reuse treatment processes?
- Because the current bulk organic surrogate measures (e.g., TOC, COD) for the control of trace organic compounds (TrOCs) do not reflect the toxicity caused by the presence of TrOCs and the safety of advanced treated water, can alternative measures be developed?
- Is TOC an appropriate surrogate to ensure the safety of advanced treated water relative to TrOCs? Are newer systems that target specific fractions of TOC (such as the trihalomethane-like TrOCs) more appropriate?
- Can online biosensing be improved to allow its use for full-scale application?
- Do short-term *in vitro* toxicity analyses adequately reflect the toxicity risks of a lifetime consumption of water produced by DPR?

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[3] A product of Nalco Water, 3D TRASAR Technology® is used to detect upsets that precede scaling, corrosion, and biofouling of reverse osmosis membranes, and then delivers the appropriate chemical response. http://www.nalco.com/services/3d-trasar.htm.

ES-3. Surrogates and Log Reduction Credits for Pathogens

Prepared by Philip Brandhuber, Ph.D., HDR, Inc.

Because the protection of human health from the harmful effects of pathogenic microorganisms is crucial for the successful implementation of DPR, the following three issues must be addressed: (1) the selection of pathogenic microorganisms and microbial indicators; (2) the establishment of acceptable risk-based levels and ensuing log reduction requirements for pathogenic microorganisms; and (3) the establishment of technology-based log reduction credits for various treatment processes. When implementing a risk-based approach, consideration must be given to the inherent uncertainties in quantifying the levels of pathogens in water, as well as the different outcomes and consequences of human exposure to these pathogens.

Given the large number of pathogens that can survive in water, selecting suitable techniques for monitoring concentrations is inherently difficult. For this reason, much effort has been focused on developing indicators (i.e., easily detectable microorganisms representative of a broader microbial group of interest) or surrogates (i.e., bulk parameters capable of measuring treatment performance). During the development of the Surface Water Treatment Rule under the Safe Drinking Water Act, the USEPA concluded that for pathogenic microorganisms, a 10^{-4} annual risk of infection represents a tolerable risk. Hence, finished drinking water produced from wastewater sources should pose a risk of no greater than one infection in 10,000 persons per year. Given that risk levels exist for various microorganisms, log reduction values must be developed that can be used for the design of AWTFs such that the sum of validated log reduction/inactivation credit for the individual treatment processes must be equal to or exceed the log reduction values needed to protect human health.

Identified key issues and a summary of principal findings related to surrogates and log reduction credits for DPR are presented below. The full text, including all reference materials, is presented in **Chapter 3** of **Part II**.

3.1 Identification of Key Issues

While current state-of-the-art treatment is capable of producing finished water from wastewater sources that is protective of human health, improvements can be made in the following areas:

- Methods to rapidly determine the concentration of relevant pathogens throughout treatment trains or, in the absence of such capabilities, suitable real-time surrogates capable of doing the same.
- Greater understanding of pathogen levels in raw wastewater and their inactivation/removal by individual and integrated treatment processes at AWTFs.
- Improved methods to verify pathogen inactivation and/or reduction so that the full capabilities of treatment technologies are reflected in their log reduction or inactivation credits.

- Improved methodologies to ensure treatment reliability is maintained through a combination of redundancy, robustness, and resilience.

3.2 Summary of Principal Findings

The following principal findings are derived from a review of literature and state regulations addressing pathogenic microorganisms found in wastewater and their reduction through various treatment processes. Each finding is considered in detail in **Chapter 3** of **Part II**.

3.2.1 What Is Known?

- No single pathogen, indicator, or surrogate can be used to gauge the microbial safety of water. Safe water can be ensured only by meeting multiple treatment objectives and measuring appropriate performance indicator parameters.

- A wide range of information is available regarding pathogen treatment credits for either chemical inactivation (disinfection) or physical separation (removal).

- Available information is sufficient to design multi-barrier advanced treatment systems capable of meeting the log reduction requirements for (1) virus, *Cryptosporidium*, and *Giardia* for groundwater injection that are considered protective of human health by the Division of Drinking Water of the California State Water Resources Control Board or (2) virus, *Cryptosporidium*, and total coliform log reduction for DPR recommended by an Independent Advisory Panel administered by the National Water Research Institute.

- Improvements in microbial detection methods will be important in expanding the existing knowledge base concerning the occurrence of pathogens in untreated wastewater and to help improve the design and operation of WWTPs. This information may lead to refinements in log reduction requirements or log reduction credits associated with specific treatment processes.

3.2.2 What Is Unknown?

- More information is needed about the occurrence of infectious microorganisms in untreated wastewater and the variables affecting such occurrences.

- Additional information and data are needed to define the actual levels of inactivation and/or reduction of these microorganisms by different treatment processes.

- A better understanding is needed of the possible transfer of pathogenicity from inactivated cells to benign cells through genetic exchange and the possible reactivation of pathogenic cells after UV irradiation through DNA repair.

- Concerns about pathogenic microorganisms are not unique to DPR scenarios and could apply to the treatment of other sources of water (e.g., shallow groundwater, surface water, etc.).

ES-4. Rapid and Continuous Monitoring of Pathogens

Prepared by Channah M. Rock, Ph.D., University of Arizona; Daniel Gerrity, Ph.D., University of Nevada, Las Vegas; and Dametreea Carr, University of Arizona

Pathogen and indicator monitoring are key issues for DPR, specifically in determining if treatment process performance is sufficient to achieve stringent public health criteria. For drinking water applications, public health protection is attained when pathogen levels are below the concentrations associated with target risk thresholds. Microbiological detection methods can be divided into several categories, including visual detection by microscopy, standard culture methods, biochemical assays, cell culture-based methods, molecular biology-based methods, immunological assays, and biosensors, among others. Each method has varying characteristics that can be useful for detecting bacteria, protozoa, and/or viruses in water intended for DPR. When attempting to detect pathogens and indicators, a variety of monitoring techniques must be considered because no single technique can include all the desired monitoring traits.

The verification of target pathogen concentrations is challenging because of limited online, real-time monitoring technologies. Not only are these technologies limited in number, but also they are costly, lack high sensitivity, and are not highly selective in distinguishing slight differences between closely related species or strains [e.g., pathogenic versus non-pathogenic *Escherichia coli* (*E. coli*)]. While a number of rapid and continuous monitoring techniques are being examined for the detection of pathogens, indicators, and surrogates with respect to sensitivity, specificity, and time, online pathogen monitoring technologies are not ready for implementation in DPR applications. Emerging monitoring technologies include advanced molecular assays and biosensors. Standard molecular assays employ the detection of DNA or RNA using Polymerase Chain Reaction (PCR) to amplify very low concentrations of genetic material to a detectible range, but are unable to distinguish between viable and non-viable microorganisms without additional tests. Biosensor technologies are improving, but current challenges include nonspecific binding, particle size variation, aggregation of nanoparticles, and the inability to differentiate viable from non-viable organisms.

Identified key issues and a summary of principal findings related to the rapid and continuous monitoring of pathogens are presented below. The full text, including all reference materials, is presented in **Chapter 4** of **Part II**.

4.1 Identification of Key Issues

With online pathogen monitoring technologies still in the early phases of development, the industry has not yet determined the practicality of detecting pathogens within sufficient time constraints and to the sensitivity needed to achieve specific risk benchmarks. Moreover, it is not clear whether such goals are necessary if robust treatment alternatives are employed. Key issues with respect to pathogen monitoring include the following:

- Rapid and continuous online monitoring for pathogen detection remains challenging due to small particle size, method sensitivity (including limits with detection and quantification), and the low concentrations of pathogens in advanced treated water, particularly with respect to verifying risk benchmarks (e.g., 10^{-4} annual risk of disease).

- Currently, limited options are available for rapid online pathogen monitoring, with several technologies in the developmental stages.

- It is difficult to detect viruses in water due to their small size and the lack of highly sensitive technologies. This difficulty limits the log reduction credits awarded to potentially robust barriers, such as low-pressure and high-pressure membrane filtration. Consequently, many technologies have focused on bacteria or the detection of suspect "particles."

- Ideal monitoring systems include the following characteristics: high specificity, rapid/real-time online capability, high sensitivity, high accuracy (i.e., minimal false positives and false negatives), high robustness with low failure rates, simplicity, and affordability for operation and maintenance.

- Given the high pathogen loading and decreased response times of DPR systems, monitoring of pathogens or robust surrogates may be critical to ensure the successful implementation of DPR projects.

4.2 Summary of Principal Findings

As existing and emerging pathogen monitoring technologies are evaluated and demonstrated (i.e., accuracy, sensitivity, etc.), their use in DPR treatment trains will become routine. Until then, the industry must rely on the use of robust indicators/surrogates for water quality evaluation, as well as treatment process validation.

4.2.1 What Is Known?

- Historically, total coliform bacteria and fecal coliform bacteria have been used as indicators of fecal contamination in drinking water applications and are monitored to demonstrate compliance with the Total Coliform Rule established by the USEPA.

- From a historical perspective, indicator monitoring has proven sufficient for validating the operations of conventional drinking water treatment facilities (DWTFs).

- Direct monitoring of protozoan pathogens, such as *Giardia* and *Cryptosporidium*, is problematic because the methods require extensive sample preparation and highly skilled technicians. A laboratory analysis of protozoan pathogens can take multiple days to complete.

- Although several real-time pathogen monitoring technologies are promising, none are ready for implementation in DPR applications.

- The potable reuse industry places a strong emphasis on critical control point (CCP) verification with surrogate parameters to ensure the integrity of unit treatment processes and to justify pathogen reduction credits. CCP verification is necessary and required regardless of the availability and use of pathogen monitoring technologies.

- Despite being unable to replicate outside of their hosts, viruses have a greater ability to persist in treated water than bacteria due to their small size and the resistance of some viruses to certain disinfection processes.

- The principal categories of detection methods for microorganisms are visual detection by microscopy, standard culture methods, biochemical assays, cell culture-based methods, molecular biology-based methods, immunological assays, and biosensors.

- Until adequate pathogen monitoring technologies are available, DPR systems will have to employ treatment trains composed of multiple treatment barriers to achieve reliability through robustness, redundancy, and resiliency.

- By employing a hazard analysis and critical control point (HACCP) framework, coupled with stringent public health criteria and sufficient degrees of conservatism (i.e., limits on pathogen credits awarded), DPR is expected to achieve adequate protection of public health even in the absence of advanced pathogen monitoring technologies.

4.2.2 What Is Unknown?

- The usefulness of emerging indicator viruses, such as Aichi, Calicivirus, and Pepper Mild Mottle Virus, for monitoring the performance of aquifer recharge, MF, and RO for virus removal is not well documented.

- The specificity and reliability of biosensors that recognize biological components ranging from a specific surface protein, antigens, enzymes, antibodies, receptors, DNA, cell components, or even the whole cell or organism by amplifying the detection of a specific target into a detectable signal are unknown.

- Problems with biosensor technologies that must be resolved include the impacts of nonspecific binding, particle size variation, aggregation of nanoparticles, and inability to differentiate viable from non-viable organisms.

- Both the sensitivity (i.e., the ability to detect very few organisms in a sample) and selectivity (i.e., the ability to distinguish slight differences between closely related species or strains) of a proposed biosensing technology must be established before it can be used.

ES-5. Risk and Removal of Constituents of Emerging Concern

Prepared by Jean Debroux, Ph.D., and Laura Kennedy, Kennedy/Jenks Consultants; and Megan H. Plumlee, Ph.D., P.E., Orange County Water District

Although anthropogenic compounds have been detected in wastewater for several decades, their occurrence was brought to the attention of the water industry and public by a major study conducted by the U.S. Geological Survey in 2002. Since then, a wide variety of wastewater-derived organic compounds have been quantified in water, including ingredients in pharmaceuticals and personal care products (PPCPs), industrial chemicals, natural and synthetic hormones, DBPs, and others. The majority of these compounds are not regulated in drinking water by the USEPA, meaning there is no maximum contaminant limit and no requirements to monitor their occurrence, though they may be regulated individually at the state level. The term “constituents of emerging concern” (CECs) is used to refer to these unregulated organic compounds, and may be extended to include other unregulated constituents found in water, such as trace metals, pathogens, and nanomaterials.

Over 400 CECs have been identified in wastewater effluent and, likely, many more are present. These compounds also have been detected in traditional drinking water and water sources. Both public and scientific concerns over the presence of CECs in potable water are due to the potential human health effects of these compounds. Unlike microbial risk (which is acute), the risk for CECs is chronic and typically based on a lifetime of exposure. The greatest potential risk appears to be due to hormonally active compounds and carcinogens that can be active at very low concentrations. Many uncertainties remain, however, because risk assessment is based on a complex process that involves four steps (i.e., hazard identification, dose-response assessment, exposure assessment, and risk characterization, which requires many assumptions). Of the wide range of potentially present CECs, the actual risk to human health is likely to be insignificant in advanced treated water, based on the technologies used at AWTFs.

Identified key issues and a summary of principal findings related to the risk and removal of CECs are presented below. The full text, including all reference materials, is presented in **Chapter 5** of **Part II**.

5.1 Identification of Key Issues

CECs in drinking water and sources of drinking water are of concern to the public and water industry. Key issues (grouped according to occurrence, treatment, and risk), current understanding and information gaps, and additional background and justification are provided in **Chapter 5** of **Part II**.

5.1.1 Occurrence

- CECs, their metabolites, and unregulated oxidation/disinfection byproducts are present in secondary- and tertiary-treated wastewater effluents throughout California, the United States, and other industrialized nations.

- Due to continuing advances in analytical chemistry in water monitoring, more CECs will be identified in the future, new CECs will emerge, and previously identified CECs may disappear, based on the use of specific chemicals by society.

5.1.2 Treatment

- No single treatment process (or combination of treatment processes) exists that is capable of removing all CECs from water. Various unit treatment processes used in conventional drinking water treatment, wastewater treatment, and advanced treatment for reuse have different efficacies in removing CECs.

- Nevertheless, advanced water treatment involving RO has been shown to remove the majority of known CECs to below the very low detection limit ranges of nanograms per liter (ng/L) to sub-ng/L.

5.1.3 Risk

- The risks associated with CECs likely will come from very few contaminants, as reported in prior risk assessment studies that evaluated a wide range of CECs and ultimately concluded only a limited number of CECs require monitoring.

- For certain California communities, public perception of the risks associated with CECs is greater than the actual risk, as indicated by public surveys conducted before and after education about the (low) risk of being exposed to or consuming advanced treated water.

5.2 Summary of Principal Findings

The principal findings related to CECs with respect to occurrence, treatment, and risk are discussed in this section.

5.2.1 Occurrence of Constituents of Emerging Concern

5.2.1.1 What Is Known?

- Depending on the level of treatment, a wide variety of anthropogenic contaminants have been found in treated wastewater, including pharmaceuticals, ingredients in personal care products, industrial chemicals, and others. Over 400 non-regulated organic compounds have been identified in secondary-treated water in the United States.

- The concentrations of CECs found in secondary-treated wastewater effluents generated from municipal wastewater are low [sub-ng/L to microgram per liter (µg/L)] as compared to the concentrations of regulated drinking water constituents (µg/L to mg/L).

- The total concentration of CECs measured in advanced treated water is relatively small compared to the measured TOC because TOC also includes natural organic matter and effluent organic matter.

- CEC occurrence is not limited to planned potable reuse. For example, recently published summary data from 61 published reports or scientific articles indicate that PPCPs and endocrine disrupting compounds are found in finished drinking waters within the United States.

5.2.1.2 What Is Unknown?

- Many contaminants have yet to be identified. For example, artificial sweeteners (e.g., sucralose, acesulfame-K) can be found in treated wastewater at up to µg/L levels, but were not identified until 2010. Additionally, as detection limits decrease, contaminants that have been present for years will be identified. Because water analysis methods are designed to target known compounds, it is not known how many unidentified CECs may be present in a given water sample, which is a recognized shortcoming of current analytical capabilities. To address this issue, “indicator” compounds thought to coincide with unknown CECs are included in monitoring programs; their removal is taken as evidence for the removal of unknown CECs as well. Furthermore, research is ongoing for new methods (e.g., bioanalytical tools, non-targeted chemical analysis) that aim to measure these unknown CECs or their potential risks.

- Contaminants enter the WWTP from the collection system, and some are degraded partially during the biological process. Rarely are the metabolites identified and quantified, yet they are part of the universe of unknown CECs. Similarly, contaminants can be altered chemically during oxidation/disinfection processes, and these unregulated oxidation/DBPs rarely are identified and quantified.

5.2.2 Removal of Constituents of Emerging Concern during Treatment

5.2.2.1 What Is Known?

- No single treatment process currently exists that removes all known CECs; therefore, combinations of processes in sequence must be employed to maximize the removal of CECs.

- Conventional biological, chemical, and physical processes used in wastewater treatment are not designed to remove CECs, and the removals at these facilities range from “nearly complete” to “very little” depending on the chemical properties of the CEC.

- It has been found that the combination of processes used in an AWTF, including RO, can remove the majority of measurable CECs to below currently detectable levels, which typically are in the range of ng/L to sub-ng/L. An example AWTF treatment train with RO may consist of MF or UF followed by RO and UV light in conjunction with an oxidant termed the “advanced oxidation process”; however, after treatment, some very low levels of CECs and TOC could remain.

- Alternative treatment process trains to the AWTF that do not involve RO also can effectively remove CECs, although low levels of non-oxidizable CECs and TOC remain. An example of an alternative AWTF treatment train would include ozone and biologically active carbon which, in combination, have been shown to reduce CECs significantly.

5.2.2.2 What Is Unknown?

- The fate of contaminants altered by oxidation (e.g., chlorination, ozonation) or partial degradation (e.g., biological treatment, biologically active carbon) is not well understood because fate studies require knowing the product compound identities and having analytical capabilities for measuring them. In many cases, this transformation of CECs is measured as removal (e.g., the reduction of concentrations of parent compounds across the treatment process), but the product compounds are not known and not measured. This issue is addressed partially by combining several treatment processes into a treatment train (i.e., product compounds – albeit unmeasured – may be removed in subsequent treatment steps).

- Research on suitable monitoring tools (e.g., sensors, online, and high-frequency measurements) and surrogates or indicators for CECs is underway, but not complete. This research is needed to confirm online treatment performance for the removal of CECs.

5.2.3 Human Health Risks Associated with Constituents of Emerging Concern in Direct Potable Reuse

5.2.3.1 What Is Known?

- Multiple studies have been conducted on the occurrence and toxicological relevance of CECs in advanced treated water. As a result, data are available for CECs in advanced treated water following different treatment processes, and the toxicity of many CECs can be evaluated using established risk assessment methodologies. Because this area of research is active and growing, information regarding occurrence and toxicity will continue to evolve.

- Lists of specific CECs with human health relevance have been developed considering both occurrence and toxicity:

    - A Science Advisory Panel convened by the California State Water Resources Control Board identified a list of CECs for monitoring for IPR.

    - For DPR, an Independent Advisory Panel administered by the National Water Research Institute developed a list of CECs that was included in WRRF-11-02. Three categories of CECs were identified: (1) DBPs; (2) unregulated chemicals with potential health risks; and (3) compounds to evaluate treatment effectiveness (i.e., surrogates).

    - Although the specific CECs may vary slightly depending on the methodology used to develop the list, a limited number of CECs have been identified as potentially posing a risk to human health.

- Risk-based levels can be derived for CECs based on existing toxicity data and drinking water exposures (same as those used by the USEPA to derive Drinking Water Equivalent Levels).

- CECs have not been detected in advanced treated water from AWTFs using RO at concentrations above the risk-based criteria used in studies that have evaluated the potential health effects of CECs.

5.2.3.2 What Is Unknown?

- Potential risks to sensitive sub-populations are not well understood. For example, additional research is needed on the potential effects of low levels of CECs (in particular, endocrine disrupting compounds) on fetuses and infants during critical developmental windows.

- Potential risks from any additive or synergistic effects of the mixtures of CECs present in potable waters are not well known.

- In general, the potential risks from newly identified metabolites, treatment degradation products, and chemicals will be unknown and may need to be quantified.

- Uncertainty factors spanning orders of magnitude are used in the current risk assessment methodology to address the above unknowns (e.g., sensitive subpopulations, children). These uncertainties are inherent in the existing risk assessment methodology and are not unique to advanced treated water.

ES-6. Monitoring Direct Potable Reuse Systems and the Critical Control Point Approach

Prepared by Andrew Salveson, P.E., and Eva Steinle Darling, Ph.D., P.E., Carollo Engineers

Treatment technologies are available that are capable of providing the necessary treatment to be protective of public health in DPR applications; however, because treatment processes *do* degrade and *may* fail, the operation, maintenance, and monitoring of these processes is of critical importance. Both end-of-pipe compliance monitoring and performance-based monitoring have been used to ensure that an AWTF produces water that is protective of public health. Because the end-of-pipe compliance monitoring approach is well-documented elsewhere in this report, the purpose of this chapter is to define the role of performance-based monitoring for potable reuse. The performance-based approach considered herein, known as HACCP, is a methodology developed to control risk from microbial hazards in food for astronauts sent into space. The HACCP methodology is a formal 12-step process for establishing a system of process controls.

In application, once a hazard has been identified, a critical step in the 12-step process is the identification of CCPs. A CCP is a point in the treatment train (i.e., a unit treatment process) that is designed specifically to reduce, prevent, or eliminate a human health hazard and for which controls exist to ensure the proper performance of that process. By focusing on monitoring and maintaining the treatment barriers rather than on end-of-pipe compliance monitoring and testing, its proponents suggest that HACCP offers the dual advantage of preventing poor water quality and allowing a reduction in end-of-pipe monitoring and associated costs. It should be noted that almost all the elements involved in HACCP are currently part of the monitoring and management strategy employed at existing potable reuse facilities. The difference is that HACCP is a more formalized procedure involving a number of prescribed steps in which critical treatment processes, associated monitoring, and corrective actions are identified in a structured process.

Identified key issues and a summary of principal findings related to the implementation of CCPs for DPR treatment trains are presented below. The full text, including all reference materials, is presented in **Chapter 6** of **Part II**.

6.1 Identification of Key Issues

Key issues that should be considered in the development of monitoring and control programs for DPR include:

- The transition from IPR to DPR results in the loss of the environmental buffer (e.g., an aquifer or lake), which provides opportunities for dilution, retention time (i.e., response time), and the attenuation of constituents of concern.
- Because of the loss of the environmental buffer, DPR requires additional focus on fail-safe methods to eliminate acute risks and minimize chronic risks.
- The lack of an environmental buffer means that DPR represents a more closely coupled system, in which less time is available to identify and respond to water quality concerns.

- Because a common sources of failure in the operation of AWTFs is human error, the development and use of effective monitoring programs and control strategies is of critical importance in the implementation of DPR.

- Continued work on existing monitoring technologies and the development of new and enhanced technologies and strategies will provide opportunities for improved performance and efficiency through better process control.

- The use of performance-based process monitoring and control strategies for potable reuse projects is not widespread in the United States.

- The use of performance-based monitoring, such as CCPs, to supplement current monitoring control strategies by adding process assessment information for operations of a potable reuse facility is gaining acceptance~~.~~

- Because direct online monitoring of pathogens of interest in potable reuse applications is currently not technologically feasible, greater reliance must be placed on monitoring and control strategies using surrogates and indicators.

- Enhanced monitoring and control strategies must be developed and demonstrated before it will be possible to assign realistic pathogen log reduction credits for individual unit processes (i.e., RO membranes) at an AWTF.

6.2 Summary of Principal Findings

The following findings on the state of knowledge with respect to monitoring and the application of the CCP approach to DPR are derived from a review of WRRF reports, published literature, and from the experience of ongoing monitoring programs.

6.2.1 What Is Known?

- Current monitoring technologies and strategies exist that can be used to ensure that DPR is protective of public health.

- Improvements are being made continuously to monitoring methods and technologies based on the results of research and field experience.

- In the United States, compliance monitoring is used for monitoring and control systems/strategies in drinking water and potable reuse applications.

- The performance-based CCP approach to monitoring has been translated successfully for use in DPR applications from other industries (e.g., NASA, the food industry) where failsafe methods are necessary to protect human health.

- The CCP approach has been applied successfully to water reuse projects in Australia and is gaining acceptance in the United States.

- The CCP approach can be used to supplement existing monitoring approaches with performance-based information.

6.2.2 What Is Unknown?

Unknowns in this context are best framed as needs for additional research and development, as follows:

- While the existing monitoring technology is adequate to determine the integrity and efficacy of advanced treatment processes, improvements in monitoring technology are needed to increase confidence in treatment performance and reduce requirements for:
    - Treatment redundancy (i.e., inaccurate and/or imprecise monitoring would require additional treatment barriers).
    - Storage, including the need for and size of ESBs (i.e., improved monitoring system accuracy allows greater removal credit for online processes, reducing the ESB hold time).
- Monitoring improvements for both IPR and DPR must focus on methods that can do the following:
    - Be used to demonstrate pathogen log reduction values higher than currently employed with existing online methods (e.g., RO membranes).
    - Provide comprehensive results for whole classes of water quality risk factors rather than individual chemical compounds (e.g., bioassays).
    - Provide early warning of unknown chemicals (e.g., non-targeted analysis).

ES-7. Operations, Maintenance, and Operator Training and Certification

Prepared by Debra L. Burris, P.E., DDB Engineering, Inc.

Proper operation and maintenance (O&M) is critical to the success and reliability of DPR projects. Operations plans for potable reuse facilities are issued at startup and updated when the facilities are expanded or modified significantly. The contents of operations manuals for public water systems and AWTFs are organized typically under the following subheadings: (1) process description; (2) process design data; (3) process schematics; (4) process control; (5) operations; (6) alarms; (7) equipment; (8) safety; and (9) process performance monitoring. To ensure that unit treatment process function properly, preventive maintenance must be performed routinely. Corrective maintenance also is essential for the proper management of assets. To assist with tracking equipment maintenance, all large drinking water, wastewater, water recycling, and potable reuse facilities have some type of computerized asset management program. Because a DPR project will involve complex treatment processes, equipment, monitoring, and control systems, the development of a comprehensive asset management program is of fundamental importance.

To protect public health, well-qualified operators with appropriate training, certifications, and experience are needed to manage normal conditions and respond to challenges. Currently, gaps exist in operator training and licensure/certification programs with respect to the advanced treatment processes that would be used in DPR projects. Potable reuse does not have its own certification curricula, but rather utilities rely on existing wastewater and water certifications from which the pool of operations staff is drawn. Because operator training programs for AWTFs have not been formalized through community colleges, universities, or professional organizations, utilities combine onsite, supervised hands-on experience and in-house examinations developed by local agencies that operate IPR facilities. The three certification options that have been proposed and examined include: (1) specific DPR certification, (2) supplemental DPR certification beyond existing water or wastewater operator certification; and (3) add-on DPR certification to append to an existing water or wastewater operator certification to fill gaps in knowledge and/or training.

Identified key issues and a summary of principal findings related to O&M and operator training and certification for DPR facilities are presented below. The full text, including all reference materials, is presented in **Chapter 7** of **Part II**.

7.1 Identification of Key Issues

O&M and operator training activities must be robust and well thought out to ensure the effective long-term performance of DPR facilities. The successful O&M of a DPR facility can serve as an example for others to emulate and promotes public acceptance of DPR. Key O&M and operator training issues for DPR projects include:

- At present, the important early operations activities (e.g., startup testing, commissioning, operator training, and final acceptance) defined by permit requirements and construction contract documents vary depending on the project and design firm.

- Guidelines and regulatory requirements for comprehensive operations plans with CCPs and action/response procedures are needed to support facility implementation and reliable routine performance.

- Operations plans for DPR projects may need to be equivalent to and/or more detailed than those for water treatment facilities for risk management.

- The importance of source control, addressing variable feedwater quality, and optimizing process performance should be emphasized in operations plans for DPR projects.

- A maintenance plan is essential to support the optimal operation of the DPR project.

- Standards for maintenance plans that preserve and manage assets for the optimum performance of facilities, equipment, and online monitoring systems often are lacking or incomplete.

- There is a need to evolve a culture change to emphasize the optimization of treatment performance over the need to meet minimal compliance requirements.

- Operator training and licensure/certification programs create knowledge gaps by separately addressing wastewater treatment, water treatment, and distribution system issues rather than using a coordinated, inclusive approach covering all aspects of DPR.

7.2 Summary of Principal Findings

The principal findings derived from a review of national and state regulations, as well as the experience of ongoing O&M and operator training programs, are summarized below with respect to what is known and unknown. Each topic area is considered in detail in **Chapter 7** of **Part II**.

7.2.1 What Is Known?

- O&M activities should begin as construction nears completion and should continue throughout the lifetime of the AWTF. Early operations tasks commonly are led by the construction contractor under the terms of the contract documents and involve facility startup testing, followed by commissioning and operator training, and finally acceptance of the facilities. At the completion of construction, the construction contract is closed out, the warranty period begins, and the O&M staff accepts responsibility for the performance of the facility.

- Based on experience with IPR projects, the first year of operation of the AWTF is a critical period for demonstrating the long-term success of the project.

- The development of comprehensive operations plans that provide O&M staff with information about the facilities (describing normal conditions and steps to take if the performance of treatment processes or equipment declines) is critical to the success of drinking water, wastewater, water recycling, and potable reuse projects.

- DPR necessitates the application of a variety of advanced water treatment technologies to meet water quality requirements.

- Much of the information needed to develop standards is available, albeit scattered among multiple design engineers and in construction documents customized for specific projects.

- Sufficient information about facility startup testing, commissioning, operator training, and acceptance procedures is available from existing construction contracts for drinking water, nonpotable recycled water, and IPR projects.

- The currently available information in operation plans for existing water treatment and distribution systems, wastewater treatment, water recycling, and IPR projects can be used as a starting point to develop operations plans for DPR projects.

- A number of approaches are being developed for DPR operator certification programs.

- Absent DPR regulations specifying operation, the “work arounds” likely would involve using existing O&M provisions and operator training and licensure/certification requirements for wastewater treatment, water treatment, and water distribution systems.

7.2.2 What Is Unknown?

- No standard specifications exist for the initial operation period for potable reuse projects. The critical early operations steps of startup testing, commissioning, operator training, and acceptance of the facilities, as defined by the design engineer and contained in the specific contract documents, are unique for each construction project.

- Although the regulatory requirements for operations plans for DPR projects may be similar to those for IPR projects, regulatory requirements for DPR projects are not available at present and are likely to be even more comprehensive because DPR projects will require a higher degree of resiliency.

- Similarly, standards for maintenance plans have yet to be developed for DPR projects. If and when DPR regulations are developed, they should incorporate specific requirements for redundancy of the facilities, enabling individual treatment units and/or equipment to be taken offline for maintenance to achieve consistency, support operations, protect public health, and reduce risk.

- When reviewed in terms of DPR projects, significant gaps exist in available operator training and licensure/certification programs. At present, potable reuse does not have its own certification curricula; rather, utilities rely on existing wastewater and water certifications.

- An operations management framework must be developed that focuses on public health protection, sufficient multiple barriers, risk assessment, water quality monitoring, operation management, and other issues for states to use in developing DPR guidelines.

- Because of the complexity of DPR projects, a computerized asset management program is needed to schedule and track the frequency of preventive maintenance, anticipated life of equipment, and record of breakdowns. Although asset management software is available, adapting to the specific requirements for treatment barriers critical to ensuring reliability may support the long-term success of the DPR project.

- Operator training and licensure/certification programs need to be developed specifically for DPR facilities. The current certification programs are considered inadequate for robust DPR operator certification.

- Operator training and licensure/certification programs for DPR are unavailable. At this time, it is unclear what the requirements might be and what organization(s) would conduct training programs. A comprehensive, uniform certification program for DPR is lacking, and the national and/or state-level organization(s) responsible for developing such programs are undetermined.

- DPR regulations will direct and administer O&M activities, as well as support operator training and licensure/certification programs. DPR facilities will operate in accordance with state-issued permits, which should include requirements for O&M and staffing. The terms of the permits will be based on future regulations.

- Risk management is needed to ensure the protection and safety of public health, as well as to garner and retain public trust.

- Potable reuse projects should have specific O&M requirements set forth in regulations and facility permits to ensure long-term operational success and the protection of public health. The focus of the drinking water industry on conservative designs, redundancy, and proper O&M of advanced systems will be important in ensuring public health protection and safety when using raw wastewater as a source for potable water.

ES-8. Resilience in Potable Reuse

Prepared by Brian Pecson, Ph.D., P.E., and Sarah Triolo, Trussell Technologies, Inc.

The two overarching pathways to achieving public health protection in potable reuse are *failure prevention* and *failure response*. These pathways are achieved through the effective design and operation of potable reuse facilities. It is possible to design DPR systems that are highly reliable and can treat water consistently to a high standard; however, even well engineered systems inevitably will experience unexpected malfunctions and failures. Because it is not possible or reasonable to design potable reuse systems to prevent failures under all possible conditions, they must be designed with "resilience," or the ability to adapt successfully or restore performance rapidly in response to treatment failures.

Resilience has long been studied in many non-engineering disciplines, such as biology, psychology, organizational science, and ecology. In these contexts, resilience is considered the ability of organizations, groups, and individuals to recognize, adapt to, and absorb variations, changes, disturbances, disruptions, and surprises. For the purpose of this discussion, it is important to define what is meant by "failure" in the context of potable reuse resilience and to distinguish between two types of failures. The first type of failure, *unit process failure*, is when an individual treatment process produces water that does not meet specifications. The second type of failure, *system failure,* is when an AWTF as a whole produces water that fails to meet specifications. Note that a unit process failure does *not* necessarily result in an AWTF system failure. The difference between the two types of failure, along with appropriate responses, are examined in **Chapter 8** of **Part II**.

Identified key issues and a summary of principal findings related to the resilience of DPR systems are presented below. The full text, including all reference materials, is presented in **Chapter 8** of **Part II**.

8.1 Identification of Key Issues

The key issues associated with resilience in potable reuse include:

- The two required functions of resilient systems are (1) recognition of and (2) adaptation to disturbances or failures.
- With respect to potable reuse, the two main components of failure response are: (1) failure detection and (2) failure response (i.e., mitigation or corrective measures).
- The application of "resilience" principles to engineered processes is a relatively new endeavor.
- There is widespread recognition that the application of resilience principles can greatly improve the safety of potable reuse systems.
- Because highly trained, skilled operators will be essential for resilient potable reuse systems, it is imperative that effective operator training and certification programs be developed for operators of potable reuse facilities.

- In addition to failures in treatment stemming from mechanical issues or improper operations, potable reuse systems must be resilient to natural and man-made disasters.

Each issue as it relates to resilience is addressed in **Chapter 8** of **Part II**. Based on the results of relevant research conducted to date, it is possible, with the current level of available technology, to design resilient potable reuse systems. While there are areas that would benefit from additional investigations, the need for additional research should not prevent DPR from moving forward.

8.2 Summary of Principal Findings

Resilience is a critical feature of potable reuse systems in use today, most of which fall into two forms of IPR: groundwater replenishment and surface water augmentation. In the regulations for both forms, it is assumed that AWTF system failures may occur and, consequently, require resilience features as safety nets to ensure these failures are managed safely. The primary resilience feature for both groundwater replenishment and surface water augmentation is the environmental buffer, which provides time to respond to system failures, as well as the dilution of water that is off-specification (or “off-spec”). Although a DPR system will not benefit from the environmental buffer, other resilience features can be designed, such as the automated shutdown of unit processes and activation of standby units.

8.2.1 What Is Known?

- California regulations for both forms of IPR require that failsafe options be included in projects, though the manner in which these options are provided differs.[4] The focus of the regulations is on mitigating the impact of *system failures*.

- Providing time between the treatment and consumption of water is the principal feature of resilience. This feature is a hallmark of California’s groundwater replenishment projects, most of which provide 6-months or more of retention time in an aquifer (i.e., an environmental buffer). The extended period between treatment and consumption provides multiple opportunities to identify a treatment failure and enact a response (e.g., additional treatment at the wellhead or DWTF) to protect public health.

- The differences in dynamics between a reservoir and groundwater aquifer impact the time available to respond to a system failure. Short-circuiting and wind convection in reservoirs mean off-spec water could be transported quickly to the reservoir outlet. As a result, greater emphasis is placed on a complementary strategy, namely dilution through mixing. The reservoir provides protection against a 24-hour pulse of off-spec water by ensuring that the concentrations of all contaminants are diluted no less than tenfold to one hundredfold in the reservoir.[5]

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[4] California promulgated regulations on indirect potable reuse using groundwater replenishment in 2014. Regulations on indirect potable reuse using surface water augmentation are currently in draft form and will be finalized by the end of 2016.

[5] Note: For dilution in the context of indirect potable reuse using surface water augmentation, it is assumed that advanced treated water previously introduced to the reservoir can serve as diluent water. This requirement is different than that for groundwater replenishment, where only non-wastewater origin water or water that has met the retention time requirements can serve as diluent water.

- Response time is required in the draft regulations for surface water augmentation, but the requirement is much shorter than that specified for groundwater replenishment (i.e., 24 hours versus 2 to 6 months). Consequently, the regulations have rebalanced these complementary components, with greater levels of dilution going from groundwater replenishment to surface water augmentation.

- More direct forms of potable reuse are distinguished, in part, by the lack of an environmental buffer. In the absence of an environmental buffer, other strategies are necessary to provide system resilience.

- Failure detection, the first component of resilience, can be accomplished through online monitoring. The technology available for continuous process performance verification can enable sufficiently rapid failure detection.

- The use of control charts can help improve the detection of failure. It involves tracking unit process performance data over time with respect to treatment targets to understand whether performance is declining toward failure. Control charts are well-established in the manufacturing industry and are being adapted for use in the context of groundwater replenishment.

- Effective failure mitigation/response can be achieved through automated alarms and responses, specific standard operating procedures, diversion schemes, and other strategies.

- An analysis of mechanical performance data from seven potable reuse plants indicates a high degree of mechanical reliability, with a miniscule proportion of mechanical issues resulting in adverse impacts to water quality.

8.2.2 What Is Unknown?

Significant progress has been made toward developing a framework for potable reuse resilience. This framework includes two major components: failure detection and failure mitigation. Work is needed to bring more clarity and definition as to how these strategies will be applied specifically to DPR. Some unknowns that would benefit from additional research include:

- **Control charts:** More work is needed to adapt traditional statistical control charts for potable reuse applications. Areas of needed study include (1) the development of a methodology for determining control limits and alarm thresholds for unit processes, and (2) an assessment of the effectiveness of this method for detecting potable reuse unit process failures. Notably, some of this work is being conducted as part of WRRF-14-12; online data collected from the yearlong demonstration testing is being used to evaluate different failure-detection strategies using control charts.

- **Operational responses:** Resilient system design requires the development of specific failure response strategies for a range of failure types, including those that incorporate communication between the operators of the AWTF and DWTF.

- **Failure mitigation:** More investigation is needed of novel strategies. Examples include (1) using redundant, back-up treatment units at a DWTF in the event of an AWTF failure, and (2) quantifying the time to respond provided by the travel time in pipelines, the flow-through time in the DWTF, and the retention time in clearwells.

- **Redundancy versus resilience:** A better understanding is needed of the balance between redundancy and system resilience. As redundancy increases, the probability of system failures presumably decreases; therefore, systems that provide high degrees of redundancy may be able to offset their reliance on resilience features in the protection of public health.

- **Operational data:** The industry would benefit from the compilation and analysis of data from existing potable reuse facilities. Such a database could be used to better understand common failure modes at these facilities and impacts on water quality, and would allow for more effective design of resilience strategies. Similar research is being undertaken as part of WRRF-14-16 to evaluate the causes of failure at full-scale facilities and assess their likelihood and impact on treated water quality.

ES-9. Demonstration of Reliable, Redundant Treatment Performance

Prepared by Ben Stanford, Ph.D., Hazen and Sawyer

Reliable treatment performance of the various unit treatment processes used in AWTFs is critical, as the processes serve as barriers in terms of mitigating public health risks. Over the past 10 to 12 years, multiple studies have been completed and operating data are available from a number of full-scale AWTFs that provide a solid basis for assessing and validating the performance of both individual unit treatment processes and treatment trains. To assess how various unit processes and treatment trains perform in terms of mitigating human health risks, two different treatment trains are evaluated. The first treatment train includes the use of RO membranes (e.g., MF, RO, UV/AOP, and chlorine). The second treatment train does not include RO, but does include ozone-biofiltration (e.g., floc/sedimentation, ozone, BAC, GAC, UV, and chlorine). The unit processes are evaluated in terms of the removal of key chemical and microbial contaminants.

Redundancy in a treatment train comprised of several unit treatment processes involves both an intra-process (e.g., having multiple RO banks whereby one or two banks can be on duty or stand-by mode) and an inter-process (e.g., having multiple barriers like UV irradiation followed by chlorination). Redundancy in a potable reuse treatment train requires that individual treatment processes be combined such that any given contaminant is addressed with more than one barrier. For example, in a redundant treatment train, microorganism control would not be solely achieved with chlorination, but rather with a combination of removal and inactivation steps in what is termed a “multi-barrier” approach. For example, microorganisms can be removed and/or inactivated by several processes, such as membrane filtration, UV irradiation, ozonation, and chlorination. The implementation of more than one treatment process to address a given contaminant minimizes the potential of contamination in finished water, even if one process is not operating at optimal performance.

Identified key issues and a summary of principal findings related to the reliable, redundant treatment performance of DPR facilities are presented below. The full text, including all reference materials, is presented in **Chapter 9** of **Part II**.

9.1 Identification of Key Issues

The benefits of including DPR in a community’s water supply portfolio are well documented, spanning economic, environmental, and social impacts. The realization of these benefits requires that DPR systems be designed and implemented with water quality performance reliability and redundancy held paramount. Reliability and redundancy are fundamental requirements of any water treatment system, but are critical for DPR due to the engineered linkages between urban wastewater collection systems and drinking water distribution systems. Key reliability and redundancy issues for DPR projects include:

- The production of high-quality advanced treated water under both ideal and non-ideal system conditions can only be achieved through the coupling of reliable and redundant treatment processes.

- To achieve reliable performance, individual treatment processes must be selected that are known to target specific contaminants for removal.

- Key aspects of reliability in DPR are verification and validation.

- To achieve redundancy, the entire treatment system must contain multiple barriers for any given contaminant.

- A barrier can be technical, operational, or managerial in nature, with each barrier providing a factor of safety in terms of contaminant removal.

- Field or pilot verification of whether a barrier can be used to mitigate or reduce identified human health risks is of critical importance.

9.2 Summary of Principal Findings

Reliability in DPR involves long-term process performance, which can only be ensured by upfront verification and validation, in addition to proper O&M and monitoring CCPs.

9.2.1 What Is Known

- During process selection, it is now possible to verify that each process selected can meet expectations to manage specific human health risks identified as controlled by that barrier.

- Process validation must be used to assess whether a barrier functions as intended to control health risks.

- Validation can be completed by measuring the removal of a specific contaminant or pathogen across a barrier during pilot testing and full-scale validation testing.

- Redundancy is both an inter-process (e.g., multiple barriers, such as UV irradiation followed by chlorination), as well as intra-process (e.g., having multiple RO banks whereby one or two banks can be on duty or in a standby mode).

- Redundant monitors (i.e., either redundant monitors that measure the same parameter or, better yet, multiple monitors of the same process that measure different parameters) must be used to improve process monitoring and response.

9.2.2 What Is Unknown

- No surrogate is available for the real-time validation of virus reduction in membrane processes. Until a real-time surrogate is developed and accepted by regulators, it will not be possible to obtain virus reduction credit for most membrane processes. Typically, RO membranes achieve credit by observation of a surrogate, such as conductivity, but are limited to 1.5 to 2.0-log reduction. Commercial products like TRASAR® may be available to monitor RO performance beyond the 2.0 log from conductivity measurements, but have yet to be accepted for creditable performance by regulatory agencies.

- The development of alternative virus surrogate parameters that exhibit similar (and measurable) removals relative to contaminant of concerns must be identified, tested, and validated for use in process monitoring.

- More information is needed about the optimal coupling of the various treatment technologies currently in use for potable reuse with the new technologies currently being developed and tested.

ES-10. Afterword

The projects and studies undertaken through the DPR Research Initiative represent a significant investment of effort and resources – undertaken by proven and knowledgeable researchers and scientists – to address fundamental issues pertaining to the implementation of DPR as a source of water supply. Such an effort has produced valuable information in the form of a vast number of draft or final reports, progress reports, presentations, articles, and other public or private documentation.

The Expert Panel convened by the California State Water Resources Control Board used this information to help in its deliberations on evaluating the feasibility of developing uniform water recycling criteria DPR. Notably, in its Final Report to the State Water Board (dated August 2016), the Expert Panel concluded:

> "After a yearlong investigation, Expert Panel finds it is feasible for the State of California to develop and implement a uniform set of water recycling criteria for DPR that would incorporate a level of public health protection as good as or better than what is currently provided in California by conventional drinking water supplies, indirect potable reuse (IPR) systems using groundwater replenishment, and proposed IPR projects using surface water augmentation."[6]

The Expert Panel also identified areas of research that should be conducted either before or concurrently with the development of regulations to further ensure the protectiveness of DPR.

The water industry is now at the beginning of the process to develop regulations for DPR. As the discussions to develop such criteria move ahead, it will be beneficial to have a comprehensive summary of the available information on DPR, as provided in this report (and which has not been available until now).

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[6] Olivieri, A.W., J. Crook, M.A. Anderson, R.J. Bull, J.E. Drewes, C.N. Haas, W. Jakubowski, P.L. McCarty, K.L. Nelson, J.B. Rose, D.L. Sedlak, and T.J. Wade (2016). *Expert Panel Final Report: Evaluation of the Feasibility of Developing Uniform Water Recycling Criteria for Direct Potable Reuse*. Submitted August 2016 by the National Water Research Institute for the State Water Resources Control Board, Sacramento, CA. http://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/rw_dpr_criteria.shtml (accessed 9/9/2016).

Part II: Synthesis Papers

The complete text for the synthesis papers are provided in **Part II**. The synthesis papers include the material highlighted briefly in the Executive Summary (i.e., the introduction, identification of key issues, and summary of principal findings), as well as additional detail in the form of background information, relevant data, analysis, and/or rationale. For ease of reference, the chapter numbering for the synthesis papers in **Part II** correspond to the numbering used for their matching summaries in **Part I**.

Chapter 1: Source Control Program

Prepared by Robert W. Emerick, Ph.D., P.E., Robert Emerick Associates (Granite Bay, CA)

The primary sources of chemical contaminants in wastewater include (1) discharges from residences, businesses, and industries; (2) corrosion within the potable water distribution system; (3) the potable water supply; (4) stormwater; and (5) drinking water and wastewater treatment processes. Because of the diversity of these sources, the organic and inorganic constituents found in wastewater can be variable. The National Pretreatment Program (NPP) was established as part of the Clean Water Act to control and regulate the discharge of pollutants to surface water by commercial and industrial dischargers of wastewater (USEPA, 2011). Although the NPP has reduced the discharge of many constituents that are difficult to manage from a treatment and environmental standpoint, it has not eliminated the discharge of such constituents. To date, the NPP is directly applicable only to effluents discharged to surface waters. Source control programs for direct potable reuse (DPR) should be designed to further control, limit, or eliminate the discharge of constituents into wastewater that can be difficult to treat or impair the final quality of treated wastewater intended for DPR (Tchobanoglous et al., 2015).

1.1 Identification of Key Issues

Key issues that should be considered in the development of source control programs for DPR include:

- Identifying sources of toxic compounds entering the sewershed from point sources that can be readily managed.
- Identifying and inventorying contaminant sources (e.g., stormwater and potable water supply chemical quality) in addition to those from commercial businesses and industry located within the sewershed.
- Identifying contaminants [e.g., corrosion, salinity, metals, N-nitrosodimethylamine (NDMA) or its precursors, Bis(2-ethylhexyl) phthalate, bromate, and other disinfection byproducts (DBPs) or their precursors] that may be formed within the potable water system or wastewater system or as part of treatment.
- Determining the most cost-effective means (e.g., source control, treatment) for removing specific contaminants.

1.2 Summary of Principal Findings

The following principal findings are derived from a review of national and state regulations, as well as the experience of ongoing source control programs. Each topic area is considered in detail in **Sections 1.4, 1.5,** and **1.6.**

1.2.1 What Is Known?

- The NPP has been successful when applied to its target objective: medium-sized to large-sized wastewater treatment plants (WWTPs) discharging to surface water. The NPP also improved opportunities to recycle and reclaim municipal and industrial wastewaters and biosolids.

- Contaminant sources that exist beyond direct discharges by commercial businesses and industries can be controlled directly by the NPP.

- Considerable experience and knowledge has been developed and is available on the implementation of effective source control programs in a variety of settings, including municipalities and special sanitary districts.

- Although beneficial, the NPP has not eliminated pollutant loadings from industrial sources. Nor was it developed with the intent to regulate at trace levels. If a surface water discharge is not the aim of the treatment facility (e.g., protecting groundwater is a State-regulated responsibility and outside the jurisdiction of the Clean Water Act), the NPP may not be statutorily applicable. The NPP should be a key element of any DPR project and may require modification to address the regulation of trace contaminants associated with DPR projects.

- Regional discharges of wastewater and stormwater – to both surface water and groundwater – require regulation in a holistic manner. Ultimately, wastewater that is disposed into the environment may impact potable water supplies that are downstream (with regards to surface water) or downgradient (with respect to groundwater).

- In many regions of the United States, DPR projects (i.e., the development of new potable water supplies) may be needed to sustain economic output. The most advantageous and cost-effective methods should be considered to eliminate contaminants. It may be more advantageous and cost effective to prevent the introduction of or treat specific contaminants at the source rather than dilute those contaminants through discharge into a collection system. Conversely, it might be more cost effective to construct more robust treatment at a downstream or downgradient central location, taking advantage of economies of scale.

1.2.2 What Is Unknown?

Although much is known about the implementation of source control programs, as the adoption of DPR becomes more widespread, additional benefits can be derived from research investigations to: (1) identify key regulatory indicators and develop corresponding cost-allocation approaches; (2) develop anti-degradation and pollutant trading options; and (3) optimize treatment process development.

- Consideration should be given to developing additional indicators and regulations to address concerns related directly to trace concentrations of contaminants applicable to DPR projects. Commercial businesses and industries are regulated routinely on items such as biochemical oxygen demand (BOD), total suspended solids, flow, and sulfate on a financial basis to fund centralized collection and/or treatment needs or to prevent corrosion-based deterioration. This approach encourages businesses and industries to evaluate whether a discharge to the wastewater system is more or less cost effective than preventing a discharge at the source.

Likely, a similar approach would be effective for trace contaminants applicable to DPR projects.

- Regulations should be developed and implemented to account for the impacts that discharges can have on far downstream (or downgradient) water-short regions. Regions that make use of DPR projects, by definition, are water short, and their potable water supplies often originate far from the community generating the wastewater that will be the source of a DPR project. For example, water that is “discharged to land” is regulated; therefore, it undergoes treatment far differently than water that is percolated to groundwater as part of IPR, although both treatment requirements are intended to protect potable water beneficial uses.

- Research is needed to quantify the specific process modifications appropriate for DPR projects. These modifications should account for the eventual need to implement DPR projects. Often, treatment systems for producing water suitable for DPR are modified treatment systems originally intended for wastewater discharge to land or surface water dispersal facilities. Because regulatory requirements associated with dispersal systems can differ markedly from DPR treatment systems, the chemicals used as part of treatment – and even the treatment process itself – can impact source water quality. Salinity, NDMA, aluminum, recalcitrant organic nitrogen, bromate, and other DBPs have been found to increase in concentration owing to the use of specific treatment processes.

1.3 Importance of a Source Control Program for Direct Potable Reuse

A crucial preventative approach to consider when pursuing and planning for DPR is the implementation of a rigorous source control program in conjunction with other applicable programs (e.g., the NPP) to eliminate or control the discharge of constituents that might impact the production of advanced treated water. Before discussing the development and elements of a source control program, it will be helpful to first review the NPP and Federal Pretreatment Standards as they provide a useful starting point for the development of any source control program (Tchobanoglous et al., 2015).

1.3.1 Overview of the National Pretreatment Program

The NPP is a component of the National Pollutant Discharge Elimination System (NPDES) program. The objectives of the NPP include: (1) preventing the introduction of chemical constituents into a publicly owned treatment work (POTW) that interfere with treatment operations or pass through the treatment process and are discharged to receiving waters; and (2) improving opportunities to recycle and reclaim municipal and industrial wastewaters and biosolids (USEPA, 2011). POTWs that discharge to surface waters under an NPDES permit and meet the following requirements in 40 CFR 403.8 are required to develop pretreatment programs, as follows:

> “Any POTW (or combination of POTWs operated by the same authority) with a total design flow greater than 5 million gallons per day (mgd) and receiving from Industrial Users pollutants which Pass Through or Interfere with the operation of the POTW or are otherwise subject to Pretreatment Standards will be required to establish a POTW Pretreatment Program unless the NPDES State exercises its option to assume local responsibilities as provided for in §403.10(e). The Regional Administrator or Director

> may require that a POTW with a design flow of 5 mgd or less develop a POTW Pretreatment Program if he or she finds that the nature or volume of the industrial influent, treatment process upsets, violations of POTW effluent limitations, contamination of municipal sludge, or other circumstances warrant in order to prevent Interference with the POTW or Pass Through."

Because POTWs are not designed to treat toxic chemical constituents from industries or commercial businesses, the NPP was created to address the discharge of toxic constituents from nondomestic sources. In the National Pretreatment Regulations, industrial and commercial dischargers (i.e., nondomestic dischargers) are defined as "industrial users." The U.S. Environmental Protection Agency (USEPA) has established General Pretreatment Regulations (40 CFR, Section 403) that define the responsibilities for federal, state, and local government, as well as industries, to achieve specific pretreatment objectives (APAI, 2015).

For wastewater agencies not subject to the Federal Pretreatment Program, local, state, or federal permitting authorities may not, in some cases, require a POTW to implement an approved pretreatment program or a program that meets all federal requirements; however, an agency that intends to operate a DPR project should develop a source control program as the first barrier to protect the quality of advanced treated water, even if it is not a permit requirement (APAI, 2015). The key elements of the NPP per 40 CFR 403.8(f) are summarized in **Table 1-1** (Tchobanoglous et al., 2015).

Table 1-1: Key Elements of the National Pretreatment Program

Element	Description
Legal authority	The publicly owned treatment work (POTW) must have the legal authority to apply and enforce any pretreatment standards and requirements.
Procedures	The POTW must develop and implement procedures to ensure compliance with pretreatment standards and requirements, including procedures for: (1) receiving and analyzing self-monitoring reports and other notices submitted by industrial users; (2) conducting random sampling and analysis of effluent from industrial users; and (3) conducting surveillance activities to identify compliance or noncompliance independently from information supplied by industrial users.
Funding	The POTW (and multijurisdictional entities) must have sufficient resources and qualified personnel to carry out the authorities and procedures specified in its approved pretreatment program.
Local limits	The POTW must develop technically-based local limits to regulate the discharge of pollutants of concern from industrial users and address the specific needs and concerns of the POTW.
Enforcement response plan	The POTW must develop and implement an enforcement response plan that contains detailed procedures indicating how the POTW will investigate and respond to instances of industrial noncompliance.
List of significant industrial users	The POTW must maintain a list of all significant industrial users.

From Tchobanoglous et al. (2015). Sources: USEPA (2011) and APAI (2015).

1.3.2 Federal Pretreatment Standards

POTWs must enforce both general and specific prohibitions in the General Pretreatment Regulations. The regulations disallow an industrial users from discharging constituents that pass through or cause interference with the treatment process. Discharge prohibitions include requirements for infrastructure protection (including the POTW collection system) and worker safety.

Categorical pretreatment standards include technology-based numeric limits or best management practices developed in accordance with Section 307 of the Clean Water Act to limit pollutant discharges to POTWs from specific process wastewaters. These national technology-based standards apply to an industrial user regardless of whether the POTW has an approved pretreatment program or the industrial user has been issued a control mechanism or permit. The standards are established based on the list of priority pollutants (APAI, 2015). Additional standards and requirements may be added by state and local regulatory agencies, as needed, to protect the POTW. After approval in accordance with 40 CFR 403.5(c), these local limits also are called Pretreatment Standards and are enforceable for the purposes of the Clean Water Act (Tchobanoglous et al., 2015).

1.4 Development of a Source Control Program for Direct Potable Reuse

Although not all POTWs are required to implement Federal Pretreatment Programs, any municipality, utility, or agency pursuing a DPR project, regardless of size, should consider the impacts of industrial and commercial contributions on the wastewater supply. In developing a source control program, it is essential to understand the sources of toxic compounds entering the sewershed from readily managed point sources. In some cases, to minimize the impact from large industrial dischargers, it may be appropriate to consider diverting highly industrialized discharges to alternative treatment facilities.

1.4.1 Source Control as a Key Element of a Potable Reuse Program

As shown in **Figure 1-1**, a multiple-barrier approach to potable reuse needs to include source control. Keeping constituents of concern out of the wastewater system through a robust source control program can be the most beneficial, efficient, and cost-effective strategy for managing and treating industrial, commercial, and other contributions to the wastewater supply. The goals of an effective potable reuse program (Tchobanoglous et al., 2015) include:

- Minimize contaminants in the potable water source.
- Minimize the discharge of potentially harmful or difficult-to-treat chemical constituents to the wastewater collection system from industries, health care facilities, commercial businesses, and homes (see the shaded source control element in **Figure 1-1**).
- Optimize the collection and treatment processes to be used to produce water suited for DPR. Select and operate treatment processes that do not themselves add problematic contaminants (see the wastewater treatment element in **Figure 1-1**).
- Provide the public with confidence that the wastewater collection system is being managed with potable reuse in mind.

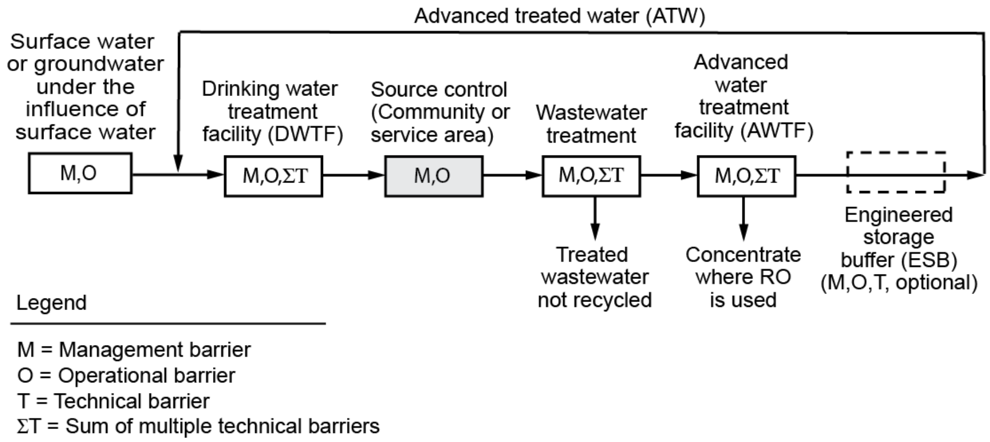

Figure 1-1: Key elements of the technical component of a potable reuse program. Note: The source control element is shaded (Tchobanoglous et al., 2015).

1.4.2 Regulatory Authority of the Source Control Program

A successful source control program should begin with the establishment of the regulatory authority to implement the program. As discussed in **Section 1.3.2**, many wastewater agencies are required to develop pretreatment programs through the NPP. These programs can be used as a foundation for establishing additional regulatory authority that targets potable reuse applications. For wastewater agencies not required to participate in the NPP, the appropriate regulatory authority should consider elements similar to those contained in it, in addition to the elements discussed in **Section 1.4.5** (Tchobanoglous et al., 2015).

1.5 Principal Elements of a Source Control Program for Direct Potable Reuse

Key to creating an effective DPR program is to recognize that source control is a critical element in creating a safe water supply and is not focused solely on wastewater compliance. Although the NPP provides a basic foundation, the focus of that program is not on potable reuse; therefore, additional elements should be incorporated into a source control program for DPR projects. The principal elements of an effective DPR source control program (**Table 1-2**) should include:

- Regulatory authority.
- Monitoring and assessment of commercial and industrial dischargers to the wastewater collection system within the service area.
- Investigation of chemical and other constituent sources.
- Maintenance of the current inventory of chemical constituents.
- Preparation of a public outreach and participation program.
- Preparation of a response plan for water quality deviations.

Table 1-2: Principal Elements of an Enhanced Source Control Program for Direct Potable Reuse

Element	Description
Regulatory Authority	
Legal authority	Ensure that the source control program has sufficient legal authority to develop and implement source control measures, including authority for the oversight and/or inspection of existing facilities, as well as reviewing 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 constituents of concern.
Enforcement	Ensure that the enforcement response program can identify and respond rapidly to discharges of constituents of concern.
Alternative control programs	Consider alternative control mechanisms, such as BMPs or self-certification for zero discharge of pollutants, for classes of industries or commercial businesses.
Monitoring and Assessment of the Wastewater Collection System Service Area (Sewershed)	
Routine monitoring program	The influent to the WWTP and secondary-treated or tertiary-treated wastewater effluent sent to the AWTF are monitored routinely for regulated constituents and other constituents of concern that may be discharged into the collection system service area.
Constituent prioritization program	Constituents of concern are identified and short-listed using results from the routine monitoring program. It may be necessary to develop separate monitoring programs for the constituents of greatest concern.
Evaluation of technically based local limits	Regulated constituents and other constituents of concern are evaluated for their potential to cause interference, pass through an AWTF, or affect human and environmental health and safety. For the development of local limits, consider including a broader spectrum of constituents of concern, such as (1) regulated and nonregulated constituents relevant to DPR (e.g., drinking water contaminants) or (2) constituents of emerging concern.
Source Investigations	
Industrial and commercial business inventory	Develop and maintain a frequently updated, comprehensive inventory of industries and businesses that may use products or chemicals containing constituents of concern or generate intermediate constituents of concern. For agencies with large service areas, multiple communities, or industrial flows coming from other wastewater entities, it may be desirable to link the inventory to a service area mapping tool, such as a geographic information system network.
WWTP-AWTF joint response plan	The response plan includes a flow chart showing key responsibilities and decision points to either investigate or mitigate constituents of concern being discharged into the collection system.
Maintenance of 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. Potential sources of information include the industries themselves, State Emergency Response Commission, Local Emergency Response Commission, or local fire departments.
Waste 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 constituents of concern encountered within the service area.

Element	Description
Public Outreach Program	
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 be partners in protecting the sewershed, such as environmental stewardship programs or award programs for consistent compliance. - Assist and encourage industries and businesses that use chemicals that contain constituents of concern to identify source control options, such as chemical substitution.
Service area pollution prevention partnership program	Develop a cooperative program with cities, counties, or other jurisdictions within the WWTP service area to disseminate information to the public about constituents of concern and acceptable discharges to the sewer.
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 (e.g., 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.
Response Plan for Identified Constituents	
Interagency collaboration	The success of a source control program will depend on strong interagency cooperation and responsiveness between the WWTP and AWTF. 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. For DPR projects where the agency that administers the source control program is not the agency that operates the AWTF, consider entering into a memorandum of understanding or other contractual agreement so that appropriate source control actions can be taken, if necessary, to protect water quality.
Response to water quality deviations	Develop an action plan for responding to water quality deviations. For example, if a specific chemical constituent is detected at the AWTF, review operation and calibration records for online meters and any analytical methods that may be involved. If a problem is not identified, then notify the WWTP to initiate a review and inspection of the WWTP for possible sources of the constituent. If no source is found at the WWTP, then initiate a wastewater collection system sampling program. If a problem is identified, the action plan should include procedures for the operations staff to notify the source control staff to respond to and correct the issue and, if necessary, procedures for bypassing or shutting down the facility.

AWTF = Advanced water treatment facility. BMP = Best management practice. DPR = Direct potable reuse. WWTP = Wastewater treatment plant.

From Tchobanoglous et al. (2015). Sources: USEPA (2011) and APAI (2015).

To ensure that source control elements will be implemented, contractual agreements also should be in place between the entity responsible for the treatment and delivery of drinking water and the entity operating the wastewater collection and treatment system. Such agreements should address the allocation of costs (Tchobanoglous et al., 2015).

1.5.1 Source Control Program Expectations

Expectations must be realistic regarding the effectiveness of source control. Source control programs are not designed to remove all unwanted constituents. What is important is the reduction of problematic constituents. According to Tchobanoglous et al. (2015), the successful reduction of problematic constituents typically occurs under the following conditions: (1) constituent concentration levels are measurable; (2) contributing sources can be identified; and (3) contributing sources are within the control of the management agency.

1.5.2 Measurable Concentration Levels of Constituents

Source control programs are most effective when the constituent is consistently found at measurable levels in the wastewater influent or collection system. If a constituent is found sporadically, it often is difficult to identify the source (APAI, 2015; Tchobanoglous et al., 2015).

1.5.3 Ability to Identify Contributing Sources

The contributing source of constituents typically is identified most successfully when it is a single source or a group of similar sources accounting for most of the influent loading. The portion of the total influent source that is identified and considered controllable must be greater than the reduction in constituent levels needed. Substances like banned pesticides that homeowners may stockpile and occasionally flush down the drain are difficult to control, but potentially can be addressed through hazardous waste collection programs or public outreach (APAI, 2015; Tchobanoglous et al., 2015).

1.5.4 Sources within the Control of the Management Agency

In general, contributing sources of constituents within the jurisdiction of the wastewater management agency are easier to control than those outside of the agency's jurisdiction. For example, industrial sources are controlled more easily because industries are regulated and required to meet collection system use permit requirements, whereas residential sources are not within the legal jurisdiction of wastewater agencies; therefore, voluntary behavioral changes are needed. If a constituent source is a commercial product, such as mercury thermometers, it may not be within the local agency's power to ban or restrict the use of the product. To be effective, the use of a product must be restricted on a local, regional, statewide, or national basis. One example of a successful statewide effort is the statutory ban in California on the use of lindane in head lice products. The ban was accomplished through the combined efforts of wastewater control agencies, a state legislator, and the National Pediculosis Association (APAI, 2015; Tchobanoglous et al., 2015).

It is important to recognize that technology exists to remove essentially all contaminants to any desired level, at some cost. The primary concern is that too costly a project can render the project unfeasible. Voluntary behavioral changes to increase water quality are possible when the consumer is made aware of costs to remove specific contaminants. In some cases there are benefits to treating constituents of concern at the point of discharge when volumes are small and concentrations high versus treating at the WWTP where concentrations are lower and the volume of water requiring treatment is high. Although DPR consumers may be different than the original producers of the wastewater source, DPR utility managers should be active in helping develop the needed regulatory permits to ensure a usable source of water for DPR.

1.5.5 Sources outside the Direct Control of the Management Agency

The potable water distribution system, potable water supply, and stormwater impacts may appear to be outside the management agency's control; however, avenues should be explored and developed to mitigate problematic areas where possible.

One overlooked source of contaminants is corrosion/leaching of the potable water distribution system. Chemicals can (and are) routinely added to potable supplies to prevent corrosion (e.g., zinc orthophosphate), but can easily be over-applied in a zealous effort to protect expensive infrastructure. These chemicals can increase concentrations of some metals (e.g., zinc) to problematic levels because maximum contaminant levels for drinking water can be far higher than regulated concentrations in wastewater. One potential solution is to regulate the potable water supplier in a manner similar to that proposed for commercial and industrial dischargers.

The drinking water supply also can be a significant source of chemical contaminants. Drinking water supplies are impacted by upstream (surface water) or upgradient (groundwater) stormwater and wastewater discharges, agricultural operations, roadway runoff, atmospheric deposition, and the demineralization of soils, among other contaminant sources. Because drinking water supplies often are regulated far less stringently than wastewater or DPR projects, chemicals can exceed DPR regulatory levels before passage through the community. One potential solution is to be active in the permit adoption process for upstream dischargers that impact sources of DPR supplies.

Large, older utilities also may make use of wastewater systems that are partly combined with stormwater systems (e.g., the City of Sacramento); therefore, contaminants associated with stormwater also will enter into the wastewater treatment system. But combined discharges are not the only source of stormwater into a collection system. Inflow and infiltration (I/I) also can impact water quality. Although it is assumed that I/I dilutes contaminant concentrations, I/I can contain contaminants that are leached from groundwater or washed from land. One potential solution is for utility managers to be active in the permit adoption process for stormwater discharges in the sewerage service area.

1.5.6 Example Source Control Programs Related to Potable Reuse

Many agencies have developed local or statewide "No Drugs Down the Drain" programs,[7] drug take-back programs, and household hazardous waste collection programs. Other agencies have enhanced pretreatment program elements to augment their pollution prevention efforts. For example, the source control program used for the Groundwater Replenishment System in California[8] includes proposed local

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[7] See http://www.nodrugsdownthedrain.org/.

[8] An indirect potable reuse project, the Groundwater Replenishment System (GWRS) uses treated wastewater effluent from the Orange County Sanitation District to produce advanced treated water at the advanced water treatment facility operated by the Orange County Water District. The Orange County Sanitation District manages the source control program for GWRS.

limits for 1,4-dioxane, NDMA, and constituents that adversely affect total organic carbon (TOC) removal, such as acetone (APAI, 2015; Tchobanoglous et al., 2015).

1.6 Research Needs

Historically, source control programs have been developed on the basis of preventing readily identified contaminants from known commercial practices and industries from being discharged into collection systems. In the past, effort was directed toward keeping acutely toxic compounds out of wastewater that might adversely affect the treatment process. In a DPR environment, it should be recognized that it may be far more cost effective to treat specific contaminants at the source rather than dilute those contaminants through discharge into a collection system. Research is required in the following areas to allow enhance the adoption of DPR in the most cost-effective manner: (1) key regulatory indicators and cost allocation; (2) anti-degradation; and (3) treatment process development.

1.6.1 Key Regulatory Indicators and Cost Allocation

Businesses and industries are routinely regulated on such items as BOD, total suspended solids, flow, and sulfate on a financial basis, with additional requirements associated with implementation of best management practices associated with specific contaminants. BOD, total suspended solids, and flowrate are correlated with the size and number of treatment processes at the reclamation facility. The regulation of sulfate is due to corrosion concerns. It is appropriate to develop an additional set of indicators to address concerns directly related to DPR.

TOC is one such indicator commonly used to assess the quality of DPR water. Ultraviolet (UV) transmittance (i.e., a measure of the attenuation of UV light via passage through water due to the presence of trace amounts of dissolved contaminants) and total dissolved solids (TDS) (i.e., an indicator of the total amount of dissolved contaminants in water) are potential indicators of the chemical quality of water. Although interferences might be present for direct measurement of these indicators, there are methods of mitigating these interferences and these indicators typically are not used to assess fees associated with wastewater discharge to the collection system. They are routinely used to assess DPR water quality. These potential indicators and others (e.g., metals, endocrine disrupting compounds, toxicity assays) should be developed in conjunction with cost-basis models to best allocate treatment costs among dischargers to the wastewater collection system. Due to the varying costs of specific tests (i.e., TDS is far cheaper to perform than biological assays), varying the frequency of application for specific tests is appropriate and may only be required when initially characterizing the quality of a specific discharge). This system provides financial motivation to consider controlling contaminants at their source where they are most concentrated.

1.6.2 Anti-Degradation and Pollutant Credit Trading

Regions that make use of DPR projects, by definition, are water short. Potable water supplies often originate far from the community generating the wastewater that will be the source water for DPR projects. The regulation of wastewater discharges should account for the impacts discharges can have on far downstream water-short regions. This approach potentially could reduce costs associated with both DPR projects and wastewater discharges, creating an opportunity to better manage water resources holistically and regionally.

For example, natural waters often exhibit UV transmittance higher than 85 percent. Tertiary effluent often exhibits UV transmittance near 65 percent. The exact chemicals responsible for reducing the UV transmittance from that which originated with the source water most often are unknown, though they often include such items as coffee and humic acids. Typically, the reduced transmittance associated with discharged effluent may not factor in at all to the associated discharge limitations. As the water moves downstream and is used as a source of potable water in downstream communities, the chemicals that affected UV transmittance may further accumulate to more problematic concentrations or adversely affect the costs of downstream treatment facilities (e.g., UV disinfection facilities).

Research is warranted as to the most appropriate conduct of Anti-Degradation Analyses for assessing the impacts of wastewater discharges on far downstream DPR projects. Owing to economies of scale, it may be far more cost effective to implement specific treatment technologies as part of DPR projects than treatment at multiple sources (provided aquatic toxicity is adequately controlled). The converse also may be possible on a project-specific basis; it may be more cost effective to treat contaminants of concern at the location where they occur in their most concentrated form.

1.6.3 Treatment Process Development

Treatment systems for producing water suitable for DPR often are modified treatment systems originally intended for wastewater discharge to land or surface water dispersal facilities. Because regulatory requirements associated with dispersal systems can differ markedly from DPR treatment systems, the chemicals used as part of treatment – and even the treatment process itself – can impact source water quality. Salinity, NDMA, aluminum, recalcitrant organic nitrogen, bromate, and other DBPs often are found to increase in concentration owing to the use of specific treatment processes.

1.6.3.1 Salinity

DPR projects might make use of dilution to control salinity and/or other specific indicators (e.g., TOC). The use of dilution for DPR compliance often is counter to water conservation efforts as dilution negates the benefits of conservation. Research is warranted on the amount of water lost to evaporation owing to specific wastewater treatment processes. Simply converting pond-based treatment to activated sludge has been observed to greatly decrease effluent salt concentrations (e.g., the City of Dixon, California).

1.6.3.2 Nutrients

Many treatment systems remove nitrogen compounds, and return flows can adversely impact treatment effectiveness. Flow equalization of return flows or equalization of the effluent can greatly reduce peak contaminant concentrations, potentially reducing the concentrations of compounds like NDMA.

1.7 Information Sources

A list is provided in **Table 1-3** of the WRRF and WRA projects that were reviewed for the preparation of this chapter. Full citations for reports related to these projects, along with citations for other references and sources of information, are included in **Section 1.8**.

Table 1-3: WRRF and WRA Research Projects Used to Prepare Chapter 1

Project No.	Project Title	Principal Investigator(s)
WRRF-13-12	Evaluation of Source Water Control Options and the Impact of Selected Strategies on Direct Potable Reuse	Alan Rimer, Black & Veatch
WRRF-14-20 (WRA-14-01)	Developing Direct Potable Reuse Guidelines	Jeffrey Mosher, National Water Research Institute

1.8 References

APAI (2015). "Final Report: Direct Potable Reuse Resource Document." Report prepared for the Texas Water Development Board by Alan Plummer Associates, Inc.: Fort Worth, TX, 2011. http://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1248321508_Vol1.pdf (accessed 9/3/2015). http://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1248321508_Vol2.pdf (accessed 9/3/2015).

Rimer, A. (in progress). *Evaluation of Source Water Control Options and the Impact of Selected Strategies on DPR*. Report pending for Project WRRF-13-12, WateReuse Research Foundation, Alexandria, VA.

Tchobanoglous, G., J. Cotruvo, J. Crook, E. McDonald, A. Olivieri, A. Salveson, and R.S. Trussell (2015). *Framework for Direct Potable Reuse*. Report from Project WRRF-14-20 (WRA-14-01), WateReuse Research Foundation, Alexandria, VA.

USEPA (2011). Introduction to the National Pretreatment Program (EPA-833-B-11-001). Office of Wastewater Management: U.S. Environmental Protection Agency: Washington, DC, 2011. http://water.epa.gov/polwaste/npdes/pretreatment/upload/pretreatment_program_intro_2011.pdf (accessed 9/3/2015).

Chapter 2: Evaluation of Potential Treatment Trains for Direct Potable Reuse

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Many advanced water treatment processes that have been investigated and applied at full-scale indirect potable reuse (IPR) projects will be appropriate for DPR projects, although implementation requires additional considerations due to the lack of the environmental buffer, which can provide natural attenuation and significant response time for unexpected events. Currently, a number of IPR treatment plants in California employ advanced water treatment facilities (AWTFs) that include the following treatment barriers: microfiltration (MF), reverse osmosis (RO), and ultraviolet (UV) disinfection with advanced oxidation processes (AOPs). Research conducted on the suitability of both RO-based and non-RO-based AWTFs for the implementation of DPR projects is reviewed in this chapter.

2.1 Identification of Key Issues

Treatment processes appropriate to the specific DPR project must be evaluated and selected to ensure the production of water quality that is protective of public health. Identifying the appropriate AWTF is a complex task that involves:

- Full characterization of the source water (i.e., raw wastewater), including diurnal variations in flows and loads, as well as the evaluation of the source water control program.
- Evaluation of the design and operation of the WWTP, including conditions that can cause a plant upset and degradation of feedwater quality at the AWTF.
- Identification of finished water quality goals, including specific regulatory requirements for DPR and site-specific aesthetic requirements (e.g., TDS, hardness, color).
- Identification of multiple treatment barriers to pathogens and bulk and trace organics to meet regulatory requirements and specific finished water quality goals.
- Determination of treatment process reliability criteria, including the ability of treatment processes to properly treat WWTP upsets.
- Identification of waste disposal constraints, including site-specific limitations that may exist for the disposal of waste streams with elevated salinity (i.e., RO concentrate).
- Determination of space constraints for the construction of treatment processes.
- Estimation of capital and operating costs, as well as other triple bottom line factors.

Although all these issues can significantly influence the design and construction of an AWTF, regulatory requirements, source water quality, and the need for multiple treatment barriers to pathogens and organics have the largest impact on the selection of treatment processes for potable reuse.

2.2 Summary of Principal Findings

The following discussion of what is known and unknown about DPR treatment technology is based on regulatory considerations, selection of DPR treatment trains, pathogen removal, trace organics and chemical contaminant removal, and other water quality considerations affecting treatment. Each topic area is considered in detail in **Sections 2.3** to **2.6**.

2.2.1 What Is Known?

- In the United States and abroad, most full-scale potable reuse projects provide multiple barriers to pathogens and organics.
- Specific treatment technologies employed at AWTFs vary depending on local regulations and site-specific requirements.
- At present, meeting low regulatory limits (or customer-dictated limits) for TOC [e.g., <0.5 milligram per liter (mg/L)] will require the use of RO. Alternative technologies, such as ozone/biological activated carbon (BAC) or granular activated carbon (GAC), often can be used at locations with higher limits for TOC (e.g., 2 to 3 mg/L).
- Non-RO-based AWTFs are more suitable for inland locations where the disposal of RO concentrate is expensive and environmentally challenging.
- Because the analysis time for biological tests is long, engineered storage buffers (ESBs) of sufficient retention time may be needed to directly confirm suitable microbial quality.
- California’s pathogen log reduction requirements for potable reuse are based on conservative maximum values in raw wastewater, derived from a review of the literature, with limited removal credited for wastewater treatment.

2.2.2 What Is Unknown?

- Can improved testing techniques for RO integrity be developed to demonstrate and, ultimately, make it possible to receive higher log reduction credits for RO, which could result in fewer treatment processes or modified operating and monitoring requirements?
- Can the need for MF or ultrafiltration (UF) treatment be eliminated if proper membrane integrity testing can be developed and demonstrated for membrane bioreactors (MBRs)? With MBRs, tertiary MF or UF membranes, which often are employed as pretreatment upstream of RO at AWTFs, may be unnecessary if suitable integrity testing methods can be developed and demonstrated for MBR systems.

- Can the need for an ESB be eliminated by providing additional log reduction credits through the use of additional treatment processes?

- Can standardized techniques be developed for establishing log reduction credits for advanced water treatment processes?

- Can advanced techniques (e.g., TRASAR® technology,[9] high-resolution online particle counting, real-time detection through multi-angle light scattering) be developed to obtain higher log reduction credits for potable reuse treatment processes?

- Because the current bulk organic surrogate measures [e.g., TOC, chemical oxygen demand (COD)] for the control of trace organic compounds (TrOCs) do not reflect the toxicity caused by the presence of TrOCs and the safety of advanced treated water, can alternative measures be developed?

- Is TOC an appropriate surrogate to ensure the safety of advanced treated water relative to TrOCs? Or are newer systems that target specific fractions of TOC (such as the trihalomethane-like TrOCs), more appropriate?

- Can online biosensing be improved to allow its use for full-scale application?

- Do short-term *in vitro* toxicity analyses adequately reflect the toxicity risks of lifetime consumption of water produced by DPR?

2.3 Regulatory Considerations Affecting Treatment Trains

Although potable reuse guidelines have been developed by the USEPA and were recently updated in 2012, no federal regulations currently exist for DPR. Potable reuse regulations, which have been developed by only a handful of states and only for IPR, vary in specific requirements. Typically, treatment selection is driven by several common regulatory requirements: (1) low bulk organic limits (e.g., TOC, COD); (2) pathogen log reduction requirements; and (3) the use of multiple treatment barriers for the control of pathogens and organics.

Examples of regulatory requirements that have driven treatment selection include:

- California's IPR regulations for subsurface application (i.e., groundwater injection) require the use of RO and limit TOC to less than 0.5 mg/L for the complete use of advanced treated water with no dilution. In addition, pathogen log reduction requirements of 12 log for viruses, 10 log for *Cryptosporidium*, and 10 log for *Giardia* are required from the raw wastewater to the finished water. Multiple barriers are required indirectly by limiting the maximum pathogen log reduction credit granted to each treatment step to 6 log, which is significantly below the total log reduction requirements, and by requiring RO and an AOP.

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[9] A product of Nalco Water, 3D TRASAR Technology® is used to detect upsets that precede scaling, corrosion, and biofouling of reverse osmosis membranes, and then delivers the appropriate chemical response. http://www.nalco.com/services/3d-trasar.htm.

- Florida's regulations for IPR limit TOC to 3 mg/L and specifically state that treatment "…shall include processes which serve as multiple barriers for control of organic compounds and pathogens" (FAC, 62-610).

- The Republic of Singapore's water quality requirements for NEWater, which is used for IPR through surface water augmentation. The TOC limit for NEWater is 0.1 mg/L.

- The Texas Commission on Environmental Quality (TCEQ) uses WWTP effluent as the starting point for pathogen reduction requirements for DPR projects (in contrast, California uses raw wastewater as the starting point for IPR projects). Consequently, for DPR trains, TCEQ has established minimum log reduction values of 8.0 log for viruses, 5.5 log for *Cryptosporidium*, and 6.0 for *Giardia*. These values may be increased by the TCEQ based on site-specific WWTP effluent concentrations. Texas has not established specific TOC limits for potable reuse projects.

- Virginia's Occoquan Policy, which is the regulatory policy defining requirements for the long-standing IPR project of the Upper Occoquan Service Authority, dictates a COD limit of 10 mg/L (approximately 4 mg/L of TOC).

Although most full-scale potable reuse projects have provided multiple barriers to pathogens and organics, the specific treatment technologies employed at each treatment plant vary depending on local regulations and site-specific requirements (**Table 2-1**).

Table 2-1: Treatment Technologies Employed at Operational Potable Reuse Plants

Project	Type of Potable Reuse	Year First Online	Capacity (mgd)	Current Advanced Treatment
Upper Occoquan Service Authority; VA	Surface water augmentation	1978	54	Lime + GMF + GAC + Cl_2
Hueco Bolson Recharge Project, TX	Groundwater recharge by direct injection and spreading basins	1985	10	Lime + GMF + O_3 + GAC + Cl_2
West Basin, CA	Groundwater recharge by direct injection, and various industrial applications	1993	12.5	MF+RO+UV/AOP
Gwinnett County, GA	Surface water augmentation	2000	60	Coag/Sed + UF + O_3 + BAC + O_3
Singapore NEWater	Industrial reuse with a limited amount (5 percent) of surface water augmentation	2000	166[a] (four plants)	MF + RO + UV disinfection
Los Alamitos Seawater Barrier, CA	Groundwater recharge by direct injection	2006	8	MF+RO +UV/AOP
Orange County Water District Groundwater Replenishment System, CA	Groundwater recharge by direct injection and spreading basins	2008	100	MF+RO+UV/AOP

From Schimmoller (2014).

Acronyms: mgd: Million gallons per day. GMF = Granular media filtration. GAC = Granular activated carbon adsorption. Cl_2 = Chlorine disinfection. O_3 = Ozone. MF = Microfiltration. RO = Reverse osmosis. UV/AOP = Ultraviolet with advanced oxidation. Coag/Sed = Coagulation/sedimentation. UF = Ultrafiltration. BAC = Biologically active carbon filtration. UV = Ultraviolet.

[a] As of August 2016.

For example, California's IPR regulations for subsurface injection require the use of RO and limit the TOC concentration in the injectate to 0.5 mg/L. Conversely, the COD limits for projects in Virginia and Georgia have resulted in non-RO-based treatment trains, which can be more suitable for inland locations.

Because existing regulations and past potable reuse projects have focused primarily on IPR, the focus of WRRF-11-02 was on the multiple pathogen and chemical contaminant barriers necessary for DPR. The Expert Panel for WRRF-11-02 established criteria for pathogens and chemical contaminants to protect public health for potable reuse projects, as described in **Sections 2.3.1** and **2.3.2**.

2.3.1 Pathogens

As measured from the raw wastewater to finished water suitable for drinking, AWTFs should provide the following pathogen removals: 12-log reduction for enteric viruses, 10-log reduction of *Cryptosporidium*, and 9-log reduction of total coliform bacteria. The Independent Advisory Panel assembled for WRRF-11-02 concluded that "…this criteria would ensure that reclaimed water would be free of pathogenic microorganisms with a large margin of safety (probably greater than being achieved for many conventional water supplies) and, therefore, could be safely used for potable purposes."

2.3.2 Chemical Contaminants

Compliance with all regulated chemicals and health advisories established by the USEPA is required. Compliance with five DBP limits should be met (i.e., trihalomethanes, HAA5, NDMA, bromate, and chlorate). Two other categories of chemicals should be monitored to evaluate the efficiency of treatment train performance in removing trace organics: (1) unregulated chemicals of interest from the standpoint of public health, and (2) compounds useful for evaluating the removal of organic chemicals during various types of treatment. The Expert Panel also noted that monitoring for surrogate parameters, such as TOC, is useful in confirming process performance. These criteria were not intended to preempt the regulatory decision-making process for permitting DPR, but were developed as guidelines to be used to evaluate proposed treatment train performance.

2.4 Recent and Ongoing Work Affecting the Selection of Treatment Trains for Direct Potable Reuse

Other recent and ongoing projects, regulatory activities, and research may have a significant impact on the evaluation and selection of DPR treatment trains. A summary of this work and its relevance to DPR treatment train selection is provided in **Sections 2.4.1** to **2.4.7**.

2.4.1 Direct Potable Reuse Pilot Project in El Paso, Texas

El Paso Water Utilities conducted a pilot test in 2015 using MF, nanofiltration (NF), RO, and UV/AOP for a future DPR project. Based on the results of this testing, El Paso is planning to use NF rather than RO. Pathogen log reduction requirements for the advanced water treatment train were established as 8 log for viruses, 5.5 log for *Cryptosporidium,* and 6 log for *Giardia*. The basis for these log reduction values is discussed in **Section 2.5.1**.

2.4.2 Establishing Additional Log Reduction Credits for Wastewater Treatment Plants (WRRF-14-02)

California's pathogen log reduction requirements for potable reuse are based on conservative maximum values in raw wastewater derived from literature review with limited removal credited to treatment at the WWTP (i.e., 1-log reduction for viruses and 1- to 2-log reduction for bacteria for activated sludge facilities with primary and secondary wastewater treatment). Pathogen concentrations in raw wastewater and secondary-treated wastewater effluent are being investigated in an ongoing study (WRRF-14-02); the findings may result in a re-evaluation of current regulatory log reduction requirements established by California.

Based on the results of the literature review, it was found that relatively high concentrations of certain viruses are present in raw wastewater (e.g., *Calciviruses* are present at concentrations of 10^9), adding credibility to the WRRF-11-02 Expert Panel's recommendation of 12-log reduction for DPR.

2.4.3 Suitability of Total Organic Carbon and Chemical Oxygen Demand as Surrogate Measures for Trace Organic Compounds (WRRF-15-04)

Historically, TOC and COD have been used as surrogate measures for the removal of TrOCs that are unknown or difficult to measure in advanced treated water; however, these bulk parameters may not be reflective of a water's safety with respect to TrOCs. The suitability of TOC as a surrogate for potable reuse and the evaluation of other possible surrogates will be investigated in WRRF-15-04, which is in the selection phase.

2.4.4 Alternative Treatment Approaches

Because of the high cost and difficulty in disposing of RO concentrate at inland locations, as well as the significant energy consumption of RO, an increasing amount of research has been conducted on alternative technologies for potable reuse. In a number of studies (e.g., WRF91188, WRRF-08-05, WRRF-12-12), it has been found that ozone, biologically active carbon (BAC), and GAC are capable of achieving excellent bulk and TrOC removals and significant pathogen reduction. The use of ozone, BAC, and GAC is being studied extensively (i.e., WRRF-13-09, WRRF-13-10, WRRF-14-16, WRRF-15-10, WRRF-15-11). Furthermore, El Paso Water Utilities has pilot tested – and is planning on incorporating into their full-scale DPR project – NF in place of RO to limit the TDS concentration in the concentrate stream and allow a surface discharge.

2.4.5 Online Biosensing

Because the analysis time for biological tests is relatively long, it may necessitate having large-volume and costly ESBs with sufficient retention of advanced treated water to confirm suitable microbial quality prior to distribution. In WRRF-11-01, it is reported that online biosensing is not yet ready for full-scale application; however, when or if online biosensing becomes practical, it could reduce the size of ESBs and possibly reduce log reduction requirements. Significantly more development and testing of biosensors are required to demonstrate their ability to provide sufficient sensitivity, precision, and long-term reliability.

2.4.6 California's Draft Regulations for Indirect Potable Reuse Using Surface Water Augmentation

California's draft regulations for surface water augmentation require 8-log reduction of viruses, 8-log reduction of *Cryptosporidium*, and 7-log reduction of *Giardia* prior to discharge to a reservoir that provides mixing such that a 24-hour pulse of advanced treated water cannot comprise more than 1 percent of the water withdrawn at any time. Where the reservoir provides mixing such that a 24-hour pulse of advanced treated water can comprise between 1 and 10 percent of the withdrawn water, an extra log reduction of each organism is required. These log reduction values are from raw wastewater to water discharged to the reservoir, not to tap. The additional log reduction required for scenarios with less mixing may influence log reduction requirements for DPR projects.

2.5 Example Treatment Trains for Direct Potable Reuse

The example treatment trains for DPR projects presented in Tchobanoglous et al. (2015) are shown in **Figure 2-1**. Although RO is included in Treatment Trains #1 and #2 and may be required in some instances to meet customer-specific TDS goals, the development of non-RO-based trains (Treatment Train #3) is critical because the use of RO may be impractical for some utilities, especially those at inland locations where the convenient (and inexpensive) disposal of RO concentrate is not feasible. Other combinations of treatment processes are possible for Treatment Train #3, but are not presented here for purposes of clarity.

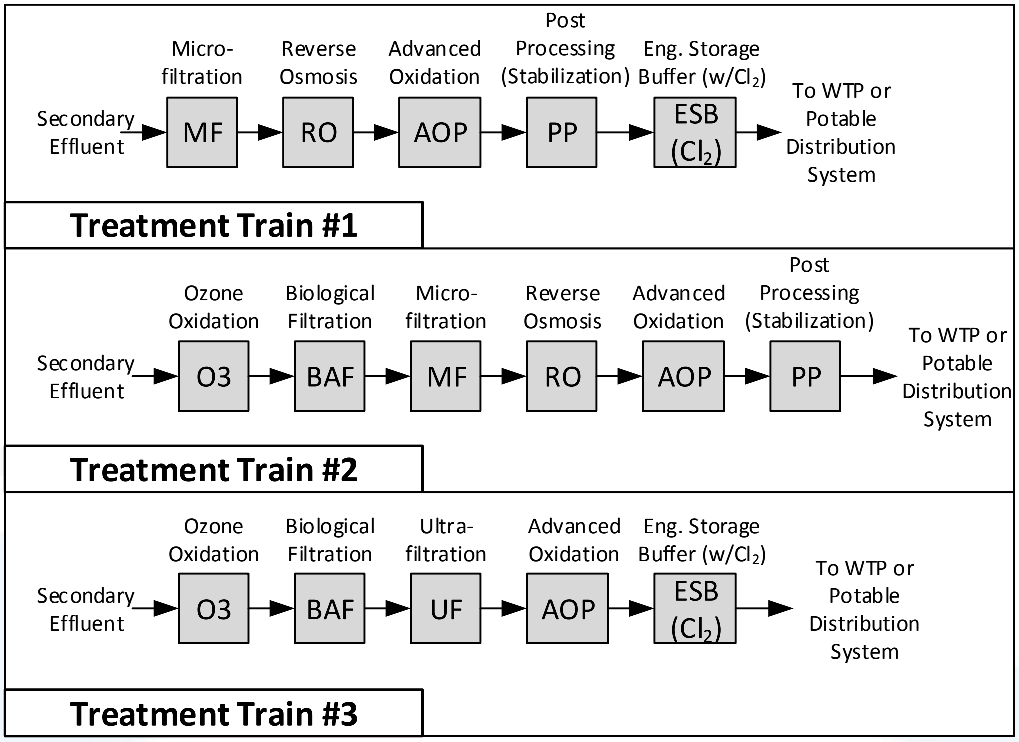

Figure 2-1: Example treatment trains for direct potable reuse (adopted from Tchobanoglous et al., 2015). Note: Direct discharge to a potable water distribution system was shown, but not considered feasible at the present time, in the source document.

Treatment Trains #1 and #3 incorporate the use of an ESB with chlorine disinfection to ensure suitable water quality before distribution, whereas Treatment Train #2 provides additional upstream treatment and forgoes the use of an ESB based on providing an additional pathogen barrier. Additional treatment in lieu of an ESB may be desirable in some locations because of the large footprint requirements and hydraulic constraints associated with ESBs, especially for treatment plants of significant size.

2.5.1 Pathogen Removal

Expected log reduction credits for each of the three DPR treatment train examples are shown in **Tables 2-2, 2-3**, and **2-4**, respectively. Note that the log reduction credits shown do not include pathogen reduction credits for the upstream WWTP or for the downstream drinking water treatment facility (DWTF) where the advanced treated water is blended upstream of the DWTF. All three example treatment trains provide significant removal of pathogens and meet the criteria developed in WRRF-11-02. Treatment Trains #1 and #2 provide more removal of *Cryptosporidium* than Treatment Train #3 (12 log versus 10 log), but Treatment Train #3 provides more removal of viruses than Treatment Trains #1 and #2 (16 log versus 12 log). Virus removal for Treatment Train #2 could be increased to 16 log with the addition of free chlorine disinfection (without an ESB), which could be provided inexpensively. If higher CTs were used, both chlorine and ozone could consistently achieve higher log reductions than shown in **Table 2-2**.

Recent and ongoing research may impact the application of some of these treatment technologies in potable reuse schemes or require special considerations for their use, including:

- **Online Monitoring for Reverse Osmosis Integrity:** Based on preliminary results from WRRF-12-07 and WRRF-14-10, it appears that online water quality monitoring techniques (e.g., TRASAR®) may lead to higher log reduction credits for RO, which could result in fewer treatment processes or modified operating and monitoring requirements.

- **Ozone Disinfection Byproducts:** Ozone has the potential to produce unwanted DBPs, such as bromate and NDMA (WRRF-08-05, WRRF-11-08). Mitigation techniques include the use of BAC downstream of ozone to remove NDMA to below pre-ozone levels [WRRF-11-08, Gerrity (2015)], and ammonia addition or the application of ozone at sub-residual doses can control the formation of bromate.

- **Membrane Bioreactors:** MBRs, which have become popular for wastewater treatment, may eliminate the need for MF/UF treatment if proper membrane integrity testing can be provided by manufacturers to confirm adequate pathogen log reduction.

- **Engineered Storage Buffer:** For DPR implementation, in WRRF-12-06, it is suggested that pathogen log reduction credit for each unit process can only be given if the failure response time (i.e., time to sample, analyze the sample, and react to the result) is less than the hydraulic retention time in the ESB. Providing adequate retention time to meet the failure response time (hours or days) can be prohibitively expensive for medium- to large-sized AWTFs; however, providing additional log reduction through the use of additional treatment processes (as shown for Treatment Train #2 in **Figure 2-1**) may eliminate the need for an ESB.

Table 2-2: Pathogen Log Reduction Credits for Treatment Train #1 for Direct Potable Reuse

Pathogen	MF[a]	RO[b]	UV/AOP[c]	ESB with Cl_2[d, e]	Total
Virus	0	2	6	4	12 log
Cryptosporidium	4	2	6	0	12 log
Total Coliform[f]	3	2	6	4	15 log

[a] Four-log reduction of *Cryptosporidium* has been assumed for microfiltration (MF), based on credit commonly granted by states for membranes passing daily membrane integrity tests.

[b] Two-log reduction of viruses, *Cryptosporidium,* and *Giardia* have been assumed for reverse osmosis (RO), based on credit commonly granted by states for online monitoring of conductivity or total organic carbon.

[c] Six-log reduction of viruses and *Cryptosporidium* have been assumed for ultraviolet/advanced oxidation processes (UV/AOP), based on testing by ultraviolet manufacturers.

[d] Per the USEPA Surface Water Treatment Rule, free chlorine provides 4-log virus inactivation at a CT of 6 mg/L-min at a temperature of 10°C.

[e] Actually demonstrated values (Gerringer et al., 2015) or values referenced by WRRF-12-06.

[f] Both chlorine and ozone likely will achieve higher log reduction values than shown if higher CTs are used.

Table 2-3: Pathogen Log Reduction Credits for Treatment Train #2 for Direct Potable Reuse

Pathogen	O_3[a,b]	BAF	MF	RO	UV/AOP	Total
Virus	4	0	0	2	6	12-log
Cryptosporidium	0	0	4	2	6	12-log
Total Coliform[c]	2-4	0	3	2	6	>13-log

[a] Per the USEPA Surface Water Treatment Rule, ozone provides 4-log virus inactivation at a CT of 1 mg/L-min at 10°C.

[b] Both chlorine and ozone likely will achieve higher log reduction values than shown if higher CTs are used.

[c] Actually demonstrated values (Gerringer et al., 2015) or values referenced by WRRF-12-06.

Table 2-4: Pathogen Log Reduction Credits for Treatment Train #3 for Direct Potable Reuse

Pathogen	O_3[a, b]	BAF	UF[c]	UV/AOP[d]	ESB with Cl_2[b,e]	Total
Virus	4	0	2	6	4	16-log
Cryptosporidium	0	0	4	6	0	10-log
Total Coliform[f]	2-4	0	3	6	4	>15-log

[a] Per the USEPA Surface Water Treatment Rule, ozone provides 4-log virus inactivation at a CT of 1 mg/L-min at 10°C.

[b] Both chlorine and ozone likely will achieve higher log reduction values than shown if higher CTs are used.

[c] Two-log reduction of viruses has been assumed based on MS-2 phage challenge testing conducted by ultrafiltration (UF) module manufacturers under National Science Foundation (NSF) Environmental Technology Verification and California Title 22 Certification Programs.

[d] Six-log reduction of viruses and *Cryptosporidium* have been assumed for UV/AOP based on testing by UV manufacturers.

[e] Per the USEPA Surface Water Treatment Rule, free chlorine provides 4-log virus inactivation at a CT of 6 mg/L-min at a temperature of 10°C.

[f] Actually demonstrated values (Gerringer et al., 2015) or values referenced by WRRF-12-06.

2.5.2 Alternative Approaches to Establishing Advanced Water Treatment Log Reductions

The DPR project for El Paso Water Utilities has taken a different approach to establishing pathogen log reduction values for the advanced water treatment train. To establish the log reduction values, the TCEQ required El Paso Water Utilities to measure levels of viruses, *Cryptosporidium,* and *Giardia* in the source water to the AWTF (unchlorinated secondary-treated wastewater effluent from the Bustamante Wastewater Treatment Plant) in a manner similar to what the USEPA requires under the Long Term 2 Enhanced Surface Water Treatment Rule to determine what level of *Cryptosporidium* reduction is required when treating surface waters serving as the source of drinking water. Log reductions were then preliminarily determined based on effluent levels and the concentration limits established for the advanced treated water, as shown in **Table 2-5**. The resulting pathogen log reductions are significantly less than those required by the Division of Drinking Water of the California State Water Resources Control Board and recommended by the Expert Panel; however, it is uncertain that the maximum secondary-treated wastewater effluent pathogen concentrations presented in **Table 2-5** include epidemic conditions that may result in higher pathogen concentrations in raw wastewater and secondary-treated wastewater effluent. Additional insight into this issue should be provided from the results of another WRRF study (WRRF-14-02).

Table 2-5: Texas Commission on Environmental Quality's Proposed Pathogen Log Reduction Requirements for El Paso Water Utilities' Direct Potable Reuse Project

Criteria	Virus[a]	*Cryptosporidium*	*Giardia*
Maximum concentration measured in secondary-treated wastewater effluent	0.46 MPN/L	238 oocysts/L	358 cysts/L
Advanced treated water goal	$<2.2 \times 10^{-7}$ MPN/L	$<3.0 \times 10^{-5}$ oocysts/L	$<7.0 \times 10^{-6}$ cysts/L
Projected inactivation/removal requirement	6.5	7	8

[a] Total culturable viruses.

From Trejo et al. (2016).

2.5.3 Trace Organics and Chemical Contaminant Removal

Historically, the presence of TrOCs and other chemical contaminants in water from AWTFs have been controlled through specific TOC or COD regulatory limits, maximum contaminant levels and notification limits for specific chemicals (e.g., SOCs, VOCs), and the requirement for additional treatment processes (e.g., advanced oxidation in California). The use of a bulk organic surrogate (e.g., TOC, COD) for the control of TrOCs has been questioned because the surrogate does not accurately reflect toxicity caused by the presence of TrOCs and, therefore, the safety of advanced treated water. Regulatory approaches range from a stringent TOC limit of 0.5 mg/L in California (for direct groundwater injection) to COD limits of 10 mg/L and 18 mg/L in Virginia (Upper Occoquan Service Authority) and Georgia (Gwinnett County), respectively, for surface water augmentation. The California TOC requirement, which also is being considered for DPR projects, is less than the TOC concentration in nearly all drinking water supplies derived from the conventional treatment of surface waters. Furthermore, regulating to such an extremely low TOC level for advanced treated water may necessitate RO treatment without materially increasing public health protection. In WRRF-11-02-2, it was reported that except for a select few contaminants that are difficult to remove by RO, AOP, or BAF, most trace organics present in wastewater are at concentrations not of concern to human health. Research project WRRF-15-04, which should begin in the summer of 2016, will investigate the suitability of TOC as a surrogate and potentially recommend alternative approaches to ensuring the safety of advanced treated water relative to TrOCs.

All three example treatment trains for DPR provide multiple barriers to TrOCs and chemical contaminants (**Table 2-6**). The RO-based trains (#1 and #2) can reliably meet California's current requirements for potable reuse and can effectively reduce TrOCs as demonstrated for many years at the Groundwater Replenishment System in Orange County, California. Treatment Train #3 could not reliably meet California's TOC limit (0.5 mg/L) at most locations, although the suitability of this limit is questionable and will be studied in WRRF-15-04 (as discussed above).

No one process removes all contaminants, so maintaining multiple barriers is important. Rejection by RO of small, polar compounds (such as NDMA) is low (Plumlee et al., 2008), as is that of low molecular weight non-ionic, hydrophilic compounds, including the DBPs chloroform and bromoform (WRRF-02-001). Alternative compounds, such as flame retardants [e.g., tris(2-carboxyethyl)phosphine (TCEP)], are resistant to AOPs (WRRF-09-10).

Table 2-6: Significant Barriers to Trace Organics and Chemical Contaminants Provided in Each Example Treatment Train for Direct Potable Reuse

DPR Treatment Train	Number of Significant Barriers	Barriers Provided
#1	2	RO; AOP
#2	3	O_3/BAF; RO; AOP
#3	2	O_3/BAF; AOP

GAC, used extensively at drinking water plants (and in some full-scale AWTFs) for the removal of trace organics and chemical contaminants, could be applied easily to the three DPR treatment train examples to significantly enhance organics removal, if desired. For example, Treatment Train #3 could be easily modified to incorporate GAC downstream of the biological filtration process by designing dual filtration contactors (**Figure 2-2**); in fact, the use of GAC downstream of BAF will be pilot tested in Virginia in summer 2016 for a full-scale potable reuse application (Schimmoller, 2016).

2.5.4 Other Water Quality Considerations Affecting Treatment

Other water quality considerations also may influence the selection of treatment train processes, including nitrogen, TDS, and DBPs.

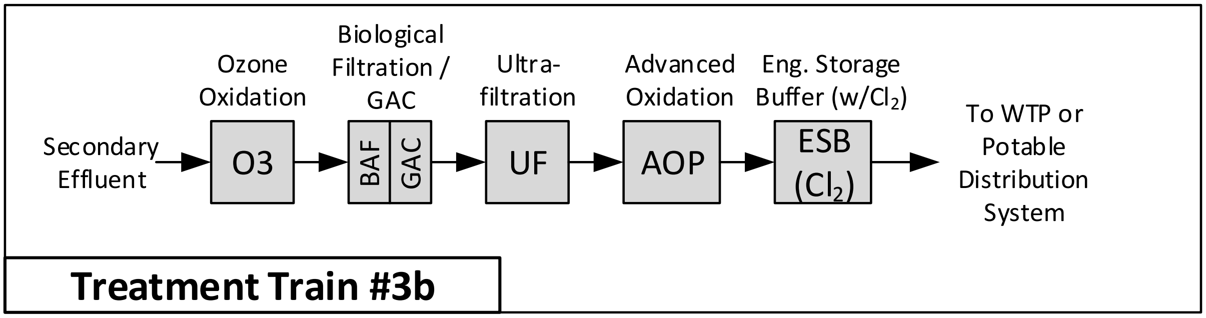

Figure 2-2: Incorporation of granular activated carbon into the process for Treatment Train #3 to enhance the removal of trace organics.

2.5.4.1 Nitrogen

Some WWTPs located in coastal areas with discharges into the ocean are not required to provide nitrogen removal. As a result, secondary-treated wastewater effluent from these plants generally contain high nitrogen concentrations either in the form of nitrate (for partially nitrifying plants) or ammonia (for non-nitrifying treatment plants). In addition, diurnal loadings and plant recycle streams (e.g., centrate return) can result in significant hourly fluctuations in the WWTP effluent nitrogen concentration, even for plants that consistently provide average nitrogen concentrations below 10 mg/L. Consequently, for DPR applications, these WWTPs should be upgraded to meet drinking water nitrogen limits (i.e., nitrate-N of 10 mg/L or less) or additional nitrogen removals must be achieved through advanced treatment processes, such as RO and ion exchange. How nitrogen removal is provided will depend on site-specific conditions, such as cost, space, and complexity of operation.

2.5.4.2 Total Dissolved Solids

The TDS concentration of secondary-treated wastewater effluent often is 200 to 400 mg/L higher than potable water for a given system, due to the addition of salt as water is used domestically and discharged to the collection system. Consequently, depending on the TDS concentration of the community's main water supply and the percentage of potable reuse practiced, some TDS removal may be required to avoid elevated concentrations.

A typical goal is to provide a TDS concentration less than the USEPA's secondary maximum contaminant level (500 mg/L), although the required value is site-specific and depends on consumer preferences in a given region considering consumers in some geographic areas are accustomed to potable water with much higher TDS concentrations.

Treatment Trains #1 and #2 provide significant TDS removal through the RO process. Treatment Train #3 does not provide TDS removal; therefore, TDS goals would need to be met by blending with other water or with additional treatment processes, such as RO and NF. NF operates at a significantly lower pressure than RO. In addition, NF provides limited rejection of monovalent ions (e.g., sodium and chloride), but provides excellent rejection of divalent ions (e.g., calcium and magnesium). Consequently, the specific ion composition of the water will influence the selection of the appropriate membrane process.

2.5.4.3 Disinfection Byproducts

Disinfectants and oxidants used in the AWTF process can react with naturally occurring materials and dissolved organic matter in water to form DBPs, which may be a concern for DPR projects. Common types of DBPs that are currently regulated or are actively being considered for regulation in drinking water systems include trihalomethanes, haloacetic acids (HAAs), chlorate, perchlorate, nitrosamines (such as NDMA), and bromate. Controlling the formation of DBPs can be complicated and includes the consideration of numerous parameters, such as pH, temperature, contact time, dosing location, bromide, DOC, organic precursors, and other factors.

Monochloramine can be added upstream of MF/UF and NF/RO to control biological fouling of the membranes; however, it has been shown to form NDMA and other nitrosamines when used in potable reuse applications. Because of the difficulty in controlling chlorine-to-ammonia ratios, higher NDMA concentrations appear to occur when ammonia and chlorine are added separately to the bulk water; this activity can lead to the formation of dichloramine, which forms NDMA more rapidly than monochloramine. Mitigation approaches have included the use of preformed monochloramine (which is prepared outside of the main bulk water stream and then dosed at the appropriate location), use of UV/AOP to destroy NDMA that has formed, and application of free chlorine followed by monochloramine, although the formation of other DBPs is of concern with this approach. Because NDMA is rejected poorly by RO membranes (25 to 50 percent), NDMA formation cannot be mitigated effectively by RO alone, requiring the UV/AOP process be sized properly to handle increased NDMA concentration.

Free chlorine disinfection sometimes is included near the end of AWTFs to provide disinfection, primarily targeted for viruses. The formation of trihalomethanes and HAAs can occur in this situation. Because of the low organic concentration in AWTF finished water, the concentrations of DBPs formed typically are well below the nationally regulated values for drinking water [80 and 60 micrograms per liter (µg/L) for total trihalomethanes and HAA5, respectively].

Ozone in DPR trains may be used for the pretreatment of MF/UF for flux improvement, oxidation of organic matter including trace organics, and disinfection of pathogens. Bromate, which is regulated at 10 µg/L for drinking water systems, can form with ozone addition, especially when bromide concentrations are elevated and a measurable ozone residual is generated. Ozone dosing must be controlled carefully to prevent the formation of bromate. As reported in WRRF-11-02 and WRRF-08-05, it was found that dosing ozone at an ozone-to-TOC ratio of less than 0.9 mg O_3/mg TOC was necessary to control bromate formation below regulated limits, although this ratio can vary significantly between waters. Mitigation techniques to limit the formation of bromate include pH suppression, ammonia addition, and chloramine addition. Ozone addition in potable reuse schemes also can form significant concentrations of NDMA, although the use of downstream BAC has been shown to effectively remove NDMA that has formed. In Project WRRF-10-11, it was found that up to 75-percent NDMA reduction could be achieved through a BAC contactor operating at an empty bed contact time of 15 minutes.

2.6 Information Sources

A list is provided in **Table 2-7** of the WRRF, WRF, and WRA projects that were reviewed for the preparation of this chapter. Full citations for reports related to these projects, along with citations for other references and sources of information, are included in **Section 2.7**.

Table 2-7: WRRF, WRF, and WRA Research Projects Used to Prepare Chapter 2

Project No.	Project Title	Principal Investigator(s)
WRRF-02-001	Rejection of Wastewater-Derived Micropollutants in High-Pressure Membrane Applications Leading to Indirect Potable Reuse: Effects of Membrane and Micropollutant Properties	Jörg Drewes, Colorado School of Mines
WRRF-08-05	Use of Ozone in Water Reclamation for Contaminant Oxidation	Shane Snyder, University of Arizona
WRRF-09-10	Use of UV and Fluorescence Spectra as Surrogate Measures for Contaminant Oxidation and Disinfection in the Ozone/H_2O_2 Advanced Oxidation Process	Shane Snyder, University of Arizona
WRRF-11-01	Monitoring for Reliability and Process Control of Potable Reuse Applications	Ian Pepper, University of Arizona
WRRF-11-02	Equivalency of Advanced Treatment Trains for Potable Reuse	R. Rhodes Trussell, Trussell Technologies, Inc.
WRRF-11-08	Formation of Nitrosamines and Perfluoroalkyl Acids during Ozonation in Water Reuse Applications	Eric Dickenson, Southern Nevada Water Authority
WRRF-12-06	Guidelines for Engineered Storage for Direct Potable Reuse	Andrew Salveson, Carollo Engineers
WRRF-12-07	Methods for Integrity Testing of Nanofiltration and Reverse Osmosis Membranes	Joseph Jacangelo, MWH
WRRF-12-12	Enhancing the Soil Aquifer Treatment Process for Potable Reuse	Shane Trussell, Trussell Technologies
WRRF-13-09	Indirect Potable Reuse Investigation in Tucson, AZ	Larry Schimmoller, CH2M Hill
WRRF-13-10	Controlling Trace Organic Contaminants Using Alternative, Non-Full Advanced Treatment Technology for Indirect Potable Water Reuse	Benjamin Stanford, Hazen and Sawyer
WRRF-13-12	Evaluation of Source Water Control Options and the Impact of Selected Strategies on Direct Potable Reuse	Alan Rimer, Black & Veatch
WRRF-13-14 (WRF4508)	Assessment of Techniques to Evaluate and Demonstrate the Safety of Water from Direct Potable Reuse Treatment Facilities	Channah Rock, University of Arizona
WRRF-14-10	Enhanced Pathogen and Pollutant Monitoring of the Colorado River Municipal Water District Raw Water Production Facility at Big Spring, Texas	Eva Steinle-Darling, Carollo Engineers
WRRF-14-20 (WRA-14-01)	Developing Direct Potable Reuse Guidelines	Jeffrey Mosher, National Water Research Institute
WRRF-15-04	Characterization and Treatability of Total Organic Carbon from Direct Potable Reuse Processes Compared to Surface Water Supplies	Larry Schimmoller, CH2M
WRRF-15-10	Optimization of Ozone/Biologically Activated Carbon Treatment Processes for Potable Reuse Applications	Zia Bukhari, American Water
WRRF-15-11	Demonstration of High Quality Drinking Water Production Using Multi-Stage Ozone-Biological Filtration: A Comparison of Direct Potable Reuse with Existing Indirect Potable Reuse Practice	Kati Bell, CDM Smith, and Denise Funk, Gwinnett County Department of Water Resources

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Chapter 3: Surrogates and Log Reduction Credits for Pathogens

Prepared by Philip Brandhuber, Ph.D., HDR, Inc. (Denver, CO)

The protection of human health from the harmful effects of pathogenic microorganisms is crucial for the successful implementation of DPR. A risk-based approach, similar to that used by the Surface Water Treatment Rule under the Safe Drinking Water Act (SDWA), is appropriate for establishing that an acceptable level of human health protection is achieved by DPR. When implementing a risk-based approach, consideration must be given to the inherent uncertainties in quantifying the levels of pathogens in water, as well as the different outcomes and consequences of human exposure to these pathogens.

3.1 Identification of Key Issues

While current state-of-the-art treatment is capable of producing finished water from wastewater sources that is protective of human health, improvements can be made in the following areas:

- Methods to rapidly determine the concentration of relevant pathogens throughout treatment trains or, in the absence of this capability, suitable real-time surrogates capable of doing the same.

- Greater understanding of pathogen levels in raw wastewater and their inactivation and/or removal by individual and integrated treatment processes at AWTFs.

- Improved methods to verify pathogen inactivation and/or removal so that the full capabilities of treatment technologies are reflected in their log reduction credits.

- Improved methodologies to ensure treatment reliability is maintained through a combination of redundancy, robustness, and resilience.

3.2 Summary of Principal Findings

The following principal findings are derived from a review of literature and state regulations addressing pathogenic microorganisms found in wastewater and their reduction through various treatment processes.

3.2.1 What Is Known?

- No single pathogen, indicator, or surrogate can be used to gauge the microbial safety of water. Safe water can only be ensured by meeting multiple treatment objectives and measuring the appropriate performance indicator parameters.

- A wide range of information is available regarding pathogen treatment credits through either chemical inactivation (disinfection) or physical separation (removal).

- Available information is sufficient to design multi-barrier advanced treatment systems capable of meeting the log reduction requirements for (1) virus, *Cryptosporidium*, and *Giardia* for groundwater injection that are considered protective of human health by the Division of Drinking Water of the California State Water Resources Control Board or (2) virus, *Cryptosporidium*, and total coliform log reduction for DPR recommended by an Independent Advisory Panel organized by the National Water Research Institute (NWRI).

- Improvements in microbial detection methods will be important in expanding the existing knowledge base concerning the occurrence of pathogens in untreated wastewater and to help improve the design and operation of WWTPs. This information may lead to refinements in log reduction requirements or log reduction credits associated with specific treatment processes.

3.2.2 What Is Unknown?

- More information is needed about the occurrence of infectious microorganisms in untreated wastewater and the variables affecting such occurrences.

- Additional information and data are needed to define the actual levels of inactivation and/or reduction of these microorganisms by different treatment processes.

- A better understanding is needed of the possible transfer of pathogenicity from inactivated cells to benign cells through genetic exchange, and the possible reactivation of pathogenic cells after UV irradiation through DNA repair.

- Concerns about pathogenic microorganisms are not unique to DPR scenarios and could apply to the treatment of other sources of water (e.g., shallow groundwater, surface water, etc.).

3.3 Selection of Microbial Indicators and Enteric Pathogens

In the USEPA document, *Guidelines for Water Reuse* (USEPA, 2012), a list has been compiled of pathogens potentially present in untreated wastewater. An abridged version of this table, noting the upper bound of pathogen concentrations reported in the literature at the time of publication, is presented in **Table 3-1**. This list is not all-inclusive, however.

Other microorganisms that potentially are spread by water and also may be present in raw wastewater include bacteria (e.g., *Acinetobacter calcoaceticus, Flavobacterium meningosepticum, Klebsiella pneumoniae, Mycobacterium avium complex, Pseudomonas maltophila, Pseudomonas putida,* and *Serratia marcescens*), protozoa (e.g., *Isospora*), algae (e.g., *Schizothrix calcicola*), and viruses that cause diarrhea but have not yet been identified as being waterborne (Rock et al., 2016).

3.3.1 Pathogen Loading

A key aspect in establishing log reduction value requirements for DPR is obtaining an accurate estimation of pathogen loading in untreated wastewater and secondary-treated wastewater effluent, with particular emphasis on the maximum concentrations of pathogens that could be present.

Table 3-1: Infectious Agents Potentially Present in Untreated (Raw) Wastewater

Pathogen	Disease	Concentration n Raw Wastewater (Number per Liter)
Bacteria		
Shigella	Shigellosis (bacillary dysentery)	Up to 10^4
Salmonella	Salmonellosis, gastroenteritis, reactive arthritis, typhoid fever	Up to 10^5
Vibro cholera	Cholera	Up to 10^5
Enteropathogenic Escherichia coli	Gastroenteritis and septicemia, hemolytic uremic syndrome (HUS)	
Yersinia	Yersiniosis, gastroenteritis, and septicemia	
Leptospira	Leptospirosis	
Campylobacter	Gastroenteritis, reactive arthritis, Guillain-Barré syndrome	Up to 10^4
Atypical mycobacteria	Respiratory illness (hypersensitivity pneumonitis)	
Legionella	Respiratory illness (pneumonia, Pontiac fever)	
Staphylococcus	Skin, eye, ear infections, septicemia	
Pseudomonas	Skin, eye, ear infections	
Helicobacter	Chronic gastritis, ulcers, gastric cancer	
Protozoa		
Entamoeba	Amebiasis (amebic dysentery)	Up to 10^2
Giardia	Giardiasis (gastroenteritis)	Up to 10^5
Cryptosporidium	Cryptosporidiosis, diarrhea, fever	Up to 10^4
Microsporidia	Diarrhea	
Cyclospora	Cyclosporiasis (diarrhea, bloating, fever, stomach cramps, and muscle aches)	
Toxoplasma	Toxoplasmosis	
Viruses		
Picornaviruses	Gastroenteritis	
Enteroviruses	Gastroenteritis, heart anomalies, meningitis, respiratory illness, nervous disorders, others	Up to 10^6
Hepatitis A and E virus	Infectious hepatitis	
Adenovirus	Respiratory disease, eye infections, gastroenteritis (serotype 40 and 41)	Up to 10^6
Rotavirus	Gastroenteritis	Up to 10^5
Parvovirus	Gastroenteritis	
Astrovirus	Gastroenteritis	
Caliciviruses (including Norovirus and Sapovirus)	Gastroenteritis	Up to 10^9
Coronavirus	Gastroenteritis	

Adapted from USEPA (2012).

Reported pathogen concentrations in raw wastewater are highly variable due to a number of factors (NWRI, 2013), including (1) inputs from contribution populations; (2) original use of water; and (3) detection methods employed. Similarly, secondary-treated wastewater effluent pathogen concentrations are influenced by a number of factors (Bukhari, 2016), including: (1) treatment process; (2) seasonal effects; (3) wet weather flows; and (4) geographic location.

The ongoing project, "Establishing Additional Log Removal Credits for Wastewater Treatment" (WRRF-14-02), will provide additional insight into WWTP pathogen removal and/or inactivation performance by completing a yearlong sampling program at several WWTPs for a range of pathogens or their indicators. A goal of the project is to refine log reduction values that can be attributed to WWTPs (Bukhari, 2016).

3.3.2 Pathogen Indicators and Monitoring

Given the large number of pathogens that can survive in water, selecting suitable techniques for monitoring concentrations is inherently difficult. Traditional monitoring methods involving parameters like *Escherichia coli* (*E. coli*) or total coliform have been used for decades. Yet these techniques, based on culture methods with long turnaround times, may not be best suited for the presence of a broad range of pathogens and the need for rapid detection associated with DPR scenarios. For this reason, much effort has been focused on developing indicators (i.e., easily detectable microorganisms representative of a broader microbial group of interest) or surrogates (i.e., bulk parameter capable of measuring treatment performance). The key features of an ideal monitoring technique are rapidity, high sensitivity, selectivity, and the capability of distinguishing viable and non-viable organisms (Rock et al., 2016). A brief summary of available pathogen indicators potentially suitable for DPR applications is presented in **Table 3-2**. Other monitoring methods that can be used to assess microbiological performance of DPR processes are summarized in **Table 3-3**. More information on pathogen monitoring is presented in **Chapter 4**.

Table 3-2: Potential Pathogen Indicators Suitable for Direct Potable Reuse

Pathogen	Possible Indicator	Comments
Viruses	Bacteriophages (phages) Adenovirus	Phages are used frequently as viral indicators. Main groups include: Somatic, Male-specific F+ RNA phage, *Bacteroides fragilis* phage. Adenovirus is detectable by cell culture and molecular methods. Resistance to UV disinfection makes adenovirus a conservative indicator organism.
Bacteria	*Escherichia coli* *Enterococcus*. Fecal coliform Campylobacter	*E.coli* recommended by the U.S. Environmental Protection Agency (USEPA) as an indicator of fecal pollution. Fecal coliform monitoring currently is performed widely and may serve as a basis of comparison to past and current practices. Campylobacter monitored in Australian reuse systems.
Protozoa	*Clostridium perfringens*	Existing methods for detection of *Giardia lamblia* and *Cryptosporidium parvum* require high degree of skill. Detection of *C. perfringens* is easier and used in Europe, but not approved by the USEPA.

Adapted from Rock et al. (2016).

Table 3-3: Comparison of Microbiological Detection Methods

Monitoring Method	Includes	Features
Physical	Turbidity Light scattering Adenosine triphosphate (ATP) Microscopic identification	Involves the analysis of bulk water samples. Turbidity or light scattering monitors the presence of particles, whose increase may indicate comprise of treatment. ATP provides indications of changes in biological activity. Microscopic identification directly observes large pathogens (e.g., protozoa) by microscope. Methods are neither specific nor sensitive (turbidity, light scattering ATP) or slow and costly (microscopic).
Cell culture	Coliform bacteria Heterotrophic plate count	Plate water samples on cell culture media and await the growth of bacterial colonies on this media, which is identified and counted. It is a well-established technique, but generally is non-specific and has a slow (i.e., days) response time.
Molecular biological assay	Polymerase chain reaction (PCR) Quantitative PCR (qPCR)	Detects the presence of genetic material (DNA or RNA) of microorganisms. Highly sensitive, but cannot distinguish between viable and dead or inactivated microorganisms.
Immunological assay	Enzyme linked immunosorbent assay (ELISA) Serum neutralization tests (SNT)	Detects the presence of antibodies (antigens) that bind to specific pathogens. Highly selective, but costly with poor sensitivity; also, unable to distinguish between viable and dead or inactivated microorganisms.
Biosensor		Emerging technology based on the recognition of specific biological components in the water matrix.

Adapted from Rock et al. (2016)

3.4 Establishment of Acceptable Risk Levels and Ensuing Log Reduction Requirements for Pathogens

The SDWA establishes the minimum drinking water quality standards for public water systems in the United States. Standards set under the SDWA must be met by public water systems regardless of the original source of water. Setting standards under the SDWA is a complex process in which the USEPA must balance public health benefits with the costs associated with implementing standards. The goal of the USEPA is to restrict exposure to regulated contaminants to a level representing *de minimis* (or insignificant) risk to the public. During the development of the Surface Water Treatment Rule, the USEPA concluded that for pathogens, a 10^{-4} annual risk of infection represents a *de minimis* risk (NWRI, 2013). Hence, to remain consistent with the concept of *de minimis* risk, finished drinking water produced from reuse projects should risk no more than one infection in 10,000 persons per year. The development of log reduction values is considered further in the following sections.

3.4.1 California Log Reduction Values

The California State Water Resources Control Board has developed minimum log reduction values for target pathogenic groups (i.e., enteric viruses and parasites) for IPR using groundwater replenishment (Olivieri et al., 2016). The required log reduction values were developed based on three assumptions:

(1) a tolerable annual risk of infection of 10^{-4} per person per year (as discussed above); (2) tolerable microorganism concentrations based on dose response studies; and (3) worst-case microorganism concentrations in untreated wastewater (Olivieri et al., 2016). Based upon these assumptions, log reduction values were developed for enteric viruses, *Cryptosporidium*, and *Giardia,* as summarized in **Table 3-4**. Additional details on the development of the log reduction values may be found in Olivieri et al. (2016).

Table 3-4: Development of Required Log Reduction Values as Determined by the State of California

Item	Enteric Virus	*Giardia*	*Cryptosporidium*
Untreated wastewater maximum concentration	10^5 virus/L	10^5 cysts/L	10^4 oocysts/L
Tolerable drinking water concentration (TDWC)	2.2×10^{-7} virus/L	6.8×10^{-6} cysts /L	1.7×10^{-6} oocysts /L
Ratio of TDWC to wastewater concentration	2.2×10^{-12}	6.8×10^{-11}	1.7×10^{-10}
Required log reduction value	12	10	10

Source: Adapted from Olivieri et al. (2016). Note: In the original report, the term "density" is used rather than "concentration," as used in this adapted table. Often, the term "density" is used in place in "concentration."

3.4.2 Texas Log Reduction Values

For DPR systems, the Texas Commission on Environmental Quality (TCEQ) has established baseline log reduction requirements (shown in **Table 3-5**) that are predicated on providing treated drinking water meeting the 10^{-4} risk level for pathogens. Unlike the recommendations of an NWRI Independent Advisory Panel (see **Section 3.4.3**), the TCEQ requirements are measured relative to treated wastewater pathogen levels. TCEQ views these requirements as a point of departure and may revise them based upon water quality data collected from the treated wastewater in question. TCEQ also does not specify a log reduction requirement for total coliform; rather, TCEQ regulates total coliform in the distribution system of drinking water systems, and DPR projects must demonstrate a concentration of zero for approval. As more information regarding the infectivity of Norovirus becomes available, it is possible that viral log reduction requirements could increase (APAI, 2015).

Table 3-5: Baseline Pathogen Log Reduction for Direct Potable Reuse Required by the Texas Commission on Environmental Quality

Microbial Group	Criterion[a] (Minimum Log Reduction)
Enteric viruses	8
Cryptosporidium	5.5
Giardia	6

[a] The reduction is between treated wastewater and finished drinking water.

3.4.3 NWRI Independent Advisory Panel Log Reduction Values

As part of project WRRF-11-02, an NWRI Independent Advisory Panel was formed to develop microbiological criteria protective of human health that could be used to evaluate the performance of treatment technologies for DPR. The criteria recommend by the Panel are presented in **Table 3-6** (NWRI, 2013). Notably, the recommended log reduction requirements are measured between the raw wastewater and finished drinking water, and could include credits for existing processes in the WWTP. The Panel concluded that water treated to the levels recommended in **Table 3-6** could safely be used for potable purposes.

Table 3-6: Pathogen Log Reduction Requirements for Direct Potable Reuse Recommended by an NWRI Independent Advisory Panel for WRRF-11-02

Microbial Group	**Criterion[a] (Minimum Log Reduction)**	**Possible Surrogates**
Enteric viruses	12	MS2 bacteriophage
Cryptosporidium[b]	10	Latex microspheres, AC fine dust, inactivated *Cryptosporidium* oocysts, aerobic spores
Total coliform bacteria[c]	9	Not applicable

[a] Reduction is between raw wastewater and finished drinking water.

[b] Also documented to provide 10-log or greater reduction of *Giardia* cysts.

[c] Also, protective for enteric pathogenic bacteria.

3.5 Establishment of Technology-Based Log Reduction Credits

When designing an AWTF, the sum of validated log reduction/inactivation credit for the individual treatment processes must equal or exceed the log reduction values needed to protect human health. Quantifying the log-reduction/inactivation performance of treatment technologies has been the subject of considerable research. State regulatory agencies grant or approve reduction/inactivation credits based on available research and guidance provided by the USEPA. The log reduction values developed by California and Texas are considered in this section.

3.5.1 Division of Drinking Water of the State Water Resources Control Board

In connection with the development of rules and regulations for IPR using groundwater replenishment, the Division of Drinking Water of the California State Water Resources Control Board also developed log reduction values for individual treatment process and for water retention times above and below ground. The approved log reduction values are reported in **Table 3-7** and represent the maximum reduction credit allowances. Based on a careful review of the allowed log reduction values, an expert panel mandated to assess the feasibility of developing regulation for DPR concluded that "a similar process for assigning log reduction value credits for individual unit treatment process is feasible for DPR, however, additional process monitoring is recommended to ensure reliable treatment" (Olivieri et al., 2016). It should be noted that California is in the process of reevaluating the validation process for allocating various treatment technology log reduction values for potable reuse.

Table 3-7: Approved Log Reduction Values for Groundwater Replenishment Projects in California

Process	Pathogen Log Reduction Values		
	Virus	*Cryptosporidium*	*Giardia*
Secondary activated sludge	1.9	1.2	0.8[a]
Microfiltration or ultrafiltration	0	4	4
Filtered and disinfected secondary	5	0	0
Reverse osmosis	2	2	2
Free chlorine post reverse osmosis	4	0	3
Ultraviolet/hydrogen peroxide[b]	6	6	6
Subsurface application retention time	6	0	0
Surface application retention time[c]	6	10	10

[a] Waiting for the results of WRRF-14-02 regarding potential additional information that may support additional log reduction credits for wastewater treatment plants.

[b] 6-log reduction of virus (including adenoviruses) and 6-log reduction of protozoa, assuming the ultraviolet dose is >300 millijoules per square centimeter (mJ/cm^2) (based on advanced oxidation, typically >900 mJ/cm^2).

[c] Based on a 6-month retention time.

Source: Olivieri et al. (2016).

3.5.2 Texas Commission on Environmental Quality

The log reductions that TCEQ uses as a basis for granting credits for a particular technology are presented in **Table 3-8**. These values are compared to “upper end reductions” that have been developed based on pilot-scale and full-scale installations, as reported in WRRF-11-02 (Trussell et al., 2013). Due to the inability to directly monitor pathogen concentration in a timely manner, indirect measures are used to verify treatment performance. These measures can include methods that: (1) predict pathogen removal performance (e.g., calibrated UV sensors for UV disinfection); (2) estimate pathogen removal performance (e.g., pressure decay tests for membrane monitoring); and/or (3) evaluate overall process performance, without assessing pathogen removal performance (e.g., turbidity) (NWRI, 2015).

In several cases, the technical limitations of integrity testing and/or monitoring programs often are the controlling factors in determining log reduction credits for treatment technologies. For example, referring to **Table 3-8,** TCEQ does not recognize log reductions for RO technology, not because the technology fundamentally fails to serve as a barrier to the passage of pathogens, but because of the lack of a direct integrity test. Improved methods for RO integrity testing and/or monitoring would allow the full pathogen removal capability of the technology to be reflected in its log reduction credit.

Table 3-8: Potential Removal/Inactivation for Pathogens and Total Coliform

Process/Technology	Pathogen and Total Coliform Log Reduction							
	Cryptosporidium		*Giardia*		Virus		Total Coliform	
	TCEQ	UER	TCEQ	UER	TCEQ	UER	TCEQ	UER
Microfiltration or ultrafiltration	4	4	4	4	0	0	NA	3
Membrane bioreactor	0	4	0	4	0	0	NA	3
Reverse osmosis	0	2	0	2	0	2	NA	4
Nanofiltration	0	---	0	---	0	---	NA	---
Chlorine	0	0	1	1	3	3	NA	3
Ultraviolet irradiation disinfection	4	4	4	4	4	4	NA	5
Ultraviolet/photolysis	4	≥4	4	≥4	4	≥4	NA	≥5
Advanced oxidation processes	4	6	4	6	4	6	NA	6
Ozone	3	3	3	3	5	5	NA	3
Ozone/biological activated carbon	3	3	3	4	5	5	NA	4
Stabilization	---	---	---	---	---	---	NA	---
Engineered storage	---	---	---	---	---	---	NA	---

Adapted from APAI (2015). See Table 5-1 of APAI (2015) for caveats and limitations associated with these values.

TCEQ = Texas Commission on Environmental Quality. UER = Upper End Reduction. NA = Not applicable.

3.6 Role of Redundant, Robust, and Reliable Systems in Maintaining Suitable Levels of Pathogen Reduction

When combined with existing processes at WWTPs and integrated into a multiple barrier treatment train, treatment technologies like those listed in **Table 3-8** are capable of meeting pathogen log reduction requirements required by the Division of Drinking Water and TCEQ and recommended by the Independent Advisory Panel, as discussed previously (**Tables 3-4, 3-5**, and **3-6**). Fundamentally, the technology currently exists to produce water that meets public health protection goals. From the perspective of the control of pathogens, the primary challenge is not their treatment, but the ability to maintain the level of treatment performance that is protective of human health. The criticality of this concept must be understood in the context that the consequences of exposure to pathogens is acute – infection can occur shortly after minimal exposure compared to the majority of drinking water contaminants, which may only cause adverse health effects after long-term and repeated (chronic) exposure. This factor, combined with the lack of a rapid method for the direct detection of pathogens, necessitates integrated treatment systems of high reliability. A highly reliable process for controlling pathogens will exhibit the following characteristics (Tchobanoglous et al., 2015):

- **Redundancy**: Multiple systems are capable of removing/inactivating pathogens.
- **Robustness**: Maintain pathogen removal/inactivation under changing water quality conditions.
- **Resiliency**: Methodology to detect and respond to failures are in place, while protecting the public from exposure to pathogens.

Actions that may improve the reliability of DPR systems are discussed in **Chapters 7** to **9** of this report.

3.7 Managing Uncertainty

As discussed in the previous sections, the approach used for managing the many uncertainties encompassed in the Surface Water Treatment Rule is applicable to DPR, specifically:

- Establish appropriate risk levels for exposure to pathogens (i.e., viruses, bacteria, and protozoa) consistent with public health protection.

- Based on an understanding of the concentrations of pathogens in untreated water, specify the log reduction values required to meet the appropriate risk levels for health protection.

- Design an integrated treatment process capable of providing the necessary log reduction values using multiple barriers that consist of treatment processes with validated treatment credits.

- Monitor the performance of both individual and integrated treatment processes to ensure their abilities to reliably provide the intended log reduction values.

Using these principles, a suitably designed, well-operated, and properly maintained integrated treatment process is capable of managing pathogen risks in a DPR scenario so that human health protection goals are met.

3.8 Information Sources

A list is provided in **Table 3-9** of the WRRF projects that were reviewed for the preparation of this chapter. Full citations for reports related to these projects, along with citations for other references and sources of information, are included in **Section 3.9**.

Table 3-9: WRRF Research Projects Used to Prepare Chapter 3

Project No.	Project Title	Principal Investigator(s)
WRRF-11-02	Equivalency of Advanced Treatment Trains for Potable Reuse	R. Rhodes Trussell, Trussell Technologies, Inc.
WRRF-14-02	Establishing Additional Log Reduction Credits for Wastewater Treatment Plants	Zia Bukhari, American Water

3.9 References

APAI (2015). “Final Report: Direct Potable Reuse Resource Document.” Report prepared for the Texas Water Development Board by Alan Plummer Associates, Inc. Fort Worth, TX.

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NWRI (2013). “Final Report, Examining the Criteria for Direct Potable Reuse, Recommendations of an NWRI Independent Advisory Panel.” Report prepared by the National Water Research Institute for Project WRRF-11-02a, WateReuse Research Foundation, Alexandria, VA.

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Chapter 4: Rapid and Continuous Monitoring of Pathogens

Prepared by Channah M. Rock, Ph.D., University of Arizona (Tucson, AZ); Daniel Gerrity, Ph.D., University of Nevada, Las Vegas (Las Vegas, NV); and Dametreea Carr, University of Arizona (Tucson, AZ)

Pathogen and indicator monitoring are key issues for DPR, specifically in determining if treatment process performance is sufficient to achieve stringent public health criteria. Numerous rapid and continuous monitoring techniques are being examined as a means of improving the detection of pathogens, indicators, and surrogates with respect to sensitivity, specificity, and time, as demonstrated in the numerous research projects dedicated to the subject.

4.1 Identification of Key Issues

With online pathogen monitoring technologies still in the early phases of development, the industry has not yet determined the practicality of detecting pathogens within sufficient time constraints and to the necessary sensitivity to achieve specific risk benchmarks. Moreover, it is not clear whether such goals are necessary if robust treatment alternatives are employed. Key issues with respect to pathogen monitoring include the following.

- Rapid and continuous online monitoring for pathogen detection remains challenging due to small particle size, method sensitivity (including limits with detection and quantification), and the low concentrations of pathogens in advanced treated water, particularly with respect to verifying risk benchmarks (e.g., 10^{-4} annual risk of disease).

- Currently, there are limited options available for rapid online pathogen monitoring, with several technologies in the developmental stages.

- It is difficult to detect viruses in water due to their small size and the lack of highly sensitive technologies. This difficulty limits the log reduction credits awarded to potentially robust barriers, such as low-pressure and high-pressure membrane filtration. Consequently, many technologies have focused on bacteria or the detection of suspect "particles."

- Ideal monitoring systems include the following characteristics: high specificity, rapid/real-time online capability, high sensitivity, high accuracy (i.e., minimal false positives and false negatives), high robustness with low failure rates, simplicity, and affordability for operation and maintenance (WRRF-12-06).

- Given the high pathogen loading and decreased response times of DPR systems, monitoring of pathogens or robust surrogates may be critical to ensure the successful implementation of DPR projects.

4.2 Summary of Principal Findings

As existing and emerging pathogen monitoring technologies are evaluated and demonstrated (i.e., accuracy, sensitivity, etc.), their use in DPR treatment trains will become routine. Until then, the industry must rely on the use of robust indicators/surrogates for water quality evaluation, as well as treatment process validation.

4.2.1 What Is Known?

- Historically, total and fecal coliform bacteria have been used as indicators of fecal contamination in drinking water applications and are monitored to demonstrate compliance with the Total Coliform Rule established by the USEPA.
- From a historical perspective, indicator monitoring has proven sufficient for validating the operations of conventional DWTFs.
- Direct monitoring of protozoan pathogens, such as *Giardia* and *Cryptosporidium*, is problematic because the methods require extensive sample preparation and highly skilled technicians. A laboratory analysis of protozoan pathogens can take multiple days to complete.
- Although several real-time pathogen monitoring technologies are promising, none are ready for implementation in DPR applications.
- The potable reuse industry places a strong emphasis on critical control point (CCP) verification with surrogate parameters to ensure the integrity of unit treatment processes and to justify pathogen reduction credits. CCP verification is necessary and required regardless of the availability and use of pathogen monitoring technologies.
- Despite being unable to replicate outside of their host, viruses have a greater ability to persist in treated water than bacteria due to their small size and the resistance of some viruses to certain disinfection processes.
- The principal categories of detection methods for microorganisms are visual detection by microscopy, standard culture methods, biochemical assays, cell culture based methods, molecular biology based methods, immunological assays, and biosensors.
- Until adequate pathogen monitoring technologies are available, DPR systems will have to employ treatment trains composed of multiple treatment barriers to achieve reliability through robustness, redundancy, and resiliency.
- By employing a hazard analysis and critical control point (HACCP) framework, coupled with stringent public health criteria and sufficient degrees of conservatism (i.e., limits on pathogen credits awarded), DPR is expected to achieve adequate protection of public health even in the absence of advanced pathogen monitoring technologies.

4.2.2 What Is Unknown?

- The usefulness of emerging indicator viruses, such as Aichi, Calicivirus, and Pepper Mild Mottle Virus, for monitoring the performance of aquifer recharge, MF, and RO for virus removal is not well documented.

- The specificity and reliability of biosensors that recognize biological components ranging from a specific surface protein, antigens, enzymes, antibodies, receptors, DNA, cell components, or even the whole cell or organism by amplifying the detection of a specific target into a detectable signal are unknown.

- Problems with biosensor technologies that must be resolved include the impacts of nonspecific binding, particle size variation, aggregation of nanoparticles, and inability to differentiate viable from non-viable organisms.

- Both the sensitivity (i.e., the ability to detect very few organisms in a sample) and selectivity (i.e., the ability to distinguish slight differences between closely related species or strains) of a proposed biosensing technology must be established before it can be used.

4.3 Overview of Pathogens and Indicators

For drinking water applications, protection of public health is attained when pathogen levels are below the concentration associated with a target risk threshold, and the target concentration depends on the pathogen-specific dose response curve. Verification of target pathogen concentrations is challenging because of limited online, real-time monitoring technologies. Not only are these technologies limited in number, but they also are costly, lack high sensitivity, and are not highly selective in distinguishing slight differences between closely related species or strains [e.g., pathogenic versus non-pathogenic *Escherichia coli* (*E. coli*)] (Rock et al., 2014).

4.3.1 Pathogens of Concern

Pathogens of concern in DPR systems include the following groups: bacteria, viruses and protozoa. Although unable to replicate outside of their host, viruses have a greater ability to persist in treated water than bacteria due to their small size (which hinders physical removal) and the resistance of some viruses to certain disinfection processes (e.g., UV resistance of adenovirus). According to Myrmel et al. (2006), viruses are resilient to environmental stresses, but they can be physically removed or inactivated to varying degrees during water treatment by coagulation/flocculation/sedimentation, media or membrane filtration, chemical disinfection, and UV disinfection. Bacteria, on the other hand, have the ability to replicate outside of their host, but are much less resilient to environmental stresses. Their larger size makes them highly susceptible to physical removal by granular media and membrane filtration processes, and they generally are susceptible to all forms of disinfection. Protozoa also are larger in size, but they are resistant to some chemical disinfectants, particularly chlorination; therefore, protozoa are commonly removed from water using membrane filtration, ozone oxidation, and UV disinfection (Khan, 2013).

4.3.2 Pathogens and Indicators Based on Guidelines of the U.S. Environmental Protection Agency

A summary of pathogens and indicators is provided in **Table 4-1**, which is based on the 2012 USEPA *Guidelines for Water Reuse*. In addition to expected concentrations in raw wastewater, the final drinking water concentrations needed to achieve a 10^{-4} annual risk of infection for each microorganism are listed. The corresponding log reductions through the overall treatment train (i.e., raw sewage to distribution system) are noted also. There are several limitations that should be noted with this approach. First, the 10^{-4} annual risk benchmark often is used in discussions of public health criteria in potable reuse applications, but it is not an official USEPA benchmark. In addition, targeting a 10^{-4} annual risk of infection for a specific pathogen does not result in an overall risk of 10^{-4} because of the collective risk posed by all pathogens. Finally, this analysis is limited by the paucity of occurrence and/or dose response data available in the literature. Dose response data (exponential or beta-Poisson) are only available for a small number of pathogens of concern in DPR applications (QMRA Wiki, 2015); however, the available data provide a general framework for developing relevant public health criteria for DPR applications.

4.3.3 Direct Detection Constraints and Workarounds

For drinking water applications, direct detection of many of the microbes listed in **Table 4-1** is hindered by constraints related to time, cost, expertise, equipment, and others. These methods and their limitations are discussed in the following sections. In these instances, drinking water systems must rely on fecal indicators or surrogates of process performance to obtain more rapid or even real-time information. A summary of some pathogens of interest and their corresponding indicators or surrogates is provided in **Table 4-2**. Unfortunately, many indicators are not ideal in that they may occur naturally in the environment or they may not be as resistant to environmental stressors or treatment as the target pathogen. Furthermore, some surrogates are not necessarily linked to fecal contamination, so while they may provide a measure of treatment performance, they may not indicate the presence of target pathogens; therefore, the industry still is seeking advancements in direct pathogen monitoring technologies to address these limitations.

4.4 Current Pathogen and Indicator Monitoring Techniques Used for Direct Potable Reuse Treatment

Microbiological detection methods can be divided into several categories, including visual detection by microscopy, standard culture methods, biochemical assays, cell culture based methods, molecular biology based methods, immunological assays, and biosensors, among others. Each method has varying characteristics that can be useful for detecting bacteria, protozoa, and/or viruses in water intended for DPR. When attempting to detect pathogens and indicators, a variety of monitoring techniques must be considered because no single technique can include all the desired monitoring traits. Monitoring techniques for viruses, bacteria, and protozoa are discussed in detail in **Sections 4.4.1, 4.4.2,** and **4.4.3**, respectively.

Table 4-1: Infectious Agents Potentially Present in Untreated (Raw) Wastewater[a,b]

Pathogen	Disease	Quantity in Raw Wastewater (per liter)	Method of Quantification	Target Risk Thresholds for Drinking Water (pathogens/L)	Required Log Reduction
Bacteria					
Aeromonas hydrophila	Gastroenteritis, peritonitis, meningitis, cellulitis, pneumonia, bacteremia	Up to 10^3	Cultural	-	-
Atypical mycobacteria	Respiratory illness (hypersensitivity pneumonitis)	-	-	-	-
Campylobacter	Gastroenteritis, reactive arthritis, Guillain-Barré syndrome	Up to 10^4	Cultural	6.93×10^{-6}	9.2
Enteropathogenic *Escherichia coli (E.coli)*(many other types of *E. coli* are not harmful)	Gastroenteritis and septicemia, hemolytic uremic syndrome (HUS)	Up to 10^7	Cultural	6.28×10^{-4}	11.0
Helicobacter	Chronic gastritis, ulcers, gastric cancer	-	-	-	-
Legionella	Respiratory illness (pneumonia, Pontiac fever)	-	-	-	-
Leptospira	Leptospirosis	-	-	-	-
Pseudomonas	Skin, eye, ear infections	-	-	-	-
Salmonella	Salmonellosis, gastroenteritis (diarrhea, vomiting, fever), reactive arthritis, typhoid fever	Up to 10^5	Cultural	1.20×10^{-3}	7.9
Shigella	Shigellosis (bacillary dysentery)	Up to 10^4	Cultural	6.04×10^{-5}	8.2
Staphylococcus	Skin, eye, ear infections, septicemia	-	-	-	-
Vibrio cholera	Cholera	Up to 10^5	Cultural	8.88×10^{-6}	10.1
Yersinia	Yersiniosis, gastroenteritis, and septicemia	-	-	-	-
Helminths					
Ascaris	Ascariasis (roundworm infection)	Up to 10^3	Cultural/ direct count	-	-
Ancylostoma	Cutaneous larva migrams (hookworm infection)	-	-	-	-
Ancylostoma	Ancylostomiasis (hookworm	Up to 10^3	Cultural/ direct	-	-

Pathogen	Disease	Quantity in Raw Wastewater (per liter)	Method of Quantification	Target Risk Thresholds for Drinking Water (pathogens/L)	Required Log Reduction
	infection)		count		
Echinococcus	Hydatidosis (tapeworm infection)	-	-	-	-
Enterobius	Enterobiasis (pinworm infection)	-	-	-	-
Necator	Necatoriasis (roundworm infection)	-	-	-	-
Strongyloides	Strongyloidiasis (threadworm infection)	-	-	-	-
Taenia	Taeniasis (tapeworm infection), neurocysticercosis	-	-	-	-
Trichuris	Trichuriasis (whipworm infection)	Up to 10^2	Cultural/ direct count	-	-
Protozoa					
Cryptosporidium	Cryptosporidiosis, diarrhea, fever	Up to 10^4	Cultural/ direct count	2.39×10^{-6}	9.6
Cyclospora	Cyclosporiasis (diarrhea, bloating, fever, stomach cramps, and muscle aches)	-	-	-	-
Entamoeba	Amebiasis (amebic dysentery)	Up to 10^2	Cultural/ direct count	4.84×10^{-7}	8.3
Giardia	Giardiasis (gastroenteritis)	Up to 10^5	Cultural/ direct count	6.88×10^{-6}	10.2
Microsporidia	Diarrhea	-	-	-	-
Toxoplasma	Toxoplasmosis	-	-	-	-
Viruses					
Adenovirus	Respiratory disease, eye infections, gastroenteritis (serotype 40 and 41)	Up to 10^6	Molecular	2.26×10^{-7}	12.6
Astrovirus	Gastroenteritis	-	-	-	-
Caliciviruses (including Norovirus and Sapovirus)	Gastroenteritis	Up to 10^9 (average 10^6)	Molecular	-	-
Coronavirus	Gastroenteritis	-	-	-	-
Parvovirus	Gastroenteritis	-	-	-	-

Pathogen	Disease	Quantity in Raw Wastewater (per liter)	Method of Quantification	Target Risk Thresholds for Drinking Water (pathogens/L)	Required Log Reduction
Picornaviruses (including Aichi virus)	Gastroenteritis	Up to 10^6	Molecular	-	-
Enteroviruses (polio, echo, coxsackie, new enteroviruses, serotype 68-71)	Gastroenteritis, heart anomalies, meningitis, respiratory illness, nervous disorders, others	Up to 10^6	Culture/ Molecular	1.29×10^{-4}	9.9
Hepatitis A and E virus	Infectious hepatitis	-	-	-	-
Polyomavirus	Progressive multifocal leukoencephalopathy (PML)	Up to 1	Molecular	-	-
Rotavirus	Gastroenteritis	Up to 10^5	Molecular	2.31×10^{-7}	11.6

[a] Adapted from USEPA (2012).

[b] Drinking water risk thresholds are calculated based on an annual risk of 10^{-4}.

Sources: NRC, 1996; Sagik et al., 1978; Hurst et al., 1989; WHO, 2006; Feachem et al., 1983; Mara and Silva, 1986; Oragui et al., 1987; Yates and Gerba, 1998; da Silva et al., 2007; Haramoto et al., 2007; Geldreich, 1990; Bitton, 1999; Blanch and Jofre, 2004; and EPHC, 2008; Poffé and Beeck, 1991; Bofill-Mas et al., 2006; Rafique and Jiang, 2008; QMRA Wiki, 2015; Kitajima et al., 2014; Schmitz et al., 2016; Symonds et al., 2014; da Silva et al., 2008; Kitajima and Gerba, unpublished data.

Table 4-2: Pathogens of Interest and Corresponding Indicators or Surrogates

Pathogen of Interest	Indicator/Surrogate
Adenovirus, Rotavirus, Norovirus, and other enteroviruses	Somatic coliphage, F+ RNA coliphage (e.g., MS2), Aichi, Calicivirus, and Pepper Mild Mottle Virus
Cryptosporidium, *Giardia*	*Bacillus subtilis, Clostridium perfringens* (spores are used)
Campylobacter, *Salmonella*	*Escherichia coli, Enterococci*

4.4.1 Monitoring Targets for Viruses

Public health criteria for potable reuse applications in the United States generally target a specific log value for the removal/inactivation of viruses from raw wastewater to finished drinking water. For example, California requires a 12-log reduction/inactivation of viruses in potable reuse applications before the water is considered safe for consumption. The use of log reduction values presents a problem because current methods lack the sensitivity necessary to demonstrate this level of treatment.

Infectious viruses are particularly difficult to detect due to their small size, relatively low concentrations, and complex cell culture methods.

In wastewater, the common practice is to use adenovirus as a representative surrogate for all pathogenic viruses because it can be detected using both cell culture and molecular methods. The USEPA listed adenovirus as one of nine microorganisms on the Contamination Candidate List because its survival characteristics during water treatment are not yet understood fully. Additionally, adenovirus is much more resistant to UV disinfection than other viruses and provides a conservative estimate of viral UV disinfection.

Other research has identified Aichi and Caliciviruses as useful targets for monitoring the performance of aquifer recharge, MF, and RO for virus removal. Pepper Mild Mottle Virus also has been identified as a useful target for treatment performance and monitoring because it is frequently detected in wastewater, and it may be preferable for laboratory analysis as it is not known to negatively affect humans (Hamza et al., 2009, 2011). Each of these viruses can be detected by virus-specific quantitative polymerase chain reaction (qPCR) assays or metagenomics approaches. They have advantages over adenovirus and other pathogenic viruses because they are detected at much higher concentrations than human pathogens, are indicative of human waste, and can be tracked easily through treatment. Although advantageous, the direct measurement of these viruses has several downfalls, particularly the complexity, high costs, and time requirements of molecular detection and viability assays. For example, molecular methods require a minimum number of hours (~2 to 4 hours), while cell culture assays can take weeks before the results are available.

An alternative to the direct detection of human viruses is the use of bacteriophages (e.g., MS2) as indicators and/or surrogates. Three main groups of bacteriophages have been evaluated for their potential use as indicators of water quality: (1) somatic coliphages, (2) male-specific or F+ RNA phages (e.g., MS2), and (3) *Bacteroides fragilis* phages (IAWPRC, 1991; WHO, 2004; Lucena and Jofre, 2010). Because bacteriophages are viruses that infect bacteria and not humans, they are easier to work with in the laboratory, and the associated methods (e.g., the double agar layer method) are well known and much simpler than pathogen alternatives. In fact, most bacteriophage assays can be completed within 24 hours, which is more rapid than many pathogen assays, but still inadequate for achieving the desired response retention times for DPR applications.

4.4.2 Monitoring Targets for Bacteria

Historically, total coliform bacteria and fecal coliform bacteria have been used as indicators of fecal contamination in drinking water applications and are monitored to demonstrate compliance with the Total Coliform Rule. With respect to potable reuse, an NWRI Independent Advisory Panel proposed a 9-log reduction/inactivation target for total coliform bacteria because they are present in wastewater at concentrations much greater than enteric bacterial pathogens, are monitored easily, and are accepted as surrogates for assessing disinfection efficacy (WRRF-14-20). Numerous technologies have been used to measure coliform bacteria since the 1970s. Two more recently developed and commercially available kits from IDEXX – Colilert™ and Colisure™ – have been designed to detect coliform bacteria. These kits detect bacterial enzyme activity through color change and take 18 to 24 hours to obtain results. Similar recently developed platforms available for enterococci include (i.e., Enterolert™); and another for *Legionella* (i.e., Legiolert™). With respect to pathogens, bacteria frequently linked to gastrointestinal disease (e.g., *Salmonella*) have been considered also for targeted monitoring and as a means to ensure adequate protection of public health. For example, in Australia, Campylobacter is used as an indicator of fecal contamination because of its prevalence in untreated wastewater, its ability to contaminate drinking water supplies, and its infectivity (Khan, 2013).

4.4.3 Monitoring Targets for Protozoa

Public health criteria for potable reuse applications in the United States generally target 10-log reduction/inactivation of *Giardia* and *Cryptosporidium* from raw wastewater to finished drinking water. Typically, protozoa are large in size (1 to 60 µm); therefore, they can be removed easily from water using sedimentation or filtration (Bukhari and LeChevallier, 2012), particularly membrane filtration (Khan, 2013). In addition, protozoa generally are susceptible to UV disinfection but resistant to chemical disinfection, particularly chlorination; however, the direct monitoring of protozoan pathogens, such as *Giardia* and *Cryptosporidium*, is problematic because the methods require extensive sample preparation and highly skilled technicians. Complete laboratory analysis for protozoan pathogens can take several days to complete.

Time may be managed more efficiently using surrogates like *Bacillus subtilis* and *Clostridium perfringens.* These bacteria can be used to mimic the disinfection resistance of protozoan pathogens while offering simpler laboratory methods that require less time; however, spore-forming bacterial surrogates are slightly more susceptible to chlorine and ozone than the target pathogens (e.g., *Cryptosporidium*), and may represent a less conservative alternative to direct pathogen monitoring. As stated in the USEPA Guidelines for Water Reuse, *Cryptosporidium* experiences a log reduction of 0 to 0.5 and 1 to 2 with typical doses of chlorine and ozone, respectively. Typically, *Clostridium perfringens* is reduced by 1 to 2 log with chlorine (i.e., less conservative), although it may be more conservative for ozonation, with an expected log reduction of 0 to 0.5 (USEPA, 2012a). Although *Clostridium perfringens* has not been approved officially by the USEPA, North Carolina uses it in conjunction with *E. coli* and coliphage for reuse applications that have the highest potential for human contact (USEPA, 2012a).

4.5 New, Emerging, and Real-Time Technologies for Pathogen and Indicator Monitoring

Real-time technologies and their current inability to quantify microbial densities with sufficient sensitivity to verify public health criteria are discussed in WRRF-12-06. Several real-time monitoring technologies examined in WRRF-11-01 show promise, but the report concludes that no pathogen monitoring technologies are ready for implementation in DPR applications.

4.5.1 Example Monitoring Technologies

LuminUltra®, a technology that rapidly quantifies adenosine triphosphate (ATP), is used to measure the total microbial content in water is examined in WRRF-11-01. This emerging technology allows for real-time feedback from ATP-containing *E. coli* and other respiring bacteria; however, ATP does not provide any measure of virus occurrence because viruses do not contain ATP. LuminUltra® functions best as an indicator of bacterial contamination via the presence or absence of biological activity. A second monitoring method examined in WRRF-11-01 is the Endetec-TECTA system, which facilitates *E. coli* growth on media. The bacteria then emit a specific enzyme that interacts with a chemical substrate, thereby releasing fluorescent molecules.

The BACTcontrol® system from MicroLAN uses substrate technology to detect bacterial activity in real time. Specific enzymatic activities of β-galactosidase (coliform bacteria), β-glucuronidase (*E. coli*), and alkaline phosphatase (total activity, biomass) are measured as indicators of bacterial contamination. Enzyme activity is detected by adding reagents (consumables) that contain a fluorescent indicator. The reagents are substrate-specific for the enzyme to be detected, meaning that there is an increase in fluorescence when the enzyme is present in the sample. The advantage of this system is its ability to concentrate bacteria from larger sample volume (1 to 3 liters) than the traditional 100-mL grab samples of conventional testing systems. It is accomplished by incorporating a robust ceramic membrane into the instrument. By increasing the sample size, the equivalent sample volume and resulting detection sensitivity are increased. The use of a larger sample size may be of critical importance for the validation and monitoring of DPR treatment trains, where lower detection limits are of great value. It was stated in WRRF-12-06 and WRF4508 that these types of systems show much promise and are worth following closely for technological advancements in DPR.

WRRF-11-01 and WRF4508 offer a thorough discussion of additional emerging monitoring technologies, including Biosentry® and flow cytometry. Biosentry®, a commercial MALS (multi-angle light scattering) based platform, reportedly allows for continuous real-time monitoring of microbial contaminants by comparing the light scattering patterns of a given water sample to a database of patterns from known pathogens. Biosentry® is not able to provide sensitive results, but it may be useful as a real-time trigger to indicate that water quality has degraded. Flow cytometry can be combined with the use of nucleic acid probes or fluorescent antibodies to rapidly identify and quantify specific microorganisms. In recent years, flow cytometry has evolved to become more sensitive and reduce background noise, which increases the possibility of this method to make near real-time measurements for total bacterial and viral counts in water. In addition, this real-time online monitoring technology may be a beneficial strategy for monitoring pathogen removal because no pretreatment or sample concentration steps are required.

4.5.2 Other Emerging Monitoring Technologies

Other emerging monitoring technologies include advanced molecular assays and biosensors. Standard molecular assays employ the detection of DNA or RNA using Polymerase Chain Reaction (PCR) to amplify low concentrations of genetic material to a detectible range. One drawback with standard molecular methods is the inability to distinguish viable and non-viable microorganisms, unless advanced approaches targeting mRNA are used (Girones et al., 2010; Aw and Rose, 2012). Consequently, PCR-based methods tend to overestimate concentrations of infectious pathogens (Jofre and Blanch, 2010). Frequently used molecular methods include PCR and qPCR, Nucleic Acid Sequence Based Amplification (NASBA), digital droplet PCR (ddPCR), and pyrosequencing. Details on each technique are explored in WRF4508.

Typically, biosensors use the recognition of biological components ranging from specific surface proteins, antigens, enzymes, antibodies, receptors, DNA, cell components, or even the whole cell or organism by amplifying the detection of a specific target into a detectable signal (Connelly and Baeumner, 2012). Biosensor technologies are improving, but current challenges include nonspecific binding, particle size variation, aggregation of nanoparticles, and the inability to differentiate viable from non-viable organisms (Vikesland and Wigginton, 2010).

4.5.3 Next Generation Sequencing

The use of next-generation sequencing (NGS), also known as high-throughput sequencing, is becoming more attractive for use in the water and wastewater industry. NGS is the term used to describe a number of different sequencing technologies, including Illumina (Solexa, MiSeq, and HiSeq), Roche 454, Ion torrent, and SOLiD sequencing. These new technologies allow DNA and RNA to be sequenced more rapidly and cost-effectively than the previously used Sanger sequencing; as such, they have revolutionized the study of molecular biology. The advantages of NGS over the more traditional Sanger sequencing include: reduced processing times, decreased cost, improved sample size/volume requiring less DNA, and increased accuracy of reads.

One critical obstacle for the widespread use of NGS as a tool for water quality monitoring is the development of shared databases for inter-laboratory comparison that can be used to validate findings and better understand water quality variability (Tan et al., 2015). From a brief review of the literature, it appears that studies leveraging NGS technologies can provide new insights into the ecology of microbiologically driven processes, such as contaminant biodegradation and pathogen dissemination, that can influence water quality. Several recent studies have used NGS to shed light on the fate of microbial populations, including pathogens, during various stages of the water treatment process (Tan et al., 2015). Ultimately, the integration of metagenomics data into quantitative microbial risk assessments (QMRA) and epidemiological frameworks will aid in the ability to better quantify microbiological risks with human health protection in mind. A summary is included in **Table 4-3** of new, emerging, and real-time technologies that hold promise for DPR applications in the future.

Table 4-3: Summary of Target Microorganisms and Detection Technology

Target Pathogen/ Indicator	Technology	Time/Complexity/Cost	Detection Limit
Respiring bacteria (ATP)	LuminUltra®	Rapid (20s), easy to read, low equipment cost	<0.2 pg/mL
Escherichia coli (E. coli)	Endetec-TECTA®	Continuous, online, real-time, moderate equipment cost	1 CFU/100 mL for *E. coli* and 1 CFU/100 mL Total Coliform
Coliform bacteria, *E. coli*	BACTcontrol®	Continuous, online, real-time, moderate equipment cost	pmol/min • mL
Cryptosporidium parvum, Giardia, E. coli, Salmonella, Shigella, Pseudomonas, Legionella,	BioSentry®	Continuous, online, real-time, moderate equipment cost	40 particles/L in 5 minutes
E. coli O157:H7, *C. parvum*, non-pathogenic *E. coli*, *particles*	Flow Cytometry	Rapid identification and quantification, high equipment cost	<10^3 cells/mL (complex matrix)
E. coli, Salmonella typhimurium, Staphylococcus aureus, others	Other biosensors	Near real-time (~2 hours), moderate to high equipment cost	10-10^4 particles/L

Sources: Rock et al., 2014; WRRF-11-01; WRRF-12-06; WRF4508; Girones et al., 2010; Aw and Rose, 2012; Connelly and Baeumner, 2012; Connelly and Baeumner, 2012; Ivnitski et al., 1999; JMAR Technologies; Miles et al., 2011; Connally, 2009; Veolia Water Technologies, 2016.

4.6 Critical Control Point Approach for Pathogen Monitoring

A CCP is a "point in advanced water treatment where: (1) control can be applied to an individual unit process to reduce, prevent, or eliminate process failure; and (2) monitors are used to confirm that the control point is functioning correctly" (Tchobanoglous et al., 2015). A discussion is included in this section of the use of CCPs as a performance monitoring approach in the absence of direct pathogen monitoring technologies to ensure that treatment objectives, regulatory requirements, and public health criteria are being met by DPR systems. The use of CCPs as part of the HACCP framework for pathogens and chemicals is discussed in **Chapter 6**.

4.6.1 Pathogen Control

With respect to pathogen control, the agency responsible for the potable reuse facilities must submit an engineering report to the regulatory agency detailing how the target pathogen log credit reduction values will be achieved. In this context, a CCP analysis is one approach that can be used to determine whether an individual treatment process is operating as expected to achieve the requested log reduction credit. An example of an AWTF and the corresponding CCP locations where log reduction credits would be verified is illustrated in **Figure 4-1**. As shown, the CCPs for MF and RO are intended to verify membrane integrity, the CCP for advanced oxidation would be used to verify the applied UV dose, and the CCP for the ESB would be used to verify the chlorine CT and/or residence time, which relates to the system's overall response retention time (RRT). The number, locations, and types of CCPs will vary between projects and treatment trains.

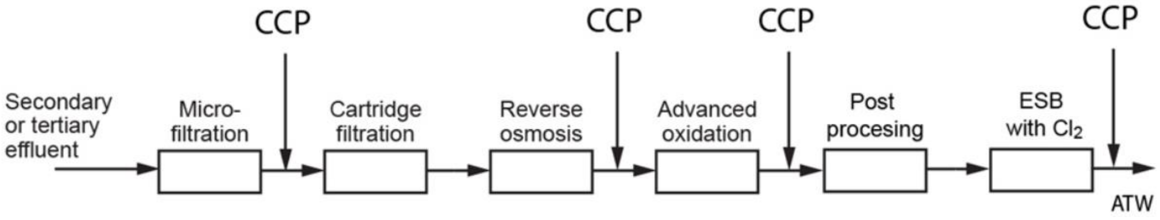

Figure 4-1: Example potable reuse treatment train with critical control points identified. Source: Tchobanoglous et al. (2015).

4.6.2 Identification of Monitors or Tests

Once the CCPs are identified, appropriate monitors or tests must be identified and implemented to demonstrate that the unit treatment process is meeting its performance criteria and that log reduction credits for bacteria, protozoa, and/or viruses are being met. The exact log reduction credits and target pathogens (e.g., inclusion or exclusion of bacteria) may vary between projects based on the regulatory structure in place, and some credits may even require site-specific verification. Examples of the types of tests used to monitor the performance of the various unit processes used in an AWTF are summarized in **Table 6-1** in **Chapter 6.**

4.6.3 Validation of Monitoring Technologies

A number of available online monitoring technologies have not yet been validated fully for use in potable reuse applications. It is important to characterize the operation and maintenance requirements of all online instrumentation to prevent fouling and compromised data from adversely impacting the operation of an automated treatment train. For example, in a recent potable reuse demonstration project, the use of free chlorine disinfection following secondary wastewater treatment was examined – an application that requires careful monitoring of upstream ammonia concentrations (i.e., ensure reliable nitrification). Some commercial monitors that were expected to differentiate free chlorine and chloramine were unable to accomplish that goal, and the tested monitors also varied in the time to respond to operational changes.

4.7 Information Sources

A list is provided in **Table 4-4** of the WRRF, WRF, and WRA projects that were reviewed for the preparation of this chapter. Full citations for reports related to these projects, along with citations for other references and sources of information, are included in **Section 4.5**.

Table 4-4: WRRF, WRF, and WRA Research Projects Used to Prepare Chapter 4

Project No.	Project Title	Principal Investigator(s)
WRF-06-003	The Occurrence of Infectious *Cryptosporidium* Oocysts in Raw, Treated and Disinfected Wastewater	Zia Bukhari, American Water
WRRF-09-03	Utilization of Hazard Analysis and Critical Control Points Approach for Evaluating Integrity of Treatment Barriers for Reuse	David Halliwell, Water Quality Research Australia Ltd.
WRRF-11-01	Monitoring for Reliability and Process Control of Potable Reuse Applications	Ian Pepper, University of Arizona
WRRF-12-06	Guidelines for Engineered Storage for Direct Potable Reuse	Andrew Salveson, Carollo Engineers
WRRF-13-02	Model Public Communication Plan for Advancing Direct Potable Reuse Acceptance	Mark Millan, Data Instincts
WRRF-13-03	Critical Control Point Assessment to Quantify Robustness and Reliability of Multiple Treatment Barriers of Direct Potable Reuse Scheme	Troy Walker, Hazen & Sawyer
WRRF-13-14 (WRF4508)	Assessment of Techniques to Evaluate and Demonstrate the Safety of Water from Direct Potable Reuse Treatment Facilities	Channah Rock, University of Arizona
WRRF-14-20 (WRA-14-01)	Developing Direct Potable Reuse Guidelines	Jeffrey Mosher, National Water Research Institute

4.8 References

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Chapter 5: Risk and Removal of Constituents of Emerging Concern

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Although anthropogenic compounds have been detected in wastewaters for several decades, a major study by the U.S. Geological Survey in 2002 (Kolpin et al., 2002) introduced their occurrence to the water industry and public. Since this seminal work, a wide variety of wastewater-derived, organic compounds have been quantified in water at concentrations of sub-nanograms per liter (ng/L) to micrograms per liter (µg/L), including ingredients in pharmaceuticals and personal care products (PPCPs), industrial chemicals, natural and synthetic hormones, DBPs, and others (Anderson, 2008; Benotti et al., 2009; Focazio et al., 2008). The majority of these compounds are not regulated in drinking water by the USEPA, meaning that there is no maximum contaminant level and no requirements to monitor their occurrence, but may be regulated individually on a state level. The term "constituents of emerging concern" (CECs) is used to refer to these unregulated organics, and may be extended to include other unregulated constituents found in water, such as trace metals, pathogens, and nanomaterials. In this chapter, the focus is on unregulated trace organic compounds that have been detected in municipal wastewater treatment systems in the United States or have the potential to enter these systems, which is relevant to potable reuse.

There are tens of thousands of chemicals used in commerce and potentially present in the environment; over 400 CECs have been identified in wastewater effluent and, likely, many more are present (Bruce and Pleus, 2015). Significant mass usage by society and specific CEC chemical properties are required for CECs to be present in WWTP effluents (Khan and Ongerth, 2004). It should be noted that CEC occurrence is not solely a wastewater or planned potable reuse issue, as these compounds also have been detected in traditional drinking waters and source waters (surface water and groundwater) impacted by treated wastewater discharges.

5.1 Identification of Key Issues

CECs in drinking water and sources of drinking water are of concern to the public and water industry. Key issues (grouped according to occurrence, treatment, and risk) are identified in **Sections 5.1.1** to **5.1.3**. Current understanding and information gaps are discussed in **Section 5.2**, and background and justification are provided in **Section 5.3**.

5.1.1 Occurrence

- CECs, their metabolites, and unregulated oxidation/disinfection byproducts are present in secondary- and tertiary-treated wastewater effluents throughout California, the United States, and other industrialized nations.

- Due to continuing advances in analytical chemistry in water monitoring, more CECs will be identified in the future, new CECs will emerge, and previously identified CECs may disappear, based on the use of specific chemicals by society.

5.1.2 Treatment

- No single treatment process (or combination of treatment processes) exists that is capable of removing all CECs from water. Various unit treatment processes used in conventional drinking water treatment, wastewater treatment, and advanced treatment for reuse have different efficacies in removing CECs.

- Nevertheless, advanced water treatment involving RO has been shown to remove the majority of known CECs to below the very low detection limit ranges of ng/L to sub-ng/L.

5.1.3 Risk

- The risks associated with CECs likely will come from very few contaminants, as reported in prior risk assessment studies that evaluated a wide range of CECs and ultimately concluded only a limited number of CECs require monitoring (SWRCB, 2010; WRRF-11-02).

- For certain California communities, public perception of the risks associated with CECs is greater than the actual risk, as indicated by public surveys conducted before and after education about the (low) risk of being exposed to or consuming advanced treated water (WRRF-13-02).

5.2 Summary of Principal Findings

The principal findings related to CECs with respect to occurrence, treatment, and risk are discussed in this section.

5.2.1 Occurrence of Constituents of Emerging Concern

5.2.1.1 What Is Known?

- Depending on the level of treatment, a wide variety of anthropogenic contaminants have been found in treated wastewater, including pharmaceuticals, ingredients in personal care products, industrial chemicals, and others. Over 400 non-regulated organic compounds have been identified in secondary-treated water in the United States (Bruce and Pleus, 2015).

- The concentrations of CECs found in secondary-treated wastewater effluents generated from municipal wastewater are low (sub-ng/L to µg/L) as compared to the concentrations of regulated drinking water constituents (µg/L to mg/L).

- The total concentration of CECs measured in advanced treated water is relatively small compared to the measured TOC because TOC also includes natural organic matter (NOM) and effluent organic matter (EfOM).

- CEC occurrence is not limited to planned potable reuse, for example, recently published summary data from 61 published reports or scientific articles indicate that PPCPs and endocrine disrupting compounds (EDCs) are found in finished drinking waters within the United States (Bruce and Pleus, 2015) (see **Section 5.4.2**).

5.2.1.2 What Is Unknown?

- Many contaminants have yet to be identified. For example, artificial sweeteners (e.g., sucralose, acesulfame-K) can be found in treated wastewater at up to µg/L levels, but were not identified until 2010. Additionally, as detection limits decrease, contaminants that have been present for years will be identified. Because water analysis methods are designed to target known compounds, it is not known how many unidentified CECs may be present in a given water sample, which is one of the recognized shortcomings of current analytical capabilities. To address this issue, "indicator" compounds thought to coincide with unknown CECs are included in monitoring programs; their removal is taken as evidence for the removal of unknown CECs as well. Furthermore, research is ongoing for new methods (e.g., bioanalytical tools; non-targeted chemical analysis) that aim to measure these unknown CECs or their potential risk.

- Contaminants enter the WWTP from the collection system, and some are degraded partially during the biological process. Rarely are the metabolites identified and quantified, yet they are part of the universe of unknown CECs. Similarly, contaminants can be altered chemically during oxidation/disinfection processes, and these unregulated oxidation/DBPs rarely are identified and quantified.

5.2.2 Removal of Constituents of Emerging Concern during Treatment

5.2.2.1 What Is Known?

- No single treatment process currently exists that removes all known CECs; therefore, combinations of processes in sequence must be employed to maximize the removal of CECs.

- Conventional biological, chemical, and physical processes used in wastewater treatment are not designed to remove CECs, and the removals at these facilities range from "nearly complete" to "very little" depending on the chemical properties of the CEC (e.g., Anderson, 2008).

- It has been found that the combination of processes used in an AWTF, including RO, can remove the majority of measurable CECs to below currently detectable levels, which typically are in the range of ng/L to sub-ng/L. An example AWTF treatment train with RO may consist of MF or UF followed by RO and UV/AOP; however, after treatment, some very low levels of CECs and TOC could remain.

- Alternative treatment process trains to the AWTF that do not involve RO also can effectively remove CECs, though low levels of non-oxidizable CECs and TOC remain. An example of an alternative AWTF treatment train would include ozone and biologically active carbon (BAC) which, in combination, have been shown to reduce CECs significantly.

- As an example, the removal efficacies of PPCPs with different water treatment processes are listed quantitatively in **Table 5-1.**

Table 5-1: Removal Efficiency of Engineered Systems for Pharmaceuticals and Personal Care Products

PPCP Classification	Cl_2	UV	O_3/AOP	GAC	NF	RO
Antibiotics	P-G	F-G	L-E	F-G	E	E
Antidepressants	P-F	F-G	L-E	G-E	G-E	E
Anti-inflammatory	P-F	E	E	E	G-E	E
Lipid regulators	P-F	F-G	E	E	G-E	E
X-ray contrast media	P-F	F-G	L-E	G-E	G-E	E
Psychiatric control	P-F	F-G	L-E	G-E	G-E	E
Synthetic musk	P-F	E	L-E	G-E	G-E	E
Sunscreens	P-F	F-G	L-E	G-E	G-E	E
Antimicrobials	P-F	F-G	L-E	G-E	G-E	E
Surfactants/detergents	P	F-G	F-G	E	E	E

From Snyder et al. (2003).

Cl_2 = Chlorination. O_3/AOP = Ozonation or other advanced oxidation process. GAC = Granular activated carbon.

NF = Nanofiltration. PPCP = Pharmaceuticals and personal care products. RO = Reverse osmosis.

E = Excellent (>90 percent). G = Good (70-90 percent). F = Fair (40-70 percent). L =Low (20-40 percent). P = Poor (<20 percent).

5.2.2.2 What Is Unknown?

- The fate of contaminants altered by oxidation (e.g., chlorination, ozonation) or partial degradation (e.g., biological treatment, BAC) is not well understood because fate studies require knowing the product compound identities and having analytical capabilities for measuring them. In many cases, this transformation of CECs is measured as removal (e.g., the reduction of concentrations of parent compounds across the treatment process), but the product compounds are not known and not measured. This issue is addressed partially by combining several treatment processes into a treatment train (i.e., product compounds – albeit unmeasured – may be removed in subsequent treatment steps).

- Research on suitable monitoring tools (e.g., sensors, online, and high-frequency measurements) and surrogates or indicators for CECs is underway, but not complete. This research is needed to confirm online treatment performance for the removal of CECs.

5.2.3 Human Health Risks Associated with Constituents of Emerging Concern in Direct Potable Reuse

5.2.3.1 What Is Known?

- Multiple studies have been conducted on the occurrence and toxicological relevance of CECs in advanced treated water. As a result, there are data for CECs in advanced treated water following different treatment processes (see **Section 5.2.2.1**), and the toxicity of many CECs can be evaluated using established risk assessment methodologies. Because this area of research is active and growing, information regarding occurrence and toxicity will continue to evolve.

- Lists of specific CECs with human health relevance have been developed considering both occurrence and toxicity:
    - A Science Advisory Panel convened by the California State Water Resources Control Board identified a list of CECs for monitoring for IPR (SWRCB, 2010).
    - For DPR, an NWRI Independent Advisory Panel developed a list of CECs that was included in WRRF-11-02 (Crook et al., 2013). As shown in **Table 5-2**, three categories of CECs were identified by the Panel: (1) DBPs; (2) unregulated chemicals with potential health risks; and (3) compounds to evaluate treatment effectiveness (i.e., surrogates).
    - Although specific CECs may vary slightly depending on the methodology used to develop these lists, there are a limited number of CECs that have been identified as potentially posing a risk to human health.
- Risk-based levels can be derived for CECs based on existing toxicity data and drinking water exposures, same as those used by the USEPA to derive Drinking Water Equivalent Levels.
- CECs have not been detected in advanced treated water from AWTFs using RO at concentrations above the risk-based criteria used in studies that have evaluated the potential health effects of CECs (such as WRRF-06-004 and WRRF-11-02).

5.2.3.2 What Is Unknown?

- Potential risks to sensitive sub-populations are not well understood. For example, additional research is needed on the potential effects of low levels of CECs (in particular, endocrine disrupting compounds) on fetuses and infants during critical developmental windows.
- Potential risks from any additive or synergistic effects of the mixtures of CECs present in potable waters are not well known.
- In general, potential risks from newly identified metabolites, treatment degradation products, and chemicals will be unknown and may need to be quantified.
- Uncertainty factors spanning orders of magnitude are used in the current risk assessment methodology to address the above unknowns (e.g., sensitive subpopulations, children). These uncertainties are inherent in the existing risk assessment methodology and are not unique to advanced treated water.

Table 5-2: Direct Potable Reuse Public Health Criteria for Constituents of Emerging Concern in the NWRI Independent Advisory Panel Final Report for WRRF-11-02

Chemical Classification	Chemical	Value (in ng/L)
Disinfection byproducts that should be evaluated	Trihalomethanes	80,000
	HAA5	60,000
	NDMA	10
	Bromate	10,000
	Chlorate	800,000
Non-regulated chemicals of interest from the standpoint of public health[1]	PFOA	400
	PFOS	200
	Perchlorate	15,000 6,000
	1,4-Dioxane	1,000
	Ethinyl Estradiol	5,000
	17β-Estradiol	5,000
Chemicals of public health concern that should be useful for evaluating the effectiveness of treatment	Cotinine, Primidone, or Phenytoin	1,000; 10,000; 2,000
	Meprobamate or Atenolol	200,000; 4,000
	Carbamazepine	10,000
	Estrone	320
	Sucralose	150,000,000
	TCEP	5,000
	DEET	200,000
	Triclosan	2,100,000

Adapted from Tables 3, 4, and 5 in Crook et al. (2013). ng/L = Nanogram per liter.

5.3 Concern about Constituents of Emerging Concern in Potable Water

Both public and scientific concerns over the presence of CECs in potable waters are due to concern for the potential human health effects of these CECs. Of the wide range of potentially present CECs, it is thought that the actual risk to human health is likely to be insignificant (Snyder et al., 2008a). The greatest potential risk appears to be due to hormonally active compounds and strong carcinogens that can be active at very low concentrations. Unlike microbial risk, which is acute, the risk for CECs is chronic and typically based on a lifetime of exposure; however, sensitive sub-populations or sub-periods based on pre-existing conditions, age, and/or gender may exist. The occurrence of CECs in waters following treatment in an AWTF with RO is very low and is equivalent or less than that of treated drinking waters influenced by low levels of wastewater discharge. Regardless, not all contaminants present in treated waters have been identified and quantified. Risk assessment is a complex process that requires many assumptions; hence, uncertainties remain.

5.4 Occurrence of Constituents of Emerging Concern

In 2004, there were over 7-million commercially available organic and inorganic chemical substances listed in the American Chemical Society's Chemical Abstract Services (Daughton, 2004). Chemicals used by society find their way into the environment and are present in treated wastewater; however, it is likely that only a very small subset of the list of commercially available chemicals result in measurable concentrations in treated wastewater. Khan and Ongerth (2004) modeled PPCP levels in secondary-treated and tertiary-treated Australian wastewaters from pharmaceutical annual dispensed mass, wastewater flow, and treatment removal estimates based on physical-chemical properties of the specific pharmaceuticals. The researchers found only 20 pharmaceuticals that could potentially be found in wastewaters at concentrations at or above 1 µg/L. This exercise has not been performed in the United States, due to lack of published chemical annual dispensed mass values but comparable results are expected.

5.4.1 Review of Data on Constituents of Emerging Concern Using Various Analytical Techniques

The Water Research Foundation Project #4387b aggregated CEC data collected using different analytical methods over the last 20 years and indicated that over 400 compounds have been identified in secondary-treated wastewater effluents (Bruce and Pleus, 2015). There are a number of analytical methods that capture groups of CECs based on their chemical properties. When analyzing CEC data (e.g., chromatograms), it is common to observe the presence of unknown chemicals (as additional peaks in a chromatogram; e.g., Soliman et al., 2004), yet compounds associated with these peaks remain unidentified without more advanced methods, analytical reference compounds, and/or pre-existing knowledge of their likely identity; therefore, it is currently not known how many CECs may be present in wastewaters at detectable concentrations (i.e., ng/L to µg/L), but the potential is likely to be greater than 400. In addition, when waters are treated with oxidants and disinfectants, an unknown number of unregulated transformation and DBPs are formed from the CECs and naturally present NOM. Regardless, the total concentration of CECs in treated wastewater is a small fraction of the TOC (WRRF-02-01).

5.4.2 Data on Constituents of Emerging Concern from Wastewater Treatment Facilities

CEC occurrence data from full-scale wastewater treatment facilities in the United States, including the impact of different final disinfection strategies, is summarized in **Table 5-3**. This dataset is considered a fair representation of typical discharge loads in potable reuse applications (WRRF-11-02). As with other states, many surface water supplies in California are impacted by wastewater discharges (WRRF-14-20) and, as a result, CECs can be present in drinking water sources and finished drinking water (Loraine and Pettigrove, 2006). A summary of CEC occurrence in drinking waters of the United States is provided in a recent Water Research Foundation report (Bruce and Pleus, 2015); the data are presented in **Figure 5-1**.

Table 5-3: Constituents of Emerging Concern in Full-Scale Conventional Wastewater

Target Compound	Secondary Wastewater Treatment (ng/L)	Tertiary Wastewater Treatment + UV (ng/L)	Tertiary Wastewater Treatment + Chlorine (ng/L)	Tertiary Wastewater Treatment + Ozone (ng/L)
Atenolol	710	120	28	<25
Atrazine	28	<10	76	<10
Bisphenol A	<50	<50	<50	<50
Carbamazepine	140	192	35	<10
DEET	54	232	30	55
Diclofenac	62	57	<25	<25
Gemfibrozil	31	12	<10	<10
Ibuprofen	<25	<25	<25	<25
Meprobamate	41	362	360	110
Musk Ketone	<100	<100	<100	<100
Naproxen	<25	<25	<25	<25
Phenytoin	110	113	270	17
Primidone	67	168	270	45
Sulfamethoxazole	570	1,150	<25	<25
Triclosan	26	38	<25	N/A
Trimethoprim	280	43	<10	<10
TCEP	540	349	370	340

Adapted from WRRF-11-02. Original source: WRRF-08-05. ng/L = Nanogram per liter.

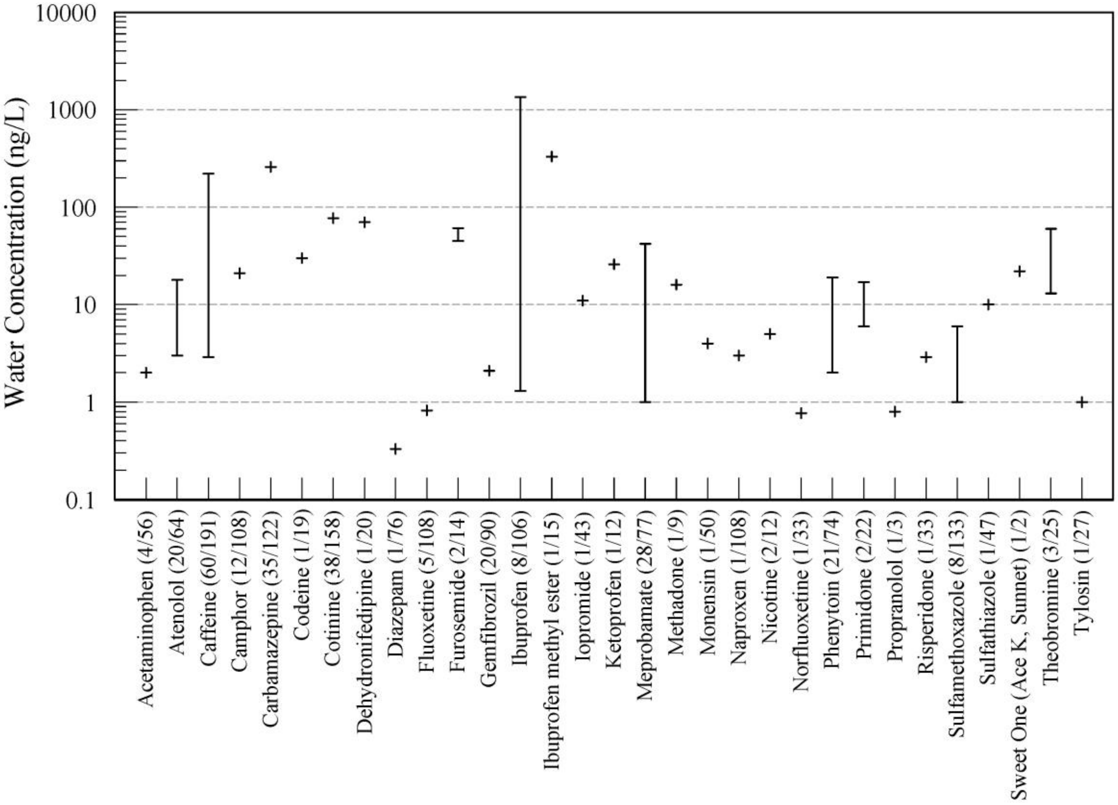

Figure 5-1: Ranges of detected concentrations of pharmaceuticals and personal care products in drinking water. The numbers detected and total number of samples analyzed are presented in parentheses (from Bruce and Pleus, 2015).

5.5 Removal of Constituents of Emerging Concern during Treatment

Performance of various treatment technologies, both conventional and advanced, for removal of CECs have been reported in several studies (e.g., Debroux et al., 2012; Monteiro and Boxall, 2010; Snyder et al., 2003, 2008b). As an example of the removal expected during advanced treatment, CEC removals for the case of PPCPs are summarized in **Table 5-4**.

5.5.1 Conventional Treatment Trains for the Treatment of Constituents of Emerging Concern

Grouping of technologies to achieve a specific treatment objective is known as a "treatment train" (Tchobanoglous et al., 2015). An AWTF treatment process train that has been accepted for potable reuse applications, as described previously, consists of MF or UF followed by RO, then UV/AOP. Using secondary-treated or tertiary-treated wastewater effluent as the source water, MF serves as pretreatment to RO and removes residual particulate material, as the pore size of the membrane typically is ~0.1 micron. A significant removal of CECs during MF has not been observed. While not having true "pores," RO membrane nominal pore size is much smaller than MF (typically less than 0.0025 microns) and readily rejects contaminants that possess a molecular weight greater than 200 Daltons.

Table 5-4: Constituents of Emerging Concern in the Effluent from Full-Scale Advanced Water Treatment

Target Compound	BAC (ng/L)	Ozone-BAC (ng/L)	Ultrafiltration-Ozone-BAC (ng/L)	MF-RO-UV/H_2O_2 (ng/L)
Acetaminophen	<5	N/A	N/A	N/A
Atenolol	30	<25	<1	<25
Atorvastatin	N/A	N/A	<0.5	N/A
Atrazine	N/A	<10	<0.3	<10
Benzophenone	<50	N/A	<50	N/A
BHA	<1	N/A	<1	N/A
Bisphenol A	<5	<50	<5	<50
Caffeine	17	N/A	<5	N/A
Carbamazepine	61	<10	<0.5	<10
Cimetidine	<0.5	N/A	N/A	N/A
DEET	46	<25	<1	<25
Diazepam	N/A	N/A	<0.3	N/A
Diclofenac	N/A	<25	<0.5	<25
Diphenhydramine	3	N/A	N/A	N/A
Estrone	N/A	N/A	<0.5	N/A
17β-Estradiol	N/A	N/A	<0.5	N/A
17α-Ethinyl Estradiol	N/A	N/A	<1	N/A
Fluoxetine	0.8	N/A	<0.5	N/A
Gemfibrozil	6	<10	<0.3	<10
Ibuprofen	2	<25	<1	<25
Iopromide	<10	N/A	<10	N/A
Meprobamate	140	190	8	<10
Musk Ketone	<25	<100	<25	<100
Naproxen	<0.5	<25	<0.5	<25
Octylphenol	N/A	N/A	<25	N/A
Phenytoin	N/A	33	<1	<10
Primidone	41	31	0.7	<10
Progesterone	N/A	N/A	<0.5	N/A

Target Compound	BAC (ng/L)	Ozone-BAC (ng/L)	Ultrafiltration-Ozone-BAC (ng/L)	MF-RO-UV/H_2O_2 (ng/L)
Sucralose	21,000	N/A	N/A	N/A
Sulfamethoxazole	5	<25	<0.3	<25
Triclosan	<1	<25	<1	<25
Trimethoprim	0.7	<10	<0.3	<10
TCEP	230	<200	<10	<200
TCPP	830	N/A	<100	N/A
Testosterone	N/A	N/A	<0.5	N/A
Triclocarbon	<1	N/A	N/A	N/A

Modified from WRRF-11-02. ng/L = Nanogram per liter.

In addition, RO membrane surface charge and the charge of aqueous contaminants will increase removal efficacy via electrostatic repulsion if both the CEC and membrane possess the same charge (WRRF-02-01). Lower molecular weight (<200 Daltons) non-polar compounds have been shown to partially pass through RO membranes. For example, NDMA and trihalomethanes are partially removed through RO membrane filtration (note: regulated trihalomethanes are not CECs, but are used as an example of low molecular weight non-polar compounds that pass RO) (WRRF-02-01).

Typically, UV is used for disinfection in the water industry. In AWTF treatment trains, UV is applied at much higher doses and combined with oxidant addition (e.g., hydrogen peroxide) to chemically dismantle CECs through photo-oxidation or radical-mediated oxidation. This approach to using UV combined with oxidants is termed “advanced oxidation processes” (AOP). AOP following RO membrane filtration is an effective, reliable approach to polishing water quality and removing residual target compounds (and other contaminants with similar sensitivity to AOP). In California, in the 2014 Groundwater Replenishment Reuse regulations, the term “full advanced treatment” is defined as the treatment of an oxidized wastewater using a RO and an oxidation treatment process that, at a minimum, meets specified criteria. For example, the AOP process must be capable providing "no less than 0.5-log (69 percent) reduction of 1,4-dioxane." Some water reuse facilities also monitor NDMA occurrence in finished water with respect to the California notification level (NL) of 10 ng/L.

5.5.2 Alternative Treatment Trains for the Treatment of Constituents of Emerging Concern

With respect to alternative trains for AWTF, such trains may include ozone and BAC in combination with other processes, such as UF or AOP (Tchobanoglous et al., 2015). Ozone (especially at doses where the ozone-to-TOC ratio is ≥1) significantly reduces the concentration of many CECs (to >90 percent or below detection limits). Two flame retardant CECs that are difficult to oxidize (e.g., TCEP, TCPP) do not respond to ozone and are not removed. Several CECs are partially removed (50 to 90 percent) during ozonation at doses where the ozone-to-TOC ratio is ≥1 (WRRF-11-02). TOC reduction has been observed during ozone/BAC treatment, but removal is less than through RO membranes. The higher level of TOC and TDS in alternative AWTF effluents are the principal differences between RO-based treatment trains and alternative ozone/BAC-based treatment trains (Tchobanoglous et al., 2015).

5.5.3 Performance of Advanced Treatment Processes and Trains

Typical final concentrations of CECs after advanced treatment process trains have been employed are reported in **Table 5-3** (from WRRF-11-02).

5.6 Human Health Risk Associated with Constituents of Emerging Concern in Direct Potable Reuse

Following the study by the U.S. Geological Survey in 2002 (Kolpin et al., 2002) regarding CEC occurrence, substantial research on the human health risks associated with those CECs has been pursued (Schwab et al., 2005; Snyder et al., 2008a; Bruce et al., 2010). These studies generally have followed the risk assessment paradigm established by the National Academy of Sciences in 1983, which includes the following four steps: hazard identification, dose-response assessment, exposure assessment, and risk characterization. This risk paradigm is the basis of the USEPA’s risk assessment framework, which has been used to establish drinking water criteria and other regulatory levels.

5.6.1 Selection of Constituents of Emerging Concern for Risk Assessment

Using the risk assessment paradigm, select CECs were identified through a screening process for further evaluation as part of the hazard identification step in the above-cited studies. The specific CECs selected and the criteria used in the screening process vary by study; however, the CECs typically are compounds to which exposures potentially could occur and that could result in adverse health effects. Dose-response data and exposure assumptions were then used to calculate concentrations of the CECs in water associated with an acceptable level of risk. While the terminology for the “acceptable” CEC concentrations varied by study, the methodology used to calculate the concentrations was consistent. The “acceptable” concentrations were then compared with occurrence data to evaluate whether CECs are occurring at levels which may pose a human health risk. These studies included both advanced treated water and drinking water, so the “acceptable” concentrations and comparisons are not directly relevant to DPR; however, the methodology is well established.

5.6.2 Evaluation Criteria for Constituents of Emerging Concern

The NWRI Independent Advisory Panel developed a list of criteria for CECs to use in evaluating treatment trains for potable reuse (Crook et al., 2013). The criteria, shown in **Table 5-2**, were developed using the same methodology as the prior risk assessment studies and are considered protective of human health; therefore, if the concentrations of CECs in advanced treated water following treatment are less than the criteria in **Table 5-2**, the risks associated with potable use of the water are acceptable. As shown in **Table 5-4**, typical concentrations of CECs following advanced treatment are well below the criteria, suggesting that risks associated with CECs can be mitigated during DPR using source control, treatment, and monitoring.

5.7 Information Sources

A list is provided in **Table 5-5** of the WRRF and WRA projects that were reviewed for the preparation of this chapter. Full citations for reports related to these projects, along with citations for other references and sources of information, are included in **Section 5.8**.

Table 5-5: WRRF and WRA Research Projects Used to Prepare Chapter 5

Project No.	Project Title	Principal Investigator(s)
WRRF-02-01	Rejection of Wastewater-Derived Micropollutants in High-Pressure Membrane Applications Leading to Indirect Potable Reuse	Jörg Drewes, Colorado School of Mines
WRRF-05-05	Identifying Hormonally Active Compounds, Pharmaceuticals, and Personal Care Product Ingredients of Health Concern from Potential Presence in Water Intended for Indirect Potable Reuse	Shane Snyder, Southern Nevada Water Authority
WRRF-06-04	Health Effects Concerns of Water Reuse with Research Recommendations	Joseph Cotruvo, Joseph Cotruvo & Associates LLC; Richard Bull, MoBull Consulting; James Crook, Water Reuse Consultant; Margaret Whittaker, ToxServices
WRRF-06-18	Development and Application of Tools to Assess and Understand the Relative Risks of Drugs and Other Chemicals in Indirect Potable Reuse Water	Margaret Nellor, Nellor Environmental Associates, Inc., and Jeffrey Soller, Soller Environmental, LLC
WRRF-08-05	Use of Ozone in Water Reclamation for Contaminant Oxidation	Shane Snyder, University of Arizona
WRRF-11-01	Monitoring for Reliability and Process Control of Potable Reuse Applications	Ian Pepper, University of Arizona
WRRF-11-02	Equivalency of Advanced Treatment Trains for Potable Reuse	R. Rhodes Trussell, Trussell Technologies, Inc.
WRRF-11-05	Demonstrating the Benefits of Engineered Direct Potable Reuse versus Unintentional Indirect Potable Reuse Systems	Glen Boyd, The Cadmus Group, Inc.
WRRF-11-10	Risk Reduction Principles for Direct Potable Reuse	Andrew Salveson, Carollo Engineers
WRRF-13-02	Model Public Communication Plan for Advancing Direct Potable Reuse Acceptance	Mark Millan, Data Instincts
WRRF-14-16	Operational, Monitoring, and Response Data from Unit Processes in Full-Scale Water Treatment, Indirect Potable Reuse, and Direct Potable Reuse	Andrew Salveson, Carollo Engineers
WRRF-14-20 (WRA-14-01)	Developing Direct Potable Reuse Guidelines	Jeffrey Mosher, National Water Research Institute

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Chapter 6: Monitoring Direct Potable Reuse Systems and the Critical Control Point Approach

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Treatment technologies are available that are capable of providing the necessary treatment to be protective of public health in DPR applications; however, because treatment processes *do* degrade and *may* fail, the operation, maintenance, and monitoring of these processes is of critical importance. Both end-of-pipe compliance monitoring and performance-based monitoring have been used to ensure that an AWTF produces water that is protective of public health. As the end of pipe compliance monitoring approach is well documented elsewhere in this document, the purpose of this chapter is to define the role of performance-based monitoring for potable reuse, including a review of the use of CCPs. The benefit of a performance-based monitoring approach is to identify and implement CCPs where hazards to human health risks can be reduced, prevented, or eliminated. Consequently, the focus is on the monitoring and control of the advanced water treatment processes and any subsequent steps prior to the point of introduction into the conventional potable water system, whether at the inlet to a conventional water treatment plant or the drinking water distribution system

6.1 Identification of Key Issues

Key issues that should be considered in the development of monitoring and control programs for DPR include:

- The transition from IPR to DPR results in the loss of the environmental buffer (e.g., an aquifer or lake), which provides opportunities for dilution, retention time (i.e., response time), and the attenuation of constituents of concern.
- Because of the loss of an environmental buffers, DPR requires additional focus on fail-safe methods to eliminate acute risks and minimize chronic risks.
- The lack of an environmental buffer means that DPR represents a more closely coupled system, in which less time is available to identify and respond to water quality concerns.
- Because a common sources of failure in the operation of AWTFs is human error, the development and use of effective monitoring programs and control strategies is of critical importance in the implementation of DPR.
- Continued work on existing monitoring technologies and the development of new and enhanced technologies and strategies will provide opportunities for improved performance and efficiency through better process control.
- The use of performance-based process monitoring and control strategies for potable reuse projects is not widespread in the United States.

- The use of performance-based monitoring, such as CCPs, to supplement current monitoring control strategies by adding process assessment information for operations of a potable reuse facility is gaining acceptance.

- Because direct online monitoring of pathogens of interest in potable reuse applications is currently not technologically feasible, greater reliance must be placed on monitoring and control strategies using surrogates and indicators.

- As enhanced monitoring and control strategies are developed and demonstrated it will be possible to assign more realistic pathogen log reduction credits for individual unit processes at an AWTF.

6.2 Summary of Principal Findings

The following findings on the state of knowledge with respect to monitoring and the application of the CCP approach to DPR are derived from a review of WRRF reports, published literature, and from the experience of ongoing monitoring programs.

6.2.1 What Is Known?

- Current monitoring technologies and strategies exist that can be used to ensure that DPR is protective of public health.

- Improvements are being made continuously to monitoring methods and technologies based on the results of research and field experience.

- In the United States, compliance monitoring is used for monitoring and control systems/strategies in drinking water and potable reuse applications.

- Performance-based CCP approach to monitoring has been translated successfully for use in DPR applications from other industries (e.g., NASA, the food industry) where failsafe methods are necessary to protect human health.

- The CCP approach has been applied successfully to water reuse projects in Australia and is gaining acceptance in the United States.

- The CCP approach can be used to supplement existing monitoring approaches with performance-based information.

6.2.2 What Is Unknown?

Unknowns in this context are best framed as needs for additional research and development, as follows:

- While the existing monitoring technology is adequate to determine the integrity and efficacy of advanced treatment processes, improvements in monitoring technology are needed to increase confidence in treatment performance and reduce requirements for:

    - Treatment redundancy (i.e., inaccurate and/or imprecise monitoring would require additional treatment barriers).
    - Storage, including the need for and size of ESBs (i.e., improved monitoring system accuracy allows greater removal credit for online processes, reducing the ESB hold time).
- Monitoring improvements for both IPR and DPR must focus on methods that can:
    - Be used to demonstrate pathogen log reduction values higher than currently employed with existing online methods (e.g., RO membranes).
    - Provide comprehensive results for whole classes of water quality risk factors rather than individual chemical compounds (e.g., bioassays).
    - Provide early warning of unknown chemicals (e.g., non-targeted analysis).

6.3 Alternative Approaches for the Protection of Public Health in Direct Potable Reuse Applications

The paramount concern in the development of DPR projects is the protection of public health. There are concerns with both acute and chronic toxicity with respect to pathogenic microorganisms and various chemicals. In developing advanced water treatment trains to deal with the constituents of concern, both compliance monitoring and performance-based approaches have been developed to protect public health. In what follows, both approaches to public health are introduced. The performance based approach is examined further in the remainder of the chapter. Example of both approaches are presented in **Section 6.7**.

6.3.1 Compliance Monitoring for Direct Potable Reuse

In the United States it is common practice to use compliance monitoring criteria and standards and for pathogenic microorganisms, chemicals, and chemical constituents of concern. The use of compliance monitoring is especially common in the development of DPR regulations. The development of performance based criteria which have been adopted in other parts of the world are considered in **Section 6.3.2**.

6.3.1.1 Pathogenic Microorganisms Requirements for Direct Potable Reuse

The principal pathogenic organisms of concern in wastewater include enteric viruses, *Cryptosporidium*, and *Giardia* as measured from the raw wastewater to finished water suitable for drinking. In California, to be protective of public health it is deemed necessary to provide the following pathogen log reductions: 12 log for enteric viruses, 10 log of *Cryptosporidium*, and 10 log for *Giardia*. In effect, these log reduction criteria are "end of pipe" values. Notably, these values are not probability based, but reflect the maximum values recorded for each pathogen category. Other states have adopted similar, but different log reduction values.

6.3.1.2 Chemical Constituent Requirements for Direct Potable Reuse

In the California regulations, all regulated chemicals and health advisories established by the USEPA must be met including five DBP limits (trihalomethanes, HAA5, NDMA, bromate, and chlorate). Two other categories of chemicals should be monitored to evaluate the efficiency of treatment train performance in removing trace organics: (1) unregulated chemicals of interest from the standpoint of public health, and (2) compounds useful for evaluating the removal of organic chemicals during various types of treatment (Schimmoller et al., see **Chapter 2** of this document).

6.3.2 Performance Based Monitoring for Direct Potable Reuse

The initial research projects on the topic of treatment process control (WRRF-09-03 and WRRF-11-10) were conducted in parallel and focused on the transfer of risk mitigation approaches from other industries where failsafe operation is required. The goal of WRRF-11-10 was to provide a "critical initial evaluation of DPR, including treatment, monitoring, and operation." Salveson et al. (2014) took a broader look at risk mitigation for DPR systems, borrowing fail-safe concepts from various industries, including space, bridge building, and nuclear (Salveson et al., 2014; WRRF-11-10). The key points from the failure analysis approach taken by collaborators from other industries are as follows:

- It is important to control potential failure points relative to the risk they represent. Focus on the elimination of acute risk and minimization of chronic risk.

- The highest-risk systems are those that are complex (i.e., requiring substantial training to operate, maintain, and monitor) and also tightly coupled (i.e., the domino effect); therefore, overall system risk can be lowered by reducing the complexity of individual components, as well as by decoupling them from one another.

- One of the most common sources of failure is human error, which can result from poor training, a failure to follow protocols, or mistakes. Simple inspection checklists provide substantial value.

- Monitoring is critical to controlling risk.

These four themes formed the foundation of a number of other WRRF projects, which have resulted in many of the central conclusions described in this chapter and those that follow, including the central role that online monitoring systems must play in managing acute risks in DPR systems, the importance of ESBs in reducing system risk by decoupling two parts of an otherwise closely coupled system, and the importance of operator training.

6.3.3 Hazard Analysis and Critical Control Point Framework for Risk Management

The HACCP framework was developed to control risk from microbial hazards in food for astronauts sent into space (Halliwell et al., 2014; WRRF-09-03). Since then, HACCP has been adopted by the United Nations Food and Agriculture Organization/World Health Organization (WHO) for use in the food sector. This framework also is in use in a number of countries around the world for controlling risks in water systems, including potable and nonpotable water systems (notably, in Australia).

Halliwell et al. (2014) note that the “purpose of a HACCP system is to put in place process controls that will detect and correct deviations in quality processes at the earliest possible opportunity.” By focusing on monitoring and maintaining the treatment barriers rather than on end-of-pipe compliance monitoring and testing, HACCP offers the dual advantage of preventing poor water quality and allowing a reduction in end-of-pipe monitoring and associated costs (Walker et al., 2016; WRRF-13-03.

It should be noted that almost all the elements involved in HACCP are currently part of the monitoring and management strategy employed at existing potable reuse facilities. The difference is that HACCP is a more formalized procedure involving a number of prescribed steps in which critical treatment processes, associated monitoring, and corrective actions are identified in a structured process

HACCP is a formal 12-step process for establishing this system of process controls. It progresses through preliminary steps involving team formation and a detailed description of the system before arriving at the central steps of:

- Hazard analysis (i.e., “What can go wrong, and what are the likelihoods, consequences, and potential control measures?”).
- Identification of CCPs. Note: A CCP is a point in the treatment train (i.e., a unit treatment process) that is designed specifically to reduce, prevent, or eliminate a human health hazard and for which controls exist to ensure the proper performance of that process.
- Identification of monitoring procedures.
- Identification of corrective actions and procedures.

These steps are then followed by validation, verification, and record keeping. Halliwell et al. (2014) noted that the HACCP approach “typically applies as one part of a broader management framework.” Approaches for identifying, monitoring, and controlling CCPs are discussed in **Section 6.4.**

6.4 Critical Control Point Approach for Direct Potable Reuse

A HACCP approach to mitigating risk in a system, as noted above, begins with a hazard analysis. For DPR applications the focus is narrowed to hazards from waterborne constituents that might affect public health. A separate HACCP approach may be applied for physical hazards to operations staff from, say, falling objects as part of a plant's health and safety plan, for example. In previous chapters, the constituents of concern in DPR, have been classified broadly as pathogens and chemical constituents. Once the hazards are identified, CCPs must be identified, along with monitoring techniques and control measures. Also, the difference between CCPs and critical operating points (COP) must be delineated. These subjects are addressed below.

6.4.1 Identification of Critical Control Points

Use of performance-based monitoring, such as CCPs, to supplement current monitoring control strategies by adding process assessment information for operations of a potable reuse facility is gaining acceptance. Halliwell et al. (2014) developed a five-question metric for identifying CCPs in reuse systems. Walker et al. (2016) modified one of the questions to be specific to a potable reuse scenario, in which the potential hazards are specifically phrased in terms of pathogen log reduction and water quality targets. The five questions are:

- Is there a hazard at this process? What is it?
- Do control measures(s) exist for the identified hazard?
- Is the process step required to achieve a log reduction of microorganisms and/or to meet water quality targets?
- Could contamination occur at or increase to unacceptable level(s)?
- Will a subsequent step or action eliminate or reduce the hazard to an acceptable level?

These five question are depicted in the form of a decision tree in **Figure 6-1**.

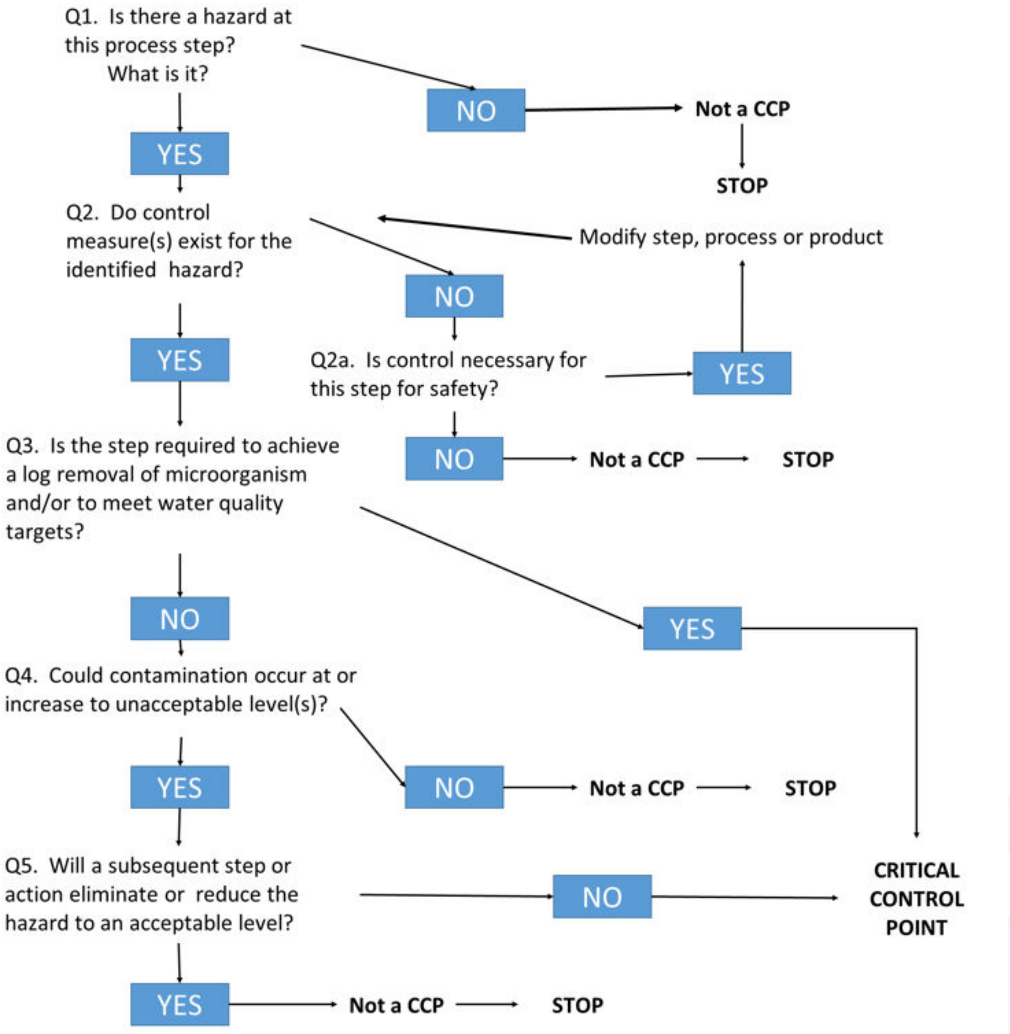

Figure 6-1: Decision pathway for the selection of critical control points (from Halliwell et al., 2016).

6.4.2 Identification of Monitoring Technologies and Procedures for Critical Control Points

As part of their broad scope to evaluate risk reduction for DPR, Salveson et al. (2014) provided a comprehensive desktop evaluation of monitoring technology available for DPR, building on the existing monitoring technology currently used in IPR facilities. Monitoring parameters that can be used for CCPs in advance water treatment facilities are summarized in **Table 6-1**.

Table 6-1: Typical Monitoring Parameters for Various Unit Processes Used in the Advanced Treatment of Water that Have Been Identified as Critical Control Points

Unit Process/Critical Control Point	Health Risk Management	Monitoring Parameters
Wastewater treatment plant effluent	Upstream water quality	Turbidity
Microfiltration or ultrafiltration	Microorganism control	Online pressure decay test (PDT); online effluent turbidity; particle counting
Reverse osmosis	Microorganisms and chemicals of concern	Online electrical conductivity (EC), online total organic carbon (TOC), UV transmittance (UVT)
Ultraviolet (UV)	Microorganism control	UV dose (based on UV transmittance, flow, and UV sensor intensity)
Ultraviolet (UV) with advanced oxidation	Microorganisms and chemicals of concern (e.g., NDMA and 1,4-dioxane)	Electric energy per order of magnitude (EEO) control (incorporating energy use, flow, UV transmittance) coupled with a minimum oxidant dose Oxidant weighted UV dose
Stabilization	Lead and copper	pH, TDS, alkalinity, applied chemical dose, corrosion indexes
Ozone	Microorganism control	Online ozone dose and residual, CT (calculated, residual concentration, C, times time, T)
Ozone/Biologically active carbon	Microorganism control	Online ozone dose, empty bed contact time (EBCT); control dose based on the ozone-to-TOC ratio
Granular activated carbon	Dissolved organic constituents, disinfection byproduct control	TOC, UVT, carbon usage
Engineered storage buffer with chlorine	Microorganisms, chlorate, disinfection byproduct management	Online free chlorine residual, CT (calculated)

6.4.3 Identification of Control Measures for Critical Control Points

Once CCPs have been identified, it is necessary to establish control limits for various actions that must be taken to correct a potential operational problem. There are a number of intermediate corrective measures that can be taken such that a CCP may not have to be taken offline. For example, by using a trending program in conjunction with a control chart program, performance trends can be identified early on and corrective measures can be taken to avoid any deterioration in performance. Other corrective measures, such as those identified in **Table 6-2**, may have to be taken when quality control limits are exceeded. Corrective measures are discussed at length by Halliwell et al. (2014; WRRF-09-03); Pepper and Snyder (2015; WRRF-11-01); and Walker et al. (2016; WRRF-13-03).

Table 6-2: Typical Corrective Measures for Various Unit Processes Used in the Advanced Treatment of Water that Have Been Identified as Critical Control Points

Unit Process/ Critical Control Point	Health Risk Management	Monitoring Options	Ultimate Corrective Action When Control Limits Are Exceeded
Wastewater treatment plant effluent	Upstream water quality	Turbidity	Water routed to discharge until the problem is identified and corrected
Microfiltration or ultrafiltration	Microorganism control	Online pressure decay test (PDT), online effluent turbidity	Additional integrity test triggered, microfiltration/ultrafiltration bank taken offline
Reverse osmosis	Microorganisms and chemicals of concern	Online electrical conductivity (EC), online total organic carbon (TOC)	Reverse osmosis bank taken offline
Ultraviolet (UV)	Microorganism control	UV dose (based on UV transmittance, flow, and UV sensor intensity), UVT of feed water	Product water diverted to discharge until the problem is identified and corrected
Ultraviolet (UV) with advanced oxidation	Microorganisms and chemicals of concern (e.g., NDMA and 1,4-dioxane)	Electric energy per order of magnitude (EEO) Oxidant weighted UV dose	Product water diverted to discharge until the problem is identified and corrected
Stabilization	Lead and copper	pH, TDS, alkalinity, applied chemical dose, corrosion indexes	Product water diverted to discharge until the problem is identified and corrected
Ozone	Microorganism control	Online ozone dose and residual, CT (calculated)	Unit taken offline until the problem is identified and corrected
Ozone/ biologically active carbon	Microorganism control	Online ozone dose, empty bed contact time (EBCT)	Unit taken offline until the problem is identified and corrected
Granular activated carbon	Dissolved organic constituents, disinfection byproduct control	TOC, UVT, carbon usage	Unit taken offline until the problem is identified and corrected
Engineered storage buffer with chlorine	Microorganisms, chlorate, disinfection byproduct management	Online free chlorine residual, CT (calculated)	Product water diverted to discharge until problem is identified and corrected

6.4.4 Critical Control Points versus Critical Operating Points

Halliwell et al. (2014) make the additional observation, echoed and emphasized by Walker et al. (2016), that when defining the list of CCPs, it is important to the success of the system to differentiate between CCPs, which pertain directly to the reduction of hazards to human health, and critical operating points (COPs), which may represent other important monitoring checks that support operational goals, such as production capacity and efficient and cost-effective operation. For example, a CCP might be the UV intensity readings of a UV reactor, which must stay within a certain range to maintain adequate disinfection, whereas a COP might be the trans-membrane pressure in a microfilter, which must be maintained below a certain threshold to prevent irreversible fouling and maintain operational efficiency, but does not affect directly the relevant water quality parameters.

While the potential harm associated with the latter error is readily apparent, the former carries with it potentially serious consequences as well. Why would it matter if a COP was identified as a CCP? For example in a typical water or wastewater treatment plant, at any given time, the Supervisory Control and Data Acquisition (SCADA) system a number of alarms are always showing. In most SCADA systems no differentiation is made between CCP or COP alerts. As a result, the oversaturation of alarms can lead to reduced vigilance on the part of the operations staff (i.e., envisioning that “one is always going off!”). Consequently, the handful of highly critical alarms must be distinguished from the remaining (literal and figurative) background noise. Alarms associated with CCPs when they deviate outside acceptable control limits are somewhat akin to fire alarms in commercial buildings, being so loud and flashy that no one can ignore them.

6.4.5 Use of Engineered Storage Buffer in Conjunction with Critical Control Points

For WRRF-12-06, Salveson et al. (2016a) evaluated how to replace the environmental buffer characteristic of IPR projects with an ESB in a DPR scenario. The lack of an environmental buffer means that DPR is a more closely coupled system, in which there is less time to monitor process water quality and respond to water quality concerns. Close coupling was identified in WRRF-11-10 as one major source of risk (Salveson et al., 2014). Because online monitoring is not 100-percent accurate or precise, the ESB provides an opportunity to decouple treatment processes from one another and a critical opportunity for monitoring systems to “catch up” with the water that is being treated.

It is especially important for water quality concerns related to acute risks, such as those presented by pathogens and selected chemicals. The ESB is a storage volume that provides sufficient time to monitor for and respond to water quality concerns representing acute risks. The ESB sizing framework developed by Salveson et al. (2016a) relies on the definition of failure response time (FRT), which depends on how long it takes to get critical monitoring data (from a CCP), understand the data, identify a potential failure, and take corrective action. This framework is complimentary with the approach outlined by Walker et al. (2016), as FRTs for all the critical parameters and their monitoring methods can be defined for each CCP.

6.5 Examples of Monitoring and Control Systems

Three examples are provided below to illustrate alternative approaches to monitoring and control have been applied in AWTFs. The first example is from Australia and illustrates a facility whose control and operation scheme was designed using the HACCP process. In the second and third examples, the monitoring and control schemes for two existing potable reuse facilities in the United States, not based on the CCP approach, are examined under the lens of a CCP analysis to illustrate similarities. It is conceivable that a retroactive CCP analysis on an existing facility might pinpoint specific vulnerabilities that can be corrected at relatively low cost in comparison to the potential beneficial impact on operational improvement and/or reduced risk to public health.

6.5.1 Example #1: Bundamba Advanced Water Treatment Plant, Australia

The Bundamba Advanced Water Treatment Plant (AWTP) is located in Ipswich, Queensland, Australia. The plant was built along with two other advanced water purification plants (Luggage Point and Gibson

Island AWTPs) as part of the Western Corridor Recycled Water Project to solve the water scarcity problem in South-East Queensland. The plant became fully operational in June 2008. The treatment process at the Bundamba AWTP includes three main steps: MF, RO, and AOP. Post-treatment with lime and carbon dioxide is used to reduce corrosivity. The advanced treated water is used to augment the region's surface water supplies. While it is a surface water augmentation project and not a DPR project per se, the facility was designed in the context of a completed urban water cycle and can be evaluated similarly. This project includes seven main barriers (Zhao et al., 2009), as follows:

- Residential and industrial source control.
- WWTP.
- MF/UF.
- RO.
- AOP.
- Natural environment (i.e., Lake Wivenhoe).
- Water treatment plant disinfection, distribution, and water quality management.

According to Seqwater's 2012-2013 Annual Report, "Real time monitoring is undertaken at all of these CCPs. An Alert Limit is set for each point, providing an early warning for operations staff to take corrective action before any of the barriers are compromised. An Action Limit at each CCP results in an automatic shutdown of process units within the barrier. A Critical Limit at each CCP also results in an automatic shutdown of the process units within the barrier. The dual shutdown Limits (Action and Critical) are set to provide an additional level of safety to ensure water quality from the AWTP is not compromised. The Critical Limit will only be triggered if the automatic shutdown does not occur when the Action Limit is triggered, or if there is catastrophic failure of a process unit" (Seqwater, 2013).

In the collection system (Barrier No. 1), pump stations and industrial discharge locations are considered CCPs (Zhao et al., 2009). Flow and pump station status are monitored in the collection system, whereas COD, suspended solids, BOD_5 organic nitrogen, and total phosphorus are measured periodically at the influent to the WWTP. At the WWTP (Barrier 2), general water quality parameters, including inorganic ions and metals, are monitored based on periodic collection of grab samples; total nitrogen, total phosphorus, and dissolved oxygen are measured online. At the advanced treatment plant (Barriers 3 through 5), each process serves as a CCP, with the following monitoring requirements: pressure decay tests for MF, online conductivity and sulfate for RO, and present power ratio for the UV. Each parameter is associated with Alert, Action, and Critical Limits.

Due to historic flooding immediately after the construction of the Bundamba AWTP and adequate rainfall since, reservoir levels in Lake Wivenhoe have never dropped below the critical level at which surface water augmentation would be implemented; therefore, the advanced treated water from the Bundamba AWTP has yet to be used for the purposes of reservoir augmentation. Online monitoring at Lake Wivenhoe and Mt. Crosby Water Treatment Plant (Barriers No. 6 and 7) were not defined in the source literature (Zhang et al., 2009).

6.5.2 Example #2: Groundwater Replenishment System in Orange County, California

The Orange County Water District's Groundwater Replenishment System is an AWTF that treats secondary-treated wastewater effluent from the Orange County Sanitation District with MF, RO, and UV/AOP to produce 120 mgd of advanced treated water, which is stabilized and injected into the local aquifer as a seawater intrusion barrier and a source of potable water. The monitoring system employed at OCWD, as shown in **Figure 6-2**, was not explicitly developed using a CCP approach; however, many similarities exist. Pepper et al. (2016) provide a summary description of the monitoring program, including target operating ranges for various surrogate parameters measured online (total chlorine, free chlorine, turbidity, conductivity, TOC, temperature, and pH), and "violation limits" for a subset of these parameters in certain locations. In this monitoring system, the locations that include violation limits could be viewed as CCPs, whereas the remaining locations and surrogates with "target operating ranges" could be viewed as COPs. In addition, the monitoring locations are extensively sampled on a periodic basis for a wide range of constituents (Pepper et al., 2016).

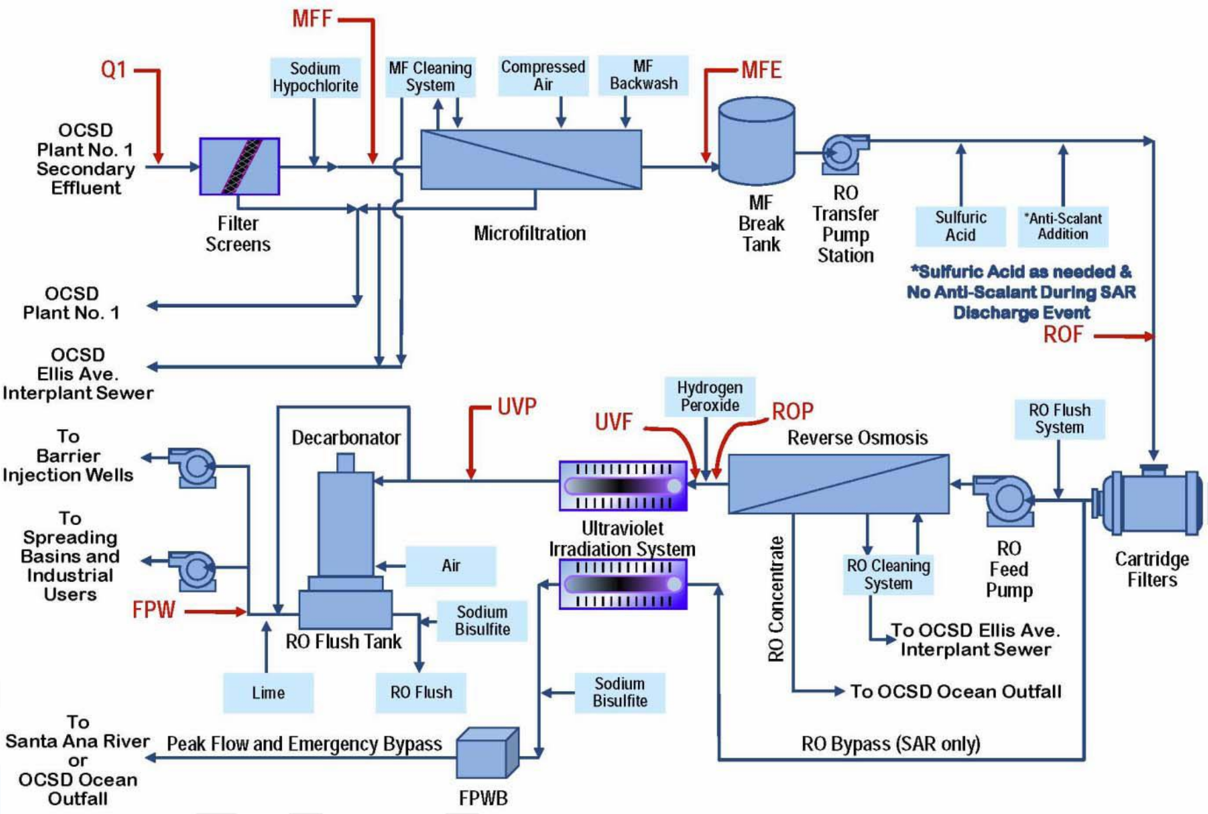

Figure 6-2: A process flow diagram and monitoring points of the advanced water treatment facility at the Orange County Water District (from Pepper et al., 2016). Note: MFF = Microfiltration feed water, MFE = Microfiltration effluent, ROF = Reverse osmosis feed water, ROP = Reverse osmosis product water, DWP = Disinfection product water, and FPW = Final product water.

6.5.3 Example #3: Raw Water Production Facility in Big Spring, Texas

Owned and operated by the Colorado River Municipal Water District, the Raw Water Production Facility (a DPR project) has been in operation since 2013. A simplified monitoring schematic for the AWTF is shown in **Figure 6-3** (Waniliesta-Berg, 2016).

Each monitoring point is identified, along with a list of required monitoring parameters and the conditions under which equipment and/or plant-shutdown is required. While not presented as a CCP approach, the monitoring requirements and shutdown conditions provide a functionally equivalent result. Superimposed on the figure are bolded black boxes that highlight the shutdown conditions. Per definition, each monitoring point associated with a shutdown condition is a CCP. For example, the influent monitoring point is a CCP, with turbidity acting as a surrogate for pathogen levels. If the turbidity in the Big Spring WWTP effluent exceeds 10 NTU, the Raw Water Production Facility cannot accept the water and must divert it back to the WWTP.

The Raw Water Production Facility relies heavily on its ability to shut down production, which may not be an acceptable strategy for every plant. A more refined (i.e., tiered) approach would involve a certain set of actions to take when CCP parameters fall outside a certain narrower operating range. A tiered approach allows for corrections before reaching a point where shutdown is required. Based on operating experience, staff at the Raw Water Production Facility already informally does this, but it is not part of the formal monitoring and control scheme for the plant.

6.6 Monitoring Needs

A number of authors have identified the need for (1) online pathogen monitoring (as pursued by WRRF-11-01), (2) a better surrogate measure for RO integrity (as has been pursued by subsequent projects, such as WRRF-12-07 and WRRF-14-10), and (3) better approaches for dealing with unknowns.

6.6.1 Online Pathogen Monitoring

Pepper et al. (2016) determined that existing technologies (based on multi-angle light scattering or UV fluorescence signature of specific biomarkers) had detection limits between 10 and 10^6 CFU/mL *Escherichia coli* (*E. coli*) in potable water. These methods do not detect pathogens most relevant to DPR (i.e., virus and protozoa), and their detection limits are many orders of magnitude above relevant concentrations (see **Chapter 3**); therefore, they are not suitable for end-of-pipe monitoring. Furthermore, the susceptibility of these technologies to interference from organic matter in treated wastewater that has not undergone significant advanced treatment (Pepper et al., 2016), means that they are at this time also unsuitable as sensors at intermediate stages of treatment. Consequently, direct online monitoring of pathogens of interest is currently not technologically feasible.

While not quite online, the output of an adenosine triphosphate (ATP) field testing kit (LuminUltra) correlated highly with heterotrophic plate counts in all tested waters (Pepper et al., 2016), with results available within minutes of sampling, making this the most promising sensor for detecting microbial presence or activity directly.

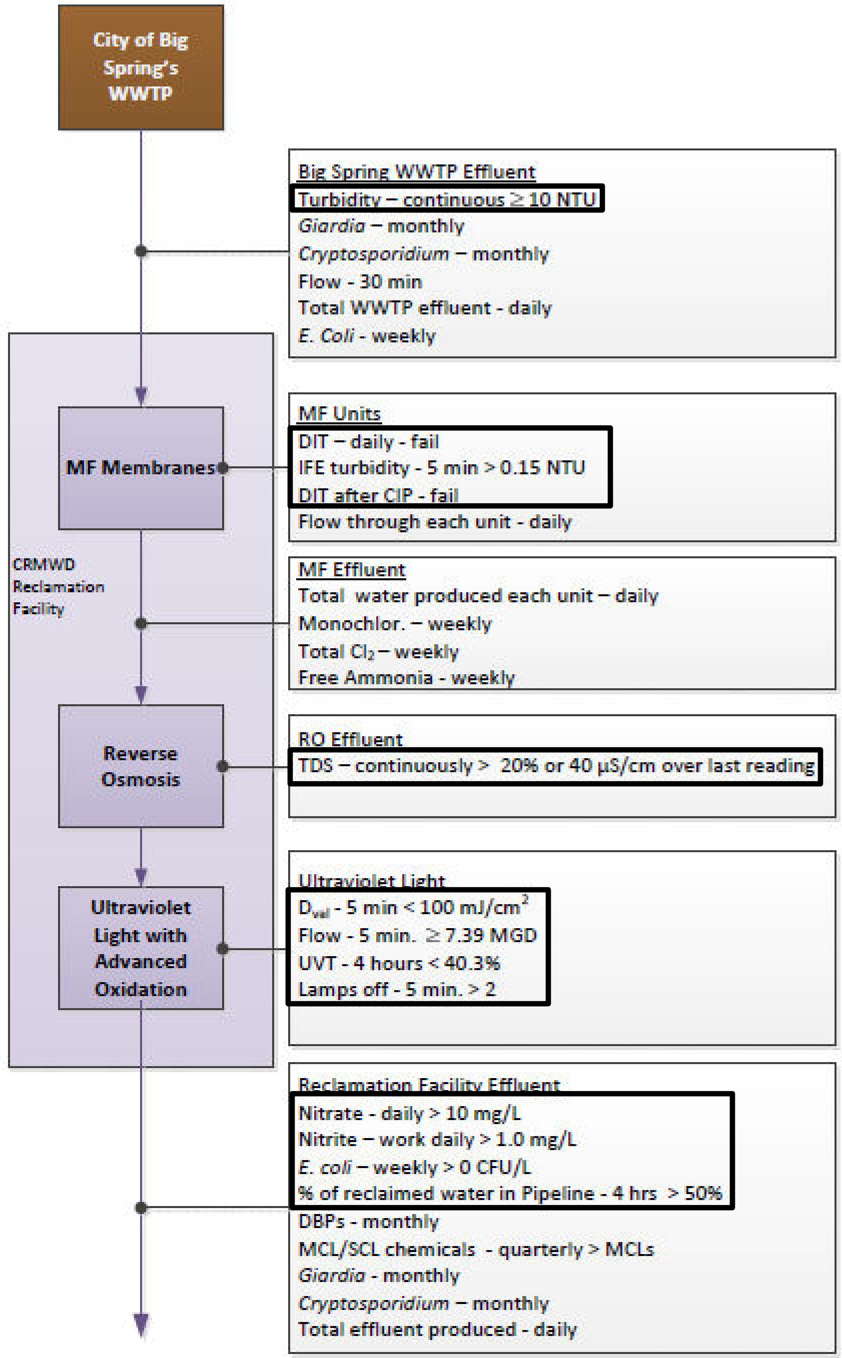

Figure 6-3: **Monitoring summary schematic for the Raw Water Production Facility of the Colorado River Municipal Water District in Big Spring, Texas. Provided by the Texas Commission on Environmental Quality (Waniliesta-Berg, 2016).**

6.6.2 Developing Surrogates for Reverse Osmosis Membrane Integrity

As identified by Salveson et al. (2014, 2016a), Jacangelo et al. (2015), and others, one area where improved monitoring has the potential to provide significant positive impact is in demonstrating RO membrane integrity. Current online monitors for RO systems rely on bulk water quality measurement [electrical conductivity (EC), and TOC]. These parameters can be measured online with robust existing sensor technology. The challenge with these surrogates is that they do not provide sufficient resolution to account for the full performance of the RO membranes, which, when intact, should provide an absolute barrier to all pathogens. The removal of both TOC and EC by RO membranes has been shown to be at ~1.5-log, though higher resolution TOC meters (online) could demonstration up to 2-log reduction of TOC across RO (e.g., Qin et al., 2005). This lower value or removal can be compared to challenge studies with well-operated RO systems, resulting in excess of 6-log reduction of model virus (e.g., Kitis et al., 2003). Both these ranges also were confirmed during pilot testing for WRF4536. The inability to monitor directly RO membrane performance for pathogen removal limits the log credits assigned to RO membranes.

The field for two ongoing WRRF projects examining potential methods for monitoring RO integrity has recently been completed. Identifying one or more appropriate surrogates for RO integrity was the focus of the study by Jacangelo et al. (2015; WRRF-12-07), and TRASAR® – a fluorescence-based method commercialized by Nalco – was tested at the demonstration scale by Steinle-Darling et al. (2016; WRRF-14-10). The stated goal of project WRRF-12-07 is to "develop a scientifically proven method for integrity monitoring of nanofiltration (NF) and RO membranes for a 4-log validation of microorganisms (primarily viruses) (Jacangelo et al., 2015). Potential integrity monitors were identified through a literature review and two information gathering workshops, and included the use of dyes (Rhodamine-WT, Uranine, and TRASAR®), MS2 bacteriophage, and polymethyl methacrylate (PMMA) nanoparticles. Pilot testing at several facilities was conducted and full results are not yet available from WE&RF as of this writing. As presented by Steinle-Darling and Jacangelo (2016), all three dyes were able to achieve 4-log reduction with the membranes used in WRRF-12-07.

The fluorescence-based TRASAR® method showed promising results in both projects. Specific log reduction values for intact membranes varied from 3 log to over 4 log, highlighting the need for additional work at the demonstration scale validating the combination of TRASAR® with different membrane types. This technology, which already has approval from the National Science Foundation (NSF) and has been in commercial use for other process control applications for several decades, is currently the most commercially viable alternative for achieving additional log reduction credit for RO membranes.

6.6.3 Monitoring for Unknowns

Existing monitoring schemes for potable reuse systems generally deploy significant resources to sample and analyze for a large list of regulated and unregulated chemical constituents, including primary pollutants (e.g., heavy metals, pesticides, and other toxic substances), as well as CECs. The challenge with this bottoms-up approach is that you can only ever find what you know or suspect to already be present. Current research targeting this challenge in traditional analytical approach is focused in two separate areas: (1) (bio)assays that test for the cumulative physiological effect of chemicals in the water [similar to a more traditional Whole Effluent Toxicity [WET] test], and a non-targeted analysis approach, which relies on frequent measurements of a full chromatographic spectrum to track any changes to what is considered the baseline signal, capturing the spectral signals of both known and unknown chemicals and alerting operators when this baseline signal changes.

6.7 Information Sources

A list is provided in **Table 6-3** of the WRRF, WRA, and WRF projects that were reviewed for the preparation of this chapter. Full citations for reports related to these projects, along with citations for other references and sources of information, are included in **Section 6.8**.

Table 6-3: WRRF, WRA, and WRF Research Projects Used to Prepare Chapter 6

Project No.	Project Title	Principal Investigator(s)
WRRF-09-03	Utilization of Hazard Analysis and Critical Control Points Approach for Evaluating Integrity of Treatment Barriers for Reuse	David Halliwell, Water Quality Research Australia Ltd.
WRRF-11-01	Monitoring for Reliability and Process Control of Potable Reuse Applications	Ian Pepper, University of Arizona
WRRF-11-10	Risk Reduction Principles for Direct Potable Reuse	Andrew Salveson, Carollo Engineers
WRRF-12-06	Guidelines for Engineered Storage for Direct Potable Reuse	Andrew Salveson, Carollo Engineers
WRRF-12-07	Methods for Integrity Testing of Nanofiltration and Reverse Osmosis Membranes	Joseph Jacangelo, MWH
WRRF-13-03	Critical Control Point Assessment to Quantify Robustness and Reliability of Multiple Treatment Barriers of Direct Potable Reuse Scheme	Troy Walker, Hazen & Sawyer
WRRF-13-15 (WRF4536)	Blending Requirements for Water from Direct Potable Reuse Treatment Facilities	Andrew Salveson, Carollo Engineers
WRRF-14-10	Enhanced Pathogen and Pollutant Monitoring of the Colorado River Municipal Water District Raw Water Production Facility at Big Spring, Texas	Eva Steinle-Darling, Carollo Engineers
WRRF-14-20 (WRA-14-01)	Developing Direct Potable Reuse Guidelines	Jeffrey Mosher, National Water Research Institute

6.8 References

Halliwell, D., D. Burris, D. Deere, G. Leslie, R. Jose, and J. Blackbeard (2014). *Utilization of Hazard Analysis and Critical Control Points Approach for Evaluating Integrity of Treatment Barriers for Reuse*. Final Report for WRRF-03-09, WateReuse Research Foundation, Alexandria, VA.

Jacangelo, J., G. Lehman, E. Bruce, S. Gray, and M. Cran (2015). "Standard Methods for Integrity Testing and On-Line Monitoring of NF and RO Membranes." Progress Report #9 for WRRF-12-07, dated October 1, 2015. WateReuse Research Foundation, Alexandria, VA.

Kitis, M., J. Lozier, J.H. Kim, B. Mi, and B. Marinas (2003). "Microbial Removal and Integrity Monitoring of RO and NF Membranes." *Journal AWWA,* 95: 12, 105-119.

Pepper, I., and S. Snyder (2015). *Monitoring for Reliability and Process Control of Potable Reuse Applications.* Draft Final Report for WRRF-11-01, WateReuse Research Foundation, Alexandria, VA.

Qin, J.-J., M.H. Oo, M.N. Wai, and K.A. Kekre (2005). "TOC Removal in Reclamation of Municipal Wastewater by RO, Separation and Purification Technology." Volume 46, Issues 1–2, Pages 125–128, November 2005.

Salveson, A., E. Mackey, M. Salveson, and M. Flynn (2014). *Risk Reduction for Direct Potable Reuse*. Final Report for WRRF-11-10, WateReuse Research Foundation, Alexandria, VA.

Salveson, A., E. Steinle-Darling, S. Trussell, B Pecson, and L. Macpherson (2016a, in press). *Guidelines for Engineered Storage for Direct Potable Reuse*. Final Report for WRRF-12-06, WateReuse Research Foundation, Alexandria, VA.

Salveson, A., J. Sutherland, E. Garvey, A. Pruden, M. Edwards, and E. Dickenson (2016b). "WRF4536/WRRF-13-15: Blending Requirements for Water from Direct Potable Reuse Treatment Facilities. Progress Report No. 6, dated 17 June, 2016, to WateReuse Research Foundation, Alexandria, VA.

Seqwater (2013). Annual Report 2012-2013 For the Western Corridor Recycled Water Scheme - Recycled Water Management Plan. http://www.seqwater.com.au/sites/default/files/PDF%20Documents/Publications/2012-13%20WCRWS%20Annual%20Report.pdf (accessed 6/24/16).

Steinle-Darling, E., A. Salveson, J. Sutherland, E. Dickenson, E. Hokanson, S. Trussell, and B. Stanford (2016). "Testing Water Quality in a Municipal Wastewater Effluent Treated to Drinking Water Standards." DRAFT Final Report and DPR Monitoring Guidance for Texas Water Development Board Contract #1348321632 and WateReuse Research Foundation Project No. 14-10, May 2016.

Steinle-Darling, E., and J. Jacangelo (2016). "Assessment of Online Verification of Virus Removal by RO Membranes Employed for Potable Reuse." Joint presentation on WRRF-14-10 and WRRF-12-07 at the Water Reuse Research Conference in Denver, CO, May 23, 2016.

Tchobanoglous, G., J. Cotruvo, J. Crook, E. McDonald, A. Olivieri, A. Salveson, and R.S. Trussell (2015). *Framework for Direct Potable Reuse*. Report from Project WRRF-14-20 (WRA-14-01), WateReuse Research Foundation, Alexandria, VA.

Walker, T., B. Stanford, S. Khan, C. Robillot, S. Snyder, R. Valerdi, S. Swivedi, and J. Vickers (2016). “Critical Control Point Assessment to Quantify Robustness and Reliability of Multiple Treatment Barriers of a DPR Scheme.” DRAFT Final Report for WRRF-13-03, WateReuse Research Foundation, Alexandria, VA.

Waniliesta-Berg, M. (2016). “Enclosure B: CRMWD Reclamation Facility Monitoring Locations, Frequency, and Action Levels.” Transmitted by email on February 22, 2016.

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Chapter 7: Operations, Maintenance, and Operator Training and Certification

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Proper operation and maintenance (O&M) is critical to the success and reliability of DPR projects. Preventive maintenance must be performed routinely to ensure equipment function and calibration, and corrective maintenance should support the management of assets. To protect public health, well-qualified operators with appropriate training, certifications, and experience are needed to manage normal conditions and respond to challenges. O&M and operator training and certification are discussed in this chapter within the context of DPR.

7.1 Identification of Key Issues

O&M and operator training activities must be robust and well thought out to ensure the effective long-term performance of DPR facilities. The successful O&M of a DPR facility can serve as an example for others to emulate and promotes public acceptance of DPR. Key O&M and operator training issues for DPR projects include:

- At present, the important early operations activities (e.g., startup testing, commissioning, operator training, and final acceptance) defined by permit requirements and construction contract documents vary depending on the project and design firm.
- Guidelines and regulatory requirements for comprehensive operations plans with CCPs and action/response procedures are needed to support facility implementation and reliable routine performance.
- Operations plans for DPR projects may need to be equivalent to and/or more detailed than those for water treatment facilities for risk management.
- The importance of source control, addressing variable feedwater quality, and optimizing process performance should be emphasized in operations plans for DPR projects.
- A maintenance plan is essential to support the optimal operation of the DPR project
- Standards for maintenance plans that preserve and manage assets for the optimum performance of facilities, equipment, and online monitoring systems often are lacking or incomplete.
- There is a need to evolve a culture change to emphasize the optimization of treatment performance over the need to meet minimal compliance requirements.
- Operator training and licensure/certification programs create knowledge gaps by separately addressing wastewater treatment, water treatment, and distribution system issues rather than using a coordinated, inclusive approach covering all aspects of DPR.

7.2 Summary of Principal Findings

The principal findings derived from a review of national and state regulations, as well as the experience of ongoing O&M and operator training programs, are summarized below Each topic area is considered in detail in this chapter.

7.2.1 What Is Known?

- O&M activities should begin as construction nears completion and should continue throughout the lifetime of the AWTF. Early operations tasks commonly are led by the construction contractor under the terms of the contract documents and involve facility startup testing, followed by commissioning and operator training, and finally acceptance of the facilities. At the completion of construction, the construction contract is closed out, the warranty period begins, and the O&M staff accepts responsibility for the performance of the facility.

- Based on experience with IPR projects, the first year of operation of the AWTF is a critical period for demonstrating the long-term success of the project.

- The development of comprehensive operations plans that provide O&M staff with information about the facilities (describing normal conditions and steps to take if the performance of treatment processes or equipment declines) is critical to the success of drinking water, wastewater, water recycling, and potable reuse projects.

- DPR necessitates the application of a variety of advanced water treatment technologies to meet water quality requirements" (WRRF-13-13, in progress).

- Much of the information needed to develop standards is available, albeit scattered among multiple design engineers and in construction documents customized for specific projects

- Sufficient information about facility startup testing, commissioning, operator training, and acceptance procedures is available from existing construction contracts for drinking water, nonpotable recycled water, and IPR projects.

- The currently available information in operation plans for existing water treatment and distribution systems, wastewater treatment, water recycling, and IPR systems can be used as a starting point to develop operations plans for DPR projects.

- A number of approaches are being developed for DPR operator certification programs (CUWA, 2016; WRRF-13-13, in progress).

- Absent DPR regulations specifying operation, the "work arounds" likely would involve using existing O&M provisions and operator training and licensure/certification requirements for wastewater treatment, water treatment, and water distribution systems.

7.2.2 What Is Unknown?

- No standard specifications exist for the initial operation period potable reuse projects. The critical early operations steps of startup testing, commissioning, operator training, and acceptance of the facilities, as defined by the design engineer and contained in the specific contract documents, are unique for each construction project.

- Although the regulatory requirements for operations plans for DPR projects may be similar to those for IPR projects; regulatory requirements for DPR projects are not available at present and are likely be even more comprehensive, because DPR projects will require a higher degree of resiliency.

- Similarly, standards for maintenance plans have yet to be developed for DPR projects. If and when DPR regulations are developed, they should incorporate specific requirements for redundancy of the facilities, enabling individual treatment units and/or equipment to be taken offline for maintenance to achieve consistency, support operations, protect public health, and reduce risk.

- When reviewed in terms of DPR projects, significant gaps exist in available operator training and licensure/certification programs. At present, potable reuse does not have its own certification curricula; rather, utilities rely on existing wastewater and water certifications.

- An operations management framework must be developed that focuses on public health protection, sufficient multiple barriers, risk assessment, water quality monitoring, operation management, and other issues for states to use in developing DPR guidelines.

- Because of the complexity of DPR projects, a computerized asset management program is needed to schedule and track the frequency of preventive maintenance, anticipated life of equipment, and record of breakdowns. Although asset management software is available, adapting to the specific requirements for treatment barriers critical to ensuring reliability may support the long-term success of the DPR project.

- Operator training and licensure/certification programs need to be developed specifically for DPR facilities, that is: "The current certification programs are not adequate for robust DPR operator certification" (CUWA, 2016).

- Operator training and licensure/certification programs for DPR are unavailable. At this time, it is unclear what the requirements might be and what organization(s) would conduct training programs. A comprehensive, uniform certification program for DPR is lacking, and the national and/or state-level organization(s) responsible for developing such programs are undetermined.

- DPR regulations will direct and administer O&M activities, as well as support operator training and licensure/certification programs. DPR facilities will operate in accordance with state-issued permits, which should include requirements for O&M and staffing. The terms of the permits will be based on future regulations.

- Risk management is needed to ensure the protection and safety of public health, as well as to garner and retain public trust.

- Potable reuse projects should have specific O&M requirements set forth in regulations and facility permits to ensure long-term operational success and the protection of public health. The focus of the drinking water industry on conservative designs, redundancy, and proper O&M of advanced treatment systems will be important in ensuring public health protection and safety when using raw wastewater as a source for potable water.

7.3 Operations and Operation Plans

Drinking water, wastewater, water recycling, and potable reuse projects have operations plans that provide O&M staff with information about the facilities, describing normal conditions and steps to take if the performance of treatment processes or equipment declines. Specific issues addressed in operation plans include:

- Water quality monitoring may use real-time online devices that signal alarms or automated reactions.
- The incorporation of CCPs and limits akin to those used in the HACCP approach is common in operations plans for IPR projects.
- "An understanding of the critical control points approach, including specific critical control points for DPR processes, water quality risk management and operational responses" is identified in the gap analysis of drinking water treatment and wastewater treatment operations certification curricula (WRRF-13-13, in progress).
- Action/response procedures with decision trees to address variable conditions and react to atypical water quality events (WRRF-14-20: Tchobanoglous et al., 2015).
- Environmental buffers may allow for longer response times for taking corrective actions when a problem arises at an AWTF as compared to drinking water facilities acting as the buffer. Required response times for DPR facilities will be brief, on the same level as those for drinking water facilities.
- Sewershed management, pollution prevention, pretreatment/source control, wastewater treatment, water recycling, and AWTF for potable reuse facilities; watershed management, water treatment and distribution for drinking water systems; and all of the aforementioned topics for DPR facilities.
- Communication protocols and data sharing to enable a seamless interface between operators and managers.

7.3.1 Operations Plans for Potable Reuse Facilities

Operations plans for potable reuse facilities are issued at startup and updated when the facilities are expanded or modified significantly. Tchobanoglous et al (2015) recommended: "For each of the major components of the AWTF, the contents of the manual are organized under the following subheadings: (1) description; (2) design data; (3) process schematics; (4) control; (5) operations; (6) alarms; (7) equipment; (8) safety; and (9) process performance monitoring." An example of the topics covered in an operations plan for an IPR project downstream of a WWTP is presented in **Table 7-1**.

Table 7-1: Topics Addressed in the Operations Plan Manual for an Indirect Potable Reuse Project[a]

Section	Topic Area	Description
1	Overview	Overall description of the advanced water treatment facility (AWTF), groundwater recharge facilities, and introduction to all subsystems by work area and function, including critical control points and limits for AWTF operation
2	Air gap structure and pump station	Description, design data, process schematics, control, operations, alarms, equipment, safety, process performance monitoring
3	Influent screening facilities	As above in Operations Plan Manual Section 2
4	Secondary-treated wastewater effluent flow equalization	As above in Operations Plan Manual Section 2
5	Microfiltration system	As above in Operations Plan Manual Section 2
6	Coordination with other indirect potable reuse facilities, if any	As above in Operations Plan Manual Section 2
7	Chemical storage and feed systems/cartridge filters	As above in Operations Plan Manual Section 2
8	Reverse osmosis	As above in Operations Plan Manual Section 2
9	Advanced oxidation/disinfection process	As above in Operations Plan Manual Section 2
10	Decarbonation/post-treatment stabilization	As above in Operations Plan Manual Section 2
11	Product water pumping facilities	As above in Operations Plan Manual Section 2
12	Substation/switchgear building	As above in Operations Plan Manual Section 2
13	Spreading basins	As above in Operations Plan Manual Section 2
14	Injection wells	As above in Operations Plan Manual Section 2
15	Plant utilities	Introduction, process components, process analysis, control and troubleshooting, preventive maintenance, description of power, backup power, water supply, waste disposal for processes
16	Process control system overview	As above in Operations Plan Manual Section 2
17	Water quality monitoring	Monitoring of influent, advanced treated water quality, reject streams, groundwater quality, and diluent water quality; also includes permit limits and reporting requirements
18	Staffing, quality assurance, and contingency plans	Staffing plan, organizational chart with roles, responsibility matrix for facilities, including assignments to specific unit process area(s), laboratory and quality assurance procedures, contingency plan

[a] Adapted from Tchobanoglous et al. (2015).

7.3.2 Operations Plans for Water Treatment and Distribution Facilities

Operations plans for water treatment and distribution facilities are prepared for new facilities, upgrades, and capacity expansions to ensure consistency and efficiently produce and deliver safe drinking water. Common elements of operations manuals for public water systems are: (1) maps, (2) water source(s), (3) treatment and disinfection, (4) water quality monitoring and reporting, (5) distribution and storage, (6) inventory lists of equipment and spare parts, and (7) emergency response and notification procedures. Typical topics covered in operations plans for drinking water facilities are summarized in **Table 7-2**.

7.3.3 Regulatory Requirements for Operations Plans

The regulatory requirements for operations plans for DPR projects may be similar to those for IPR projects; however, the requirements are undetermined at present and are likely be even more comprehensive because DPR projects will require a higher degree of resiliency. For example, a DPR project operations plan will be required to incorporate real-time monitoring and action/response plans to respond to process and equipment failures to maintain water quality at all times for the protection of public health. The importance of source control, addressing variable feedwater quality, and optimizing process performance should be emphasized in operations plans for DPR projects. Operations plans for DPR projects may need to be equivalent to and /or more detailed than those for a water treatment facility for risk management.

7.4 Maintenance Plans

In general, large drinking water, water recycling, and potable reuse facilities have computerized asset management programs that assist with tracking equipment maintenance. Maintenance plans usually include:

- A schedule for the preventive maintenance of equipment, online instrument calibration, and alarms to track and keep a record of performance of the facilities.
- References to manufacturer manuals for detailed instructions about equipment repairs and calibration methods. “To ensure efficacy of treatment, water quality must be evaluated in real-time to verify that the barriers are operated as designed” (WRRF-11-01, in progress).
- DPR projects will involve complex treatment processes, equipment, monitoring, and control systems, and will need similar asset management programs and detailed maintenance plans.
- Because of the complexity of DPR projects, a computerized asset management program is needed to schedule and track the frequency of preventive maintenance, anticipated life of equipment, and record of breakdowns.

While asset management software is available, adaptation to the specific requirements for key treatment barriers that are critical for ensuring reliability may support the long-term success of the DPR project. Work is underway to develop an operations management framework that focuses on public health protection, sufficient multiple barriers, risk assessment, water quality monitoring, and other issues for states to use in developing DPR guidelines. Successful maintenance plans for drinking water, wastewater, and potable reuse facilities share many of the same elements, as listed in **Table 7-3**.

Table 7-2: Topics Addressed in the Operations Plan for a Typical Drinking Water System

Section	Topic Area	Description
1	System description	Overall description of raw water source(s), water treatment, distribution, pumping, storage, and emergency power, design criteria, equipment, chemicals and dosages, flow meters, backflow prevention devices, interconnections, pressure zones, booster stations, pressure reduction/regulation
2	Routine operation and maintenance procedures	Start-up and shut down operations, daily operations, routine operations, emergency indicators, recordkeeping, equipment inventory, spare parts, and vendor information
3	Emergency response and action plan	Protocols to be followed in the event of a deviation from routine procedures (e.g., power outages, storm/fire preparedness, pipe breaks, pump failures, accident procedures, security and bioterrorism preparedness and response action plan, reporting
4	Water quality monitoring plan	Sampling locations, monitoring frequency, laboratory, reporting
5	Water quality violation and response procedures	Acute violations, non-acute violations, notifications
6	Operator training	Staffing, positions and duties, safety, equipment operation

Table 7-3: Elements of Maintenance Plans for Typical Drinking Water and Potable Reuse Facilities

	Topic Area	Description
1	Asset list	Asset (e.g., equipment) name, description, manufacturer/supplier, location, purpose, criticality (for operations/regulatory compliance), condition, value
2	Maintenance practices	Implementation of best maintenance practices [e.g., Failure Mode Effect Analysis (FMEA) or Root Cause Analysis (RCA)]
3	Preventive (proactive) maintenance program	For all assets; and particularly for critical equipment (e.g., cleaning, calibration, oil change, greasing, and replacing consumables); manufacturer/equipment maintenance procedures (may be separate documents)
4	Emergency (reactive) maintenance procedures	Definition of what constitutes and emergency, hierarchy of importance, action plans, work-arounds during long-term outages
5	Spare parts inventory	Lists of critical spare parts and lubricants, including correct quality, quantity, supplier, estimated cost, lead time, location (if warehoused)
6	Tracked work orders	Method of keeping records of maintenance work orders and prioritizing preventive maintenance, generally using computerized maintenance management software (CMMS) or a similar style spreadsheet
7	Staffing and communications	Schedule and use of personnel; staff qualifications and training; organization hierarchy and coordination between departments (especially if equipment is shared)

For drinking water systems, regulatory review of maintenance plans often is a component of source water protection programs and sanitary surveys. Sanitary surveys are conducted that involve "onsite review of the water source, facilities, equipment, O&M of a public water system for the purpose of evaluating such source, facilities, equipment, operation, and maintenance for producing and distributing safe drinking water" (USEPA, 2011).

In addition, "Proper maintenance is imperative to protect the capital investment of any water processing facility, but it is even more critical for DPR projects to ensure successful operation and protection of public health. The maintenance staff at an AWTF should be as large as the operations staff and perform all preventive maintenance necessary to ensure proper operation of the mechanical equipment and online meters. An effective facility maintenance strategy would have some form of an asset management program and software to ensure that requirement maintenance is scheduled and performed prior to potential equipment failure" (Tchobanoglous et al., 2015).

O&M and management procedures for drinking water facilities should take precedent over those for wastewater facilities to minimize risks and maximize public health and safety for DPR projects. DPR operators must be mindful at all times of the need to deliver safe, reliable drinking water that meets public health standards. Maintenance staff should be trained not only in analyzer/sensor servicing and data management techniques, but also in the importance of proper maintenance to enhance the resilience of the DPR facility.

7.5 Operator Training and Certification

Significant gaps in operator training and licensure/certification programs exist for DPR, that is: "Potable reuse does not have its own certification curricula, but rather utilities rely on these existing wastewater and water certifications from which the pool of operations staff is drawn. DPR necessitates the application of a variety of relatively advanced water treatment technologies to meet water quality requirements" (WRRF-13-13, in progress).

7.5.1 Operator Training and Certification Programs

Operator training and licensure/certification programs for water and wastewater treatment and water distribution are highly specific and administered by national organizations and state associations, as shown in **Table 7-4**. In California, wastewater treatment, water treatment, and distribution system operators are certified by the Office of Operator Certification of the State Water Resources Control Board (State Water Board), which defines the training needed to meet designated competency requirements for levels or grades of operators. While under the umbrella of the State Water Board, the certifications are separate programs.

7.5.2 Operator Training and Certification Programs for Drinking Water

Within the State Water Board's Office of Operator Certification (OOC), the Drinking Water Operator Certification Program has established five grades for drinking water system operators. Individuals must (1) meet minimum education and experience requirements, (2) pass a written exam, and (3) apply for certification. Drinking water treatment operator certification grades and qualification requirements are described in **Table 7-5**.

Table 7-4: Existing Operator Training and Licensure/Certification Programs

Organizations	Section or Association	Focus of Operator Training and Licensure/Certification
American Water Works Association (AWWA)	CA-NV Section AWWA	Water treatment and water distribution
Water Environment Federation (WEF)	California Water Environment Association (CWEA)	Wastewater treatment
International Ultraviolet Association (IUVA)		Ultraviolet light treatment
American Membrane Technology Association (AMTA)	Southwest Membrane Operator Association (SWMOA)	Membrane treatment

Adapted from Tchobanoglous et al. (2015).

Education programs for California drinking water treatment operators are available at public and private institutions, as well as online courses, such as those listed in **Table 7-6**. Lower level courses focus on conventional groundwater and surface water treatment systems; the upper level course includes training for membrane treatment processes at DWTFs, as well as at AWTFs and IPR systems.

Water treatment plants require certain operator certification levels based on facility size and classification using a point system for complexity, treatment processes, and source water. For example, under the point system, groundwater meeting primary and secondary drinking water standards and requiring only chlorination for disinfection would only require a Grade T1 or T2 chief water treatment operator. Larger water treatment systems utilizing physical or chemical treatment processes to remove contaminants would require a Grade T4 or T5 as the chief water treatment operator. Water distribution systems are covered by separate operator certifications (D1 through D5). Distribution system operators have expertise in disinfection, hydraulics, equipment O&M, water piping, water quality, water regulations, system management, and safety.

7.5.3 Operator Training and Certification Programs for Wastewater Treatment

In a similar, but separate manner within the OOC, the Wastewater Operator Certification Program has established five grades for wastewater system operators. Individuals must: (1) meet minimum education and experience requirements, (2) pass a written exam, and (3) apply for certification. Descriptions of the wastewater operator certifications grades and requirements are summarized in **Table 7-7**. WWTPs are operated by a graded scale of operators who have passed tests and meet designated qualifications for each grade. WWTPs are classified by size and complexity of the treatment processes, from I to V. The chief operator must be certified at the same level of the plant, or higher. Shift supervisors must be certified at no less than one grade below the plant classification, with a few exceptions. For example, a Class III WWTP having a primary treatment capacity between 5 and 20 MGD and up to 5 MGD of activated sludge secondary treatment capacity would require the chief operator to possess a Grade III or higher license and the shift supervisor(s) would need at least a Grade II license. A Class V WWTP producing more than 10 MGD of tertiary effluent would require a chief operator with a Grade V license.

Table 7-5: Eligibility Criteria for Taking a Water Treatment Operator Licensure/Certification Examination in California

Minimum Education and Training	Minimum Experience Qualifications
Drinking Water Treatment Operator Grade T1	
High school diploma or equivalent, or successful completion of the SWRCB DDW course "Basic Small Water System Operations," or one (1) year as an operator of a facility that required un understanding of chemical feeds, hydraulic systems, and pumps.	None
Drinking Water Treatment Operator Grade T2	
High school diploma or equivalent, or successful completion of the SWRCB DDW course "Basic Small Water System Operations," or one (1) year as an operator of a facility that required un understanding of chemical feeds, hydraulic systems, and pumps. and successful completion of at least one course of specialized training covering drinking water treatment fundamentals.	None
Drinking Water Treatment Operator Grade T3	
High school diploma or equivalent. and successful completion of at least two courses of specialized training that includes at least one course in drinking water treatment fundamentals.	One (1) year of operator experience working as a certified T2 operator at a T2 or higher facility. and one (1) additional year of operator experience working as a certified treatment operator.
Drinking Water Treatment Operator Grade T4	
Valid Grade T3 operator certificate. and successful completion of at least three courses of specialized training that includes at least two courses in drinking water treatment.	One (1) year of operator experience working as a shift or chief operator while holding a valid T3 operator certificate at a T3 or higher facility. and three (3) additional years of operator experience working as a certified treatment operator.
Drinking Water Treatment Operator Grade T5	
Valid Grade T4 operator certificate. and successful completion of at least four courses of specialized training that includes at least two courses in drinking water treatment.	Two (2) years of operator experience working as a shift or chief operator while holding a valid T4 operator certificate at a T4 or higher facility. and three (3) additional years of operator experience working as a certified treatment operator.

Adapted from California Code of Regulations (CCR, 2015). Title 22 Division 4 Chapter 13 Operator Certification, §63675 and §63800. SWRCB = State Water Resources Control Board. DDW = Division of Drinking Water.

Table 7-6: Existing Drinking Water Treatment Operator Education

Education/Training	Topics Covered
Basic Small Water Systems Operations[a] *Appropriate for Grade T1, not for educational credit*	• Roles and responsibilities of operators • Sources of water • Wells • Small water treatment plants • Water storage and distribution • Drinking water laws and regulations • Math for small water system operators
Water Treatment Plant Operation, Volume I[b] *Appropriate for Grades T1, T2, T3, and T4*	• Water treatment plant operator • Water sources and treatment • Reservoir management and intake structures • Coagulation and flocculation • Sedimentation • Filtration • Corrosion control • Taste and odor control • Plant operation • Laboratory procedures
Water Treatment Plant Operation, Volume II[c] (continuation of Volume I) *Appropriate for Grades T2, T3, and T4*	• Iron and manganese control • Fluoridation • Softening • Specialized treatment processes (trihalomethanes and arsenic) • Membrane treatment processes (membrane filtration, reverse osmosis, electrodialysis, and demineralization) • Handling and disposal of process wastes • Maintenance • Instrumentation and controls systems • Safety • Advanced laboratory procedures • Drinking water regulations • Administration

[a] Division of Drinking Water, State Water Resources Control Board.

[b] University Enterprises, Inc., 2008. Office of Water Programs, California State University, Sacramento.

[c] University Enterprises, Inc., 2015. Office of Water Programs, California State University, Sacramento.

Table 7-7: Eligibility Criteria for Taking a Wastewater Treatment Operator Licensure/Certification Examination in California[a]

Path	Minimum Education and Training	AND	Minimum Experience Qualifications
Wastewater Operator Grade I			
1	High school diploma or equivalent, and 6 educational points[b].		1 year of full-time qualifying experience.
Wastewater Operator Grade II			
1	High school diploma or equivalent, and 9 educational points[b].		18 months of full-time qualifying experience as a Grade I operator.
2	High school diploma or equivalent, and 12 educational points[b].		2 years of full-time qualifying experience.
3	Associate's degree or higher degree, or At least 60 college semester units, including a minimum of 15 semester units of science courses.		1 year of full-time qualifying experience.
Wastewater Operator Grade III			
1	High school diploma or equivalent, and 12 educational points.		3 years of full-time qualifying experience as a Grade II operator.
2	High school diploma or equivalent, and 18 educational points.		4 years of full-time qualifying experience.
3	Associate's degree, or At least 60 college semester units, including a minimum of 15 semester units of science courses.		2 years of full-time qualifying experience.
4	Bachelor's degree or higher degree, including a minimum of 30 semester units of science courses.		1 year of full-time qualifying experience.
Wastewater Operator Grade IV			
1	High school diploma or equivalent, and 32 educational points.		6 years of full-time qualifying experience.
2	Associate's degree, or At least 60 college semester units, including a minimum of 15 semester units of science courses.		4 years of full-time qualifying experience.
3	Bachelor's degree or higher degree, including a minimum of 30 semester units of science courses.		3 years of full-time qualifying experience.
4	Valid registration as a chemical, civil or mechanical engineer issued by the State of California or other state, territory, or Indian tribe		2 years of full-time qualifying experience
Wastewater Operator Grade V			
1	High school diploma or equivalent, and 48 educational points.		10 years of full-time qualifying experience.
2	Associate's degree, or At least 60 college semester units, including a minimum of 15 semester units of science courses.		6 years of full-time qualifying experience.
3	Bachelor's degree or higher degree, including a minimum of 30 semester units of science courses.		5 years of full-time qualifying experience.
4	Valid registration as a chemical, civil or mechanical engineer issued by the State of California or other state, territory, or Indian tribe		4 years of full-time qualifying experience

[a] Adapted from CCR, 2001. Title 23, Division 3, Chapter 26, Articles 3 and 4 and from WRRF-13-13 (in progress).

[b] Educational points based on completion of wastewater related courses or approved continuing education units.

Water recycling facilities are classified as WWTPs with tertiary treatment facilities for purposes of designating operator certification requirements, except that certification/licensure as either a wastewater or water treatment operator is accepted. Certification equivalency requirements for operation of water recycling plants are summarized in **Table 7-8**.

Table 7-8: Certification Requirements for Water Recycling Plants

Wastewater or Water Recycling Plant Classification	Water Treatment Plant Operator Certificate	Wastewater Treatment Plant Operator Certification
I	T1	Grade I
II	T2	Grade II
III	T3	Grade III
IV	T4	Grade IV
V	T5	Grade V

Adapted from CCR, 2001. Title 23, Division 3, Chapter 26, Article 1, CUWA (2016), and WRRF-13-13 (in progress).

7.5.4 Operator Training and Certification Programs for Advanced Water Treatment

Operator certification exams do not currently cover potable reuse regulations or advanced water treatment processes, such as RO. Potable reuse commonly features complex treatment involving multiple barriers to maintain water quality under variable and sometimes challenging source water conditions.

Operator training programs for AWTF have not been formalized through community colleges, universities, or professional organizations; instead, they combine onsite, supervised hands-on experience and in-house examinations developed by local agencies that operate IPR facilities.

Presently, water recycling and IPR facilities typically require that operators possess wastewater treatment certifications, although water treatment certifications at the appropriate grade are acceptable. In either case, these licensure/certification programs do not include membrane processes. Separate certificates from the American Membrane Technology Association and the International Ultraviolet Association demonstrate qualifications for operators of AWTFs for IPR. At present, no licensure/certification programs exist specifically for AWTF. Frameworks for DPR operator certification programs have been developed (CUWA, 2016; WRRF-13-13, in progress). The advantages and disadvantages of four framework approaches for operators of DPR projects are presented in **Table 7-9** (CUWA, 2016).

In a similar comparison, three framework options were evaluated (WRRF-13-13, in progress): (1) specific DPR certification, (2) supplemental DPR certification beyond existing water or wastewater operator certification; and (3) add-on DPR certification to append to an existing water or wastewater operator certification to fill gaps in knowledge and/or training.

Table 7-9: Summary of Potential Direct Potable Reuse Operator Certification Approaches

Certification Approach	Description	Benefits	Limitations
Separate direct potable reuse operator certification program	Separate program developed solely for DPR system operators. Open to either wastewater operators or water treatment operators at a pre-set Grade Level (e.g., Grade II or T3).	Specifically tailored to the needs of the job of operating a DPR facility	Would likely result in a very small pool of qualified operators Would not cover other water/wastewater systems with advanced technologies
Add-on to wastewater operator certification	Supplemental certificate for existing wastewater operator certification that verifies a defined skill level in potable reuse/advanced water treatment facility (AWTF).	Would allow wastewater agencies to use internal staff in new potable reuse projects.	Might not require knowledge of drinking water treatment, rules and protocols. Would preclude water treatment operators from operating potable reuse systems.
Add-on to water treatment operator certification	Supplemental certificate for existing water treatment operator certification that verifies a defined skill level in potable reuse/AWTF.	Would staff potable reuse plants with individuals who are well-versed in potable water requirements and protocols.	Might not require knowledge of wastewater-specific treatment, rules and protocols. Would preclude wastewater operators from operating potable reuse systems.
Hybrid that can be added on to either license	Supplemental certification program that supplements both the wastewater operator certification program or water treatment operator certification that verifies a defined skill level in potable reuse/AWTF.	Would allow potable reuse plants to hire diverse staff.	If focused solely on advanced treatment, water treatment operators would potentially miss exposure to wastewater topics and vice versa, possibly leading to inevitable knowledge gaps for all operators. If focused solely on potable reuse, might not draw enough potential applicants.

Adapted from CUWA (2016).

In lieu of a completely new DPR certification program (Option 1), another approach (Option 2) would be to develop an “add-on” certification program for operators who already have a water or wastewater license/certificate. For example, wastewater operators could become certified for AWTFs and water treatment processes, or vice versa (i.e., DPR operators would possess two licenses/certifications: water plus DPR or wastewater plus DPR). A similar approach (Option 3, illustrated in **Figure 7-1**) would involve developing certification/training programs to fill in knowledge gaps while still maintaining existing operator certifications; water treatment operators would be tested for wastewater knowledge and vice versa. Option 3 (WRRF-13-13, in progress) is similar to the hybrid approach above (CUWA, 2016) and was recommended because it can “leverage from existing operator certification programs for water and wastewater and thus attention can be focused on developing the additional curriculum that is required, rather than starting a system afresh” (WRRF-13-13, in progress).

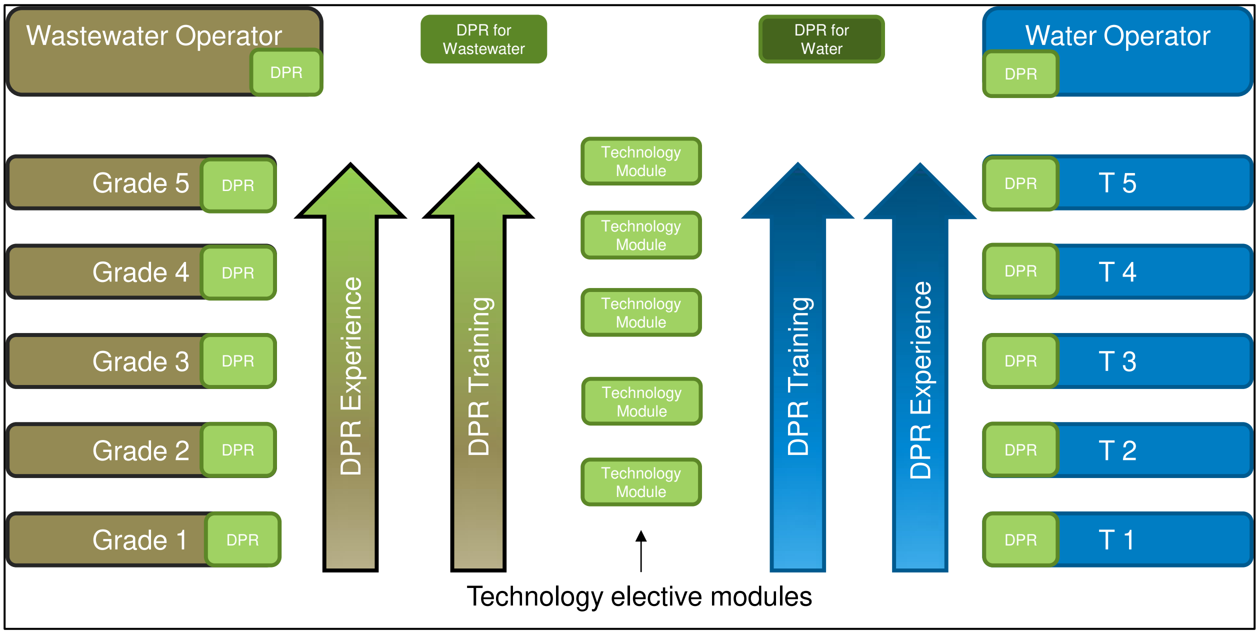

Figure 7-1: Recommended framework for operator certification for direct potable reuse (WRRF-13-13, in progress).

7.5.5 Need for Operator Training and Certification Programs for Direct Potable Reuse

Operator training and licensure/certification programs need to be developed specifically for DPR facilities. Notably, "The current certification programs aren't adequate for robust DPR operator certification" (CUWA, 2016). Results of a WateReuse California membership survey indicate the need for "new certification options to fill "holes" in existing programs and allow water treatment and wastewater operators to obtain advanced treatment certification for potable reuse" (CUWA, 2016).

Existing water and wastewater operations certification curricula with additional training for DPR are compared in **Table 7-10**. Detailed education and training programs oriented towards DPR certification need to be developed to fill the gaps between water treatment and wastewater operator licensure/certification programs.

The current system of separate certification programs for wastewater treatment and water treatment, and water distribution may be useful as a foundation to develop a framework for a new DPR program.

At a potable reuse workshop, participants comprised of utility staff and California regulators "achieved consensus on the basic structure of the future certification program and a strategy to move it forward," agreeing with survey respondents that a "special advanced water treatment or potable reuse module to enhance existing certification is the best choice" (CUWA, 2016). Representatives from the CA-NV Section of American Water Works Association and the California Water Environment Association attending the workshop generally agreed that collaboration of the organizations would help promote operator training and licensure/certification programs for potable reuse systems.

Table 7-10: Water and Wastewater Operations Certification Curriculum – Gap Analysis Summary for Direct Potable Reuse

Topic Area	Existing Curriculum Helpful for DPR		Additional Requirements for DPR
	Drinking Water Operations	**Wastewater Operations**	
Source Water/Water Quality (Groundwater/Surface Water/Raw Water Storage)	Provides basic knowledge of water quality assessment and characteristics, including a knowledge of microbial contamination (which provides a solid base for operators moving to a future DPR certification). Some important items include: • Water quality characteristics. • Source water assessment • Ability to recognize abnormal conditions. • Microbial contamination. • Interpretation of water quality reports • Flow and flow measurement. • Calculation of chemical dose. • Measuring pH.	Relatively small amount of information on sewershed and source control.	Additional information for sewershed management and source control. Understanding of industrial waste contributions and other source contaminants that may risk treatment processes. The source water for DPR treatment processes is municipal wastewater. For drinking water operators, a basic knowledge is needed of wastewater processes. In addition: • Understanding source water risks from wastewater sources. • Ability to develop and manage a water quality risk register. • Understanding process changes and impacts from wastewater treatment processes. • Understand important key process monitoring parameters at the inlet of an advanced treatment plant.
Coagulation/ Flocculation/ Sedimentation	Provides a thorough coverage of these processes. This knowledge likely is adequate for DPR operators where such technology is employed (i.e., non-RO-based treatment train).	Some knowledge of clarification processes for primary sedimentation and secondary clarification.	No additional curriculum is required for DPR.
Filtration	Provides a thorough coverage of conventional media filtration, with a limited coverage of granular activated carbon.	Minimal information.	Conventional filtration appears well covered; however, granular activated carbon and biologically active carbon will require significantly more coverage. Membrane filtration (MF/UF) will require substantial coverage.
Disinfection	Provides thorough knowledge of chlorination practices, including analysis of free and total chlorine, calculation of CT, calculation of chemical dose, and breakpoint chemistry. Includes some material for ozone, UV disinfection, and chloramines.	Provides some knowledge of calculating chlorine demand, operation and maintenance procedures for disinfection, and calculating disinfection usage.	Will require additional detail for chloramine dosing, which is used for membrane disinfection. Additional content required includes: (1) knowledge of chloramine control, and (2) protection of RO membranes from chlorine. Ozone also requires additional information, including: • Basic understanding of ozone chemistry. • Basic ozone generation management. • Knowledge of UV absorbance analyzer calibration. • Ozone residual analyzer management. • Ozone dose-control strategies.

Topic Area	Existing Curriculum Helpful for DPR		Additional Requirements for DPR
	Drinking Water Operations	Wastewater Operations	
Demineralization (RO, NF, and Ion Exchange Treatment)	Contains some water quality analysis content, knowledge of electrical conductivity, and total dissolved solids analysis. There is subject matter relating to ion exchange, but none for RO.	Not included.	RO is a core technology for the RO-based treatment train. Content for this process is required, including: • Operation and maintenance of membranes. • Measurements of process performance and membrane integrity. • Monitoring and measurement of chemical rejection and log reduction of pathogens.
Corrosion Control	Useful basic knowledge of corrosion, including health effects from lead and copper.	Not included.	Will provide a useful basis for the additional chemical stabilization process required for the RO-based treatment train.
Iron and Manganese Removal	Thorough knowledge of iron and manganese removal.	Not included.	Not specific to DPR treatment processes; however, will provide some useful knowledge for RO system membrane scaling and fouling.
Fluoridation	General knowledge of fluoridation processes.	Not included.	Not specific to DPR treatment, unless fluoridation is required in a DPR system that operates directly to distribution.
Softening	Knowledge of water hardness chemistry, hardness removal, and softening processes.	Not included.	Not directly related to DPR, but has some value to RO treatment processes. May be important for non-RO membrane-based treatment.
Wastewater Treatment Technologies	Not included.	Material is focused on main wastewater treatment processes, including: • Preliminary treatment (screening, grit removal). • Primary treatment processes. • Anaerobic sludge digestion. • Stabilization ponds. • Secondary treatment processes, including trickling filters and activated sludge. • Sludge handling and solids thickening. • Tertiary treatment. • Overall process control.	Valuable knowledge for DPR treatment to understand the impacts upstream of advanced treatment. It also is important to understand the difference between monthly compliance goals/environmental impacts versus continuous water quality goals for DPR and drinking water quality goals.
Best Available Technology (BAT)	Knowledge of waterborne pathogens, best available technologies for removal, adverse health effects from regulated contaminants, and emerging contaminants.	Not included.	Specific knowledge is required of technologies/BATs used in drinking water treatment (and DPR).

Topic Area	Existing Curriculum Helpful for DPR		Additional Requirements for DPR
	Drinking Water Operations	Wastewater Operations	
Operations and Maintenance (O&M)	Requires knowledge of key process plant mechanical components, including: • Chemical feeder. • Pumps and motors. • Blowers and compressors. • Water meters. • Instruments and analyzers. • SCADA components and online analyzers. • Calibration of some key instruments.	Thorough review of some maintenance requirements, including: • Electrical equipment. • Motors. • Pumps. • Valves.	Specific knowledge of treatment process maintenance requirements, including membrane management, UV lamps, ozone generation, and lime/CO_2 systems for stabilization. The understanding of detailed instrument verification and calibration for multiple analyzers is an important addition for DPR.
Laboratory	Thorough requirements for laboratory analysis, chains of custody, sampling, and analysis, as well as detail on a number of specific common water quality analyses.	Thorough review of sampling and analysis requirements for wastewater treatment applications.	Some additional knowledge is needed for the management of numerous water quality analysis parameters, including knowledge of sampling and sample management for complex contaminants.
Safety	General knowledge of safety, safe working practices, lock out-tag out procedures, and some first aid.	General knowledge of safety, including importance of hygiene, lock out tag out, safe work practices, and specific safety requirements for wastewater technologies.	Suitable for DPR, with a focus on safety requirements included for technologies specific to DPR.
Administration	Covers a broad range of administrative requirements, including organization, monitoring and reporting requirements, reviewing and transcribing data, review of overall plant performance, review of reports, and evaluating facility performance.	Covers a broad range of administrative requirements, including staffing, financial management, capital planning, and data management.	Additional requirements include: • Critical control point (CCP) methodology. • CCP response procedures and communication protocols. • CCP incident investigation and follow-up action methodology.
Regulations	Knowledge of key regulatory requirements, including disinfection requirements, knowledge of maximum contaminant levels, consumer confidence reports, Surface Water Treatment Rule, development of operations plans, disinfection requirements, and other regulatory aspects.	Some regulatory content, including classification of wastewater treatment plants and operator certification regulations, and requirements for reclamation and reuse (although not focused on IPR/DPR).	Additional knowledge must be included of future DPR regulatory requirements. In addition, any specific reporting and communication protocols for regulators must be included. An important aspect will be comparison and contrast with water and wastewater regulations. A specific example will be how water quality treatment requirements likely will be a single maximum target rather than monthly averages or means (as is common in wastewater treatment).

Topic Area	Existing Curriculum Helpful for DPR		Additional Requirements for DPR
	Drinking Water Operations	Wastewater Operations	
Math	Specific calculations for major water treatment operations, including: • Flow rate calculation. • Volume calculation. • Chemical dosing rates. • Detention times. • Backwash rates. • Production rates. • CT calculations.	Specific calculations for wastewater, treatment operations including: • Removal efficiencies. • Overflow rates. • Hydraulic loading. • Solids loading. • Chemical dosing. • Evaluation of specific processes.	Additional calculations will be required for specific unit processes not covered in the existing curricula, but required for DPR.
Communication			Effective communication is critical for the success of DPR. Operators must understand the importance of timely communication within the facility to assist in rapid, effective operational responses to issues. They also must understand the importance of clear communication across operational interfaces and to external stakeholders, including regulators and the public.
Management of Analyzers and Instruments.			There is a high reliance on analyzers and instruments for successful IPR and DPR plant operation. Specific curriculum material is required that covers the importance of regular instrument verification, calibration, and key maintenance requirements for important instruments.
SCADA, Reporting, and Alarm Management			Covering important SCADA management and reporting with a focus on alarm management and operator response.
Operational Interfaces	General knowledge of water treatment processes.	General knowledge of wastewater treatment processes.	Knowledge of requirements is required at operator interfaces between wastewater treatment and advanced treatment, and advanced treatment and drinking water treatment. For some utilities, the full suite of treatment may be operated by a single entity. For others, there will be different organizations operating these entities. An understanding is required of process and treatment at these interfaces.
Critical Control Points and the HACCP Process			An understanding is needed of the critical control point (CCP) approach, including specific CCPs for DPR processes, water quality risk management, and operational responses.

From WRRF-13-13, in progress.

7.5.6 Need for Collaboration among Certification Organizations

Collaboration among the organizations that administer the existing licensure/certification programs will be essential because DPR bridges the fields of qualifications and experience. Operator training and licensure/certifications for DPR projects must involve education and testing for a range of topics, including wastewater treatment, advanced water treatment, drinking water treatment and distribution, as well as CCPs and limits, water quality, and regulatory requirements for reliable protection of public health.

Training programs for operators of DPR systems should address any gaps in education or experience specifically related to advanced treatment processes, multiple barriers, and potable reuse regulations for individuals coming from either water treatment or wastewater backgrounds. When surveyed, water and wastewater operators identified certain aspects of existing training programs essential for DPR projects, as well as missing components that should be added, as summarized in **Table 7-11**.

Table 7-11: Direct Potable Reuse Operator Training and Certification Program: Essential Elements and Gaps

Essential Topics for DPR Operator Knowledge and Training	Gaps in Existing Water or Wastewater Certification Programs that Need to be Addressed for DPR
Wastewater treatment processes	Ultraviolet/advanced oxidation process (UV/AOP)
Water treatment processes	Microfiltration
Drinking water regulatory requirements	Reverse osmosis
Wastewater regulatory requirements	Ozone
Wastewater treatment plant operation/maintenance	Unified approach to failure analysis, prediction, and avoidance
Water treatment plant operation/maintenance	Automation and process control
Laboratory procedures	Monitoring protocol (e.g., contaminants and total organic carbon detection)
Distribution system operation/maintenance	UV disinfection
Source water	Biologically active filters
Administrative duties (reporting)	Emergency response
Collection system operation/maintenance	Drinking water regulatory requirements
	Multiple discharge requirements
	Control of discharges to sewer system (source control)
	Monitoring of wastewater quality

Adapted from CUWA (2016).

In California, since the Division of Drinking Water became part of the State Water Resources Control Board in 2014, programs for certification of both water and wastewater operators are under the jurisdiction of the State Water Board's OOC. The combined management of water and wastewater operator licensure/certification programs may facilitate solutions for DPR projects. Notably, "It is recommended that a DPR operator certification be a system that is appended to the existing water and wastewater certification. This system also will leverage from existing operator certification programs for water and wastewater and thus attention can be focused on developing the additional curriculum that is required, rather than starting a system afresh" (WRRF-13-13, in progress). Operations staff should participate in continuing education programs to remain current with the latest water quality requirements, CECs, and new drinking water regulations.

7.6 "Work Arounds" Until the Needed Information for Direct Potable Reuse Becomes Available

Within the near future, DPR regulations will direct and administer O&M activities, as well as support operator training and licensure/certification programs. DPR facilities will operate in accordance with state-issued permits, which should include requirements for their operation, maintenance, and staffing. The terms of the permits will be based on regulations. Absent DPR regulations, "work arounds" likely would involve using existing O&M provisions and operator training and licensure/certification requirements for wastewater treatment, water treatment, and water distribution systems.

- While it may be feasible to use elements of existing programs for guidance, this approach may be fragmented and difficult to manage successfully.

- The development of curricula for DPR operator training and licensure/certification programs is underway to address gaps in the existing (yet distinctly separate) operator training and licensure/certification programs.

- The most practical solution envisioned at this time, as discussed above, involves appending existing wastewater or water treatment certifications with additional training and competency requirements.

- With the State Water Board leading both the drinking water and wastewater operator certification programs, enhanced communications should help address the needs of DPR projects.

Risk management will be critical for DPR projects for safety and public health protection, as well as garnering and retaining public trust. Important issues that must be considered include:

- A robust design combined with a robust O&M program will enhance overall facility reliability and mitigate risks to an acceptable level.

- Operations plans using HACCP principles and action/response plans, similar to those currently used for IPR projects, will underscore the resilience of the DPR project and help manage unexpected conditions before they become public health and safety issues.

- Maintenance programs emphasizing preventive maintenance combined with equipment redundancy will minimize costs and improve operational efficiency.

- Risk management strategies for DPR projects will be based on those currently in place at water, wastewater, and IPR projects reinforced by applying water treatment safeguards for public health protection to the wastewater and water recycling arenas.

"The drinking water industry's focus on conservative designs and redundancy, proper operation, and maintenance of advanced systems will be an important element in ensuring public health when using raw wastewater as a source for potable water" (WRRF-11-02, 2012). DPR projects should have specific O&M requirements set forth in regulations and facility permits to ensure long-term operational success and the protection of public health.

7.7 Information Sources

A list is provided in **Table 7-12** of the WRRF and WRA projects that were reviewed for the preparation of this chapter. Full citations for reports related to these projects, along with citations for other references and sources of information, are included in **Section 7.8**.

Table 7-12: WRRF and WRA Research Projects Used to Prepare Chapter 7

Project No.	Project Title	Principal Investigator(s)
WRRF-11-01	Monitoring for Reliability and Process Control of Potable Reuse Applications	Ian Pepper, University of Arizona
WRRF-11-02	Equivalency of Advanced Treatment Trains for Potable Reuse	R. Rhodes Trussell, Trussell Technologies, Inc.
WRRF-13-13	Development of Operation and Maintenance Plan and Training and Certification Framework for Direct Potable Reuse Systems	Troy Walker, Hazen & Sawyer
WRRF-14-01	Integrated Management of Sensor Data for Real Time Decision Making and Response	Jeff Neeman, Black & Veatch
WRRF-14-16	Operational, Monitoring, and Response Data from Unit Processes in Full-Scale Water Treatment, Indirect Potable Reuse, and Direct Potable Reuse	Andrew Salveson, Carollo Engineers
WRRF-14-20 (WRA-14-01)	Developing Direct Potable Reuse Guidelines	Jeffrey Mosher, National Water Research Institute
WRRF-15-05	Developing Curriculum and Content for Direct Potable Reuse Operator Training	Ben Stanford, Hazen & Sawyer

7.8 References

California Code of Regulations (2001). Title 23 “Waters,” Division 3, Chapter 26 “Classification of Wastewater Treatment Plants and Operator Certification,” Article 3 “Grades of Operator Certification for the Operation of Wastewater Treatment Plants” (Section 3680), and Article 4 “Minimum Qualifications” (Sections 3683-3686).

California Code of Regulations (2015). “Title 22 “Social Security,” Division 4 “Environmental Health,” Chapter 13 “Operator Certification,” Article 2 “Operator Certification Grades,” and Section 63675 “Water Treatment Facility Staff Certification Requirements,” and Section 63800 “Eligibility Criteria for Water Treatment Operator Certification.”

California Urban Water Agencies (2016). “Potable Reuse Operator Training and Certification Framework, White Paper.”

Neeman, J. (In progress). “Integrating Management of Sensor Data for Real Time Decision Making and Response System.” WateReuse Research Foundation 14-01.

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Pecson, B. M., R.S. Trussell, A. N. Pisarenko, and R. R. Trussell (2015). “Achieving Reliability in Potable Reuse: The Four Rs.” *American Water Works Association Journal*. 107, 3, 48-58.

Salveson, A. (In progress). “Operational, Monitoring and Response Data from Unit Processes in Full-Scale Water Treatment, IPR, and DPR.” WateReuse Research Foundation 14-16.

Tchobanoglous, G., J. Cotruvo, J. Crook, E. McDonald, A. Olivieri, A. Salveson, and R.S. Trussell (2015). *Framework for Direct Potable Reuse*. Report from Project WRRF-14-20 (WRA-14-01), WateReuse Research Foundation, Alexandria, VA.

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University Enterprises, Inc. (2008). “Water Treatment Plant Operation, Volume I,” 6th edition, California State University, Sacramento, College of Engineering & Computer Science, Department of Civil Engineering, Office of Water Programs.

University Enterprises, Inc. (2015). “Water Treatment Plant Operation, Volume II,” 6th edition, California State University, Sacramento, College of Engineering & Computer Science, Department of Civil Engineering, Office of Water Programs.

USEPA (2011). Code of Federal Regulations (40 CFR Ch. 1, Subpart A, Section 141.2 “Definitions”). U.S. Environmental Protection Agency, Washington, D.C.

Walker, T. (In progress). “Development of Operation and Maintenance Plans and Training and Certification Framework for Direct Potable Reuse (DPR) Systems.” WateReuse Research Foundation 13-13.

WRRF (In progress). “Developing Curriculum and Content for DPR Operator Training.” WateReuse Research Foundation 15-05, WateReuse Research Foundation, Alexandria, VA.

Chapter 8: Resilience in Potable Reuse

Prepared by Brian Pecson, Ph.D., P.E., and Sarah Triolo, Trussell Technologies, Inc. (Oakland, CA)

The two overarching pathways to achieving public health protection in potable reuse are *failure prevention* and *failure response*. These pathways are achieved through effective design and operation of potable reuse facilities. It is possible to design DPR systems that are highly reliable and can treat water consistently to a high standard; however, even well engineered systems will inevitably experience unexpected malfunctions and failures. Because it is not possible or reasonable to design potable reuse systems to prevent failures under all possible conditions, they must be designed with "resilience,"[10] or the ability to adapt successfully or restore performance rapidly in response to treatment failures (Pecson et al, 2015; Tchobanoglous et al., 2015).

8.1 Identification of Key Issues

The key issues associated with resilience in potable reuse include:

- The two required functions of resilient systems are: (1) recognition of and (2) adaptation to disturbances or failures.
- With respect to potable reuse, the two main components of failure response are: (1) failure detection and (2) failure response (i.e., mitigation or corrective measures).
- The application of "resilience" principles to engineered processes is a relatively new endeavor.
- There is widespread recognition that the application of resilience principles can greatly improve the safety of potable reuse systems.
- Because highly trained, skilled operators will be essential for resilient potable reuse systems, it is imperative that effective operator training and certification programs be developed for operators of potable reuse facilities.
- In addition to failures in treatment stemming from mechanical issues or improper operations, potable reuse systems must be resilient to natural and man-made disasters.

Each issue as it relates to resilience is addressed in **Sections 8.3** through **8.9**. Based on the results of relevant research conducted to date, it is possible, with the current level of available technology, to design resilient potable reuse systems. While there are areas that would benefit from additional investigations, the need for additional research should not prevent DPR from moving forward.

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[10] While the focus of this review is on the failure response aspects of resilience, other uses of the word have been used. The Australian Water Recycling Centre of Excellence recently defined "resilience" as a potable reuse system's ability "to maintain routine function under normal and unexpected circumstances" (Tng et al., 2015). In this context, resilience is focused more on the issue of system availability or up-time, with resilience measuring mechanical reliability parameters, such as mean-time-to-failure.

8.2 Summary of Principal Findings

Resilience is a critical feature of potable reuse systems in use today, most of which fall into two forms of IPR: groundwater replenishment and surface water augmentation. In the regulations for both forms, it is assumed that AWTF system failures may occur and, consequently, require resilience features as safety nets to ensure these failures are managed safely. The primary resilience feature for both groundwater replenishment and surface water augmentation is the environmental buffer, which provides time to respond to system failures, as well as the dilution of water that is off-specification (or "off-spec"). Although a DPR system will not benefit from the environmental buffer, other resilience features can be designed, such as the automated shutdown of unit processes and activation of standby units.

8.2.1 What Is Known?

- California regulations for both forms of IPR require that failsafe options be included in projects, though the manner in which these options are provided differs[11]. The focus of the regulations is on mitigating the impact of *system failures*.

- Providing *time* between the treatment and consumption of water is the principal feature of resilience. This feature is a hallmark of California's groundwater replenishment projects, most of which provide 6-months or more of retention time in an aquifer (i.e., an environmental buffer). The extended period between treatment and consumption provides multiple opportunities to identify a treatment failure and enact a response (e.g., additional treatment at the wellhead or DWTF) to protect public health.

- The differences in dynamics between a reservoir and groundwater aquifer impact the time available to respond to a system failure. Short-circuiting and wind convection in reservoirs mean off-spec water could be transported quickly to the reservoir outlet. As a result, greater emphasis is placed on a complementary strategy, namely dilution through mixing. The reservoir provides protection against a 24-hour pulse of off-spec water by ensuring that the concentrations of all contaminants are diluted no less than tenfold to one-hundredfold in the reservoir.[12]

- Response time is required in the draft regulations for surface water augmentation, but the requirement is much shorter than that specified for groundwater replenishment (i.e., 24 hours versus 2 to 6 months). Consequently, the regulations have rebalanced these complementary components, with greater levels of dilution going from groundwater replenishment to surface water augmentation.

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[11] California promulgated regulations on potable reuse involving groundwater in 2014. Regulations for indirect potable reuse using surface water augmentation are currently in draft form and will be finalized at the end of 2016.

[12] Note: For dilution in the context of indirect potable reuse using surface water augmentation, it is assumed that advanced treated water previously introduced to the reservoir can serve as diluent water. This requirement is different than that for groundwater replenishment, where only non-wastewater origin water or water that has met the retention time requirements can serve as diluent water.

- More direct forms of potable reuse are distinguished, in part, by the lack of an environmental buffer. In the absence of an environmental buffer, other strategies are necessary to provide system resilience.

- Failure detection, the first component of resilience, can be accomplished through online monitoring. The technology available for continuous process performance verification can enable sufficiently rapid failure detection.

- The use of control charts can help improve the detection of failure. It involves tracking unit process performance data over time with respect to treatment targets to understand whether performance is declining toward failure. Control charts are well-established in the manufacturing industry and are being adapted for use in the context of groundwater replenishment.

- Effective failure mitigation/response can be achieved through automated alarms and responses, specific standard operating procedures, diversion schemes, and other strategies.

- An analysis of mechanical performance data from seven potable reuse plants indicates a high degree of mechanical reliability, with a miniscule proportion of mechanical issues resulting in adverse impacts to water quality.

8.2.2 What Is Unknown?

Significant progress has been made toward developing a framework for potable reuse resilience. This framework includes two major components: failure detection and failure mitigation. Work is needed to bring more clarity and definition as to how these strategies will be applied specifically to DPR. Some unknowns that would benefit from additional research include:

- **Control charts:** More work is needed to adapt traditional statistical control charts for potable reuse applications. Areas of needed study include (1) the development of a methodology for determining control limits and alarm thresholds for unit processes, and (2) an assessment of the effectiveness of this method for detecting potable reuse unit process failures. Notably, some of this work is being conducted as part of WRRF-14-12; online data collected from yearlong demonstration testing is being used to evaluate different failure detection strategies using control charts.

- **Operational responses:** Resilient system design requires the development of specific failure response strategies for a range of failure types, including those that incorporate communication between AWTF and DWTF operators.

- **Failure mitigation:** More investigation is needed of novel strategies. Examples include (1) using redundant, back-up treatment units at a DWTF in the event of an AWTF failure, and (2) quantifying the time to respond provided by the travel time in pipelines, the flow-through time in the DWTF, and the retention time in clearwells.

- **Redundancy versus resilience:** A better understanding is needed of the balance between redundancy and system resilience. As redundancy increases, the probability of system failures presumably decreases; therefore, systems providing high degrees of redundancy may be able to offset their reliance on resilience features in the protection of public health.

- **Operational data:** The industry would benefit from the compilation and analysis of data from existing potable reuse facilities. Such a database could be used to better understand common failure modes at these facilities and impacts on water quality, and would allow for more effective design of resilience strategies. Similar research is being undertaken as part of WRRF-14-16 to evaluate the causes of failure at full-scale facilities and assess their likelihood and impact on treated water quality.

8.3 Types, Frequencies, and Detections of Failures

In the context of this review, failure is used to describe events that cause negative impacts on water quality (either of a unit process or of the treatment train effluent). Other studies have used a broader definition to examine failures in the context of potable reuse, including events that impact the production capacity, or availability, of the system. The Australian Water Recycling Centre of Excellence compiled data from seven potable reuse systems around the world to quantify the likelihood of failures impacting production and/or water quality. They concluded that 95 percent of failure events in a modeled reference plant (using data from actual facilities) *did not* have an adverse impact on final product water quality (Tng, 2015). This perspective is useful as the focus of the following discussion is on failures that impact water quality. These failures are of highest significance because they have the potential to impact public health, but they constitute a small minority of the issues likely to occur at an AWTF.

The series of actions needed to detect and respond to failures and the time to complete all these steps known as the “failure response time.” is examined in WRRF-12-06. The first step in the process is rapid failure detection, which comprises both the detection of unit process failures and the integration of results from each process to determine if there is a system failure. The reliance on rapid detection means that a system’s monitoring capabilities directly impact its resilience. Significant research has been done in the area of enhanced monitoring, both in terms of the availability and suitability of analytical methods, as well as in terms of the design of monitoring systems.

8.4 Monitoring System Design

Potable reuse monitoring systems must be designed to detect relevant failures rapidly. The CCP framework provides a basis for developing monitoring systems that prioritize the detection of unit process failures with the largest potential impact on public health. For WRRF-13-03, the HACCP framework was used to set up a system for monitoring CCP performance, with the data used to estimate the public health protection provided by a potable reuse treatment system was demonstrated. Rather than rely on end-of-pipe testing to verify that product water quality goals are met, HAACP focuses on verifying the performance of individual barriers. The ability to quickly identify the source of a failure enables rapid responses to be enacted. Many facilities, such as the Groundwater Replenishment System (GWRS) in Orange County, California, have been using a similar approach for many years to assess system performance.

8.4.1 Statistical Process Control

Another approach gaining increasing attention is the use of statistical process control to improve failure detection. Using information from continuous online monitors, control charts can help identify variations in performance and, in some cases, allow operators to detect process excursions before they become failures. Such a system is used for GWRS to detect deviations in process performance and prompt the implementation of corrective actions, either automatically or by operations staff. For example, online TOC data from GWRS are shown in **Figure 8-1**.

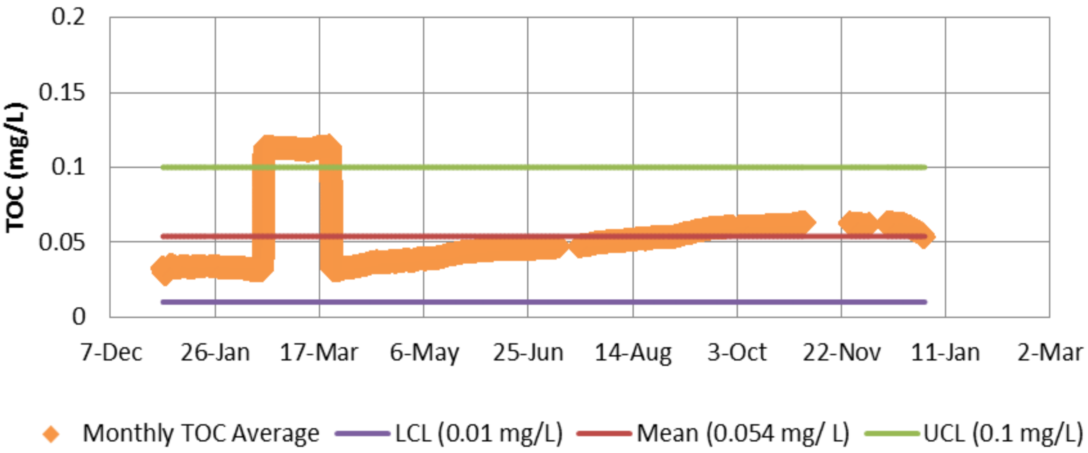

Figure 8-1: Orange County Water District's Groundwater Replenishment System monthly online total organic carbon data for 2013 with upper and lower statistical control limits shown (from Gonzalez, 2015).

Typically, the process runs within a narrow range of values, which are used to calculate and delineate the upper and lower statistical control limits. Alarms are then set to alert operators if TOC readings exceed these limits. Note that the upper control limit (0.1 mg/L) is significantly lower than the absolute regulatory TOC threshold of 0.5 mg/L. Accordingly, control charts provide a rational basis for setting alarms to indicate process instability with the goal of detecting this instability before it leads to process excursions or failures.

8.4.2 Monitoring Equipment and Methodology

Having identified CCPs and appropriate monitoring locations, the next research focus has been on identifying and improving the capabilities of the monitoring equipment and methodology itself. The frequency of measurements should be commensurate with the acuteness of the contaminant risk, meaning that contaminants that pose the most acute threats (e.g., pathogens) should be monitored more tightly than those posing chronic threats. The characteristics of ideal monitors were identified in WRRF-11-01 (see **Chapter 4**) and used to evaluate the performance of different monitoring technologies for specific functions. The authors concluded that the technology for real-time monitoring is feasible and rapidly growing. Nevertheless, real-time monitoring of pathogens is not yet attainable, particularly in demonstrating the safety of final treated product water. In the absence of the direct measurement of pathogens, surrogate monitoring can provide information about process performance, often with online, continuous measurements. Ongoing project WRF4508 is providing the next level of evaluation, assessing the analytical methods for chemicals and pathogens to recommend those that provide the best assessment of the safety of DPR waters. Similarly, WRRF-14-17 is developing a white paper to review and assess the current state of rapid microorganism monitoring methods, and to evaluate their potential application in potable reuse systems.

8.4.3 Data Management

The DPR demonstration facility in WRRF-14-12 has developed an enhanced monitoring system, providing rapid and redundant monitoring in line with potential future regulations for DPR. An issue that has emerged is the need to store and process large quantities of data produced by such a highly monitored system. As part of the work being done for WRRF-14-12, recommendations are being developed for the set-up of data acquisition and storage systems that can handle high volumes of data. Managing monitoring data effectively is essential for rapid failure detection.

8.5 Failure Response

When a failure occurs, an appropriate response must be enacted to prevent off-spec water from being delivered to consumers. WRRF-12-06 identified the failure response time (FRT) as the "maximum possible time between when a failure occurs and the system has reacted such that the final product water quality is no longer affected." Each process has its own FRT, which is composed of the time it takes to detect and confirm a failure, plus the reaction time to respond and correct the failure. The process with the highest individual FRT then dictates the overall system FRT.

According to WRRF-12-06, there are three main categories of failure response strategies:

- Management of off-spec water (e.g., through diversion).
- Activation of standby treatment units upon failure of primary units.
- Inclusion of redundant treatment as part of the process train to ensure that failure in a single unit does not result in system failure.

These categories are not necessarily mutually exclusive, and various combinations of these strategies can be equally protective of public health. In addition, it may be possible to idle process units (e.g., run to waste, internal recycle, etc.) to avoid time-consuming equipment start-up. For DPR, effective failure responses can place greater emphasis on advanced monitoring, redundant treatment, and effective operations to compensate for the loss of the environmental buffer.

8.5.1 Components of Failure Response Time

The FRT of each unit process is composed of three parts: sampling interval, sample turnaround time, and system reaction (**Figure 8-2**). The length of each part will vary for different unit processes; ideally, in a DPR system, the first two steps involving failure detection will occur rapidly through the aid of online monitoring. The system reaction time is dependent on both technical and institutional factors. For example, automated responses could be implemented through a Supervisory Control and Data Acquisition (SCADA) system to immediately divert water or default to a safe mode. Responses requiring human intervention might increase the reaction time from a matter of minutes to a matter of hours or days. Process FRTs can be decreased using effective online monitoring, standard operating procedures, and effective automated responses.

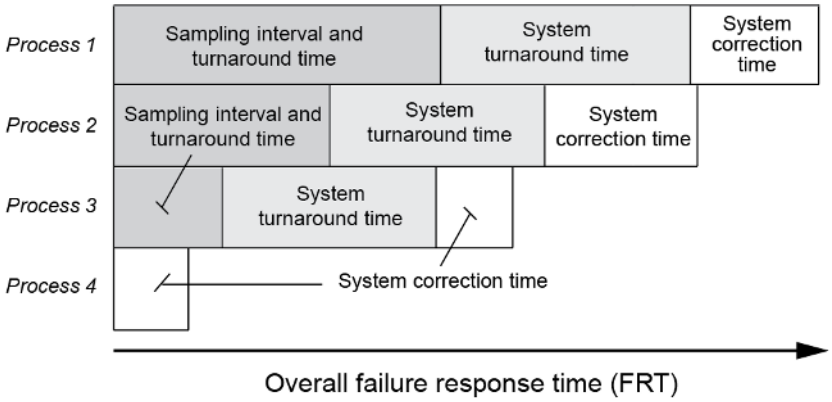

Figure 8-2: Treatment train failure response time (from Tchobanoglous et al., 2015).

8.5.2 Management of Off-Specification Water

Failure response must ensure that off-spec water is dealt with prior to reaching consumers, either through diversion, additional treatment, or another strategy. The time available to enact such a response depends on the “directness” of the potable reuse system (i.e., the time and distance between advanced treatment and consumption). When an environmental buffer is present, several strategies are available to manage off-spec water that may not be available in a DPR system. For example, wellhead treatment can be used to further treat off-spec water in groundwater replenishment projects, and DWTFs can cease drawing off-spec water from a reservoir in a surface water augmentation project.

Today’s monitoring technology can provide rapid monitoring to detect failures even prior to the environmental buffer. The diversion of off-spec water is a realistic design feature being considered for projects with shorter retention times. For example, the surface water augmentation project for the City of San Diego has planned facilities for diverting off-spec water in multiple locations along the pipeline that delivers advanced treated water to the surface water reservoir. The high degree of temporal control means that diversion also can be planned to address failures before leaving the AWTF. For example, the product water from both RO and UV/AOP could be discharged through a line connected with the wastewater line or returned to the AWTF headworks to prevent the discharge of off-spec water to the reservoir. Other locations for diversion also are being considered. The use of multiple diversion points for failure response is an effective way to prevent off-spec water from reaching consumers.

Another strategy for managing off-spec water when there is no environmental buffer is the use of engineered storage. An ESB can replicate some of the benefits of the environmental buffer, such as providing additional treatment or temporary storage of product water while its quality is being verified. ESBs provide additional time to detect failures, as well as an engineered diversion point for any water failing to meet specifications. As a design element, the use of an ESB would balance with the other protections provided by a project (i.e., treatment and monitoring). Providing storage for water quality verification would mean a longer monitoring interval could be used. Conversely, such storage might be deemed unnecessary with the use of continuous online monitoring to rapidly detect failures. The ability to balance the elements of project resilience will enable flexibility in potable reuse system design.

8.6 Redundant Treatment for Failure Prevention

As projects become more direct and the time available to enact a system failure response decreases, strategies like wellhead treatment are no longer an option. The use of an ESB can provide greater response time, but their cost may render them infeasible for some systems. Given the reality of limited response times, more emphasis must be placed on failure prevention, which can be effectively achieved through treatment redundancy.

Using redundancy (i.e., providing more than the minimum treatment required), a single unit process could experience a failure without causing a system failure. With a high degree of redundancy, a system of graded alarms and responses could be used to implement responses commensurate with the level of risk posed to public health. For example, consider a process providing 20-log reduction of virus when the requirement is 12 log. If a single unit process failed such that the system was achieving only 16-log reduction, no immediate failure response would need to be implemented; operators would have time to diagnose and fix the problem while allowing the system to continue running. As the performance continues to drop toward the minimum requirement, the graded responses could become more urgent. For failures that drop performance below the minimum, immediate responses could be planned. In projects where little to no retention time in an environmental or engineered buffer will be provided, increasing the amount of treatment redundancy can allow for a greater degree of operational flexibility when dealing with failures.

8.6.1 Alternative Approaches for Public Health Protection

The concept that different combinations of treatment, monitoring, and storage can achieve equivalent levels of public health protection has been acknowledged by the drinking water regulatory community. In a 2012 presentation, the Division of Drinking Water of the California State Water Resources Control Board proposed two potential pathways for achieving safe DPR: (1) using infallible monitoring, or (2) using the best available monitoring with redundant treatment. This acknowledgement supports the idea that different system elements can balance each other to achieve equivalent protection; a loss in one element can be compensated for by another.

8.6.2 Use of Standby Units

Another form of redundant treatment is the inclusion of standby units for each treatment process. The use of standby units is common practice in both water and wastewater systems. The benefit is that the failure of a given unit process can be rapidly resolved through the activation of the standby unit. For example, at Helix Water District’s R.M. Levy Water Treatment Plant, the ozone disinfection system is designed with a lead/lag/stand-by configuration. If the lead generator fails to meet the disinfection targets or shuts down, the lag generator is able to come on within seconds. A standby chlorine disinfection system serves as a second back-up to this configuration, providing another form of disinfection in the event of failure of the duty and standby ozone generators. This type of fail-safe operation with standby units can be used to increase the resilience of DPR operations.

8.7 Need for Skilled Operators

Both the monitoring and reaction components highlight the need for skilled and effective operations staff; therefore, a key aspect of ensuring rapid failure response is in operator training and standard operating procedures. If a detected failure requires human intervention, the operators must be able to enact the appropriate response in a timely and effective manner. WRRF-13-13 identified the following key components of the operator training and certification process for DPR:

- Intensive requirements for water quality sampling and analysis.
- Specific requirements for all CCP instruments, including calibration, verification, and documentation of most common causes of inaccurate readings.
- Critical operational monitoring, reporting, and effective operational responses.

The proposed curriculum for DPR operator training includes training in CCP methodology, alarm management, effective and rapid communications, and response procedures. Highly trained, skilled operators will be essential for resilient potable reuse (see **Chapter 7**). A demonstration-scale DPR study carried out in Denver used the existing operations staff at the conventional DWTF (Lauer, 2015), indicating that specific training can lead to successful operations of more complex potable reuse treatment systems.

8.8 Global Perspective of the Resilience of Direct Potable Reuse Systems

WRRF-14-13 directly addresses a more “systems-perspective” of DPR resilience, looking at strategies for control from the collection system to the household water tap. The objectives of WRRF-14-13 include:

- Identify common failure modes in all stages of DPR, including wastewater source control, wastewater treatment, and advanced water treatment.
- Identify interdependencies between different aspects of the DPR system where a failure in one component could cause adverse impacts downstream.
- Develop a design guideline to improve DPR resilience.

The intention of this work is to characterize common failures (e.g., types of failure, where they occur, relative impact on performance) in an effort to provide a more rational approach to failure response (See **Figure 8-3**). The project also has a broad perspective in that it traces potential failure locations from the source water through to distribution. The project intends to develop a set of guidelines that focus on design, monitoring, control systems, communications protocols, and standard operating procedures. This “collection system to tap” perspective and the development of design guidelines will be important steps in understanding how to ensure potable reuse systems are highly resilient.

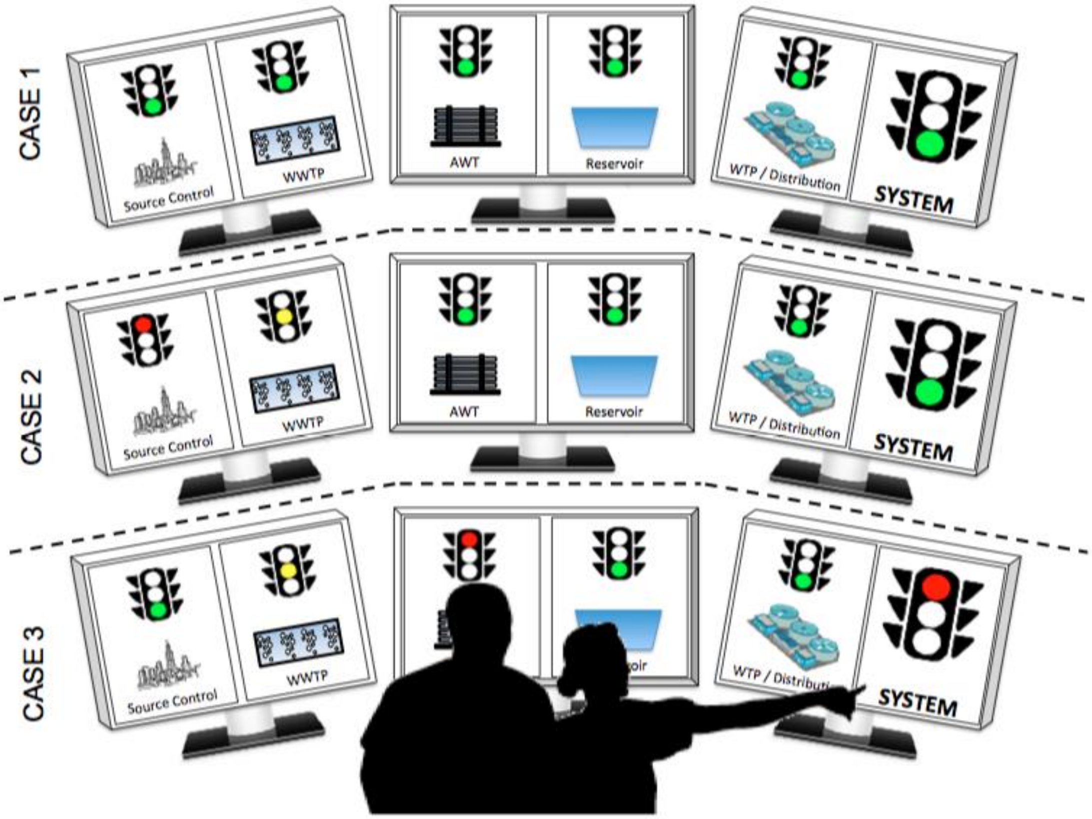

Figure 8-3: Example of how failure response requirements might be assessed based on the performance of multiple system components. Not all failures in individual components will lead to an overall failure to protect public health (Case 2). Failure responses must differentiate between safe conditions (Case 1 and 2), and those where failures threaten public health (Case 3).

8.9 Resilience to Natural and Man-Made Disasters

In addition to failures in treatment stemming from mechanical issues or improper operations, potable reuse systems must be resilient to natural and man-made disasters. The American Water Works Association has published a standard for Risk Analysis and Management for Critical Asset Protection that provides a framework for managing risk and resilience in water and wastewater systems (AWWA, 2010). The focus of the framework is on identifying threats of the highest likelihood and consequence, and prioritizing investments to minimize impacts from these threats. Prioritizing the high-probability, high-consequence events can help utilities maximize the benefit of investment in resilience strategies. Utilities that have implemented this strategy have considered threats (e.g., power loss and hurricanes) and their impacts with respect to potential injuries, economic losses, service denial, and public confidence. A similar analysis would be beneficial for any potable reuse system, as it would enable utilities to make investments decisions that would improve public health protection in the face of emergency threats.

8.10 Information Sources

A list is provided in **Table 8-1** of the WRRF and WRF projects that were reviewed for the preparation of this chapter. Full citations for reports related to these projects, along with citations for other references and sources of information, are included in **Section 8.11**.

Table 8-1: WRRF and WRF Research Projects Used to Prepare Chapter 8

Project No.	Project Title	Principal Investigator(s)
WRRF-11-01	Monitoring for Reliability and Process Control of Potable Reuse Applications	Ian Pepper, University of Arizona
WRRF-12-06	Guidelines for Engineered Storage for Direct Potable Reuse	Andrew Salveson, Carollo Engineers
WRRF-13-03	Critical Control Point Assessment to Quantify Robustness and Reliability of Multiple Treatment Barriers of Direct Potable Reuse Scheme	Troy Walker, Hazen & Sawyer
WRRF-13-13	Development of Operation and Maintenance Plan and Training and Certification Framework for Direct Potable Reuse Systems	Troy Walker, Hazen & Sawyer
WRRF-13-14 (WRF4508)	Assessment of Techniques to Evaluate and Demonstrate the Safety of Water from Direct Potable Reuse Treatment Facilities	Channah Rock, University of Arizona
WRRF-14-12	Demonstrating Redundancy and Monitoring to Achieve Reliable Potable Reuse	R. Shane Trussell, Trussell Technologies, Inc.
WRRF-14-13	From Sewershed to Tap: Resiliency of Treatment Processes for Direct Potable Reuse	Sharon Waller, Sustainable Systems, LLC.
WRRF-14-16	Operational, Monitoring, and Response Data from Unit Processes in Full-Scale Water Treatment, Indirect Potable Reuse, and Direct Potable Reuse	Andrew Salveson, Carollo Engineers
WRRF-14-17	White Paper on the Application of Molecular Methods for Pathogens for Potable Reuse	Krista Wigginton, University of Michigan
WRRF-14-20 (WRA-14-01)	Developing Direct Potable Reuse Guidelines	Jeffrey Mosher, National Water Research Institute

8.11 References

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Chapter 9: Demonstration of Reliable, Redundant Treatment Performance

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A preliminary review and summary has been completed of peer-reviewed published studies related to the "demonstration of reliable and redundant treatment performance" as part of WRRF-15-01. While this project has focused on the information available from the 34 research studies related to the WateReuse DPR Research Initiative, additional studies have been incorporated that provide merit and further substantiation of the observations and recommendations provided in the DPR reports. The remainder of this chapter provides a brief summary of key findings related to the reliability and redundancy of several DPR processes and combined configurations.

9.1 Identification of Key Issues

The benefits of including DPR in a community's water supply portfolio are well documented, spanning economic, environmental, and social impacts. The realization of these benefits requires that DPR systems be designed and implemented with water quality performance reliability and redundancy held paramount. Reliability and redundancy are fundamental requirements of any water treatment system, but are critical for DPR due to the engineered linkages between urban wastewater collection systems and drinking water distribution systems. Key reliability and redundancy issues for DPR projects include:

- The production of high-quality advanced treated water under both ideal and non-ideal system conditions can be achieved only through the coupling of reliable and redundant treatment processes.
- To achieve reliable performance, individual treatment processes must be selected that are known to target specific contaminants for removal.
- Key aspects of reliability in DPR are verification and validation.
- To achieve redundancy, the entire treatment system must contain multiple barriers for any given contaminant.
- Notably, a barrier can be technical, operational, or managerial in nature, with each barrier providing a factor of safety in terms of contaminant removal.
- Field or pilot verification of whether a barrier can be used to mitigate or reduce identified human health risks is of critical importance.

Reliability and redundancy are examined in **Sections 9.4** and **9.5**, respectively.

9.2 Summary of Principal Findings

Reliability in DPR involves long-term process performance, which can be ensured only by upfront verification and validation, in addition to proper O&M and monitoring CCPs.

9.2.1 What Is Known

- During the selection of treatment processes, it is now possible to verify that each process can meet expectations to manage specific human health risks identified as controlled by that barrier.

- Process validation must be used to assess whether a barrier functions as intended to control health risks.

- Validation can be completed by measuring the removal of a specific contaminant or pathogen across a barrier during pilot testing and full-scale validation testing.

- Redundancy is both an inter-process [e.g., multiple barriers, such as UV irradiation followed by chlorination] and an intra-process (e.g., having multiple RO banks whereby one or two banks can be on duty or in a standby mode).

- Redundant monitors (i.e., either redundant monitors that measure the same parameter or, better yet, multiple monitors of the same process that measure different parameters) must be used to improve process monitoring and response.

9.2.2 What Is Unknown

- No surrogate is available for real-time validation of virus removal in membrane processes. Until a real-time surrogate is developed and accepted by regulators, it will not be possible to obtain virus reduction credit for most membrane processes. Typically, RO membranes achieve credit by observation of a surrogate (such as conductivity), but are limited to 1.5 to 2.0-log reduction. Commercial products such as TRASAR® may be available to monitor RO performance beyond the 2.0-log from conductivity measurements, but have yet to be accepted for creditable performance by regulatory agencies.

- The development of alternative virus surrogate parameters that exhibit similar (and measurable) removals relative to contaminants of concern must be identified, tested, and validated for use in process monitoring.

- More information is needed about the optimal coupling of the various treatment technologies currently in use for potable reuse with the new technologies currently being developed and tested.

9.3 Reliable Process Performance for Direct Potable Reuse

To support the process of understanding how various barriers perform in terms of mitigating human health risks, multiple studies have been completed over the past 10 to 12 years that provide a solid basis of data that can be used to verify and validate process performance. The main processes summarized here are part of a treatment train based on RO membranes (e.g., MF, RO, UV/AOP, and chlorine) or an alternative treatment train based on ozone-biofiltration (e.g., floc/sed, ozone, BAC, GAC, UV, and chlorine). Summaries are provided in **Subsections 9.3.1** to **9.3.7** of process performance and the removal of key chemical and microbial contaminants.

9.3.1 Microfiltration

Traditionally, the primary goal of MF in potable reuse was to prevent solids from fouling downstream RO membranes; however, because MF also provides pathogen control, it can be used as an additional pathogen removal barrier integrated with RO membranes or as a pathogen barrier in other process combinations.

- Trussell et al. (2013) conducted a review for WRRF-11-02 and found 2-log to 3-log reduction of virus was observed for coagulation in front of MF. The team also reported multiple sources where 4-log to 7-log reduction of *Giardia* and 6-log reduction of *Cryptosporidium* were measured.

- The USEPA Membrane Filtration Guidance Manual provides a means for validating *Cryptosporidium* and *Giardia* using pressure decay testing/membrane integrity testing; however, no surrogate is available for real-time validation of virus removal, so virus reduction credit typically is not provided. Previous work, however, has shown that using fluorescent dyes may assist in obtaining virus reduction credit in the future.

- Walker et al. (2016) used 2 years of full-scale data from an IPR facility and found that the performance of three parallel treatment trains of MF membranes had a tight distribution that ranged from 4.5-log to 4.73-log reduction of *Cryptosporidium* and *Giardia*, indicating reliable performance.

- Walker et al. (2016) used a full-scale reuse facility to induce fiber breaks and remove O-rings to examine the impact of a substantial breach on performance of UF membranes in a rack of 204 membrane units. While the pressure decay tests were able to detect as few as five broken fibers in a membrane module, cutting 50 fibers and removing the module's O-ring still did not result in a loss of performance below 4.5-log reduction of *Cryptosporidium* and *Giardia*. At this level of breakage, the total number of cut fibers within the entire 204 module rack represented only 0.0025 percent of the total membrane fibers, yet caused an observable impact on pressure decay test results, indicating that even minor imperfections can be observed before negative impacts on log-reduction goals occurs.

- MF membranes are not intended to remove organic chemical contaminants, though some ancillary removal can occur and is enhanced by the use of UF membranes or MBRs (Snyder et al., 2014; Stanford et al., 2014; Trussell et al., 2013). MF can be a barrier to metals and other constituents that are oxidized or coagulated in upstream treatment processes.

9.3.2 Reverse Osmosis

RO membranes were first used to control salinity in water reuse schemes, beginning in the 1970s with Water Factory 21 in Orange County, California; however, RO membranes also provide an excellent physical barrier to microbiological and chemical contaminants.

- In multiple studies, it has been demonstrated that RO membranes are capable of rejecting organic and inorganic chemical contaminants, though some contaminants are still able to pass through RO membranes at varying levels of rejection, including NDMA, 1,4-dioxane, and several low molecular weight molecules, including some carbonaceous DBPs (Doederer et al., 2014; Farre et al., 2015; Kimura et al., 2003; Plumlee et al., 2008; Stanford et al., 2014; Steinle-Darling et al., 2007; Trussell et al., 2013)

- Trussell et al. (2013) conducted a review for WRRF-11-02 and included information from several sources that found 4-log reduction of bacteria across RO membranes, 3-log to 7.9-log reduction of viruses, and 4.2-log to 4.6-log reduction of protozoa.

- In one study, two different spiral-wound RO membrane elements were found to provide an effective barrier capable of rejecting MS2 Bacteriophage with log reduction values equal or greater than 5.4 (Mi et al., 2004).

- The limitation on real-time validation of RO performance with respect to pathogen removal has been in the ability to detect the removal of physical surrogates. TDS is an easily monitored parameter; however, TDS rejection by RO is a conservative measure of RO integrity as a microbial barrier because, typically, TDS is not rejected at greater than a 2-log reduction by RO.

    - Other integrity parameters for RO membranes are being examined to determine whether these parameters can more closely demonstrate the occurrence of high log reduction values of particles (e.g., Jacangelo, Ongoing Research).

    - Uranine has been identified as a suitable fluorescent marker for pulsed-marker membrane integrity monitoring for the quantification of log reduction values up to 4 or higher (Frenkel et al., 2014). The fraction of total marker passage for a given monitoring period could be correlated with membrane breach size and location. Uranine is an orange read dye with a molecular weight of 361 Daltons. Viruses have molecular weights over 10,000 Daltons.

    - Commercial products like TRASAR® may be available to monitor RO performance beyond the 2.0 log from conductivity measurements, but have yet to be accepted for creditable performance by state regulatory agencies.

- Walker et al. (2016) used 7 years of operating data to model RO membrane performance at full-scale and found a mean rejection of 2.75 log of sulfate, with 2.26-log rejection greater than 95 percent of the time, indicating highly reliable and stable performance.

9.3.3 Ultraviolet Irradiation

UV irradiation is used in water and wastewater treatment as a barrier to pathogenic contamination of the finished product. Disinfection using UV irradiation is a physical process in which UV light damages nucleic acids, rendering bacteria, viruses, and protozoa incapable of reproduction and infection. The *NWRI Guidelines for UV Disinfection* typically are used for the design and operation of UV disinfection systems, which require a validated UV dose of 100 millijoules per square centimeter (mJ/cm^2) for media-filtered effluents, 80 mJ/cm^2 for membrane-filtered effluents, and 50 mJ/cm^2 for RO-filtered effluents (NWRI, 2012). UV doses expressed as mJ/cm^2 represent the product of UV intensity (mW/cm^2) and exposure time (seconds). The following test data are from low pressure high output lamps (254 nm) unless otherwise stated.

- The *NWRI Guidelines for UV Disinfection* state that the following parameters must be monitored continuously to ensure the provision of adequate disinfection: flowrate, UV intensity, UV transmittance, turbidity, and operational UV dose (NWRI, 2012).

- The USEPA has established dose response-relationships between UV and pathogen inactivation (USEPA, 2006, 2015). For viruses, this relationship is linear, whereas for *Cryptosporidium* and *Giardia,* the relationship is log-linear, which means that increasing larger doses are needed for an equivalent increase in response from protozoa.

- The disinfection capabilities of UV irradiation have been demonstrated in multiple water reuse applications. The results of several investigations were summarized by Trussell et al. (2013):

    - Protozoa: >3-log inactivation of *Giardia* at 100 mJ/cm^2, >3-log inactivation of *Cryptosporidium* at 100 mJ/cm^2.

    - Bacteria: >5-log inactivation of *Escherichia coli* (*E. coli*) at UV doses of 100 mJ/cm^2.

    - Viruses: >4-log inactivation of adenovirus at 100 mJ/cm^2; up to 7-log inactivation at 300 mJ/cm^2.

- Recent work has demonstrated that UV reactors in series provide adequate mixing and the dose-inactivation relationships are additive (Lawryshyn and Hofmann, 2015); therefore, inactivation rates higher than that reported in disinfection guidance documents are possible.

- Using filtered secondary-treated wastewater effluent in pilot-scale testing, 2-log to 5-log reduction of MS2 were observed for UV doses ranging from 33 to 100 mJ/cm^2, as well as total coliform concentrations in the effluent around 1 to 1.5 CFU/100 mL for the same range of UV doses (Tang et al., 2010).

- Adenovirus requires a higher UV dose (e.g., >100 mJ/cm^2) for inactivation to below detection limits, but adenovirus is more susceptible to inactivation by chlorination (Tang et al., 2010). Medium-pressure UV lamps have proven to be much more effective than low-pressure UV lamps for the inactivation of adenovirus (Linden et al., 2014). The USEPA recommends 186 mJ/cm^2 for 4-log reduction of adenovirus.

- One year of full-scale continuous monitoring data from an anonymous drinking water facility in the United States indicated excellent reliability and performance of UV disinfection systems (Walker et al., 2016), based on measurements of factors like UV fluence, UV transmittance, turbidity, flow, and power rather than direct enumeration of the concentration of microorganisms in water. Even when turbidity and fluctuations in plant operation, maintenance, and so on were considered, *Cryptosporidium* and *Giardia* were inactivated from a minimum of 5.0 log to a maximum of 5.7 log. Viruses were inactivated from a minimum of 0.8 log to a maximum of 1.8 log under these disinfection dose conditions. Here, the disinfection dose ranged from 40 to 100 mJ/cm^2 in filtered surface water.

- The benefits of disinfection using UV irradiation include the minimization of DBP formation. The use of UV reduces the required chlorine dose, thereby also reducing the production of chlorinated DBPs. UV irradiation alone does not result in the formation of bromate (Stanford et al., 2013); however, UV alone generally is ineffective for the removal of bulk organic matter and trace organic contaminants (Snyder et al., 2014; Trussell et al., 2013).

9.3.4 Ultraviolet Advanced Oxidation Process

The term "advanced oxidation process" (AOP) is defined as a process in which hydroxyl radicals are the primary driver of organic contaminant oxidation (Glaze et al., 1987). In this case, the discussion is limited to hydrogen peroxide (H_2O_2) or chlorine with UV irradiation at doses typically around 10 times higher than disinfection doses (e.g., >400 mJ/cm^2); therefore, UV/AOP provides a concurrent opportunity for the disinfection and oxidation of organic contaminants.

- The results of several investigations were summarized by Trussell et al. (2013):
  - Protozoa: >3-log inactivation.
  - Viruses: >3-log inactivation.
  - Estrodiol equivalents: 15-percent removal at 100 mJ/cm^2 and 5 mg/L H_2O_2, 70-percent removal at 500 mJ/cm^2 and 5 mg/L H_2O_2.
  - Trace organic compounds (TrOCs) vary widely in their ability to be removed by UV/AOP, depending on whether they are photolabile, oxidizable by hydroxyl radical, or resistant to both photolysis and hydroxyl radical attack.
  - NDMA: 10-percent removal at 100 mJ/cm^2 and 5 mg/L H_2O_2, 90-percent removal at 500 mJ/cm^2 and 5 mg/L H_2O_2.

- The proven efficacy of disinfection by UV irradiation alone holds true for UV/AOP. For UV doses up to 680 mJ/cm^2 and a peroxide dose of 10 mg/L, the inactivation of *E. coli* can reach approximately 7-log, inactivation of MS2 can reach >8-log, and inactivation of *Bacillus* spores is greater than 3-log (Snyder et al., 2014).

- Because of the additive nature of UV systems (Lawryshyn and Hofmann, 2015), UV/AOP systems are able to obtain much higher log reduction of pathogens. Recent work indicated that, based on full-scale operating data, virus removal could be achieved at greater than 7.5-log reduction (assuming 400 mJ/cm^2 dose), while *Cryptosporidium* and *Giardia* could be removed to greater than 7.4 log 100 percent of the time (Walker et al., 2016).

- It has been found that some trace organic contaminants are highly susceptible to oxidation by UV/AOP (e.g., diclofenac), but that UV/AOP is less effective than ozone-based oxidation for overall contaminant mitigation (Snyder et al., 2014). In addition, ~75 percent of 20 tested TrOCs were removed by more than 90 percent at low flows (i.e., high UV fluences) and an H_2O_2 dose of 13 mg/L, with removal being a function of UV fluence and H_2O_2 dose. Out of the 20 TrOCs tested, musk ketone, TCEP, TCPP, and iopromide proved to be the most resistant to removal by UV/AOP (Rosario-Ortiz et al., 2011).

- Based on several years of data from the Groundwater Replenishment System (GWRS), greater than 1.3-log reduction of NDMA is achieved 95 percent of the time (Walker et al., in press); however, under the same dose conditions, contaminants such as diuron were removed at less than 1.0-log reduction 95 percent of the time. Consequently, UV/AOP is effective only on contaminants susceptible to UV photolysis or oxidation by hydroxyl radical.

- Similar to UV irradiation without the addition of H_2O_2, flowrate, UV intensity, UV transmittance, turbidity, and operational UV dose should be continuously monitored, in addition to the applied H_2O_2 dose (NWRI, 2012; Trussell et al., 2013).

9.3.5 Ozone/Biologically Active Carbon

Ozone (O_3) and biologically active carbon (BAC) (i.e., biofiltration) are close-coupled processes because the stability of ozonated water depends on downstream biofiltration, while the extent to which organic contaminants are converted/consumed during biofiltration depends on upstream ozonation. The primary purpose of ozone is disinfection (and, secondarily, the oxidation of organic compounds). The combination of ozone with biofiltration enhances the removal of bulk organic matter and TrOCs. When treated as a conventional filter by adding coagulation and operating with turbidity goals, biofiltration also can remove pathogens.

- Ozone can effectively inactivate pathogens (~6.5-log reduction of MS2 at an ozone-to-TOC ratio of 1), with the notable exception of *Bacillus subtilis* spores (~0.1-log reduction of *Bacillus subtilis* spores at an ozone-to-TOC ratio of 1 mg O_3/mg TOC) (Snyder et al., 2014). *Cryptosporidium* is less affected by ozone. *Bacillus subtilis* is not harmful to humans.

- The results of several investigations were summarized by Trussell et al. (2013):
    - TrOCs: >80-percent removal for many compounds at an ozone-to-TOC ratio of 1 mg O_3/mg TOC, TCEP is resistant to oxidation by ozone.
    - Estrodiol equivalents: 90- to 99-percent removal of estrogenicity as measured by the yeast estrogen screen assay at ozone doses of 1 to 1.25 mg/L.

- Full-scale data from a facility in the United States that included hourly measurements of flow, ozone dose, residual, temperature, pH, and calculated CT for a period of 1 year were examined to determine the reliability and performance of ozone systems using established CT tables

(USEPA, 1999). Hourly ozone-to-TOC ratios were not provided, but this facility typically has TOC in the range of 1.5 to 2.5 mg/L, pH from 7.5 to 8.3, and lower fifth percentile CT of 2.2 and upper fifth percentile of CT of 9.0. Based on CT measurements in addition to temperature and pH, *Giardia* was removed to greater than 7.4 log 95 percent of the time (3.0-log minimum) and viruses were removed to greater than 15-log reduction 95 percent of the time (6.0-log minimum). *Cryptosporidium* was not as well removed by ozone, achieving only >0.4-log reduction 95 percent of the time (Walker et al., 2016).

- The addition of a post-ozone/BAC step (with coagulation, flocculation, and sedimentation) can provide significant additional log reduction depending on filter operation and turbidity set points. One study indicated that using a 0.1 NTU maximum breakthrough before filter backwashing resulted in 4.8-log to 5.2-log reduction of particulates like *Cryptosporidium* and 4.5-log reduction of viruses (Douglas et al., 2015). This study also provided turbidity-log reduction curves that were used by Walker et al. (2016) in evaluating long-term filter performance. It is noteworthy that BAC alone may not provide sufficient removal of pathogens, but when operated as a biological filter (i.e., understanding that the filter is really a particle storage device) that includes a flocculation step prior to filtration and operation of the filter with 0.1 or 0.15 NTU turbidity goals, reliable and consistent pathogen reduction can be achieved.

- Ozonation has been shown to significantly transform bulk organic matter, converting high-molecular-weight, hydrophobic organic fractions into simpler, low-molecular-weight, hydrophilic organic matter. These changes translate to an increase in the overall bioavailability of the organics, which benefits organic carbon removal in the downstream biofiltration process (Snyder et al., 2014).

- Overall, ozone is effective for removing TrOCs, the extent of which depends on the specific compound in question (Rosario-Ortiz et al., 2011; Serna et al., 2014; Snyder et al., 2013b; Snyder et al., 2014; Stanford et al., 2013). It should be noted that typical ozone doses are not high enough to result in the complete mineralization of oxidized compounds, highlighting the need for subsequent biofiltration to minimize overall toxicity and encourage biological stability of the final product (Snyder et al., 2014).

- Snyder et al. (2013b) found that ozone/H_2O_2 significantly reduced nearly half of all target contaminants, but several contaminants failed to achieve their respective method reporting limits. After a subsequent biological filtration step, however, all target contaminants were reduced to their limits of quantification or at least 95 percent of their initial concentrations.

- Major concerns related to ozone include the formation of NDMA (Serna et al., 2014; Snyder et al., 2013b) and bromate (Snyder et al., 2014). NDMA precursors can be removed with biofiltration, GAC, and peroxidation without ozone. Formed NDMA is best removed with UV irradiation or biofiltration (Dickenson et al., 2015; Sedlak and Kavanaugh, 2006). Bromate formation can be prevented with an optimized chlorine-ammonia strategy by tying up bromide through the formation of bromamine (analogous to chloramine) (Snyder et al., 2014).

- An increase in microbial contamination following biofiltration is possible; hence, a downstream disinfection process is needed (Snyder et al., 2013b). Media type, influent nutrient balances, availability of dissolved oxygen, and other head loss mitigation strategies are important factors to consider for biofiltration design and operation (Azzeh et al., 2015; Lauderdale et al., 2012).

- UV absorbance (UV_{254}) has been shown to be a reliable predictor of contaminant oxidation and disinfection (as a change in UV_{254} before and after ozone) in several studies (Balcolu and Ötker, 2002; Snyder et al., 2014; Snyder et al., 2013a; Wert et al., 2009) and may be useful as a process monitor in ozone applications for water reuse (Serna et al., 2014).

9.3.6 Granular Activated Carbon

GAC is an absorbent media made from high carbon content organic materials, with the final product ranging from 1.2 to 1.6 millimeters in diameter. In the floc/sed-ozone-BAC-GAC-UV-chlorine treatment train, GAC is post-filtration (i.e., post-filter contactor or adsorber), thereby making the only objective of GAC to remove dissolved organic compounds. It should be noted that GAC also can be used as a filtration-adsorption unit for the concurrent removal of turbidity, solids, and dissolved organic compounds if designed properly, though it is not the typical configuration expected in post-filtration applications. Key elements to consider when designing and operating a post-filter GAC adsorber are breakthrough for targeted contaminants, empty bed contact time, design flow rate, and carbon usage (exhaustion) rate (Summers et al., 2014).

- In drinking water applications, GAC has been shown to significantly reduce TrOC concentrations, the extent of which tends to be positively correlated with hydrophobicity and regeneration frequency. Unlike biofiltration, avoiding contaminant breakthrough with (abiotic) GAC requires regular regeneration to ensure the availability of sorptive media sites (Snyder et al., 2007).

- The extent to which TrOCs and estrodiol equivalents are removed by GAC during potable reuse applications depends on competition for sorptive media sites by bulk DOC. For example, the removal of estrone and 17β-estadiol by activated carbon was demonstrated using pure water, but removal rates fell significantly when tested in river water and secondary-treated wastewater effluent (Fukuhara et al., 2006; Zhang and Zhou, 2005).

- Based on research results, it appears that that UV_{254} and total fluorescence are better surrogate parameters for monitoring TrOC removal by GAC than DOC (Anumol et al., 2015); however, if ozone/BAC is used upstream of GAC, limited fluorescence will be available for measurement.

- GAC can be used for the removal of NDMA precursors, which minimizes NDMA formation during ozonation (Dickenson et al., 2015).

- When operated for TOC removal and DBP control, GAC provides highly reliable performance; typically, TOC breakthrough occurs well before most trace organic contaminants (Summers et al., 2014). This process was modeled using full-scale GAC data by Walker et al. (2016).

9.3.7 Chlorination

Chlorine is the most commonly used disinfectant at both water and wastewater treatment facilities across the United States. In a 2008 survey conducted by the Water Environment Research Foundation, it was found that 75 percent of publicly owned treatment works with design capacities greater than 1 mgd use chlorine disinfection (Leong et al., 2008). Chlorination serves as a barrier to pathogenic contamination because it is toxic to most bacteria, viruses, and other microorganisms, the extent of which depends on the applied dose and contact time. When treated wastewater is discharged to the environment, dechlorination must follow chlorination to minimize adverse effects to the receiving waters. In DPR, however, a chlorine residual helps ensure continued disinfection potential in the water distribution system, provided simultaneous compliance with other regulations (including DBPs) is not impacted negatively.

- Overall, chlorine is highly effective for viruses and bacteria, but less effective for protozoa, which drives disinfection strategies. The results of several investigations were summarized by Trussell et al. (2013):
    - Bacteria: CT >3 mg-min/L (residual chlorine concentration, C times time, T) needed for 3-log reduction of bacteria.
    - Viruses: CT >4 mg-min/L needed for 3-log reduction of viruses.
    - Protozoan cysts: CT >70 mg-min/L needed for 3-log reduction of protozoan cysts.

- The USEPA has extensive tables and regression equations to describe the efficacy of chlorine disinfection (USEPA, 1999). Typically, N chlorine disinfection in water systems is dosed (and monitored as CT) for *Giardia* and, therefore, far surpasses the CT required for viruses. For example, at pH 7.0 and 10°C, a CT of 10 mg-min/L is required for 4-log reduction of virus whereas over 10 times that CT condition is required for 3-log reduction of *Giardia*.

- By extrapolating CT values beyond 3- and 4-log reduction, it is possible to look at CT values over time. Two years of continuous compliance data from a full-scale facility were examined to look at the long-term performance of chlorination in finished water (Walker et al., 2016). At this facility, chlorine provided greater than 0.8-log reduction of *Giardia* 100 percent of the time and >1.3-log reduction 95 percent of the time. For those same operating conditions, the minimum virus log reduction observed over the entire period was 22 log. While this extrapolated value is well beyond the limit of the CT tables (4 log is the maximum provided), it is clear that free chlorine contact time provides an excellent, reliable barrier for viruses well above the 4-log provided in the USEPA's tables.

- Additional evidence of virus inactivation beyond 4 log was provided in WRRF-10-15 (Tang et al., 2010). Here, free chlorine doses ranging from 2 to 6 mg Cl_2/L with 10 minute contact times (CT values of 20 to 60 mg-min/L) resulted in 1- to 6-log reduction of MS2.

- When average ammonia levels are kept low, it has been shown that free chlorine is more economical than chloramine disinfection. Chlorination and chloramination economics break even at 0.8 mg/L of ammonia because at ammonia concentrations above 0.8 mg/L, high chemical costs are incurred to achieve breakpoint chlorination (Williams, 2015).

- The most significant drawback of chlorination is the production of DBPs (e.g., trihalomethanes, haloacetic acids, and NDMA). NDMA formation can be minimized by removing precursors prior to chlorination [e.g., using biological nutrient removal to limit ammonia and nitrite, using MF-RO prior to chlorination (although MF-RO is not recommended for the removal of NDMA itself), or using GAC or biofiltration (e.g., BAC) in the treatment train] (Farre et al., 2011; Sedlak and Kavanaugh, 2006). Trihalomethane and haloacetic acid formation are minimized through the removal of bulk DOC prior to chlorination.

- From a redundancy and reliability standpoint, chlorine has a long history of use for controlling waterborne pathogens. When used in conjunction with technologies that limit precursors (e.g., GAC, BAC, coagulation/filtration, enhanced coagulation, ion exchange, NF or RO), it can provide a synergistic control of pathogens while also limiting DBPs (Becker et al., 2013).

9.4 Redundant Barriers for Direct Potable Reuse

Redundancy in a potable reuse treatment train requires that individual treatment processes be combined such that any given contaminant is addressed with more than one barrier. For example, in a redundant treatment train, microorganism control would not be solely achieved with chlorination; rather, a combination of removal and inactivation steps in what is termed a "multi-barrier" approach. As shown in **Table 9-1**, microorganisms can be removed and/or inactivated by several processes, such as membrane filtration, UV irradiation, ozonation, and chlorination.

Table 9-1: Assessment of Treatment Processes as Contaminant Barriers[a]

Process Configuration	**Treatment Process**	**Microorganisms and Pathogens**				**Regulated Chemicals**					**Unregulated Chemicals**		
		Cryptosporidium	*Giardia lamblia*	Total Coliforms	Viruses	Inorganics and Metals	Radionuclides	Volatile Organics	Synthetic Organics	DBPs and Disinfectants	Trace Organic Contam.	1,4-dioxiane	NDMA[b]
RO membrane-based treatment train	Microfiltration (MF)	A	A	A	B	B	B	C	B	B	B	C	C
	Reverse Osmosis (RO)	A	A	A	A	A	A	B	A	A	A	B	B
	UV/AOP[c] (UV/H_2O_2)	A	A	A	A	C	C	C	B	B	A	A	A
	Chlorination	B	A	A	A	B	C	B	B	A	B	C	B
Alternative ozone-biofiltration-based treatment train	Flocculation/ Sed/Filtration	A	A	A	A	B	B	C	B	B	C	C	C
	Ozone	A	A	A	A	B	C	C	A	A	A	B	B
	Ozone + Biofiltration (BAC)	A	A	A	A	B	C	B	A	A	A	B	A
	Granular Activated Carbon (GAC)[d]	C	C	C	C	B	C	A	A	A	A	B	B
	UV	A	A	A	A	C	C	C	C	A	C	C	C
	Chlorination	B	A	A	A	B	C	B	B	A	B	C	B

[a] "A" (green) indicates that the treatment process provides controllable removal of a given contaminant; "B" (yellow) indicates that the treatment process provides incidental or ancillary removal of a given contaminant, but that this removal is not its primary purpose; "C" (no shading) indicates that the treatment process is not intended for the removal of a given contaminant; therefore, it provides no barrier.

[b] NDMA = N-Nitrosodimethylamine; California has established a drinking water notification level of 0.01 microgram per liter (µg/L), but it remained unregulated in other parts of the United States.

[c] AOP = Advanced oxidation process.

[d] GAC refers to the use of granular activated carbon as an adsorptive media, not as media filtration.

The implementation of more than one treatment process to address a given contaminant minimizes the potential for contamination in finished water even if one process is not at optimal performance. Stated differently, if the rows in **Table 9-1** were reduced to only those in a particular treatment train, each contaminant column should include at least two green (or yellow) boxes, because these colors indicate that the treatment process provides controllable (green) or incidental removal (yellow).

- Recall that redundancy is both inter-process [between processes (e.g., having multiple barriers, such as UV followed by chlorination)], as well as intra-process [within a process (e.g., having multiple RO banks whereby one or two banks can be on duty or stand-by mode)].
- The redundancy needed for contaminant removal across (between) processes is outlined in WRRF-13-03 (Walker et al., 2016) and WRRF-13-13 (in draft review), as shown in **Table 9-1**.
- These projects also outline the need for redundant monitors (i.e., either redundant monitors that measure the same parameter or, better yet, multiple monitors of the same process that measure different parameters) to improve process monitoring and response.

9.5 Information Sources

A list is provided in **Table 9-2** of the WRRF projects that were reviewed for the preparation of this chapter. Full citations for reports related to these projects, along with citations for other references and sources of information, are included in **Section 9.6**.

Table 9-2: WRRF Research Projects Used to Prepare Chapter 9

Project No.	Project Title	Principal Investigator(s)
WRRF-01-02	Removal and Destruction of NDMA and NDMA Precursors during Wastewater Treatment	Michael Kavanaugh, Malcolm Pirnie, and David Sedlak, University of California Berkeley
WRRF-06-11	Enhanced Disinfection of Adenoviruses with UV Irradiation	Karl Linden, Duke University and Jeanette Thurston, U.S. Department of Agriculture
WRRF-06-12	Optimization of Advanced Oxidation Processes for Water Reuse: Effect of Effluent Organic Matter on Organic Contaminant Removal	Fernando Rosario-Ortiz, University of Colorado Boulder
WRRF-06-15	Combining UV and Chlorination for Recycled Water Disinfection	Chi-Chung Tang, Sanitation Districts of Los Angeles County
WRRF-08-05	Use of Ozone in Water Reclamation for Contaminant Oxidation	Shane Snyder, University of Arizona
WRRF-08-08	Pilot-Scale Oxidative Technologies for Reducing Fouling Potential in Water Reuse and Drinking Water Membranes	Benjamin Stanford, Hazen and Sawyer
WRRF-09-06 (Phase B)	New Techniques for Real-Time Monitoring of Membrane Integrity for Virus Removal	Val Frenkel, Erler & Kalinowski, Inc., and Yoram Cohen, University of California Los Angeles

Project No.	Project Title	Principal Investigator(s)
WRRF-09-10	Use of UV and Fluorescence Spectra as Surrogate Measures for Contaminant Oxidation and Disinfection in the Ozone/H_2O_2 Advanced Oxidation Process	Shane Snyder, University of Arizona
WRRF-10-15	Establishing Nitrification Reliability Guidelines for Water Reuse	Gordon Williams, Trussell Technologies
WRRF-11-02	Equivalency of Advanced Treatment Trains for Potable Reuse	R. Rhodes Trussell, Trussell Technologies, Inc.
WRRF-11-08	Formation of Nitrosamines and Perfluoroalkyl Acids during Ozonation in Water Reuse Applications	Eric Dickenson, Southern Nevada Water Authority
WRRF-12-07	Methods for Integrity Testing of Nanofiltration and Reverse Osmosis Membranes	Joseph Jacangelo, MWH
WRRF-13-03	Critical Control Point Assessment to Quantify Robustness and Reliability of Multiple Treatment Barriers of Direct Potable Reuse Scheme	Troy Walker, Hazen & Sawyer

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WE&RF Stock No. Reuse-15-01
WE&RF ISBN: 978-1-94124-263-6

December 2016