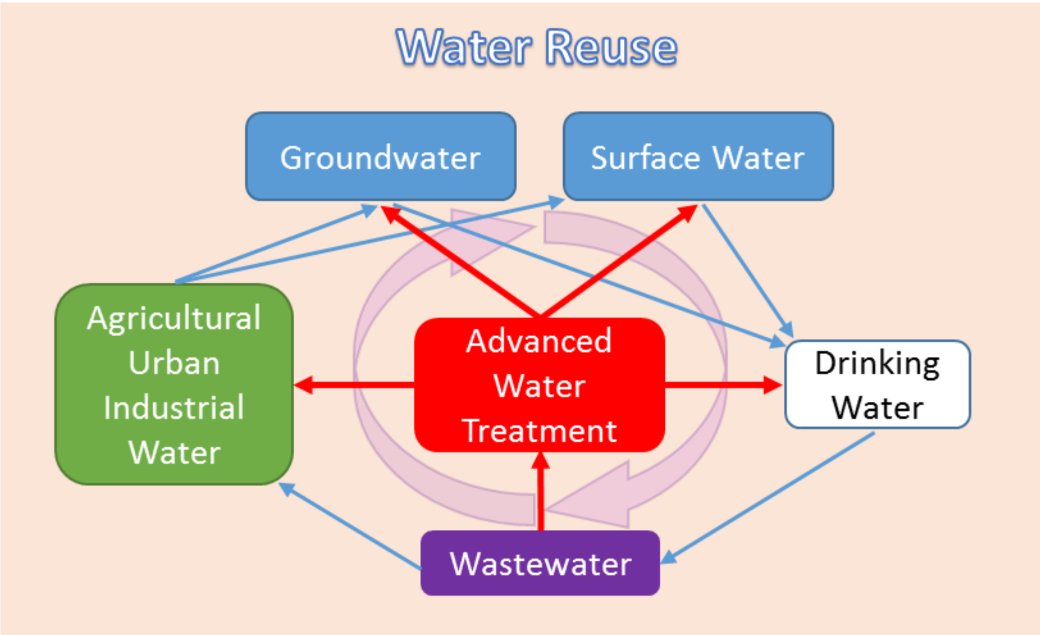
RECLAMATION

Managing Water in the West

Monitoring Strategies for Direct Reuse of Reclaimed Water

Research and Development Office
Science and Technology Program
Final Report ST-2016-0365-01



U.S. Department of the Interior
Bureau of Reclamation
Research and Development Office

September 2016

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

REPORT DOCUMENTATION PAGE					*Form Approved OMB No. 0704-0188*
T1. REPORT DATE September 2016	**T2. REPORT TYPE** Research				**T3. DATES COVERED** 10/1/2015-9/30/2016
T4. TITLE AND SUBTITLE Monitoring Strategies for Direct Reuse of Reclaimed Water					**5a. CONTRACT NUMBER** 16XR0680A1-RY1541AW201610365 (8)
					5b. GRANT NUMBER
					5c. PROGRAM ELEMENT NUMBER 1541 (S&T)
6. AUTHOR(S) Julie Korak, PhD Miguel Arias-Paic, PE, PhD					**5d. PROJECT NUMBER** ST-2016-0365-01
					5e. TASK NUMBER
					5f. WORK UNIT NUMBER 86-68190
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Water Treatment Group U.S. Department of the Interior, Bureau of Reclamation, PO Box 25007, Denver CO 80225-0007					**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Research and Development Office U.S. Department of the Interior, Bureau of Reclamation, PO Box 25007, Denver CO 80225-0007					**10. SPONSOR/MONITOR'S ACRONYM(S)** **R&D: Research and Development Office** **BOR/USBR: Bureau of Reclamation** **DOI: Department of the Interior**
					11. SPONSOR/MONITOR'S REPORT NUMBER(S) ST-2016-0365-01
12. DISTRIBUTION / AVAILABILITY STATEMENT **Final report can be downloaded from Reclamation's website: https://www.usbr.gov/research/**					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT *(Maximum 200 words)* Population growth, freshwater demands and impacts of climate change impact water supply and demand. Water reuse will play an increasingly important role for augmenting fresh water supply sources by implementing beneficial reuse of treated wastewater. Reclaimed water can be used in a range of applications spanning from non-potable uses to potable uses such as indirect and direct potable reuse. The treatment objective held paramount is the biological stability and disinfection of pathogens. Specific applications have specific water quality criteria that must also be met. The area of greatest growth potential is the full scale implementation of optical sensors that monitor surrogate parameters related to organic matter composition.					
15. SUBJECT TERMS Water reuse, reclaimed water, monitoring, potable reuse					
16. SECURITY CLASSIFICATION OF: U			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Julie Korak, PhD
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	**U**	29	**19b. TELEPHONE NUMBER** 303-445-2264

S Standard Form 298 (Rev. 8/98)
P Prescribed by ANSI Std. 239-18

PEER REVIEW DOCUMENTATION

Project and Document Information

Project Name: Monitoring Strategies for Direct Reuse of Reclaimed Water WOID Z0365

Document Final Report 2016-0365-01

Document Author(s) Julie Korak, PhD and Miguel Arias-Paic, PE PhD

Document Date 9/29/2016

Peer Reviewer Anthony Kennedy, PhD

Review Certification

Peer Reviewer: I have reviewed the assigned items/sections(s) noted for the above document and believe them to be in accordance with the project requirements, standards of the profession, and Reclamation policy.

Reviewer /s/ Anthony Kennedy (Signature) Date reviewed 9/27/2016

Disclaimer

Acronyms and Abbreviations

BOD	Biological oxygen demand
CDPH	California Department of Public Health
CECs	Contaminants of emerging concerns
Cl_2	Free chlorine
DOC	Dissolved organic carbon
DPR	Direct potable reuse
E2:E3	Ratio of absorbance at 254 nm to 365 nm
IPR	Indirect potable reuse
meq/L	milliequivalents per liter
mg/L	milligrams per liter
mg-N/L	milligrams of nitrogen per liter
mS/cm	millisiemens per centimeter
NOM	Natural organic matter
ORP	Oxidation-reduction potential
psig	pounds per square inch (gauge)
SAR	Sodium absorption ratio
SCADA	Supervisory control and data acquisition
TDS	Total dissolved solids
TOC	Total organic carbon
TSS	Total suspended solids
USEPA	United States Environmental Protection Agency
UV-VIS	Ultraviolet-visible
UV_{254}	Ultraviolet absorbance at 254 nm

Executive Summary

Population growth, freshwater demands and impacts of climate change impact water supply and demand. Water reuse will play an increasingly important role for augmenting fresh water supply sources by implementing beneficial reuse of treated wastewater.

Reclaimed water can be used in a range of applications spanning from non-potable uses (i.e., agricultural irrigation, urban irrigation, industrial cooling water, wetland and surface water augmentation) to potable uses such as indirect and direct potable reuse. In each application, the treatment objective held paramount is the biological stability and disinfection of pathogens. Specific applications, however, have specific water quality criteria that must also be met. For example, sodium, nutrients, free chlorine and salinity are important considerations for agricultural applications. Nitrate concentrations are important for applications where groundwater could be impacted. Finally, contaminants of emerging concern, operational integrity, and process stability are important for potable reuse applications.

Technical decisions regarding water quality still need to be fine-tuned to ensure that guidelines for reuse meet end user needs, without additional treatment processes, while still delivering water that is safe for its intended use. This study reviewed criteria for different end users, specifically the 2012 Environmental Protection Agency *Guidelines for Water Reuse* to identify the needs of different user groups. The proposed guidelines focus primarily ensuring biological stability and disinfection, but do not close the loop with respect to end user needs. In many cases, additional treatment would be needed to meet end user requirements (e.g., no free chlorine residual).

There are many opportunities for enhanced monitoring for water reuse. Real-time monitoring, in particular, will allow for acceptable water quality to be maintained and communicate with end users if minimum requirements for proper usage are being met. Monitoring can play a significant role not only in potable water reuse, but also to monitor the suitability of reclaimed water for industrial and agricultural applications. Proper selection of indicator and surrogate measurements and demonstration of monitoring reliability are important considerations in reuse monitoring. The area of greatest growth potential is the full scale implementation of optical sensors that monitor surrogate parameters related to organic matter composition. These sensors could be implemented to identify shifts in organic matter that detect changes in biological growth, (e.g., biological oxygen demand) or act as a surrogate for contaminants of emerging concern. There are currently eleven ongoing research projects addressing some aspect of monitoring and direct potable reuse funded by the WateReuse Foundation and Water Research Foundation. To guide future work, the results from these studies should be reviewed once published to identify areas for future research.

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Introduction

In regions where freshwater sources are scarce, water reuse is one method for augmenting water resources to meet regional needs. As of 2009, it is estimated that only 7-8% of municipal wastewater effluent in the United States is reused for beneficial purposes (USEPA, 2012). With continued population growth, increased freshwater demands and adverse impacts of climate change, water reuse will play an increasingly important role for meeting the Nation's freshwater needs (National Research Council of the National Academies, 2012).

A concern of any water reuse application is managing risks associated with reusing wastewater. Human exposure to pathogens is a primary concern for any water reuse application, but the successful implementation of water reuse extends beyond microbial considerations. Ensuring that reclaimed water reliably meets water quality standards specific to its designated use is crucial for the acceptance and expansion of water reuse programs. To meet both the risk management and designated use needs, real-time monitoring of operational and regulatory parameters is central to successful water reuse.

The objectives of this study were to 1) review the water quality needs of different water reuse applications, 2) identify key parameters that require or would benefit from real-time monitoring, and 3) recommend novel monitoring strategies for future studies.

Water Reuse Overview

Water reuse is a broad term that refers to any beneficial reuse of treated municipal wastewater as shown in Figure 1. Conventional wastewater treatment processes have stages of progressive treatment. Primary treatment includes clarification processes that separate solids from liquids. Secondary treatment includes biological processes (e.g., activated sludge, trickling filters) that reduce the biochemical oxygen demand (BOD) and may include nitrification and/or denitrification processes. Tertiary treatment typically involves media filtration. Disinfection may be included with either conventional secondary treatment or tertiary treatment. For some water reuse applications, advanced water treatment applied after tertiary treatment could include granular activated carbon treatment, membrane filtration, biological filtration, and advanced oxidation processes, among others.

While potable reuse garners the most attention, the largest uses of reclaimed water are for other non-potable applications, such as agricultural and environmental uses. California and Florida are the two largest users of reclaimed water in the United States. In California, the majority of reclaimed water is used for agricultural and natural system applications. In Florida, primary uses include agricultural and groundwater recharge (USEPA, 2012). Different water reuse applications are summarized in Table 1. To develop robust monitoring strategies for water reuse, it is important to recognize the breadth of applications and specific needs of each water reuse application, which is addressed in the following section.

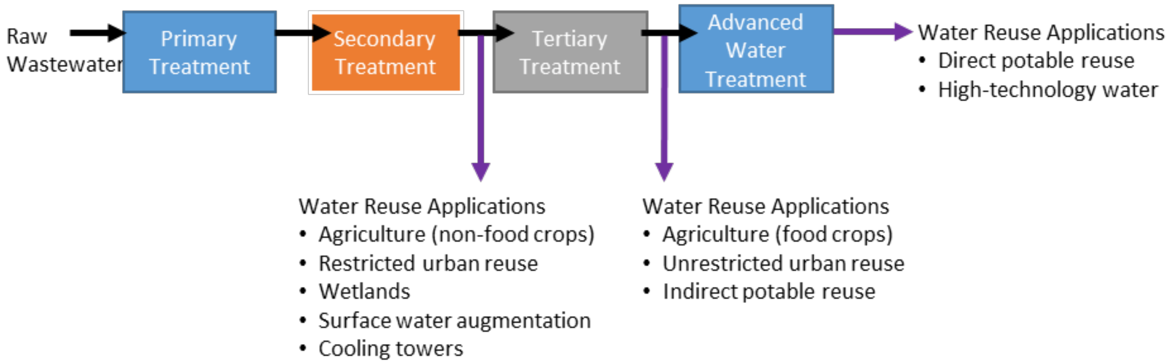

Figure 1. Schematic of different degrees of wastewater treatment with potential water reuse applications.

For potable reuse, it is important to note that unplanned water reuse has been a necessary and common practice although not termed 'water reuse'. Unplanned water reuse occurs when treated wastewater effluent is discharged to a receiving surface water, which is used downstream as a drinking water source. This practice is called indirect potable reuse (IPR) or *de facto* water reuse, because it uses an environmental buffer between wastewater and drinking water plants, as opposed to direct potable reuse (DPR). Engineered IPR systems with deliberate reuse now face increased public scrutiny and regulations to address emerging concerns related to water reuse. Several states and territories have developed regulations or guidelines for non-potable water reuse (Table 1) with different sets of criteria for specific applications (i.e., restricted vs. unrestricted public access and food vs. non-food crops). Several states have developed regulations or guidelines for IDR, but none have developed criteria for DPR.

Table 1. Summary of water reuse applications and regulatory implementation in the United States

Environmental	Type	Number of States or Territories with Rules, Regulations or Guidelines
Natural Environment	Wetlands	17
	Surface water augmentation	
	Groundwater recharge Surface recharge Vadose zone recharge Direct injection	16
	Snowmaking	
Urban	Urban irrigation Golf course watering Park and greenway irrigation	Restricted public access: 40 Unrestricted public access: 32
	Landscape impoundment	
	Brownfield development	
	Non-potable uses Toilet flushing Fire protection	
Agricultural	Food crop watering	Food crop: 27 Non-food crop: 43
	Livestock watering	
Industrial	Cooling water	31
	Boiler water	
	High-Technology Water	
Potable	Indirect potable reuse	9
	Direct potable reuse	0

Water Quality Monitoring

Monitoring is an integral component for water treatment process control to ensure reliable water quality. In conventional drinking water and wastewater treatment processes, monitoring is conducted using both online sensors and offline analysis of manually collected samples. Online sensors have an advantage of collecting data in short time intervals and can be directly integrated in to supervisory control and data acquisition (SCADA) systems. The disadvantages, however, are that online sensors are limited in the types of measurements and analytes that can be measured. More advanced measurement techniques require samples to be collected and measured in an on-site or off-site laboratory. While a greater suite of techniques can be used, the time lag between sample collection, data analysis and results are not amenable to rapid feedback for process control.

Table 2 includes a summary of different monitoring strategies for both online and offline techniques. Between online sensors and online analyzers, a wide range of parameters can be measured with high frequency. Many parameters important for drinking water and wastewater treatment (e.g., bulk properties, inorganic constituents, oxidant residuals) have been integrated into online sensors and analyzers. In contrast, characterization of organic matter, contaminants of emerging concern (CECs) and microbial-related parameters are largely left to offline methods. The absence of online or rapid microbial monitoring tools represents an area of much needed improvement across all water reuse applications, which has been recognized by a California Expert Panel advising the DPR criteria development (Olivieri et al., 2016).

Optical sensors represent one analytical approach that is making a transition from laboratory to field implementation and is promising with respect to water reuse applications. Ultraviolet-visible absorbance (UV-VIS) measures how dissolved constituents (e.g., nitrate, organic matter) absorb light. In water treatment, absorbance at 254 nm (UV_{254}) has been commonly used to characterize natural organic matter (NOM), because it can assess both the concentration of total organic carbon (TOC) or dissolved organic carbon (DOC) and its composition. Fluorescence approaches have also spurred recent research, because it is relatively easy to measure and can discern more complex photochemical behaviors. Fluorescence measures how a water sample can both absorb and emit light at different wavelengths due to the chemical make-up of the sample. Fluorescence is primarily used to characterize NOM.

Table 2. Commercially-available methods for measuring water quality parameters relevant to water treatment

Implementation	Parameter	Technique
Online Sensor	Conductivity	Electrode
	Temperature	Thermocouple
	Oxidation Reduction Potential (ORP)	Electrode
	Ammonium	Ion selective sensor
	pH	Electrochemical sensor
	Nitrate	Ion selective probe Optical sensor
	Dissolved oxygen	Optical sensor Galvanic sensor
	Suspended solids	Light scattering
	Dissolved carbon dioxide	Membrane with thermal conductivity
	Natural organic matter (NOM)	UV_{254} (single wavelength) UV-VIS spectroscopy (full scan) Fluorescence sensor (limited wavelengths)
Online Analyzer or Sensor	Particles	Turbidimeter Dynamic light scattering
	Oxidants (Free chlorine, chlorine dioxide, ozone)	Amperometric electrode Colorimetric analyzer
	Total and Dissolved Organic Carbon (TOC, DOC)	Online organic carbon analyzer
	NOM characterization	Absorbance spectroscopy
	Inorganic ions (nitrate, chloride, etc) Ammonium Ammonia monochloramine Fluoride Phosphate Silica Sodium Hardness	Ion selective electrode Ion selective electrode Online analyzer Ion selective electrode Colorimetric analyzer Online analyzer Ion selective electrode Automatic titration
	Trace Metals (e.g., arsenic, chromium, selenium)	Voltammetry
Offline/Grab Sample Analysis	NOM quantity (e.g., TOC, DOC)	Organic carbon analyzer UV_{254}
	NOM quality (e.g., molecular size, optical properties, molecular chemistry)	Absorbance spectroscopy Fluorescence spectroscopy Size exclusion chromatography High resolution mass spectroscopy Nuclear magnetic resonance Radical formation
	Contaminants of emerging concern (CEC) (e.g., pharmaceuticals, endocrine disrupting compounds, personal care products, pesticides, algal toxins)	Gas chromatography-mass spectrometry Liquid chromatography-mass spectrometry
	Major anions and cations (e.g., nitrate, sulfate, calcium, magnesium, chloride)	Ion chromatography Flow injection analysis
	Trace metals (e.g., iron, manganese, chromium, arsenic, uranium)	Inductively coupled plasma-mass spectroscopy Atomic emission spectroscopy
	Microorganisms (e.g., *E. Coli, Giardia, Cryptosporidium, Legionella, Norovirus*, Cyanobacteria)	Microscopy Microbial cultures Bioassays Genotoxicity and cytotoxicity assays

Reclaimed Water Guidelines and Treatment Needs

To identify strategic areas for enhanced monitoring of water reuse, it is important to identify the key operational and water quality parameters for different end-users. The needs for agricultural reuse are different from those of industrial users, such as cooling towers. The following sections outline the water quality needs identified for different end-users of reclaimed water. Most of the guidelines draw from a comprehensive report published by the USEPA (2012) that define water quality criteria for protecting human health (e.g., microbial risks) as well as specific nutrient and salinity requirements for beneficial reuse.

Agricultural Reuse

Agricultural irrigation is one area where there is a high potential to implement water reuse. Agricultural irrigation accounts for nearly 38% of freshwater withdrawals in the United States (115,000 million gallons per day) (Maupin et al., 2014). The USEPA (2012) guidelines identified several benefits to using reclaimed water for agricultural irrigation:

- Supply is reliable and increases with population growth
- Secondary treated wastewater is more economical than desalinated water for irrigation
- Allocating reclaimed water to irrigation is usually less expensive than other reclaimed uses (e.g., potable reuse, environmental reuse)
- Reclaimed water can supplement or expand other freshwater sources
- Nutrient content can act as a fertilizer depending on crop nutrient requirements

Similar to urban reuse applications, the USEPA developed guidelines, shown in Table 3, for reclaimed water quality for agricultural irrigation with distinctions between food, non-food and processed food crops. Most of the guideline parameters are targeted at managing the biological risk using BOD, turbidity, total suspended solids (TSS), fecal coliform and free chlorine (Cl_2) residual. The guidelines recommend a higher degree of biological stability (low BOD) and higher degree of disinfection (no detectable fecal coliforms) for use on food crops compared to non-food and processed food crops. For food crops, the recommended level of treatment is secondary treatment, filtration and disinfection. For processed food and non-food crops, the recommended level of treatment is secondary treatment and disinfection. Treatment to reduce microbial risks is particularly important for food crops (e.g., lettuce, cucumbers and fruits), whereas irrigation of non-food crops generally presents fewer regulatory and public acceptance barriers than food crops.

Table 3. Recommended guidelines for agricultural reuse from USEPA (2012)

Parameter	Food Crops		Processed Food and Non-food Crops	
	Water Quality	**Monitoring**	**Water Quality**	**Monitoring**
Treatment	Secondary, filtration, disinfection		Secondary, Disinfection	
pH	6.0 - 9.0	weekly	6.0-9.0	weekly
BOD	≤ 10 mg/L	weekly	≤ 30 mg/L	weekly
TSS	--	--	≤ 30 mg/L	daily
Turbidity	≤ 2 NTU	continuous	--	n/a
Fecal coliform	No detectable / 100 mL	daily	≤ 200 / 100 mL	daily
Chlorine residual	≥ 1 mg/L Cl_2	continuous	≥ 1 mg/L Cl_2	continuous

From an operational perspective, TSS in reclaimed water is also important for irrigation operations. TSS concentrations in secondary effluent may be problematic for drip irrigation systems due to clogging, which may require some systems to implement filtration to meet end-user needs.

Some states have guidelines or regulations in addition to Table 3. North Carolina monitors coliphages as a viral indicator. Florida and North Carolina also monitor pathogenic organisms (e.g., *Giardia*, *Cryptosporidium*, *Clostridium*). Several states (i.e., Arizona, New Jersey and North Carolina) monitor nitrogen concentrations.

The guidelines in Table 3 address criteria targeted at managing microbial risk, but not the suitability of reclaimed water specifically for agricultural purposes. Other water quality parameters, such as conductivity, total dissolved solids (TDS), sodium absorption ratio (SAR) and boron, are important for plant health. SAR compares the concentration of sodium to the sum of calcium and magnesium, and this ratio is important to maintaining soil quality and adequate water infiltration. Table 4 summarizes other water quality criteria that affect the suitability of water for irrigation. Care must be taken when applying irrigation water with water quality parameters that fall in the slight to moderate and severe categories. In terms of sodium concentrations, SAR is important for reclaimed water applied via surface irrigation, because it affects the long-term soil stability. On the other hand, sodium concentration (regardless of calcium and magnesium) is used as a guideline for sprinkler irrigation.

Table 4. Recommended nutrient and salinity guidelines for agricultural reuse adapted from USEPA (2012)

Parameter	Units	Degree of Restriction on Use		
		None	Slight to Moderate	Severe
Conductivity	mS/cm	< 0.7	0.7 - 3.0	> 3.0
TDS	mg/L	< 450	450 - 2,000	> 2,000
Sodium				
surface irrigation	SAR	< 3	3 - 9	> 9
sprinkler irrigation	meq/L	< 3	> 3	--
Chloride				
surface irrigation	meq/L	< 4	4 - 10	> 10
sprinkler irrigation	meq/L	< 3	> 3	--
Boron	mg/L	< 0.7	0.7 - 3.0	> 3.0
pH	su	--	6.5 - 8.4	--
Nitrate	mg-N/L	< 5	5 - 30	> 30
Bicarbonate	meq/L	< 1.5	1.5 - 8.5	> 8.5

A benefit of applying reclaimed water for irrigation is the enriched macronutrient concentrations that are important for plant growth, including nitrogen, phosphorous, and potassium. While wastewater effluent can be an important source of nitrogen and phosphorous, many wastewater treatment plants have a treatment objective to remove nitrogen and phosphorous to avoid eutrophication of receiving water bodies. Therefore, reclaimed water from municipal wastewater plants may not be sufficient to meet nutrient needs and fully substitute additional fertilizer needs. Other macro- and micronutrients enriched in reclaimed water include calcium, magnesium, sulfur, boron, copper, iron, chloride, manganese, molybdenum and zinc (USEPA, 2012).

Many trace elements are essential to crop growth but become toxic at high concentrations. USEPA (2012) proposed guideline maximum concentrations for many micronutrients in reclaimed water used for agricultural irrigation, shown in Table 5. These concentrations should be interpreted as guidelines as crop tolerance is heavily dependent on soil conditions and crop selection. For example, the effects of some elements (e.g., aluminum, cobalt, and nickel) are reduced in neutral and alkaline soils compared to acidic soils. Other elements are toxic to sensitive crops at concentrations less than those proposed in Table 5. For example, citrus trees are impacted by lithium concentrations as low as 0.075 mg/L (USEPA, 2012). Therefore, treatment objectives for agricultural irrigation is site-specific and requires cooperation between the municipal wastewater providers and receiving agricultural community.

Table 5. Guidelines for maximum concentrations in reclaimed water used for agricultural irrigation from USEPA (2012).

Parameter	Maximum Concentration (mg/L)
Aluminum	5.0
Arsenic	0.1
Beryllium	0.1
Boron	0.75
Cadmium	0.01
Chromium	0.1
Cobalt	0.05
Copper	0.2
Fluoride	1.0
Iron	5.0
Lead	5.0
Lithium	2.5
Manganese	0.2
Mercury	N/A
Molybdenum	0.01
Nickel	0.2
Nitrate + Nitrite (as N)	N/A
Nitrite (as N)	N/A
Sodium	See Table 4
Sulfate	N/A
Selenium	0.02
Vanadium	0.1
Zinc	2.0

There are conflicting treatment objectives for reclaimed water treatment for agricultural purposes with respect to chlorine residual. To manage biological risks associated with using reclaimed water, Table 3 recommends a minimum chlorine residual of 1 mg/L. Disinfection of reclaimed water has to be balanced with the adverse effects of chlorine residual on crops. Residuals less than 1 mg/L normally does not pose a problem for most applications, although some sensitive crops may need residuals less than 0.05 mg/L. Concentrations above 5 mg/L cause damage in most plants (USEPA, 2012). The impact of chlorine also depends on application method used (sprinkler vs. surface irrigation) as chlorine can accumulate in the tissues of some crops and cause leaf-burning in others (USEPA, 2012). Many applications may require dechlorination prior to irrigation.

Urban Reuse

Urban Irrigation

Irrigation of urban landscapes is another opportunity for reclaimed water. Examples of urban irrigation include parks, athletic fields, landscaped areas and golf courses. In particular, golf course irrigation is a specific application that has been identified as an important niche for water reuse, especially in the arid southwest. For example, a longstanding water reuse program in Scottsdale, Arizona meets the irrigation needs of 23 local golf courses (Nunez, 2015).

For urban irrigation, the USEPA recommends different water quality standards depending on public access. Irrigation in locations with unrestricted access is recommended to have a high degree of treatment (secondary treatment, filtration and disinfection) and no detectable fecal coliform as described in Table 6. For applications with restricted public access (e.g., physical barriers or advisory signs), the treatment standards are lower and tolerate higher BOD, TSS and fecal coliform concentrations.

Table 6. Recommended guidelines for urban reuse by irrigation and impoundments from USEPA (2012)

Parameter	Unrestricted Use		Restricted Use	
	Water Quality	**Monitoring**	**Water Quality**	**Monitoring**
Treatment	Secondary, filtration, disinfection		Secondary, disinfection	
pH	6.0-9.0	weekly	6.0 – 9.0	weekly
BOD	≤ 10 mg/L	weekly	≤ 30 mg/L	weekly
TSS	n/a	n/a	≤ 30 mg/L	
Turbidity	≤ 2 NTU	continuous	–	
Fecal coliform	No detectable / 100 mL	daily	≤ 200 / 100 mL	daily
Chlorine residual	≥ 1 mg/L Cl_2	continuous	≥ 1 mg/L Cl_2	continuous

In addition to these guidelines, some states have regulations for additional parameters. For example, Arizona has additional requirements for reclaimed water if nitrogen concentrations are greater than 10 mg/L as NO_3 to protect groundwater. New Jersey and North Carolina have ammonia and/or nitrate limits. Florida requires periodic sampling for *Giardia* and *Cryptosporidium* depending on production capacity for unrestricted uses (USEPA, 2012).

The water quality guidelines in Table 6 are largely related to human health indicators to manage microbial activity. To meet irrigation needs, other water quality parameters are important for plant health and groundwater protection (Table 4). Salinity and nutrient content are important factors for turf management (USEPA, 2012). Nitrate percolation to groundwater aquifers and salt accumulation in root zone are key concerns. An added complexity with respect to irrigation is the seasonal dependence of nutrient requirements. In dormant seasons, nitrate transport below the root zone can become more prevalent and application rates need to be adjusted to prevent groundwater contamination. Table 7 summarizes how water quality impacts the suitability of applying reclaimed water for urban irrigation. Reclaimed water with low salinity, low SAR and boron content can be readily applied without restriction.

Table 7. Recommended guidelines for urban irrigation from USEPA (2012)

Parameter	Units	Degree of Restriction on Use		
		None	Slight to Moderate	Severe
Conductivity	mS/cm	< 0.7	0.7 - 3.0	> 3.0
TDS	mg/L	< 450	450 - 2,000	> 2,000
SAR	-	< 3	3 - 9	> 9
Sodium	meq/L	< 3	> 3	-
Root Absorption	mg/L	< 70	> 70	-
Foliar Absorption	meq/L	< 2	2 - 10	> 10
Chloride	mg/L	< 70	70-355	> 355
Root Absorption	meq/L	< 3	> 3	
Foliar Absorption	mg/L	< 1	1.0 - 2.0	> 2
Boron	mg/L	< 1.0	1.0 - 2.0	> 2.0
pH	su	-	6.5 - 8.4	-

Impoundments

In addition to golf course irrigation, recreational and storage impoundments are another common example of urban water reuse. In this application, reclaimed water is stored until future use for urban irrigation or to support recreational activities. The treatment objectives and water quality standards are the same as urban irrigation (Table 6). In this case, unrestricted use would apply to recreational impoundments that allow human contact, such as swimming. Restricted use would apply to impoundments that do not permit recreational activities. These impoundments would be used for primarily landscaping or aesthetic purposes.

Nutrients are a key concern for urban impoundments due to eutrophication. Excess nutrients in reclaimed water stored in impoundments can lead to severe algal blooms and deteriorate water quality. Algal blooms can produce taste and odor compounds (e.g., 2-methylisoborneol and geosmin) that are aesthetically unpleasing, and harmful algal blooms can produce toxins which lead to fish kills and pose a risk to human health if exposed. In the case of urban impoundments, monitoring and ultimately restricting nutrient inputs to urban impoundments is important to maintain water quality.

Environmental Reuse

Wetlands

Wetlands provide a range of functions within the greater ecosystem. Compared to wastewater treatment plants, wetlands provide an additional level of treatment through enhanced biological and photochemical treatment before reclaimed water is recycled back to another surface water body (e.g., river, reservoir). Wetlands provide habitat for wildlife and is an important aquatic habitat. Wetlands also play an important role in attenuating run-off during floods and providing storage in the local hydrologic cycle.

Treatment objectives for reclaimed water used in wetlands vary by state and by wetland nature. According to USEPA (2012), three states have regulations specific to reclaimed water and wetlands (Florida, South Dakota and Washington). Federal regulations governing discharges to wetlands depend on whether the wetland is natural or constructed. Natural wetlands are protected under the National Pollutant Discharge Elimination System (NPDES) permit and water quality standards. Reclaimed water entering natural wetlands should be treated to secondary standards or better. Engineered wetlands constructed for the purpose of treating water do not fall under the NPDES programs.

Table 8 summarizes the recommended criteria for using reclaimed water in natural wetlands. For this application, the guidelines state that these are the minimum criteria and that more stringent water quality parameters may be needed depending on site-specific needs of receiving surface water. Similar to irrigation applications, the guidelines recommend a minimum Cl_2 residual to ensure adequate disinfection, but direct discharge of water with a Cl_2 residual to a wetland may impact wetland biological activity. Dechlorination may be necessary.

Table 8. Recommended guidelines for environmental reuse applications by USEPA (2012)

Parameter	Wetlands and Surface Water Recharge	
	Water Quality	Monitoring
Treatment	Secondary, disinfection (minimum)	
BOD	≤ 30 mg/L[1]	weekly
TSS	≤ 30 mg/L[1]	daily
Fecal Coliform	≤ 200 / 100 mL[1]	daily
Chlorine residual	> 1 mg/L Cl_2	continuous
[1]Not to exceed		

Surface Water Recharge

River and stream flow augmentation by reclaimed water can play an important role in maintaining minimum stream flows, promoting native aquatic life and meeting water demands. With respect to surface water augmentation, many of the challenges and treatment objectives faced by water reuse are the same as *de facto* water reuse. Discharging treated wastewater to a surface water body must meet specific NPDES limits, as determined by local regulatory agencies. In the USEPA (2012) guidelines, the recommended discharge quality for surface water augmentation is the same as wetlands (Table 8) with basic criteria similar to other restricted uses.

While the practice *de facto* water reuse precedes engineered water reuse systems, new areas of concern emerge as water reuse becomes a formal component of regional water portfolios. While not formally addressed in most discharge permits, CECs are important for public perception of water reuse projects with surface water augmentation in natural systems. CECs are anthropogenic contaminants such as pharmaceuticals, pesticides, and personal care products that are present at low concentrations (e.g., nanogram per liter) (Benotti et al., 2009). Even at low concentrations, the presence of these compounds can be harmful for aquatic life by disrupting basic biological functions (Arcand-Hoy and Benson, 1998; Campbell et al., 2006)

Groundwater Recharge (Non-Potable)

Groundwater recharge (non-potable) is another beneficial use for reclaimed water. This approach is specific to scenarios where reclaimed water does not contact a potable groundwater source. While historically viewed as a disposal method, groundwater recharge offers three main benefits: water recovery and storage for future use, natural recharge of adjacent surface waters, and seasonal storage for agricultural purposes. No specific guidelines are offered for water quality standards, but USEPA (2012) does recommend treatment techniques based on recharge method. For spreading applications, primary treatment is recommended as a minimum. For injection applications, secondary treatment is the recommended minimum degree of treatment; filtration may be needed operationally to prevent clogging. Otherwise, water quality criteria and monitoring requirements are site-specific depending on local hydrology.

Industrial Reuse

The primary use of reclaimed water for industrial purposes is for cooling tower purposes in primarily the pulp, paper and textile industries. In the past decade, use has broadened to include electronics, food processing and power-generation industries (USEPA, 2012). In addition to cooling water applications, reclaimed water can also be used for industrial process water, boiler feed water, and toilet flushing.

Cooling Towers

Cooling towers use circulating water as a heat sink for a variety of chemical processes, primarily thermoelectric power generation. Cooling towers can either operate as a single-pass unit or with recirculating water. When optimized, cooling towers have evaporative losses of 1.5-1.75% of the circulating water per 10°F of temperature change, and make-up water needs to be added to maintain operation. The use of reclaimed water in cooling water towers represents a significant opportunity, because water withdrawal for thermoelectric applications account for 45% of all water withdrawals in the United States (Maupin et al., 2014).

Water quality of reclaimed water used in cooling towers is important to maintain operations. TDS concentration is important in cooling water due to the accumulation of solids through water evaporation. Although TDS concentration is managed by wasting a portion of the recycled cooling water as blow-down, incoming water quality is important to prevent mineral scaling. Mineral scaling occurs when dissolved solids accumulate in cooling water, precipitate on solid surfaces, and form a mineral layer. The most common scaling occurs due to calcium phosphate, calcium sulfate and silica (USEPA, 2012). Less common minerals of concern include calcium carbonate, calcium fluoride and magnesium silicate. In addition to monitoring make-up water chemistry, scaling inhibitors are commonly used to control scaling.

Controlling biological growth is also an important aspect of using reclaimed water in cooling water applications. While reclaimed water is normally disinfected, nutrients support biological growth within the cooling towers. Biofilm growth disrupts process operation by reducing heat transfer efficiency and clogging process components. Biological activity can also promote infrastructure corrosion. As a result, nutrient concentrations (i.e., nitrogen and phosphorous) in reclaimed water are important to monitor and control.

In the 2012 guidelines, the USEPA recommends water quality standards and monitoring frequency for reclaimed water used in cooling water towers as summarize in Table 9. The guidelines suggest that reclaimed water be treated to at least a secondary treatment level with disinfection if water is to be used in a recirculating configuration. Three of the guidelines (i.e., BOD, fecal coliform and chlorine residual) are important for managing biological growth.

Table 9. Water quality guidelines for cooling water towers by USEPA (2012)

Parameter	Once-through Cooling		Recirculating Cooling Towers	
	Water Quality	Monitoring	Water Quality	Monitoring
Treatment	Secondary		Secondary, Disinfection (Coagulation and filtration may be needed)	
pH	6.0 - 9.0	weekly	--	--
BOD	≤ 30 mg/L	weekly	≤ 30 mg/L	weekly
TSS	≤ 30 mg/L	weekly	≤ 30 mg/L	daily
Fecal coliform	≤ 200 / 100 mL	daily	≤ 200 / 100 mL	daily
Chlorine residual	> 1 mg/L Cl_2	continuous	> 1 mg/L Cl_2	continuous

There are a couple of aspects not captured in the USEPA (2012) guidelines. None of the parameters measured provide a good indicator for inorganic chemical parameters important for mineral scaling. Additionally, state-specific regulations for reclaimed water use in cooling water towers also focus on the formation of aerosols (i.e., mists). Aerosols can be an avenue of exposure to microbial risks via on-site human contact, especially for *Legionella*.

Boiler Make-Up

Reclaimed water can also be used as make-up water for industrial boilers. In contrast to cooling towers, boilers require highly treated water due to the operational temperatures. Boilers are used to generate steam at a range of pressures (0 – 2,000 psig). The American Boiler Manufacturers Association specifies target water qualities depending on the boiler operating pressure, which is summarized in Table 10. In general, high pressure steam generation requires a higher quality source water for inorganic and organic constituents. Primary concerns regarding water quality are mineral scale, corrosion and foaming. Mineral scale formation is similar to cooling water towers. Additional corrosion mechanisms are present in boilers compared to cooling water due to the carbon dioxide formation from source water alkalinity. Finally foaming can form due to both organic material and alkalinity (USEPA, 2012).

Table 10. Water quality guidelines for industrial boilers (American Boiler Manufacturers' Association, 2005).

Drum Operating Pressure (psig)	0-300	301-450	451-600	601-750	751-900	901-1000	1001-1500	1501-2000	OTSG[1]
Steam									
TDS max (mg/L)	0.2 - 1.0	0.2 - 1.0	0.2 - 1.0	0.1 - 0.5	0.1 - 0.5	0.1 - 0.5	0.1	0.1	0.05
Boiler Water									
TDS max (mg/L)	700 - 3500	600 - 3000	500 - 2500	200 - 1000	150 - 750	125 - 625	100	50	0.05
Alkalinity (mg/L as $CaCO_3$)	350	300	250	200	150	100	n/a[2]	n/a	n/a
TSS max (mg/L)	15	10	8	3	2	1	1	n/a	n/a
Conductivity max (µS/cm)	1100 - 5400	900 - 4600	800 - 3800	300 - 1500	200 - 1200	200 - 1000	150	80	0.15 - 0.25
Silica max (mg/L)	150	90	40	30	20	8	2	1	0.02
Feed Water (Condensate and Make-up, after Deaerator)									
Dissolved oxygen (mg/L)	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	n/a
Total iron (mg/L)	0.1	0.05	0.03	0.025	0.02	0.02	0.01	0.01	0.01
Total copper (pmg/L)	0.05	0.25	0.02	0.02	0.015	0.01	0.01	0.01	0.002
Total hardness (mg/L as $CaCO_3$)	0.3	0.3	0.2	0.2	0.1	0.05	ND[3]	ND	ND
pH @ 25 °C	8.3 - 10	8.3 - 10	8.3 - 10	8.3 - 10	8.3 - 10	8.8 - 9.6	8.8 - 9.6	8.8 - 9.6	n/a
Nonvolatile TOC (mg/L)	1	1	0.5	0.5	0.5	0.2	0.2	0.2	ND
Oily matter (mg/L)	1	1	0.5	0.5	0.5	0.2	0.2	0.2	ND

[1] OTSG: Once through steam generation
[2] n/a: not available
[3] ND: non-detect

Due to the high water quality needed for steam production, reclaimed water would have to undergo advanced water treatment, such as reverse osmosis (1 or 2 pass) and ion exchange to reduce TOC at a minimum. While the salinity of reclaimed water may be sufficient for low pressure steam generation (0-600 psig), secondary treated wastewater effluent will not be able to meet the low TOC requirements (< 1 mg/L). High pressure steam generation would require membrane based treatment (i.e., nanofiltration or reverse osmosis) to meet salinity requirements. Deaerators are also common to meet the low dissolved oxygen requirements.

Potable Reuse

The approach for defining potable reuse treatment objectives is different from other reclaimed water uses. For agricultural, industrial and urban applications, emphasis is placed on the water quality of reclaimed water as it leaves the wastewater treatment plant prior to reuse. For example, agricultural purposes have specific nutrient and salinity concentrations. The suitability of reclaimed water is dictated by the water quality leaving the treatment facility as additional treatment is not normally applied prior to irrigation. For industrial applications, emphasis is placed on the quality of water necessary to operate boilers and cooling water towers, and additional advanced water treatment may be applied to produce high quality water from reclaimed wastewater. In the case of potable reuse, Safe Drinking Water Act standards govern the water quality of finished drinking water. There is a gap, however, between the Safe Drinking Water Act and the level of public protection that is deemed necessary for potable reuse applications. For example, CECs are a recognized potential risk in potable reuse projects, drive public acceptance but have no regulatory limits in drinking water. Some states, such as California, have started to fill this gap with regulations that specifically address potable reuse concerns. California Department of Public Health (CDPH) Title 22 Code of Regulations govern water reuse projects and cover IPR applications (California State Water Resources Control Board, 2015). There are, however, no federal or state standards dictating how water is to be treated to protect health in DPR applications. California is in the early stages of developing uniform DPR regulations (California State Water Resources Control Board, 2016). Contrary to other applications, an overarching theme in potable reuse is that standards not only focuses on wastewater water quality and potable water quality, but *how* to safely and reliably produce potable water and minimize risk to human health through process redundancy.

Indirect Potable Reuse

For planned IPR, the treatment objectives depend on both the receiving water body constraints and public perception. In some communities, advanced water treatment objectives may be driven by the need to reduce nutrient loads to a receiving reservoir, as was the case for Lake Lanier in Georgia (USEPA, 2012). On the other hand, public perception of CECs with unknown health effects and pathogens may dictate the need to implement additional treatment techniques (USEPA, 2012).

Based on approaches taken at the state level, USEPA (2012) recommends guidelines for reclaimed water to be used for IPR summarized in Table 11. These guidelines apply to reclaimed water as discharged not finished drinking water quality, which is governed by the Safe Drinking Water Act. Compared to the guidelines for non-potable applications, the IDR guidelines are more stringent. Additional levels of treatment either through natural processes (soil aquifer treatment) or engineered systems are recommended. Microbial guidelines do not permit for any detection of total coliforms. In addition, a TOC threshold is also stipulated at 2 mg/L. The guideline specifies ‘wastewater derived’ TOC, although no guidance is provided to differentiate TOC of wastewater and non-wastewater origin. Another major difference is that reclaimed water for IDR should also meet all drinking water standards, which would encompass organic and inorganic contaminants under the Safe Drinking Water Act.

Table 11. Guidelines for IPR application from USEPA (2012)

Parameter	Groundwater Recharge by Spreading		Groundwater Recharge by Injection		Surface Water Supply Augmentation	
	Water Quality[1]	Monitoring	Water Quality[1]	Monitoring	Water Quality[1]	Monitoring
Treatment	Secondary, Filtration, Disinfection, Soil aquifer treatment		Secondary, Filtration, Disinfection, Advanced water treatment		Secondary, Filtration, Disinfection, Advanced water treatment	
pH	6.5 - 8.5	daily	6.5-8.5	daily	6.5-8.5	daily
Turbidity	≤ 2 NTU	continuous	≤ 2 NTU	continuous	≤ 2 NTU	continuous
TOC[2]	≤ 2 mg/L	weekly	≤ 2 mg/L	weekly	≤ 2 mg/L	weekly
Total Coliform	No detectable / 100 mL	daily	No detectable / 100 mL	daily	No detectable / 100 mL	daily
Chlorine Residual	> 1 mg/L Cl_2	continuous	>1 mg/L Cl_2	continuous	>1 mg/L Cl_2	continuous
Other	Meet drinking water standards after percolation through vadose zone[3]		Meet drinking water standards[3]			
[1] Non-exclusive list [2] "of wastewater origin" [3] Measured quarterly						

The criteria in Table 11 are not exhaustive and several states have adopted more stringent and complex criteria. Florida requires pathogen sampling for *Giardia* and *Cryptosporidium* quarterly, rather than rely on credits from specific treatment technologies (USEPA, 2012). California has also adopted concepts developed through recent research of surrogate and indicator compounds. Indicator compounds are individual chemicals that are representative of a class of compounds with specific physical or chemical characteristics (e.g., caffeine, sucralose, triclosan, etc.). Surrogates are a measurable quantity (e.g., TOC, absorbance, fluorescence) that is correlated with indicator compounds (Dickenson et al., 2009). CDPH Title 22 regulations for IPR include criteria for monitoring indicator compounds approved by the State Water Resources Control Board, but does not list specific indicator compounds. For advanced water treatment processes, Title 22 regulations do specify that indicator compounds need to be representative of different chemical characteristics (e.g., hydroxyl aromatic, deprotonated amine, saturated aliphatic, etc.) (California State Water Resources Control Board, 2015).

Direct Potable Reuse

The USEPA (2012) guidelines do not offer guidelines for DPR as for other water reuse applications. At the time of publishing the 2012 report, no state had developed or implemented criteria from which to draw. As of September 2016, no regulations exist in the United States for DPR. California is in the early stages of developing criteria. An Expert Panel appointed by the State of California submitted a final report to the State Water Resources Control Board in August 2016 (Olivieri et al., 2016), and the State of California released a draft report on the feasibility of developing uniform standards in early September 2016 (California State Water Resources Control Board, 2016).

The Draft Report from the California State Water Resources Control Board recommends that the state move forward with developing uniform criteria for DPR. Of particular interest to this project, the report recognizes the importance for monitoring for DPR. As criteria are developed, the Expert Panel recommends further research along the following monitoring-related themes:

1) Source water control and final water quality monitoring.
2) Monitoring of pathogens in the raw wastewater

To support the efforts of the State of California, the WateReuse Foundation launched the California Direct Potable Reuse Initiative to fund research that would fill knowledge gaps and provide a basis for future regulation and implementation of DPR. As of Summer 2016, this initiative has invested $6 million in 34 DPR research projects (WateReuse Foundation, 2016). Table 12 summarizes WateReuse and Water Research Foundation projects what address different aspects of monitoring for direct potable reuse. At the time of writing, only one research project from the WateReuse Initiative was complete and published.

Table 12. Summary of recent funded research projects regarding monitoring of direct potable reuse processes

Organization	Project Number	Title	Summary	Status
WateReuse Water Research Foundation	13-15 WRF 4508	Assessment of Techniques for Evaluating and Demonstrating Safety of Water from Direct Potable Reuse Treatment Facilities	This is a literature review study to provide practical guidance on monitoring and control tools for DPR	Ongoing
WateReuse	15-04	Characterization and Treatability of TOC from DPR Processes Compared to Surface Water Supplies	This study is a conducting research project that investigates and develops guidelines for the concentration, character and DBP formation of organic carbon exiting a DPR facility and entering a surface water treatment plant or directly into the distribution system.	On-going
WateReuse	14-01	Integrating Management of Sensor Data for a Real Time Decision Making and Response System	The objective of this study is to develop a decision tool that integrates real-time sensor data to detect operational anomalies in DPR processes.	On-going
WateReuse	14-20	Framework for Direct Potable Reuse	This white paper study produced a framework document regarding regulatory considerations, treatment issues and public support regarding DPR. A chapter on monitoring strategies in included.	Complete
WateReuse	14-17	White Paper on the Application of Molecular, Spectroscopic, and Other Novel Methods to Monitor Pathogens for Potable Reuse	This study will assess molecular and spectroscopic methods and limitations for detecting pathogens in DPR applications. The focus will be on genetic based molecular methods (e.g., qPCR, DNA sequencing) but will also cover light scattering, flow cytometry, electrochemical, mechanical and immunological methods.	On-going
WateReuse	13-13	Development of Operation and Maintenance Plan and Training and Certification Framework for Direct Potable Reuse Systems	While not directly monitoring related, one objective of this project is to develop O&M criteria for different advanced water treatment trains.	Ongoing
WateReuse Water Research Foundation	13-03 WRF 4541	Critical Control Point Assessment to Quantify Robustness and Reliability of Multiple Treatment Barriers of a DPR Scheme	This study will evaluate two commonly used DPR process trains to conduct a hazard analysis and identify critical control points for system reliability. This approach includes developing monitoring practices at critical control points	Ongoing

Organization	Project Number	Title	Summary	Status
WateReuse Bureau of Reclamation	11-01	Monitoring for Reliability and Process Control of Potable Reuse Applications	This study will evaluate monitoring the removal of regulated and unregulated micropollutants using direct and surrogate approaches at both the bench and full-scale scales.	Ongoing
WateReuse	14-16	Operational, Monitoring, and Response Data from Unit Processes in Full-Scale Water Treatment, IPR, and DPR	This study includes a case study analysis of unit operations common to DPR to identify process anomalies, failures, and operation responses. Design and operating strategies will be proposed for process upsets.	Ongoing
WateReuse	14-13	From Collection System to Tap: Resiliency of Treatment Processes for Direct Potable Reuse	This study will investigate the effects that upsets have on downstream DPR processes. The study will evaluate the best use of existing monitoring techniques for DPR reliability.	Ongoing
WateReuse	12-07	Standard Methods for Integrity Testing and On-line Monitoring of NF and RO Membranes	This study will identify parameters that can be measured continuously to confirm membrane integrity and develop a standard methodology to be implemented at the bench and pilot-scale for low and high TDS source waters.	Ongoing
WateReuse	13-12	Evaluation for Source Water Control Options and the Impact of Selected Strategies on DPR	This study will identify how upstream wastewater treatment variations impact downstream DPR processes and develop guidelines for source water controls, for which online sensor monitoring is one aspect.	Ongoing
WateReuse Bureau of Reclamation	09-06 (Phase B)	New Techniques for Real-Time Monitoring of Membrane Integrity for Virus Removal: Pulsed-Marker Membrane Integrity Monitoring System	This study developed a methodology for monitoring high pressure NF and RO membranes using pulsed dosing and fluorescent tracers.	Complete
WateReuse	11-06	Real-Time Monitoring Tools to Characterize Microbial Contaminants in Reclaimed Water: State-of-the-Science Assessment	This study investigated real-time and near real-time detection approaches for microbial detection. Findings identified the need for monitoring for a broad range of microbial constituents.	Complete

Organization	Project Number	Title	Summary	Status
WateReuse Bureau of Reclamation	09-06 (Phase A)	New Techniques for Real-Time Monitoring of Membrane Integrity for Virus Removal Using Submicron Particle Characterization Methods	This study evaluated the use of dynamic light scattering to identify compromised RO membranes.	Complete
Water Research Foundation	4536	Blending Requirements for Water from Direct Potable Reuse Treatment Facilities	This study will evaluate impacts of blending water treated with advance water treatment processes with different water qualities including impacts on corrosion	Ongoing

DPR presents an opportunity for monitoring not found in other water reuse applications. Compared to IPR, DPR applications have the added complexity of removing an environmental or engineered buffer. In the absence of a buffer, response times to identify fluctuating raw water quality and loss of process integrity are small compared to IPR. As a result, real-time monitoring of process performance is even more important due to the direct risks to human health.

The added complexity of DPR processes broadens the scope of important parameters to monitor from microbial parameters to ones that impact operational stability as summarized by Stanford et al. (2016). With DPR, changes in raw wastewater or treated wastewater quality can resonate through the entire DPR treatment train and cause operational issues downstream. For example, changes in ammonia or organic matter concentrations can impact downstream disinfectant doses, contact time requirements and disinfection byproduct formation. Another operational concern for DPR processes is the impact of blending water from advanced water treatment processes with surface water either upstream or downstream of conventional drinking water treatment processes. Blending is of particular concern for DPR processes that use reverse osmosis, because the treated water chemistry is unstable compared to surface water as reverse osmosis permeate has practically no buffering capacity, organic matter or chlorine demand. Changes in blending ratios can occur seasonally due to water demand or suddenly due to DPR process upsets. Changes in blending ratios upstream of conventional drinking water treatment plants will affect chemical dosing (i.e., coagulant and disinfectant), filter performance, corrosion control processes and aesthetic qualities (i.e., flavor profile) (Stanford et al., 2016). Reliable operation of DPR processes require a comprehensive monitoring plan to detect changes in raw water quality and can respond to changing treatment operations or sudden process upsets.

Potential Monitoring Strategies

Between the potential water reuse applications, there are several common themes for strategic monitoring. Nutrient monitoring is important for all applications from the perspective of groundwater protection (i.e., irrigation, groundwater recharge), microbial growth mitigation (i.e, impoundments, cooling water, surface water augmentation), and water treatment process control (i.e., DPR). Inorganic water quality of reclaimed water (e.g., salinity, mineral content, hardness) is important for irrigation and industrial reuse applications. Aside from nutrients, microbial stability in general is important for all applications as BOD is a common treatment criteria between applications. Lastly, CECs are primary concern to potable and environmental reuse applications. The following sections outline potential monitoring opportunities in each of these common categories.

Many water quality parameters important for water reuse already have commercially available solutions for real-time monitoring. Examples include pH, conductivity, nutrient analyzers, TOC analyzers, chlorine analyzers, turbidimeters, and TSS sensors (Table 2). The focus of this section will be on unconventional methods or novel implementations of existing technology to meet specific water reuse monitoring needs.

A primary monitoring focus for DPR applications is monitoring the integrity of reverse osmosis membranes. A recent review paper outlines current methodology used to monitor process integrity, such as direct and indirect methods (Pype et al., 2016). Direct methods include vacuum decay tests, bacteriophage MS-2 phage injections, and tracer dyes (e.g., Rhodamine and Trasar3D). Indirect methods include conductivity, TOC, sulfate and optical property measurements. Since this information is well-documented and expected to be further developed through pending research projects (Table 12), this section will focus on other applications besides reverse osmosis membrane integrity.

Nutrients

Nutrient monitoring is common in wastewater treatment plants, but there may be additional niches specific to water reuse. For agricultural purposes, measurement and communication of nutrient content in reclaimed water could be beneficial to optimize fertilizer addition. By quantifying the nutrient content (i.e., ammonia, nitrate, phosphate) of reclaimed water at the time of application, end-users can adjust application rates of applied fertilizers to prevent over-application, which is not only expensive but can lead to groundwater contamination. Trace metal online analyzers based on voltammetry could also be implemented to monitor the metal composition of reclaimed water. It would not be economical for individual land-owners to invest in the instrumentation and data acquisition interfaces. Instead, utilities supplying reclaimed water could provide real-time data to end-users. Transparent communication may also instill end-user confidence and increase regional implementation.

A risk associated with using reclaimed water for irrigation (or applying fertilizer) is the contamination of groundwater with nitrate. Another monitoring opportunity is the implementation of soil nitrate sensors that measure nitrate in the vadose zone. With a network of sensors strategically installed across a region, excessive nitrate infiltration could be identified and mitigated. This approach could be beneficial on a regional scale or for local applications, such as golf course irrigation. These sensors could help identify regions susceptible to groundwater contamination due to the over application of reclaimed water or fertilizer.

Potentially the most impactful area for enhanced nutrient monitoring is looking forward to new systems that tailor the wastewater treatment process to meet specific agricultural requirements. Rather than use secondary treated wastewater for agricultural irrigation, which is relatively depleted in nutrients compared to raw wastewater, wastewater treatment processes could be tailored to meet specific agricultural irrigation needs. A study by Tran et al. (2016) developed a decision-support model for selecting treatment trains and blending ratios from each process to tailor effluent quality to specific irrigation needs. This approach would require enhanced monitoring and process control to produce a target effluent given the diurnal and seasonal fluctuations in raw water quality (Tran et al., 2016). If water scarcity provides the driving force to develop more complex wastewater treatment approaches, advanced monitoring, particularly of nutrients and salinity, will play a central role to its implementation.

Inorganics and Salinity

A new implementation of existing technology would be the specific monitoring of SAR and salinity for irrigation. If reclaimed water exhibits significant fluctuations in SAR and salinity diurnally or seasonally, real-time data available to end-users would allow them to make informed decisions about applying reclaimed water for irrigation. Sodium concentrations can be monitored using ion-selective probes. Hardness can also be analyzed using online analyzers. Coupling both techniques could allow for monitoring SAR with high frequency. Similar to nutrient sensors, the most practical application would be centralized instrumentation and data acquisition that makes data available to all end-users.

Microbial Growth

Monitoring and controlling microbial growth is an area of greatest potential for strategic monitoring. Sensors for targeted nutrients, salinity and specific inorganic are well established in commercial products. Their implementation (or lack thereof) is largely driven by specific needs and economics.

Monitoring for microbial growth is an area where research has developed tools that are in transition to commercial products. Rather than measure specific nutrients (e.g., phosphorous) or specific organisms (e.g., fecal coliform), several tools based on optical properties of NOM have been demonstrated that look for shifts in the bulk NOM chemistry as a surrogate for biological activity. The benefit of monitoring optical properties is that real-time surrogates can be used to screen water quality rapidly, whereas more direct measurement (i.e., BOD and coliforms) require days to conduct.

The chemistry of NOM in water is a function of its source and environmental processing. NOM derived from plant materials (allochthonous) has a chemical signature indicative of lignins and condensed aromatic structures. NOM derived from microbial activity (autochthonous) exhibits a different signature that is rich in aliphatic carbon (e.g., carbohydrates) and amino acids.

These differences in chemistry can be captured using optical measurements. When the composition of NOM shifts to more hydrophilic, smaller molecular weight compounds, this transformation is accompanied by a shift in the optical properties, which can be readily identified with online sensors. Key surrogates to investigate include: E2:E3 ratio (spectral slope), phenol- and indole-like fluorescence, and the fluorescence index. E2:E3 ratio is the ratio of sample absorbance at 254 nm over 365 nm, and this ratio has been associated with molecular weight (Helms et al., 2008). Fluorescence intensity associated with phenolic and indolic function groups is associated with waters with high microbial activity due to protein-like material. Protein-like fluorescence has been correlated with BOD (Hudson et al., 2008). The fluorescence index is the ratio of two fluorescence intensities and is associated with aromaticity, where increases are associated with microbial activity (McKnight et al., 2001).

Increases in microbial activity would alter the NOM chemistry and lead to an optical response for all three surrogate (E2:E3, protein-like fluorescence and fluorescence index). These sensors could be used to identify eutrophication episodes in surface waters or the onset of biofouling in cooling water towers.

A number of commercial products have been introduced that rely on optical properties. Modern Water developed a fluorometer that measures in the protein-like region (BODChek). S::can developed a UV-Vis absorbance sensor (Spectro::lyser) that can measure properties such as absorbance at 254 nm, E2:E3 ratio, and nitrate. Fluorescence sensors targeting chlorophyll and phycobiliprotein fluorescence have also been developed to monitor algal blooms in surface waters (e.g., YSI, Turner).

Optical sensors designed to measure signatures of specific compounds (e.g., chlorophyll) are more widely adapted and implemented in monitoring applications. Techniques that sense changes in bulk NOM optical properties (e.g., E2:E3 and fluorescence index) are less widely accepted as surrogate techniques. Research that demonstrates the utility of these techniques at full-scale applications would provide a basis for further implementation.

Contaminants of Emerging Concern

Monitoring for CECs is an area of interest particularly for potable reuse applications due to the unknown impacts of CECs on human health. Due to the nature and environmental concentrations of CECs, direct measurement using online technology is not feasible with current analytical methods (Table 2). While CDPH Title 22 regulations support the monitoring of select indicator compounds, quantifying indicator compounds is not conducive to rapid feedback in potable treatment operations. Therefore, surrogate approaches have been developed that relate changes in NOM absorbance and fluorescence to changes in indicator compound concentrations in water treatment operations (Anumol et al., 2015; Gerrity et al., 2012; Yu et al., 2015).

A potential area of improvement is through more targeted fluorescence surrogates. Published approaches use an entire fluorescence excitation-emission matrix, which is measured across a wide range of wavelengths, as a surrogate. This approach requires a specialized spectrofluorometer and is not conducive to real-time measurements. Surrogate development that can be implemented with contemporary fluorescence sensor technology would be beneficial to potable reuse application and allow for full-scale testing.

References

American Boiler Manufacturers' Association, 2005. Boiler Water Quality Requirements and Associated Steam Quality for Industrial/commercial and Institutional Boilers. American Boiler Manufacturers Assoc.

Anumol, T., Sgroi, M., Park, M., Roccaro, P., Snyder, S.A., 2015. Predicting trace organic compound breakthrough in granular activated carbon using fluorescence and UV absorbance as surrogates. Water Res. 76, 76–87. doi:10.1016/j.watres.2015.02.019

Arcand-Hoy, L.D., Benson, W.H., 1998. Fish reproduction: An ecologically relevant indicator of endocrine disruption. Environ. Toxicol. Chem. 17, 49–57. doi:10.1002/etc.5620170108

Benotti, M.J., Trenholm, R. a, Vanderford, B.J., Holady, J.C., Stanford, B.D., Snyder, S. a, 2009. Pharmaceuticals and endocrine disrupting compounds in U.S. drinking water. Environ. Sci. Technol. 43, 597–603. doi:10.1021/es801845a

California State Water Resources Control Board, 2016. Investigation on the Feasibility of Developing Uniform Water Recycling Criteria for Direct Potable Reuse (DRAFT). Retrieved from http://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/documents/rw_dpr_criteria/draft_report_to_legislature_dpr_public_review.pdf

California State Water Resources Control Board, 2015. State Water Resources Control Board Regulations Related to Recycled Water . Retrieved from http://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/Lawbook.shtml

Campbell, C.G., Borglin, S.E., Green, F.B., Grayson, A., Wozei, E., Stringfellow, W.T., 2006. Biologically directed environmental monitoring, fate, and transport of estrogenic endocrine disrupting compounds in water: A review. Chemosphere 65, 1265–1280. doi:10.1016/j.chemosphere.2006.08.003

Dickenson, E.R. V, Drewes, J.E., Sedlak, D.L., Wert, E.C., Snyder, S.A., 2009. Applying surrogates and indicators to assess removal efficiency of trace organic chemicals during chemical oxidation of wastewaters. Environ. Sci. Technol. 43, 6242–6247. doi:10.1021/es803696y

Gerrity, D., Gamage, S., Jones, D., Korshin, G. V., Lee, Y., Pisarenko, A., Trenholm, R.A., von Gunten, U., Wert, E.C., Snyder, S.A., 2012. Development of surrogate correlation models to predict trace organic contaminant oxidation and microbial inactivation during ozonation. Water Res. 46, 6257–6272. doi:10.1016/j.watres.2012.08.037

Helms, J.R., Stubbins, A., Ritchie, J.D., Minor, E.C., Kieber, D.J., Mopper, K., 2008. Absorption Spectral Slopes and Slope Ratios as Indicators of Molecular Weight, Source, and Photobleaching of Chromophoric Dissolved Organic Matter. Limnol. Oceanogr. 53, 955–969.

Hudson, N., Baker, A., Ward, D., Reynolds, D.M., Brunsdon, C., Carliell-Marquet, C., Browning, S., 2008. Can fluorescence spectrometry be used as a surrogate for the Biochemical Oxygen Demand (BOD) test in water quality assessment? An example from South West England. Sci. Total Environ. 391, 149–158. doi:10.1016/j.scitotenv.2007.10.054

Maupin, M., Kenny, J., Hutson, S., Lovelace, J., Barber, N., Linsey, K., 2014. Estimated Use of Water in the United States in 2010 Circular 1405, US Geological Survey Circular 1405.

McKnight, D.M., Boyer, E.W., Westerhoff, P.K., Doran, P.T., Kulbe, T., Andersen, D.T., 2001. Spectrofluorometric characterization of dissolved organic matter for indication of precursor organic material and aromaticity. Limnol. Ocean. 46, 38–48.

National Research Council of the National Academies, 2012. Water Reuse: Potential for Expanding the Nation's Water through Reuse of Municipal Wastewater. The National Academies Press, Washington D.C. doi:10.17226/13303

Nunez, A., 2015. The City of Scottsdale's Water Reuse Program, in: Arizona Water Reuse Symposium. Flagstaff, AZ, July 27th, 2015.

Olivieri, A., Crook, J., Anderson, M., Bull, R., Drewes, J., Haas, C., Jakubowski, W., McCarty, P., Nelson, K., Rose, J., Sedlak, D., Wade, T., 2016. Evaluation of the Feasibility of Developing Uniform Water Recycling Criteria for Direct Potable Reuse - Expert Panel Final Report. Retrieved from http://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/documents/rw_dpr_criteria/app_a_ep_rpt.pdf

Pype, M.-L., Lawrence, M.G., Keller, J., Gernjak, W., 2016. Reverse osmosis integrity monitoring in water reuse: The challenge to verify virus removal – A review. Water Res. 98, 384–395. doi:http://dx.doi.org/10.1016/j.watres.2016.04.040

Stanford, B.D., Becker, W.C., Debroux, J.F., Ishii, S.K.L., Khan, S.J., Khunjar, W.O., 2016. Planning for Direct Potable Reuse: Operational Aspects of an Integrated Drinking Water System. J. Am. Water Work. Assoc. 108, 48–55.

Tran, Q.K., Schwabe, K.A., Jassby, D., 2016. Wastewater Reuse for Agriculture: Development of a Regional Water Reuse Decision-Support Model (RWRM) for Cost-Effective Irrigation Sources. Environ. Sci. Technol. 50, 9390–9399. doi:10.1021/acs.est.6b02073

USEPA, 2012. Guidelines for Water Reuse. Report Number EPA16251R-921004

WateReuse Foundation, 2016. California Direct Potable Reuse Initiative Reporting on Significant Progress. Retrieved from https://watereuse.org/wp-content/uploads/2015/01/Direct-Potable-Reuse-Progress-Report-2016-Spring-Summer.pdf.

Yu, H.-W., Anumol, T., Park, M., Pepper, I., Scheideler, J., Snyder, S.A., 2015. On-line sensor monitoring for chemical contaminant attenuation during UV/H2O2 advanced oxidation process. Water Res. 81, 250–260. doi:10.1016/j.watres.2015.05.064