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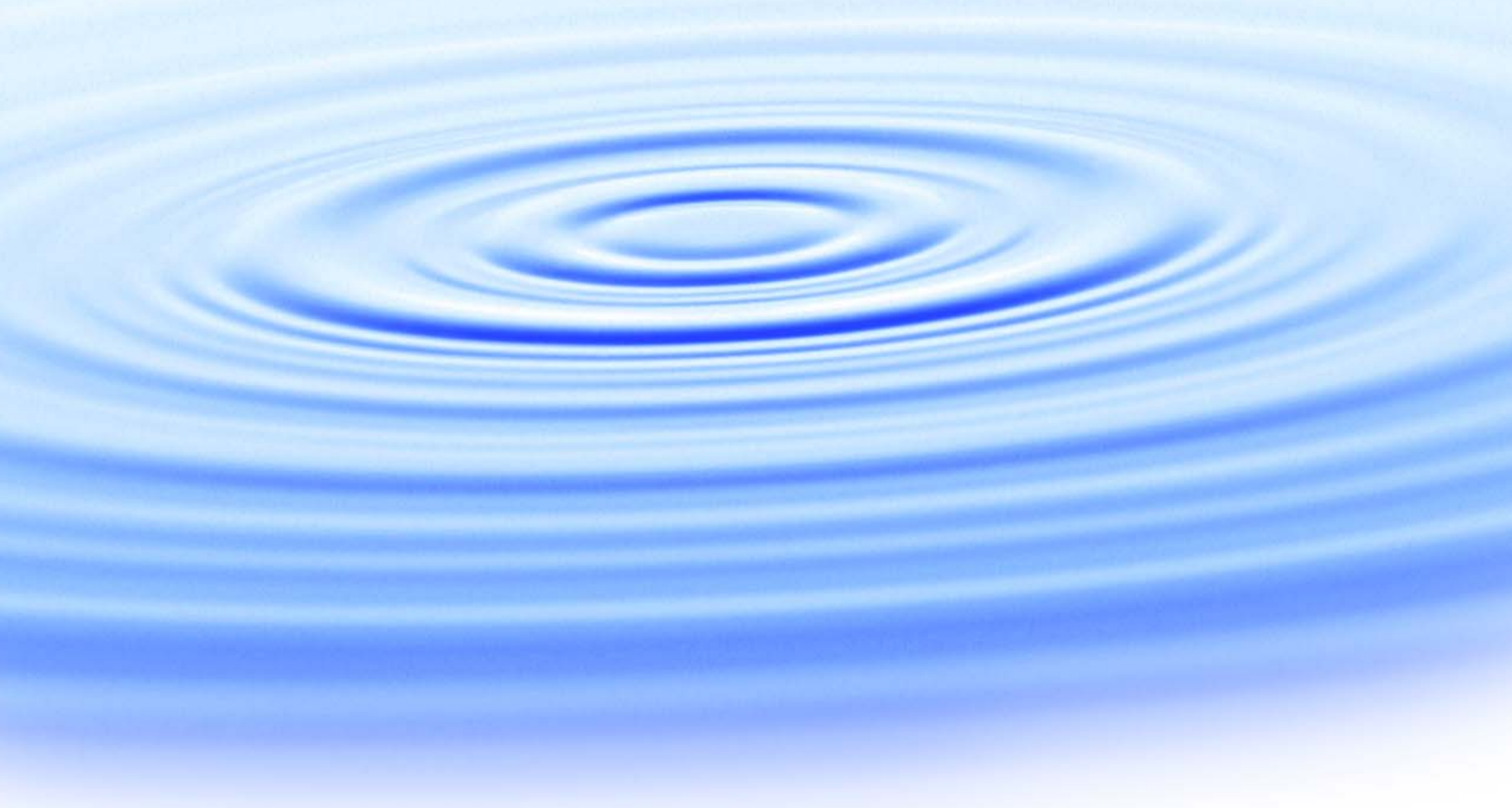
Develop Best Management Practices to Control Potential Health Risks and Aesthetic Issues Associated with Reclaimed Water Storage and Distribution



WateReuse Research Foundation

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About the WateReuse Research Foundation

The mission of the WateReuse Research Foundation is to conduct and promote applied research on the reclamation, recycling, reuse, and desalination of water. The Foundation's research advances the science of water reuse and supports communities across the United States and abroad in their efforts to create new sources of high quality water for various uses through reclamation, recycling, reuse, and desalination while protecting public health and the environment.

The Foundation sponsors research on all aspects of water reuse, including emerging chemical contaminants, microbiological agents, treatment technologies, reduction of energy requirements, concentrate management and desalination, public perception and acceptance, economics, and marketing. The Foundation's research informs the public of the safety of reclaimed water and provides water professionals with the tools and knowledge to meet their commitment of providing a reliable, safe product for its intended use.

The Foundation's funding partners include the supporters of the California Direct Potable Reuse Initiative, Water Services Association of Australia, Pentair Foundation, and Bureau of Reclamation. Funding is also provided by the Foundation's Subscribers, water and wastewater agencies, and other interested organizations.

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This report was sponsored by the WateReuse Research Foundation and cosponsored by Singapore Public Utilities Board (PUB). PUB and the Foundation, its Board Members, and the project cosponsors assume no responsibility for the content of this publication or for the opinions or statements of facts expressed in the report. The mention of trade names of commercial products does not represent or imply the approval or endorsement of the WateReuse Research Foundation, its Board Members, or the cosponsors. This report is published solely for informational purposes.

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WateReuse Research Foundation Project Number: 11-03
WateReuse Research Foundation Product Number: 11-03-1

ISBN: 978-1-941242-25-4

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Acronyms

A2O	anaerobic/anoxic/oxic process
AOC	assimilable organic carbon
AS	activated sludge
AWWA	American Water Works Association
BDDA	booster disinfectant design analysis
BDOC	biodegradable dissolved organic carbon
BG/year	billion gallons per year
BMPs	best management practices
BNR	biological nutrient removal
BOD	biochemical oxygen demand
CAC	Citizen Advisory Council
Cal-OSHA	California Occupational Safety and Health Program
CBOD	carbonaceous biochemical oxygen demand
CCP	critical control point
CDPH	California Department of Public Health
CFD	computational fluid dynamics
CFU	colony forming unit
COC	cycles of concentration
COD	chemical oxygen demand
CPI	consumer price index
CSC	concrete steel cylinder
CSD	Community Services District
CT	contact time
CWA	Clean Water Act
DAF	dissolved air floatation
DCS	distribution control system
DBP	disinfection byproducts
DFB	demand free buffer
DO	dissolved oxygen
DOC	dissolved organic carbon
DOH	Department of Health
DOM	dissolved organic matter
DS	distribution system
DSS	decision support system
EC	electrical conductivity
ECD	Environmental Control District
EEM	excitation-emission matrices

EQ	equalization (tank)
ERP	enterprise resource planning
FEEM	fluorescence excitation-emission matrices
GIS	geographic information system
GOWA	Government of Western Australia
GPD	gallons per day
HACCP	hazard analysis critical control point
HCF	hundred cubic feet (equivalent to 748 gallons)
HDPE	high-density polyethylene
HPC	heterotrophic plate count
IDS	inorganic dissolved salts
kPa	kilo Pascal
LIMS	laboratory information management system
MBR	membrane bioreactor
MG/year	million gallons per year
MGD	million gallons per day
MLE	modified Ludzack-Ettinger process
MPN	most probable number
NCWRP	North City Water Reclamation Plant
NDMA	nitrosodimethylamine
NIMBY	not in my backyard
NOV	notice of violation
NPDES	National Pollution Discharge Elimination System
NSA	nonspecific agglutination
NTU	nephelometric units
ORP	oxidation-reduction potential
PCR	polymerase chain reaction
PE	polyethylene
PER	piping efficiency ratio
PEX	cross-linked polyethylene
PLC	programmable logic control
PP	polypropylene
ppm	parts per million
PRP	Poisson rectangular pulse
psi	pounds per square inch
PU	public utility
PVC	polyvinyl chloride
RAS	return activated sludge
RCP	reinforced concrete pipes
RI	resilience index
RIB	rapid infiltration basin

RO	reverse osmosis
RWCB	Reuse Water Control Board
RWQCB	Regional Water Quality Control Board
SBR	sequencing batch reactor
SBWRP	South Bay Water Reclamation Plant; NCWRP
SCADA	supervisory control and data acquisition
SMCL	secondary maximum contaminant levels
SOP	standard operating procedure/protocol
SUVA	specific ultraviolet absorbance
SVMM	strategic value management model
TAC	template assisted crystallization
TDS	total dissolved solids
TKN	total Kjeldahl nitrogen
TOC	total organic carbon
TrOC	trace organic chemical
TRC	total residual chlorine
TSS	total suspended solids
TTA	tolyltriazole
UIC	underground injection control
U.S. EPA	Unites States Environmental Protection Agency
USIS	ultrasonic irradiation system
UV	ultraviolet light
UVT	ultraviolet light transmittance
VFD	variable flow drive
VOC	volatile organic carbon
WAS	waste activated sludge
WDR	waste discharge requirements
WEF	Water Environment Federation
WWTP	wastewater treatment plant

Foreword

The WateReuse Research Foundation, a nonprofit corporation, sponsors research that advances the science of water reclamation, recycling, reuse, and desalination. The Foundation funds projects that meet the water reuse and desalination research needs of water and wastewater agencies and the public. The goal of the Foundation's research is to ensure that water reuse and desalination projects provide sustainable sources of high-quality water, protect public health, and improve the environment.

An Operating Plan guides the Foundation's research program. Under the plan, a research agenda of high-priority topics is maintained. The agenda is developed in cooperation with the water reuse and desalination communities including water professionals, academics, and Foundation subscribers. The Foundation's research focuses on a broad range of water reuse and desalination research topics including:

- Defining and addressing emerging contaminants, including chemicals and pathogens
- Determining effective and efficient treatment technologies to create "fit for purpose" water
- Understanding public perceptions and increasing acceptance of water reuse
- Enhancing management practices related to direct and indirect potable reuse
- Managing concentrate resulting from desalination and potable reuse operations
- Demonstrating the feasibility and safety of direct potable reuse

The Operating Plan outlines the role of the Foundation's Research Advisory Committee (RAC), Project Advisory Committees (PACs), and Foundation staff. The RAC sets priorities, recommends projects for funding, and provides advice and recommendations on the Foundation's research agenda and other related efforts. PACs are convened for each project to provide technical review and oversight. The Foundation's RAC and PACs consist of experts in their fields and provide the Foundation with an independent review, which ensures the credibility of the Foundation's research results. The Foundation's Project Managers facilitate the efforts of the RAC and PACs and provide overall management of projects.

This study was conducted to leverage existing operator (or institutional) knowledge and management practices for maintaining reclaimed water quality in storage and distribution systems. Literature about managing health and aesthetic issues associated with reclaimed water storage and distribution coupled with a survey, extended interviews, visits, and an expert workshop were conducted to develop best management practices.

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Acknowledgments

The authors are very grateful to the Project Advisory Committee (PAC), namely

- Fred Bloetscher (Florida Atlantic University)
- Earle Hartling (LACSD)
- Joseph Jacangelo (MWH)
- Harry Seah (Singapore PUB)
- Craig Riley (Washington State Health Department)
- Tom Weiland (LACSD)

Additional advice and guidance was provided by the Technical Advisory Group (TAG) comprised by

- Nick Ashbolt (University of Alberta)
- Rick Cisterna (Natural Systems Utilities)
- Jim Crook (Water reuse consultant)
- Valentina Lazarova (Suez Environment)
- Bahman Sheikh (Water reuse consultant)
- George Tchobanoglous (UC-Davis)

We also appreciate the WateReuse Research Foundation project manager, Stefani McGregor. This research was made possible by funding from the WateReuse Research Foundation, with additional funding from utility subsidiaries of American Water, Voorhees, NJ. TOC and AOC analyses were conducted by Lauren Weinrich and Marina Kreminskaya.

The study would not have been possible without participation of 71 reclaimed water utilities in the United States and Australia. To these we are truly grateful, as participation from the onset (online questionnaire) highlighted the major management issues. Special thanks are expressed to the utilities that participated in subsequent in-depth analysis culminating in the formulated best management practices (BMP) presented in the document.

Executive Summary

Reclaimed water is a perishable product with a shelf life requiring packaging and preserving during storage to minimize deterioration in quality. Such deterioration includes algal growth, odors, color, turbidity, and pathogen regrowth, creating health-related and aesthetic issues that ultimately impact acceptance of reclaimed water by the end user. Adopting effective management practices can improve water quality during storage and distribution. This study was conducted to leverage existing operator (or institutional) knowledge and management practices for maintaining reclaimed water quality in storage and distribution systems.

A brief online survey of 71 utilities, followed by more detailed phone interviews of 25 utilities, was conducted to identify issues associated with reclaimed water storage and distribution. One hundred fifty-five issues were raised, as 72% of the utilities raised multiple issues. A majority (80%) of the raised issues could be grouped into five categories: infrastructure, water quality, customer, operational, and cost/pricing of reclaimed water. Details from interviews in conjunction with information from literature were used to develop 14 best management practices (BMPs) and were fine-tuned by a panel of experts during a 2-day workshop:

1. Optimizing reclaimed water storage
2. Minimizing the impact of reclaimed water corrosivity
3. Improving customer perception
4. Managing reclaimed water total dissolved solids (TDS)
5. Controlling algae in reclaimed water reservoirs and distribution systems
6. Managing snails and other macroorganisms in reclaimed water
7. Minimizing regrowth, odor, and biofilms in reclaimed water systems
8. Monitoring of cross-connection control
9. Managing reclaimed water age to enhance quality and operational bottlenecks
10. Ensuring pressure sustaining reclaimed water systems
11. Staying within reclaimed water turbidity targets
12. Managing operations of reclaimed water supply and demand challenges
13. Monitoring the distribution system
14. Managing concerns about emerging contaminants in reclaimed water

Ten of the 25 sites were visited to examine the management practices vis-à-vis the water quality in the distribution system. Based on the intended use, a set of water quality targets was proposed in relation to the expected uses of the reclaimed water. Most challenging was maintaining dissolved oxygen in the distribution system. Dissolved oxygen guidelines were exceeded 30% of the time, whereas turbidity and *Legionella* density limits were exceeded 26% of the time.

Chapter 1

Current Reclaimed Water Storage and Distribution Challenges

In most urbanized settings wastewater generation and treatment are continuous processes; however, beneficial reclamation for processes, such as landscape irrigation, golf course irrigation, aquifer recharge, surface water, and augmentation, may be practiced only during high demand seasons. Alternatively, treatment may occur at one location but the reclaimed water may be used at several geographically distinct locations. To handle the variable demands at dispersed locations, it is often necessary for centralized treatment facilities to utilize seasonal or long-term storage in open or closed reservoirs. Whereas reclaimed water reservoirs tend to be smaller than freshwater reservoirs, they receive treated (i.e., secondary clarification, tertiary sand filtration, membrane bioreactors) effluents, which can contain up to ten-fold higher nutrient levels than potable water reservoirs. Open reclaimed water reservoirs may also receive additional nutrients from storm water runoff.

Management of water quality begins with design of the storage and distribution system. Although oversizing systems may be financially beneficial to accommodate future expansion, this has to be carefully balanced with water quality implications that occur from reduced turnover and increased water age in an oversized system. Storage, especially in deep reservoirs, can cause water quality problems, such as algal growth, odors, color, turbidity, and pathogen regrowth. Other problems associated with stratification (temperature, pH, and nutrients) and decay of dead algae in the deeper areas (hypolinmion) of the reservoir can include oxygen depletion, formation of hydrogen sulfide, and dissolution of iron, manganese, and phosphorous from sediments in the reservoirs (Miller et al., 2009; Rimer and Miller, 2012). Further deterioration of the reclaimed water can occur during its distribution, especially where large pipe lengths, poor hydraulics, and multiple dead ends exist.

It may be useful to think of reclaimed water as a perishable product analogous to food products with a shelf life, packaging, and preservatives. The deterioration of reclaimed water is analogous to one preparing a good meal and leaving it on the kitchen counter for a long time before its consumption. The shelf life refers to minimization of water detention time in storage or a distribution system. Prolonged detention time will reduce water quality. After production, reclaimed water is often kept in some form of storage system prior to use. There is usually a 12 h offset between peak reclaimed water production and peak reclaimed water demand. Water reclamation is highest during the daytime hours when people are active and producing wastewater. Unfortunately, it is also the time when reclaimed water irrigation systems are generally inactive to allow for uninterrupted use of public greenbelts. Irrigation demand is much higher at night when the public is not using parks, school yards, golf courses, and other municipal areas but are also not producing wastewater, resulting in a pronounced drop in reclaimed water production. The packaging would be the nature and types of storage tanks and pipes, and the preservatives would be the disinfectants and anticorrosion agents. Chlorine as a disinfectant (i.e., preservative) can dissipate with time on the basis of water demand and distance of water flow. By comparison, the loss of chlorine residual typically is not viewed by consumers as a problem for they do not want to smell chlorine in potable water.

Water quality issues can be categorized as aesthetic (e.g., yellow, red, or rusty water; odor), microbiological (e.g., algae, biofilms, bacterial regrowth, viruses, parasites), or chemical/physical (e.g., dissolved oxygen, pH, nutrients, disinfection residuals, odors, trihalomethanes, volatile organic carbons, pH, metals, scales, and sediments, etc.).
All three types of the water quality issues described may occur in the same system. For example, sediments and metals (i.e., iron, manganese) can discolor the water (aesthetic problem), reduce disinfectant residuals (a physicochemical problem), and harbor microorganisms that can then amplify to cause turbidity, odor, or health-related issues. In any case, reclaimed water storage and distribution systems are not inert networks but are biological and chemical reactors with complex interactions. Clearly reservoir size (i.e., detention time) and type (i.e., open versus closed) are critical factors; however, a variety of other factors (i.e., total dissolved solids, assimilable organic carbon (AOC) biodegradable dissolved organic carbon (BDOC), turbidity, temperature, residual disinfectant, residence time, nitrogen, phosphate, density of heterotrophic bacteria (HPC), and other bacteria, odor, color, flow, etc.) are inextricably linked in impacting the reclaimed water quality during storage and distribution.

1.1 The Need for Best Management Practices (BMPs)

Complex physical, chemical, and biological interactions during storage and distribution can create health-related and aesthetic issues that ultimately impact acceptance of reclaimed water by the end user. Adopting effective management practices can improve water quality during storage and distribution. This study was conducted to leverage existing operator (or institutional) knowledge and management practices for maintaining reclaimed water quality in storage and distribution systems. The project tackled this through six specific tasks summarized in Figure 1.1.

TASK 1: Conduct a literature review of reclaimed water storage and distribution system facility guidelines, regulations, and case studies using peer-reviewed and gray literature.

TASK 2: Document facility characteristics and practices as to collate treatment, storage, distribution, and water quality information of geographically dispersed reclaimed water systems. This task also documents the issues and practices associated with management of reclaimed water distribution and storage facilities.

TASK 3: Conduct site visits to evaluate storage and distribution system design and management practices

TASK 4: Use the literature review, questionnaires, and case studies to develop solution-oriented BMPs.

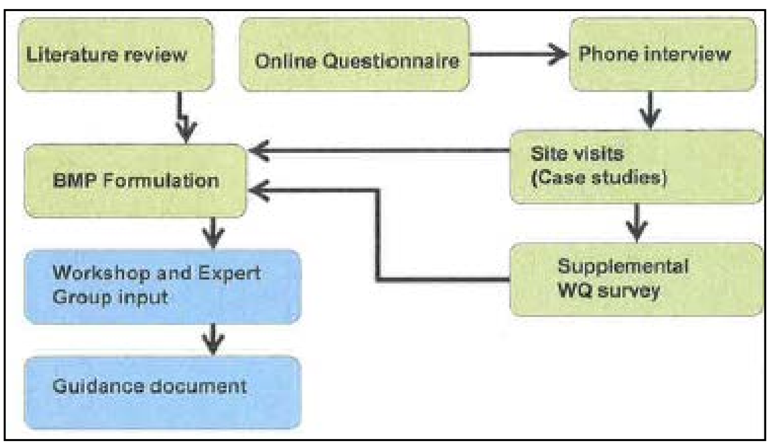

Figure 1.1. Summary of project tasks.

TASK 5: Streamline the developed BMPs through a workshop and/or interview of industry leaders.

TASK 6: Develop a report and user-friendly guidance manual for the reclaimed water industry for distribution and storage BMPs.

The literature review, results from the online questionnaire, phone interviews, site visits, and supplemental water quality data were cross-referenced in the formulated BMPs where applicable.

Chapter 2

Methodology for Studying the Problems Associated with Reclaimed Water Storage and Distribution

2.1 Preliminary Survey

The problems associated with reclaimed water storage and distribution were identified at two levels: a brief online survey and a more detailed phone interview of a subset of respondents to the online survey. The brief survey (http://www.zoomerang.com/Survey/WEB22F35BUE9K4/) presented in Appendix A was developed by the project team in close consultation with the Project Advisory Committee (PAC) and Technical Advisory Group (TAG). It was deliberately designed to be simple and quick (<2 min), limited to10 questions. This “snapshot” approach was considered ideal to maximize responses yet provide adequate information on a range of quality, operational, and management practices. The survey was emailed to 341 contacts identified from the WateReuse Research Foundation database and a few other supplemental sources, such as WateReuse conference contact lists for the past 4 years. If nonresponsive, the prospective participants were reminded up to four times and encouraged to respond. The online survey was conducted between April 2, 2012, and May 16, 2012.

On the basis of production capacity, the utilities were classified into small, midsize, large, very large, and extremely large to enable subsequently more detailed studies. Information about the production capacity, treatment technology, type of disinfectant, type of storage (open or closed; underground or aboveground), additional treatment before distribution, distribution system size (short, medium, or long), type of distribution system (branched or looped), and multiple pressure zones (present or absent) was used to develop unique algorithms (see example in Table 2.1). The algorithms were submitted to an unweighted pair group method with arithmetic (UPGMA) mean program (http://genomes.urv.cat/UPGMA), which is widely used for cluster analysis to develop a dendogram and evaluate the relatedness of the utilities in terms of treatment technologies and distribution systems. Within those clusters, a scoring system was developed to select at least one of the two utilities with similar characteristics by looking at the category (type) of issues and problems raised by the utility. The utility with the higher cumulative score was selected (unless otherwise noted) to advance to the next phase of the study (i.e., phone interviews). A total of 31 utilities were selected as phone interview candidates with the goal of interviewing 24 utility participants over the phone. One selection criterion was to automatically include any utilities for which there was no other response from the state.

The survey also provided management practice issues and problems associated with reclaimed water storage and distribution. The frequency of occurrence of a problem was used to prioritize a literature of the core problems associated with reclaimed water storage and distribution. Both the survey and literature review were then used to develop BMPs for addressing the issues.

Table 2.1. Sample Unique Algorithm Development for Each Utility System

Utility	Utility Size Category					Treatment System				
	Small	Midsize	Large	Very Large	Extremely Large	AS	Lagoon	MBR	RBC	SBR
Utility A	0	0	1	0	0	1	0	0	0	0
Utility B	0	0	0	1	0	1	0	0	0	0
Utility C	0	0	1	0	0	1	0	0	0	1
Utility D	0	1	0	0	0	0	0	0	0	1

Notes: 1 = yes; 0 = no; AS = activated sludge; MBR = membrane bioreactor; RBC = rotating biological contactor; SBR = sequential bioreactor.

2.2 Review of the Challenges in Maintaining Reclaimed Water Quality During Storage and Distribution

To explore intricacies of issues raised through the survey, information about each issue was reviewed in the literature. Information sources were initially identified using a set of keywords (i.e., reclaimed water, reclaimed water storage, reclaimed water distribution, and reclaimed water management) with 28 search engines (Table 2.2). The outputs for each search engine were organized in descending order and results for the top five search engines (shown in bold text in Table 2.2) selected. The relevance of the outputs for each search term was calculated after reviewing abstracts for the first 100 results from each search. The relevancy assessment suggested approximately 20% and 10% for Scirus and Google Scholar, respectively, were potentially of value for the project goals. With these low relevancies, the original keywords used in the search engines were refined further by using exact-phrase searches (i.e., keywords in quotation marks) with the original search terms initially used. This modification improved the relevancy of the recovered citations (Table 2.2).

Table 2.2. List of Search Engines Screened for the BMP Literature Review

Scirus (22%, 62%, 49%)	Ocean Technology, Policy, and Nonliving Resources
Google Scholar (11%, 42%, 29%)	Conference Papers Index
Science Direct (18%, 38%, 31%)	Risk Abstracts
BIOSIS Previews	National Service Center for Environmental Publications (NSCEP)
Wiley Online Library (15%, 0%, 24%)	General Science Abstracts
CAB Abstracts (9%, 1%, 32%)	Aquatic Pollution and Environmental Quality (ASFA 3)
The National Technical Information Service	Water Environment Federation (WEF)
PubMed Central	Industrial and Applied Microbiology Abstracts
Web of Science	Aquaculture Abstracts (ASFA)
Environmental Sciences and Pollution Management	Health and Safety Science Abstracts
Biological and Agricultural Index Plus	Biotechnology Research Abstracts
Water Resources Abstracts	Oceanic Abstracts
Ebsco Host	Marine Biotechnology Abstracts
Aquatic Sciences and Fisheries Abstracts	American Water Works Association (The Water Library)

Notes: For the search engines shown in bold, searches were refined in three rounds (% hits shown in brackets), whereby round 1 = the search phrase without quotation marks (e.g., reclaimed water storage), round 2 = with quotation marks (e.g., “reclaimed water storage”), and round 3 = with split quotation marks (e.g., “reclaimed water” “storage”).

The search results were improved further by splitting each search-phrase into two exact-phrases (i.e. “reclaimed water” “storage” instead of “reclaimed water storage”), reducing the hits to approximately 10,000 for both Scirus and Google Scholar. The search engine databases were also reviewed on other aspects of their functionality, such as how results are displayed and ranked, search refinement tools, user options to sort results using various parameters, and the variety and sources of publications available in the search engine database. On the basis of these analyses Scirus was selected as the most robust search engine for sourcing the literature as it retrieves citations from major literature databases such as ScienceDirect, Wiley Online Library, and

PubMed and also provides extensive options to sort and refine results on the basis of type of reference, source of publication, and topic category. In addition to these citations, reports and industry position papers were obtained from agencies, such as the WateReuse Research Foundation, Water Research Foundation, Water Environment Research Foundation, and the World Health Organization. Additional literature was obtained from some references cited by these formally compiled sources.

2.3 Detailed Interviews and Site Visit Selection

The phone interviews, conducted between July 1, 2012, and December 14, 2012, were designed to last about an hour (http://www.zoomerang.com/Survey/WEB22FZ4ENPUAU; Appendix B) and were used to obtain a more complete picture of the system and its practices. Based on the results from the phone interviews, responses about distribution system and storage problems (question 10), water quality issues (question 11), operational issues (questions 16–23), management issues (question 24), and future plans (questions 26 and 27) were quantitatively evaluated. Specifically, significant responses or cues from these responses were highlighted to develop a quantitative score. These scores were used to prioritize and identify utilities most likely to provide significant information from onsite visits and sampling.

2.4 Case Studies and Critical Control Point Analysis

The site visits also provided an opportunity to review each facility comprehensively and verify previously provided information. Verified information included wastewater source, system size, treatment type, nature of disinfection, storage type and storage size, distribution type, and reuse application, as well as storage, operational, hydraulic, monitoring and reporting information, material associated with utility management, quality assurance and documentation (i.e., BMPs, SOPs) data. During site visits to 10 facilities, samples were collected from the effluent, reservoir, and three points in the distribution system. The water was tested onsite for free chlorine using a Hach Test kit (Cat# 2231-01). Water temperature (^{o}C), pH, conductivity, and dissolved oxygen were also determined using the Hach HQ40d Dual-Input Multi-parameter meter. Water samples were shipped overnight on ice to the laboratory to determine TOC, AOC, turbidity, chlorophyll a, sulfide, and *Legionella* spp. Turbidity was determined using a nephelometer (Hach 2100N) turbidimeter as specified by the manufacturer.

2.4.1 TOC Determination

TOC was measured as nonpurgeable organic carbon according to Standard Method 5310B (high temperature platinum-catalyst) by using a Shimadzu TOC-5000 (Columbia, MD) with ASI-5000A autosampler. Samples were collected in glassware described prepared as described by Weinrich et al. (2010) and were transferred upon receipt into 10 mL of TOC vials in duplicate and acidified (pH≤2). Samples prepared in this manner could be stored at 4 °C up to 28 days, although generally they were analyzed immediately. Laboratory-fortified blanks were analyzed once per analytical run as verification standards. Acceptance criteria were ±25% of the true value. Sample analysis was performed in triplicate and reported as mg/L.

2.4.2 AOC Determination

AOC was determined by luminescence using *P. fluorescens* P17 and *Spirillum* strain NOX mutagenized with *luxCDABE* operon fusion and inducible transposons (Haddix et al., 2004; Weinrich et al., 2010). The luminescence was determined at specific intervals, and the maximum growth and growth rate of these bioluminescent strains were also monitored over time using a sensitive, photon-counting luminometer with a programmable 96-well microtiter plate format. Luminescence was converted to acetate carbon equivalents using the Monod model (from standard curve).

2.4.3 Sulfide Determination

The sulfide concentration of the water sample was measured by the methylene blue method (Hach method 8131). Twenty-five milliliters of sample was poured into the 25-mL Hach sample cell; then 1.0 mL of sulfide 1 reagent and 1.0 ml of sulfide 2 reagent were added and thoroughly mixed. Hydrogen sulfide and acid-soluble metal sulfides reacted with *N*,*N*-dimethyl-*p*-phenylenediamine sulfate to form methylene blue. The intensity of the blue was proportional to the sulfide concentration. After a 5 min reaction period, the absorption at 665 nm wavelength was used to determine the sulfide concentration.

2.4.4 Chlorophyll *a* Determination

A 500 mL volume of reclaimed water was filtered (0.45 µm pore size) (Whatman) using one or more filters. The filter(s) for each sample was inserted into a glass tissue grinder (Kontes, Vineland, NJ) and then dissolved in a mixture of acetone with $MgCO_3$ (Eaton et al., 2005). The $MgCO_3$ mixture was made by initially adding 1 g of $MgCO_3$ to 100 mL of distilled water and then combining 90 parts of acetone with 10 parts of saturated $MgCO_3$ solution. The dissolved mixture was stored (4 ^{o}C) in the dark for at least 4 h and then centrifuged (500 × g for 20 min) to remove the debris. The supernatant was used to determine the absorbance at 664 nm. Because pheophorbide *a* and pheophytin *a*, two common chlorophyll *a* degradation products, can interfere with the determination of chlorophyll *a* as they absorb light and fluorescence in the same region as chlorophyll *a*, determinations can be optimized by acidification. Such acidification leads to loss of the magnesium atom in chlorophyll *a*, generating pheophytin *a*. The OD_{664} of the acidified mixture was then determined by taking 3 mL of the mixture, determining the OD_{664} and then adding 0.1 mL of 0.1 N HCl and finally reading the OD_{664} within 90 s. The volume assayed and the length of time after acidification and before the reading was taken were highly critical in this process. To standardize the OD_{664} readings, chlorophyll stocks of 0, 0.125, 0.25, 0.5, and 1 mg/10mL were made and their OD_{664} determined. That determination generated a correlation coefficient (R^2) of 0.91.

2.4.5 *Legionella* sp. Determination

Legionella spp. were detected using Standard Method 9260 with a stock of *Legionella pneumophila* (Philadelphia-1 strain, ATCC 33152) as the positive control. Water sample aliquots of 100 mL were filtered through a 0.45 µm pore size filter to concentrate *Legionella* sp. The filters were submerged aseptically in 10 mL of sterile phosphate-buffered solution. This solution was vortexed for 30 s to dislodge the concentrated bacteria. A 1 mL aliquot of the suspension was mixed with an equal amount of acid (HCl-KCl, pH = 2.2) to reduce the numbers of competing bacterial flora and yeasts. After a 15 min incubation, the suspension was neutralized with KOH-KCl. Aliquots of 0.1 mL (and subsequent tenfold dilutions) were then spread-plated on BCYE agar supplemented with L-cysteine and incubated at 36.5 °C under 2.5% CO_2 with 91% relative humidity. Growth on the plates was monitored for up to 10 days. Verification of *Legionella* was achieved by immunological testing using latex agglutination tests (M45 Microgen *Legionella* test kits, Hardy Diagnostics) to differentiate *L. pneumophila* serotype 1 from *L. pneumophila* serotypes 2–15.

2.5 Critical Control Point

Critical control point (CCP) analysis was used to outline ways for the respective utility to eliminate or reduce the risk or hazards associated with reclaimed water on the basis of their intended use. The concept of hazard analyses critical control point (HACCP) loosely examined how best each case study could implement best management practices to improve water quality in the reservoir and distribution system. Its purpose is to detect and, therefore, allow an opportunity to correct deviations in quality processes at the earliest possible opportunity. Note that under application of the HACCP concept to water, hazard has focused on the health impact of microorganisms to public health. Under the present context, hazard is broadly defined to include loss or damage of equipment (e.g., corrosion of pipes by reclaimed water) and the broad effects on quality (e.g., reduced appeal of the water as a result of algal growth or development of odor). Control point criteria and corrective action is assessed through seven consecutive steps. Under the present context, the first five of the seven steps were used. The steps were as follows:

1. Conduct a hazard analysis by evaluating/confirming treatment process and intended uses.
2. Establish determinants for CCPs (location in the distribution system under which water quality deterioration is likely to be reduced/controlled, e.g., pressure zones, storage type/duration).
3. Establish critical limits (to differentiate acceptable from unacceptable limits) based on target water quality parameters.
4. Establish a system for monitoring CCPs.
5. Establish corrective actions when limits in item 3 are not under control.
6. CCP analysis also typically includes procedures to verify and validate effectiveness of control process for meeting intended reuse(s) and documentation for all procedures and records appropriate to these principles and their application (i.e., obtain available BMPs and SOPs).

However, these last two steps are geared to implementation of a CCP program and were not explored further.

For process monitoring a “critical limit” is defined based on specific criteria (e.g., scientific data, expert knowledge, regulation, industry reference, or historical performance). Thus, for step 3 as stated, critical limits were based on peer-reviewed and gray literature sources combined with prior knowledge about historical performance. To set realistic goals, setting the proposed quality targets considered the expected level of human contact with the water, which, in turn, depended on the intended use of the reclaimed water. Defining and implementing CCPs provided control and consistency in reclaimed quality, improved responsiveness to deviations in process performance, and provided a framework for enhancing public health protection. For each monitored parameter, a corrective action was also developed to ensure the CCP could be quickly corrected to “normal operation” to meet the intended use of the reclaimed water. The risk from biological contaminants has to be interpreted in the context of immunity and treatment intervention. This is as opposed to chemical contaminants where clear dose and effect impacts can be easily demonstrated. Thus, for *Legionella* sp., a single dose value may only be used as a guide with the goal of reducing the potential risk as opposed to focusing on a preset concentration of the organisms.

2.6 BMP Prioritization and Development

The problems raised by the utilities either from their own experiences or from the customers' perspective (Section 3.1 to 3.3) provided valuable information regarding management practices already available to the industry. These and their associated remedial strategies were used to formulate BMP topics. The information obtained from the extensive literature review conducted in parallel to the online survey, phone interviews, and cases studies was also tapped to supplement the indigenous solutions suggested by the utilities. Using this set of guidelines, 15 BMP topics were developed as problem-based and solution-oriented BMPs. The BMPs were fine-tuned by an expert panel during a 2-day workshop. Each BMP write-up included a brief description of the problem, its causes and repercussions, and the range of hierarchal options a utility can take to solve the problem. These were further developed into a guidance document.

Chapter 3

Management Practices from Reviewed Literature Sources

Although the concept of best management practices (BMPs) is not new, it successful adaption greatly benefits from taking advantage of what is already practiced and forging ways to make improvement for specific situations. Examining the literature is a convenient way of establishing what is working to address those challenging situations. The interest areas to focus the review process were identified through an initial industry-wide survey (presented in Chapter 4, Table 4.2), which revealed infrastructure issues followed by water quality, customer, operations, cost, capacity or supply, regulations, and workforce as areas of focus. These categories were used as the basis for informing the process of extensively surveying the literature to document management practices used to address various issues.

3.1 Infrastructure

Infrastructural issues are of paramount concern to reclaimed water utilities nationwide (Asano et al., 1996; Asano et al., 2007; Selvakumar and Tafuri, 2012). The generic infrastructural issues identified by utilities are summarized in Table 4.2. They range from system designs that are unable to handle water pressure variations, poor conveyance, deterioration because of corrosion from high disinfectant residuals, metals or salts, metering, and, most important, provision of adequate storage of the reclaimed water. Reclaimed water infrastructure displays a high level of engineering systems. These attributes are discussed in the following.

3.1.1 Storage

Storage issues also encompass the lack of redundancy in the system and challenges of conveying water to the site. There is usually a 12 h offset between peak reclaimed water production and peak reclaimed water demand. Water reclamation is lowest during the daytime hours when people are active and producing wastewater but also during the time when irrigation systems are generally inactive to allow for uninterrupted use of public greenbelts. Irrigation demand is much higher at night when the public is not using parks, school yards, golf courses, and other municipal areas but coincides with the time when the plants are not producing wastewater. To offset the discrepancy between wastewater generation and reclaimed water demand, reclaimed water is often kept in some form of storage system prior to use. These extremes dictate the need for a reservoir that may be open or enclosed. It is also likely that under these extremes, reservoir space may never be enough to meet the ever-changing needs. Reservoirs may be aboveground (elevated tank) or belowground (pond). Because of the volumes of reclaimed water and the variation in demand, the latter form of storage is more commonly used. Management and maintenance of reclaimed water tanks may not be too different from the management of potable water tanks. Standard requirements include regular inspection of the foundation, as well as the outside and inside of the tank, and periodic draining and removal of debris.

Reservoirs can have a critical influence on reclaimed water quality (Jjemba et al., 2010). Enclosed reservoirs have minimal influence from direct sunlight, which minimizes algal growth. By contrast, open reservoirs are exposed to direct sunlight, which favors proliferation of algae and various water weeds, such as duckweed (*Lemma* sp.). Presence of such vegetation may necessitate operational practices, such as chemical spraying draining (Rimer and Miller, 2012). Fornarelli and Antenucci (2011) reported excellent results from the transferring of water from one reservoir to another to control vegetation. This practice dictates two operational decision variables, the magnitude and timing of water transfers, which should be considered for integrated management of the reservoir system. The timing of the transfer is important in controlling phytoplankton biovolume. By specifically avoiding pumping during algal bloom periods in the source reservoir, the diatom and cyanobacteria biovolume was reduced by one half in the receiving reservoir. No cyanobacteria growth was documented when transfers occurred during summer.

3.1.2 Corrosion and Deterioration of Structures

Infrastructure assets can undergo continuous oxidation and reduction through both chemical and microbiological processes, leading to corrosion. Corrosion involves the dissolution of a structure from anodic sites with the subsequent acceptance of electrons at cathodic sites. It occurs both in oxic and anoxic environments. During corrosion, the consumption of electrons varies, depending on the redox potential of the surface. In oxic environments, oxygen serves as the electron acceptor, forming a variety of oxides and hydroxides (Jjemba, 2004). At a low redox potential, protons become the electron acceptors yielding H_2 and other reduced products (Mahanna et al., 2009; Yu et al., 2011). The hydrogen ions penetrate most metals and cause structures to become brittle, leading to damage owing to blistering or cracking. Corrosion is accelerated by the removal of the end products, a scenario likely to prevail in reclaimed water storage and distribution systems. Thus, in the presence of bacterial biofilms on the infrastructural surfaces, the uptake of oxygen is enhanced, creating localized zones of differential aeration. This, in turn, produces cathodic areas where electrons are continuously accepted, leading to the reduction of the structure, and anodic areas where the oxidized metal dissolves, resulting in a corrosion current and the dissolution of the structure in question. Distinguishing chemical and microbial corrosion is often difficult because the two processes enhance one another.

Baird (2011) identified several types of localized corrosion and the different ways they may be prevented or remediated. The combined action of cyclic stresses and a corrosive environment contribute to corrosion fatigue, reducing the life of components below that expected by the action of fatigue alone. Its effects can be minimized by coating the material using a good design that reduces stress concentration, avoiding sudden changes of sections, and removing, or isolating, sources of cyclic stress. Corrosion is quantified by measuring its rate (mm/year). The measured value has to be interpreted in the context of the composition of the material. A color-coded chart (Corrosion-Rx; www.waterandwastetesting.com) summarizes, based on corrosion rates, the condition (i.e., excellent to unacceptable) for various materials including ductile iron, cast iron, aluminum, mild steel, copper and its alloys, and galvanized steel, as well as stainless steel (not listed in the same order as Figure 3.1). For example, 0.054 mm/year for mild steel pipe represents pipe that is still in excellent condition, whereas a stainless pipe or copper alloy pipe of the same corrosion rate is in an unacceptable condition.

Although not a universal standard, the use of purple plastic (PVC) pipes for reclaimed water systems, originally introduced in California, is widely used. PVC and similar materials offer advantages over steel and concrete pipes as they are 30–70% less expensive, easy to install, come with 50-year warranties, are noncorrosive, and are durable with an expected design life of more than 100 years without the extensive and expensive corrosion treatments (Baird, 2011). Concrete purple pipe with attached purple tape or stenciling (CDEH, 2001; COR, 2012) is also becoming increasingly acceptable. Permissible sizes range between 2½ in. through 12 in. (6.35–30.48 cm) in diameter and conforming to specific ASTM and pressure requirements.

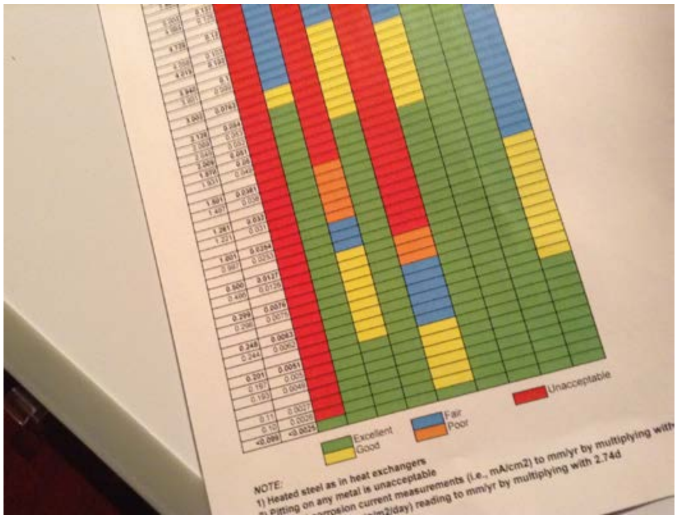

Figure 3.1. A coded Corrosion-Rx tool for guiding decisions in the extent of material corrosion.

Generally, pipes are buried, invisible and, therefore, inaccessible. Sinha (2012) developed a program for efficiently assessing pipes (www.waterid.org). Utilities submit their own case studies to the site. After editing, the information is available for the industry, researchers, and developers. The submitted data and information are analyzed as to determine the current and future structural and hydraulic condition of pipelines based on acoustics, electromagnetics, flow testing, gyroscope analysis, inclinometer, physical testing, pressure testing, temperature testing, vibrational technology, or visual inspection. WATERID is ultimately intended to allow utilities to compare methods and learn from the experience of other utilities on various techniques and technologies. The designers of that Web site envision WATERID as a resource that will never be complete but rather will dynamically evolve through utility experiences to the latest technologies of best infrastructure management practices. Free chlorine residuals of 0.5 mg/L or higher aggressively attack metallic materials (copper, cast iron, carbon steel, mild steel), increasing the corrosion rates (Hsieh et al., 2010). Corrosion is greatly reduced with monochloramine compared to free chlorine (MacQuarrie et al., 1997).

3.1.3   Distribution System Management

Valve management is an essential aspect of distribution system management. The overall reliability of a distribution system largely depends on having an adequate number of valves, as well as their location and reliability. Implementing a valve management program and adding valves to the system in strategic locations are ways to achieve system reliability (Deb et al., 2012). Managing valves can also address some distribution system pressure and cross connection challenges. Management programs that include regular exercising and maintenance of valves are more cost-effective than the addition of new valves to an existing system. Deb et al. (2006) developed a strategic valve management model (SVMM) allowing the user to delineate segments, perform deterministic and probabilistic analyses, and calculate the performance indicators.
For a utility to fully benefit from using the SVMM software, it should collect and maintain data on valve location, accessibility, exercising, operation, and replacement, then link these data with the utility's geographic information database. In the absence of SVMM software, utilities should

consider the following aspects of valve management in developing a cost-effective valve management program (Deb et al., 2012):

- Provide enough valves to satisfy the *n*–1 rule (*n* –1 valves at a junction of n pipes).
- Average pipe length per valve should be between 500 and 700 ft (i.e., 152–213 m).
- To isolate a break, the maximum number of valves to be closed should be four or fewer.
- Utilities should set a goal of exercising valves once every two to three years and annually for valves 16 in. (40.64 cm) or larger.
- Dedicated crews for valve maintenance and repairs should be considered. However, cross-training staff should be considered, particularly during emergency conditions.

3.1.4 Cross-connection Control

Cross connection in this instance intuitively suggests a link between two systems, notably the reclaimed water and the potable water system. However, there can also be a link between the reclaimed water and sewer system. Such linkages can compromise the quality of potable water or reclaimed water, threatening public health. A cross-connection control manual developed by the U.S. EPA presents the methods and devices used for preventing backflow and backsiphonage (U.S. EPA, 2003). The U.S. EPA manual describes and discusses the six basic types of devices that can be used to correct cross connections: air gaps, barometric loops, vacuum breakers (both atmospheric and pressure type), double check with intermediate atmospheric vent, double check valve assemblies, and reduced pressure principle devices. The selection of the appropriate device generally is based on the level of hazard posed by the cross connection. Additional considerations are based on piping size, location, and the potential need to test devices to ensure proper operation (U.S. EPA, 2003). Although not associated with reclaimed water, outbreaks related to water distribution systems have been reported (Laine et al., 2011; Westrell et al., 2003, Craun et al., 2002). Methods for instantly detected cross-connection incidents are still lacking, but technologies, such as fluorescence excitation-emission matrices (FEEM), are promising (Hambly et al., 2010; Yan et al., 2000). The FEEM technique develops fingerprints (spectra) for different water bodies based on salinity, humic acid, and protein content. Also increasingly used is specific conductivity comparisons between potable and water suspected to be under influence of cross-connection events (Figure 3.2).

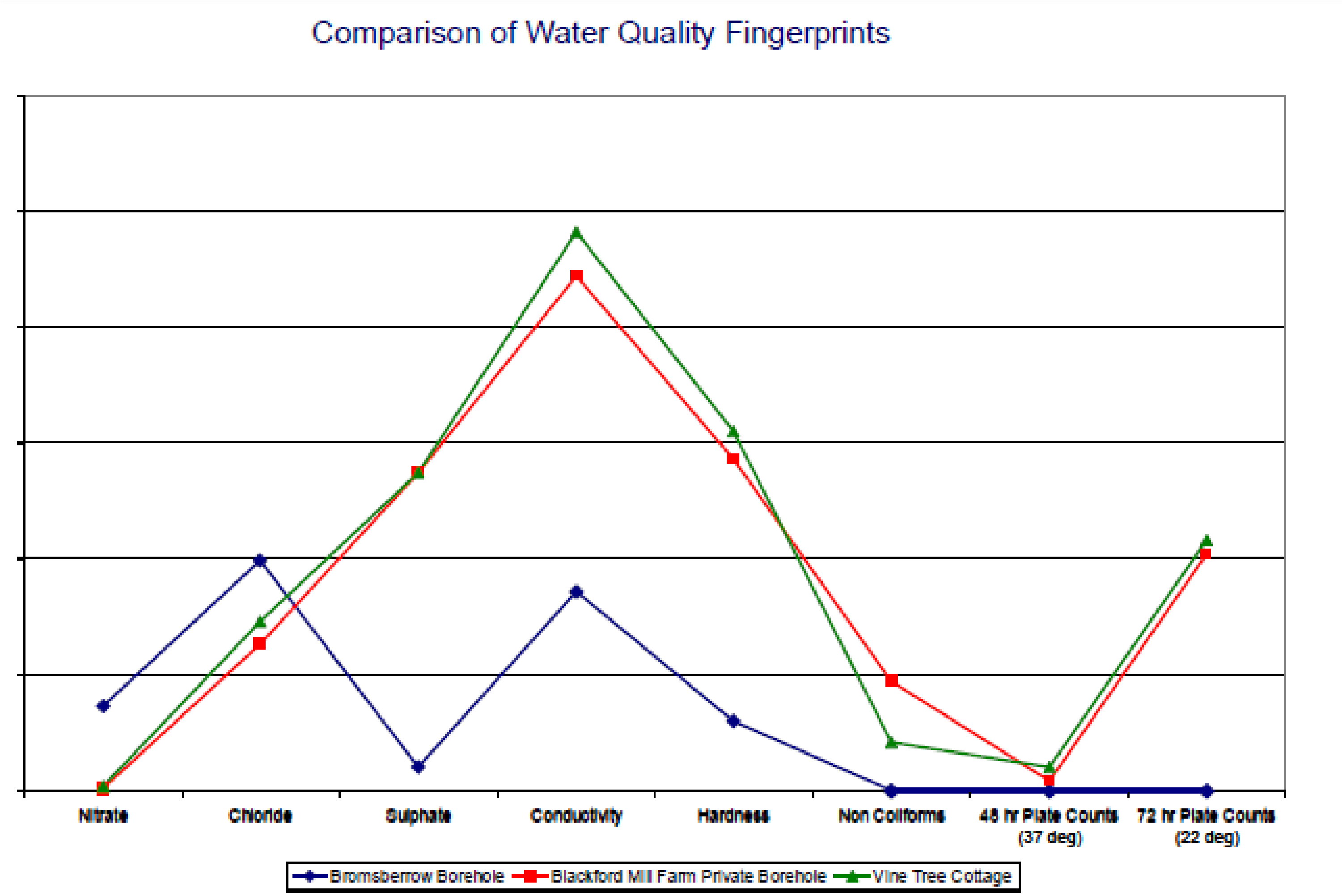

Figure 3.2. Altered characteristics of Bromsberrow borehole water at Vine Tree Cottage that is due to intrusion from Blackford Mill Farm.
Source: Mitchell, undated.

3.1.5 Hydraulic Pressure

It is preferable that end users have a reliable supply of reclaimed water. This requires the capability to provide adequate supply under both normal and abnormal conditions. One aspect of ensuring enough hydraulic pressure is the proper design of the distribution network with a combination of pipe diameters that meet layout, connectivity, and water demand. A resilience index (RI) to overcome failure while still satisfying pressure needs and demand has been used in potable water systems. Equation 3.1 presents this index, whereby N is the number of demand nodes, q_j is demand at node j, R is the number of reservoirs, Q_r is flow from the reservoir r when it is feeding the system, H_r is the elevation plus water level in reservoir r, B is the number of pumps, P_b is the power introduced by pump b into the system, and γ is the specific weight of water whereas ha_j and hr_j are the pressure available and required at node j, respectively (Baños et al., 2011).

$$RI = \frac{\sum_{j=1}^{N} q_j(ha_j - hr_j)}{\left(\sum_{r=1}^{R} Q_r H_r + \sum_{b=1}^{B} \frac{P_b}{\gamma}\right) - \sum_{j=1}^{N} q_j hr_j} \quad 3.1$$

Pipe size optimization in the distribution system is an area of active research as it minimizes capital expenditure, reduces operating costs, and helps in maintaining adequate hydraulic pressure (Daccache et al., 2010; Lamaddalena et al., 2012).

In most instances, the design issues associated with pressure drops and pumping of reclaimed water have not been adequately addressed, as most systems traditionally have handled water-using operations and water treating operations as separate entities. Hung and Kim (2012) published an automated design method able to simultaneously calculate pressure drop and design water pumping in the context of a distribution network. In the pipe, the drop in pressure depends on the Manning friction factor, density of the flow, velocity of the flow, pipe diameter, and pipe length. The entrained air in pipes can cause severe pressure fluctuations that may damage the pipes. The transition between pressurized and free flow that occurs in a distribution system is classified into six stages, namely pressurized flow, slug flow initiation, fully developed slug flow, transition to wavy stratified flow, wavy stratified flow, and ultimately to stratified flow (Kabiri-Samani et al., 2007). Pressurized flow occurs when the water head (h) to the conduit inside diameter or height (D) ratio is equal to or greater than 1.5 (i.e., $h/D \geq 1.5$). By contrast, with stratified flow, the flow is nearly uniform and smooth. Kirmeyer et al. (2000) presented some distribution system pressure requirements (Table 3.1).

Table 3.1. Distribution System Pressure Requirements

Requirement	Value	Location	Sources
Minimum pressure	35 psi	All points within distribution system	AWWA 1996; U.S. EPA and California DHS 1989
	20 psi	All ground level points	Great Lakes Upper Mississippi River Board of State Public Health and Environmental Managers (TSS, 1997)
Desired maximum	100 psi	All points within distribution system	AWWA 1996; U.S. EPA and California DHS 1989
Fire flow minimum	20 psi	All points within distribution system	AWWA 1996; U.S. EPA and California DHS 1989
Ideal range	35–60 psi	All points within distribution system	Great Lakes Upper Mississippi River Board of State Public Health and Environmental Managers (TSS, 1997)

Although designed for potable water, models, such as EPANET (http://www.epa.gov/nrmrl/wswrd/dw/epanet.html), are useful in tracking water flow in pipes, pressure at each node, water height at each tank/reservoir, concentration of chemicals, and decay of the disinfectant in reclaimed water systems. It can also be used to simulate water age and water quality, model valve shutoff, as well as regulate and control pressure. EPANET also is capable of modeling pressure-dependent flow issuing from sprinkler heads (U.S. EPA, 2012a). It can be used to evaluate alternatives for improving water quality, modifying pumping regimens, locating disinfection booster stations to maintain target residuals, planning pipe cleaning and replacement as well as improving the overall system's hydraulic performance. More customized applications involving complex reaction schemes between multiple biological species (including biological regrowth) and chemicals in the bulk flow and pipe wall has been incorporated into an improved EPANET-Multi-Species eXtension (EPANET-MSX) (U.S. EPA, 2012a).

Joksimovic et al. (2008) published a decision support system for developing design principles for water reclamation systems. The publication focused on designing the treatment train, although it also tangentially considered distribution system optimization with regard to pipe sizing, reliability, pumping stations, reservoirs, and redundancy, as well as future development and related changes in water demand. The software developed in that study permits evaluation of the distribution system by allowing users to specify the location of pumping, transmission, and storage facilities and providing a least-cost preliminary sizing that meets operational requirements. The software included a knowledge base and control modules for evaluating treatment performance, distribution system sizing, and system optimization. Its knowledge base is centered on five categories, namely preliminary, primary, secondary, tertiary, and disinfection. Of most relevance to the present review is the distribution system sizing module for locating pumping and storage facilities on a predetermined branched layout. This function is used to identify reclaimed water volumes transferred to each user, calculate the pipe head losses for optimal pipe sizes and pumping stations based on monthly flow rates, and determine size and cost for seasonal storage elements of the distribution network using maximum storage carryover arcs.

3.2 Customer Relations and Satisfaction Issues

Sustaining reclaimed water production and usage requires satisfying customer requirements and reservations about the quality of the product. Public perception on the use of reclaimed water as an alternative water supply has to be favorable. The increasing interest in water reclamation for agricultural, landscaping, industrial and other nonpotable applications demands assurances to the customers to change perceptions about the safety of reclaimed water. Perception and acceptance are negatively influenced, especially when reclaimed water turbidity and color are objectionable (Rowe and Abdel-Magid, 1995). Jjemba et al. (2010) reported a high correlation between turbidity and apparent color in two systems with open ponds ($R^2 \geq 0.8$), which had significant algal growth than in two MBR systems ($R^2 \leq 0.6$). Elevated levels of bacterial growth can result in a loss of oxygen and the creation of anoxic conditions resulting in odor. The odor is attributed to hydrogen sulfide and black water (iron sulfides), which give water a "rotten egg" smell (Delgado et al., 1998). Odor can also generate customer complaints. Its management is discussed in Section 3.3.

Irrigation is the most common use of reclaimed water (Table 5.1). Thus, its demand can be largely impacted by the prevailing season leading to rationing so as to meet client demand in some locations (Jjemba et al., 2010). In terms of nutrients, reclaimed water is deemed superior to potable water for irrigation purposes. If the reclaimed water is primarily to be used for irrigation purposes, operators have to be mindful of nutrient levels. If excessive, nutrients can cause injury to the irrigated vegetation and also increase the possibility of contaminating the groundwater. Reclaimed water that is used for irrigation also has to be treated to minimize salinity, which can occur if the water contains high levels of sodium bicarbonates (Wu et al., 2008). Saline soils display a high electrical conductivity (namely, >4 mS/cm), which can negatively affect vegetation by lowering the free energy of water in the soil matrix and reducing the ability of the plant roots to extract moisture from the soil owing to the osmotic pressure generated by the electrical conductivity.

Most of the issues raised about customer relations and perception (Table 4.2) can be addressed through a multipronged approach that requires the following:

- Putting reclaimed water into larger context of a water portfolio
- Maintaining constant communication with customers through open house activities, newsletters, webcasts, and similar outreach activities
- Branding reclaimed water through advertising and highlighting the associated benefits and shortfall of its use (Davis, undated)
- Involving customers in the decision-making processes
- Developing partnerships at all possible levels
- Providing avenues for constant feedback to and from the customers

Macpherson and Slovic (2011) developed several guidelines for engaging customers about reclaimed water issues.

3.3 Water Quality in Reservoirs and Distribution Systems

Within the United States, there are no federal regulations about reclaimed water use. Some states have their guidelines or regulations of varying scope (U.S. EPA, 2012b). Overall, the states have specific water quality standards regarding organic content (BOD or TOC), nitrogen, bacteria (particularly fecal coliform), and chlorine residuals in the effluent. Most of these requirements are focused on reclaimed water effluent. However, monitoring reclaimed water immediately after treatment does not provide a true representation of quality at the point of use. Storage, age, and conveyance cause deterioration in water quality, with aesthetic and public health implications. Deterioration of water quality during storage in reservoirs and the distribution network is a major challenge for the industry.

In addition to microbial criteria for reclaimed water, some specific physical and chemical surrogates for microbiological water quality have also been identified. For example, total nitrogen concentrations ≤ 10 mg/L, turbidity ≤ 2 NTU, total suspended solids (TSS) ≤ 5 mg/L, biochemical oxygen demand (BOD) ≤ 45 mg/L, total organic carbon (TOC) ≤ 5 mg/L, and residual chlorine concentrations > 1 mg/L are reflective of high-quality effluents. A recent survey of 21 reclaimed water plants (activated sludge with secondary treatment as extended aeration, oxidation ditches, trickling filters, A2O, RBC, MBR, or MLE) showed a median TOC of 5.5 mg/L and median AOC of 450 µg/L (Weinrich et al., 2010). Jjemba et al. (2010) noted less frequent occurrence of common indicator organisms in two MBR systems, which also had lower carbon levels (Figure 3.3). However, no association between human pathogens (e.g., *Legionella* and *Mycobacterium*) and carbon levels was observed in these reclaimed waters.

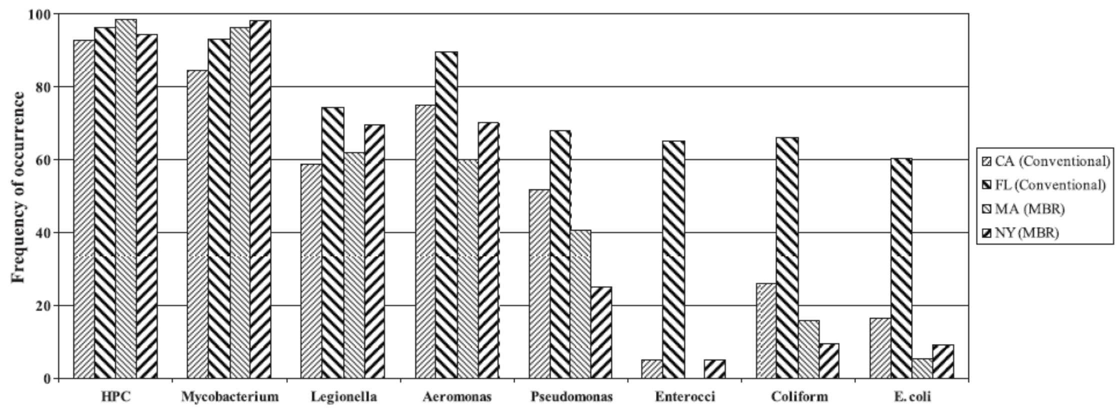

Figure 3.3. Frequency of occurrence of opportunistic pathogens and indicator bacteria in reclaimed water.
Source: Jjemba et al., 2010.

Aesthetics and water quality are primary issues affecting consumer perceptions, permits, and water use choices (e.g., irrigation versus cooling towers toilet flushing, etc.). A major driver for such deterioration is the loss of disinfectant residual. This section is, therefore, devoted to examining reclaimed water quality issues of aesthetic, physical, operational, and biological nature.

3.3.1 Algae and Macroorganisms Management

Long retention times coupled with high nutrient loads typical of reclaimed water are ideal for intense algae growth in open reservoirs. Excessive nitrogen and phosphorus support photosynthesis and algal biomass accumulation, which is also influenced by climatic conditions, specifically sunlight and warm temperatures. Thus, most algal biomass is accumulated in summer and fall. Algal proliferation is not only limited to the reservoir but also impacts the distribution system, clogging sprinkler heads and also generating objectionable odors because of the formation of hydrogen sulfide (Jjemba et al., 2010). The hydrogen sulfide was several magnitudes higher in two conventional systems compared to membrane bioreactors (MBRs). Water systems with as little as 1 µg of sulfide/L are corrosive (Miller and Mancl, 1997). Rashash et al. (1996) found that odor type and intensity related to the number of algal cells and the life stage of the algae, with the younger less dense algal cultures producing less intense odors.

Algal growth results in severe operational (e.g., flow disruption, clogging of sprinklers, etc.) and water quality issues in reclaimed water distribution systems. Algal problems were the most common issue during the storage phase for 11 of the 12 water utilities covered in a recent study by Rimer and Miller (2012). Some utilities controlled algae using copper sulfate ($CuSO_4$) or Cutrine-Plus. Dosages of 1–2 ppm (1.4–2.7 lb $CuSO_4$ /acre-ft) were recommended when water temperatures are above 60 ^oF (Haman, 2011). Cutrine-Plus had more efficacy than copper sulfate (Rodgers et al., 2010). It is a liquid copper-based formulation with ethanolamine chelating agents to prevent copper precipitation in water. If algaecides are used when cell numbers are high (i.e., >5,000 cells/mL), the subsequent cell lysis can lead to high concentrations of toxins and odor compounds, which are difficult to remove (Brooks et al., 2008). Potassium permanganate, which may be applied directly or indirectly (by coating reservoir walls), may also be used to control algae. For chemical control strategies, users have to be mindful of the potential impact on nontarget organisms.

Enhanced coagulation, scraping walls, ozoflotation, dissolved air floatation, and ultrasonication have also been used to control algae (Benoufella et al., 1994; Lee et al., 2002; Ahn et al., 2007). Ultrasonication was demonstrated by Lee et al. (2002) on algal blooms on 32 hectare Lake Senba in Japan using a set of prototypes (i.e., the ultrasonic irradiation system USIS). Ahn et al. (2007) used ultrasonication in a 9000 cu m eutrophic pond, whereas Klemencic et al. (2010) used a similar strategy in a fish pond. Ultrasonication destroyed the algal gas vacuoles, enhancing contact between the cyanobacteria and their lysing Myxobacter, which, in turn, accelerated cell destruction. The ruptured cells sink in the reservoir.

The accumulation of algal cells can be controlled by using fine-mesh screens post-storage or regular flushing of the reclaimed water systems (Jjemba et al., 2010). In a Sarasota distribution system, farmers used basket type filters (80–100 μ) at each irrigation pump station to control blockage from algae (Rimer and Miller, 2012). Recently, American Water launched a water-energy nexus oriented project using floating solar modules on a reservoir (Figure 3.4). Arrangements like this in a reclaimed water open reservoir can minimize algal growth and maintain good water quality while providing other economic benefits (Anonymous, 2012a).

Figure 3.4. Floating solar panels on a reservoir at Canal Brook WTP (Somerset, NJ).

Reclaimed water may also be invaded by macroorganisms, such as snails, worms (e.g., redworms), zebra mussels, turtles, fish, weeds (e.g., duckweed, moss, water hyacinth), and ferns (e.g., *azolla*). Although chemical control is effective (Nelson et al., 2001; Turgut, 2005), it may not always be the most desirable option. Biological control can be a viable alternative in some instances. For example, Tipping et al. (2008) reported good results with a weevil (*Cyrtobagous* *salviniae*) controlling a water fern (*Salvinia molesta*) in Texas and Louisiana (Figure 3.5). However, biological control agents have to be local as to avoid unintended consequences of trying to eliminate an invasive species with another invasive species. Table 3.2 summarizes some chemical and biological remedies for respective macroorganisms.

Table 3.2. Control Measures for Various Macroorganisms in Reclaimed Water

Macroorganism	Control Chemical*	Biological Control**
Snails and other molluscs	Chlorine at ≥3 mg/L; copper sulfate at 504 mg/L (Oplinger and Wagner, 2009)	Cover with gas impermeable benthic barriers such as EPDM suffocates mussels (Wittmann et al., 2012).
Worms (Oligochaete)	Shock chloramination with 32 mg/L for 75 min (Broza et al., 1998); superchlorination	Reduced organic materials, e.g., through aeration, as high oligochaete presence is an indicator for such contamination
Mussels and other bivalves	EarthTec for at 17 mg/L (Watters et sl., 2013), Bayer 73, Sodium hypochlorite (Kilgour and Baker, 1994)	Cover with gas impermeable benthic barriers such as EPDM suffocates mussels (Wittmann et al., 2012); predation by crayfish (*Pacifastacus leniusculus*; zu Ermgassen and Aldridge, 2011), sparker pressure pulses application of 5.8 J/m2 per pulse (Schaeffer et al., 2010)
Duckweed	Herbicide spray (e.g., metazachlor, diuron at 60 µg/L especially when combined with copper, linuron at 70 µg/L). Also reported was Aquathol K; Increase water to pH >8	Spraying a fungi species (*Myrothecium roridum* in S. Korea) inhibited duckweed plants (Lee et al., 2008)
Ferns	Herbicides (e.g., diquat, glyphosate); Increase water to pH >8 (only effective in early invasion)	Fungi, weevils (e.g., *Cyrtobagous salviniae* in Texas and Louisiana)
Moss	Increase water to pH >8; fluoridone (low doses of 5–15 µg/L over a long duration work best; Getsinger et al., 2008)	No known biocontrol measure

Notes: *Pesticide, herbicide applications have to conform to U.S. EPA guidelines. Their use should also be mindful of potential impact on nontarget organisms including the irrigation fields. **The biological control agent of choice should preferably be local (or certified by USDA/ARS) as to avoid unintended consequences of trying to eliminate an invasive species with another invasive species.

Figure 3.5. Documentation of the water fern (*Salvinia molesta*) infestation before and after release of a weevil (*Cyrtobagous salviniae*) at a reservoir in Louisiana.

Source: Tipping et al., 2008.

Midge flies are quite a nuisance at some reclaimed water facilities and point of use. Although no reports have been associated with reclaimed water, some species can bite and transmit arbovirus diseases to both animals and humans. Reports of allergic reactions to midge flies have also been documented (Hirabayashi et al., 2008). Because of sensitivity to temperature, midges are more prevalent in spring and summer but even within a single reclaimed water treatment and distribution system, dominant sub-families can change throughout the year. Current biological and chemical control strategies for biting midge target destruction of adult forms. However, targeting larvae and pupae in their brooding environment also can be effective. Chloramination and superchlorination are effective against midges (Broza et al., 1998). Sound and light also have been used to control midge populations because of the effects on fly behavior (Haribayashi and Nakamoto, 2001).

3.3.2 Microbial Problems in Distribution System

A summary of the common microbial problems associated with distribution systems and how they can be resolved is presented in Table 3.3. From an operational perspective, free chlorine disinfectant residual throughout the reclaimed water distribution system should at least be maintained at 0.2 mg/L (Narasimhan et al., 2005). Higher chlorine concentrations may be necessary depending on site-specific conditions. For example, utilities that do not provide nutrient removal may require higher residuals to prevent the growth of biofilm. For systems using free chlorine, a temporary switch to chloramine may be as effective in inactivating biofilm denizens (Flannery et al. 2006).

Table 3.3. Common Microbial Problems and Potential Solutions

Problem	Potential Cause	Mitigation Alternatives
High bacterial levels at point of entry	• Inadequate treatment • Insufficient disinfection • Intrusion	• Treatment assessment and optimization • Increase disinfectant application • Infrastructure inspections and improvements
High bacterial levels in distribution pipes	• Insufficient residual maintenance • Biofilm growth and sloughing: sediment accumulation • Intrusion	• Provide booster disinfection or increase residual at existing booster stations • Decrease system residence time • Loop versus branch system design • Biofilm control: Flush and disinfect distribution mains, or occasional use of chloramine disinfectant • Infrastructure inspections and improvements
Poor microbial quality in storage facilities	• Inadequate turnover • Sediment or biofilm accumulation • Algae growth in open reservoir	• Decrease detention time • Reconfigure inlet/outlet piping • Install internal baffling • Inspect and clean storage facilities • Close reservoir, if feasible • Algaecide application (e.g., Cutrine-Plus) • Post-storage strainers/filters • Nutrient removal at treatment plant • Watershed control
Clogged sprinkler heads at point of use	• High bacterial levels in distribution system • Stagnation in service connection	• See above • Increase frequency of flushing of service connection

3.3.3 Biofilms

Most bacteria in water systems are attached to surfaces and piping material in intricate aggregate structures called “biofilms” (MacDonald and Brözel, 2000; Lazarova and Manem, 1995). Such aggregation of the cells increases the resistance to disinfection by several-fold (LeChevallier and Au, 2002). Some of the cells slough off the biofilm and shed into the aquatic matrix (van der Wende et al., 1989) as a result of changes in flow rates, pH, nutrient status, disinfectant concentration, or disinfectant type. Based on Hausner et al. (2012), planktonic heterotrophic plate counts (HPC) were strongly correlated with biofilm growth, suggesting that high planktonic cell counts can also be indicative of potential biofilm problems. In the study by Hausner et al. (2012), water age was not correlated with biofilm growth metrics consistently, suggesting that distribution models calibrated only for water age will not reliably diagnose biofilm-prone systems. By contrast, biofilm growth was highly correlated with total chlorine demand, suggesting that models calibrated for chlorine demand can be used to identify areas of potential biofilm growth. Biofilm densities of *Mycobacterium avium* increased with increasing levels of AOC (Norton et al., 2004). A more diverse microbial population was documented on metallic than plastic surfaces (Norton and LeChevallier, 2000) signifying complex but important relationships between pipe materials and biofilm proliferation (see “Biofilm and Corrosivity” section below).

3.3.3.1 Biofilm Sampling and Analysis

Biofilm growth can be evaluated on coupons of different pipe materials. Owing to the complexity of microbial communities and diverse materials found in water distribution systems, several methods are used to assess biofilm development:

- Detection of viable microorganisms able to replicate under test conditions
- Direct counting of microorganisms using microscopy (e.g., fluorescence, CLSM, flow cytometry, and others)
- Biochemical assay methods, such as ATP

However, Hausner et al. (2012) reported limited capability from flow cytometry for biofilms in drinking water systems owing to interferences associated with common pipe materials, such as particulate debris from cast iron and cement. The assay for ATP on surfaces (including coupons) as a surrogate for biofilm formation has a very short turnaround time that is ideal for water distribution systems.

3.3.3.2 Biofilm and Corrosivity of Materials

Corrosion and bacterial growth are confounded and can influence one another. Thus, several studies have compared biofilm growth on various pipe materials and found corrosion as a significant factor in biofilm formation. Materials such as unlined cast or ductile iron pipe have shown the greatest biofilm accumulation, whereas materials such as polyvinyl chloride (PVC) have shown the least accumulation and related corrosion (Camper 1996). On the contrary, Cloete et al. (2003) reported higher biofilm formation on PVC than galvanized pipe surfaces, whereas Pedersen (1990), Zacheus et al. (2000), Wingender and Flemming (2004), as well as Lehtola et al. (2004, 2005) did not detect any differences in biofilm formation between PVC, stainless steel, and polyethylene (PE). Similarly, Manuel et al. (2007) did not detect differences in biofilm development on PVC, cross-linked polyethylene (PEX), high-density polyethylene (HDPE), and polypropylene (PP) in three types of reactors. These seemingly conflicting results may be explained by the relatively new biofilms used for some of the studies. The more stable laboratory conditions in which some of these studies were conducted (as opposed to what happens in real distribution systems, which are impacted by temperature extremes), nutrient fluxes contributed by the pipe surface composition, as well as hydrodynamic conditions may also have contributed to the contradictory results. From a remedial perspective, copper pipes required a higher chlorine dose than plastic pipes to disinfect biofilms effectively (Lehtola et al., 2005).

3.3.4 Disinfectants and Water Quality

Disinfection is intended to manage the risk of waterborne disease transmission. In the United States, chlorine and chloramines are commonly used disinfectants. Both react with many trace compounds within the bulk water, natural organic matter, and the pipe wall material, leading to a loss in disinfectant residual (Vasconcelos et al., 1996; Valentine et al., 1997). Several other factors, including the disinfectant to nitrogen ratio, pH, disinfectant dose, temperature, inorganics, and organic carbon, contribute to disinfectant decay (Lieu et al., 1993; Jafvert and Valentine, 1992; Valentine et al., 1997). During decay, disinfection byproducts (DBPs) are also formed. In general, increasing the Cl:N ratio inhibits nitrification but increases the formation of DBPs. Inorganics, such as ferrous (Fe^{2+}), copper (Cu^{2+}), and manganese (Mn^{2+}), also consume chlorine disinfectant, becoming themselves oxidized in the process (Nguyen et al., 2011). Dissipation of the disinfectant leaves water vulnerable to the regrowth of bacteria and proliferation of biofilms as well as contamination from system breaches and intruding contaminants (Jjemba et al., 2010). Thus, managing disinfectant loss in distribution systems also has to manage the potential impact of these setbacks.

In a survey of 4000 water treatment plants, 800 (15%) of utilities used disinfectant booster stations to maintain distribution systems residuals and control biological regrowth (Uber et al., 2003). Mostly used in booster disinfection was chlorine gas (Figure 3.6). However, only 25% of the utilities used distribution system hydraulic or water quality simulation models to optimize where to place the booster. The general finding was to place them near areas experiencing obvious difficulties in maintaining disinfectant residual.

Using a booster disinfection stations strategy physically separates the disinfection doses, with multiple delivery coordinated doses applied throughout the distribution system (Tryby et al., 1999). This approach separates the microbial inactivation (disinfection efficiency) requirements of the effluent from the need to maintain disinfectant residual in the distribution system. Thus, a booster disinfection management style introduces flexibility in the operations of the reclaimed water plant and distribution system as network usage characteristics change over time. The strategy enables matching the dose to the unique residence time of the water parcel, reducing disinfectant use and its associated disinfection byproducts.

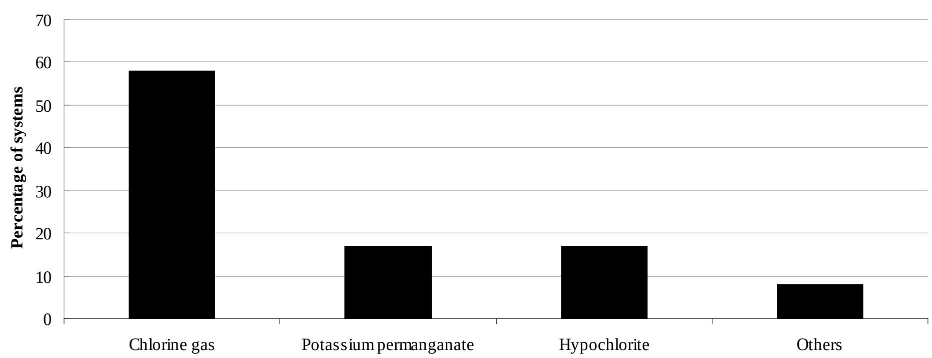

Figure 3.6. Percentage of systems using specific disinfectants at booster stations.
Source: Based on data from Uber et al., 2003.

Linear superposition in a booster disinfection design and analysis (BDDA) software was developed to optimize the effects of multiple booster dosages and station performance (Uber et al., 2003). For the same system, the introduction of four booster stations reduced the amounts of chlorine used by 50% compared to the conventional approach. Boosters also had the added advantage of a better redistribution of the disinfectant mass from the treatment plant into the distribution system, resulting in a more uniform (less variable) residual throughout the distribution system (Figure 3.7). It should be noted that booster chlorination still requires disinfection at the treatment plant while still relying on disinfection within the distribution system to maintain adequate residuals. Despite the potential improvements in maintaining residuals using BDDA software, there is no evidence that reclaimed water utilities are using such resources for guiding decisions on locating booster stations.

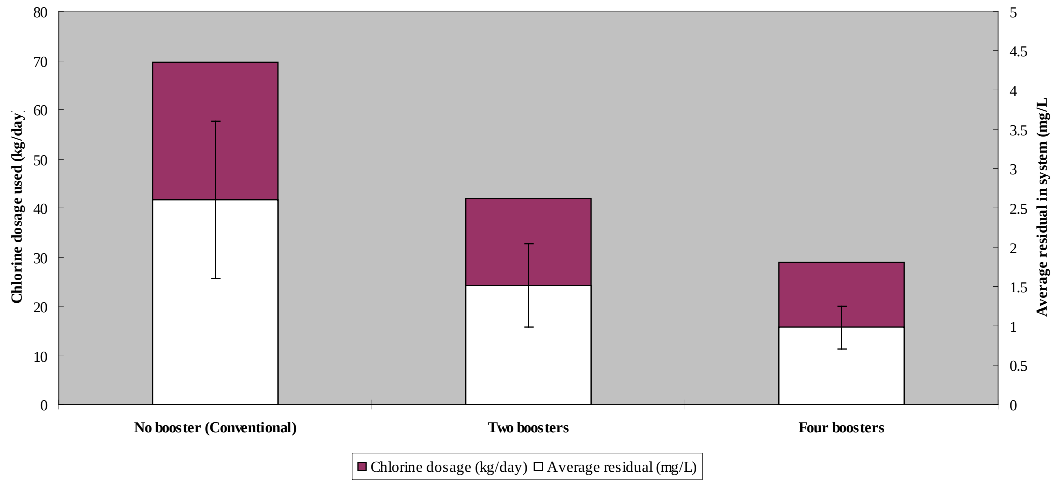

Figure 3.7. Differences in the amount of chlorine used and residual levels in the system after adding two and four booster stations.

Note: Error bars represent the standard deviation of chlorine residuals.

Source: Based on data from Uber et al., 2003.

Combining disinfectants has attracted increasing attention because of benefits such as

- disinfection of a wider range of pathogens,
- improved reliability through redundancy,
- reduced disinfection byproducts,
- improved regulatory compliance, and
- potential cost savings.

However, limited data on combined disinfectants particularly about the optimum configuration of a combined UV/chlorine reclaimed water system are available. Tang et al. (2010) evaluated UV disinfection in combination with either free chlorine or chloramines. UV was tested at doses of 33, 67, or 100 mJ/cm², alone or in combination with free chlorine at applied doses of 2, 4, or 6 mg Cl_2/L, or chloramines at CT values of 150, 300, or 450 mg-min/L. Bench-scale experiments tested UV in combination with free chlorine, the ammonia-chlorine process (where chloramines were formed from the addition of ammonia, followed by free chlorine), and the chlorine-ammonia process (where chloramines were formed from the addition of free chlorine, followed by ammonia). The effects of disinfectant application order were investigated by dosing UV before, simultaneously with, or after chlorine in the bench-scale experiments, and by dosing UV before or simultaneously with chlorine in the pilot-scale experiments. Synergistic effects were also analyzed in both the bench- and pilot-scale experiments. The water was seeded with poliovirus and MS2. The seeded organisms, together with indigenous total coliforms, were monitored in fully nitrified secondary effluent, fully nitrified filtered secondary effluent, and chlorine-demand-free buffer (DFB). In another experiment, disinfection of seeded adenovirus was tested on a filtered effluent. Coliphage MS2 and indigenous total coliform levels were monitored in filtered effluent, and indigenous adenovirus was tested in selected experiments with filtered effluent. The samples were also analyzed for DBPs and trace organic chemicals (TrOCs).

Free chlorine residuals decayed rapidly in DFB, filtered effluent, and secondary effluent samples seeded with MS2. Total chlorine residuals decayed more slowly than free chlorine residuals, and total chlorine residuals formed by chloramines decayed more slowly than residuals formed by free chlorine. In free chlorine experiments, UV at doses of 2 mg Cl_2/L of free chlorine followed by 67 mJ/cm² of UV light or with the same amounts of chlorine and UV applied simultaneously caused approximately 10 to 15% loss of total chlorine residuals in filtered and secondary effluents (Tang et al., 2010). At doses of 4 mg Cl_2/L of free chlorine followed by 33 mJ/cm² of UV or 4 mg Cl_2/L of free chlorine and 33 mJ/cm² of UV applied simultaneously, the chlorine losses were smaller in filtered effluent and not statistically significant in secondary effluent. The loss of the chlorine residuals indicated that the compounds composing the total chlorine residual were sensitive to UV radiation. In chloramine experiments, UV did not significantly alter total chlorine residual concentrations.

Free chlorine doses of 4–6 mg Cl_2/L increased ultraviolet light transmittance (UVT) by approximately 2%, possibly because of the reaction of free chlorine with compounds that absorb UV radiation. Based on the collimated beam dose calculation (U.S. EPA, 2006), increased UVT translated to an increase of less than 2% in UV radiation exposure dose. Chloramines at CT values between 150 and 450 mg-min/L decreased UVT by an average of 3.7 percentage points, possibly because of absorption of the UV radiation by chloramines. This decrease in UVT translated to a decrease of approximately 3% in UV radiation exposure dose.

UV was tested in combination with the ammonia-chlorine and chlorine-ammonia processes (Tang et al., 2010). In one experiment, 1.3 mg N/L of ammonia was first mixed into the effluent, followed by 6.5 mg Cl_2/L of free chlorine. The combined UV/ammonia-chlorine treatment provided more than 5-log poliovirus but less than 2 CFU/100 mL total coliforms inactivation. By comparison, chloramines alone did not inactivate MS2 coliphage. These results suggest that combining UV with chloramine would improve virus disinfection. Further comparison of disinfection using UV combined with chloramine was generally similar to or worse than disinfection using UV coupled with free chlorine, even though the chlorine-ammonia process used higher doses of free chlorine. The chloramine treatments provided a disinfectant residual. Disinfection efficacy with combined UV/free chlorine disinfected total coliforms to median levels below 2 CFU/100 mL and provided greater than 5-log inactivation of poliovirus, adenovirus, and MS2. Doses of 4 mg Cl_2/L of free chlorine and 33 mJ/cm² (applied together or simultaneously) provided more disinfection than 2 mg Cl_2/L of free chlorine and 67 mJ/cm² of UV light (applied together or simultaneously) in filtered effluent, probably because the full dose of free chlorine provided more disinfection than the full dose of UV for most organisms.

These results are consistent with UV-induced formation of radical species from free chlorine (Watts and Linden, 2007). The formed radical species ultimately disinfect MS2 and react with the TrOCs to increase microbial inactivation. Alternatively, chlorine may weaken MS2 and make it more susceptible to UV disinfection. Chlorine may also react with TrOCs to form intermediates that are then susceptible to photolysis by UV radiation. Table 6.4 summarizes the benefits of combining chlorine with UV disinfection.

3.3.4.1 Disinfection with Ozone and Other Disinfectants

Ozone provided optimal coliform disinfection, reduced the color, and removed trace contaminant while minimizing DBP formation (Snyder et al., 2006; Wert et al., 2007). Color reduction is important for public perception for water reuse. Color, UV254, and specific ultraviolet absorbance (SUVA) were all also reduced with O_3/H_2O_2 disinfection (Wert et al., 2007). However, compared to ozone treatment by itself at similar doses, O_3/H_2O_2 produced greater concentrations of AOC (5–52%), aldehydes (31–47%), and carboxylic acids (12–43%), indicating their formation is largely dependent on ·OH exposure. In addition, O_3/H_2O_2 leaves an H_2O_2 residual in water, which can quench subsequent post-disinfection chlorine or chloramine, resulting in increased chlorine demand. Ozone reduced the toxicity potential of reclaimed water by 20%, which would benefit water reclamation systems by reducing DBP formation. On the basis of these findings, O_3 may be preferred to O_3/H_2O_2 in reclaimed water disinfection.

Table 3.4. Summary of Benefits of Combining UV and Chlorine

Effluent	Single Disinfectant	Change	Benefits
Fully nitrified	Chloramines	Add UV	Improved disinfection of viruses and protozoa Decreased DBPs
			Removal of a slightly wider range of TrOCs
	Chloramines	Change to free chlorine and UV	Improved disinfection of viruses and protozoa Decreased DBPs
			Removal of a slightly wider range of TrOCs
	Free chlorine	Add UV	Improved disinfection of viruses and protozoa Decreased DBPs
			Removal of a slightly wider range of TrOCs
			Possible synergistic effects to increase disinfection and/or removal of TrOCs
	UV	Add free chlorine	Improved disinfection of viruses and protozoa Decreased DBPs
			Removal of a slightly wider range of TrOCs
			Possible use for disinfection of peak flows and/or stormwater
			Backup disinfection system in case of problems with UV
Non-nitrified	Chloramines	Add UV	Improved disinfection of viruses and protozoa
			Decreased DBPs
			Removal of a slightly wider range of TrOCs
	UV	Add chloramines	Residual for distribution of reclaimed water
			Possible use for disinfection of peak flows and/or storm water
			Backup disinfection system in case of problems with UV

3.3.4.2 Influence of pH

The efficacy of chlorine disinfection is dependent on pH. At a pH <7.5, HOCl is the predominant species, whereas at higher pH levels, the less efficacious OCl^- is the predominant species. Results from two reclaimed water systems on consecutive days showed predictable pH increases in the storage and distribution systems compared to the effluent (Figure 3.8). The increase can negatively impact the efficacy of a residual disinfectant in the distribution system. For example, White (1992) showed much lower disinfection efficacy at pH 9 possibly because of predominance of the less efficacious OCl^-. A slight increase in chlorine decay with increasing pH was reported by Fleischacker and Randtke (1983). Changes in pH also affect the stability of chloramines. For example, between pH 6–8, decreasing the pH increased the decay of monochloramines owing to the formation of dichloramine (Jafvert and Valentine et al., 1992). Collectively, these observations have implications as the water pH in the system at the point where a booster disinfectant is applied can impact disinfection efficacy.

3.3.4.3 Temperature and Chlorine Demand

The rate of disinfectant decay increases with temperature. To that effect, higher temperatures increase the disinfectant demand (Valentine et al., 1997). Estimates indicate a decay increase of two- to three-fold for every 50 ^{o}F (10 ^{o}C) rise in temperature (Brandt et al., 2004).

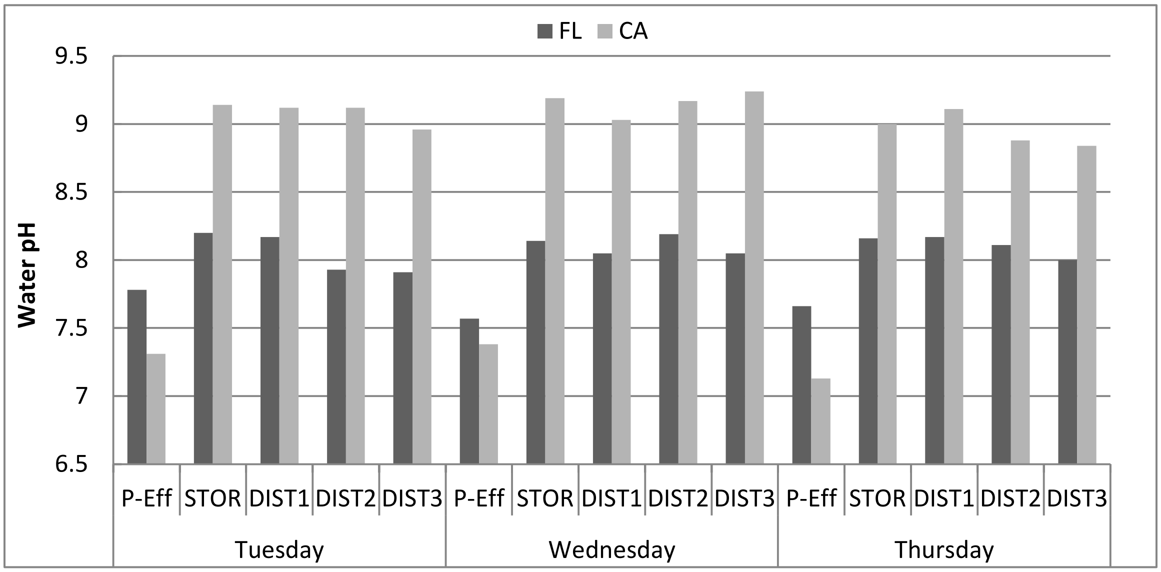

Figure 3.8. The pH of reclaimed water from two conventional facilities in summer 2007.

Note: For each facility, the water was sampled from the effluent, storage, and three points within the distribution system.

Source: Jjemba et al., unpublished.

3.3.4.4 Effect of Infrastructure Types

The type of pipe wall also has an impact on disinfectant decay. For chlorine, decay increases with polyethylene, PVC, epoxy, cement, and iron pipes, in that order, whereby polyethylene is least reactive and iron is most reactive (Brandt et al., 2004). The rate of decay of chloramine is comparatively lower than chlorine decay. The difference in rates of decay between chloramines and chlorine is estimated at a factor of 10 (Brandt et al., 2004). At this point, it is not clear what fraction of reclaimed water plants chlorinate to breakpoint as opposed to those that use chloramine.

The rate of disinfectant decay is inversely proportional to the pipe diameter. This is inherently assumed in the EPANET decay model (U.S. EPA, 2012a). Furthermore, high water velocity may disturb sediments that, in turn, increases their reaction with chlorine. It may also increase the rate at which chlorine transfers to the pipe wall. It is not clear as to what proportion of the reclaimed water utilities use EPANET in guiding their disinfection or modeling their hydraulic and water quality behavior of water in reclaimed water distribution piping systems.

3.3.5 Retention Time in the Reservoir and Distribution System

Studies by Brandt et al. (2004) attributed water quality in the distribution system to the (1) quality of the treated water supplied into the network, (2) condition of distribution assets within the network, and (3) retention time within the network. The importance of retention time of water in the reservoir and distribution system on water quality cannot be emphasized enough. Impacts of storage-associated water quality problems are summarized in Table 3.5. Managing acceptable retention time with or without hydraulic models will, in turn, address these problems. Other considerations for managing this important parameter include altering valves in the network, installing time varying valves, flushing, downsizing the mains (see Minimizing Retention in the Pipes section following), adjusting pump schedules, altering reservoir configuration, and altering distribution system configuration.

Table 3.5. Reclaimed Water Quality Problems Associated with Retention Time

Problem	Parameter to Measure	Potential Causes	Impacted Area(s)
Regrowth	• Bacteria (e.g., coliforms, HPC, *Legionella*, etc.)	• Reduced residual disinfectant • Intrusion	Reservoir and pipes
Algal and cyanobacteria growth	• Chlorophyll	• Excessive nutrients in presence of sunlight	Open reservoir and pipes
Loss of disinfectant	• Chlorine • Chloramine	• Matrix demand • Wall demand • Dissipation	Open reservoir and pipes
Nitrification	• Nitrite • Ammonia • Dissolved oxygen	• Microbial activity • High organic content • Low dissolved oxygen	Open reservoir and pipes
Discoloration	• Metals (e.g. iron, manganese, copper) • Turbidity • Color • pH	• Pipe corrosion • Sediment accumulation • pH changes	Reservoir and pipes
Odor	• Hydrogen sulfide • Mercaptans • Phenolics	• Anaerobic conditions • Diminished disinfectant • Algal cell accumulation and death	Pipes

Retention time is controlled by the physical characteristics of the system and the operation regime. Physical characteristics include the pipe roughness, pipe size, frequency of dead-ends, pipe slope, and leakages. Operational regimes may be structured (e.g., pumping schedule) or uncontrolled as is the case for response action to meet demand needs. Brandt et al. (2004) focused on retention time in potable water distribution systems, but some of the principles (i.e., parameters influenced by retention time, analysis tools and methodologies for determining retention time, water quality issues associated with retention time) and practices (i.e., operational and engineering solutions for reducing retention times) identified in their study may apply to reclaimed water systems as well.

In a survey of various utilities, review of water quality data, hydraulic modeling, rule of thumb information (e.g., for specific chlorine dose, expect dissipated chlorine where water age is more than *y* hours) and simple calculation were the most relied on to determine water retention time (Brandt et al., 2004). Other methods used include

- tracer compound (Robertson et al., 2013),
- geographic information system (Nobel and Allen, 1995),
- computational fluid dynamics (Baléo et al., 2001), and
- neural network models.

Several strategies for managing retention time are presented in Table 3.6. However, most of these practices are implemented by utilities without necessarily classifying them as retention time management techniques but rather as water quality improvement measures. Some of the practices are adapted to solve a specific water quality problem (reactive) rather than proactively during the day-to-day operation of the network. Most widely used by potable water systems to minimize retention time is flushing of pipe networks. However, as noted in a recent survey, flushing is not always accepted for reclaimed water distributions systems (Jjemba et al., 2010). A recommendation to flush the reclaimed water back into the sewer has been suggested. Altering the valving of the network (manually or using an automated system) is also used to control water retention time in localized parts of the distribution system. Retention time can be reduced by minimizing the number of shut valves required to produce hydraulic boundaries. Alternatively, shutting valves can reroute the water through part of the system with high demand.

3.3.5.1 Minimizing Retention in Pipes

For design purposes, the smallest pipes for potable water systems in the United States are commonly 6–8 in. (100–200 mm) in diameter, whereas in most other countries, diameters of 3–6 in. (75–150 mm) are maintained to meet peak diurnal drinking and fire flow demands (Twort et al., 2000). Systems with pipes larger than the water inherently demanded by the areas they serve have water quality problems, such as long residence time, low water velocity, flow stagnation, and accumulation of sediments. This makes the management, operation, and maintenance of such systems harder. The Netherlands' designs recently adapted downstream declining pipe diameters reaching much smaller minimum sizes of 1.5–2.5 in. (40–63 mm) to achieve 1.31 ft/s (0.4 m/s) but preventing sediment accumulation and, thus, producing a "self-cleaning" network (Brandt et al., 2004; Buchberger et al., 2008; Slaats et al., 2002). Such a declining diameters design provides unidirectional velocities with a critical scouring velocity flow, resuspending the particles. The declining diameter concept is also supported by Zhang (2004) who used piping efficiency ratio (PER, i.e., the piping length to flow rate) to model reclaimed water distribution decisions. PER values of 2–378 were recorded (Figure 3.9). The smaller the ratio, the more economically suitable the potential reclaimed water supply, reflecting the economies of scale for the investment. Zhang et al. (2005) used a theoretical estimate of peak flow derived from a Poisson rectangular pulse (PRP) model to simulate the stochastic process of instantaneous water demands, characterizing the frequency, intensity, and duration of water demands. Those kinds of studies showed a decrease in peak flow with increased users.

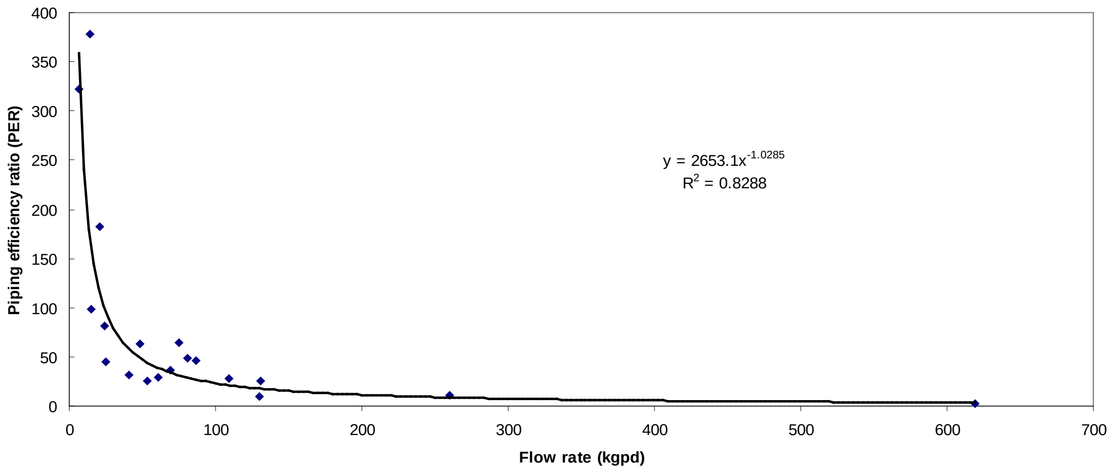

Figure 3.9. Relationship between water flow rates and the piping efficiency ratio (PER).
Source: Based on data provided by Zhang, 2004.

3.3.5.2 Minimizing Retention in Reservoirs

The quality of reclaimed water in reservoirs may decrease over time, especially in circumstances where residence time in storage is prolonged or fluctuates throughout the year. Residence time in reservoirs is dictated by climatic parameters (i.e., rainy season/dry season) and also by the intended use of the water. Stabilization reservoirs can upgrade the quality of the effluents during long residence times within the reservoirs. Stabilization reservoir management provides for continuous or discontinuous input of the water into the reservoir (Juanico, 1996). The intricacies of reservoir management are covered later under operational practices.

Table 3.6. Practices for Controlling Water Retention Time

Method/Practice	Details	Remarks
Altering valves in the network	Travel times and water rerouting as to maximize flow velocities implemented by changing valve arrangements and hydraulic boundaries	Applied in response to a specific problem (i.e., reactive) as opposed to proactively managing retention time and water age
Installing time varying valves	Control valves timed to control the flow	Increases efficiency as physical monitoring and operation are not required; cuts down on labor costs
Flushing	To remove sediments, biofilms, and reduce water age in dead ends and low flow sections of the distribution system; it can be manual (e.g., based on a flushing timetable) or automatically triggered by an event (or timer)	Flushing of reclaimed water systems is currently not permitted in some jurisdictions (Jjemba et al., 2010)
Downsizing mains	Reduce system capacity to increase water velocities	For potable water, engineering design standards require specific pipe sizes for specific parts of the system (i.e., standard minimum size pipes to meet peak diurnal and seasonal demands for drinking and fire flows; Twort et al., 2000); not clear whether similar standards for reclaimed water systems exist or whether those for potable water are the ones directly adapted for reclaimed water
Increase turnover in the reservoir	Reducing strategic storage and managing diurnal storage depending on pump capacity and other resources	May not always be possible as, depending on end use, reclaimed water needs can be seasonal
Reducing the top water level of the reservoir	Reducing the strategic storage level based on the season	Especially in open reservoirs where algal growth can be an issue
Adjusting pump schedules	Optimizing pumping regimes to match supply and demand and minimizing energy requirements	Can be linked to increasing the rate of turnover in the reservoir
Altering the reservoir configuration	Install baffles to avoid dead zones	Applied in response to a specific problem (i.e., reactive) as opposed to proactively managing retention time and water age
Altering the distribution system configuration	Redesign certain sections as to avoid dead zones	Applied in response to a specific problem (i.e., reactive) as opposed to proactively managing retention time and water age

Source: Table modified from Brandt et al., 2004.

3.3.6 Odor Control

Odorous compounds are formed slowly. Thus, retention time can impact their presence indirectly. Solving odor problems in reclaimed water storage and distribution systems should begin by investigating the following:

- How the systems or reservoir was designed
- Whether operation of the systems or reservoir has changed

- Whether odors are apparent on certain days or at certain times and not others
- Whether any part of the system or reservoir has been closed or added

Understanding these questions may provide some clues to solving odor problems. In most instances, the odor is attributable to sulfur and sulfur-containing compounds. Sulfur is an essential component of organic materials present in proteins and some enzymes. Under aerobic conditions, it is decomposed to odorless sulfates. Under anaerobic conditions, however, it is converted to sulfides, notably hydrogen sulfide, mercaptans, and thiols. These gaseous compounds are toxic and corrosive at relatively low concentrations. For example, H_2S may be oxidized to sulfuric acid (H_2SO_4) on the moist surface of the pipe exacerbating corrosion problems (Islander et al., 1991). From a management perspective, anaerobic reduction of sulfate does not take place if dissolved oxygen (DO) or another more thermodynamically favored electron acceptor (e.g., nitrate) are present in water. Thus, aeration to more than 5 mg DO/L can significantly minimize H_2S formation (Rimer and Miller, 2012). Mechanical aeration can be provided by a system, such as SolarBee (Bleth, 2012). Other factors affecting the rate of H_2S generation include pH, temperature, nutrients, organic matter content, time of contact, presence of biofilm on the pipe surface, absence of sulfate reduction inhibitors, and the oxidation-reduction potential (ORP). Sulfide formation in reclaimed water increased rapidly at −140 to −211 mV but was diminished above −100 mV (Elmaleh et al., 1998).

3.3.7 Water Discoloration

Discoloration of reclaimed water can be caused by a number of processes. Most notable is the growth of algae and cyanobacteria, giving the water a greenish color. It can also develop a reddish color because of iron (Fe^{3+}) oxides or a blackish coloration because of manganese (Mn^{4+}) oxides. Increasing pH from 7 to 9 decreases the release of iron. In some instances, coloration is enhanced by stagnation and the associated corrosion.

3.3.8 Salinity

As highlighted in the “Customer Relations and Satisfaction” section, salinity is a serious problem in reclaimed water. Salinity can damage crops and landscape vegetation (Fipps, 2003; Camberato, 2001). Plant damage occurs because of the high chloride and bromide concentrations or indirectly by forming sodic soils. Most tree crops (e.g., avocadoes), vine crops (e.g., grapes, pistachios, and pomegranates), and vegetables (e.g., beans, potatoes, spinach, strawberries, squash, and turnips) cannot withstand high TDS. By contrast, some crops, such as barley, cotton, and Bermuda grass are tolerant to salinity. High TDS can also corrode pipes, cooling towers and other structures. For cooling towers, TDS levels, together with nutrients such as phosphates, affect the cycles of concentration (COC). As TDS increases, the COCs decrease (see the “Metals and Nutrients” section following).

Salinity is measured as TDS (Equation 3.2), reflecting the amount of dissolved minerals in water. TDS is related to electrical conductivity (Figure 6.11), whereby electrical conductivity is a material’s ability to conduct an electric current when an electrical potential difference is applied across it. Total dissolved solids in reclaimed water are attributed to sodium, sulfate, and chloride. A major source of these salts is from the human dietary intake, gray water (through detergents), self-regenerating water softeners, and swimming pools, as well as industrial and commercial discharges. Salts may also be added during the treatment system (e.g., addition of lime) or enter the system through infiltration. For wastewater and reclaimed water, TDS also includes an organic fraction in the form of organic solutes represented by dissolved organic matter (DOM).

DOM is estimated from dissolved organic carbon [i.e., DOM is approximately 2 × dissolved organic carbon (DOC); Thompson et al., 2006]. To account for the effects of high organic content, inorganic dissolved salts (IDS; Equation 3.3) is a better measure of salinity in reclaimed water.

$$TDS = Ca^{2+} + Mg^{2+} + Na^{+} + K^{+} + Cl^{-} + HCO_3^{-} + SO_4^{2-} \quad 3.2$$
$$IDS = TDS - (2 \times DOC) \quad 3.3$$

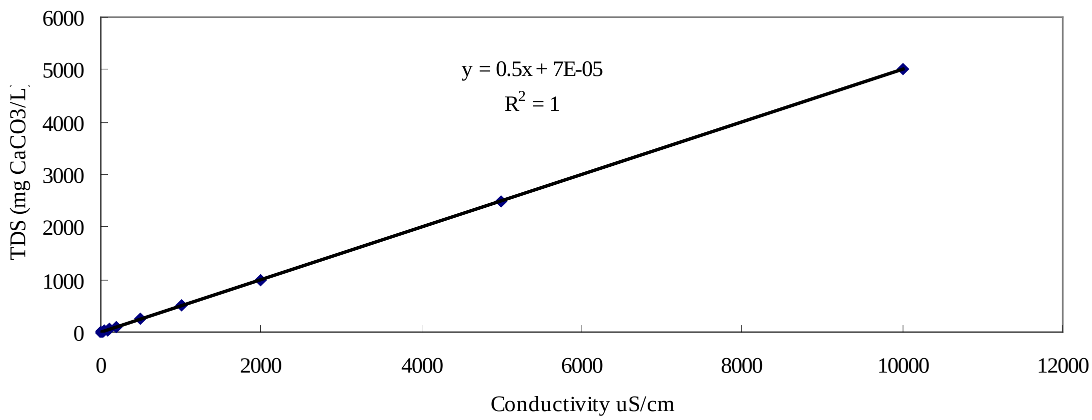

Figure 3.10. Relationship between TDS and electrical conductivity in water.
Source: Based on data from FWI, 2005.

In a survey of 85 reclaimed water utilities, only 25% identified TDS as one of the constraints for use of reclaimed water. A majority had no plans to implement best management practices to limit salinity, 25% had been or were considering such measures, whereas 28% were not sure (Thompson et al., 2006). These findings are not entirely surprising because salinity is not associated with public health and is not included in most of the regulatory guidelines for reclaimed water. Reclaimed water for the surveyed utilities was primarily for golf course irrigation (61%), landscape irrigation (35%), agricultural irrigation (28%), and industrial use (11%). In a follow-up detailed survey, effluent average TDS levels were 768 mg/L.

Typical TDS levels for reclaimed water from various parts of the world are summarized in Table 3.7. Salinity levels for drinking water (100 mg/L), restriction on drinking water (500 mg/L), freshwater limits (1000 mg/L), agricultural water limits (2000 mg/L), mildly brackish water (1000–5000 mg/L), moderately brackish water (5000–15,000 mg/L), heavily brackish water (15,000–35,000 mg/L), seawater (30,000 mg/L), and brine (>50,000mg/L) have been published (Anonymous, 2012b). It is apparent that most reclaimed water TDS (Table 3.7) is within the mildly brackish water range. TDS levels >500 mg/L are representative of salinity conditions under the U.S. EPA's secondary maximum contaminant levels (SMCL) guidelines (U.S. EPA, 2012c). These guidelines are voluntary and only used to assist water systems in managing aesthetic considerations, such as color and odor. High TDS can cause scaling in water pipes, boilers, and heat exchangers, restricting or even blocking water flow. When used for irrigation, high TDS water imparts osmotic stress, reduced soil permeability, and direct toxicity from specific ions (Tchobanoglous, 1994). Thus, high TDS affects crop yields, but from an infrastructure perspective, it also corrodes pipes and other structures. High TDS levels may also contain toxic ions that affect biotic communities (Marshall and Bailey, 2004).

3.3.8.1 Salt Pickup and Management

A major problem with water treatment is the phenomenon of "salt pickup," which is the process by which water gains salts as it passes through the system, typically adding 200–400 mg TDS/L. Therefore, minimizing salt pickup is part of the salinity management process in the reclaimed water industry. Proper assessment of salt loading has to consider flow rates and the size of the area (or population) served by the reclaimed water system. It can be modeled from Equation 3.4:

$$\text{TDS} = \frac{\sum (Input[Flow]) * Input[TDS]) - \sum (Output[Flow] * Output[TDS])}{\sum (Input[Flow] - \sum Output[Flow])} \qquad 3.4$$

Table 3.7. Typical TDS Values in Reclaimed Water

Location	TDS (mg/L)	Conductivity (µS/cm)	Source or Type of Water	End Use	Reference
Cartagena (Spain)	1589±362	2.82±0.26	Secondary effluent	Irrigation	Pedrero and Alarcón (2009)
Campotejar (Spain)	945±54	2.10±0.10	Tertiary effluent	Irrigation	Pedrero and Alarcón (2009)
Yanhu Al Sinayah (Saudi Arabia)	3054	Not reported	Industrial WWTP	Industrial equipment cleaning; cooling; firefighting	Ahmad et al. (2010)
Yanhu Al Sinayah (Saudi Arabia)	1081	Not reported	Sewage treatment plant effluent	Landscape irrigation	Ahmad et al. (2010)
Wadi Shueib (Jordan Valley, Jordan)	1843 (range 324.9 to 7312.9)*	2905 (range 798 to 8310; n=365)	Groundwater recharge	Irrigation	Kuisi et al. (2008)
El-Salaam Canal (Egypt)	Range of 291 to 2556 depending on the season and location downstream	Range of 630 to 3300 µmhos depending on the season and location downstream	Sampled at seven locations; each sampling point receiving a fresh inflow of effluent	Irrigation	Hafez et al. (2008)
Ocotillo Electric Generating Station (Tempe, Arizona)	1725	1149	Reclaimed water from power plant (electric blow down cooling process)	Irrigation and groundwater recharge	Glenn et al. (1998)
Imperial Valley (California)	Range of 3000 to 15,000	Not reported	Agricultural wastewater	Irrigation and surface water recharge	Kharaka et al. (2003)
Las Vegas Valley (Nevada)	1650	Not reported	Return flow from treated wastewater effluent	Surface water recharge	Venkatesan et al. (2011)

Note: *Values calculated from the provided anion and cation data as TDS is equal to the sum of cations and anions.

Various ways to manage salinity include source control, blending, brine line, reverse osmosis, electrodialysis, and avoiding the use of rock salt and potassium chloride-based softeners. Alternatively, patrons should be encouraged to use portable-exchange softeners instead of self-regenerating softeners. Electrodialysis is whereby an electrical potential attracts dissolved ions through ion exchange membranes that are impermeable to water (Burbano and Brandhuber, 2012). However, electrodialysis can be energy intensive; Veerapaneni et al. (undated) presented a linear relationship with the required energy (i.e., $y = 0.004x + 2.432$; $R^2 = 0.977$, where y is electrodialysis energy required in kWh/1000 gal and x is the TDS in mg/L). Based on their estimate, reclaimed water of TDS 1000–5000 mg/L consumes 20–40 kWh/1000 gal.

Thompson et al. (2006) combined the Economic Model and the Water Quality Analyst software program to understand contributors to salinity, as well as the options for mitigating salinity in reclaimed water. The developed tool was used to consider the total TDS removed versus the associated cost. Reverse osmosis is preceded by low-pressure membranes to remove large particles and foulants. The rejected waste is disposed, crystallized, or evaporated. Fox (2013) described the use of template assisted crystallization (TAC) with a device that forms submicron crystals of carbonates. The crystals remained suspended in the water. Initial nucleation was facilitated by polystyrene beads and required temperatures ranging from 60 to 80 ^{o}C, with low watt density (i.e., <5 W/cm^2) to ensure even distribution of heat and scale formation. Scale formation with TAC was reduced by 89% to 97% compared to untreated water.

3.3.9 Metals and Nutrients

The occurrence of higher levels of heavy metals in reclaimed water compared to potable water has been reported (Sacks and Bernstein, 2011). Pereira et al. (2011) reported cumulatively higher concentrations of boron and copper on citrus groves irrigated with reclaimed water compared to those irrigated with well water. Similar incidences of high boron and copper were reported in soils and lemon leaves irrigated with secondary treatment effluents (Pedrero et al., 2012). However, long-term effects and yield differentials can differ greatly from one type of crops to another (Pereira et al., 2012).

Metals, such as magnesium and calcium salts, can precipitate in the reservoir and distribution system, especially where higher than pH 7.94 is maintained (Pedrero and Alarcón, 2009). The accumulated metals can clog irrigation systems. This problem can be remedied by adding acid (e.g., HCl, phosphoric, or sulfuric) continuously into the water system (Haman, 2011). Such acidification can also remove existing scale buildup within the distribution system.

The corrosive nature of reclaimed water because of high concentrations of nutrients (e.g., organic matter, orthophosphate, TDS, and ammonia) has to be controlled for successful cooling recirculating systems. The nutrients also promote microbial growth, enhancing microbiologically influenced corrosion (biofouling). Corrosion can be minimized with inhibitors, such as orthophosphate (Schneider et al., 2007). Other inhibitors are presented in Table 3.8.

3.3.9.1 Effects of Nutrients on Cooling Towers

With cooling towers, the cycles of concentration (COC) are very important, representing the concentration factor for the water in evaporative cooling systems. For example, COC5 implies that recirculating cooling water has five times the total dissolved solids concentration compared to makeup water. The Electric Power Research Institute provided chemical constituent guidelines for water used in cooling towers. These in mg/L include Ca (300), Ca × SO4 (500,000), Mg ×

SiO_2 (35,000), SiO_2 (150), total Fe (<0.5), Mn (<0.5), Cu (<0.1), Al (<1), S (5), NH3 (<2), M alkalinity (30–50), pH (6.8–7.2), TDS (2500), and TSS (100–150) (EPRI, 2003). The pH and M alkalinity are applicable in the absence of corrosion inhibitors. If phosphate is present, the circulating water has to be strictly maintained between pH 6.8 and 7.2 to avoid formation of tricalcium phosphate [$Ca_2(PO_4)_2$], a very persistent scale. For each of these constituents, the maximum number of COC (N) is used to establish the critical cooling tower operating conditions, which represent the makeup and blowdown rates (Equation 3.5). For ion pair limits (e.g., Ca and SO_4), N is calculated from Equation 3.6.

$$\mathrm{N} = \frac{CLimit}{CMU,j} \qquad 3.5$$

$$\mathrm{N} = \sqrt{\frac{CLimit,ij}{CMU,jCMU,j}} \qquad 3.6$$

where CLimit, i = water quality limit for constituent i, CMU, i = concentration of constituent i in the makeup water, CLimit, ij = water quality limit for constituents i and j, CMU, i = concentration of constituent i in source water, CMU, j = concentration of constituent j in source water.

For each of the constituents or constituent pair, the lowest calculated N will be the most limiting for that water. Determining N is critical as it establishes the operating concentration of key constituents and is used to establish flow conditions for the tower (see Equation 3.7). Staying below N minimizes corrosion and scaling of the cooling loop (EPRI, 2003).

As the water evaporates, the salts in the matrix become more concentrated. The cooling tower wastewater stream (i.e., blowdown) is used to mitigate salt concentration. The feed (or makeup) water delivery rate is adjusted to compensate for losses from evaporation, drift, and blowdown. If the evaporation rate (E) and the drift rate (D) are known in gallons per minute (gal/min), the blowdown rate BD, gal/min. can be established from Equation 3.7:

$$\mathrm{BD} = \frac{E}{N-1} - D \qquad 3.7$$

The smaller N is, the larger the blowdown rate, and blowdown is dramatically increased below 4.5 cycles (EPRI, 2003). The makeup rate (MU; or flow balance, gal/min) is then established from Equation 3.8:

$$\mathrm{MU = E + BD + D} \qquad 3.8$$

To predict cooling tower water quality, EPRI developed WinSEQUIL software to address the complexity of cooling system chemistry. The software helps users identify operating scenarios likely to result into scaling from source water by preventing precipitation of ionic moieties because of increased solubility, allowing higher cycles of concentration (N). A search of Google and Web of Science did not show any significant use of this program by reclaimed water plants or power plants, possibly because its full utilization requires an understanding of reaction chemistry and multiphase equilibrium relationships. The situation is remedied with makeup potable water and treatment with chemicals (Hsieh et al., 2010; Li et al., 2011).

Table 3.8. Corrosion and Scaling Control Agents

Corrosion/Scaling	Category	Agents
Corrosion control	Inorganic-anodic	Chromate, nitrite, nitrate, molybdate, orthophosphate, and silicates
	Inorganic-cathodic	Zinc and polyphosphate
	Organic inhibitors	Azoles, amines, and fatty polyamines
Scaling and fouling control	Chelant	Glucoheptonates
	Traditional inhibitors	Amines and fatty polyamines, phosphonates, phosphate esters
	Polymer	Polycarboxylic acid (PCA), polyacrylates (PAA), polymaleic acid (PMA)
	Natural dispersants	Ligno-sulfonates and tannins

Source: Dzombak, 2011.

3.4 Operational Issues

Operation in this instance refers to the systematic design, direction, and control of processes that transform wastewater into reclaimed water. Also included are the processes to deliver the reclaimed water to its intended use. The operational issues pertinent to water treatment, preservation, and distribution are presented in Table 4.2. Working under the assumption that reclaimed water effluents meet high quality standards, this section focuses on operational challenges to ensure maintaining such quality to the point of use. In this regard, the storage and conveyance of reclaimed water become critical for handling a perishable product. However, upstream processes are quite crucial to the quality of water downstream and are at least given a cursory discussion.

3.4.1 Upstream Treatment

Organic carbon greatly impacts reclaimed water quality, influencing color, turbidity, and regrowth of microorganisms. The most labile form of organic carbon, AOC, is a good indicator of the propensity of microorganisms to proliferate in reclaimed water (Jjemba et al, 2010). Weinrich et al. (2010) reported great variability in reclaimed water effluent quality for activated sludge, SBR, and RBC (Figure 3.11). Some AS and SBR systems provided effluents of equal quality with the advanced MBR systems. Those results strongly suggested the tremendous operational differences between plants. It is imperative to understand these management practices.

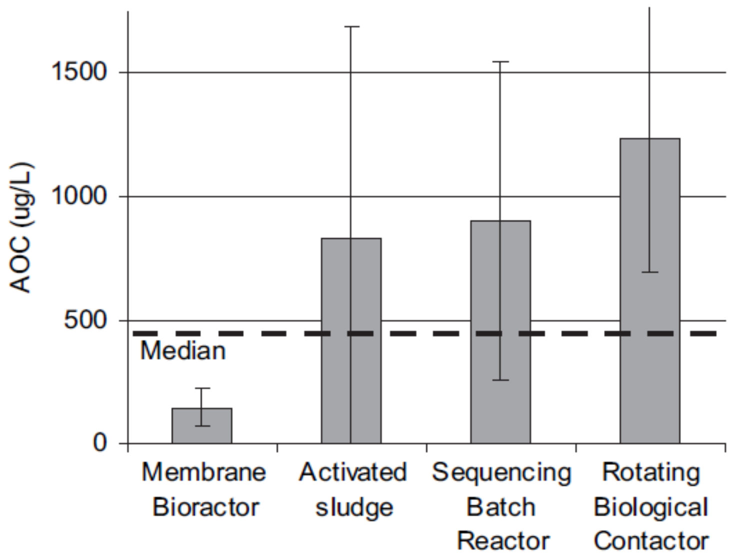

Figure 3.11. Average AOC in effluents from MBR.

Notes: Error bars represent the standard deviation of AOC for each treatment type**;** (n = 3), AS (n = 12), SBR (n = 4), and RBC (n = 2).

Source: Weinrich et al., 2010.

3.4.2 Reservoir Design and Management

Proper storage minimizes regrowth of microorganisms in reclaimed water (Gauthier et al., 2000). Product integrity in the reservoir can depend on the physical design of the reservoir and how it is operated.

3.4.2.1 Reservoir Design Attributes

Grayman (2000) evaluated the deterioration of water quality in the reservoirs. Possible causes of water deterioration under these circumstances include

- loss of disinfectant residual,
- odor production,
- leaching from linings,
- biofilm development on surfaces, and
- sedimentation.

Some of the design recommendations achieve good mixing through either complete mixing or a plug flow. The latter generally loses more disinfectant than the former. The difference in disinfectant loss between the two regimes grows with increasing disinfectant reactivity, increasing ratio of withdrawal time to filling time, and decreasing ratio of maximum to minimum water level. Thus, by default, good mixing reservoirs lose disinfectant at a lower rate than plug flow systems.

3.4.2.2 Baffling Versus Mixing

Internal baffles are mounted in reservoirs to direct and control the flow. However, in reservoirs where mixed flow is preferable to plug flow, introduction of baffles inhibits mixing and can produce stagnant zones. Thus, baffling should, under most circumstances, be avoided in distribution system reservoirs. Water in distribution reservoirs should instead be mixed through the development of a turbulent (as opposed to a laminar) jet. To minimize energy requirements for such mixing, the inlet jet should not be pointed directly toward nearby impediments, such as a wall, the reservoir bottom, or deflectors. Fully turbulent jets are characterized with Reynolds numbers greater than 3000.

3.4.2.3 Stratification

Stratification can be a major problem in reservoirs and conditions that promote it should be avoided. Whenever there is a temperature difference between the contents of a reservoir and its inflow, the potential for poor mixing and stratification exists. Temperature differences result in a buoyant jet. Positive buoyancy is whereby temperature of the inflow is higher than ambient water temperature. It causes the inflow to rise toward the water surface. Negative buoyancy occurs under the opposite conditions and causes the opposite effect. The critical temperature difference (ΔT in °C) can lead to stratification and can be estimated based on the following equation:

$$|\Delta T| = C\,Q^2 / (d^3\,H^2) \qquad 3.9$$

where C = coefficient dependent on inlet configuration, buoyancy type, and tank diameter; Q = inflow rate (cfs or Lpm); H = depth of water (ft or m); d = inlet diameter (ft or m).

On the basis of this relationship, deep reservoirs or ones with large diameter inlets have a greater tendency toward stratification. If significant temperature differences are experienced, then increasing the inflow rate is an effective strategy for reducing the propensity for stratification. Continuous temperature monitoring can be used to assess stratification in reservoirs.

3.4.2.4 Mixing Duration

The duration of mixing in a reservoir ideally should be less than the time it typically takes to fill the reservoir. For a wide range of tank and reservoir designs, experimentation has shown that the mixing time is dependent primarily on the volume of water in the facility, diameter of the inlet, and the rate of flow (Grayman, 2000). Equation 3.10 was developed for cylindrical reservoirs under fill and draw operation whereby V is volume of water in the reservoir at start of fill, Q is inflow rate and d is inlet diameter:

$$\text{Mixing time} = 9\,V^{2/3}\,(d/Q) \qquad 3.10$$

Because of the highly significant effect of inlet diameter and amount of water exchanged during the fill cycle on mixing time, it is recommended that inlet diameters be sized in order to ensure adequate mixing.

3.4.2.5 Managing Detention Time

Long detention times can lead to low disinfectant residuals, even in well-mixed reservoirs. Detention time can be estimated by dividing the duration of an average fill and draw cycle by the fraction of the water that is exchanged during the cycle (Equation 3.11):

$$\text{Average detention time} = [0.5 + (V / \Delta V/)]\ (\tau_f + \tau_d) \qquad 3.11$$

where τ_f is the fill time, τ_d is draw time, V is volume of water at start of the fill period, and ΔV is change in water volume during the fill period (Grayman, 2000).

The detention time then can be used with the disinfectant decay rate to estimate disinfectant residual.

3.4.2.6 Managing Stabilization Reservoirs

Managing stabilization reservoirs can provide continuous movement of water in the reservoir. The operations can be designed for the following:

- Continuous flow (or continuous input) regimes
- Sequential batch regimes whereby water is received by the system all the time, but the reservoir that releases effluents stops to receive water before its outlet is opened
- Quasi-sequential batch regime whereby the input into the reservoir is stopped simultaneously with the opening of the outlet

In testing of these three regimes by Juanico (1996), sequential batch reservoirs in parallel or in series performed best, reducing fecal coliforms, BOD, COD, detergents, and other pollutants to a greater extent.

3.4.3 Flushing the Distribution System

To minimize sediment build up, regular flushing of the pipelines is recommended as part of routine operation of a reclaimed water network. Flushing of distribution systems has the three common objectives of

- replacing stale water,
- removing loose deposits, and
- scouring and cleaning the pipe surface to rid of biofilms.

Flushing should begin from the mains, then proceed to sub-mains, manifolds, and finally to the laterals. Utilities often determine the velocity, duration, and frequency of flushing pipelines with guesswork and generalizations but “site-specific” velocity recommendations may be developed as several processes appear to impact the stability or removability of deposits in distribution mains. Friedman et al. (2003) published a site-specific flushing decision tree. At the root of the tree is establishing objectives for flushing and establishing an applicable flushing velocity. The former can aim at removing loose debris or scouring the pipe wall. The degree of pipe tuberculation and particle density are the two most critical factors for predicting the behavior of loose deposits during flushing. Of less importance is particle size and pipe diameter. Flushing velocities of 2.5–3 ft/s are effective for removing sand and silt debris (Kirmeyer et al., in press). At the bare minimum, flushing should be continued until clean water runs from the flushed line for at least 2 min (Haman, 2011).

3.5 Cost and Pricing of Reclaimed Water

Because it is essential for life, water is a priceless resource. However, a lot of investment goes into its purification, treatment, and delivery. These are the services on which water pricing is, at least in theory, based.

3.5.1 Cost of Producing Reclaimed Water

Water reclamation requires infrastructure layout in the form of plant design, buildings, reactors, equipment, as well as pipes. Electricity, chemicals, personnel, waste management, and maintenance for water reclamation processes also cost money. They are easier to quantify as wastewater is treated through the primary, secondary, and tertiary stages to meet various reuse purposes (Figure 3.12). The higher the level of treatment, the higher the cumulative associated internal costs. However, some of the costs associated with water reclamation are external and not easily quantifiable unless they are examined from an environmental impact perspective (Molinos-Senante et al., 2011). They impact water reuse from a health and environmental perspective.

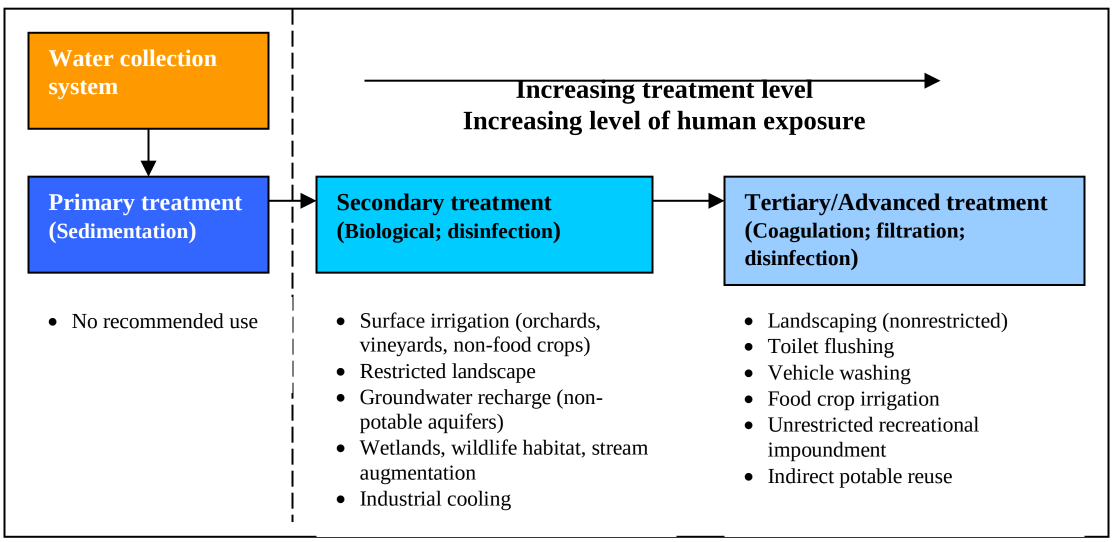

Figure 3.12. General treatment recommendations and types of reuse.
Source: Figure modified from U.S. EPA, 1998.

3.5.2 Pricing Reclaimed Water

Setting reclaimed water rates is important in successfully establishing and operating a reclaimed water system. Oftentimes it costs more to generate reclaimed water than it costs to generate potable water (Cuthbert and Hajnosz, 1999). If the recycled water has to be treated to a usable level just for disposal, then this cost is borne by the users of the sewage system. To that effect, reclaimed water users are only on the hook for distribution system costs and any treatment above that needed for discharge. Furthermore, reclaimed water costs only have to compete with the most expensive source of potable water. To remain attractive and competitive, reclaimed water cannot be priced higher than potable water as, in the eyes of most consumers, it is generated to supplement potable water supplies. Customers also perceive reclaimed water to be of lower quality than potable water. However, potable water quality is not needed for most non-potable reclaimed water applications. Cuthbert and Hajnosz (1999) found actual pricing of reclaimed versus potable water was based on the following:

- A comparable competitive option (i.e., the potable water price)
- Maintenance of a feasible economic alternative
- Incentives for using reclaimed rather than potable water
- Rates that other utilities charge

However, setting reclaimed water prices below production costs creates a shortfall that has to be made up typically through subsidies. The subsidies are indirect (e.g., sewer fees) or directly from the respective utility budget. Cuthbert and Hajnosz (1999) and more recently the U.S. EPA (2012d) identified several types of rates for pricing reclaimed water (Table 3.9). These have more recently been characterized as volumetric fees (U.S. EPA, 2012a). Flat rate was the most predominant practice followed by the seasonal rate structure (Cuthbert and Hajnosz, 1999). However, at the time of that study, connection fees, assessment fees, and impact fees were not a common practice. These three practices were only recently highlighted by the U.S. EPA (2012a).

Table 3.9. Common Reclaimed Water Rate Types

Type of Rate	Description
Flat rate	A fixed amount of money is paid by the customer over a fixed duration (e.g., $7/month) irrespective of the amount of water used; therefore, provides for an unlimited use
Commodity-based rate	A fixed amount of money is paid per unit volume of water, e.g., $0.44 per 1000 L; generally for commercial and industrial users
Base plus volume charge	A fixed base charge plus an amount of money charged per unit volume consumed, e.g., $3.25 plus $0.02 per 1000 L
Seasonal rate	A lower rate charged per unit volume used up to a certain volume; thereafter, a slightly higher rate charged for medium volumes consumed; an even higher rate charged for larger volumes used, e.g., $0.27 per first 1000 L (low volume rate). $0.32 per next 1000 L used (medium), and $0.41 per L thereafter; generally for commercial and industrial users
Declining block rate	Rates decline as more volume of water used, e.g., $0.13 (first block); $0.03 (second block), $0.02 (third block); typically used for agricultural purposes
Inverted block rate	Rates increased as more volume of water used, e.g., $0.16 (Tier 1); $0.20 (Tier 2), $0.41 (Tier 3), 0.82 (Tier 4), and $1.64 (Tier 5); most suited for non-agricultural purposes
Time-of-day-based rate	Different rates under varying demand scenarios, e.g., $0.34 during peak demand and $0.31 during off-peak hours; peaking customer had total average daily demand occurring between 9:00 p.m. and 6:00 a.m., whereas off-peak customers occurring at a continuous 24 h period
Take-or-pay-based contracts	Customer-negotiated rates and terms under service agreements; can be a single rate or a multilayered complex rate structure depending on water demand and supply, quality, or a variety of other factors
Customer-specific negotiated rate	Rates varying or remaining fixed based on negotiated agreements
Connection fees	A one-time fee for each user before they are connected to the system
Assessment fee	To defray capital cost of the reuse system
Impact fees	Covers cost of wastewater treatment and disposal (i.e., sewer rates)

Source: From Cuthbert and Hajnosz, 1999; U.S. EPA, 2012a.

Many utilities set reclaimed water rates based on market analysis or what customers are willing to pay. The average reclaimed water rates in 2007 ranged between 50 and 100% of the potable water rate, and 42% of respondents set their reclaimed water rates to promote the use of reclaimed water (HDR, 2008). Of 89 utilities studied, most recovered less than 25% of their operating costs. However, the pricing did not include significant necessary expenses incurred or savings realized by utilities including the cost of purchasing water rights to new supplies (applicable in the western United States) replaced by the reclaimed water. Also not reflected was the reduction in the National Pollutant Discharge Elimination System (NPDES) permitting, permit fees, outfall dilution and mixing requirements, environmental mitigation, human health protection, and more difficult outfall construction avoided by reusing all or a portion of what would have been discharged (Chen and Wang, 2009). These beneficial factors are typically nonmonetary but Chen and Wang (2009) monetized them and found them economically advantageous. Similar approaches and conclusions have been reported by Liang and van Dijk (2008) and Molinos-Senante et al. (2011).

Overall, designing reclaimed water rates has to put several things into considerations as highlighted by HDR (2008):

- Rates that are easy for the customers to understand
- Rates that are easy for the utility to administer
- Consideration of the customer's ability to pay
- Policy considerations (encouraging conservation and economic development)
- Revenue stability from month to month and year to year
- Rates that are equitable and nondiscriminating (cost-based)

If reclaimed water rates were set at the cost of service, they would be higher than potable water rates because of the increased treatment required, as well as the cost of a secondary distribution system. The cost difference will have to be generated from other sources, whether through the potable water rate, wastewater rate, municipal or regional subsidy, state or federal subsidy, or others. To encourage reclaimed water use, many utilities provide some level of technical support or assistance to their customers in the form of installation and conversion of equipment, financial assistance with conversion to reclaimed water system, or ongoing rate assistance.

Results of an extensive search for potable and reclaimed water rates for some cities in the United States where water reclamation is rampant are presented in Figure 3.13. The figure shows that in 2012 reclaimed water was less expensive in all cities for all user types except for the single-family rate in Tucson, AZ. The discrepancy in Tucson may be explained by the cost of the new construction necessary to deliver to single-family homes. The largest difference in price was found in San Diego, CA, where reclaimed water cost about 78% less than potable for all user types. There is increasing recognition of the need for generating sufficient revenues from reclaimed water systems to provide annual capital improvements, operating and maintenance, repairs, working capital, and reserves (U.S. EPA, 2012d). This requires equitably distributing the cost of water services based on cost-of-service principles. This strategy strengthens the water portfolio.

3.5.3 The Water Portfolio

Traditionally, wastewater systems have made agreements with reclaimed water customers at little or no cost as a means to dispose of wastewater effluent. This situation is changing because of recognition of reclaimed water's role as an important component of an integrated water resources planning. In a majority of instances, the economic value of reclaimed water to the user depends on (1) the availability and price of freshwater supplies and (2) the reclaimed water supply characteristics. According to the Institute of Public Utilities, the amount individuals pay for potable water in the United States is rising faster than the rate of inflation. It also is rising faster than the amount paid for any other utility service including gas, electricity, cable, or telephone charges (Beecher et al., 2012). Reclaimed water may be more attractive than potable water for some uses based on other characteristics, such as nutrients and a variety of environmental benefits associated with reusing water (U.S. EPA, 1998; Axelrad and Feinerman, 2009; Chen and Wang, 2009).

It is apparent from this cost and pricing discussion that costs of reclaimed water compared to potable water should be discussed in a portfolio context. Under that context, the question becomes what happens to cost when potable water is not an option. Thus, consideration of the costs of alternative water supply and wastewater management that are avoided by adapting reclaimed water is factored into the water demand and supply equation. This approach avoids straight costs in favor of a cost–benefit analysis. For example, Orlando, FL, showed an average residential irrigation demand of 506 GPD compared to 350 GPD for in-house use (Anonymous, 2012c). In this instance, using reclaimed water to meet irrigation needs, a process that does not have to use potable water, can reduce residential potable demand by almost 60%, conserving potable water resources.

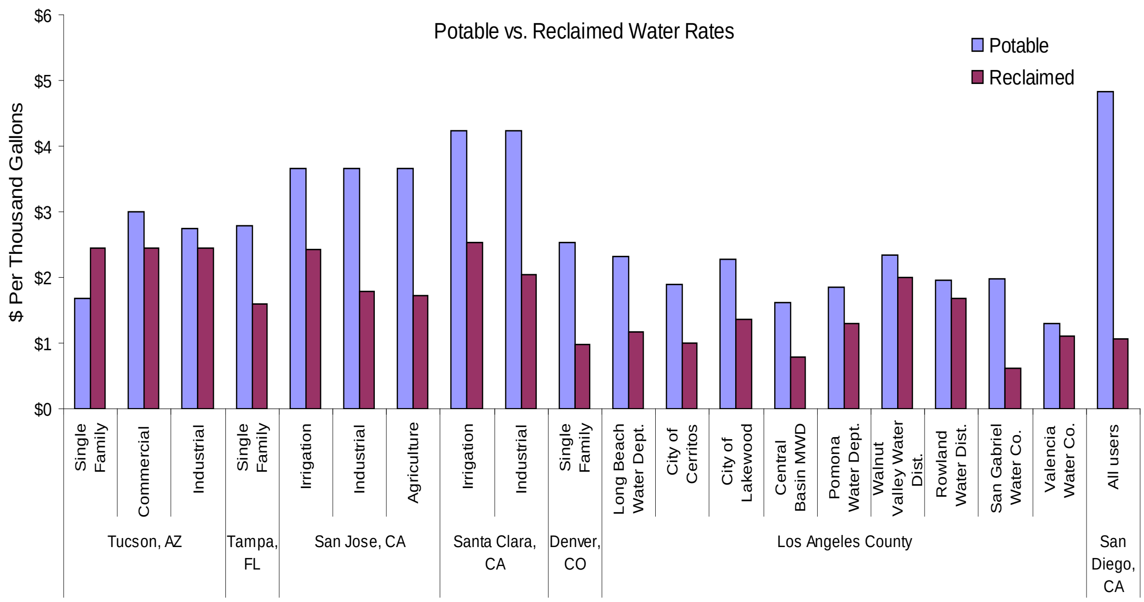

Figure 3.13. Potable versus reclaimed water rates.

Sources: Compiled from: http://cms3.tucsonaz.gov/water/reclaimed; http://www.sanjoseca.gov/sbwr/rates.htm; http://www.tampagov.net/dept_water/information_resources/rates_and_fees/index.asp; http://www.denverwater.org/BillingRates/RatesCharges/2012Rates/NonPotable/; http://www.lacsd.org; and http://www.sandiego.gov/water/recycled/faq.shtml#else).

3.6 Production Capacity and Supply

Depending on the intended use, weather conditions, influent availability, and other factors, reclaimed water supply and demand can change dramatically. Some reclaimed water utilities with chronic shortages continue to add new customers, making the shortages even more severe (Ammerman and Ceather, 2009). The limitations of supply and demand can be mitigated by integrating the potable and reclaimed water systems (Kuo and Smith, 1998; Ng et al., 2007a, b; Argaez et al., 1999; Foo et al. 2006). Using GIS, Zhang (2004) modeled reclaimed water use and distribution for Waterloo (Canada) by calculating the shortest paths between any pair of source and sink in the network. The stochastic modeling approach satisfied water demand and quality. It also helped decision makers in managing water supply uncertainties associated with different levels of demand. Optimal allocations (in light of potable and reclaimed water sources) for each receiving facility were established under various constraints, such as capacity, quality, demand, and network balance, to generate a composition of water supply (Figure 3.14). The model takes in consideration the cost of delivering water to different locations, intended use, distance from the plant or reservoir, piping efficiency ratio (i.e., piping length to flow rate), and desired quality. From this model, it is apparent that residential 2 (RE-2) received most of their demands from reclaimed water compared to RE-1 and RE-3, which are located farther away from the reservoir.

That decision not only cuts down on the cost for delivering reclaimed water to RE-1 and RE-3 but also ensured that most of the reclaimed water to residences went to close proximities to minimize water age and degradation. By contrast, golf course 2, which was located within the same vicinity as RE-3, received 100% of its needs from reclaimed water, as irrigating that golf course had lower quality requirements compared to what was demanded at a residential facility.

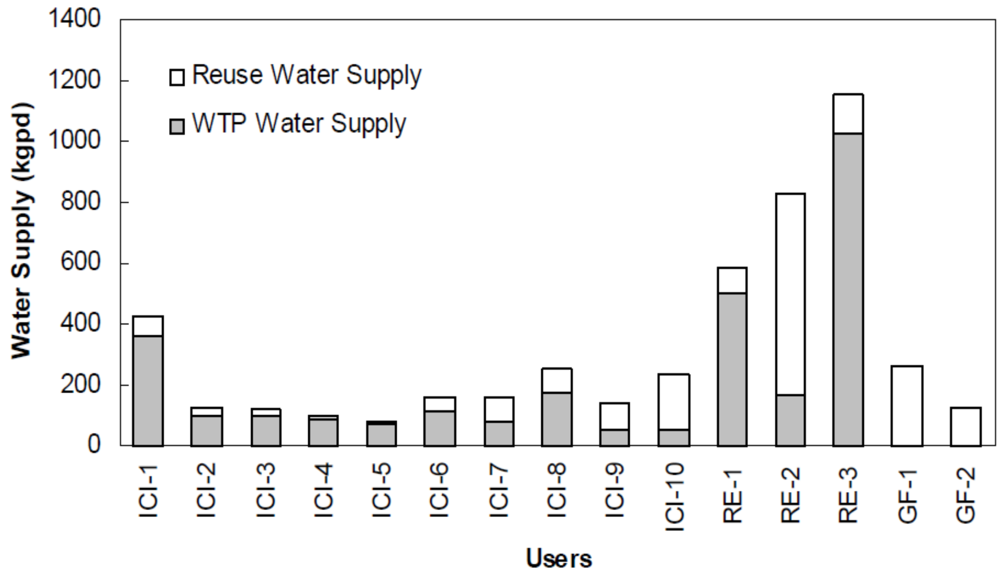

Figure 3.14. Daily water supply to 15 users in Waterloo.

Notes: ICI = industrial/commercial/institution, RE = residential, and GF = golf course.

Source: Zhang et al., 2005.

Zhang (2004) further used the mean demand per user (μ), coefficient of variation (CV), and corresponding standard deviation (σ; Note σ =CV × μ) to determine the relationship between demands among the users in the system so as to minimize uncertainty.

$$r_{i,j} = \frac{Cov(x_i, x_j)}{\sigma_{xi}\sigma_{xj}} \qquad 3.12$$

where *r* is the correlation coefficient, $Cov(x_i,x_j)$ is the covariance of variables i and j.

3.7 Regulatory Challenges

The pertinent regulatory issues raised by the reuse industry are summarized in Table 4.2. There are no federal regulations governing water reclamation and reuse in the United States, although the U.S. EPA has published and upgraded guidelines for water reuse (U.S. EPA, 2004, 2012d). Reclaimed water standards and guidelines vary among states, although states with extensive reuse experience tend to have similar conservative guidelines. Many state water reuse regulations specify both reclaimed water quality limits and treatment process requirements. Some states, such as Texas and New Mexico, do not require certain treatment processes and rely only on water quality limits.

Not directly reflected in these reclaimed water regulations and guidelines are impacts from cooling systems. Cooling systems may involve all environmental media (i.e., air, water, and land), with potential public health effects. To that effect, cooling towers are subject to many guidelines and regulations directed toward cooling towers in general and not exclusively aimed at those using reclaimed water. At the federal level, the most notable are the Clean Air Act, the

Clean Water Act, the National Emissions Standards for Hazardous Air Pollutants (NESHAPS), as well as the Resource Conservation and Recovery Act. Drift from reclaimed water cooling towers may pose concern as some organisms in reclaimed water are most efficacious through aerosols. To limit bacterial activity in aerosols leaving the tower (as drift), U.S. EPA guidelines recommend a minimal residual of 1 mg chlorine/L in the reclaimed water feedstock to the cooling tower. These disinfectant levels limit fecal coliforms to ≤200 cfu per 100 mL (daily monitoring). Several states have also developed their regulations applicable to reclaimed water use in cooling towers. State regulations are typically focused on minimizing water aerosol emissions. Of most concern is the potential release of airborne pathogens, such as *Legionella* and *Mycobacterium*.

3.8 Workforce Issues

Several workforce problems were identified by the utilities (see Table 4.2). The education and training requirements for water professionals in all 50 states typically require reclamation operators to go through licensing requirements. Although requirements vary from one state to another, a common theme is the convoluted licensing process for these professionals.

Utilities must plan and prepare for the impending demographic shift and workforce gap. To accomplish this, utilities should identify and retain critical operational knowledge. Knowledge is different from information (data and facts) in that knowledge is the capacity to make effective decisions (Frigo, 2006). There are three types of knowledge key to a utility:

- Technical knowledge (e.g., individual capabilities and skills to operate a particular pump)
- Social knowledge (e.g., individual's ability to interact with other people and to fit into the social networks of organizations)
- Structural knowledge that is embedded in an organization's systems, processes, policies, and procedures. Structural knowledge tends to be explicit or rule-based (e.g., knowledge of how to follow the procurement process at a specific utility)

To ensure continuity of a talented and well-trained workforce, the Gwinnett County, GA, reuse facility resolved to maintain an annual training budget line that could not be eliminated over time by management. That guaranteed retraining to address long-term maintenance without the staff becoming complacent (Hartley, 2006).

To determine the scope of the effect of workforce changes, utilities must use a variety of tools including retirement profiles, tenure profiles, and critical knowledge at-risk profiles (Frigo, 2006). Retirement profiles quantify the percentage of people who are, or will soon be, eligible for retirement (Figure 3.15). On the basis of Figure 3.15, the utility has a critical workforce issue, as nearly 50% are eligible for retirement within the next 5 years. The risk of losing critical knowledge increases as the percentage of personnel eligible to retire within five years increases. Tenure profiles quantify the levels of utility staff experience. The tenure profile in Figure 6.16b shows a high percentage of personnel who either have little (<10 years) or a significant amount (>20 years) of tenured experience. If the highly tenured personnel were to leave, the organization could suffer from a lack of organizational knowledge.

In light of an aging reclaimed water workforce, innovative strategies for water utilities to recruit and retain qualified workers across different generations are needed. Competency modeling offers a way to improve human resource management and development. A recently completed water sector competency model highlighted six key generic positions and tools: water treatment plant operator, distribution system operator, process control (such as data acquisition) specialist, instrument technician, water plant supervisor, and mechanical maintenance technician (McTigue and Mansfield, 2011). In addition to the six prototype competency models, the Internet sites www.waterrf.org and www.eetinc.com/competency include guidance and materials that utility staff can use to develop and implement competency modeling in water utilities. Adapting these models may help alleviate some labor shortages in the wastewater/reclaimed water industry.

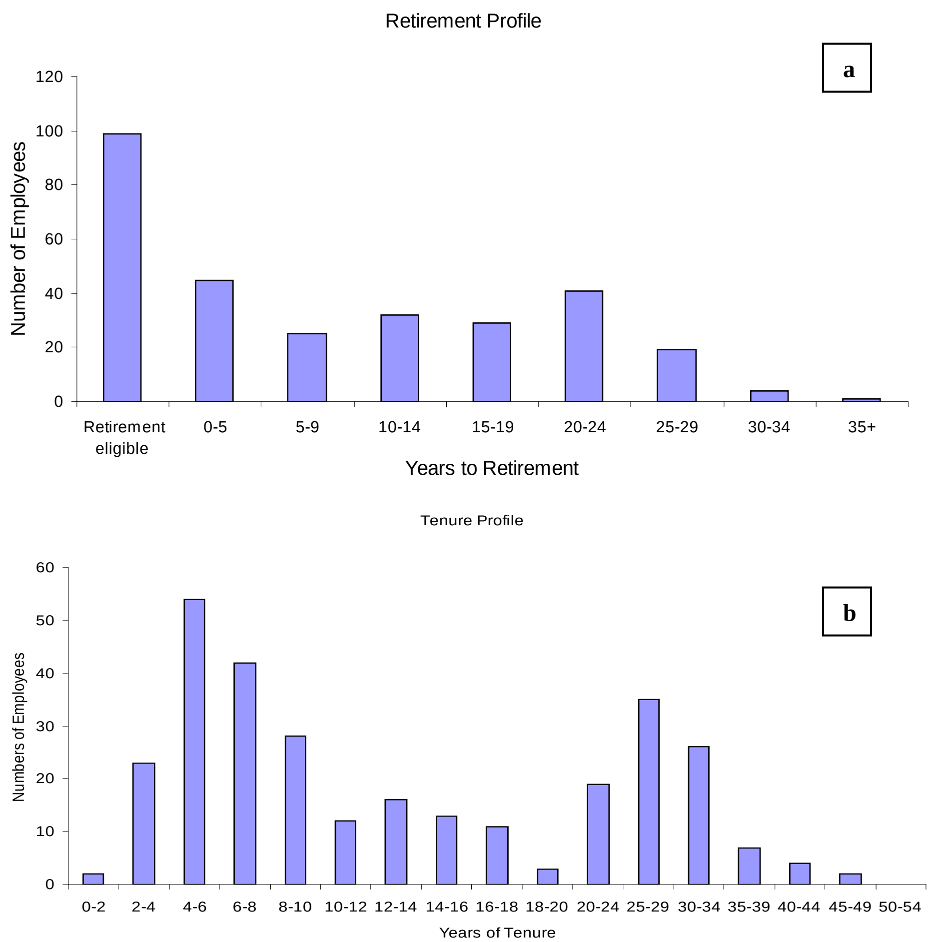

Figure 3.15. Example of a (a) retirement profile and (b) tenure profile.
Source: Adapted from Frigo, 2006.

Besides the traditional sources, H2Opportunity.net has expanded the labor pool for the water industry as a whole Developed by the Georgia Association of Water Professionals (GAWP) in 2008 (Davis et al., 2009), the site has the following features:

- Information for college and vocational students about scholarships, job banks, student chapters, and young professionals groups, as well as the opportunity to participate in a blog
- Links to databases with information on current job openings in the water industry
- Opportunities to explore potential career paths by linking to descriptions of a variety of job classifications in the water industry
- Opportunities to ask professionals about water and careers in the water industry

3.9 Other Miscellaneous Issues

Lack of recognition for water conservation efforts and monitoring wells to minimize the impact of fertilizers applied on golf courses were also identified as important issues. Although these issues could not directly fit into the other eight broad interest areas, they are important in keeping employee morale up and meeting discharge permits, respectively. They can also enhance acceptability of reclaimed water by the general public, widening the industry's range of stakeholders and customer base.

Chapter 4

Management Practices for Reclaimed Water Systems

Out of 341 individuals surveyed, 71 responded, a 20.8% response rate. Most respondents were from California (26%), Florida (23%), Arizona (17%), and Texas (10%) (Figure 4.1). Colorado and Washington each had 7% of the respondents. Australia contributed 3% of the respondents. Idaho, North Carolina, South Carolina, Nevada, and Virginia had one respondent each. The proportions seem very much in line with water reuse nationally. The respondent location dots are coded (available in color for electronic version of the report) to various stages of the selection process; the red dot sites participated in the initial questionnaire but were not considered in subsequent phases of the study.

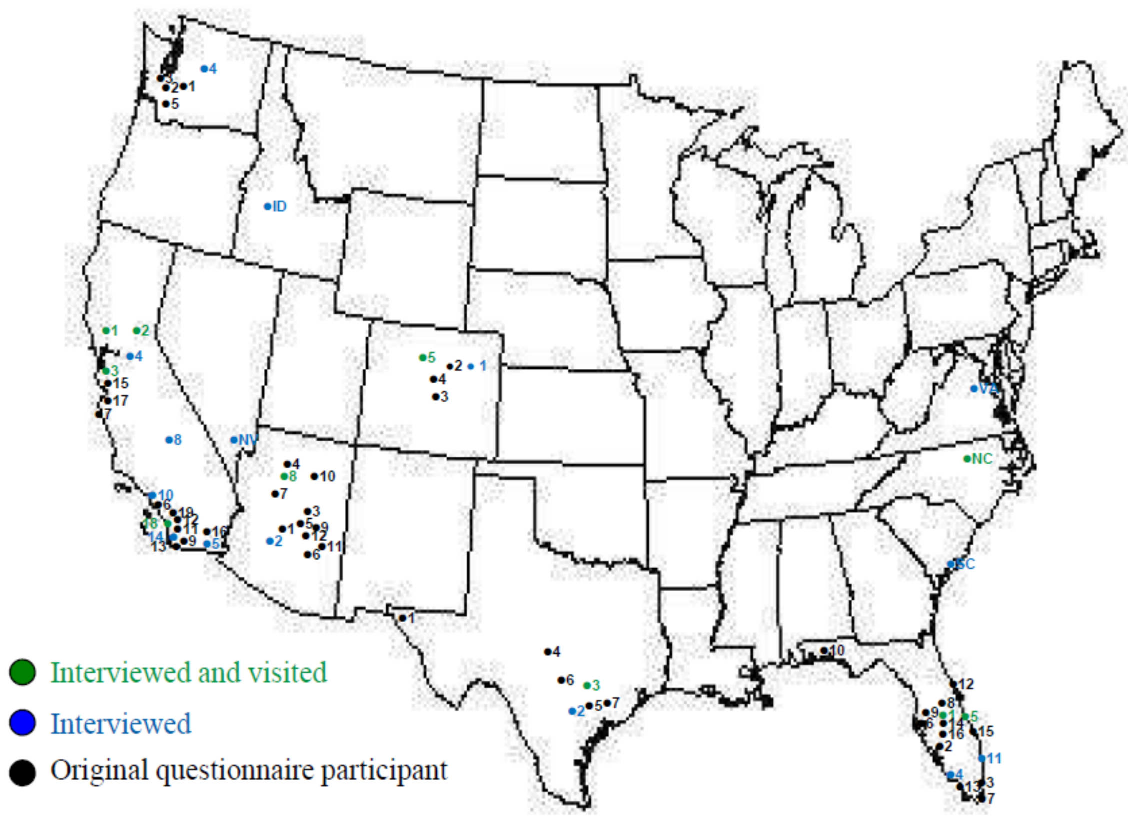

Figure 4.1. Distribution of U.S.-based respondents to the online questionnaire.

Notes: Excluded are two respondents from Australia. The respondent location dots are color-coded (available in color for electronic version of the report) to various stages of the selection process.

Most systems were categorized as large or very large (Figure 4.2). Eighty-three percent of the utilities surveyed used activated sludge (AS) alone or in combination with media filtration as the treatment process (Figure 4.3). AS combined with filtration media was a common treatment strategy in water reclaiming plants. Other combinations with AS that occurred at similar frequency (3%) included AS+SBR, AS + Lagoon, AS + RO, and AS+SBR+media filtration. AS+MBR, AS+MBR+media filtration or AS+Rotating biological contactor + media filtration were least (1.5%) frequent. An MBR is a modified version of an AS system with combined membrane filtration and a combined set of advantages, such as the ability to operate at higher mixed liquor suspended solids (MLSS) compared to conventional AS and longer solids retention time. This modification results in complete nitrification, reduced sludge production, and superior effluent quality compared to conventional AS. Providing a media filter can reduce the levels of assimilable organic carbon (AOC) and, through physical and chemical processes. also reduce the level of trace organic compounds. The only utility that did not use AS predominantly used media filtration alone (13.8%) or media filtration combined with sequential batch reactor (SBR; 3%).

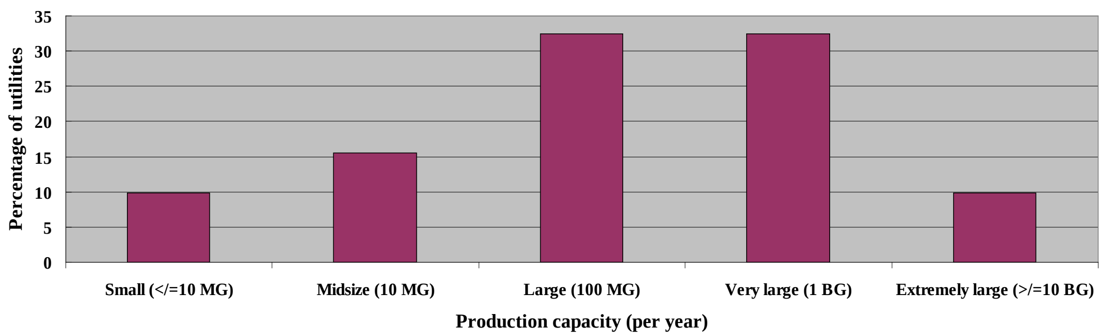

Figure 4.2. Industry-wide utility production capacity profile.

Notes: System size categorized as small ($\leq 10^7$), midsize (10^7), large (10^8), very large (10^9) and extremely large ($\geq 10^{10}$) gal/year.

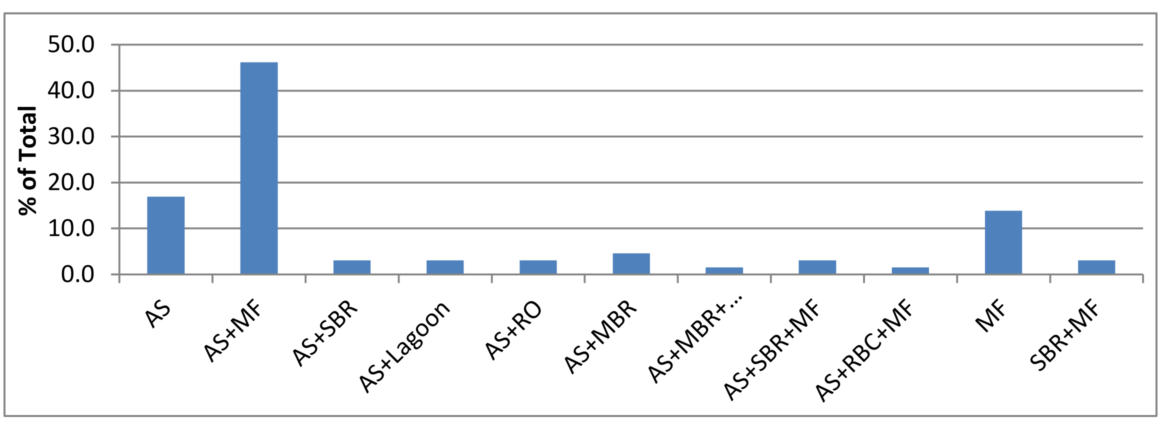

Figure 4.3. Frequency of use of wastewater treatment processes.

Chlorine was the dominant disinfectant (80% of the utilities), although a few utilities combined it with UV or ozone (Figure 4.4). Seven percent of the utilities used only UV disinfection, but more than three times as many utilities combined UV with another disinfectant, such as sodium hypochlorite, to provide a residual. A few (13%) other utilities did not disinfect or disclose information about disinfection practices.

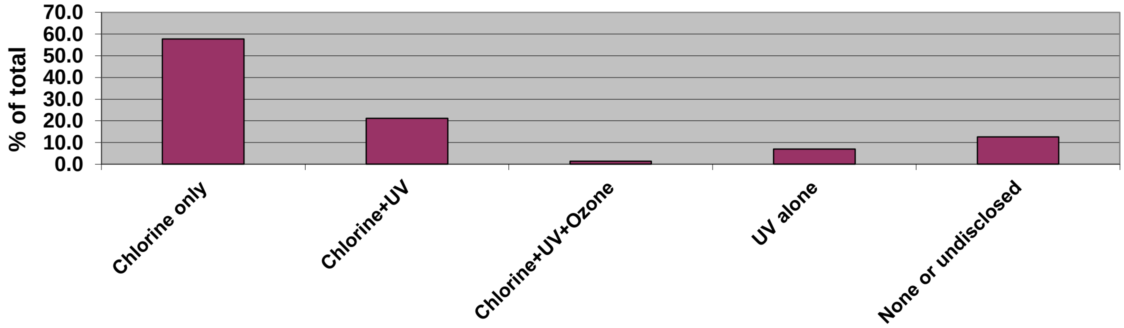

Figure 4.4. Disinfectants used by the reclamation industry.

Reclaimed water may not be used right away, requiring storage. Typically, the reclaimed water remained in the reservoirs for 1 to 120 days, with the longer durations often occurring during winter. It may also be delivered several miles away from the treatment plant. Most of the utilities (52.1%) had more than 10 mi of distribution system pipeline, 14.1% had pipelines of 6–10 mi, and the rest had 5 mi of pipelines or less. The reclaimed water systems were by design linear (i.e., from the plant directly to a reservoir), branched, or looped. The distribution system was mostly branched (62% of the utilities) and only 10% of the systems were looped (Figure 4.5). Some utilities (15.5%) had both branched and looped distribution portions of the system. Depending on storage practice and system configuration, reclaimed water could remain in the system for an extended duration. However, most (73.2%) of the utilities did not conduct any additional treatment after the effluent had been stored. Where conducted, post-storage treatment primarily involved disinfection with UV, chlorine, or sodium hypochlorite. One of the utilities filtered the stored water prior to disinfection and pumping into the distribution system.

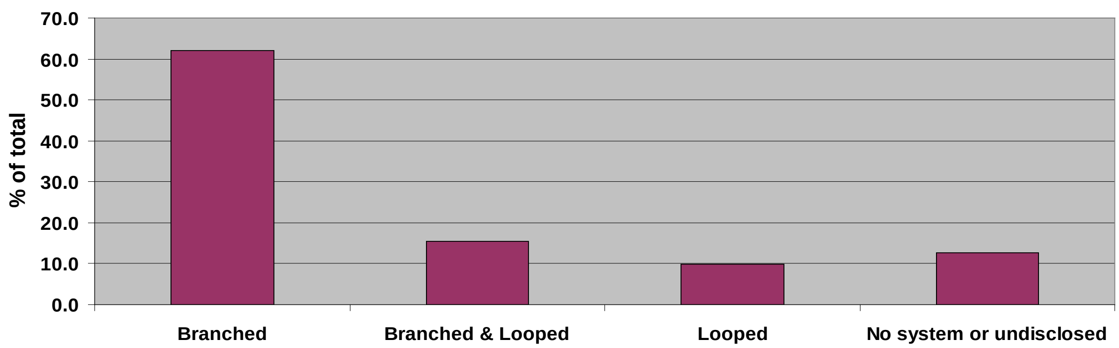

Figure 4.5. Reclaimed water distribution system configuration.

A limited number (18.3%) of utilities reported multiple pressure zones. Most (83.3%) of these multiple pressure-zoned systems also had at least 10 mi of pipeline. At the systems that did not disinfect or disclose their disinfection practices, the reclaimed water was stored in open or closed reservoirs generally located aboveground (Table 4.1). The water was used primarily for landscape irrigation, fountains, construction, and groundwater recharge. Most of these utilities also provided minimal information in a number of other aspects during the survey (see Section 4.1).

Table 4.1. Reclaimed Water Use Storage and Use at Locations without Disinfection

Utility	Reservoir Characteristics	Reclaimed Water Usage
CA-8	Open; aboveground	Landscaping/Irrigation and groundwater recharge
CA-11	Closed; aboveground	Landscaping/Irrigation, fodder, and construction
CA-12	Closed; aboveground	Landscaping/Irrigation, industrial, and fountain
TX-5	Not provided	Landscaping/Irrigation
AZ-10	Open	Landscaping/Irrigation
CA-16	Aboveground	Landscaping/Irrigation
TX-6	Aboveground	Landscaping/Irrigation
AZ-12	Not provided	Not provided

4.1 Key Operational and Distribution System Problems Facing the Industry

Operators and utility managers were a valuable source of information about operational, storage, and reclaimed water distribution issues. To maintain focus, the survey limited requested information about this aspect to the top three issues or challenges for each utility. Most of the utilities identified at least three major problems or issues, and a majority (72%) of systems had multiple issues (Figure 4.6). A total of 155 problems were identified (Table 4.2). They varied widely in nature, magnitude, and complexity. Ultimately, they were classified into eight major categories. The frequency of occurrence of the problem reflected the importance of each category compared with the other categories. Infrastructure issues were most frequently identified, followed by water quality, customers, operations, cost, capacity/supply, regulations, and workforce.

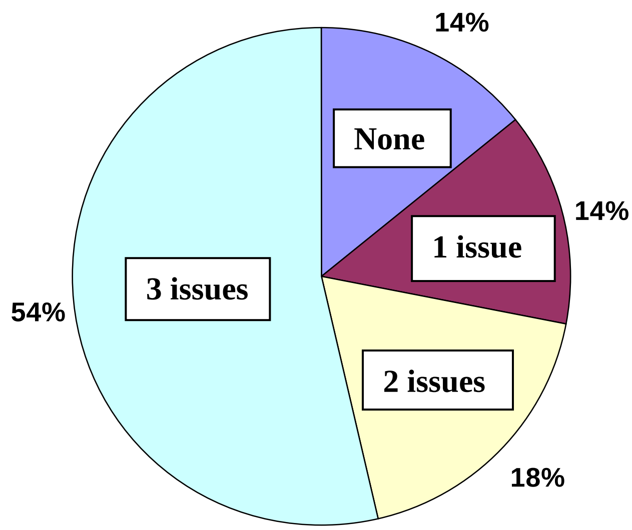

Figure 4.6. Distribution of major issues identified through the initial industry-wide survey.

4.2 Utility System Clusters

A total of 45 clusters were developed based on the UPGMA system (Figure 4.7). Details about the common attributes within each cluster are summarized in Appendix C. The closer the utilities were on this clustering tree, the greater the similarity in their attributes. For example, the two utilities at the top (CO-1 and WA-4) were large, activated sludge utilities with open reservoir, long-branched or looped distribution system. Both utilities disinfected with UV or a combination of UV and chlorine. Similarly, the bottom of the tree showed TX-9 and AZ-12 in the same cluster. In general, both of these systems provided minimal information about themselves in the questionnaire, but both were small utilities. The former had a short-branched distribution system. Whereas CO-1 and WA-4 both had the greatest similarities, in this example they both had the least degree of similarity with TX-9 or AZ-12.

On the basis of cluster analysis alone, 27 of the original 45 clusters were selected as candidates for further evaluation through a more detailed phone interview whose results are reported in the next chapter. Specifically, for each cluster with ≥2 utilities, frequency of issues or problems provided by respondents were used to develop a quantitative score whereby infrastructure, water quality, customer, operations, cost, capacity or supply, regulations, workforce, and miscellaneous issues or problems obtained in Section 4.1 were used in order of frequency to assign a score of 1, 2, 3, 4, 5, 6, 7, 8, and 9, respectively. The cumulative scores are presented in column 6 of Appendix C. Thirty-one utilities were selected for the phone interview phase. Both utilities in clusters 1 and 37 were selected, as they had the same score.

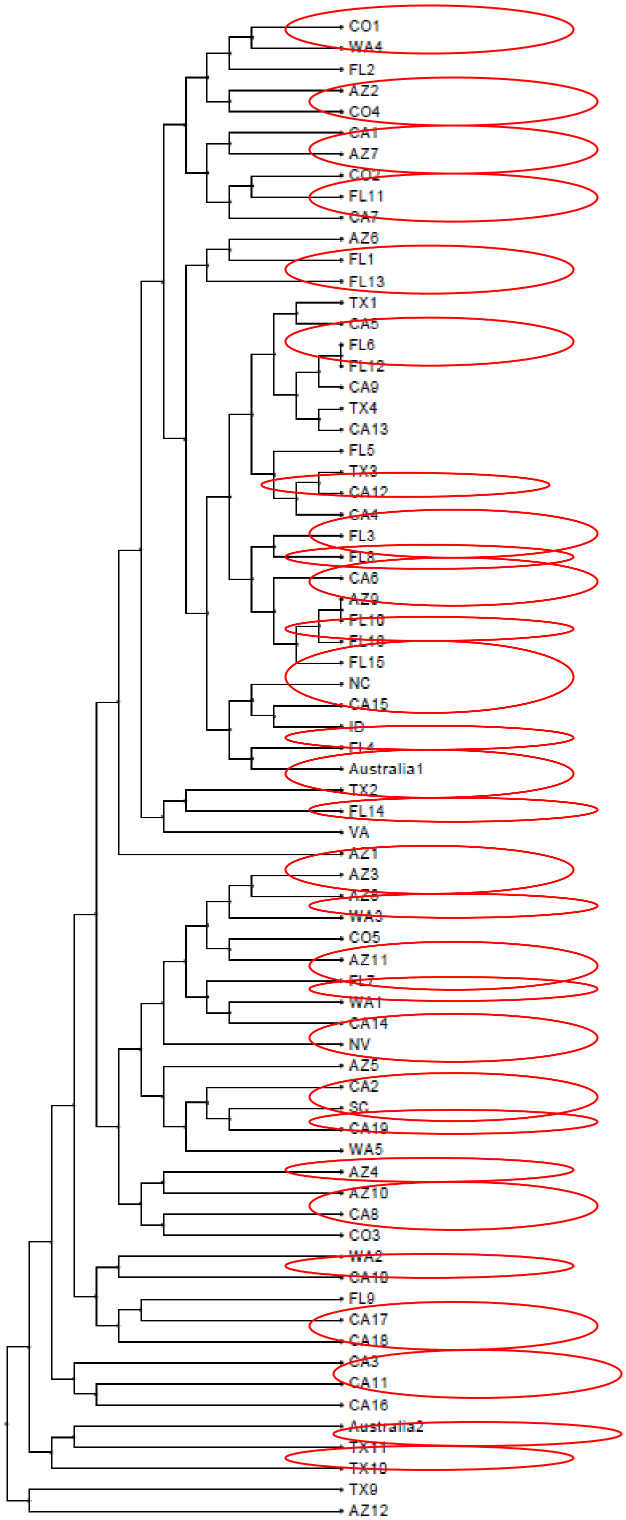

Figure 4.7. Classification of the 71 utility systems (coded by state or country) using cluster analysis.
Note: The highlighted clusters were selected as candidates for advancing into the phone interview phase of study.

Table 4.2. Summary of Operational and Distribution System Issues and Problems Identified by Reclaimed Water Utilities

Category	Generic Issues and Problems Identified	
Infrastructure (21.9%)	• Distribution pressure (low or inconsistencies) • Nonlooped distribution system (associated with a lack of redundancy on supply) • System pressure to end users (particularly at end of the system) • Cost to extend system to potential customers • Branched distribution system; distribution system limitations • Pressure fluctuations • Infrastructure/equipment deterioration from high chlorine residual • Corrosion of metal components in distribution system • Lack of enough storage	• Managing cross connection (especially beyond customer meter) • Challenges in conveying water to recharge (or reuse) site • Surges in reclaimed water pressure • Frequent leaks in chlorination system (liquid feeds) • Damage to transmission mains (by contractors) • Cross-connection control; meeting the total coliform limits of <23 daily and <2.2 monthly • Water quality (requirements) for cooled water chillers (CWCs) and industrial cooling unclear; inadequate metering in cases where users may be located further apart • Finding cost-effective means to expand distribution system to more customers
Water Quality (17.4%)	• Growth of algae and other aquatic organisms in reservoir • High corrosivity (toward metals including specific cut-off valves) • High salinity/TDS/salts (and effects on plants) • Managing nutrient (ammonium, nitrate) levels • Reducing TDS/managing salts; poor quality at end of branched system; inadequate chlorine residual • Biofilm concerns	• THM production in the system (because of chlorination requirements) • Sulfide odors from irrigation systems operated biweekly • Maintaining quality in reservoir • Not enough nutrients to keep the grass green • Lack of information on water quality parameter requirements for discharge
Customers (17.4%)	• Customer dissatisfaction with the water • Public perception (sewer water) and acceptance • Misconceptions about availability of reclaimed water services • Satisfying customer demand in late summer • Educating customers about overwatering/watering days and restrictions • A high variability in system (customer) demand	• Meeting demands set by customers; demanding end users • Getting customers to convert to reclaimed water • Expanding uses for reclaimed water • Customers not utilizing reclaimed water to full capacity • Drought • Widening the customer base (e.g., getting industrial or cooling tower customers to use reclaimed water)

Category	Generic Issues and Problems Identified	
	• Customers not following the rules • Lack of policing against watering day violations	• Customer practices, such as poor control of runoff from properties • Minimal winter demand
Operational (11.6%)	• Handling solids; maintaining chlorine residual in the distribution system • Adequate storage of rechlorination tablets • Dealing with high flows • Coordination with wastewater utility (supplier) • Wet weather disposal • Setting pump to operating levels that turn over the tank more frequently • Debris in distribution system and clogging of irrigation heads and meters • Concerns about how numeric nutrient criteria may affect treatment requirements	• Managing reclaimed water supplies during the dry season when demand is greatest • Reduced flow volume because of water conservation • Debris that gets into the system because of trappings requiring flushing operations for removal • Lack of clarity on who should maintain the system (i.e., sewer or water) • Variability in treatment operations that is centered on disinfection variables • Down time because of increased backwash frequency in summer months
Cost (11.0%)	• Current rates unable to cover costs • High capital requirements to meet “green” initiatives • Competing revenue with potable water • Cost of operation vs. returns • Managing treatment costs; cost of distribution system (capital)	• Product value; reduction in revenues • Keeping the cost of reclaimed water below cost of potable water • Cost of treatment versus returns • Capital cost to increase use and storage
Capacity/Supply (8.4%)	• Return flow obligations limiting reuse quantities • Lack of inexpensive long-term (≥3 days) storage • Managing demand vis-à-vis pressure requirements • Finding adequate storage vs. demand • Customer demand vs. availability • Wet weather storage; storage in winter • Meeting demand during peak usage • Pressurized system reliability	• Difficulties with disposal during wet weather periods • End-user management; maintaining pressure at far end of system during daily/seasonal peak demands • Flow fluctuations posing operational challenges in maintaining quality treatment • Storage issues associated with balancing a consistent treatment process with fluctuating demand, both diurnally and seasonally

Category	Generic Issues and Problems Identified	
Regulations (7.7%)	• Keeping up with or meeting permit requirements with less budgets • Overlapping regulations between agencies/jurisdictions • Obtaining permits to recharge/reuse • Negative and punitive regulatory environment • Governance of regional distribution entities • A lack of understanding by regulators • The county being more stringent that the state • Overly stringent regulatory requirements; voluntary connection policy; local (e.g., county) permitting process	• Onerous state regulations pertaining to distribution system leaks • Confusing regulations [Washington state currently has a dual standard for Class A reclaimed water (0.5 NTU vs. 2.0 NTU) for the different types of treatment] • Permitting standards for additional uses of reclaimed water vary greatly by permit writer (example from Washington state where some permit writers are allowing cities to use reclaimed water to its fullest potential, whereas others have imposed ridiculous restrictions so as to prohibit reclamation)
Workforce (3.2%)	• Finding qualified well-rounded operators to fill succession planning • A lack of staff for operations • Education	• Site supervisor training • Perception that the plants "run themselves" is affecting the staff to maintain the facilities adequately
Miscellaneous (1.3%)	• Lack of recognition for conservation efforts	• Monitoring wells on golf courses create issues from fertilizer applications

Note: The numbers in parentheses represent the frequency of mention (n = 155) whereby the most frequently mentioned category was regarded most important.

Chapter 5

Further Documentation of Management Practices

Staff from 25 utilities were interviewed by phone to acquire a more detailed examination of management practice aimed at controlling potential health risks and aesthetic issues associated with storage and distribution of reclaimed water.

5.1 Reclaimed Water Treatment and Disinfection

Most of the interviewed utilities used variations of activated sludge treatment technology. The only exceptions were FL-11 (Biofilter), CA-2 (Lagoons), CA-10 (Biofilter), and CA-18 (MBR) (Table 5.1). Disinfection was mainly with chlorine gas or sodium hypochlorite. However, seven utilities used chlorination as a secondary disinfectant to provide a residual where the primary disinfectant was UV. WA-4 and NV used only UV and, therefore, did not have a disinfectant residual. CA-10 used chlorine as disinfectant and sodium bisulfate to eliminate the chlorine residual. CA-8 did not use any disinfectant, confirming information provided in the initial survey, which is presented in Table 4.1. Use of reclaimed water for irrigating fodder crops and groundwater recharge was also confirmed during the interview (Table 5.1). Of the 24 systems that disinfected, 75% did not redisinfect the reclaimed water after the reservoir or in the distribution system. Of the 25% that redisinfected, a majority did so as part of their management practice. One exception (CO-5) redisinfected in the reservoir when deemed necessary. Except for Virginia, which provided reclaimed water solely for indirect potable surface reuse (water supply augmentation), all of the other utilities provided reclaimed water for irrigation and landscaping. Other uses included groundwater recharge, industrial power generation, cooling towers, manufacturing, dust control, incinerators, toilets and urinals, construction, manufacturing, and process water (Table 5.1). The uses corresponded to what the utilities had specified in the initial online survey. On the basis of these results, disinfection was identified as one of the key management and operational differences among utilities. It had important ramifications for water quality and biostability in the distribution system.

5.2 Utility Production, Pipes, and Valves

Production capacity ranged from 1.2 MG/year at CA-10 to 3258 BG/year at CA-3 (Table 5.2). The interviewed utilities represented a similar production capacity and belonged to all of the five production categories identified in the original pool of 71 utilities (Figure 5.1). Distribution pipe length ranged between 2 mi (AZ-8) to 110 miles (TX-2) with an average length of 29 miles and the median of 11 miles. Utility age was between 2 years (ID) and 42 years (CA-8). The average age of the systems was 20 years with a median age of 15 years. PVC piping was exclusively used in 29% of the distribution system and 50% used PVC pipes combined with some other type of material such as ductile iron, concrete, or steel. Twenty percent of the systems had steel alone or some component of steel pipes. These results highlighted the potential problems of infrastructure age, corrosion, and microbial regrowth in the system. Large distribution systems and topological changes point to issues with long detention times and pressure management.

Table 5.1. Type of Treatment, Disinfection, and Use of Reclaimed Water by the Interviewed Utilities

Utility	Treatment	Disinfection	Redisinfection Locations	Uses
CO-1	AS with BNR (i.e., primary clarification); secondary clarification with Dynasand and continuous biological filter	UV (primary); Sodium hypochlorite for additional disinfection to provide a residual	No	Irrigation of parks and golf courses throughout the city
WA-4	AS with BNR	Sodium hypochlorite	No	Irrigation of parks and golf courses
AZ-2	SBR (3) and conventional oxic ditch (1)	UV	No (all meet Class A+)	Irrigation (school yards, parks), fire, groundwater recharge
CA-1	AS (nitrification/denitrification)	UV; Sodium hypochlorite (3mg/L) at pump stations giving (≈ 0.5–1 mg/L residual)	Yes (3)	Industrial (power, geyser at 75%, irrigation)
FL-11	Media filtration	Chlorine	Yes (1)	Public access for landscaping and irrigation of golf courses
FL-1	AS with 5-stage Bardenpho	Chlorine	No	Irrigation, landscaping, cooling towers, vehicle washing, toilet, firefighting, concrete, recharge
CA-5	AS + Reverse osmosis (RO)	NCWRP uses chlorine (Sodium hypochlorite), whereas SBWRP uses UV	Yes (Storage tanks)	Irrigation (97%), urinals, industrial, cooling towers
FL-5	AS /A2O (two plants)	Sodium hypochlorite	No	Irrigation
TX-3	Advanced AS + filtration	Chlorine	No (still meets residual)	Irrigation (85%), cooling towers (10%), toilets, manufacturing
CA-4	AS + biotowers	Sodium hypochlorite (Bleach)	No	Industrial (power plant; 90%), landscaping
NC	AS with BNR	UV and then Sodium hypochlorite	No (chlorine decay)	Irrigation, chillers, industrial (e.g., concrete)
ID	AS with BNR	UV and then Sodium hypochlorite	No	Irrigation (mainly), car washing, dust control/suppression, industrial, toilets
FL-4	AS with Bardenpho	Sodium hypochlorite	No	Mostly for golf courses (three golf courses) irrigation; also cooling towers and for incinerators

Utility	Treatment	Disinfection	Redisinfection Locations	Uses
TX-2	Advanced secondary activated sludge with primary clarification and solids retention	Chlorine	Yes (three; at each booster station to aim at maintaining a chlorine residual of 0.2 mg/L at point of use)	Irrigation mainly but also industrial and dust suppression
VA	AS-MLE with BNR	Free chlorine (CTs >45mg/L then adjust to high pH (i.e., lime to pH11 for several hours)	Yes	Indirect potable surface reuse, reservoir, water supply augmentation
AZ-8	AS with nutrient removal	Chlorine gas	No. Dechlorinated with sulfur dioxide if designated for stream disposal	Primarily for irrigation of golf courses. Also used for construction and dust control
CO-5	AS with extended aeration with secondary clarification prior to disinfection	UV then chlorine	Redisinfect into pond if needed	Irrigation of golf course (municipal owned), one community park, and two sports complexes
CA-14	AS floating chain (Biotrac) extended aeration	Chlorine	No	Golf course irrigation (80%) and process water for wastewater plant (20%)
NV	AS	UV	No	Indirect reuse to large turf irrigators
CA-2	Lagoons (i.e., secondary treatment through facultative ponds all year around)	Chlorine gas	No	Irrigation of two 18-hole golf courses. Also have arrangement to supply reclaimed water to adjacent ranch for irrigating pasture in wet years
SC	Extended aeration AS	Chlorine gas	No	Golf course irrigation
CA-8	Two plants (AS and SBR)	No disinfection	No	Irrigation, groundwater recharge
CA-10	Bio-filter/Solids contact channel secondary system	Sodium hypochlorite, Sodium bisulfite	No	Irrigation
CA-18	MBR	UV then low of chlorine (0.3 ppm) applied as continuous flow	No	Irrigation and groundwater recharge
CA-3	AS	Chloramines	No	Irrigation (2/3) and the rest for industrial use, e.g., cooling towers, toilet flushing, community garden

Note: [a]Plant requested anonymity and, therefore, its actual name is not used. N/A = not applicable; N/P = not available.

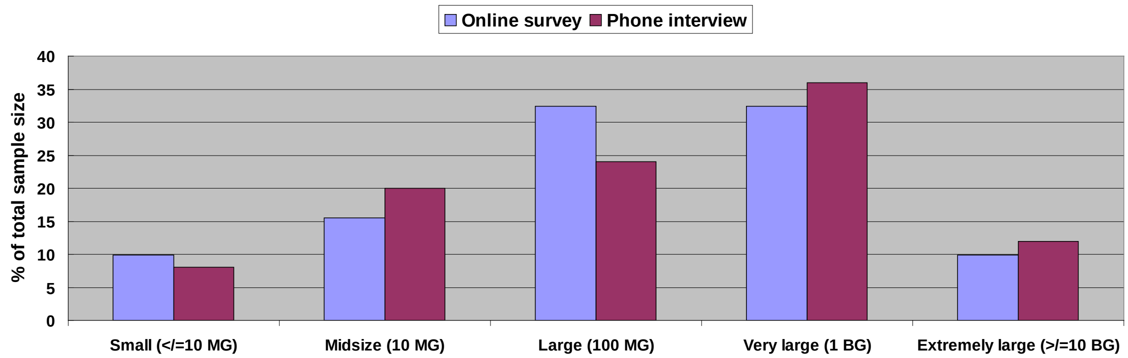

Figure 5.1. Relationship between the production capacity of the original 71 respondent pool and the 25 utilities interviewed over the phone.

Table 5.2. Production Capacity and System Composition of the Interviewed Utilities

Utility	Cap (mg/year)	Miles	Age (year)	Pipe Material
CO-1	500 (L)	21	12	AC PVC, ductile iron
WA-4	100 (L)	4	15	Ductile iron main (1.2 mi), C900 PVC (approximately 2.8 mi)
AZ-2	814.6 (L)	5	7	Ductile iron
CA-1	6700 (VL)	74	34	Concrete, PVC
FL-11	2555 (VL)	N/P	37	HDPE, PVC, ductile iron pipes
FL-1	4400 (VL)	80	42	Ductile iron (≥16 in.) and DR14 PVC (<16 in.)
CA-5	3993 (VL)	83	15	Concrete, Steel, PVC
FL-5	1058.5 (VL)	20	16	Ductile iron
TX-3	1450 (VL)	43.5	38	Ductile iron, PVC, HDPE
CA-4	2043 (VL)	13	11	PVC
NC	50 (M)	11	3	Ductile iron
ID	30 (M)	4.8	2	C900 PVC
FL-4	1011 (VL)	13	16	PVC
TX-2	11510 (EL)	110	15	HDPE, PVC, and concrete steel cylinder (CSC) pipe
VA	11680 (EL)	N/A	34	N/A
AZ-8	75 (M)	0.2	18	PVC
CO-5	40 (M)	2	8	PVC
CA-14	4.6 (S)	2	11	Cast iron, PVC
NV	41.5 (M)	14	13	Mortar lined and coated steel, PVC, ductile iron, and steel
CA-2	163 (L)	1.7	24	Most are concrete lined with ductile iron. Others are concrete ductile iron and asbestos-cement (AC) transite 8-in. diameter pipe
SC	120 (L)	4.5	40	PVC
CA-8	4562 (VL)	3.5	42	PVC
CA-10	1.2 (S)	7	18	Steel and PVC
CA-18	350 (L)	7	3	Ductile iron, PVC
CA-3	3258514 (EL)	140	14	Coated steel pipe mostly; ductile iron, PVC, and reinforced concrete pipes (RCP)
Mean		**29**	**19.5**	
Median		**11**	**15**	

Note: S = small; M = medium; L = large; VL = very large; EL = extremely large.

Most valves were of ductile iron, cast iron, or stainless steel (Table 5.3). Thus, even systems which exclusively used PVC pipe could experience iron-related corrosion from metallic valves. In one-third of the systems, the distance between valves was unknown or undisclosed. For the rest, valves were mostly located at 1000 ft to 0.5 mi. Half of the utilities did not have a valves exercising schedule or only exercised the valves as needed. This category included utilities which only exercised the valves when they needed to shut off the flow or to perform maintenance tasks. Most of those with a program exercised the valves at least once a year but some programs were every 3 to 4 years. Valve management is an essential component of proper distribution system maintenance and improves system reliability (Deb et al., 2012).

Table 5.3. Valve Composition, Frequency, and Management

Utility	Valve Type	Valve Frequency	Valve Management
CO-1	Butterfly	No set distance but anywhere from 300 ft to 1000 ft between valves. Spacing generally based on elevation and isolation needs in terms of water breaks	No valve exercising schedule
WA-4	Mostly Kennedy valves but also have a variety of other types of valves	Not specified	The process of winterizing the system by blowing out water at end of summer involves exercising some valves. Process of zone isolation also exercises valves. The whole system is connected and controlled by Maxicom (an irrigation program)
AZ-2	Not specified	Not specified	No regular exercising routine. Turned on/off as needed by golf course or if encounter microbial exceedances
CA-1	Steel/stainless steel butterfly (mains); gate valves (<12 in. lines)	Every mile	Exercised through an annual preventative maintenance program
FL-11	Unknown	Unknown	No valve management program
FL-1	Cast iron or ductile iron gate valves	Approx. 0.5 mi	Each exercised at least once per year
CA-5		Every 0.5 mi transmission or every 1200 ft for 12 in. lines	Exercised every 4 years (for less than 10 in. pipes) or every 2 years (for 10–16 in. pipes)
FL-5	Ductile iron resilient set	Every 1000 in.	Generally not regularly exercised except when isolating areas (periodically) or during high demand periods
TX-3	Ductile iron	Approx. 2000 ft apart	No routine schedule (potable side does not have program either)
CA-4	Butterfly valves (stainless steel and rubber)	Approx. 1000 ft	Only as needed (planning to start an annual exercising program)
NC	Ductile iron (similar to potable system)	Unknown	No program in place (will adapt potable system practices about this in future)
ID	Epoxy-coded ductile iron		Exercised every 4 years
FL-4	Gates valves with epoxy lining.	At major road intersections (approx. 1500 ft to 2000 ft intervals)	Exercised as needed for example during service or when adding new users
TX-2	150 class to 250 class rating butterfly and gate valves. (Note: 150 and 250 refer to pressure ratings)	Not specified	As need arises
VA	Not applicable	Not applicable	Not applicable
AZ-8	Steel and ductile iron	At the receiving pond	Approximately every 90 days
CO-5	Not specified	At the reuse plant, halfway in distribution system (isolation valves for golf course). Also plug valve at end of the system to avoid freezing in winter	As needed
CA-14	Unknown	Unknown	Once a year
NV	Gate and butterfly valves	At variable distance in the distribution/ system (can be up to 4800 ft)	Very rarely because of constant demand unless it is absolutely needed
CA-2	Gate valves	Not specified	Operated as needed
SC	Unknown	Unknown	Every 3 years
CA-8	Ductile iron	As required to control delivery	Exercised with each irrigation
CA-10	Total of 87 Gate and Butterfly type valves	Spaced at varying distances	Once a year
CA-18	Ductile iron (AWWA spec); CLA-VAL low for regulating pressure	Approx. 1000 ft	Exercised once a year
CA-3	Butterfly valves mostly but also a few gate valves	Isolation valves are not evenly spaced.	Aim at once a year but some are not that frequently exercised because of manpower limitations

5.3 Pressure Management

Sixty-seven percent of the utilities had at least one booster station. CA-1, a very large system of 6700 MG/year with 74 mi of pipeline, had 45 booster stations (Appendix D). By comparison, TX-2, an extremely large system with the longest pipeline (110 mi total), had three booster stations and several other subsidiary boosters (Figure 5.2).

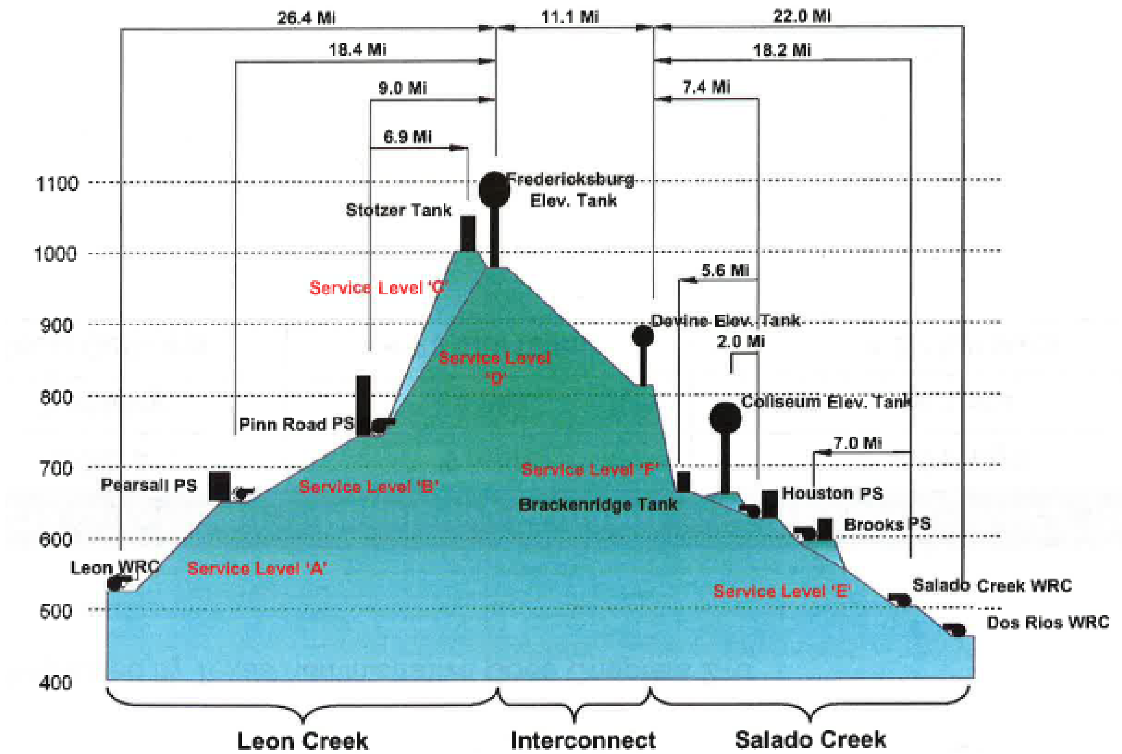

Figure 5.2. Cross section of the TX-2 reclaimed water distribution system.

It is preferable that end users have a reliable supply of reclaimed water. One aspect of ensuring reliable supply is maintaining adequate hydraulic pressure. A majority of systems (54%) used a hydraulic model in managing flow requirements of the system. Commonly used models included InfoWater, Synergee, EPANET, WaterGem, Wonderware, WaterCAD, and H2OMap. One-third of the utilities had experienced at least one main break (Appendix D). However, main breaks typically were infrequent and, therefore, not a major problem in the reclaimed water systems surveyed. Only one-quarter of the systems conducted leak detection. Leak detection methods used ranged from the use of acoustics (CO-1), SCADA (NC), or field crew physically monitoring the system during routine operations (FL-1 and CA-5). Seventy-one percent of the utilities did not monitor leaks or only used pressure drops as a warning sign of possible leakages in the system.

Dead ends can be a zone for prolonged water age and low flow. To a certain extent, dead ends are unavoidable, but 30% of the systems surveyed lacked specific design criteria to eliminate or minimize dead ends (Appendix D). The lack of advance planning to limit dead ends was, in some instances, propagated by the growth of the system as more customers were added. Improperly planned system expansions can lead to pressure management problems and reduced system reliability.

5.4 Monitoring Requirements

All of the utilities surveyed had some type of monitoring requirements for the treated reclaimed effluent. Monitoring of the treatment effluent was frequently continuous (i.e., online), and all the utilities typically met their effluent monitoring requirements as stipulated by their permits. However, monitoring programs typically did not extend into the distribution system (Appendix E). Thirty-three percent of the utilities did no monitoring of water quality changes in their distribution system. Even a majority of those that did monitor indicated that it was not required of them by their respective regulations or guidelines. Monitoring in the distribution system was only required at CA-1 and North Carolina. For CA-1, distribution system monitoring was only conducted if the water was for discharge rather than reuse. At North Carolina, monitoring was required as part of the permit, but submitting the results to regulators was not a requirement. Monitoring of groundwater wells (but not the distribution system) was required every 6 months for South Carolina to maintain the permit. Typical parameters monitored in the distribution system included chlorine residual, pH, turbidity, conductivity, and dissolved oxygen. In those instances, the absence of sufficient chlorine residual in the distribution system was used as a surrogate for tracking likely regrowth of bacteria. Several options for restoring parameters that go out of range are summarized in Appendix E. Some of these included manipulating polymer levels to reduce turbidity, adding carbon source to remove nutrients (in upstream processes to encourage microbial growth), monitoring data to optimize the process and product quality, increasing the level of disinfectant, and shutting down the reclamation process until the problem is resolved (e.g., increasing the sludge return rate, pH adjustments, etc.)

5.5 Cross-connection Control and Flushing Programs

Cross connections with potable water supplies are not acceptable, and measures must be implemented to avoid and verify separation of different systems. A cross connection intuitively suggests a link between two systems, notably the reclaimed water and the potable water system. However, there also can be a link between the reclaimed water and sewer system. Such linkages can compromise the quality of potable water or reclaimed water, threatening public health and leading to severe consequences. The interview explored practical measures the utilities were taking to control cross connections between the potable and reclaimed water system. Those measures are summarized in Appendix F. Because of the importance of this issue from a public health perspective, most systems took several measures to monitor and guard against cross connection of the reclaimed water and potable water. The use of backflow preventers was widely implemented. For several utilities, customers had to go through a plan review or physical inspection prior to connecting to a reclaimed water system. These practices were very proactive. For example, TX-3 prided itself as having one of the most stringent cross-connection control programs, even to the possible extent of deterring some customers from using reclaimed water. Reclaimed water customers were required to have a double-check valve so the water would not flow in the opposite direction. The system was pressurized and met state mandate separation of 4 in. between the reclaimed water distribution system and the potable water line. Added to those layers were distinct program characteristics, such as purple pipes and purple sprinkler heads, as well as signs.

Several utilities used random and annual inspections as well as a pressure test every four years for possible cross connections. However, under California's Title 22, this mandated 4-year "shutdown" test was for "dual-plumbed" sites which were specifically defined as single family homes with outside irrigation using reclaimed water and buildings plumbed internally with reclaimed water. Public sites that used reclaimed water for irrigation were not required to conduct the test every 4 years.

Most potable water systems routinely flush their systems to remove accumulated sediments, minimize hydraulic retention time, and maintain good water quality (Pachepsky et al., 2012). However, a majority

(79%) of the reclaimed water utilities did not have a reclaimed water flushing program (Appendix G). Flushing of reclaimed water was either directly discouraged or indirectly prohibited. For example, unauthorized discharge of reclaimed water under California laws is not permitted (Stone, 2001). As a precaution, this restriction is often interpreted by utilities to include restrictions on routine flushing a part of distribution system maintenance. To circumvent flushing restrictions, one agency in Southern California recommended to its customers to flush the pipes onto greenbelt areas already permitted to use recycled water.

Not flushing the reclaimed water system results in accumulation of algae, sediments, and other forms of debris that further degrades water quality, particularly in systems with open reservoirs. Where practiced, flushing was done by directing the flushed water into the nearby sewer or into surface water bodies. None of the utilities surveyed could provide detailed information about the flushing velocity, duration, or the effectiveness of the overall flushing program. As a result, the effectiveness of flushing was difficult to evaluate.

5.6 Seasonal Production and Storage

The adequacy of storage is a major infrastructural and operational problem for the reclaimed water industry. Information about the size of reservoirs and production capacities for two seasonal extremes (i.e., winter versus summer) are presented in Table 5.4. Eighty percent of the utilities increased their reclaimed water production in summer as compared to winter. In most locations, production and demand were highest in the warmer months (summer) compared to the winter months so as to meet increased need for irrigation, cooling, and other forms of use. Exceptions to this characterization were CA-1, FL-4, FL-11, CA-8, and CA-18, where higher production in winter versus summer was attributed to increased rainfall in summer, reducing the need for reclaimed water. Another exception was modest winter temperatures in the area, permitting irrigation to maintain the vegetation. Modest winter conditions, although able to sustain vegetation, may not have sufficient precipitation to meet winter crop demand, increasing the need for irrigation with reclaimed water. Reclaimed water storage requirements ranged between 1.1 and 12 times higher in the summer as compared to the winter. This presented a need for flexibility in reclaimed water storage—flexibility that is not easily attainable as storage infrastructure and capacity are usually expensive, whereas most reclaimed water entities are not profitable financially. They are subsidized by potable and wastewater revenues, which themselves may be capped by regulators rather than based on true demand–supply economic forces.

In the CA-5 system, each of the water reclamation plants treated wastewater to secondary level at a constant target flow throughout the year. During the winter, a portion of the secondary flow was converted or treated to reclaimed water standards on the basis of demand of the reclaimed water system. Operations monitored the storage tanks closely and increased or decreased the treatment of secondary to reclaimed water based on the rate of reclaimed water usage. Decreasing the production was immediate, whereas increasing the production took between 1 and 8 h depending on the operating conditions. The storage tanks were large enough to buffer these adjustments. Thus, for CA-5, the reservoirs were for short-term storage to meet a single day's water needs. This is a form of reclaimed water production-on-demand that ensured rapid turnover and minimal effects from water age.

Table 5.4. Reclaimed Water Storage and Turnover

Utility	Reservoir Size	Production			Rationing
		Winter	Summer	Adjustment	
CO-1	Unknown but have 15 users with eight storage ponds of variable in size, each with 3 days' worth of water	0 (zero); System completely shut down	4.2 MGD	IR[a]	Occasionally based on percent-irrigated acreage that user has versus whole number of acres.
WA-4	10–15 MG	0 (zero); System completely shut down (Oct 1–April)	0.6–1 MGD	IR	Yes. Have a plan written in 1997 for two customers' needs. One customer gets 500,000 and the other gets 700,000 gal/day (conserve sometimes)
AZ-2	Golf course has constantly filling lake with use	0.36–0.54 MGD	0.54 MGD	1.5×	No (system still expanding)
CA-1	1.5 BG	25 MGD	15 MGD	1.7×[b]	Yes
FL-11	26.1 MG (potentially 120 days' worth of storage)	7 MGD (wet)	7 MGD (dry)	0 (zero)	Yes. Agreements allow curtailing, e.g., 20% across the board in case of a drought
FL-1	15 MGD	Not specified	Not specified	N/D[c]	No. If reaches that point, everybody rationed equally
CA-5	9 MG, 3 MG, and 0.75 MG tanks	A portion of summer production levels is converted to reclaimed water standards based on the demand	8.5 MGD (SBWRP) and 17 MGD (NCWRP)[d]	N/D	No. Use raw water from L. Miramar to make up difference as total treatment capacity is 30 MGD
FL-5	2 MG (Blue Heron) and 1.5 MG tanks (Osprey). Also have a 262/acre-ft treatment wetland (>100 MG).	Typically 3.5 MGD	4–4.5 MGD	1.1×	No. Recycle from wetland to meet demand when needed
TX-3	Two elevated 2 MG and 0.5 MG	3.8 MGD	7.5 MGD	2×	No
CA-4	Have a 2.26 MG tank to supply the power plant. Golf courses also have their reservoirs	4 MGD	10 MGD	2.5×	No (may need to in the future)
NC	Two storage tanks of 0.25 MG and 0.75 MG	0.07 MGD	0.2 MGD	3×	No
ID	1 MGD	0 (zero)	0.5 MG	IR	No but at a point where night-time use is increasing signifying the need

Utility	Reservoir Size	Production			Rationing
		Winter	Summer	Adjustment	
					for additional storage
FL-4	6 MG (i.e., two tanks of 3MG each)	3.47 MGD	2.27 MGD	1.5×[b]	Yes. Most usage/demand is in winter compared to summer, which is rainy and with less demand
TX-2	Six ponds of 1.5 MG each (i.e., total of 9 MG)	5–10 MGD (depending on annual dryness/drought conditions)	Approx. 25 MGD	>2.5×	No. Meet contract specifications
VA	Not specified	Not specified	Not specified	N/D	Not specified
AZ-8	Onsite is 30,000 gal but golf courses also have a 5MG reservoir	18 MG (normal dry season) but increased to 280 MG if needed	Avg. flow of 210 gal/day; 60,000 per day in summer. Avg. 25 gal/day (total)	12×	No. Hope they take all they receive
CO-5	1500 gal onsite but also have 456.2 MG (at golf course with 3.3 MG irrigation pond), 500,000 gal (at community park); golf course x3 5 MG. Have holding pond to catch up for needed demands. Need enough water to dump in creek to meet water rights obligations	0 (zero)	71.9 MG (i.e., 6.1 MG for football field, 7.7. MG for community park, and 58.1 MG for golf course)	IR	Not this year. If not enough, could be rationed for potable. For next year, will keep golf course and ballpark green.
CA-14	1.5 MG	0.6 MG	0.8 MG	1.3×	No
NV	2 MG reservoir	Approximately 1.9 MGD	Approximately 4.1 MGD	2×	No
CA-2	Effluent storage (onsite) is 1.8 MG for prior to discharge (to creek for water rights). Rest is to CC produced on demand. At south course CC golf course has a pond of 3.2 MG capacity and the north course CC has a pond of approx. 8.1 MG capacity	0 (zero)	180 MG	IR	No as the country club has option of using raw water from River Cosumnes as a supplement to the end of May or early June. This way, tertiary-treated reclaimed water delivery is delayed to later in the season
SC	Pond (lagoons) of 3.9 MG monitored daily	30 MG (total)	Average of 120 MG (i.e., 90 MG to	>4×	No, supplement with deep well water

Utility	Reservoir Size	Production			Rationing
		Winter	Summer	Adjustment	
			more than 200 MG)		
CA-8	5 months of discharge	12.5 MGD	12.5 MGD	0	No. Sequential deliver until it is gone
CA-10	No storage	66.5 MG (Nov–Jan total)	120.6 MG (July–Sep)	2×	No as water irrigation is based on irrigation demand but user contracts restrict amount and timeframe
CA-18	1 MG tank	1 MGD	1 MGD	0	No
CA-3	9.5 MG storage	2–5 MGD (wet vs. dry)	10–20 MGD depending on demand	>4×	No. Users can have as much as they want

Notes: [a]IR = instantly ramps production from zero; [b]higher winter than summer production; [c]not determined; [d]SBWRP = South Bay Water Reclamation Plant; NCWRP = North City Water Reclamation Plant.

Most systems (80%) did not ration reclaimed water. Additional demand was met through increased production or substituting or supplementing the system with potable water. For FL-5, water from the treatment wetland was recoverable when demand increased. Reclaimed water at ID was not produced during the winter because of no demand, but in the summer, demand increased to approximately 0.5 MG/day (Table 5.4). CA-4 did not ration reclaimed water; however, they recently completed a master plan and anticipated beginning rationing in the near future depending on consumption. For AZ-2, no rationing was practiced, but some areas received more water than they needed as the system was still expanding. Besides piping, irrigation canals at AZ-2 helped in moving the reclaimed water to where it was needed. TX-3 did not ration but rather did the opposite of what the potable system practiced by not imposing any restrictions on watering frequency. Reclaimed water use was allowed at any time of the year. For CA-18, reclaimed water was not rationed, and whatever was not used for irrigation was used to recharge groundwater. CO-1 occasionally rationed reclaimed water on the basis of irrigated acreages. WA-4 had only two customers but rationed reclaimed water when demand exceeded the supply by encouraging both of its customers to conserve reclaimed water. CA-1 rationed reclaimed water, especially in summer.

Collectively, these results showed the challenges utilities faced in meeting demand across seasons vis-à-vis the fixed wastewater supply and restrictions on how and when to use the water, as well as the wide range of reclaimed water uses, which may require different standards.

5.7 Water Turnover and Reservoir Maintenance

Reclaimed water should be viewed as a perishable product analogous to food products with a shelf life, signifying the need for minimal water detention time in storage or distribution system (i.e., increased turnover). A rapid turnover minimizes the deterioration in water quality, whereas low water turnover increases water age in the system. Table 5.4 presents several strategies utilities used to increase water turnover. These include the following:

- Managing production levels to quantities that just meet existing demand (i.e., continuous use, 37.5% of utilities)
- Continuous/semicontinuous mixing in the reservoir (12.5% of utilities; TX-3, Idaho, and Virginia)
- Serial/sequential pond transfers (continuous discharge at FL-11 and FL-5; 8% of utilities)
- Intake and outlet on opposite sides or at different depths (8% of utilities, CO-1, and CO-5)
- Seasonal drainage (target to use up the water by end of season; 8% of utilities)
- Aim at rule-of-thumb approaches to attain a 1–3 day residence time (8% of utilities; North Carolina and CA-3)

AZ-8 had several water turnover strategies including multiple interconnected reservoirs with inlets and outlets at different depths. The other utilities surveyed did not have specific water turnover strategies. AZ-2 did not have a reservoir onsite and, therefore, turned over the water from the plant quickly to the customers where it may have stayed in the customers' reservoirs and deteriorated. WA-4, FL-4, and the City of CA-8 did not have any deliberate plan for promoting reclaimed water turnover.

CA-1 promoted reservoir turnover by emptying the ponds by the end of the irrigation season in summer (an annual empty-out policy). By comparison, North Carolina used a rule-of-thumb of 2 days in the smaller tank and 3 days in the large tank for managing turnover by manipulating pump levels to stay within those limits.

Half of the utilities surveyed had established routines for reservoir cleaning (Table 5.5). Intervals between cleanings varied from every year (CA-5, Idaho, and CA-18) up to 7 years (North Carolina). Cleaning frequency was not directly related to reservoir type or location. CO-1, FL-4, and Nevada water systems did not have a set cleaning schedule and cleaned as needed. FL-1 and Nevada inspected the reservoirs but had not yet found it necessary to clean. These systems are 42 and 13 years old, respectively (Table 5.2). The FL-1 facility conducted extensive reservoir surveillance using divers and robotic cameras. Reservoirs at WA-4 and FL-5 had never been cleaned. The systems were 15 and 16 years old, respectively. Reservoir cleaning used a variety of methods ranging from scraping combined with chemical treatment (North Carolina), vegetation management (FL-11), jetting, pressure washing, or vacuuming (Table 5.5).

5.8 Employee Training

Most systems had a formal training program for employees (Table 5.6). Training was either informal (on-the-job) or formal (on-the-job combined with workshops, seminars, and standardized courses). In a number of cases, the training occurred on an as-needed basis (or when new employees were hired). CA-5 indicated requirements for mandatory training, although TX-2 also enforced employee professional development education required by state regulators.

Potable systems have access to funding through capacity assessment planning, which provides assistance in assessing and protecting source water, certified operators, and technical, managerial, and financial capacity. These services were made available under the Safe Drinking Water Amendments (SDWA) of 1996. However, water reclamation or reuse was not directly referenced in any of the SDWA documents, an omission that could undermine water reclamation as part of a water portfolio. Successful management of water resources should integrate the water cycle to include reclaimed water as part of the potable and wastewater treatment mix. Thus, training requirements similar to those for potable water employees should be extended to reclaimed water operators.

Table 5.5. Reclaimed Water Turnover and Reservoir Management

Utility	Turnover Promotion	Reservoir Type and Location	Reservoir Cleaning Frequency	Cleaning Method
CO-1	Intake and outlet are on opposite side of one another	Open	Done as needed (only once when maintenance was needed)	Not applicable
WA-4	Not promoted	Open	Never	Not applicable
AZ-2	The utility does not have reservoirs and the water is used in a few days (rapid turnover); however, users have reservoirs on their premises	Not applicable	Not applicable	Not applicable
CA-1	Using up water by irrigation season's end in summer	Open; aboveground	Ponds are never cleaned; sump pumps are cleaned every 2 years; others (e.g., geyser) are by inspection	Yes, use tractor and truck to vacuum the silt (geyser) or tractor to scoop up the silt
FL-11	Reclaimed water reservoirs designed in sequential order with level of linear flow	Open; underground	Open surface water lakes are cleaned with vegetation management plan (i.e., removal of vegetation)	As needed by mechanically removing the vegetation
FL-1	Rapid (1.5 days' storage at most)	Closed; aboveground	Inspected every 3–4 years; have not had any cause for cleaning; divers or robotic camera used	Not applicable
CA-5	By managing volumes that are treated	Closed; aboveground	Annually	Yes, a set of standards and procedures are in place for cleaning tanks and reservoirs with dive teams; jetting and scraping silt and solids
FL-5	Have series of seven ponds with pump in one pond to a single tank; ponds are shallow and enable adjustments in late fall and late summer drain wetland because of high demand	Closed; aboveground	Never cleaned; had prices on inspection but not done at the tank	No
TX-3	Pump starts and stops based on elevation in the tank that enables them to run until the tanks are full	Closed; aboveground	Biannual (same people who maintain potable system tanks manage our storage cleaning too)	Potable water protocol is used; cleaning is by spraying down

Utility	Turnover Promotion	Reservoir Type and Location	Reservoir Cleaning Frequency	Cleaning Method
CA-4	Have continuous use	Closed; one is aboveground and another one is underground	Tank cleaned every 5 years; at one of the golf courses, a new reservoir (just a year) with continuous mixing (by design); the other golf course tank is cleaned once every 3 years	Yes, by vacuuming out (work done by a contractor)
NC	2–3 days in tank depending on tank size	Closed; aboveground	Once every 7 years	Contractor uses scraping, possibly combined with chemicals
ID	Turnover is by pump mixing and draining (back to plant) every winter	Closed; aboveground	Every winter	Drained back to plant and hosed with potable water
FL-4	No, deliberate turnover promotion	Closed; aboveground	As needed	Yes, using jetting
TX-2	Through operational adjustments: in summer the reservoirs are filled up to a higher elevation; filling up is to a lower elevation (i.e., the floats are set lower) in winter	Closed; aboveground	Every 5 years	Yes, through contractors whose divers vacuum out sediments and inspect spots for integrity
VA	Water reservoir provides some longitudinal mixing along normal plug flow path, less mixing occurs in summer during thermal stratification and low flows, more significant mixing and flushing during high flow meteorologically induced events	Open; underground	Never been dredged	No
AZ-8	Two interconnected reservoirs, which are aerated; supply into the distribution system draws water from the bottom of the reservoir; interconnection moves water from one reservoir to the other	Open; underground	Onsite reservoir is cleaned once every 2 years by draining the water; golf course clay-lined reservoir has not been cleaned in 15 years (had sediments before then)	Divert water to equilibration tank by pumping down; cleaning is by high-pressure water washing
CO-5	Intake is at bottom of reservoir to help with turning over; one pond has aerators, but some may have stagnation	Open; underground	Very frequently, reservoir at the community park modified liner and cleaned in 2006; had holding pond cleaned out 2 years ago	Yes, by drying out and shoveling the sediments

Utility	Turnover Promotion	Reservoir Type and Location	Reservoir Cleaning Frequency	Cleaning Method
CA-14	Level controls are set lower in winter and higher in summer; winter reservoir is approximately 3 days' worth, whereas summer levels are approximately 1 day's consumption worth.	Open; one underground and one aboveground	Every 2 years	Same as potable system by jetting and scraping
NV	Has 1–2 MG reservoir to supply all customer demand; winter daily average is approximately 2.8 MGD; water is rapidly used, i.e., have a "pass through" system from plant through to the customers' ponds	Open; underground	As needed; divers have inspected the reservoir and found very little silt accumulation	Yes, divers vacuum reservoir floor
CA-2	Produced as needed and sent out to customers right away	Open; underground	Equilibration basin cleaned at end of the season (Oct 15) and again at the beginning of the season (April 15). Natural lake at the country clubs are not cleaned	Empty out to second pond and then fire hosing
SC	Produce/supply only what is demanded (i.e., from demand-supply)	Open; underground	Never	Not applicable
CA-8	Natural occurrence	Not applicable	Not applicable	Not applicable
CA-10	Not applicable (no reservoir)	Not applicable	Not applicable	Not applicable
CA-18	Continuous discharge through irrigation and groundwater recharge	Closed; aboveground	Annually	SOP for superchlorination (thus chemical treatment)
CA-3	Try to use as much as reservoir has in a day; manage daily fill/drain cycle	Closed; aboveground	2–3 years	Yes, by vacuuming

Table 5.6. Human Resource Training at Reclaimed Water Utilities

Utility	Training Programs
CO-1	Reuse training for all user site staff, seasonal workers once a year: 10 workshops per year
WA-4	Sewer plant does training every week for professional growth, meeting licensing requirements
AZ-2	Wastewater team has training plus potable water team has training but not separate for reclaimed water
CA-1	Supervisor training program for chemical users; employees trained on equipment when hired. Workshop for managers annually
FL-11	Yes, reclaimed water operators are licensed and they have to receive continuing education to maintain license; they also participate in annual training
FL-1	(1) Backflow prevention training, (2) Cross-connection training, (3) Reclaimed water system operated as potable water system
CA-5	Yes, mandatory training conducted on a regular basis as required by Cal-OSHA regulation. (Annual recycle water system training for field personnel and new employees)
FL-5	In-house training as need arises
TX-3	Yes, pumping division conducts these as needed
CA-4	Yes, train as new users come online to address questions (do's and don'ts of RW). Each user has a supervisor who stays in touch to address issues; new employees are trained
NC	Have SOPs on shared drive with master copies kept separately; common version updated every time master copies are edited
ID	Workshops of priority departments (2 years ago); will do some training
FL-4	Yes, as needed
TX-2	Cleaning operations are through contractors: SAWS has operations and certification from state that have to be maintained through certain hours of professional development hours (PDHs)
VA	Yes
AZ-8	Training classes as needed; have low turnover
CO-5	Brochure given to parks and golf course; intern put together PowerPoint presentation for use in future; brochure given to parks and golf course; intern put together PowerPoint presentation for use in future
CA-14	Training is informal, e.g., target training sessions; covered under employee orientation and target meetings
NV	No, we hire contractors
CA-2	Yes, upon hire and then prior to conducting operations; utility also has a joint operation plan with the country club
SC	Yes, yearly
CA-8	No
CA-10	Regarding specific regulations for distribution; operators are certified for cross connection by a reclaimed water supervisor for things to be done by customers on a case-by-case basis
CA-18	Yes, conducted as needed, e.g., if new employee joins
CA-3	Continuous training programs for new staff; ongoing training for rest of staff members

5.9 Strategic Planning

The reclaimed water industry is growing rapidly within the United States. Its continued growth therefore requires proper planning. Information collected through the interviews about strategic planning for infrastructure, customer relations, compliance issues, and technological investments, is summarized in Appendix H. Under the U.S. Safe Drinking Water Act and Clean Water Act, potable water and wastewater systems must prepare rigorous strategic plans. Similar national regulations do not apply for reclaimed water systems. Even so, 76% of the utilities had some form of strategic plan to grow or meet their infrastructure needs. Strategies were in the form of a master plan, city and local planning initiatives, or a water/groundwater strategic assets plan. Through those planning opportunities, utilities had, in some instances, been able to make technological advancements in their operations, monitoring systems, system communication, and water quality testing processes. Thus, 80% of the utilities had a supervisory control and data acquisition (SCADA) system that gave real-time monitoring. About 20% of them also had a laboratory information management system (LIMS). Approximately one-third of the utilities indicated having some standard operating procedures (SOPs). Virginia had made an extensive investment into SCADA, LIMS, distribution control system (DCS), enterprise resource planning (ERP), software asset management systems, process models, and GIS (Appendix G). The WA-4 reclaimed water irrigation system used a sophisticated system (Maxcom; Rain Bird Corp.) to determine what levels of irrigation were delivered at specific locations and for what duration.

Overall, the utilities had effective levels of public relations management capabilities and communication channels to streamline information flow and enhance customer service (Appendix H). Some of the channels highlighted included plant visits (CA-5), webcast information sessions (CA-4), user meetings (CA-1), facilitating citizen advisory councils (North Carolina), and posting pertinent information on Web sites. South Carolina did not view reclaimed water users as customers but rather as partners who took the effluent, saving the South Carolina coastal utility the challenges associated with discharging the water. Reclaimed water at this facility was not viewed as a commodity for sale. It was given to the users for free, with the users only being charged if surface water was used to blend with reclaimed water. Thus, the fees would be for the surface water. However, blending with surface water was least desirable at this location as it increased TDS and the associated salinity.

The utilities handled regulatory compliance issues in fairly divergent ways. For some of them, adhering to the permit requirements and documenting performance satisfied their compliance needs. Some of the permits (e.g., CA-2) referred to “waste” discharge, which perpetuated the perception of reclaimed water being equivalent to wastewater or some undesirable product. This could depress the value of reclaimed water, an otherwise very valuable product in their water portfolio. Compliance was enforced through inspections or self-assessed or reported incidents. CA-10, which was the smallest utility interviewed, had a full-time person in charge of communicating regulatory issues. A few others sought representation in the rules and guidelines framing processes through lobbying and letter writing. For example, as a stakeholder, North Carolina maintained legal counsel to address desirable reclaimed water rulemaking issues through a national and state government affairs committee.

5.10 Reclaimed Water Pricing and Cost Elements

Information about reclaimed water cost recovery is summarized in Table 5.7. Only 24% of the utilities indicated full recovery of their water reclamation costs. However, the cost recovery statement either was not explained (in a majority of those cases) or qualified by tying reclaimed water costs to sewer rates. For the rest of the utilities, cost recovery was reported with a qualifier of directly building reclaimed water rates into the sewer or wastewater rates. AZ-2 and North Carolina recognized the direct link between cost recovery and infrastructural and distribution challenges. Specifically, reclaimed water production at AZ-2 was covered in the pricing structure but the related infrastructure cost was not. Similarly, although North Carolina covered its reclaimed water costs, the charges did not cover distribution, leading to a net negative cost recovery. CA-18 viewed reclaimed water costs as a better offset of NPDES permits (Table 5.7), thus making reclaimed water costs part and parcel of sewer operations. The price of reclaimed water to potable water (P_R:P_P) ratio ranged between 0.1 (FL-4) and 2 (CA-1). In a majority of instances, reclaimed water cost only a fraction of potable water (i.e., P_R:P_P ratio of less than 1). Reclaimed water was only more expensive than potable water at CA-1. Well water blended with reclaimed water in South Carolina was also more expensive than potable water. However, if not blended, reclaimed water at that location was free of charge to the users. For all of the locations where potable water was more expensive, the cost differential was least pronounced at FL-1 and CA-14 (Table 5.7). The cost of reclaimed water at FL-1 was deliberately designed as an incentive to use reclaimed water with an inbuilt disincentive to waste it. All of the utilities except Virginia metered their supply to customers, although FL-5 metered only some industrial and commercial customers. TX-3 metered some but not all of its customers. Despite the majority of the utilities metering their product, some utilities (e.g., FL-5) only charged a hookup fee or did not charge anything for the water.

Table 5.7. Reclaimed Water Cost Perspectives from Various Utilities

Utility	Production Cost Recovery	Metering and Cost Relative to Potable Water	P_R:P_P Ratio
CO-1	Cost of reclaimed water production is not fully covered; approximately 80% of cost; 20% in operating budget, i.e., sewer rates	Metered with two meters (i.e., one at each customer site and another through and SCADA system storage into reservoir over 24 h). Reclaimed water is approx. $2.25/1000 gal; potable water approx. $5.60/1000 gal	0.4
WA-4	Not fully covered; arbitrarily set rates at percentage of potable water (i.e., 15%)	Delivery into reservoir/lake metered; individual customers do not have meters but usage monitored through Maxcom program, which bases on sprinkler heads, system pressure, etc., to estimate delivery; cost of reclaimed water is 15% of the cost for potable water	0.15
AZ-2	Production is covered but infrastructure is not	Customer usage metered; charge half potable rate $1.53 per 1000 gal of reclaimed water	0.5
CA-1	Not at all because of restriction of zero discharge in summer time farmers receive it for free as part of discharge; no need for treated WW no flow in streams. Probably recovering only 10%	Customer usage metered. Cost is $700/acre-ft (1MG) to treat + $150 gal water customers = $900/MG; comparable to industry figures. Potable water is $460/acre-ft	2.0
FL-11	There is ambiguity between wastewater treatment and reclaimed water; thus, the question for costing comparisons is where to draw the line between wastewater treatment and reclaimed water production; can probably be resolved by looking at the revenues coming in vs. the cost of sending (distribution)	Customer usage metered; reclaimed water is cheaper but exact dollar value not available	Not determined
FL-1	Between the wastewater and reclaimed water fully set up to recover costs; price of reclaimed water approx. 80% of potable water; this rate is an incentive to use and disincentive to waste	All customer usage metered; potable water is $1.22/1000 gal; reclaimed water is $0.93/1000 gal	0.76
CA-5	Not fully covered; lower in 2001 by city in order to encourage retrofit; water pricing study is underway	All customer usage is metered; effective March 1, 2012, $.80/HCF for recycled water (very discounted) and $3.757/HCF for potable water commercial site rate	0.21
FL-5	Not fully recovered; only partially recovered	Some (industrial and commercial) are metered; some are metered monthly but others are not metered; if $\geq$6 in. water is metered; for others we charge by hookup. Each user has a reclaimed water agreement specifying size based on type of connection; potable rates are based on consumption, but we charge based on connection; reclaimed water is a maintenance charge	Not determined
TX-3	Yes, fully covered; not in reclaimed water but rather in wastewater rates; if meeting permit limits, meeting reclaimed water limits for replenishing potable water (i.e., indirect potable reuse), conventional reuse, or returned to environment	Most customers are metered; reclaimed water costs $1.30/1000 gal compared to $4.85–$5.00/1000 gal (peak rate) for potable	0.27
CA-4	Yes	Customer consumption is metered; raw water cost is $330/acre-ft; reclaimed water cost is $550/acre-ft.; potable water is $1200/acre-ft; some consumers prefer raw water	0.46

Utility	Production Cost Recovery	Metering and Cost Relative to Potable Water	P_R:P_P Ratio
NC	Probably not (master planning in-house model to study cost is extremely sensitive; cost is mainly distribution, because we were already producing RW quality product before we got a distribution system; reuse does not cover costs but neither do our potable or sewer systems cover their costs because of aging infrastructure)	Usage metered at the point of use; reclaimed water rate arbitrarily set at 50% of potable water	0.5
ID	No	Metered, but the water is free; cost is lumped into wastewater as it is form of disposal (i.e., reclaimed water is used as a disposal mechanism); competing for irrigation is the much cheaper untreated canal surface water from Boise River, for which canal companies charge only $40/year (almost free to use)	Not determined
FL-4	Yes	Metered; reclaimed water is approximately 10 times cheaper than potable water	0.1
TX-2	System designed to cost $418/acre-ft (i.e., $1.28/1000 gal) of reclaimed water but charging $300/acre-ft (i.e., $0.92/1000 gal) potable water thus there is a subsidy.	Metered; reclaimed water is $1.00/1000 gal, whereas potable is $2.50/1000 gal at the lowest tier; higher cost for other tiers for potable but no tier system for reclaimed water	0.4
VA	Not really	No metering, cost is unknown	Not determined
AZ-8	Not recovered; approximately $2–3 to produce but $1.50 from consumer and $1 from golf course; the idea is to maintain production and quality	Metered; reclaimed water is $1.00–1.50/1000 gal, whereas potable water is $4/1000 gal	0.38
CO-5	Cheaper to use raw water than reclaimed water $107/acre-ft. (i.e., $0.33/1000 gal), labor, lab, electric, no capital included	Metered; comparative cost not available, but raw water is relatively cheaper than reclaimed water; reclaimed water system only run in July, Aug, and Sep.	Not determined
CA-14	No, but will get closer in the future	Metered; reclaimed water is $860/acre-ft, whereas potable water is 30% higher than reclaimed water	0.77
NV	No	Metered, reclaimed water is $2.33/1000 gal, whereas average potable water is approximately $3.89/1000 gal	0.6
CA-2	Yes	Water is metered but not charged to customers as system is fully funded through sewer rates under collection, treatment, and reclaimed water production; payment will be instituted in the future when utility starts supplying to residences; relative cost is unknown	Not determined
SC	Fully covered; no charge as we are nondischarge system; golf courses are our discharge	Metered; reclaimed water costs $0; however, if injected into deep well, the deep well water is $5/1000 gal; potable = $3/1000 gal (from Charleston)	1.67 (blend)
CA-8	Yes, reclaim water delivered without cost	Metered, but there is no cost (charge) for reclaim water	Not determined
CA-10	No	Metered, reclaimed water is $2.76 per 100 cu ft but cost of potable water is unknown	Not determined
CA-18	Yes, as we are part of sewer operation; reclaimed water option was done to eliminate NPDES permits and our costs	Metered but cost is unknown	Not determined
CA-3	No	Metered index of reclaimed water to raw water is 50%	0.5

Note: P_R:P_P ratio = price of reclaimed water to price of potable water ratio.

Not reflected in this pricing model was the capital cost credits to account for the following:

- Cost of purchasing water rights that would have been required to gain access to the daily production rate of the reclaimed water
- Avoided cost for potable water source capacity increases, avoided potable water storage for nonpotable needs (e.g., irrigation, fire flow, industrial peaks)
- Avoided costs and investments for increasing discharge permits, outfall modeling, and outfall construction

Thus, reclaimed water rates must be competitive with similar potable uses and rates. For example, the rates for reclaimed water supplied for summer irrigation should be equal to comparable block rates for systems using conservation-based rate making.

5.11 Delivery of Best Management Practice Needs

A majority of the utilities preferred to get best management practice (BMP) information in an electronic form, but there was also a preference for brief overviews in the form of factsheets or brochures. Workshops and seminars were also identified as possible delivery avenues (Table 5.8). A combination of electronic documents that can be downloaded and printed easily appeared to satisfy most of the utilities.

Table 5.8. Preferred Mode to Find or Receive BMPs

Mode of Delivery	Respondents with Preference (%)*
Electronic/online/e-mail	60
Hardcopies/publications/factsheets	20
Reuse conferences/workshops/seminars/webinars	12
Regulators/peers/agencies	8
Consultants	4

Note: *Total percentages are more than 100 as some utilities mentioned more than one preference.

The information generated from the phone interviews of 25 utilities was further summarized and significant responses and cues (highlighted in Appendix I-1 to I-4) used to develop a quantitative score. Ten utilities with the highest scores were selected for case studies. Three other backup sites were also selected. Based on these criteria, the selected sites are presented in Figure 5.3. It is apparent that the selected sites are still very diverse.

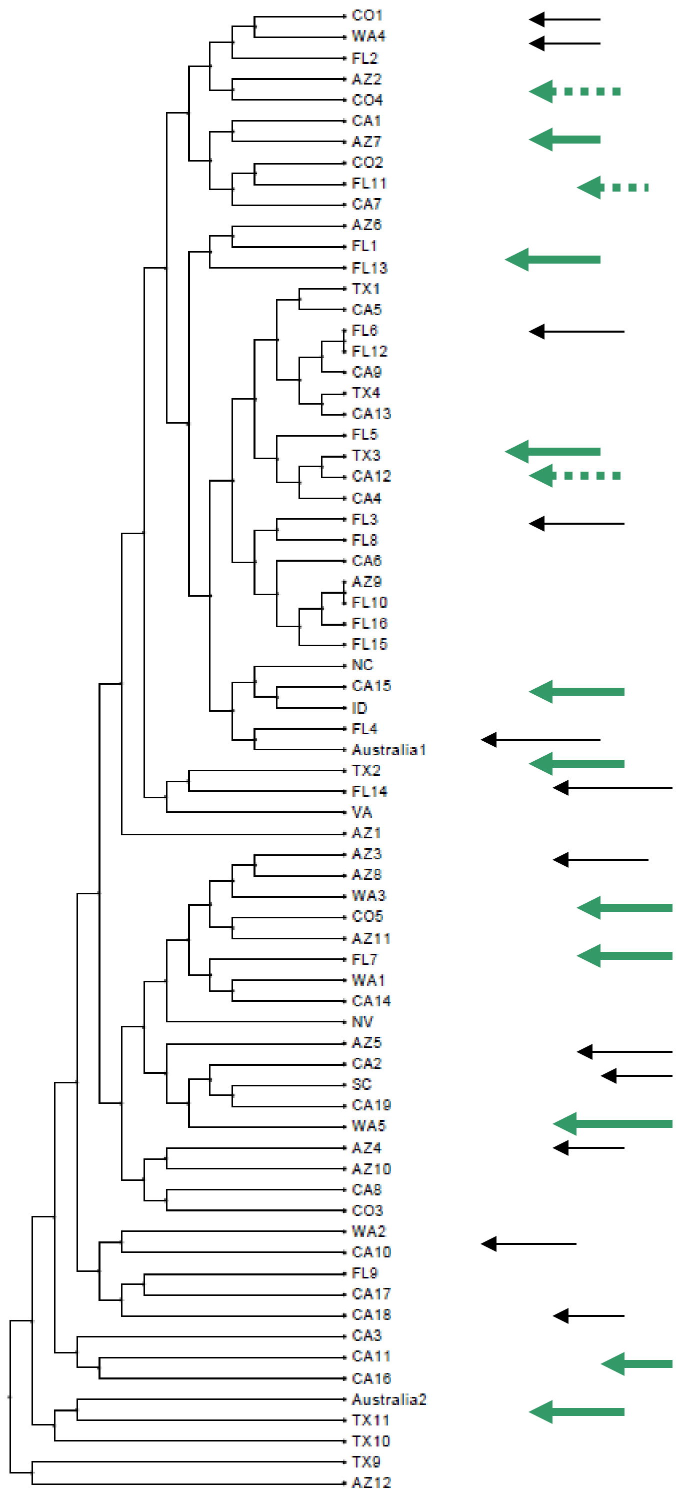

Figure 5.3. Select utilities (identified with a thick arrow) for case studies out of the 71 original utilities surveyed.

Note: The broken arrows identify three other backup sites. All utilities with an arrow were included in the phone interview phase. However, the ones with a thin arrow were not visited for the case study phase.

Chapter 6

Management Practice Case Studies

Case studies were based on site visits to evaluate the storage system, distribution system design, and best management practices (BMPs). Not all reuse purposes have the same level of exposure and, therefore, carry a different level of risk and aesthetic appeal (Jjemba et al., 2013). This concept minimizes costs of excessive treatment. A standard for evaluating reclaimed water quality in the distribution system based on the intended use was developed, therefore, prior to the site visits as to establish data for critical control points (CCPs; Table 6.1). It should be emphasized the proposed CCP target values are not regulatory values. There is a difference between BMP guidance and regulations. Regulations are set by a regulatory agency and require compliance with certain standards containing numerical criteria. Under a regulatory environment, utilities would be compelled to change their storage and distribution systems to comply with numerical values specified under their permit. Some of the embedded standards may be qualitative. For example, the standard may include specification of a nondiscernible odor. By contrast, best management practice guidances are typically voluntarily implemented to prevent negative impacts and connotations. They are considered as the "best" available and practical means of preventing a particular impact or connotation without stifling production, storage, and distribution of reclaimed water economically and efficiently (Boyd, 2003; Yeager, 2006).

For each intended use, a key question during a brainstorming session of the research team was to determine the level (high, moderate, or low) of physical or visual exposure of the reclaimed water to humans (Table 6.1). Critical concentrations of various water quality parameters corresponding to the respective level of exposure were then determined based on information from the literature and used to evaluated water quality. Reclaimed water used for purposes where there is a high likelihood of exposure requires a proposed high quality (i.e., *low* TOC, AOC, turbidity, algal growth reflected by low chlorophyll levels hydrogen sulfide, conductivity, and *Legionella* but *high* chlorine residual to ensure adequate disinfection and high DO). Conductivity, free chlorine, and dissolved oxygen were selected as CCP targets, because they are easily measured in the field. Turbidity is measured routinely by most utilities, although turbidity measurements are only typically restricted to the effluent. TOC, AOC, chlorophyll, and hydrogen sulfide were selected on the basis of a previous assessment of reclaimed water biostability in the distribution system (Jjemba et al., 2010).

Water samples were collected from each system during the visit and tested for quality. Summary statistics for the field data from 10 locations are presented in Table 6.2. The water was sampled from the effluent, reservoir, and three points in the distribution system. TOC ranged between 1.66 mg/L and 14.99 mg/L, a nine-fold difference, whereas the minimum and maximum AOC in the systems differed 18 fold. Dissolved oxygen ranged between 0.86 mg/L and 14.64 mg/L, a 17-fold difference. Turbidity differed by almost 390 fold. Thirty-eight percent of the samples had detectable levels of *Legionella* spp. Based on skewness values, DO, temperature, chlorophyll, and conductivity had nearly symmetric distribution. By comparison, the distribution of turbidity was highly skewed to the right (skewness = 6.22) implying highly turbid reclaimed water at a few locations. The distribution of *Legionella* spp. was also highly skewed although not to the extent of water turbidity.

Table 6.1. Proposed Reclaimed Water Quality Guidelines for Various Reclaimed Water Applications[1]

Likelihood of Exposure[2]	Intended Use	TOC (mg/L)	AOC (µg/L)	Turbidity (NTU)	Chlor a (µg/mL)	H-sulfide (µg/L)	Conductivity (µS/cm)	Free Cl (mg/L)	DO (mg/L)	*Legionella* (cfu/mL)[3]
High	Irrigation of parks, lawns, school yards, golf courses	≤8	≤1000	≤3	≤200	≤5	≤2000	≥0.1	≥6	<100
	Washing vehicle/windows									
	Cooling towers									
	Potable augmentation									
	Irrigation (edible)									
	Aesthetic impoundments									
Moderate	Fire protection	8.1–14	1001–1500	3.1–5	201–400	5.1–10	2001–10,000	0.05–0.09	4–5.9	101–1000
	Dust control									
	Street sweeping									
	Snowmaking									
	Watering (dairy)									
	Toilet and urinal flushing									
Low	Highway median irrigation	15–20	1501–2000	5.1–10	401–800	10.1–50	10,001–30,000	0.01–0.04	2–3.9	1001–3500
	Construction (concrete)									
	Groundwater recharge									
	Watering (non-dairy)									

Likelihood of Exposure[2]	**Intended Use**	**TOC (mg/L)**	**AOC (µg/L)**	**Turbidity (NTU)**	**Chlor a (µg/mL)**	**H-sulfide (µg/L)**	**Conductivity (µS/cm)**	**Free Cl (mg/L)**	**DO (mg/L)**	***Legionella* (cfu/mL)**[3]
	Irrigation (non-edible)									
	Boiler makeup water									
	Restore/create wetlands									
Reference		Weinrich et al. (2010)[4]	Weinrich et al. (2010)[4]	CDPH (2012)[5]		GOWA-DOH (2009)[6]	Anonymous (2012)[7]	(Thakanukul et al., 2013)[8]	Fan & Wang (2008); Beutel (2003) [9]	Schoen and Ashbolt (2011)[10]

Notes:

[1]*Low* TOC; AOC; turbidity; chlorophyll; hydrogen sulfide, conductivity and *Legionella*, as well as *high* chlorine residual and high DO represent high-quality reclaimed water.

[2]Not only limited to physical exposure but also includes visual exposure (i.e., appeal).

[3]*Legionella* densities are geometric means (±SD).

[4]Based on trends from a long-term study of four systems with divergent treatment technologies.

[5]Although CDPH's highest quality requirement is 2 NTU, it also provides for an allowance of less than 5 NTU for 5% of the time in 24 h. Thus, a comprised value of 3 NTU was adapted for this characterization.

[6]Based on guidelines by Government of Washington State-Department of Health (2009) Environmental Health Guide: Hydrogen sulfide and public health. Cited study focused on concentrations in the air and the proposed values here assume about 50% volatilization from water into the air (http://www.public.health.wa.gov.au/cproot/2652/2/11548%20hydrogen%20sulphide% 20and%20public%20health.pdf; accessed 3/5/2013).

[7]Brackish water classification key based on information from http://www.engineeringtoolbox.com/water-salinity-d_1251.html; accessed Oct 31, 2012).

[8]Chlorine residuals of >0.1 were not associated with any microbial regrowth in reclaimed water (Thakanukul et al., 2013).

[9]Values extrapolated from these two studies that focused on DO in sediments.

[10]Based on estimates by Schoen and Ashbolt (2011) for absolute low predictions of *Legionella* sp.of respirable size in water necessary to result in infection from inhalation of aerosols over a 15 min duration.

The concentration of free chlorine ranged between 0 and 2.1 mg/L (Table 6.2). Further examination showed the free chlorine residual diminished rapidly with distance from the plant (Figure 6.1). Rapid dissipation was also reported in three other systems studied previously (Jjemba et al., 2010). A few of the utilities redisinfected in the distribution system, but the residual dissipated again. The dissipation occurs in reservoirs (especially open reservoirs) but is also facilitated by the typically high concentrations of organic carbon in reclaimed water. Dissolved oxygen and AOC also generally gradually decreased further in the distribution systems (Figures 6.2 and 6.3). Decreases in both of these parameters suggested consumption and related growth of microorganisms.

Table 6.2. Summary Statistics of Water Quality for 10 Reclaimed Water Distribution Systems

	TOC (mg/L)	AOC (µg/L)	Turbidity (NTU)	Chlorophyll (µg/mL)	Sulfide (µg/L)	Conductivity (µS/cm)	Free Cl (mg/L)	DO (mg/L)	*Legionella* sp.
Mean	6.33	634.5	3.25	65.99	2.79	855.33	0.30	6.57	440
Standard Error	0.21	42.7	0.61	5.33	0.25	32.46	0.03	0.19	112
Median	6.24	450.9	1.99	59.76	2	719	0.15	6.89	94
Mode	4.67	604.4	3.08	0	2	713	0.1	8	12
Standard Deviation	2.61	522.5	7.47	65.27	3.10	397.61	0.42	2.28	844.69
Sample Variance	6.83	273038.3	55.77	4260.72	9.63	158094.6	0.18	5.20	711805.25
Kurtosis	3.42	3.4	39.99	−0.49	5.79	−0.37	6.12	1.86	13.71
Skewness	1.34	1.9	6.22	0.65	2.36	0.76	2.53	−0.06	3.44
Range	13.33	2400.7	53.96	253.62	16	1456	2.1	13.78	4797
Minimum	1.66	141.4	0.14	0	0	290	0	0.86	3
Maximum	14.99	2542.1	54.1	253.62	16	1746	2.1	14.64	4800
Count	150	150	150	150	150	150	147	150	57

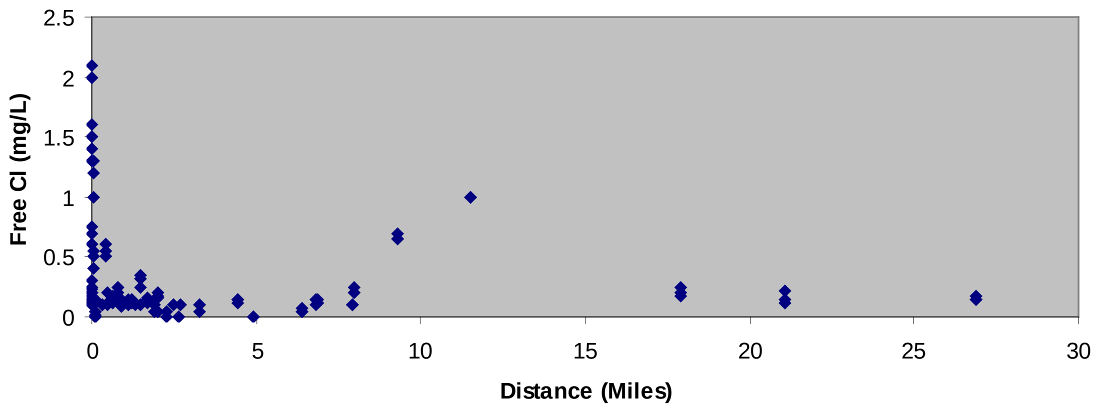

Figure 6.1. Trend of free chlorine residual concentrations with distance in 10 reclaimed water distribution systems.

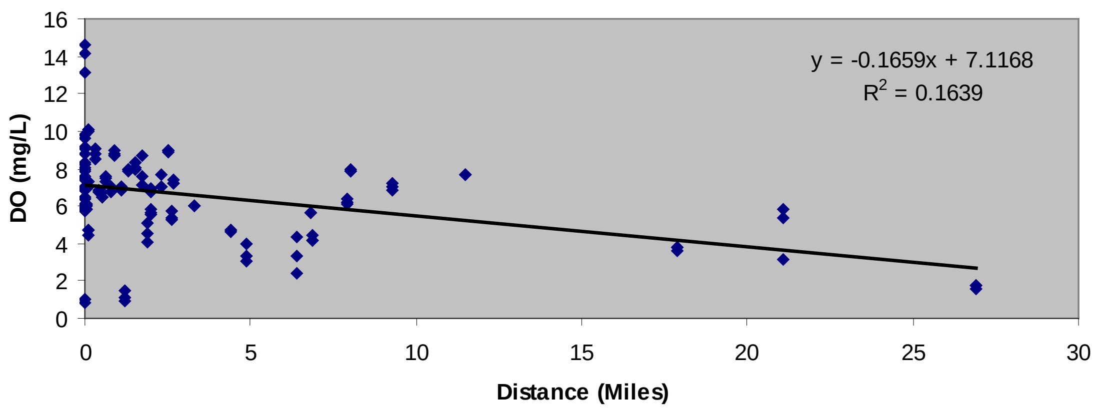

Figure 6.2. Trend of dissolved oxygen with distance in 10 reclaimed water distribution systems.

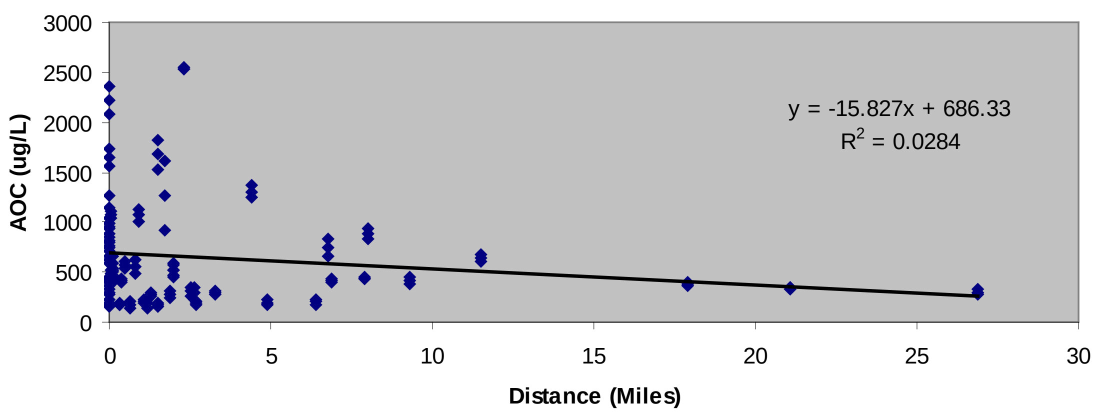

Figure 6.3. AOC decrease with distance in 10 reclaimed water distribution systems.

6.1 Case Study for CA-18 Reclaimed Water

The system derived wastewater from the city (population 15,000). A total of 50 acres were irrigated with reclaimed water, which met California's Title 22 requirements. Treatment and distribution of the reclaimed water consumed substantial electrical power. The system has peak flows between 10 a.m. and 6 p.m. However, this was also the time when electric energy costs were highest. To minimize energy costs, the wastewater was stored onsite in a 0.3 MGD equalization tank (Figure 6.4; Panel A) until the electrical off-peak hours when treatment was initiated. The initial step was removal of grit through a Pista Grit chamber (Smith and Loveless Inc.). It was passed through a fine screen and sent to the activated sludge bioreactor to remove BOD and nitrogen. The bioreactor was comprised of a pre-anoxic zone, swing-air (aeration) zone, aeration (maintained about 0.1 mg O_2/L), and a post-anoxic zone.

To minimize foaming and the impact of *Nocardia* spp., process water was continuously sprayed into the oxidation tanks (Panel B). The wastewater was passed through a 0.3 micron GE Zenon MBR (three cassettes but plant had space for an additional cassette if needed) to remove TSS and turbidity along with most bacteria commonly associated with conventional wastewater treatment processes. The permeate was pumped to a white polyethylene tank (Panel C). An occasional problem with this tank was algal growth (a better option would have been a black polyethylene tank), but the tank was periodically cleaned with chlorine (approximately every 3 months) and the cleaning water disposed of into the ponds on site (Panel D). The soil in the ponds was a loose pack with low organic matter to allow good soil infiltration. If not cleaned, the UVT downstream (delivered by a Trojan ultraviolet radiation chamber) dropped. Return activated sludge (RAS) was pumped back to the pre-anoxic zone. Two of the three membranes were backwashed each week with sodium hypochlorite. To remove scaling, citric acid was also used simultaneously with chlorine four times a year (i.e., once every season). The treated effluent was reclaimed and beneficially reused for irrigation water at the local school yards and parks. The sludge was dewatered with a screw press (Panel D) and biosolids collected for landfilling. The layout of the distribution system and related sampling points are shown in Figure 6.5.

Figure 6.4. CA-18 Reclaimed water treatment system.

Panel A: wastewater collection tank
Panel B: bioreactor 1 (left) and 2 (right), with noticeably reduced foaming in 1 compared to 2 because of better distribution of the spray nozzles
Panel C: permeate tank (occasionally cleaned to get rid of algal growth which can impact UVT downstream
Panel D: one of the three disposal ponds onsite; to avoid mosquito infestation, usage is rotated between three ponds, and the ponds can be seeded with western mosquitofish (*Gambusia affinis*) to supply fish for a countywide mosquito abatement program
Panel E: sampling and testing from the plant and distribution system.

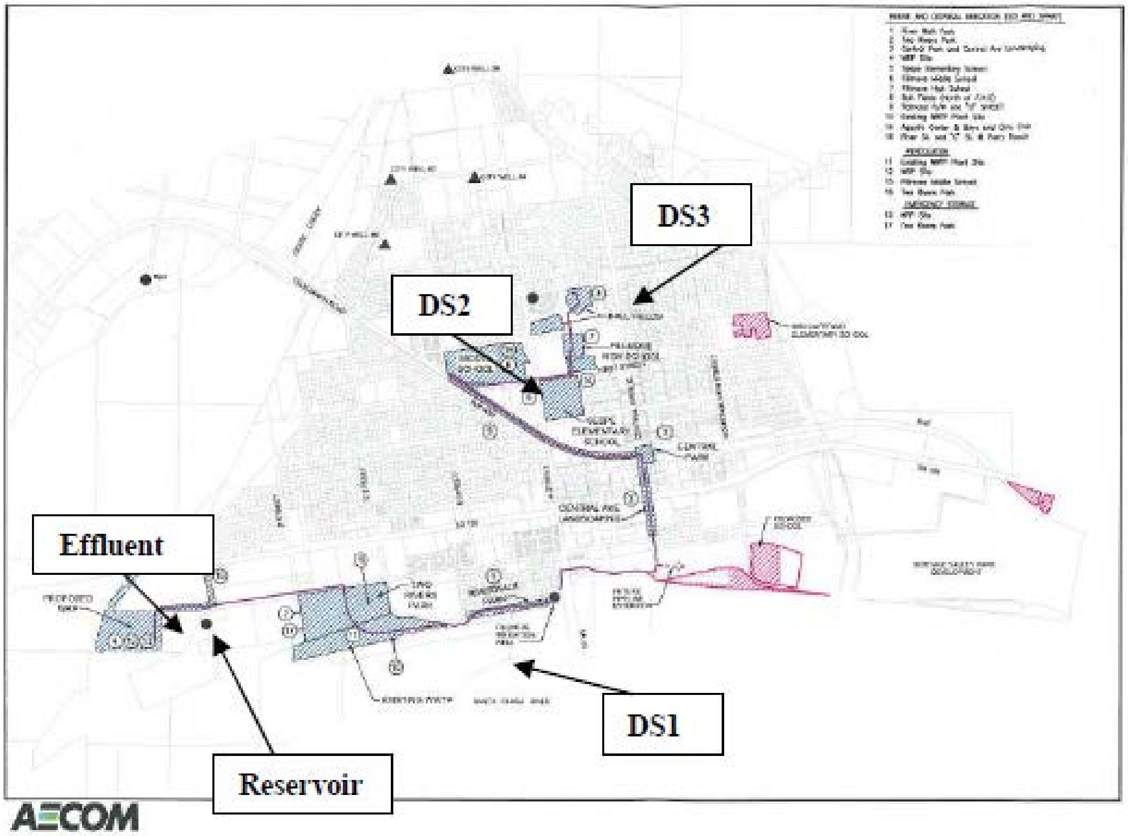

Figure 6.5. Layout of the CA-18 reclaimed water distribution system.

6.1.1 Determinants for CCPs

This large (350 MG/year production capacity) MBR system was 3 years old. It had a closed 1 MG reservoir and a medium-size branched distribution system of 7 miles. It had 6 miles of ductile iron and 1 mile of PVC pipes. The reclaimed water was disinfected with UV, but the plant also provided a low concentration (0.3 mg/L) of chlorine applied as a continuous feed as a residual. The generated water was typically used up in 1 day, which provided a rapid water turnover, considering its short shelf life. It was primarily used for irrigation (landscaping) and recharging groundwater. No post-storage redisinfection was practiced, and the system did not limit the number of dead ends deliberately, although each branch ended at an irrigation facility. The valves in the system were located approximately every 1000 ft and were composed of ductile iron. Leakage in the system was indirectly monitored by monitoring pressure and water flow. The disinfected tertiary-treated demonstrated 99.999% inactivation or removal of MS-2 bacteriophage (a requirement used for full-body contact recreational impoundments), met a 2 NTU turbidity standard and <2.2 coliform bacteria colonies per 100 mL. It was permitted by the California DPH for subsurface irrigation and could in fact be acceptable for full-body contact recreational use.

The irrigation network was a subsurface drip system, and rodents disrupted it in some instances. Although the distribution system was not monitored directly, the area covered by the system had 10 groundwater monitoring wells, which were tested quarterly (under the permit requirements) for total coliforms, fecal coliforms, pH, enterococci, methylene blue active substance (MBAS; for anionic surfactants), nitrate, NH_3-N, NO_2-N, organic nitrogen, TDS, boron, sulfate, BOD, pesticides, and metals. The water pressure in the system ranged between 55 and 100 psi, the former applicable at high elevations. The utility had a constant pressure pumping system with variable flow drive (VFD) to save energy. Annual cross-connection control inspections were conducted by the county. The system was flushed daily by default every time the drip system was running, the remaining water automatically discharged into the groundwater aquifer. The reservoir was cleaned once a year by superchlorination.

6.1.2 Water Quality Critical Limits

Results of the sampling event are presented in Table 6.3. The risk level will depend on the intended use. Because uses slightly differ at the respective utilities, this level is not uniform across the board but rather driven by the use requiring most stringent quality. The water met the proposed target TOC concentrations, turbidity, chlorophyll (i.e., algae), hydrogen sulfide, conductivity, dissolved oxygen, and *Legionella* spp. throughout the system for irrigation and groundwater recharge. Turbidity was stable and very low in the system. The levels of assimilable AOC were appropriate for irrigation systems. AOC represented the fraction readily available for microbial growth. Because the water had been disinfected with UV, chlorine was not added to the effluent prior to storage. Even though the residuals were low (≤0.1 mg/L), they were very stable and met the proposed residuals targets for the intended use. Although low levels of *Legionella* were detected in the water (Table 5.4), they did not pose a substantial risk of exposure to humans as irrigation was through a drip system.

6.1.3 Actions to Correct Exceeded Proposed Limits

The utility largely met all of the proposed targets but can substantially gain by reducing conductivity as the proposed limits could be exceeded in case of continued salt buildup. Conductivity can be reduced by blending reclaimed water with potable water at a 1:1 ratio, adapting reverse osmosis technology, or using electrodialysis technology. It did not warrant further corrective action even in the distribution system.

Table 6.3. Proposed Reclaimed Water Quality Targets at Point of Use for Various Purposes[1,2]

Use category and System Attributes		TOC (mg/L)	AOC (µg/L)	Turbidity (NTU)	Chlor a (µg/mL)	H-sulfide (µg/L)	Conductivity (µS/cm)	Free Chlorine (mg/L)	DO (mg/L)	*Legionella* (cfu/mL)[1]
Site	**Miles**									
CA-18		**Uses: H-Parks, L-Recharge**								
Effluent	0	5.04±0.3	299±23	0.14±0.01	81.3±23.3	1.7±0.6	1703±37	N/A[8]	9.0±0.2	<3
Reservoir	0.004	4.8±0.1	167±9	0.22±0.01	112.4±40.5	2±0	1681±8	0.1±0	8.1±0.2	<3
DS1	0.3	4.92±0.02	181±14	0.22±0.01	134.9±49	0.7±0.6	1686±2	0.1±0	8.8±0.3	<3
DS2	1.5	4.6±0.1	180±17	0.25±0.01	≤1	1.7±0.6	1689±2	0.1±0	8.2±0.2	3
DS3	2.5	4.68±0.02	306±43	0.28±0.02	≤1	2±0	1677±4	0.1±0	8.9±0	46±19
FL-1		**Uses: H-Parks, H-Washing, H-Cooling, M-sweeping, M-Fire, M-Toilets, L-Construction, L-Recharge**								
Effluent	0	4.31±0.06	423.9±26.1	0.66±0.01	<1	<1	731.3±18.5	2.03±0.06	6.9±0.1	2300 (L)
Reservoir	0.05	4.09±0.04	525.9±44.9	0.71±0.02	<1	<1	716.0±4.36	1.17±0.15	6.97±0.06	<3
DS1	0.4	4.15±0.03	414.4±20.8	0.27±0.01	<1	<1	715.7±2.3	0.55±0.05	6.8±0.01	<3
DS2	1.1	3.93±0.03	213.2±17.8	0.8±0.01	<1	<1	711.0±2.7	0.12±0.03	6.9±0.1	3
DS3	2.7	3.84±0.04	190.5±12.1	0.37±0.02	<1	<1	709.0±1	0.10±0	7.3±0.08	29±2
NC		**Uses: H-Parks, H-Cooling, M-Toilets**								
Effluent	0	6±0	763±60	1.2±0.1	<1	2.3±0.6	616±2	0.65±0.09	6.1±0.2	36
Reservoir	7.9	5.7±0.1	440±12	0.9±0.2	27±14	1±0	610±23	0.1±0	6.2±0.1	55
DS1	0.8	6±0.1	555±75	1.4±0.1	96±13	1.7±1	607±3	0.2±0.03	6.9±0.2	9
DS2	8.0	6.1±0.2	882±50	4.6±0.3(M)	138±21	1.7±0.6	597±5	0.22±0.03	7.9±0.1	47 ±17
DS3	9.3	6±0	413±30	3.8±0.1(M)	187±22	2.7±1.2	596±3	0.67±0.0003	7.0±0.2	23±9
CA-3		**Uses: H-Edibles, H-Cooling, M-Toilets**								
Effluent	0	6.8±0.1	931.8±53.8	1.22±0.04	10.3±16.5	0.3±0.6	1254.3±6.4	1.33±0.06	6.96±0.05	660±300 (M)
Reservoir	21.1	7.1±0.1	338.7±14.7	0.54±0.01	70.8±24.8	1±0	1258.7±29.3	0.16±0.05	4.79±1.45 (M)	9
DS1	11.5	7.1±0.1	642.4±38	0.66±0.01	54.5±26.4	1±0	1267.7±2.1	1±0	7.68±0.02	140±30 (M)
DS2	17.9	7.1±0.1	383.3±24	0.71±0.01	58.0±21.8	2±0	1206±5.3	0.21±0.04	3.76±0.10 (L)	<3
DS3	26.9	6.7±0	302.9±22.4	0.55±0.01	117.4±32.0	2.3±0.6	1240.3±9.5	0.16±0.02	1.68±0.14 (L)	6
CA-2		**Uses: H-Parks, L-Non-Diary Watering**								
Effluent	0	6.05±0.07	396.9 ±29.7	0.8±0.02	63.8±21.1	<1	589.7±2.3	0.21±0.04	7.5±0.1	<3
Reservoir	0.002	7.08±0.12	993.9±45.8	3.8±0.1(M)	119.7±31.3	3.3±0.6	596±17.7	0.21±0.02	9.7±0.1	1600±1100 (L)
DS1	0.63	6.43±0.07	175.0±32.1	2.4±0.1	76.7±14.1	2±0	598±6.8	0.15±0.03	7.5±0.1	24
DS2	1.71	6.53±0.1	1262.4±343.8(M)	7.8±0.1(L)	41.7±19.2	2.3±0.6	498.3±12.4	0.14±0.02	7.8±0.8	45
DS3	2.62	6.41±0.08	292.3±59.2	2.4±0.1	134.9±16.0	4.7±0.6	496.3±7.2	<0.01 (L)	5.5±0.3 (M)	3
CO-5		**Uses: H-Parks**								
Effluent	0	7.54±0.09	625±41	1.09±0.02	81.3±10.7	2±1	527±21	0.14±0.01	6.2±0.2	130 (M)
Reservoir	0.006	7.53±0.07	2221±135 (L)	3.71±0.10(M)	244.3±10.7	12.7±0.6 (L)	523±29	0.15±0.03	13.9±0.8	460±160 (M)
DS1	0.1	7.45±0.1	595±60	1.22±0.05	158.2±11.2	2.7±0.6	522±4	0.14±0.02	7.2±0.2	810±340 (M)
DS2	1.3	6.27±0.03	277±10	3.18±0.09(M)	134.9±16.0	4±1	456±37	0.11±0.01	7.9±0.1	220±270 (M)
DS3	2	7.41±0.07	518±56	1.36±0.08	110.4±17.5	3.7±0.6	578±55	0.18±0.02	6.9±0.1	92±2

Use category and System Attributes		TOC (mg/L)	AOC (µg/L)	Turbidity (NTU)	Chlor a (µg/mL)	H-sulfide (µg/L)	Conductivity (µS/cm)	Free Chlorine (mg/L)	DO (mg/L)	*Legionella* (cfu/mL)[1]
Site	**Miles**									
CA-1		**Uses: H-Parks, H-Edibles, L-Boilers**								
Effluent	0	4.89±0.02	198.1±24	0.8±0.03	<1	1.0±0	757±12	0.16±0.04	0.97±0.09 (L)	<3
Reservoir	0.1	5.74±0.03	498.4±21.9	2.4±0.1	27.8±20.5	1.3±0.6	648.3±1.5	<0.01 (L)	10.04±0.06	220±270 (M)
DS1	2.3	8.12±0.12 (M)	2533.7±8.4 (L)	1.9±0.1	140.7±29.7	4.3±1.2	766.3±8.4	0.03±0.03 (L)	7.26±0.39	3300±1900 (L)
DS2	4.4	6.81±0.06	1308.8±66.3 (M)	53.5±0.8 (L)	<1	14.0±1.7 (L)	769.3±2.5	0.14±0.02	4.69±0.07 (M)	45
DS3	6.9	7.36±0.01	424.1±16.6	2.1±0.1	81.3±22.7	3.0±1.0	738.7±9.7	0.13±0.02	4.27±0.15 (M)	12
AZ-8		**Uses: H-Parks, M-Dust, L-Construction**								
Effluent	0	6.07±0.12	798.5 ±58.3	4.3±0.1 (M)	<1	7.3±1.2	573±1	0.22±0.03	6.5±0.1	<3
Reservoir	0.9	2.38±0.04	1067.1±54.6 (M)	10.1±0.5 (L)	151.2±5.3	13±0 (M)	298±0	0.11±0.04	8.8±0.1	12
DS1	0.1	1.71±0.04	457.7±64.7	1.9±0.2	<1	3.7±0.6 (L)	303.6±12.4	0.04±0.02 (L)	4.6±0.2 (M)	30
DS2	1.2	1.67±0.01	184.7±43.3	2.8±0.1	<1	3±0	298±7.2	0.14±0.02	1.2±0.3 (L)	3
DS3	2	1.97±0.03	518.9±66.2	2.6±0.1	137.2±17.3	6±0 (L)	292.3±2.5	0.05±0 (M)	5.7±0.1 (M)	<3
TX-3		**Uses: H-Parks, H-Cooling, M-Toilets**								
Effluent	0	7.5±0.1	1150±112(M)	2.9±0.1	≤1	3±1.7	1013±5	0.4±0.3	8.1±0.2	120±130 (M)
Reservoir	1.5	7.7±0.1	1674±148(L)	6.4±0.2 (L)	≤1	4±2	1024±3	0.3±0.1	8.0±0	500±310 (M)
DS1	1.9	6.4±0.1	279±29	3.0±0.2	94±16	1.7±0.6	954±1	0.08±0.03	4.6±0.6 (M)	3
DS2	4.9	5.5±0.1	196±26	2.6±0.1	≤1	2.7±0.6	1018±2	≤0.01 (L)	3.5±0.5 (L)	3
DS3	6.4	4.9±0.1	200±19	3.9±0.1 (M)	≤1	0.7±1.2	1005±3	0.06±0.1 (M)	3.4±1 (L)	9
FL-5		**Uses: H-Parks, H-Cooling; L-Wetlands**								
Effluent	0	13.9±0.19(M)	1643.1 ±86(L)	3.62±0.06 (M)	<1	2.3±0.6	1337±6.1	1.53±0.06	5.83±0.05 (M)	870±990 (M)
Reservoir	0.04	14.98±0.01(L)	1073.5±32(M)	2.3±0.1	42.9±19.9	1.7±0.6	1321±3.6	0.48±0.08	5.99±0.15	45±19
DS1	0.5	14.15±0.06(L)	567.8±36.6	3.14±0.14 (M)	69.7±16.5	1.3±0.6	1324±5.3	0.14±0.05	6.56±0.14	33
DS2	3.3	8.38±0.05(M)	295.6±17.9	2.41±0.10	130.2±35.0	2.3±0.6	826.3±1.2	0.08±0.03 (M)	6.02±0.02	105±140 (M)
DS3	6.8	8.41±0.07(M)	751.3±87.6	2.48±0.08	151.2±40.5	2.0±0	843.7±30.7	0.13±0.03	5.64±0.02 (M)	45
Frequency proposed limits were exceeded		12%	18%	26%	0	10%	0	16%	30%	26%

Notes:

[1]Numbers in highlighted cells followed by (M) have moderate-quality water, whereas those followed by (L) have low-quality water. All others have high-quality water for the intended uses.

[2]Because uses slightly differ at the respective utilities, the risk level is not uniform across the board but rather driven by the use requiring most stringent quality.

[8]Not applicable as the effluent is initially disinfected with UV; chlorine was added in a continuous flow to the reservoir.

Table 6.4. Occurrence of *Legionella* spp. in 10 Reclaimed Water Systems*[§]

Location	Distance in miles	Total	*L. pneumophila* serotype 1	*L. pneumophila* serotype 2-15	*Legionella* sp.	*Legionella* sp. NSA
CA-18						
Effluent	0	<3	N/A	N/A	N/A	N/A
Reservoir	0.004	<3	N/A	N/A	N/A	N/A
DS1	0.3	<3	N/A	N/A	N/A	N/A
DS2	1.5	3		3		
DS3	2.5	46±19	32±31	8.5	40±25	
TX-3						
Effluent	0	120±130		51±70		55±160
Reservoir	1.5	500±310		230±20	90±320	
DS1	1.9	3				3
DS2	4.9	3		3		
DS3	6.4	9		3	6	
NC						
Effluent	0	36	33			3
Reservoir	7.9	55	36			18
DS1	0.8	9		9		
DS2	8.0	47±17	30	36		30
DS3	9.3	23±9			18	30
FL-1						
Effluent	0	2300		300		2000
Reservoir	0.05	<3	N/A	N/A	N/A	N/A
DS1	0.4	<3	N/A	N/A	N/A	N/A
DS2	1.1	3				3
DS3	2.7	29±2	21±10	12		
FL-5						
Effluent	0	870±990			24	840±1000
Reservoir	0.04	45±19	18		27±34	3
DS1	0.5	33	24	9		
DS2	3.5	105±140	35±6	140±171		3
DS3	6.8	45	33			12
AZ-8						
Effluent	0	<3	N/A	N/A	N/A	N/A
Reservoir	0.9	12		12		
DS1	0.1	30		30		
DS2	1.2	3	3			
DS3	2	<3	N/A	N/A	N/A	N/A
CA-2						
Effluent	0	<3	N/A	N/A	N/A	N/A
Reservoir	0.002	1600±1100	1200±500			3000
DS1	0.63	24	24			
DS2	1.71	45	45			
DS3	2.62	3	3			
CA-1						
Effluent	0	<3	N/A	N/A	N/A	N/A
Reservoir	0.1	220±270	420±1400			
DS1	2.3	3300±1900	3200±1900			
DS2	4.4	45	15	30		
DS3	6.9	12	12			
CA-3						
Effluent	0	660±300	570±380			120
Reservoir	21.1	9		9		
DS1	11.5	140±30	140±24			9
DS2	17.9	<3	N/A	N/A	N/A	N/A
DS3	26.9	6	6			
CO-5						
Effluent	0	130	6		3	110
Reservoir	0.006	460±160	230 ± 80	220 ± 80		
DS1	0.1	810±340	580	470 ± 170		150
DS2	1.3	220±270	360	766 ± 60		60
DS3	2	92±2	47 ± 5	24	40	6

Notes: *The numbers are geometric means ± standard deviation (cfu/mL). [§]Total refers to the total density of *Legionella* spp. including *Legionella* spp. NSA (i.e., *Legionella* spp. with nonspecific agglutination, which are inconclusive with results based on the Microgen Legionella M45 latex agglutination test kit; Microgen Products). N/A = not applicable.

6.2 Case Study for FL-1 Utility

The plant is a five-stage biological nutrient removal (BNR; i.e., Bardenpho system) with enhanced removal of nitrogen and phosphorus. It has a capacity of 15–20 MGD and maintains a rigorous preventative maintenance program. The five stages are anaerobic, first anoxic, aerobic, second anoxic, and reactivation treatment. The headworks (Figure 6.6) has a 3-mm screen for grit removal followed by two clarifiers. The second clarifier provides return activated sludge (RAS) by gravity. The reclaimed water is filtered and chlorinated prior to storage in a closed reservoir.

The distribution line sizes are similar to those of the potable water system. It is operated at pressures similar to the potable system and meets 25 to 30% of total water demand in the area. Depending on the demand and season, up to 45% of the reclaimed water is discharged into a rapid infiltration basin (RIB) to replenish groundwater. The RIB system is comprised of 85 1-acre ponds that can accommodate 12.5 MGD (modeled for a maximum of 17.5 MGD).

Portions of the treatment process are presented in Figure 6.6. The reclaimed water at this location is used for a variety of purposes, including irrigation (parks, golf courses, residential and hotel lawns), cooling towers, washing the resort's fleet of buses, cleaning the sidewalks, street sweeping, fighting and suppressing fires, concrete mixing, and flushing toilets and urinals, as well as recharging the groundwater.

6.2.1 Determinants for CCPs

The system was 42 years old, had a covered reservoir and a long (80 mi) looped distribution network (Figure 6.7) with branches in some areas. Pipes of 16 in. or larger were composed of ductile iron, whereas most of the pipes of smaller diameter were made of DR14 PVC with long-term hydrostatic strength. The plant effluent was disinfected with chlorine and was not redisinfected in the system. The system was well pressurized, and the water was used rapidly (1–3 days). Whatever was not used in that timeframe was utilized to replenish the groundwater through the RIB.

6.2.2 Water Quality Critical Limits

The reclaimed water was of equally high quality as the MBR-generated water at CA-18 (Table 6.3). It met the proposed quality target for all intended uses except for the unusually high levels of *Legionella* in the effluent. However, most of the *Legionella* spp. in the effluent was not further identified by the antibody assay as it was nonspecific (Table 6.4). A few in the effluent and at DS2 in the system belonged to *L. pneumophila* serotype 2-15. DS3 had the same serotypes together with *L. pneumophila* serotype 1, which is normally associated with human disease. However, *Legionella* levels in the distribution system where human contact is most likely were much lower compared to the densities in the effluent. AOC was high in the water but gradually declined as the water flowed farther in the system representing AOC consumption. AOC consumption is an indicator of microbial growth. The chlorine residual in the system dissipated as the water flowed through the system. This, coupled with AOC consumption, may explain the increase in *Legionella* spp. at DS2 and DS3.

Figure 6.6. Portions of the treatment and distribution system for an FL-1 utility.

Panel A: headworks
Panel B: anaerobic tank
Panel C: anoxic tanks
Panel D: second anoxic tank
Panel E: disinfection chamber (effluent tank)
Panel F: sampling from the reservoir
Panel G: DS1 sampling point.

Figure 6.7. Sampling sites at the FL-1 system.

6.2.3 Actions to Correct Exceeded Proposed Limits

The desired target levels in any system should be driven by the reclaimed water uses demanding the highest quality associated with the intended use. In this instance, irrigation of parks, school yards, and golf courses drove the quality requirements, but other uses included cooling towers, washing vehicles, and washing streets and sidewalks, as well as recharging groundwater. Disinfection with oxidants, such as chlorine, break down higher molecular weight organic molecules into smaller, more degradable organic matter. To attain lower AOC levels in the effluent, the plant should consider pretreating the effluent with UV prior to chlorination. Low AOC levels in the effluent were attained by CA-1 using this approach (see Section 6.7.3). The strategy is expected to sustain the low chlorine residuals over a long distance in the distribution system because of reduced organic matter and possibly reduce the *Legionella* spp. Occurrence of *Legionella* spp. (and other pathogens) also could be reduced by maintaining a flushing program with scouring velocities. As the system expands, piping of decreasing diameter also can be implemented to optimize the piping efficiency ratio (PER) and provide a self-cleaning system (Buchberger et al., 2008).

6.3 Case Study for NC Public Utility

The sewer system served a population of approximately 485,000 people and had developed a reuse water system to provide an alternative water resource for demands not requiring potable water quality. The headworks included fine screens and vortex for grit removal and a 45 MG equalization basin to handle wet weather flow and even out the flow. Presence of the EQ basin also enables scheduling septic tank deliveries. The wastewater was pumped into aeration basins for primary treatment and then to clarifiers for secondary treatment. The primary and secondary sludge was mixed (60:40 ratio) for activated sludge treatment. The liquid was skimmed off to obtain a thicker sludge for biosolids production using either windrowing (Class B) or liming (Class A). The effluent was disinfected with UV. If it was for disposal into a nearby river, no further disinfection was required. However, if it was tapped for reuse, chlorine was added to achieve a 1 mg/L residual. The general public was encouraged to collect some reclaimed water free of charge from the plant to meet their needs. This offer was largely exploited by many local landscaping companies. The bulk of the reclaimed water was pumped to an aboveground open tank for distribution to key users around the city. Some of the treatment processes, sampling sites and uses are shown in Figure 6.8. A schematic of the distribution system and related sampling points is presented in Figure 6.9.

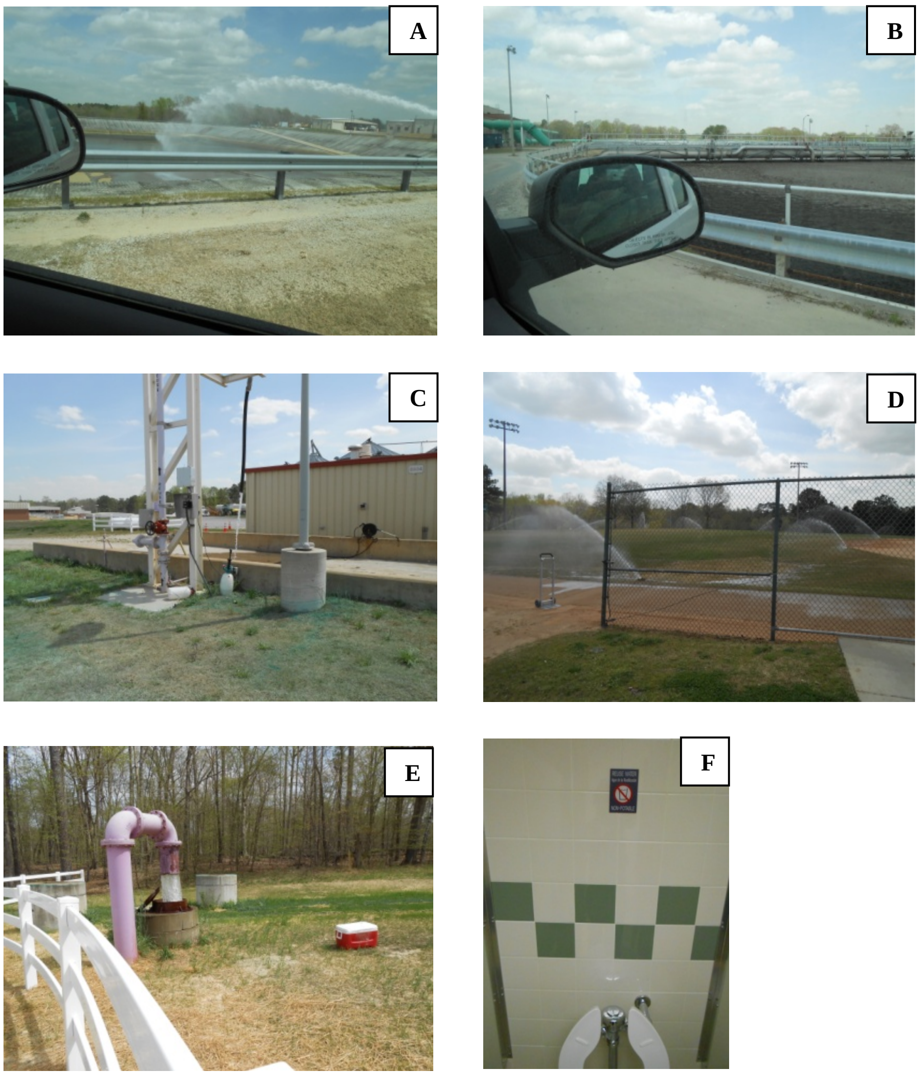

Figure 6.8. Some wastewater treatment processes and distribution at a NC WWTP.

Panel A: EQ basin watered with reclaimed water to contain odor
Panel B: activated sludge basin
Panel C: effluent sampling point (outlet for reclaimed water truckers)
Panels D and E: distribution system sampling points 2 and 3
Panel F: Reclaimed water for toilet flushing at the treatment plant (notice the nonpotable water sign in the background)

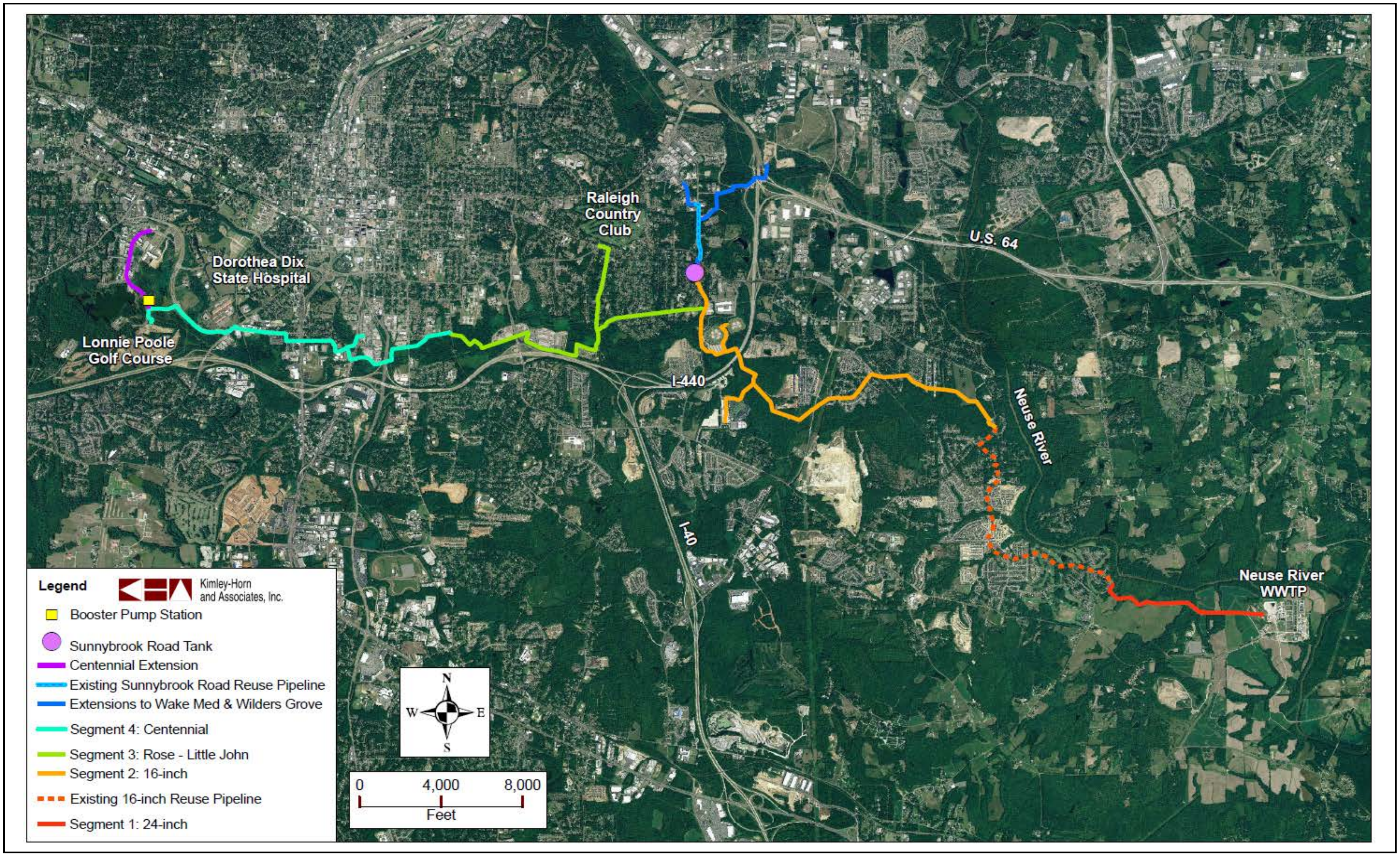

Figure 6.9. Schematic of the North Carolina (NC) reclaimed water distribution system showing the respective sampling points.

6.3.1 Determinants for CCPs

The North Carolina (NC) reuse system had been in operation for only 3 years. It had a production capacity of 50 MG/year, which is considered mid-size capacity. The water was not redisinfected in the distribution system. It had a closed aboveground reservoir. The branched distribution system was 11 miles long and composed of ductile iron pipe. The reclaimed water was used for irrigation of parks, golf courses, lawns, and chillers, as well as for toilet flushing. Leakage was detected because of unusual tank level drops using the SCADA system. These leaks were further investigated using isolation valves. Occasional discoloration of the water owing to pipe corrosion was reported. A reduction in the number of cycles for chillers (i.e., five cycles instead of the typical seven cycles with potable water) was also reported. The system periodically experienced snails in the treatment train. As part of the permit, monitoring the distribution system chlorine residual, turbidity, pH, and conductivity were required. A cross-connection test was required before connecting the user. Acquiring the permit also required a professional inspector who consequently shut off the potable source, turned on the reuse system, and checked whether any water was detectable from the potable system. The system was flushed on an as-needed basis, the water disposed of into the river or back into the reuse system. Flushing at the end of the system was at a rate of 17.4 GPM. Pressure in the system ranged between 20 and 100 psi. Reclaimed water production in winter was 70,000 GPD but almost tripled during summer. The water was typically stored for 2 to 3 days, but depending on demand, it could be stored for up to 5 days. The plan was to clean the reservoirs every 7 years by scraping and applying chemical treatment.

6.3.2 Water Quality Critical Limits

The utility met the proposed targets for irrigation, cooling towers and flushing toilets except for the moderately high turbidity levels experienced at the last two sampling points (Table 6.3). Turbidity was possibly attributed to increased chlorophyll at the end of the distribution system. Chlorine residual diminished in the reservoir and most of the distribution system. The only exception to this trend was an unusually high level of residual chlorine at the furthest sampling point in the system. There was no chlorine booster station in the system, and the system operators noted that a day earlier there was heavy use at one of the facilities farther down the line from the sampling point. From their perspective, this could have been freshly disinfected water with increased free chlorine and turbidity at DS3. *Legionella* spp. were detected in the distribution system but did not exceed the proposed targets for the intended uses. *Legionella* spp. were mostly *L. pneumophila* serotype 1 or *L. pneumophila* serotype 2-15 (Table 6.4).

6.3.3 Actions to Correct Exceeded Proposed Limits

TOC and AOC can be reduced further in the system by initially disinfecting with UV to reduce the organic matter content. Disinfection with UV is known to transform organic compounds by breaking some bonds of the organic compound into low molecular weight compounds, which are more susceptible to degradation (Jorgensen et al., 1998; Paul et al., 2012). The decreased organics would also reduce the amount of chlorine disinfectant and possibly decrease corrosion of the pipes. Reduced corrosion would decrease turbidity. Although not in excess of the proposed targets, *Legionella* can be reduced by maintaining a disinfectant residual or implementing a routine flushing program. Such a program could also minimize localized turbidity increases.

6.4 Case Study for CA-3 Municipal Water System

The plant was located on 2600 acres with 175-acre wastewater operations, a 750-acre sludge drying area, and an 850-acre former salt production pond. The remaining acreage was open land buffering adjacent communities from odors and hazardous operations. CA-3 served eight cities (San José, Santa Clara, Milpitas, Cupertino, Campbell, Saratoga, Los Gatos, and Monte Sereno) with a combined population of 1.4 million residents and businesses. The respective cities contributed 71%, 6%, 5%, 4%, 3%, 3%, 2%, and <2%, respectively, of the wastewater. The service area had more than 300 square miles with 17,000 main sewer connections. It treated an average of 110 MGD but has the capacity to treat 167 MGD. The wastewater underwent a sophisticated 10.5-h treatment process. Most of the treated water was discharged into the South San Francisco Bay, and only about 10% was recycled for various uses, such as industrial processes, cooling towers, and toilet flushing. Advanced (tertiary) level treatment was necessary to meet the region's strict state regulations for water reuse and discharge to the sensitive Southern Bay ecosystem.

Wastewater underwent a three-step treatment process to remove solids, pollutants, and pathogenic microorganisms. At the headworks, large bar screens removed rags, sticks, rocks, and other debris that could otherwise clog machinery. Debris was then transported to the landfill. Further primary treatment occurred in primary clarifiers to remove settleable material and light materials, such as fat, oil, and grease. The 24-h primary treatment process removed about 50% of wastewater contaminants. In large tanks, the flow was slowed to allow gravity to separate large particles. This process mimicked the natural processes of creeks and rivers where sediments settle to the bottom. Fat, grease, and oils were skimmed off by fiberglass bars that gradually rotated from the top to the bottom. The skimmed material was then sent to anaerobic digesters for 25 to 30 days, generating methane, which the plant used to meet 30 to 35% of its energy needs.

Under secondary treatment, the water was aerated in basins where bacteria consumed some of the degradable fraction, reducing BOD. Further secondary treatment in clarifiers facilitated more degradation, generating effluent meeting 90% of the intended final product quality. The water was subjected further to tertiary (advanced) treatment in dual media filter beds (anthracite and sand) and disinfected with chloramine in a serpentine contact tank.

For practical purposes, the distribution system was divided into three zones, whereby Zone 1 ended at sampling point DS1 and Zone 2 ended at sampling point DS2 (Figure 6.10). Both of those locations were booster pump stations. DS2 was located at one of the reservoirs at Yerba Buena Pump Station. A second reservoir (highlighted as the reservoir in Figure 6.10) was located at an elevation in Zone 3. Once generated at the plant, the water was pumped to the Yerba Road reservoir or to the reservoir in Zone 3. Thus, the sampled water at DS1 and DS2 could have been flowing from either end of the distribution systems.

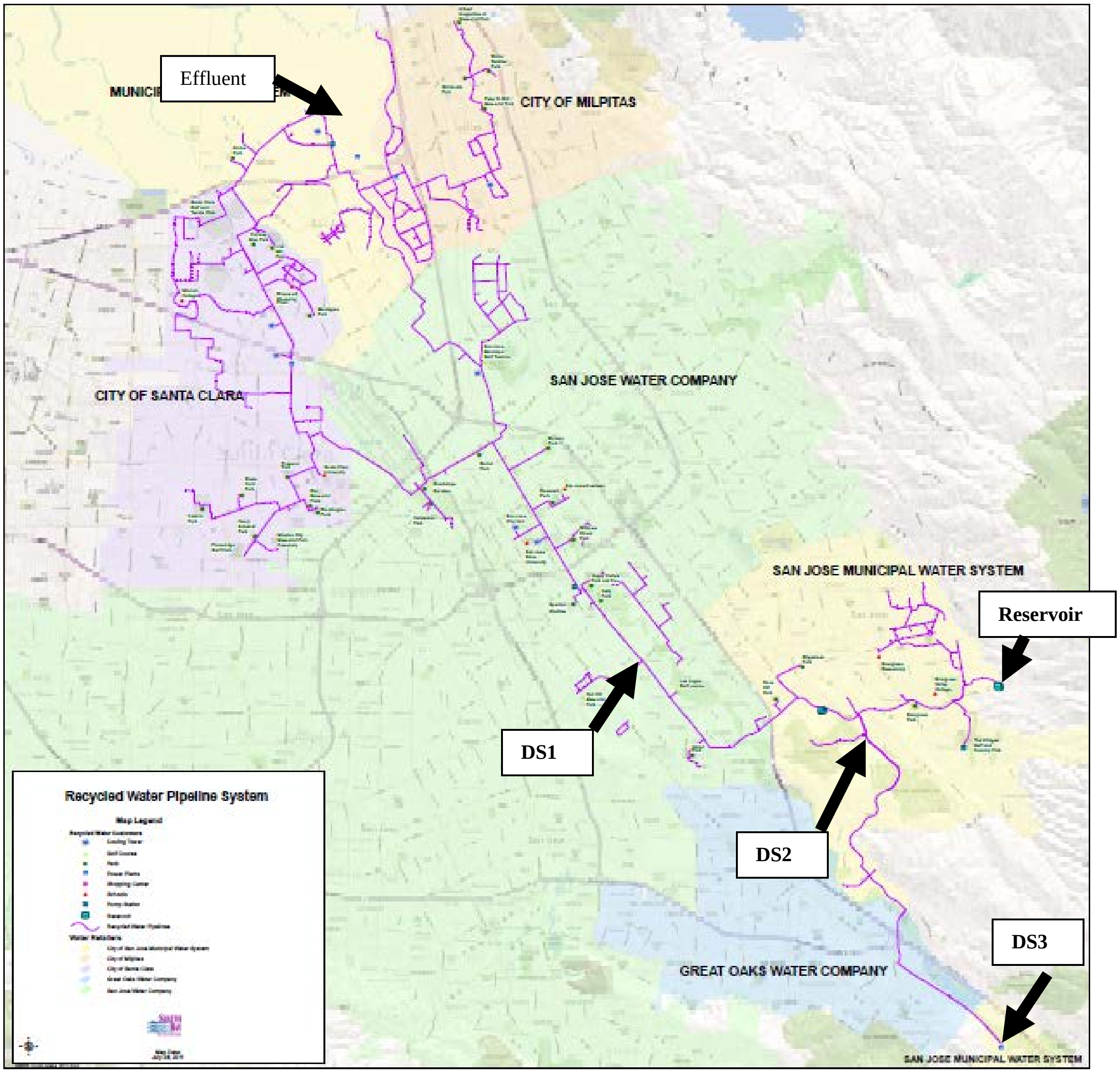

Figure 6.10. Schematic of the CA-3 municipal reclaimed water distribution system.

6.4.1 Determinants for CCPs

This extremely large (3,258,514 MG/year; Figure 6.11A) system was 14 years old and had a long (140 miles) branched distribution network composed of mostly coated steel, but ductile iron, PVC, and reinforced concrete pipes (RCP) were also typically used. It had unevenly spaced valves, most of which were butterfly valves, but also a few gate valves. Most, but not all, of the valves were exercised once a year. The system had experienced five main breaks since inception because of water hammer effects. One main break had occurred the year before the study was conducted. Initially the system was constructed to divert the water flow into the irrigation system. In this context, it had a flow cap based on irrigation needs. More recently, the focus shifted onto supplementing potable water under the notion that every gallon of water recycled decreases dependency on imported water and preserves potable water supplies for current and future generations in the area. Using reclaimed water at various facilities for cooling towers, irrigation, and flushing toilets since 1997 helped conserve more than 37 BG of potable water, enough for 180,000 households per year (Anonymous, undated). That use required additional storage and the resultant construction of two reservoirs farther downstream (Figure 6.10) to include industrial uses (e.g., Figure 6.11B).

Reclaimed water production in winter ranged between 2 and 5 MGD, the latter amount applicable to dry winters and vice versa. During the summer, production ranged between 10 and 20 MGD depending on the demand. Rationing of reclaimed water was not necessary, and the facility followed a cycle of filling and draining the closed reservoirs on a daily basis. This approach did not allow for long water age in the distribution system. The reservoirs were cleaned every 2 to 3 years by vacuuming. The system had leakage problems, and the water was colored because of corrosion of steel pipes. The system also experienced high levels of hardness and salinity issues.

The water was disinfected with chloramine and not redisinfected. No breakpoint was achieved, and no ammonia was added. The facility used a combined residual. The system had a few dead ends, but efforts were made to minimize this by avoiding extension of the distribution line to areas where there was no customer. No water quality monitoring was required or conducted after the effluent water met Title 22 requirements. Typical hydraulic pressure ranged between 40 to 200 psi depending on location and pressure related damage (e.g., broken sprinkler heads) was reported. A cross-connection test had to be done for each location where reclaimed water was distributed prior to approval. For locations with dual sources (i.e., potable and reclaimed water), a cross-connection control test had to be performed every 4 years.

6.4.2 Water Quality Critical Limits

A summary of the water characteristics in the distribution system is presented in Table 6.3. AOC levels decreased as the water flowed farther from the plant signaling possible regrowth of bacteria. Although conductivity did not change in the system, it remained consistently high and unfavorable for irrigation of crops and vineyards. Free chlorine in the system was greatly diminished at all sampling locations in Zone 2 and Zone 3 but still met the proposed residual targets for irrigation (of crops and vineyards) and cooling towers. However, because the utility used chloramine, disinfection could still be occurring at these low free chlorine levels. The water met the proposed targets except for dissolved oxygen and *Legionella* at several points in the distribution system. Dissolved oxygen was specifically quite low Zone 2 and Zone 3. Low levels of *Legionella* spp. were detected at all sampling locations except DS1 (Table 6.3). Most of them were *L. pneumohila* serotype 1, which is known to be pathogenic (Table 6.4).

6.4.3 Actions to Correct Exceeded Proposed Limits

The treatment process could be enhanced to remove more AOC by maintaining longer hydraulic retention times and using a coagulant. Dissolved oxygen can be increased by aerating the water in Zone 2 and at the reservoir in Zone 3. To increase disinfection efficacy, the utility should chlorinate to achieve breakpoint, which can control *Legionella* densities more effectively (Flannery et al., 2006). To reduce TDS and salinity-related problems, the utility should consider blending reclaimed water with potable water at a 1:1 ratio and adapting reverse osmosis technology or electrodialysis technology. Corrosion, possibly owing to the chlorides, was a major problem of the system leading to water coloration. This problem was possibly attributed to steel and steel-coated pipes. Both materials have a higher propensity to corrode (see CorrosionRx chart). Whenever an opportunity arises to replace any pipes, the utility should consider other, more robust materials, such as ductile iron.

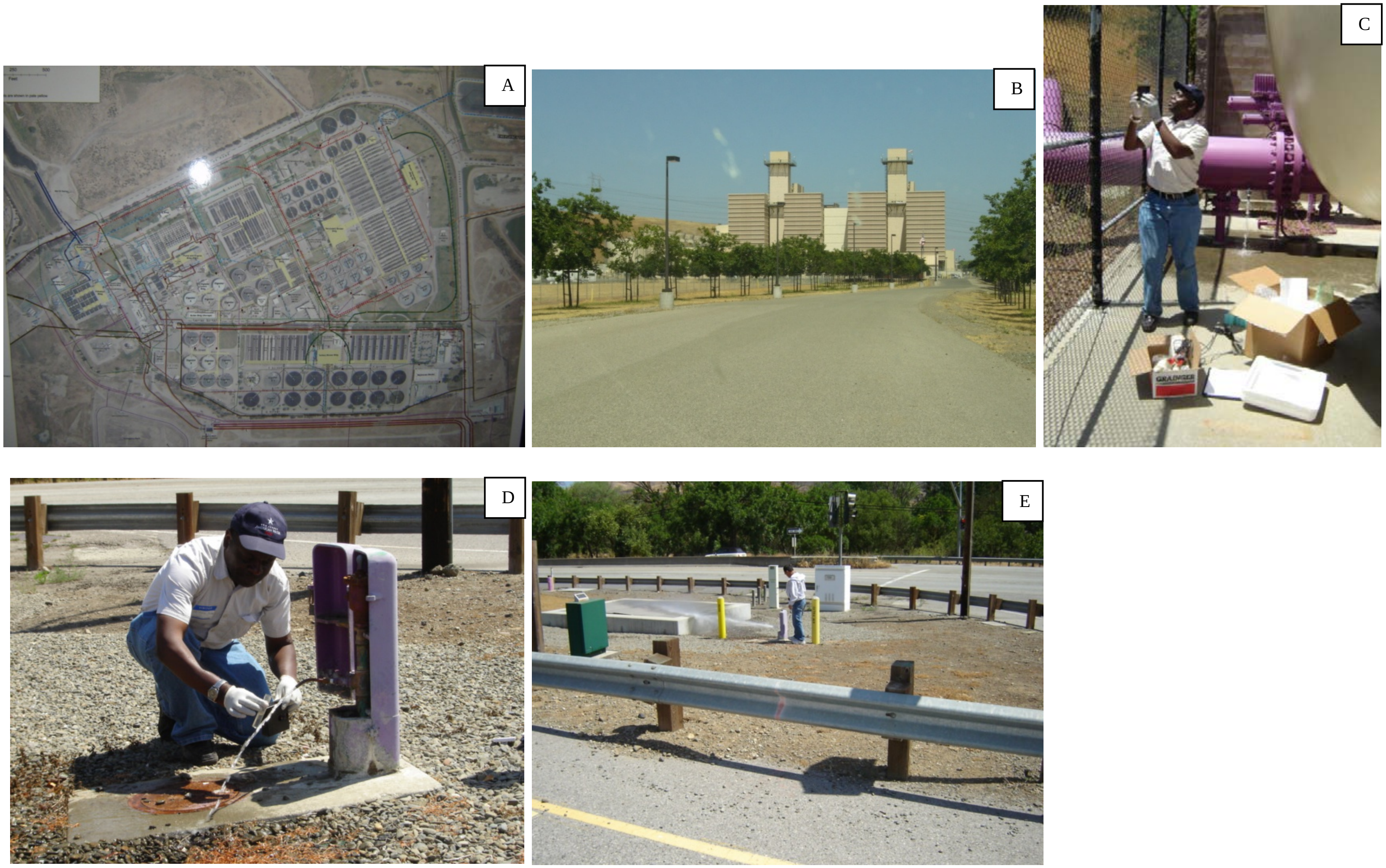

Figure 6.11. CA-3 reclaimed water plant system.

Panel A: Layout
Panel B: Service area to a power plant
Panels C, D, and E: Sampling from various parts of the system

6.5 Case Study for CA-2 Community Services District

Wastewater from two primary pump stations was initially treated in two facultative ponds (primary treatment; Figure 6.12A) where the dissolved oxygen levels were about 3 mg/L. The ponds had a combination of vertical aerators and brush aerators. The brush aerators helped with removal of personal wipes. Grease and oil were also sucked off the wastewater with bacterial enzymes in the collection system during this phase. The partially treated water was released to ponds 3, 4, and 5 where increased oxygen concentrations (8–10 mg/L) and high pH facilitated a reduction in BOD. The ponds were 12 to13 ft deep. Sludge buildup in ponds 1 and 2 was removed periodically as needed using a septic truck with a vacuum suction device. The effluent from ponds 3, 4, and 5 was stored in a large intermediate reservoir (Figure 6.12B), which was, through a local water balance program, tapped into for further (tertiary) treatment for reuse. To minimize algal uptake in the intermediate reservoir, the intake into the tertiary treatment system drew water from 3 to 4 ft below the surface of this intermediate reservoir. The intermediate reservoir was treated periodically with copper sulfate (initial rate at 150 lb followed by 250 lb 2 to 3 weeks later) to control algae. The solids were treated with alum and dried to reduce pathogens. The generated biosolids were used on surrounding farms and for landscaping needs.

The tertiary treatment started with a chlorine pretreatment or coagulation. The water was then subjected to dissolved air floatation (DAF; Figure 6.12C) in a clarifier, whereby the water was saturated with air at 70 to 80 psi, creating microbubbles (Figure 6.12D). Alum was added during this process only when turbidity was greater than 10 NTU. The water was then filtered through a 10 in. sand filter (three cells of 1.5MGD capacity). The filter cells were backwashed in rotation each day. After DAF, the water was disinfected with chlorine in a serpentine basin. A minimum pH 6.5 was maintained in the serpentine basin by adding NaOH if necessary. Chlorine contact was continued in a contact pond (Figure 6.12F) before pumping the water to the golf course (Figure 6.12G). The basin was cleaned once a year.

The reclaimed water was applied to two golf courses with a total of 250 acres. The water was required to meet Title 22 of the California Code of Regulations with specified quality criteria summarized in Table 5.5. The golf courses had Bermuda grass, which was more drought-tolerant compared to rye grass the course had used in the past. Irrigation decisions were made based on the hydrologic conditions at the golf courses, and reclaimed water was the primary source to meet those needs, although occasional shortages were supplemented with raw water from Cosumnes River or Lake Bass. Pumping to the reservoirs was conducted only after requests from the golf course on an as-needed basis. Spray irrigation was, under California Regional Water Quality Control Board (Central Valley Region) stipulations, prohibited when wind velocities exceed 30 mph. It also was prohibited before, during, or within 24 h after precipitation.

Table 6.5. Specified Criteria for Meeting California's Title 22 Requirements at CA-2

Parameter	Must Not Exceed:
Total coliform (MPN)	2.2/100 ml (7 day median) 23/100 ml in one sample in 30 days 240/ml at any time
Turbidity (NTU)	Average of 2 within a 24 h period 5 more than 5% of the time within a 24 h period 10 at any time

Source: Anonymous, 2010.

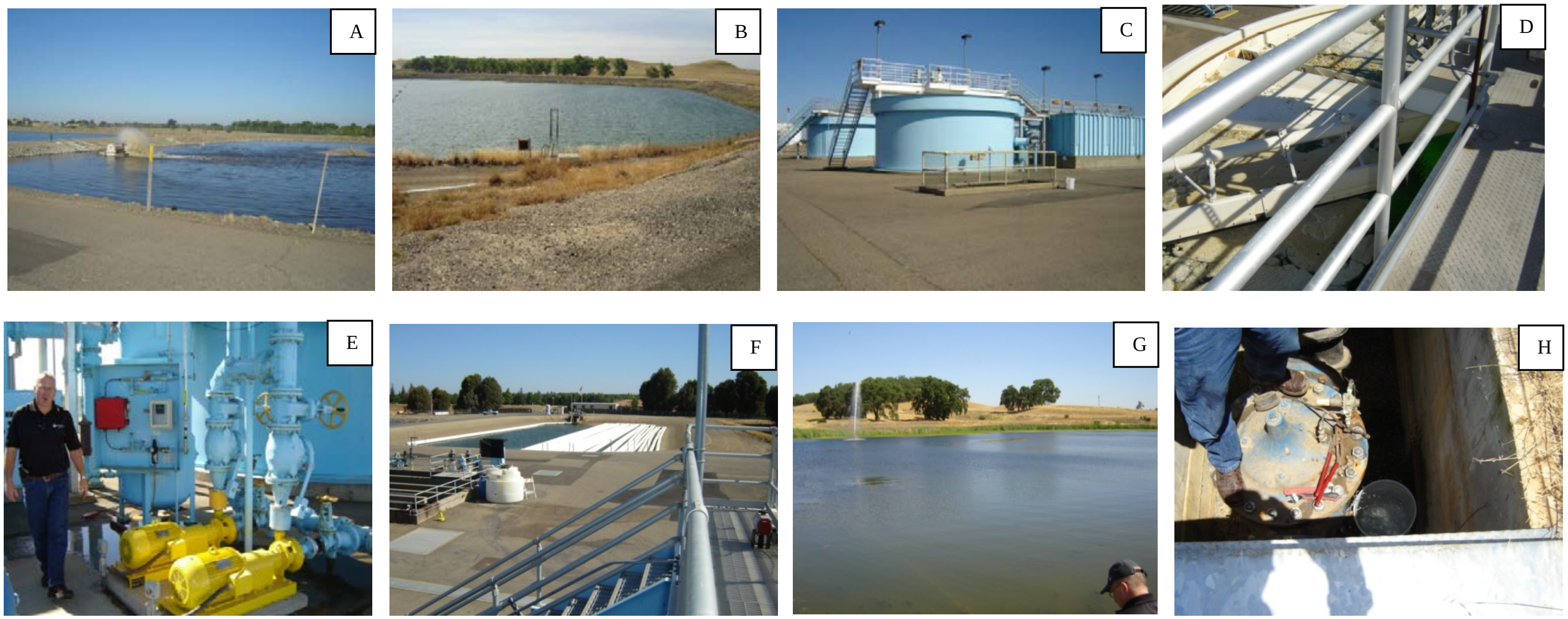

Figure 6.12. CA-2 treatment process and distribution system sampling sites.

Panel A: oxidation pond
Panel B: post-oxidation intermediate storage pond
Panel C: DAF assembly
Panel D: DAF process (notice floating granules because of DAF treatment)
Panel E: cylindrical DAF
Panel F: disinfection pond
Panel G: reservoir
Panel H: DS3 sampling site.

A schematic of the distribution system is presented in Figure 6.13. The sampling focused on the part of the system that delivered to the golf course on the north side of Cosumnes River. The second (DS2) and farthest (DS3) sampling points were presented in Figure 5.12G and 5.12H, respectively.

6.5.1 Determinants for CCPs

This 24-year-old system was classified as large (163 mg/year) with lagoon treatment technology, whereby secondary treatment in facultative ponds was operated throughout the year. The reclaimed water was filtered and subsequently disinfected with chlorine gas prior to storage. No post-storage redisinfection was practiced presenting vulnerability to regrowth of microorganisms after open storage. There was no demand for reclaimed water between October 15 and April 15 of each year. Thus, all the treated water during that period was either stored in the intermediate pond (pretertiary treatment) or discharged to the river.

The distribution system was fairly short (1.7 mi) but had a branched network of PVC pipes. Despite the branching, there were no dead ends, as each end led into a pond. Gate valves were operated only as needed. The systems had two booster pumping stations, one on the north and the other on the south course of the Cosumnes River. The north course (which the sampling focused on) had a 25 acre-ft pond, whereas the south course pond had a capacity of 10 acre-ft. Neither of these two ponds was cleaned regularly. No main breaks were reported, but the system lacked a leak detection system. The system did not have a flushing program, as reclaimed water disposal was prohibited under its discharge permit (i.e., a zero-discharge permit).

Algal growth in the reservoirs was a common problem because of stagnation. Other reported problems included growth of water fern (Azolla) and surface weed (Duckweed). To minimize odor, reclaimed water was drained from the irrigation system piping back into the reservoirs immediately before start of the annual irrigation cycle and each instance when the irrigation water delivery was interrupted for more than 2 days. The practice was adapted after odor complaints from residents, but aesthetic appearance elicited periodic complaints from residents. To increase the level of dissolved oxygen in the reservoir, the golf course used an aeration/mixing device to prevent stagnation of the water (Figure 6.12G). Aeration was also intended to reduce algal growth and mosquito problems. The operation manual for CA-2 repeatedly referred to its product as recycled “wastewater,” despite the fact that the water had been treated adequately to meet the outlined California Title 22 reuse standards.

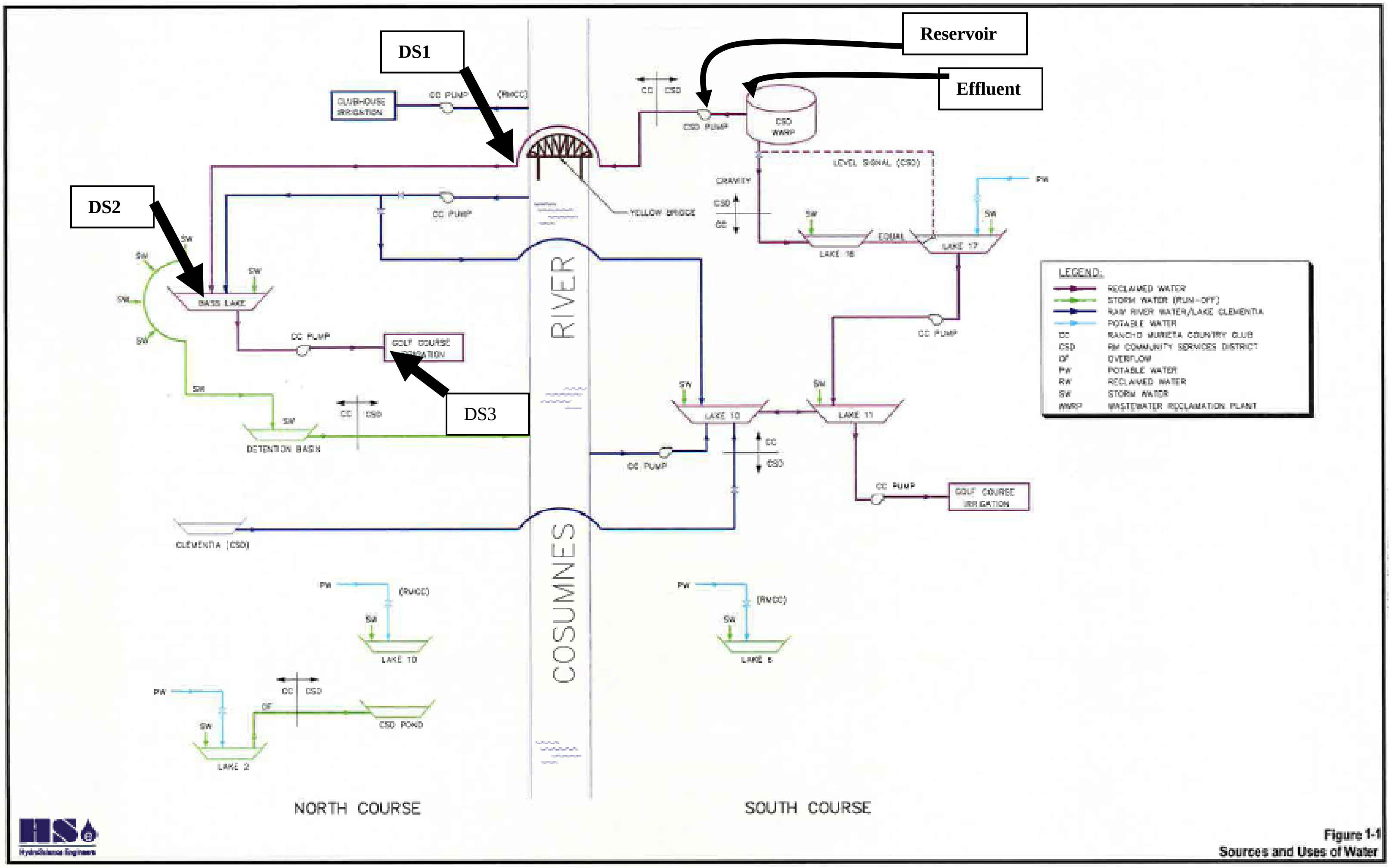

Figure 6.13. Schematic of the CA-2 reclaimed water distribution system showing the sampling points (DS1, DS2, and DS3).

6.5.2 Water Quality Critical Limits

The water quality in relation to proposed targets for both intended reclaimed water uses at CA-2 was summarized in Table 6.3. TOC levels remained unchanged in the effluent and distribution system. AOC levels were extremely elevated in the pond (DS2) at the golf course, exceeding the proposed guidelines. Whereas the effluent initially met targets for AOC, turbidity, free chlorine, DO, and *Legionella* spp., all four parameters increased at various points in the distribution system. The largest turbidity increases occurred in the reservoir and the pond (DS2) because of sediments. Free chlorine also gradually decreased in the system and was undetectable at the end of the system (DS3). The end of the system also had low levels of dissolved oxygen. *Legionella* sp. was not detected in the effluent but emerged in the reservoir and downstream (Table 6.3). All of the detected *Legionella* sp. at this location was *L. pneumophila* serotype 1 (Table 5.4), which is typically associated with disease. The water met target levels for TOC, chlorophyll content, hydrogen sulfide, and conductivity for both end uses (i.e., irrigation and for watering ranches).

6.5.3 Actions to Correct Exceeded Proposed Limits

Disinfectant residual was monitored routinely at the plant but not in the distribution system. Although free chlorine persisted throughout most of the distribution system ($\geq$0.14 mg/L), it dissipated at the end of the system (DS3). Chlorination also increased AOC in the reservoir and downstream. UV disinfection prior to chlorination may be useful. This could also help reduce *Legionella* sp. and other microorganisms in the distribution system. Common practice was not to add alum to the DAF process if turbidity was <10 NTU. Although that provided an effluent that met the proposed turbidity target, the turbidity increased because of sedimentation in the reservoirs and possibly corrosion. The reclaimed water in the distribution system (including ponds) should be protected from turbidity and AOC increase resulting from sedimentation, algal growth, and biofilm formation. Emptying the disinfection pond and at DS2 between October 15 and April 15 when there is no demand for reclaimed water coupled with cleaning of the ponds can ensure starting off the season with a clean distribution system.

6.6 Case Study for CO-5 Wastewater Treatment Facility

The plant had a 900,000 GPD extended aeration activated sludge treatment system. To meet its discharge requirements, the process was supplemented with a clarifier coupled with UV disinfection. It routinely discharged the treated water in Coal Creek located approximately one-quarter mile east of the plant. The process flow is presented in Figure 6.14. The gravity-fed sewer system fed into the headworks where heavy debris, such as rags and trash, were removed through the grit chamber (Figures 6.14, 6.15A). The material proceeded to an extended aeration basin where combination with activated sludge decomposed the organic fraction, consuming oxygen (Figure 6.15B). The aeration basin had a retention time of 30 to 40 hours and was oxygenated with a 200 hp centrifugal blower. The blower operated intermittently three times per day, and the process drove the DO to approximately 1 mg/L, driving the nitrification process.

The mixed liquor flowed into a secondary clarifier unit that separated the solids (heavier sludge) from the liquid. The former settled at the bottom of the clarifier and was pumped back to the aeration basin (i.e., return activated sludge, RAS) for continued treatment together with incoming raw wastewater. The excess heavy sludge (i.e., wasted activate sludge, WAS) in the clarifier was pumped to an aerobic digester for further treatment and stabilization, generating biosolids. The liquid fraction was disinfected with UV and discharged into Coal Creek. The system was designed to deliver UV fluences of 40,635.28 μW-sec/cm^2 (40,635.28 mJ/cm^2) using UltraTech's

40-lamp × 58 in. arc length Terminator in-channel vertical module based on the peak design flow rate of 7.2 MGD.

Owing to demand patterns, the water was only reclaimed during the summer time, and even then only about 40% was processed beyond UV disinfection reclaimed for reuse, the rest destined for disposal into the creek (Figure 6.14). The fraction destined for reuse was disinfected further with chlorine gas by injecting 10 to 15 lb gas/day in 1000 gal/min. Chlorine doses for the previous 5 years are shown in Table 5.6. The disinfected effluent was filtered through a pack of eight cloth filters.

Table 6.6. Average Chlorine Doses for the Last 5 Years

Year	Chlorine concentration (mg/L)	Quantity
2009	1.44	394 lb with 32.793 MG
2010	1.58	580 lb with 44.154 MG
2011	1.31	343 lb with 31.321 MG
2012	1.80	1053 lb with 70.116 MG
2013	1.47	148 lb with 12.100 MG

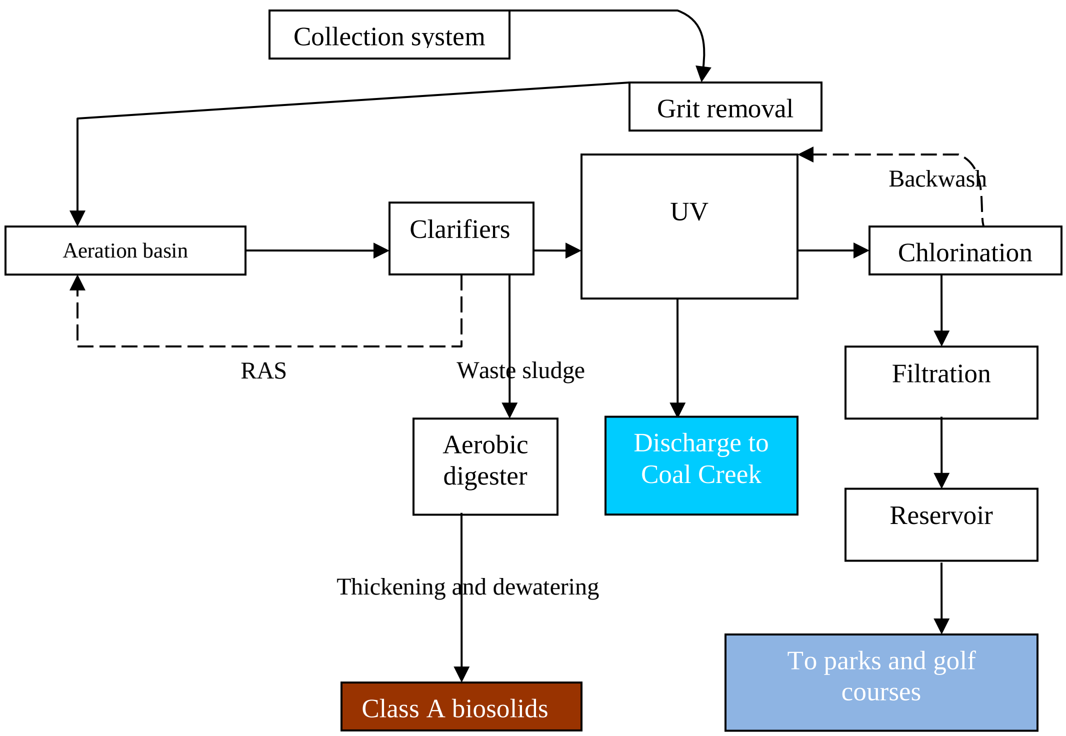

Figure 6.14. Process flow of the CO-5 wastewater treatment system.

6.6.1 Determinants for CCPs

A map of the system displaying the sampling points was presented in Figure 6.16. The system was classified as a mid-size (40 MG/year) 8-year old AS system with an activated sludge with extended aeration treatment practice followed by UV disinfection. Sixty percent of the water is returned to a creek to meet water rights requirements and the rest treated further for reuse by specifically disinfecting with chlorine (to provide a residual) and filtering through a cloth filter (AquaDisk filter; Figure 6.15D). The water was stored in a 1.5 MG polyethylene-lined reservoir equipped with an aeration system (Figure 6.15E). It was distributed to various city parks and a golf course through a 2 mile PVC pipe along the city trail. The pipe discharged into ponds at each of the destinations (Figure 6.15F and Figure 6.15H). Water use at the parks was managed by the City's Parks Department. However, at two of the destinations (DS1 and DS2), the ponds were mostly loaded with algae and various types of waterweeds (Figure 6.15F and Figure 6.15G). The water was only redisinfected in the distribution system with chlorine as needed. Two algaecides, Cutrine-Plus and Aquathol K, were periodically used to control water vegetation. The former was a liquid copper-based formulation whereas the latter was a diasodium salt of endothall.

6.6.2 Water Quality Critical Limits

The water quality at various parts in the system is presented in Table 6.3. Unlike most systems where reclaimed water had multiple uses, reclaimed water at CO-5 was primarily for irrigation of parks and the golf course. The water did not meet the proposed AOC, turbidity, and hydrogen sulfide levels in the reservoir. The open reservoir had substantial waterweed. Turbidity was also moderately high at the end of the distribution system. CO-5 met the proposed quality requirements for TOC, chlorophyll, conductivity and free chlorine residual at all sampling sites. All of the sampling locations exceeded the proposed *Legionella* target for reclaimed water used to irrigate parks and golf courses (Table 6.3). Most of them were *L. pneumophila* serotype 1 and *L. pneumophila* serotype 2-15 (Table 6.4).

6.6.3 Actions to Correct Exceeded Proposed Limits

The utility should consider increasing the UV fluence to control *Legionella* sp. Its fluency was only 28.2% of the fluence at CA-1 (see Section 6.7). This would enhance disinfectant residuals and minimize microbial growth.

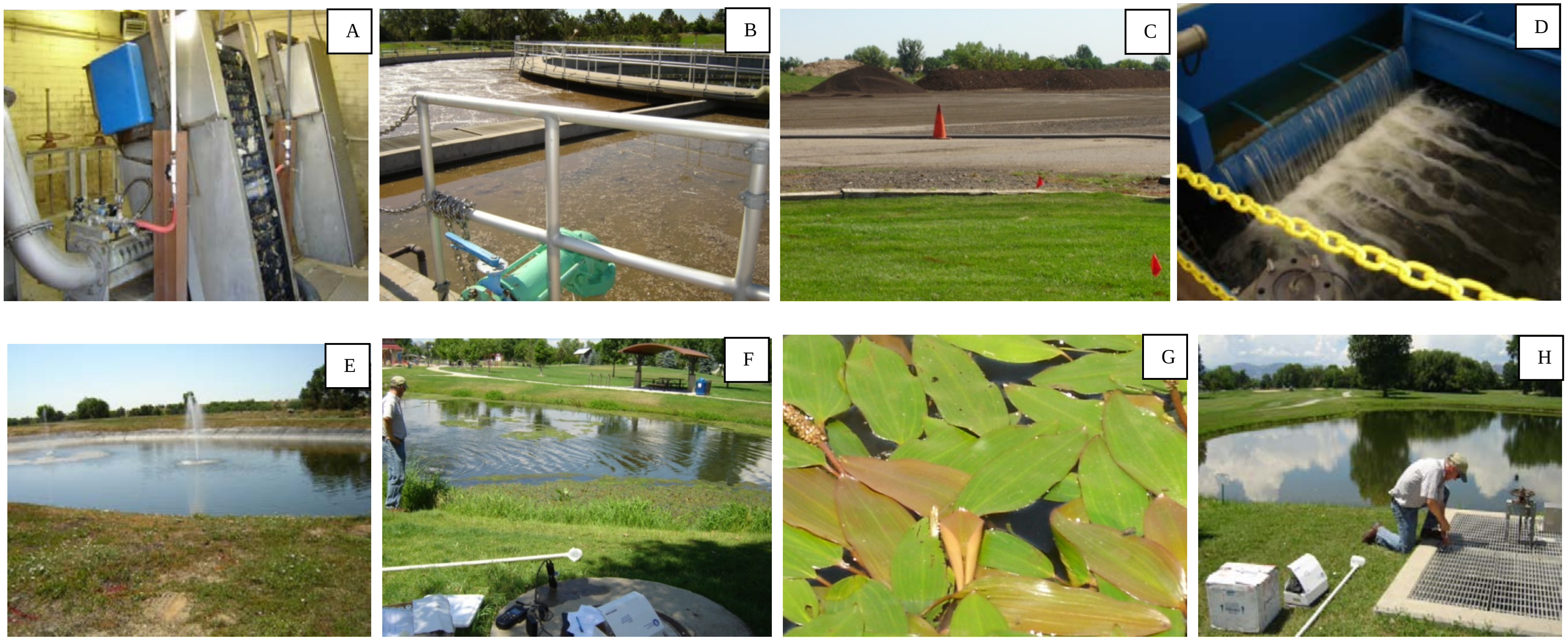

Figure 6.15. CO-5 wastewater and reclamation system.

Panel A: Trash removal system at the headworks
Panel B: Aerobic basin
Panel C: Biosolids windrow
Panel D: Cloth filter basin
Panel E: Aerated reservoir
Panel F: Pond at one of the parks (DS2) overgrowing with algae
Panel G: American pondweed (*Potamogeton nodosus*)
Panel H: DS3 sampling point with pond and the golf course in the background.

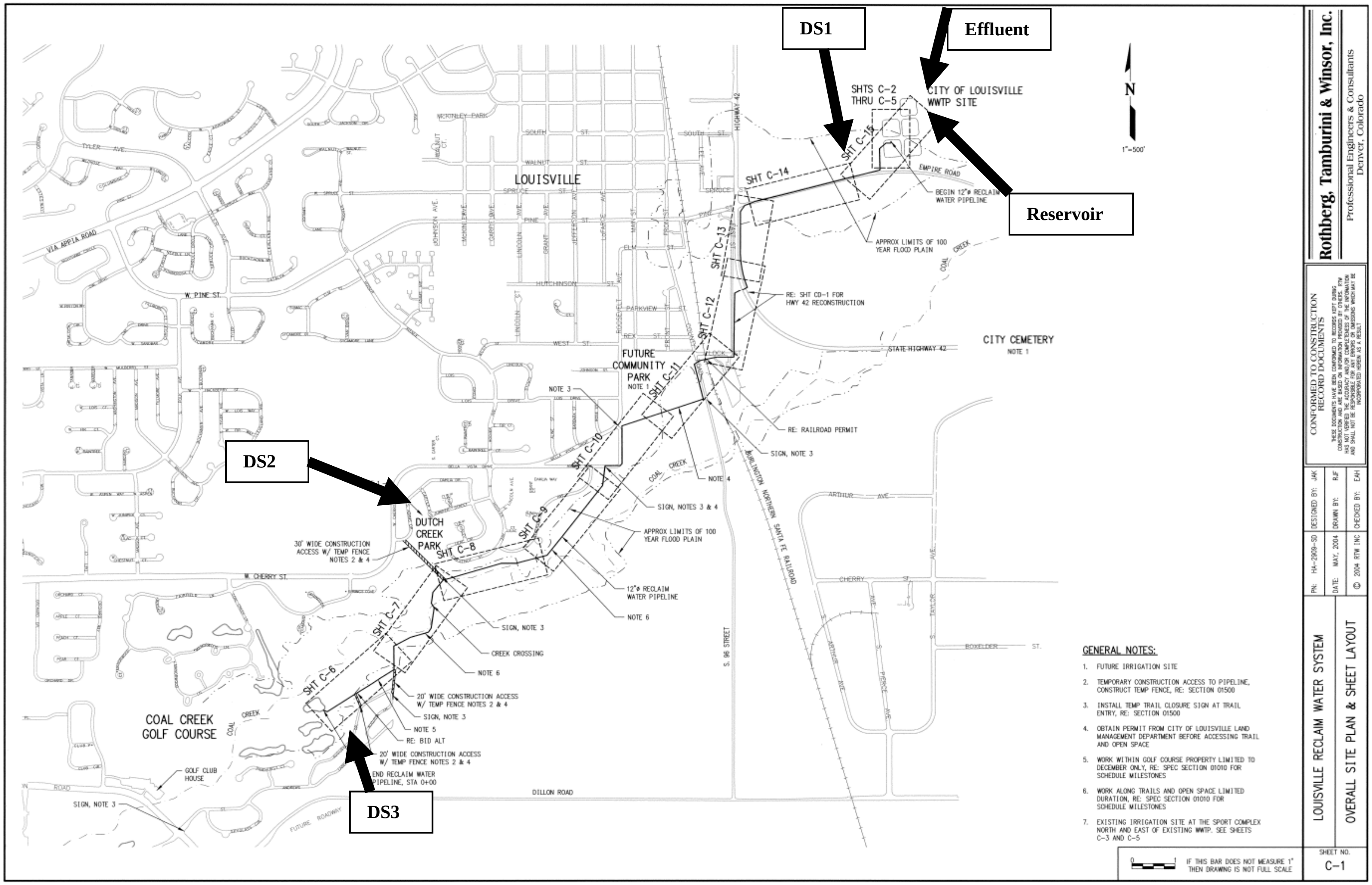

Figure 6.16. Map of the CO-5 reclaimed water distribution system.

6.7 Case Study for CA-1 Subregional Water Reclamation District

The CA-1 treatment plant drew wastewater from homes, businesses, and industry located within the CA-1 Subregional Water Reuse System. It served the cities of Santa Rosa, Rohnert Park, Sebastopol, and Cotati. Average wastewater flow was 16 MGD, and the collection system was more than 500 mi long. The wastewater underwent primary, secondary, and tertiary treatment prior to disinfection, storage, and reclamation using an activated sludge process. The primary treatment removed grit, paper, wood, plastic, and a variety of other solids using a set of screens. The treatment train is presented in Figure 6.17.

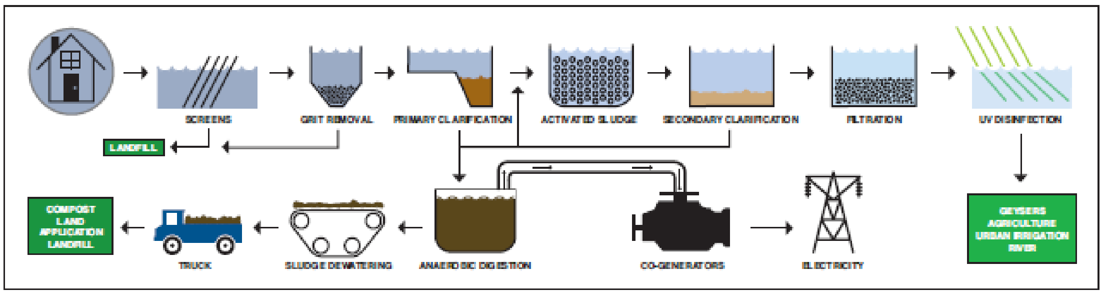

Figure 6.17. CA-1 WWTP train.

Source: http://ci.santa-rosa.ca.us/doclib/Documents/recycledwatertreatmentprocess.pdf.

During the primary phase, the waste was incubated in four anaerobic digesters to generate methane for energy production using a set of generators (Figure 6.18A). This process serves one-sixth of the plant's energy requirements. Primary treatment reduces the solids by 50%, and the remaining solids are used for biosolid production (Figure 6.18D). After equilibration to remove most of the solids, the post-primary products are subjected to secondary activated sludge treatment with nitrification/denitrification. An anoxic phase facilitated nitrification combined with a fine bubble diffuser (Figure 6.18B). The plant had a total of four aeration basins, and a retention time of 12 h was maintained in the basins. The plant had five secondary clarifiers (Figure 6.18C) used to treat the activated sludge. Some of the sludge reseeded the secondary (anoxic) process (as RAS). The clarified liquid was filtered through any of the 4 to 5 ft anthracite (coal) filtration beds. Each bed was backwashed once a day, triggered by water depth. The filter media had never been changed, but its depth was replenished as needed to maintain the 4 to 5 ft depth. Typical turbidity at this stage was ≤2 NTU but if it got higher (>10 NTU) alum was added prior to filtration. The plant aimed at final effluent nitrate concentrations of 10mg/L.

The filtered water was disinfected using UV at a typical fluence of 144,000–180,000 µW-sec/cm^2 (144,000–180,000 mJ/cm^2). The UV system had 10 wafers with 36 lights each. The lights were equipped with a curvature wiper. Low levels of chlorine were sometimes used prior to UV to control algae, which, if uncontrolled, can impact the UV lights. An aerial photo of the reservoirs in relation to the treatment plant is shown in Figure 5.18J, and the geysers supplied by the plant are in shown the horizon, about 20 mi away from the plant. Total reservoir capacity stood at 1.5 BG. Reclaimed water production was 15 MGD in summer and 25 MGD in winter. At the geysers, reclaimed water was injected into the geothermal field. That type of reuse consumed two-thirds of the reclaimed water volume.

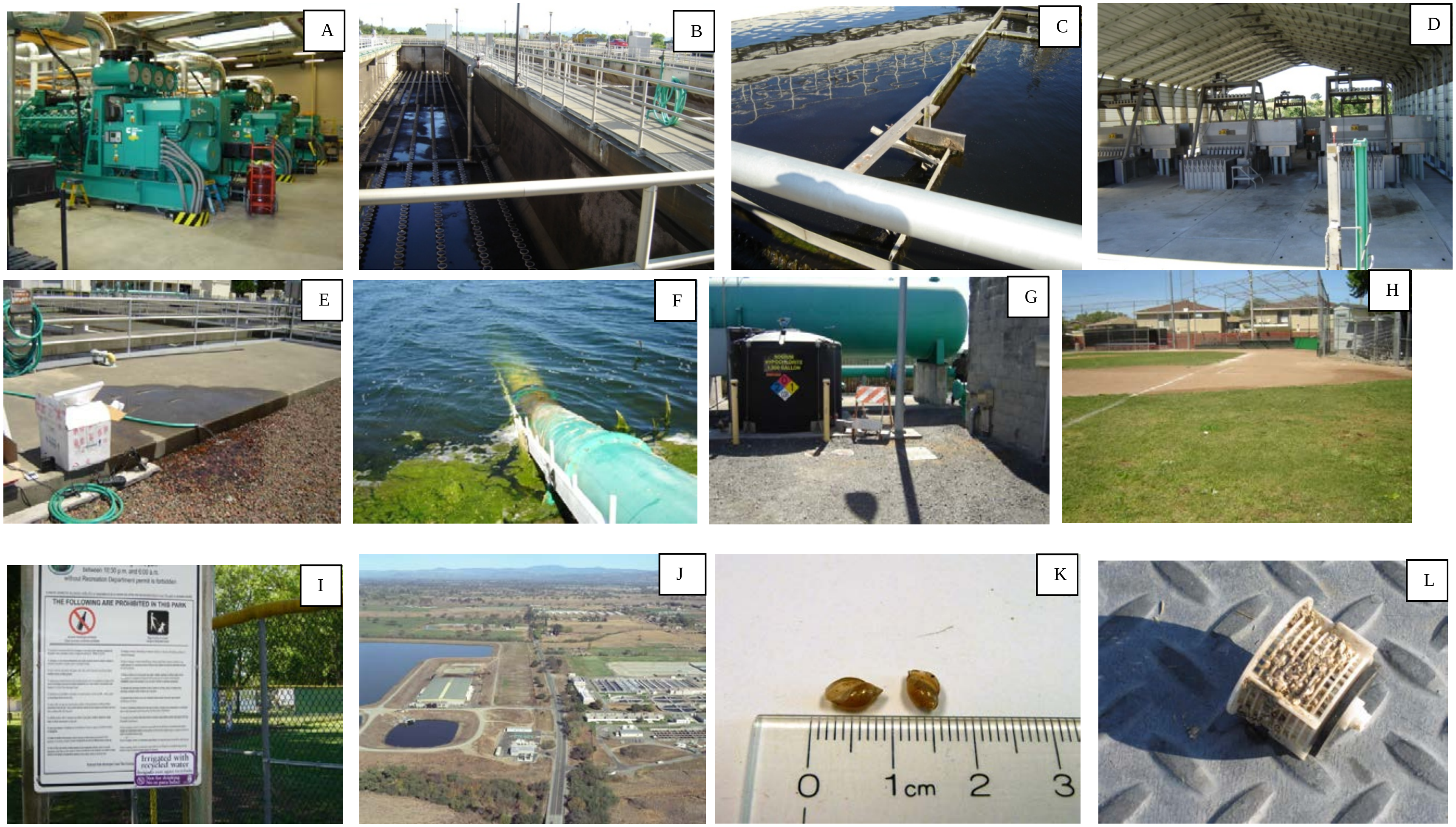

Figure 6.18. Reclaimed water treatment and distribution processes at CA-1.

Panel A: power generator utilizing methane from the digester
Panel B: anoxic/aeration basin
Panel C: clarifier
Panel D: UV dosing station.
Samples were obtained from the (Panel E) effluent, (Panel F) reservoir, (Panel G) DS1 at a baseball park, and (Panel H) DS2.
Panel I shows signage at the ballpark displayed at the DS2 location, whereas Panel J shows an aerial view of the plant and reservoirs with the geysers in the horizon.
Panel K shows a sample of snails that clogged irrigation devices (Panel L).

6.7.1 Determinants for CCPs

The system was 34 years old. It was classified as a very large system with a capacity of 6700 MG/year, which translated into peak daily use in excess of 35 MGD. The distribution system was long and branched totaling 74 mi (Figure 6.19). Of the 33 mi that fed the nongeyser system, the main line (≥24 in. diameter) was a concrete cylinder pipe. By comparison, 45% of the system had diameter <24 in. and was comprised of PVC pipes. The 41 mi that fed the geyser system was all composed of concrete cylinder pipe. Figure 6.19 also displayed the sampling locations. Algal growth was noticeable in the reservoir (Figure 6.18F). After UV treatment, post-storage chlorination with sodium hypochlorite was conducted at DS1 and two other pump stations. Redisinfection was aimed at providing a residual of 0.5 to 1 mg/L. In some instances, the system developed snails (Figure 6.18K) that clogged irrigation heads (Figure 6.18L). Chlorination dosages of 3 mg/L providing a residual of 0.5 to 1 mg/L successfully controlled the snails.

To limit the number of dead ends, the system managers tried to have a user or a pond where the dead end would have been located. However, one part of the system had a 24 in. pipe without enough customers (demand), which led to long water detention times and odor issues. The system had a valve every mile. The valves were composed of steel. As part of a preventative measure, they were exercised annually. It had about 35 booster pump stations of which 10 were owned by the farmers and the reclaimed water was redisinfected at three of those stations. It had not experienced many main breaks (only one in the year the study was conducted), and it had a leak detection system. The system did not have a distribution system monitoring requirement and only conducted such monitoring when there was a specific issue or when the reclaimed water was destined for discharging in receiving waters. Absence of distribution system monitoring provided an avenue for water quality deterioration to go unnoticed.

The system had multiple pressure zones. The main pump station at the plant provided 14 to 17 psi, but pressure in the distribution system differed by location with some locations at 90 psi, whereas others had 75 to 85 psi. The urban sites had to conduct annual cross-connection inspection and were required to have pressure reducing valves on potable systems that were checked annually. Dual system owners had to conduct an annual cross-connection test as specified under California’s Title 22 summarized in Section 4.5. For city properties, the test was provided by the city, whereas private users obtained the test from private contractors. There was no formal flushing program, but where disposal was necessary, it had to be flushed into the sewer.

The reservoirs at the plant (Figure 6.18F) had never been cleaned, but the ones at various pumping stations were cleaned every two years using a tractor to scoop the silt. Cleaning of the reservoirs at the geysers was based on inspections. It was conducted using a vacuuming truck.

6.7.2 Water Quality Critical Limits

Uses included irrigation of parks, school yards, residential lawns, golf courses, edibles and vineyards, and manufacturing and industrial processes (e.g., geyser). Water quality requirements were driven by irrigation of parks, school yards, residential lawns, and edible crops, which require the highest water quality (Table 6.3). With the exception of chlorophyll and conductivity, all the parameters did not meet the proposed targets at one or more sampling locations suggesting inherent instability in the distribution system. TOC and AOC increased in post-storage, which, in turn, increased turbidity and hydrogen sulfide. Chlorine was dissipated but redisinfection was implemented at DS1. Dissolved oxygen levels were only high enough in the reservoir and at DS1.

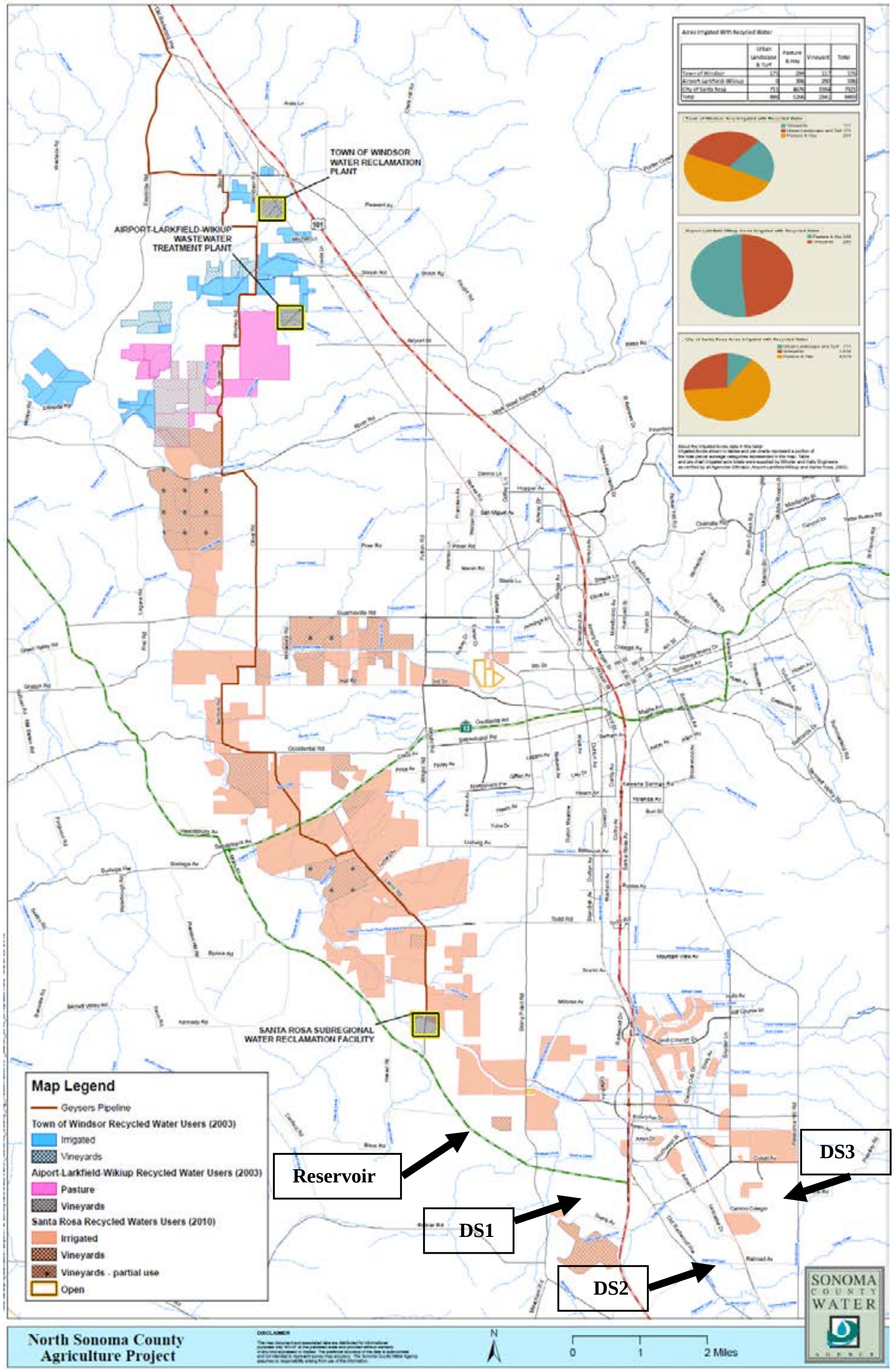

Figure 6.19. CA-1 plant and reclaimed water distribution system.

Note: Sampling focused on the southbound pipeline; the northbound pipeline delivers reclaimed water to the geysers**.**

The effluent DO was extremely low possibly as a carryover from the secondary nitrification/denitrification process. Although *Legionella* was not detected in the effluent, its abundance increased in the reservoirs and distribution system. In most instances, this belonged to *L. pneumophila* serotype 1, which was a known pathogen (Table 6.4). *Legionella* sp. emergence was possibly enhanced by favorable AOC and low disinfectant residual (Table 5.3).

6.7.3 Actions to Correct Exceeded Proposed Limits

AOC was quite low in the effluent, possibly because of UV disinfection and prechlorination processes. UV photolysis transforms organic matter to simple substrates that are more easily metabolized by microorganisms (Gonsior et al., 2009). However, post-storage booster chlorination could have increased the AOC. Water quality could be enhanced by periodic flushing so as to limit microbial growth, biofilm development, and sedimentation. The system also could improve water quality greatly in the reservoirs by aeration. This could increase the DO in the distribution system and reduce potential odor at DS2. The system also could benefit greatly from periodically cleaning the reservoirs at the plant or connecting them to ensure continuous circulatory flow. These measures would minimize algal growth as well.

6.8 Case study for AZ-8 Sanitary District

The AZ-8 treatment system was all gravity-fed receiving wastewater from approximately 600 full-time residents. However, the number of residents increased to around 3500 from March through early September. The area also experienced significantly higher population spikes around the three major summer holidays (Memorial Day, Independence Day, and Labor Day). These population spikes required the need for additional capacity within the system. The incoming wastewater was screened into a 150,000 gal EQ tank (Figure 6.20) which removed particles of one-fourth in. or larger. EQ tank contents flowed into three aeration basins, two of which carried 150,000 gal/day, and the other one contained 300,000 gal/day. Biological treatment occurred in these aeration tanks at ambient temperature and a close-to-neutral pH balance. The oxygen was supplied from air bubble diffusers (Figure 6.21B) using four blowers combined with a submerged mechanical propeller. The aeration tanks had an anoxic zone where the mixed liquor dissolved solids attained a low DO of 0.07 mg/L to enhance nitrification/denitrification. Although rarely needed, methanol could be added to provide additional carbon for these processes. The liquor underwent further treatment in a chembox by adding a polymer or alum (for phosphorous removal).

The treated liquor (containing 1–2% solids at this point) flowed to traveling bridge clarifiers (Figure 6.21D) to separate solids from the liquid phase, generating a clear liquid that flowed to the disinfection process. The solids were returned to the EQ tank for reprocessing or sent to a 30,000 gal digester as excess solids. The digester further reduced solids with additional biological treatment. After digestion, the solids were processed on a belt press for generating biosolids destined for the landfill. Disinfection was achieved with chlorine gas injected into the input side of the contact chamber to ensure thorough mixing with the effluent from the clarifiers. Thorough mixing was also enhanced by internal baffling. A minimum contact time of 45 min was observed for complete disinfection.

The disinfected liquid was filtered through one of four gravity-fed sand and anthracite cells designed for a flow rate of 600,000 gal/day. The filter cells were backwashed in tandem. Filtration was bypassed only if the filter system was overloaded, but this happened <1% of the time. To improve on efficiency, minimize wear and tear, provide a better process control, and save energy, the pumps in the plant were operated at variable frequency control mode.

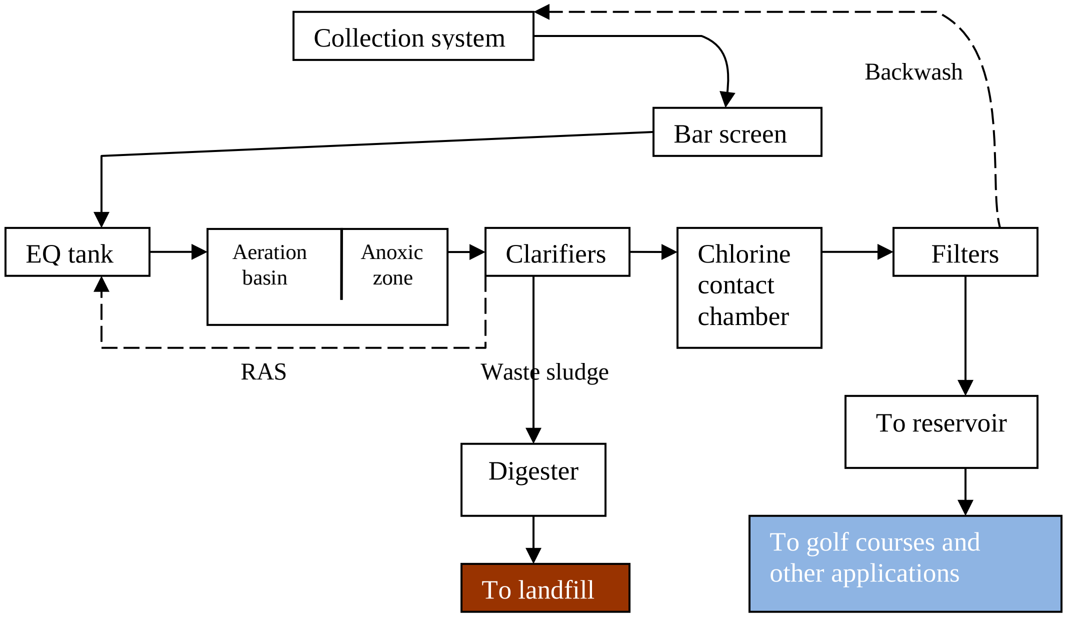

Figure 6.20. Process flow of the AZ-8 wastewater treatment system.

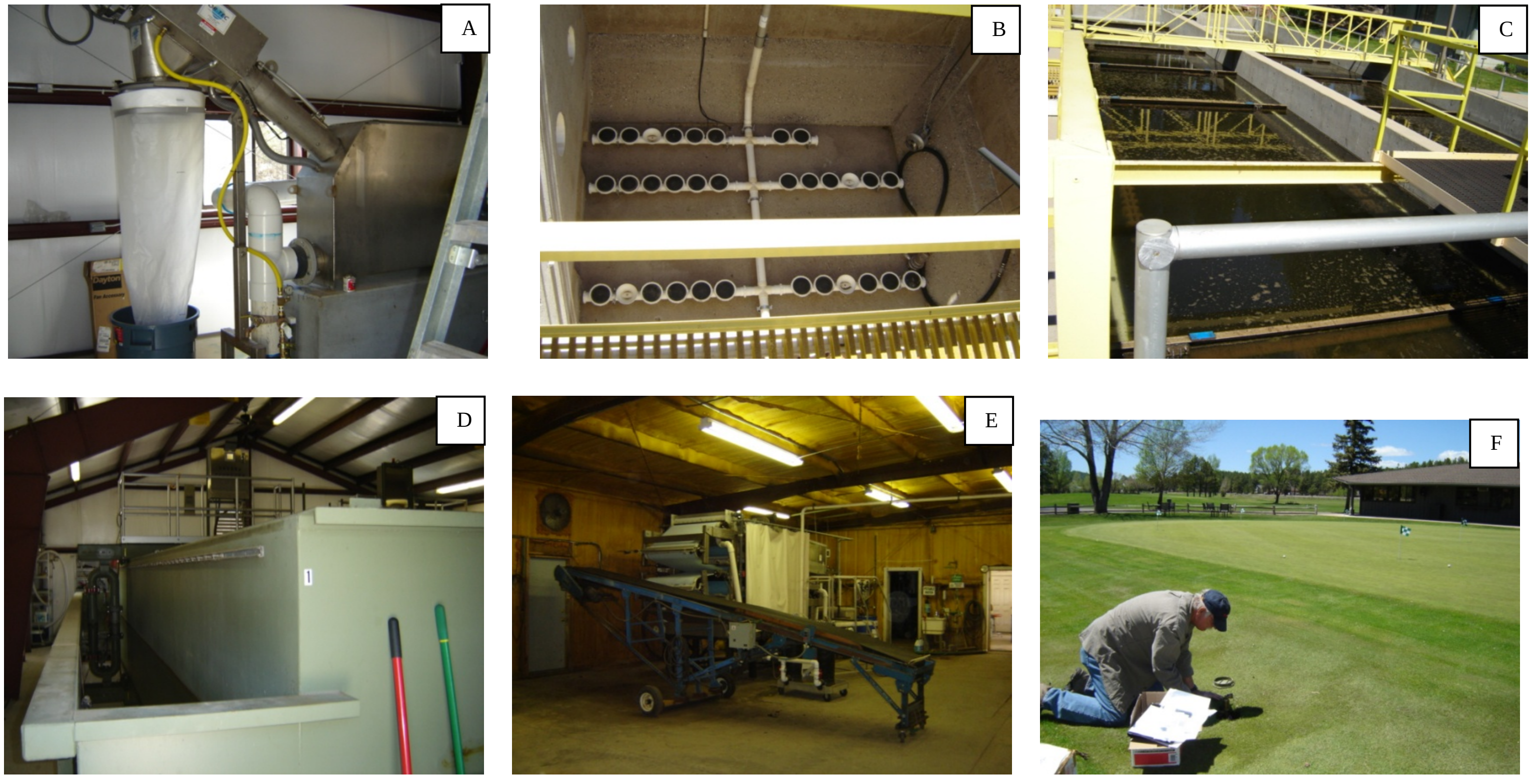

Figure 6.21. AZ-8 sanitation district processes and applications.

Panel A: bar screen and grit removal system
Panel B: empty aeration tank with noticeable air diffuser system
Panel C: anoxic tank
Panel D: traveling bridge
Panel E: belt press for landfillable solids
Panel F: sampling from the golf course (DS2) with driving range and clubhouse in the background.

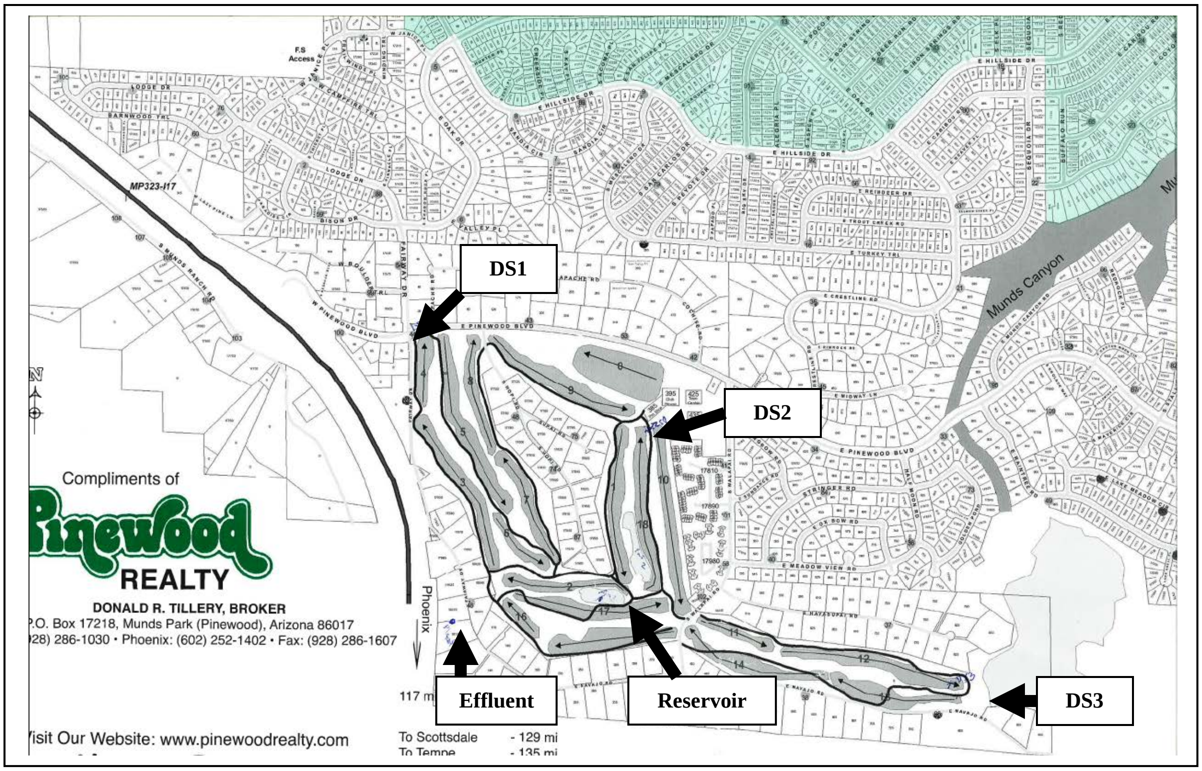

Figure 6.22. AZ-8 distribution system.

6.8.1 Determinants for CCPs

The system was 18 years old. It had two interconnected open ponds, each with 5 MG capacity. The reservoirs were located at the golf course. The water was distributed through a looped PVC pipe system (Figure 6.22). It did not have any dead ends and was completely looped. It had some steel and ductile iron valves, which were exercised approximately every 3 months. The water was disinfected at the plant and there was no post-storage redisinfection. It was actually dechlorinated with sulfur dioxide if designated for disposal into the stream. Disposal to the river was the option during the monsoon rain season when reclaimed water demand was lowest. The water was used mainly for irrigation of the golf course, but approximately 15% and 5% was used for construction and dust control, respectively. The plant was responsible only for water quality effluent, which was sent to the reservoirs at the golf course. Beyond that point, the golf course had custody and responsibility for the water. The reclaimed water system did not have any leaks but acknowledged leaks in the sewage collection system. Midge flies were detected occasionally in the traveling bridge filters. They were controlled with an insect growth regulator (Strike). In some instances, nitrogen and phosphorous concentrations exceeded target ranges for class A reclaimed water, requiring process adjustments and addition of aluminum sulfate [$Al(SO_4)_3$]. The hydraulic pressure of the system was not known, and although the system had one flushing station, it was rarely used, as the water was scoured with chlorine. When flushed, the water was collected and recirculated through the treatment process.

Winter production was typically 0.06 MGD in a normal dry season but increased to 0.28 MGD if needed (e.g., during long holiday weekends). By comparison, summer products averaged 0.2 MGD but could not fully meet all water requirements in summer. Wet summers or winters had elevated daily flows of 1.5 to 2.0 MGD for short durations, depending on storm events owing to infiltration and storm flow, as well as to water line breaks. The water was pulled from the bottom of the ponds into the distribution system. The ponds were clay-lined and had not been cleaned for the last 15 years.

6.8.2 Water Quality Critical Limits

All of the sampled locations in AZ-8 met the proposed chlorophyll and conductivity targets (Table 6.3). Effluent TOC greatly declined as the water flowed through the system. Although the reasons for TOC decrease are not clear, it could be attributed to the formation of biofilms. AOC, turbidity, hydrogen sulfide, free chlorine residual, and DO did not meet the proposed quality targets at one or more sampling points. However, turbidity improved as the water flowed through the system, possibly because of reduced TOC. Dissolved oxygen was also below the proposed quality target throughout the distribution system except at the plant and in the reservoir. However, the reservoir had high AOC, turbidity, and hydrogen sulfide. *Legionella* sp. was not detected in the effluent or at DS3 but was detected at the other portions of the distribution system (reservoir, DS1, and DS2). *L. pneumophila* serotype 2 to 15 were predominant in the reservoir and at DS1, whereas the more pathogenic *L. pneumophila* serotype 1 was detected at DS2 (Table 6.4). However, overall *Legionella* sp. densities in the system were low compared to most of the other activated sludge systems surveyed (Table 6.3).

6.8.3 Actions to Correct Exceeded Proposed Limits

The reclaimed water was used for three main purposes: irrigation of the golf course, construction, and controlling dust. The proposed water quality target demands in that systems were driven by quality of water for irrigating golf courses and lawns. Aeration of the reservoir could increase the DO and minimize hydrogen sulfide (associated with odor) in the distribution system, whereas coagulation could reduce turbidity and enhance retention of the disinfectant residual. That would, in turn, decrease microorganisms in the distribution system even further.

6.9 Case Study for TX-3 Reclaimed Water

The system had two plants—William Cannon WWTP and Walnut Creek WWTP. The distribution systems were not yet connected, but it was the long-term plan of the city to connect the networks (Figure 6.23). The William Cannon WWTP was the smaller system, serving TX-3 south of the Colorado River. Despite its small size, it had the largest demand coupled with limited storage (0.5 MG elevated tank). Walnut Creek plant served TX-3 north of the Colorado River. It featured a lower demand but had four times (2 MG elevated) the storage. Because they were not connected, the two systems were regarded as separate, although they were under the same management. Because of the large storage coupled with lower demand, the system serving the northern part of the city was the focus of the site visit. The Walnut Creek WWTP in TX-3 Texas served approximately 350,000 customers north of the Colorado River and had a capacity to treat 60 MGD. Wastewater flowed through screens and grit basins to remove trash and sand then subjected to primary treatment in a large clarifier. The wastewater then flowed to the equalization basins to ensure constant flow through subsequent biological treatment. This process was enclosed totally underground to contain odors. Wastewater was then pumped into the aeration basins for secondary treatment through an activated sludge process. During this stage, microorganisms consumed the remaining dissolved organic matter. The bacteria and absorbed material settled out and were returned to the aeration basins. As the microbial biomass increased, some of it was removed and pumped to the sludge-handling facility. The respective locations sampled at this site are shown in Figures 6.23 and 6.24.

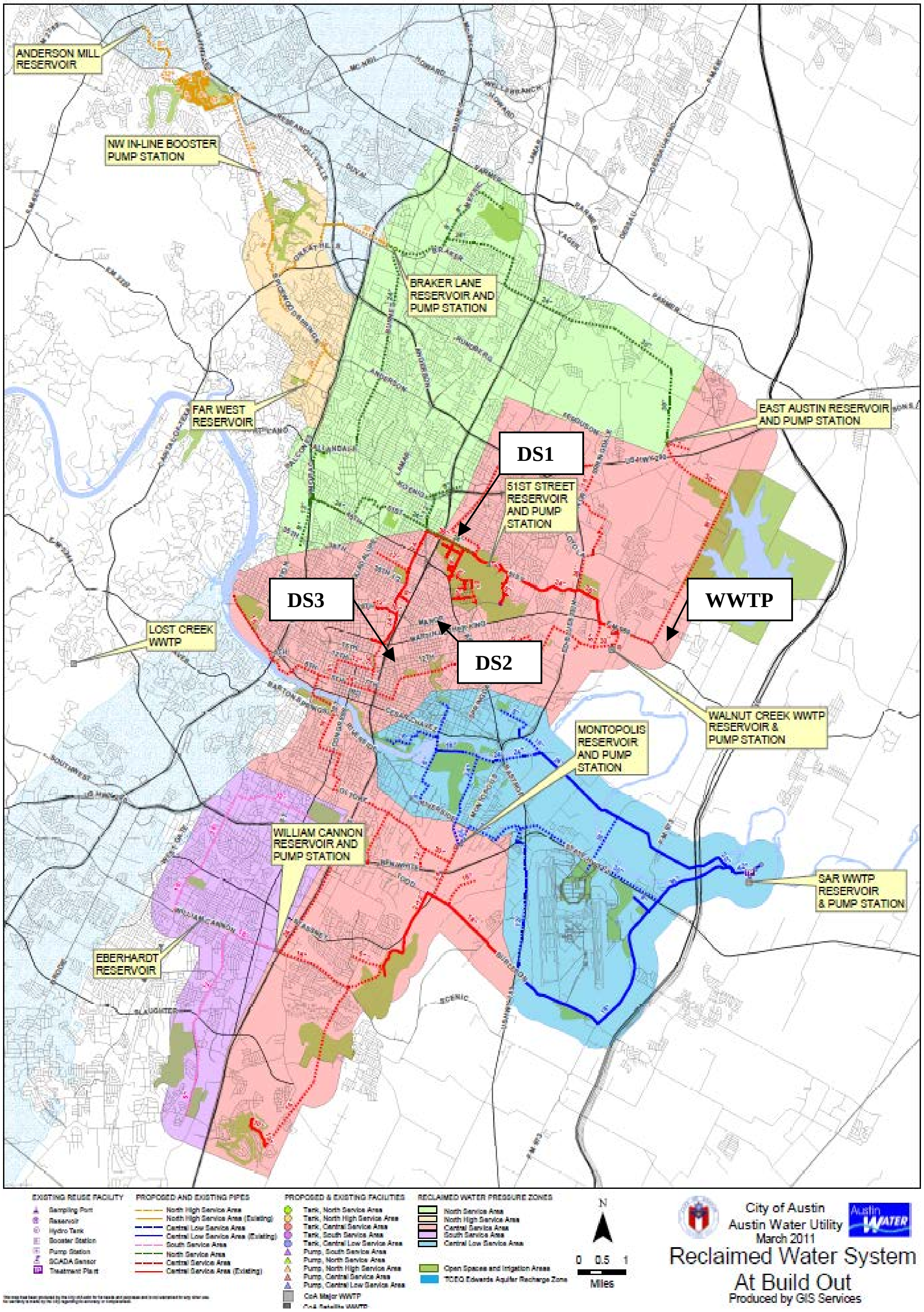

Figure 6.23. Schematic of the TX-3 reclaimed water distribution system.

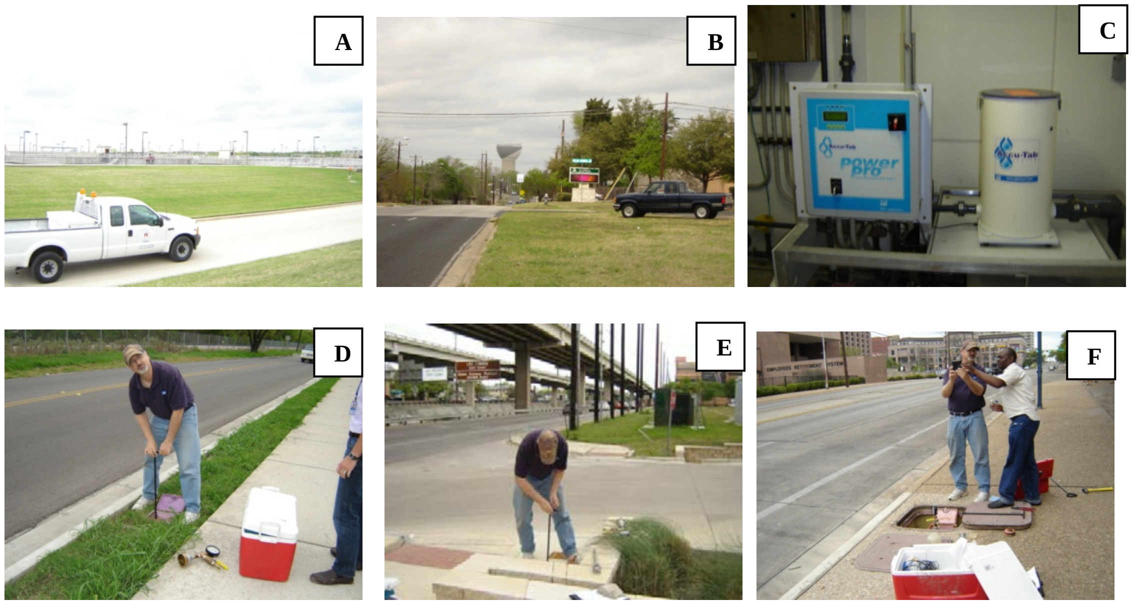

Figure 6.24. Field sampling from the TX-3 reclaimed water distribution system.

Panel A: treatment plant in the background
Panel B: reclaimed water storage tank (one of the city's landmarks)
Panel C: disinfection booster station at the storage tank
Panels D, E, and F: sampling at DS1, DS2, and DS3, respectively.

6.9.1 Determinants for CCPs

The system had been in existence for 38 years, with a very large production capacity of 1450 MG/year. It had a closed aboveground reservoir. Reclaimed water was disinfected with chlorine and no redisinfection was conducted. It had a 43.5 mi branched distribution system with ductile iron (approx. 60%; >12 in.), PVC (approx. 38%; ≤12 in.), and the rest as HDPE pipes. It had some dead ends, although it was trying to ensure a customer at each end to minimize dead ends. Typical pressure ranged between 35 to 120 psi. Most (85%) of the water was used for irrigation, but cooling towers accounted for 10% of the usage; the rest was used for toilet flushing and manufacturing purposes. The reclaimed water was stored in the 2 MG reservoir for several days, depending on the demand. Winter production stood at 3.8 MGD, and this almost doubled to 7.5 MGD in summer. The reservoirs were cleaned every 2 years by scooping the debris. Flushing of the system was not permitted by the state. The system practiced a rigorous cross-connection prevention and monitoring system.

6.9.2 Water Quality Critical Limits

The water met the proposed targets for TOC, chlorophyll, hydrogen sulfide, and conductivity (Table 6.3). However, AOC and turbidity in the effluent or reservoir did not meet the proposed targets. Turbidity was high (6.4 NTU) in the reservoir, diminishing water quality. The water at DS1, DS2, and DS3 was also quite rusty. The dissolved oxygen was greatly diminished in the distribution system as well. Decline in DO indicated an increase in metabolic activity because of microbial growth and onset of anoxic conditions. Regrowth was also evidenced by AOC consumption and a rapid decline of residual free chlorine. *Legionella* spp. were most prevalent in the effluent and reservoir but only detected in low densities in the distribution system, ultimately reducing the risk of exposure to the general population. Most isolates belonged to the *L. pneumophila* serotypes 2–15 and other *Legionella* spp. (Table 6.4).

6.9.3 Actions to Correct Exceeded Proposed Limits

Meeting the proposed targets for TX-3 should be driven largely by irrigation of parks, school yards, lawns, and golf courses, as this provided the most stringent reuse water quality. To reduce turbidity, the plant should consider adding a filtration step. This could also reduce the AOC. However, some of the AOC might be resulting from chlorination. It can be reduced by implementing a UV disinfection step prior to chlorination. That strategy should also help reduce the density of *Legionella* sp. in the effluent and reservoir. The system should consider routinely flushing the water back into the sewer at scouring velocities to remove biofilms, reduce turbidity, and minimize corrosion.

6.10 Case Study for FL-5 Water Reclamation System

FL-5 had two water reclamation plants—the Blue Heron Water Reclamation Facility and the Osprey Water Reclamation Facility. Both of these facilities provided advanced wastewater treatment. The reclaimed effluent from these plants was used for irrigation and cooling towers. The site visit focused on the Osprey Wastewater Reclamation Plant and related distribution system, although the flow from both systems is interconnected (Figure 6.25). Osprey Wastewater Reclamation Plant had a 2.75 MGD capacity and an anaerobic-anoxic-oxic (i.e., A2O) treatment process to remove BOD and TSS. The process also reduced nitrogen (through nitrification/denitrification) and phosphorus. The raw influent wastewater was pumped to the automatic bar screen to remove some the grit and sand (Figure 6.26A). Additional removal was provided by a vortex-type grit removal unit. The screened and degritted wastewater flowed by gravity to the anaerobic basins. The RAS was pumped to the anaerobic basins and mixed with the screened and degritted wastewater. The two anaerobic basins were piped and valved so they can be operated either in series or in parallel. The mixed liquor (RAS and wastewater) was pumped from the anaerobic basins to the anoxic tanks where it was mixed with the pumped internal recycle. The mixed liquor plug flowed through the anoxic tanks and into the oxic tanks, which were aerated with a combination of slow speed surface aerators and diffused air (Figure 6.26C). The plant had two independent anoxic/oxic treatment trains, and each train had three anoxic tanks and four oxic tanks.

The mixed liquor flowed by gravity from the oxic tanks, through the mixed liquor effluent channel, and into one of the two clarifiers for settling the solids (Figure 6.26D), then to one of the two tertiary filters. The solids from the clarifiers were pumped to either the anaerobic basins as RAS or the solids stabilization system as waste activated sludge (WAS) for further aerobic processing and subsequent use as biosolids. The effluent was then disinfected with chlorine (Figure 6.26E) and pumped to the reuse effluent storage tank. If deemed unsuitable for public reuse, the effluent was channeled to the reject storage tank and ultimately back into the treatment train. In terms of compliance, the Osprey Plant used a SCADA system that continuously monitored turbidity and chlorine residual to ensure timely decisions about effluent acceptability. The effluent permit limits specified 20 mg/L CBOD, 5 mg/L TSS, 2.0 mg/L minimum chlorine residual, 2.5 maximum turbidity (NTU), and a pH range of 6.0 to 8.5. In the event of turbidity exceeding 3.0 NTU or chlorine residual below 2.0 mg/L, the online monitoring system triggered an alarm and automatically diverted unsuitable effluent to the rejection reservoir.

6.10.1 Determinants for CCPs

The system was 16 years old and had a 20-mi branched ductile iron distribution system. It had some dead ends where water could stagnate. It was a long system with different pressure zones and some delivery points operated well below the required flow. The water was not redisinfected, and although the online system at the plant guided the treatment process, no such monitoring was required in the reservoir or distribution system. In terms of operations, the valves were not exercised routinely and were used only as needed to isolate specific areas. It did not have a flushing program or a system for cleaning the reservoir in place. The location's strategic planning is focused on incorporating reclaimed water into groundwater recharge through a wetland enhancement system (Figure 6.27). These attributes and practices could individually or collectively impact water quality.

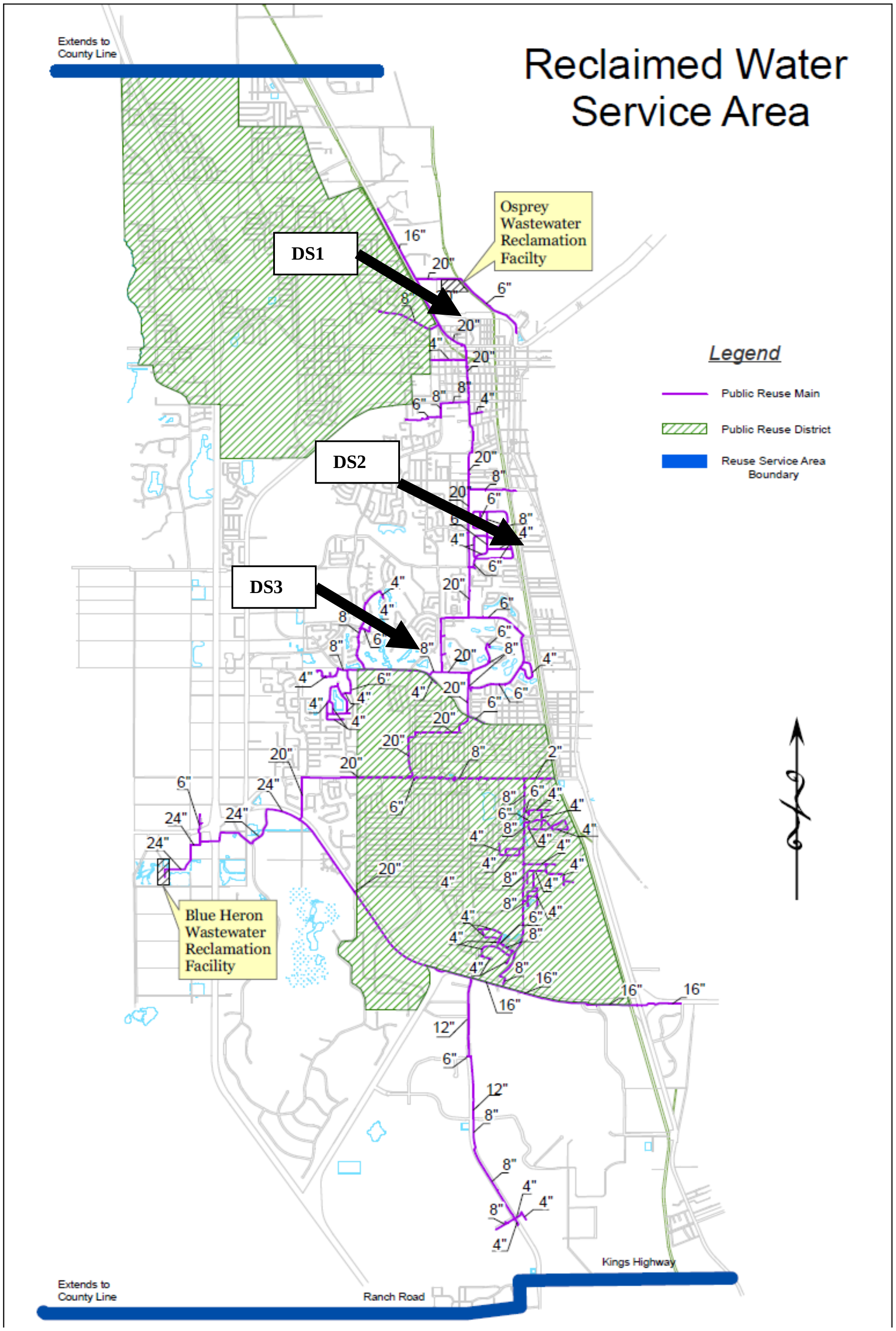

Figure 6.25. Sampling sites in the FL-5 distribution system.

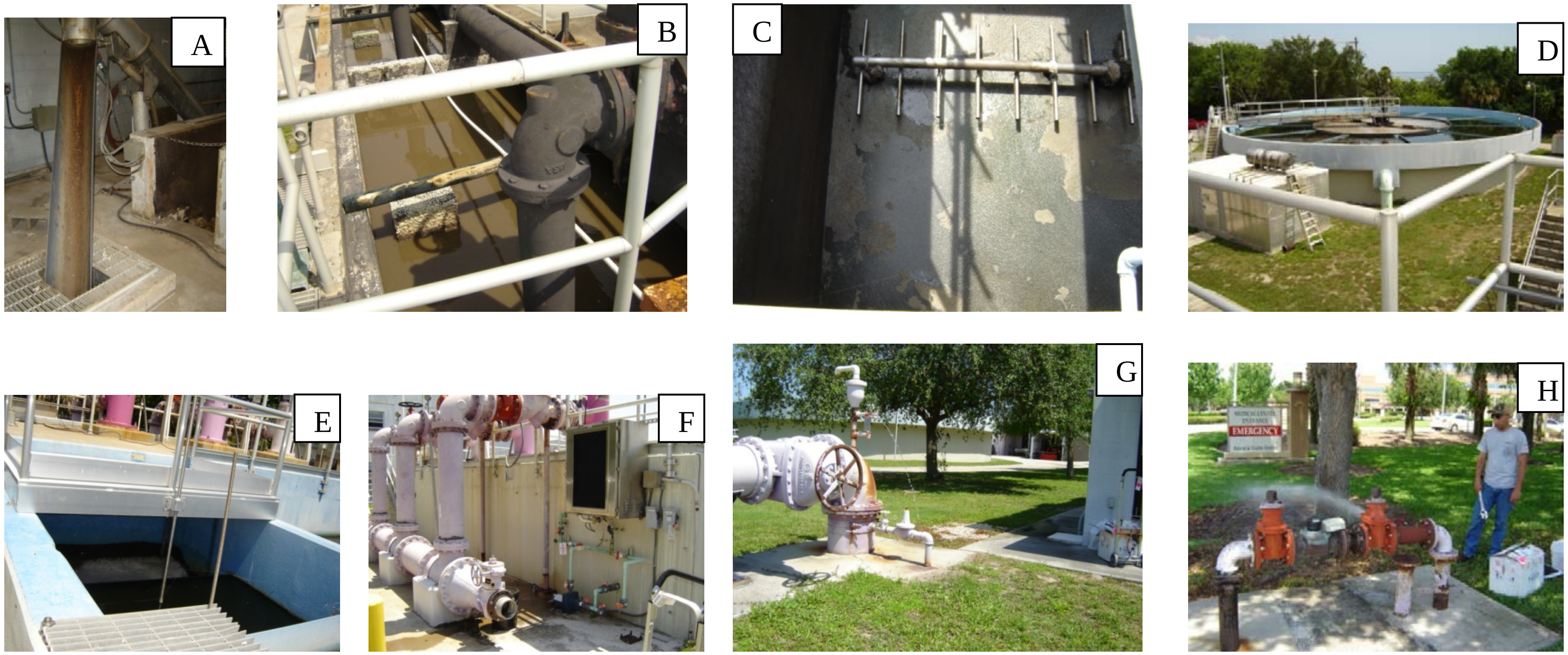

Figure 6.26. Images from the Osprey WWTP and distribution system.

Panel A: rags and trash trapping system
Panel B: Anoxic zone
Panel C: empty aerobic tanks (note air diffuser system)
Panel D: clarifier (one of four)
Panel E: chlorine contact chamber
Panel F–H: sampling points for effluent, reservoir, and DS1, respectively.

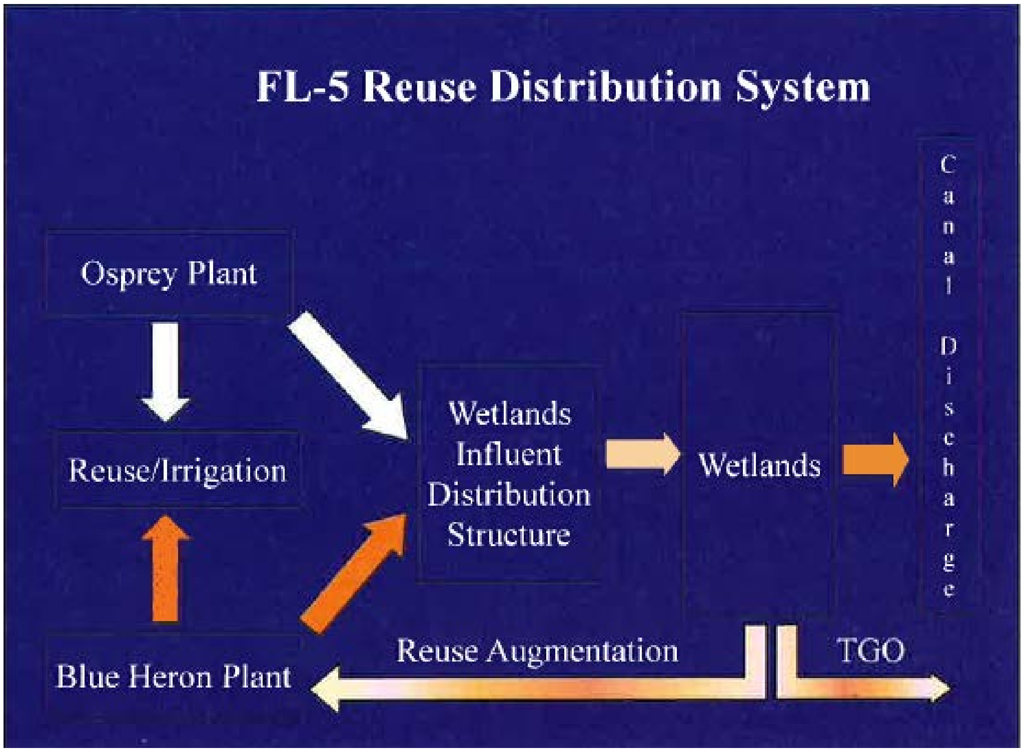

Figure 6.27. Future expansion of reclaimed water use for groundwater recharge at FL-5.

6.10.2 Water Quality Critical Limits

Results of the sampling event are presented in Table 6.3. They were compared with the proposed water quality targets for irrigating parks, school yards, golf courses, and lawns, as well as use for cooling towers. The reclaimed water did not meet the proposed targets for TOC, AOC, turbidity, dissolved oxygen, and *Legionella* spp. at various points in the distribution system. *Legionella* spp. were most prevalent in the effluent, although most of them were nonspecific to the antibody used (Table 6.4). Although not detected in the effluent, *Legionella pneumophila* serotype 1 was consistently detected throughout the rest of the distribution system. The disinfectant was dissipated to below target levels at DS2. Algal content, hydrogen sulfide, and water conductivity were within the proposed target for all three types of intended end uses.

6.10.3 Actions to Correct Exceeded Proposed Limits

The quality requirements for this location were driven by the proposed targets for irrigation (parks, school yards, golf courses, residential lawns; Table 6.2). TOC and AOC levels in the effluent are quite high. Adapting longer hydraulic retention time and combining UV disinfection with chlorination can reduce these parameters in the effluent. The proposed strategy will also improve on retention of the chlorine residual especially if coupled with redisinfection booster stations, as this is a long system with many dead ends. Improving residual retention could also reduce microbial (*Legionella* sp.) growth. Turbidity and the associated TOC could be reduced by introducing coagulation as part of the treatment process (Volk et al., 2000). Both AZ-8 and CA-1 used coagulation and attained relatively low TOC effluents. Flushing the system could also reduce biofilms and thus microbial growth, improve distribution system aeration, and enhance overall water quality. The proposed use of reclaimed water for groundwater recharge through a wetland will provide additional treatment of the water.

6.11 General Remarks about Water Quality

In general, the respective parameters posed variable challenges to utilities. Most challenging was maintaining dissolved oxygen in the distribution system. Dissolved oxygen guidelines were exceeded 30% of the time (Table 6.3). Turbidity and *Legionella* density limits were exceeded 26% of the time. Chlorophyll and conductivity guidelines were not exceeded by any of the studied systems. However, sampling was conducted between March 20, 2013, and July 18, 2013, a time when algal growth typically is not yet a major problem. Most algal growth in the systems peaks in later summer and early fall (Jjemba et al., 2010).

Chapter 7

Formulated Best Management Practices (BMPs)

The issues raised by the utilities through survey and case studies provided valuable information about management practices already available to the industry. Fifteen BMPs (Appendix M) were identified and formulated briefly defining the nature of the problem to be addressed, laying out the possible causes, and providing a range of solutions based on institutional knowledge obtained from interacting with utility managers and operators or from information accumulated from the literature.

"Best" in this instance does not imply that the BMP will always be the best, but rather it is selected on the basis of identified issues at the moment. BMPs are subject to revision as new information and technology become available. Thus, these BMPs were issue-based and solution-oriented so as to foster continuous improvements in quality and promote sustained learning as outlined by Bogan and English (1994).

The original 15 formulated BMPs were reviewed by a panel of experts during a 2-day-long workshop. During the workshop, participants were asked to determine how they would rate the relevance of each BMP topic for the reclaimed water industry (e.g., high, medium, low) and what additional information would help complete the BMP. They also were asked about future needs that could dovetail into the BMP by specifically establishing whether the participants were aware of existing or ongoing planned research that could provide additional solutions for issues identified in the BMP and whether adoption of this BMP could provide other (unintended) benefits. In addition, participants were asked what other BMPs could be proposed for inclusion in the guidance document.

On the basis of the working group's recommendations, the BMPs ranked lowest either were eliminated or combined with other similar BMPs. A BMP for addressing emerging contaminants with particular focus on pharmaceuticals was suggested by the working group. From this process, a total of 14 BMPs are presented underneath. To assist the operator in navigating the more detailed text, where applicable, various aspects of the BMPs are cross-linked to the literature review, survey information, and case studies.

7.1 Optimizing Reclaimed Water Storage

7.1.1 Nature of the Problem

Lack of sufficient storage capacity is a major infrastructural and operations problem for reclaimed water systems. At the opposite extreme are instances when demand far exceeds the available quantity of reclaimed water and conversely when little reclaimed water is used. These extremes dictate the need for adequate planning and storage, which may be an open pond or an open or enclosed tank. It is also likely that under these extremes, reservoir space may never be enough to meet the ever-changing needs. The magnitude and timing of water transfers influences the water quality in the reservoir. Reclaimed water is a perishable product with a short shelf life of a few days. Maintaining good quality requires minimization of water detention time in storage or distribution system (i.e., increased turnover). A rapid turnover minimizes the deterioration in water quality, whereas low water turnover increases water age in the system, impacting total dissolved solids (TDS), assimilable organic carbon (AOC), biodegradable dissolved organic carbon (BDOC), turbidity, temperature, residual disinfectant, nitrogen, phosphate, bacterial density, odor, and water color. Avoiding or minimizing these effects requires optimizing reclaimed water storage. Lack of storage was also ranked highly important by the expert panel. The panel also foresaw adoption of this BMP as an important element for dovetailing future research on the storage of reclaimed water for direct potable reuse (DPR) and a lead for more general consumer acceptance of reclaimed water.

7.1.2 Causes

Daily variance: Water reclamation is highest during the daytime hours when people are active and producing wastewater. However, most reclaimed water irrigation systems generally are inactive during daytime hours to minimize contact of the water with the public (Ammerman and Ceather, 2009). Irrigation demand is much higher at night when the public is not using parks, school yards, golf courses, or other municipal facilities.

Seasonal variance: Water typically remains in reservoirs for 1 to 120 days, with the longer durations occurring during winter. A majority (80%) of reclaimed water utilities increase their reclaimed water production in summer compared to winter. Production increased between these two seasons can range between 1.1 to 12 times. This presents a need for flexibility in reclaimed water storage —flexibility that is not easily attainable as storage infrastructure and space are usually expensive.

7.1.3 Suggested Solutions

For design, consider establishing multiple interconnected reservoirs to allow for sequential utilization and to maximize economic utility of the reservoir (e.g., floating solar panels). Minimum storage capacity needs to be equal to the average daily consumption; where practical, keep a maximum of 3 days' average consumption. Larger storage volumes can deteriorate in quality. Design the reservoir with easy access to cleaning in mind. Use baffled reservoir inlets to maximize plug flow and reduce stratification.

For turnover management, increase turnover in reservoirs by matching storage volumes to available reclaimed water production if there is no permitted wastewater disposal site available (i.e., continuous use, although this could be problematic for large plants) is suggested. In addition, link production to consumption using decision support system (DSS) software to optimize pumping, transmission, storage (Joksimoric et al., 2008), and continuous or semi-continuous mixing in the reservoir through mechanical aeration or continuous water flow (Juanico, 1996). Alternatively, overflow the reservoir instead of draining. Turnover management also includes serial or sequential pond transfers (i.e., continuous discharge). This practice dictates two operational decision variables: the magnitude of water transfers and the timing of water transfers. In addition, this strategy requires one to recognize the significance of maximum residence time. Solutions include locating intake and outlet on opposite sides or at different depths, as well as seasonal drainage (i.e., emptying the reservoirs by the end of the irrigation season and instituting an annual empty out policy).

For cleaning, clean inside the reservoir tank once every 1 to 2 years by scraping, jetting, or any other convenient cleaning method. Other considerations include filtration or disinfection after storage, if feasible.

7.2 Minimizing the Impact of Reclaimed Water Corrosivity

7.2.1 Nature of the Problem

Reclaimed water by its nature can be corrosive. Corrosion of infrastructure material (pipes, valves, reservoirs, equipment, etc.) is a widespread problem of reclaimed water systems in the United States, even though 29% of reclaimed water systems exclusively use purple plastic pipes. Most of these systems can experience iron-related corrosion from metallic valves. Another 50% of the systems use PVC pipes combined with some other type of material, such as ductile iron, concrete, or steel.

7.2.2 Causes

Oxygenated and oxygen-limited conditions: Corrosion occurs under environments with low levels of oxygen and in environments with high oxygen concentrations. Oxygen is a powerful electron acceptor, forming a variety of oxides and hydroxides as part of the corrosion process. Under oxygen-limiting conditions, protons become the alternative electron acceptors yielding H_2 and other reduced corrosion products. Corrosion increases in lower pH water because of the direct dissolution of metals and a number of mechanisms. These effects are exacerbated in the presence of tensile stresses. Corrosion is accelerated by the removal of the end products, a scenario likely to prevail in reclaimed water storage and distribution systems. During corrosion, the consumption of electrons varies, depending on the redox potential of the surface.

Disinfectants and salts: Because of their highly oxidative nature, most disinfectants are corrosive. This is especially consequential in reclaimed water where disinfectant doses are typically high. Free chlorine residuals of 0.5 mg/L or higher aggressively attack metallic materials (copper, cast iron, carbon steel, mild steel), increasing the corrosion rates. Reclaimed water also contains high levels of dissolved salts.

Microbial activity: Although sometimes discussed separately, chemical and microbial corrosion are often indistinguishable, because the two processes enhance one another. For example, anoxic conditions (a chemical attribute) can enhance sulfide formation through a microbial process. The sulfide may then be oxidized to sulfuric acid (H_2SO_4) exacerbating corrosion problems. The nutrients, such as organic matter, orthophosphate, TDS, and ammonia, also promote microbial growth, enhancing microbiologically influenced corrosion (biofouling). These reactions are especially important in cooling systems.

7.2.3 Suggested Solutions

Select appropriate materials of construction for pipe, fitting, valves, and appurtenances. Use compatible material (e.g., PVC 900 without mixing brass and ferrous iron together). Provide cathodic protection of the system where it is needed based on soil characteristics (e.g., resistivity of the soil). With soil resistivity, connect the infrastructure to be protected with a piece of another more easily corroded “sacrificial metal” to serve as an anode or break the electrical contact using plastic insulators or coatings between the metals. An additional method is to insulate the structure to be protected. Use corrosion inhibitors as appropriate for equipment and materials that require protection. Examples include orthophosphate, polyphosphates, tolyltriazole (TTA), zinc, azoles, amines, and fatty polyamines, but site-specific conditions should be considered before final selection. Inhibitors form a barrier layer on the surface of a metal, decreasing the rate of corrosion. Corrosion is greatly reduced with monochloramine compared to free chlorine

(MacQuarrie et al., 1997). Go to breakpoint chlorination first, then add ammonia to generated chloramines.

For management solutions, maintain a well-aerated system. Aeration to more than 5 mg DO/L can significantly minimize H_2S formation. However, this can have cost implications if aeration typically consumes energy. This includes distribution system aeration mechanisms (e.g., inline injection of air) and corrosion rate monitoring using a CorrosionRx index card decision tool for different types of materials. For management of cooling towers, keep below the maximum number of the cycles of concentration (COCs) by one to two cycles (EPRI, 2003).

7.3 Improving Customer Perception

7.3.1 Nature of the Problem

Water reclamation for various industrial, agricultural, and domestic purposes has a long history; however, there are no documented cases of waterborne disease from exposure to reclaimed water. Continued future success for reclaimed water demands a strategic development of favorable customer perception regarding the quality and reliability. Some customers may perceive reclaimed water to be of lower quality than potable water. Perhaps some forget that through the water cycle, every water droplet on earth is actually reclaimed water. Recent advances in water reclamation only speed up and compress the water cycle through engineering and treatment processes. This BMP is for nonpotable systems and does not attempt to deal with complexities of direct or even indirect potable reuse. The assumption is that dealing with the latter is still a higher challenge.

For industrial, agricultural, or commercial customers, the perception of water quality may not be as important as whether the water chemistry or water availability meets their needs. It is important, therefore, to address the needs of various customer groups differently.

7.3.2 Causes

Reclaimed water is generated when wastewater is treated through the primary, secondary, and sometimes tertiary stages to meet various reuse purposes. Perception and acceptance are influenced negatively, especially when reclaimed water turbidity, color, or odor is objectionable. Support for reclaimed water wanes in practices with an increased likelihood of human contact, representing public health concerns. Reuse previously has been defined by the media with a level of “yuck” factor.

7.3.3 Suggested Solutions

For distributed water quality, discolored water, odors, slimes, or other water quality problems may increase customers’ concerns about reclaimed water. Industrial or commercial customers may object to increased TDS, biocide demand, sediments, or scale formation. Utilities should make sure that the end customer has a positive experience with reclaimed water quality. Monitoring and controlling quality in the delivery system is an important step in maintaining the customer’s confidence in the water.

There is a need to create awareness of water supply issues in a larger context of the water portfolio with minimal adverse impact to the environment. Constant communication with customers is necessary through periodic (monthly, quarterly, annual) newsletters about billing, system repairs, production levels and processes, improvements done, production efficiency, and quality statistics. Pertinent information should also be posted on a Web site. Conduct customer training and awareness sessions about reclaimed water benefits and shortfalls (Davis, undated). Organize periodic plant visits, webcast information sessions and user meetings for the general public. Advertise product and associated benefits through commercial media to create a positive brand for the local reclaimed water product. Marketing particularly to industrial, agricultural, and commercial clients should be conducted. Advertising reuse has been successful with NEWater–Singapore, as well as several Australian companies.

To encourage civic participation, engage customers (e.g., through citizen advisory boards and councils) to provide input to key decisions through stakeholder meetings and information sessions. Create easily accessible tools to provide constant feedback from customers and other stakeholders and provide readily accessible information. These include a customer call center, Web site, annual meeting, and social media (Facebook, Twitter). Develop partnerships with customers and organize community events.

Solutions for technical and financial support include providing technical support to encourage reclaimed water use including but not limited to system installation, conversion of equipment, and financial assistance (sliding rate structure packages).

7.4 Managing Reclaimed Water Total Dissolved Solids (TDS)

7.4.1 Nature of the Problem

Total dissolved solids (TDS), an indicator of the amount of dissolved minerals in water, measures salinity. The solids include sodium, sulfate, and chloride salts. Conductivity measurements provide a good approximation of TDS [i.e., $y = 0.5x + (7*10^{-5})$, where y is conductivity in µg $CaCO_3$/L and x is conductivity in the range 0.056 µS/cm to 10,000 µS/cm]. Salinity levels for different types of water are summarized in Table 6.1. Reclaimed water tends to have slightly higher salt content than source water from which the recycled water is derived; however, its use is manageable with proper irrigation practices. Under the U.S. Environmental Protection Agency (U.S. EPA) secondary maximum contaminant levels (SMCL) guidelines, TDS levels >500 mg/L are representative of salinity conditions. Salinity in reclaimed water is not associated with public health risks. However, high TDS levels may cause problems when reclaimed water is used for irrigation of some salt-sensitive crops and landscape plants. Salinity lowers the free energy of water in the soil matrix, reducing the ability of plant roots to extract moisture from the soil because of the osmotic pressure generated by the electrical conductivity. The high chloride and bromide concentrations can lead to the formation of sodic soils with very poor structure and permeability. Soils of poor structure have a diminished ability to supply nutrients and store moisture. Collectively, these problems reduce plant yield.

High TDS can also cause scaling and corrosion of pipes, boilers, heat exchangers, cooling towers, and other structures. For cooling towers, high TDS levels, together with nutrients, also decrease the cycles of concentration (COCs).

Table 7.1. Published Salinity Restriction for Various Uses

Water Type or Restriction Limits	**TDS (mg/l)**	**Conductivity (mS/cm)**
Drinking water	100	200
Restriction on drinking water	500	1000
Freshwater limits	1000	2000
Agricultural water limits	2000	4000
Mildly brackish water	***1000–5000***	***2000–10,000***
Moderately brackish water	5000–15,000	10,000–30,000
Heavily brackish water	15,000–35,000	30,000–70,000
Seawater	30,000	60,000
Brine	>50,000	>100,000

Source: Compiled from Anonymous, 2012c.

7.4.2 Causes

Source of municipal water impacts the conductivity of reclaimed water, with most of the dissolved salts in reclaimed water being derived from self-regenerating water softeners, human dietary intake, detergents, and swimming pools, as well as industrial and commercial discharges. Salts may also be added during the wastewater treatment process (e.g., addition of sulfuric acid and lime). For wastewater and reclaimed water, TDS includes an organic fraction in the form of organic solutes represented by dissolved organic matter (DOM).

7.4.3 Suggested Solutions

For source control, if operating a satellite plant, one can bypass influent flow during the night or early morning to avoid picking peak TDS flow. One way to do this is with the model mass balance of TDS using the Water Quality Analyst model (Thompson et al., 2006) to minimize "salt pickup." Recognize and deal with infiltration areas by line reservoirs to guard against salt intrusion (especially in coastal areas, such as Florida).

For treatment, generated brine can be landfilled, contained in evaporation ponds, or disposed of by deep injection (Brandhuber et al., 2009). Another treatment is blending with potable water (e.g., 50% potable to 50% reclaimed water). Flush potable water into the reclaimed water near the location where chillers are used to blend and dilute the salts. In addition, add reverse osmosis (RO) technology to treat part of the treatment train (e.g., sidestream) or add RO technology to treat reclaimed water at the point of use to meet water quality targets (which include the need to manage salts). Avoid use of sodium chloride and potassium chloride-based softeners. Encourage the use of nonchemical softeners instead of sodium chloride-based softeners, for example, template assisted precipitation, whereby water is passed through a device forming submicron crystals of carbonates that remain suspended in the water. The device contains treated resin loaded with nucleation sites (Fox et al., 2013). Treatment also is effective with electrodialysis, whereby an electrical potential attracts dissolved ions through ion exchange membranes that are impermeable to water (Burbano and Brandhuber, 2012). However, the process can be energy intensive, i.e., $y = 0.004x + 2.432$; $R^2 = 0.977$, whereby y is electrodialysis energy required in kWh/kgal and x is the TDS in mg/L. Last, utilize the benefit of high rainfall to flush TDS from soils (applicable in high rainfall areas, such as Florida).

7.5 Controlling Algae in Reclaimed Water Reservoirs and Distribution Systems

7.5.1 Nature of the Problem

Reclaimed water typically has more nutrients (N and P) compared to potable water. These nutrients present a high propensity for algal growth in open reservoirs owing to exposure to direct sunlight. Under severe conditions, algal blooms occur. Algal growth results in severe operational issues (e.g., flow disruption, clogging of sprinklers and pumps), as well as water quality issues in reclaimed water distribution systems. More than half (53%) of the reclaimed water utilities responding to the survey in the United States have open reservoirs. Algal problems are the most common issue during the storage phase for >90% reclaimed water utilities with open reservoirs. Some algal species and actinomycetes release geosmin (an earthy-smelling substance) and other toxins into the water. The toxins can pose a danger to reclaimed water application in instances where dermal exposure occurs. Algal proliferation is limited not only to the reservoir but also impacts the distribution system, clogging sprinkler heads and generating objectionable odors because of the formation of hydrogen sulfide (Jjemba et al., 2010). Algal growth is quantified using chlorophyll concentrations as a surrogate. Other modes of quantification include odor type and intensity, with the younger, less dense algal cultures producing less intense odors. Algal growth can also exert pH changes in the distribution system or get into distribution systems and die off, increasing nutrient levels, which, in turn, increases the regrowth of microorganisms.

7.5.2 Causes

Long retention times coupled with high nutrient loads typical of reclaimed water are ideal for intense algae growth in open reservoirs. Excessive nitrogen and phosphorus support photosynthesis and algal biomass accumulation, which is influenced by climatic conditions as well, specifically sunlight and warm temperatures. Thus, most algal biomass is accumulated in summer and fall. Open reclaimed water reservoirs may receive additional nutrients from storm water runoff and droppings of wild and domestic animals. The algae also can exude nutrients as they die off, supporting new algae. They color the water, increase turbidity, and support regrowth of bacterial pathogens. With stratification, decayed algal cells settle in deeper areas (hypolimnion) of the reservoir, depleting oxygen and favoring anoxic microbial activity responsible for odor. Proliferation and buildup of algae, sediments, and other forms of debris in the distribution systems is even more intensified if flushing is not practiced.

7.5.3 Suggested Solutions

For management, remove nutrients (particularly N and P) at a treatment plant. Decrease detention time to prevent algal buildup or wash out residual algal cells. Flush to achieve adequate durations or scouring velocities. Where typical flushing is not encouraged, consider flushing by draining into the sewer or onto areas where reclaimed water application is already permitted. Apply more frequent irrigation for shorter durations rather than long spans less frequently. Enhance water mixing by providing a water aeration system, reconfiguring inlet/outlet piping pumping to recirculate the water, and installing internal baffling. Install post-storage screens (e.g., wire mesh) or filters (e.g., sand filter boxes; 80–100 μ pore size). Screens and filters should be automatic or cleaned often. Install fixed or floating covers (e.g., duckweed, foam, plastic sheet/balls, or solar panel assemblies). However, this can be a drawback if sunlight is used to provide additional disinfection. Inspect and clean storage reservoirs, including scraping of the walls. Close the reservoir (i.e., drain and switch among several reservoirs). Continuously harvest algal cells as a source of biofuel production (water-energy nexus).

For treatment, be sure to consider downstream effects before adapting these algaecides (recommended only when algal cell numbers are still low (<5,000 cells/mL) to minimize the concentrations of algae. Be aware, however, that high algaecide concentrations can generate toxicity and offensive odor. Apply copper sulfate ($CuSO_4$) at dosages of 1 to 2 ppm (1.4 to 2.7 lb/acre-ft). The treatments may be repeated at 2 to 4 week intervals, depending on the nutrient load. A copper-based algaecide (Cutrine-Plus) has been used with success. Apply potassium permanganate, which may be applied directly or indirectly by coating reservoir walls and also may be used to control algae.

Another solution is dissolved air floatation, such as ozoflotation, whereby ozone oxidizes the algal cells and, combined with flotation, inactivates the cells. Ultrasonication, demonstrated at fullscale by Lee et al. (2002), can be used with algal blooms in a 32 hectare lake (Ahn et al., 2007), in a 9000 cu m eutrophic pond, or in a fish pond (Klemencic et al., 2010). This is because of enhanced coagulation using aluminum electrodes (Azarian et al., 2007) or fish to feed on the algae. Be sure to include screens to guard against blocking the distribution system.

7.6 Managing Snails and Other Macroorganisms in Reclaimed Water

7.6.1 Nature of the Problem

Reclaimed water can contain macroorganisms, such as snails, worms (e.g., Oligochaeta, Chironomidae, Diptera), zebra mussels, turtles, fish, aquatic weeds [e.g., duckweed (*Lemna* spp.; *Spirodela* spp.), moss, water hyacinth], and ferns (e.g., *Azolla, Salvinia*). Some of these are more visible than others. For example, reports of allergic reactions to midge flies (Diptera) have been documented (Hirabayashi et al., 2008). However, even those species that do not bite can pose health hazards by serving as vectors for bacterial pathogens on their bodies. On accumulation, sizeable macroorganisms, such as turtles, can clog the system reducing flow. They also can act as vectors for some pathogens (e.g., mosquitoes that can, in turn, cause human diseases including encephalitis, dengue fever, and malaria), reduce the appearance of reclaimed water, and generally reduce water quality indicators (e.g., reduced dissolved oxygen and increased hydrogen sulfide and the associated odor).

7.6.2 Causes

The occurrence of macroorganisms in reclaimed water can be attributed to several factors. However, various factors favor different kinds of macroorganisms. For example, excessive nutrients (N and P) can enhance invasion of water weeds. Snails and worms (Oligochaeta, Chironomidae, Diptera) appear in water associated with metal and organic pollutants. Similarly, dissolved oxygen plays a role in the proliferation of Diptera larvae and pupae.

7.6.3 Suggested Solutions

For management, treatment, and biological control, various solutions have been proposed in Table 7.2. All management solutions should be customized as needed and according to local conditions. For dipteral, the biological and chemical control strategies target destruction of adult forms. However, targeting larvae and pupae in their brooding stage can be effective as well. For construction and treatment, install deterrents, like nets, to reduce spread of the macroorganisms.

Table 7.2. Control Measures for Various Macroorganisms in Reclaimed Water

Macroorganism	Management	Control Chemical*	Biological Control**
Snails and other molluscs	Mechanical removal using screens and harvesters	Chlorine at ≥3 mg/L; copper sulfate at 504 mg/L (Oplinger and Wagner, 2009)	Cover with gas impermeable benthic barriers, such as EPDM, suffocates mussels (Wittmann et al., 2012).
Flies, midges, worms (including larvae) (i.e. Chironomidae, Diptera, Oligochaeta)	Periodic drawdown or dredge shallow areas and introduce mosquitofish (Gambusia)	Shock chloramination with 32 mg/L for 75 minutes (Broza et al., 1998); superchlorination; Application of pheromone such as Strike® (http://www.strikeproducts.com/page.php?id=11)	Reduced organic materials (e.g., through aeration as high oligochaete presence) is an indicator for such contamination. Sound-light field traps to attract males creating a fertility imbalance and subsequent population decline (http://www.allpetsolutions.com).
Mussels and other bivalves	Mechanical removal using screens and harvesters	EarthTec at 17 mg/L (Watters et al., 2013), Bayer 73, Sodium hypochlorite (Kilgour and Baker, 1994)	Cover with gas impermeable benthic barriers such as EPDM suffocates mussels (Wittmann et al., 2012); predation by crayfish (*Pacifastacus leniusculus*; zu Ermgassen and Aldridge, 2011), sparker pressure pulses application of 5.8 J/m2 per pulse (Schaeffer et al., 2010)
Duckweed	Shorten mean residence time, periodic drawdown or introduce grass carp	Herbicide spray (e.g., metazachlor, diuron at 60 µg/L especially when combined with copper, linuron at 70 µg/L); Other herbicides used include Aquathol K. Increase water to pH >8	Spraying a fungi species (*Myrothecium roridum* in South Korea) inhibited duckweed plants (Lee et al., 2008)
Ferns	Shorten mean residence time, periodic drawdown or introduce grass carp	Herbicides (e.g. diquat, glyphosate, Aquathol K); Increase water to pH >8 (only effective in early invasion)	Fungi, weevils (e.g., *Cyrtobagous salviniae* in Texas and Louisiana)
Moss		Increase water to pH >8; fluoridone (low doses of 5-15 µg/L over a long duration work best; Getsinger et al., 2008)	No known biocontrol measure

Notes: *Pesticide, herbicide applications should conform to U.S. EPA guidelines. Their use may impact nontarget organisms in irrigated areas (e.g., metazachlor diuron, diquat, and glyphosphate may impact susceptible lawn vegetation, pasture, or crops).

**The biological control agent of choice should preferably be local (or certified by USDA/ARS) to avoid unintended consequences of trying to eliminate an invasive species with another invasive species.

7.7 Minimizing Regrowth, Odor, and Biofilms in Reclaimed Water Systems

7.7.1 Nature of the Problem

The use of chlorine to disinfect against microorganisms in reclaimed water is a common practice. However, despite the superb ability of water reclamation technologies and disinfection to remove microorganisms in the effluent, some surviving bacteria can regrow in the reservoir and distribution system. Thus, treatment plants have to maintain programs aimed at controlling bacterial regrowth in distribution systems. Most reclaimed water systems are not compelled to monitor regrowth of bacteria in the distribution system. Disinfectant residual in the distribution may be used as a surrogate for tracking the likely regrowth of bacteria.

Overall, testing for microorganisms relies on indicators, notably coliforms, *E. coli*, or enterococci. These indicators are mostly nonpathogenic and generally susceptible to common disinfectants. Pathogenic microorganisms in reclaimed water (e.g., *Aeromonas, Pseudomonas, Mycobacterium,* and *Legionella*) may survive disinfection because of their inherent resistance to disinfectants, ability to form spores, or because of physical protection provided through host protozoa. Rough distribution system surfaces (i.e., pitting and crevices) also can provide protection from disinfectants. In addition, microbial aggregates and biofilms reduce the effectiveness of various disinfectants.

Microbial proliferation and biofilms in reclaimed water storage and distribution systems can cause public health and aesthetic issues. Aerosolisation (e.g., spray irrigation, cooling towers) rather than ingestion may be a primary route for pathogen transmission. Furthermore, biofilm establishment can lead to clogging of sprinkler heads, as well as aesthetically unpleasant color and odors.

7.7.2 Causes

Bacterial regrowth needs nutrients, such as carbon, nitrogen and phosphorus, which are typically at high concentrations in reclaimed water. The carbon content in the water is reflected by organic matter content. For example, easily assimilable organic carbon (AOC) concentrations in reclaimed water can be more than five-fold higher than potable water. High organic matter content and nutrient content often lead to regrowth of microorganisms, formation of biofilms, and a general breakdown in the quality of the water where disinfectant residuals are not maintained. Disinfecting the water with chlorine or ozone can also increase the AOC and, therefore, the regrowth potential of the bacteria in the water. AOC may be a useful indicator of microbial regrowth potential.

Corrosion products can react and deplete disinfectants. Dissipation of the disinfectant residual leaves the water system vulnerable to the regrowth of bacteria and proliferation of biofilms, as well as contamination from system breaches and intruding contaminants. Some injured organisms that survive disinfection may be missed by monitoring programs. In addition, natural microbial cell lysis, including lysis of algal cells, can release organic matter into the water, stimulating both the chlorine demand and bacterial regrowth. The resulting microbial growth, in turn, further depletes disinfectant, favoring even further microbial proliferation. Storage of reclaimed water in open reservoirs can deplete the disinfectant residual rapidly.

7.7.3 Suggested Solutions

For management, be sure to avoid stagnation. Keep the reservoir well aerated to maintain dissolved oxygen above 5 mg/L. Monitor organic carbon levels, especially AOC (aim at <1000 µg AOC/L). Flushing the system removes biofilms and debris. This would require maintaining scouring velocities and durations. Flushing velocities of 2.5 to 3 ft/sec are effective for removing sand and silt debris (Kirmeyer et al., in press). Cover open reservoirs to minimize algal growth.

For treatment, reduce nutrients (nitrogen and phosphorus) to low levels; include a nutrient removal treatment process in the treatment train (e.g., biological nutrient removal [BNR] or

Bardenpho for phosphorus removal), limiting growth. Keep in mind that removal processes have to consider the intended end use of the water. For example, agricultural reuse typically requires the nutrients as they are beneficial for the plants. Maintain sufficient disinfectant residual by using multiple disinfectant points by installing redisinfecting booster stations. Avoid large single doses, because they may form a lot of AOC and DBPs. Optimizing the location of the disinfectant boosters can save on disinfectant quantities and provide better residual retention in the distribution system (Uber et al., 2003). Use chloramine as a disinfectant compared to chlorine. Chloramines are more stable and likely to persist longer in reclaimed distribution systems, especially at ≥pH 8.3. At this pH, nitrification is also greatly diminished. In any case, if not completely nitrified, chloramine may be forming already. Use multiple disinfectant barriers, such as disinfection with UV or ozone (low AOC production), followed by chlorine/chloramine for a residual.

7.8 Monitoring of Cross-connection Control

7.8.1 Nature of the Problem

Cross-connection intuitively suggests a link between two systems, notably the reclaimed water and the potable water system. However, there can be a link between the reclaimed water and sewer system as well. Cross-connected systems can experience backflow or backsiphonage compromising the quality of potable water or reclaimed water and threatening public health. Outbreaks related to cross-connection in water distribution systems have been reported, but none of the outbreaks have been directly associated with reclaimed water. Chemical burns, fires, explosions, poisonings, illness, and death have all been caused by backflow through cross-connections. Managing cross-connection (especially beyond customer meter) is still a challenge.

7.8.2 Causes

The reclaimed water should flow from the distribution system to the customer. However, it is possible for the flow to be reversed as a result of a loss of pressure in a piping system. The pressure loss may be attributed to a decrease in the flow rate as a result of a difference in elevation, main break, or pump capacity limitations. This condition allows liquids, gases, and other contaminants from elsewhere to enter the water supply. Cross-connection can occur from an intentional or unintentional connection between reclaimed water and potable water lines.

7.8.3 Suggested Solutions

Install backflow preventers on potable service at all dual-plumbed sites and check them periodically by conducting a "shutdown" test. For example, California recommends this once every 4 years. Sites that use recycled water for irrigation and domestic water for nearby buildings are required to conduct this test prior to receiving reclaimed water, then again if any major plumbing changes are made onsite every 4 years. If a site cannot be shut down, use the dye option. Monitor specific conductivity. Significant increase in potable water conductivity is suggestive of intrusion (i.e., cross-connection intrusion). Monitor with three-dimensional fluorescence excitation-emission matrices (FEEM) devices (Hambly et al., 2010). Inspect for cross-connections at applicable frequencies at dual systems with certified inspectors. Different plumbing fittings and color is coded (includes purple pipe or taping) for reclaimed water. Curbside identifications can be made for residential reclaimed water customers. Where applicable, install and maintain pressure relief valves to help reduce potential backsiphoning caused by water hammering. Monitor for fluoride if the potable water fluorinates the water. If fluoride is removed during wastewater treatment, presence of fluoride in the reclaimed water is a sign of cross-connection.

7.9 Managing Reclaimed Water Age to Enhance Quality and Operational Bottlenecks

7.9.1 Nature of the Problem

Reclaimed water is a perishable product with a shelf life, delivered in packaging (reservoirs and piping). To maintain quality, a preservative (disinfectant) should be maintained. The importance of retention time of water in the reservoir and the distribution pipeline on water age and quality cannot be emphasized enough. A rapid turnover minimizes the deterioration in water quality, whereas low water turnover increases water age in the system. Managing acceptable retention time with or without hydraulic models will, in turn, address these problems.

7.9.2 Causes

Retention time is controlled by the physical characteristics of the system and the operation regime. In the reservoir, water quality may decrease over prolonged durations of storage. The durations may be dictated by climatic parameters (i.e., temperature, rainy season/dry season) and also by the intended use of the water. In the pipeline, physical characteristics impact water age and retention time based on pipe surface roughness, pipe size, frequency of dead-ends, slope, and leakage. Quality in reservoirs and the pipeline is impacted owing to regrowth of microorganisms and increases in turbidity, odor, and color. Operational regimes may be structured (e.g., pumping schedule) or uncontrolled, as is the case for response action to meet demand needs.

7.9.3 Suggested Solutions

Minimize detention in reservoirs by providing for continuous flow within the reservoir. This includes managing production levels to quantities that just meet existing demand (i.e., production-on-demand model) to maximize tank turnover. It also includes continuous/semi-continuous mixing in the reservoir using pumping or static/mechanical mixer (aeration), transfer from between reservoirs in series or in sequential layout, and mounting intake and outlet to avoid short circuiting, in addition to seasonal drainage (i.e., target to use up the water by end of season). Establish a rule of thumb of 1 to 3 day residence time supply. Use tracers, such as boron and artificial sweeteners (e.g., saccharin, sucralose, and acesulfame), as well as tritium and helium ratios (Robertson et al., 2013). Other tracers include fluoride, lithium, and TDS, hydraulic modeling, which can include a geographic information system (GIS) with software packages, such as ArcGIS8.3 or ArcView3.3, to combine spatial and descriptive data and evaluate flow-path length measurement, as well as flow allocations (Nobel and Allen, 1995). In addition, computational fluid dynamics (CFD) can be used for better control of the flow, which minimizes short circuiting and formation of dead space in the reservoir. CFD also can be used to optimize reservoir geometry to minimize residence time distribution (Baléo et al., 2001). Hydraulic modeling is useful for altering the distribution system configuration and adjusting pumping schedules (e.g., fill reservoir to lower elevation during low demand periods).

An additional solution is minimizing retention in pipes. Operate network valves (manual or automated system) to minimize localized retention, minimize the number of shut valves required to produce hydraulic boundaries, close some valves to reroute the water through part of the system with high demand, and install time varying valves. Routinely flush the distribution system to attain scouring velocities (flush the reclaimed water back into the sewer or onto irrigation sites if typical flushing is not permitted). Continuously discharge through irrigation and groundwater recharge, increase water velocity, and reduce age with a downstream declining diameter piping system (system is also “self-cleaning” with no sediments as described by Buchberger et al., 2008). The smaller the piping efficiency ratio (PER: the piping diameter to flow rate) is, the better the flow rate.

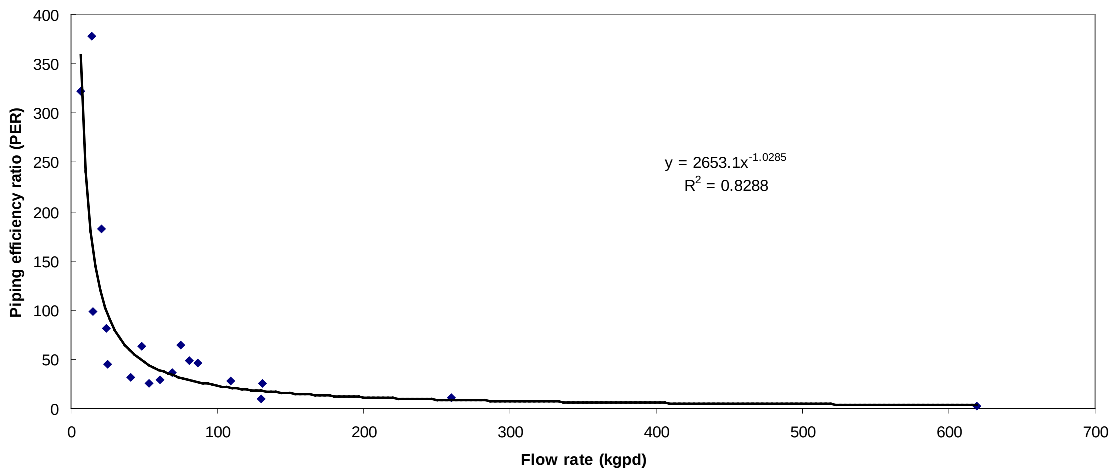

Figure 7.1. Relationship between water flow rates and the piping efficiency ratio (PER).

7.10 Ensuring Pressure Sustaining Reclaimed Water Systems

7.10.1 Nature of the Problem

A lack of sufficient water pressure can be a source of customer aggravation and complaints. Pressure can affect water flow rates but also affect the integrity of the water. Low hydraulic pressure including complete depressurization (i.e., zero pressure) can lead to intrusion by microorganisms and sediments, negatively affecting water quality. Ideally, distribution system pressure should range between 35 to 60 psi (240–410 kPa) although a minimum of 20 psi (138 kPa) at all points within the distribution system can be acceptable. Some pipe materials, such as ductile iron, can also support even higher pressure ranges. However, reclaimed water system growth and water utilization often varies depending on acceptability, inherent distribution restrictions, and demand and supply variables. All of these collectively restrict the wholesale transfer and application of potable water engineering standards to reclaimed water systems.

7.10.2 Causes

Loss of positive pressure can be a result of main breaks, demand spikes, operational failures (e.g., loss of pumping capacity), construction, and non-uniform growth of the distribution system.

7.10.3 Suggested Solutions

For operations management, develop a constant communication with key customers to plan and schedule water requirements to minimize peak demand episodes. Monitor pressure and make flow adjustments using the valving system. Depending on distribution system size, adapt a remote controlled SCADA system. To satisfy pressure needs, avoid exceeding a resilience index of 0.4 as determined from the relationship as follows:

$$RI = \frac{\sum_{j=1}^{N} q_j (ha_j - hr_j)}{\left(\sum_{r=1}^{R} Q_r H_r + \sum_{b=1}^{B} \frac{P_b}{\gamma}\right) - \sum_{j=1}^{N} q_j hr_j}$$

whereby N is the number of demand nodes, q_j is demand at node j, R is the number of reservoirs, Q_r is flow from the reservoir r when it is feeding the system, H_r is the elevation plus water level in reservoir r, B is the number of pumps, P_b is the power introduced by pump b into the system, γ is the specific weight of water, whereas ha_j and hr_j are the pressure available and required at node j, respectively (Baños et al., 2011). Install boosters (elevated storage or pump station) based on the reclaimed water volumes transferred to each user, pipe head losses, monthly flow rates, and system size. Hydraulic pressure modeling with models, such as Synergee, EPANET, WaterGem, Wonderware, WaterCAD, and H2OMap to track water flow in pipes, pressure at each node, and water height at each reservoir. Encourage residential users to use low-pressure irrigation.

For design solutions, design the system to maintain acceptable pressure (i.e., reduce major pressure variations). Loop the system. Design or retrofit the distribution network with a combination of pipe diameters that meet layout, connectivity and water demand (i.e., downstream declining diameter piping system; Brandt et al., 2004). Reclaimed water pressure should be lower than potable water pressure to minimize cross-contamination events. Design the system with future growth in mind; where applicable utilize topography for design advantages.

7.11 Staying within Reclaimed Water Turbidity Targets

7.11.1 Nature of the Problem

Turbidity is a key parameter for water quality. It represents the cloudiness of the water and is highly correlated with color. Typically it is determined by every utility as a water quality indicator for effluents but rarely determined in the distribution system. In some instances it is continuously monitored online. Depending on the intended use, the reclaimed water in the distribution system should not experience substantial changes from the permitted effluent turbidity levels. Turbidity upsets are an important first step in detecting major operational and water quality problems. Perception and acceptance of reclaimed water are influenced negatively by higher turbidity levels.

7.11.2 Causes

Turbidity is attributed to existing tiny suspended particles. The particles could be of inorganic nature from metals, sand, silt, or biological matter including increases in bacteria (i.e., regrowth) in the water. Regrowth may occur because of increases in nutrients, elevated temperatures, loss of disinfectant residuals, and result in objectionable flocs or slime layers. Changes in flow rates or flow direction can cause hydraulic shear leading to sloughing of biofilm or pipe wall material. Turbidity may also be attributed to accumulation of algal cells or corrosion of infrastructure in the system.

7.11.3 Suggested Solutions

Utilities should set their own goals for acceptable deviations in distribution system turbidity levels based on customer needs, operations, health goals, and other factors. Supplement tertiary treatment with a coagulant or polymer to improve effluent turbidity levels if needed. Indirectly manage apparent color by maintaining pH 7 to pH 9. Use of strong oxidizing agents, such as hydrogen peroxide, ozone, or chlorine also provides additional disinfection. Flush the pipe network and clean storage tanks to remove accumulated sediments. Implement algal control measures as discussed earlier. Evaluate the efficacy of the corrosion control for infrastructure materials.

7.12 Operational Management of Reclaimed Water Supply and Demand Challenges

7.12.1 Nature of the Problem

In most settings wastewater generation and treatment are continuous processes; however, beneficial reclamation may be practiced mostly during certain times of the year. It is preferable that end-users have a reliable supply of reclaimed water. This practically requires the capability to provide adequate supply under both varying conditions. These extremes call for the need to minimize uncertainty in reclaimed water demand and supply.

7.12.2 Causes

Reclaimed water is mostly used for landscaping, golf course irrigation, aquifer recharge, surface water augmentation, and others. These requirements peak in certain times of the year. Specifically, reclaimed water supply and demand can change dramatically with minimal demand in winter and greatest demand in summer. In a majority of instances, reclaimed water costs only a fraction of potable water. As the general needs for water increase, reclaimed water is typically viewed as a less expensive alternative for supplementing nonpotable purposes.

7.12.3 Suggested Solutions

For management, encourage conservation of reclaimed water by customers by determining irrigation requirements coupled with assimilative capacity during winter based on field information. Optimize pumping regimes to match supply and demand requirements, which involves several components. Link production to consumption using decision support system (DSS) software to optimize pumping, transmission, and storage. Model (e.g., Poisson rectangular pulse model, stochastic models) to characterize the intensity and duration of water demand aimed at a decrease in peak flow with increased demand. Model with GIS software packages (e.g., ArcGIS, ArcView) through operations, such as network analysis and flow-path length measurement, to assess reclaimed water demand; treat water users as nodes and connections from sources to sinks as arcs (Nobel and Allen, 1995). Supplement composite reclaimed water with potable water in reclaimed water distribution system, which also can dilute salinity. Meter the water and set competitive reclaimed water rates with similar potable use rates. For example, the rates for reclaimed water supplied for irrigation should be equal to comparable rates for systems using potable water. This includes accounting for water rights otherwise required to gain access to the daily production rate of the reclaimed water. The avoided cost for potable water increases source capacity and may generate savings from investing in increased discharge permits.

Designing options include building excess reservoir capacity, which may include use of wetlands tapped to meet demand.

7.13 Monitoring Water Quality in the Distribution System

7.13.1 Nature of the Problem

Most utilities are not required to monitor reclaimed water in the distribution system. However, the distribution system is a dynamic entity with many biological and chemical factors driving the stability of reclaimed water. Reclaimed water has to be stored for extended duration prior to use or transmitted long distances to its end use. However, it can have a short shelf life and can degrade in storage or transit. These attributes make it imperative to establish credible monitoring strategies to ensure good quality and reliable performance. Monitoring requirements for effluent water does not ensure continued acceptable water quality in the distribution system. Moreover, it almost exclusively focuses on indicator organisms, particularly coliforms.

7.13.2 Causes

Reclaimed water can be a rich medium, typically containing higher levels of organic carbon (TOC, AOC, and BDOC) and a variety of other nutrients compared to potable water. It also rapidly consumes chlorine, leaving very low residuals. These characteristics collectively favor regrowth of microorganisms, increased turbidity, consumption of dissolved oxygen, buildup of hydrogen sulphide, and, if stored in open reservoirs, growth of algae. The degradation can be enhanced under favorable temperatures (15–55 ^{o}C).

7.13.3 Suggested Solutions

Monitor at the points of storage and at representative locations in the distribution system on a periodic basis for the intended use of the water and utility goals. The utility should set their own targets for acceptable deviations in normal operations in the distribution system based on customer needs, operations, health goals, and so on. Recommended online monitoring parameters include pressure, flow, tank levels, pH, conductivity/TDS (temperature), dissolved oxygen, turbidity, and disinfectant residuals. Supplemental water quality parameters for consideration include HPC or yeast and molds, nitrite (as a measure of nitrification), total nitrogen and phosphorus, color, hydrogen sulfide, corrosion rate, TOC-AOC-UV absorbance, chlorophyll, and *Legionella*.

7.14 Concerns about Emerging Contaminants in Reclaimed Water

7.14.1 Nature of the Problem

Pharmaceutical and personal care products (PPCPs) are increasingly being recognized as emerging contaminants in the environment. PPCPs are a diverse group of chemicals that include prescription and nonprescription medications, veterinary drugs, nutritional supplements, and diagnostic agents, as well as a variety of consumer products, such as fragrances, sunscreens, and cosmetics. They are quite diverse and are, therefore, not expected to have a homogenous set of characteristics once they are introduced into the environment. Most of the documented removal of PPCPs during water reclamation are based on measurements of the concentration in the wastewater influent and reclaimed water effluent (Ternes, 1998; Agus et al., 2011). They show variable average removals based on the matrix, type of compound, and treatment technology. With increasingly sophisticated detection systems, PPCPs residues are detected in reclaimed water, albeit in very low concentrations. The chemical and biological effects of those residues can be disconcerting to some reuse purposes (impacting public perception) but unknown as this is an area of active research.

7.14.2 Causes

PPCPs are introduced directly or indirectly into wastewater through two main routes: disposal and excretion (Bound and Voulvoulis, 2005; Jjemba, 2008). Other compounds, particularly personal care products, also enter the environment through routine practices such as showers, swimming, and conducting laundry operations. Veterinary medicines, herbicides, pesticides, and related farm compounds can also end up in wastewater through runoff and leaching events (Wu et al., 2009).

7.14.3 Suggested Solutions

Support voluntary sampling and participation of the utility in ongoing research (including ecological and wildlife impacts) on this topic whenever possible. Provide flexibility in treatment technology and future recommended requirements as supported by science. Frame the conversation of PPCPs in reclaimed water around the concept of risk, which is a function of the dose and the level of exposure. The detected levels typically are in parts per trillion or quadrillion range (i.e., very low) vis-à-vis the cost associated with additional treatment and the limited instances of exposure to reclaimed water.

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Appendix A

Online Questionnaire Distributed to Reclaimed Water Utilities

Initial Questionnaire for Quality, Operational and Management Practice Issues for Reclaimed Water Systems
Questions marked with an asterisk (*) are mandatory

1 *Please tell us about yourself
Utility name
State (or Country if outside US)

2 Indicate your average annual reclaimed water production
Amount

Indicate units (gallons (G), liters (L) or cubic meters (CM)

3 Indicate treatment type (check all that apply)
- o Activated sludge
- o Lagoon
- o Membrane bioreactor
- o Rotating biological contactor
- o Sequential batch reactor
- o Media filtration
- o Reverse osmosis
- o Chlorine
- o Ultraviolet light
- o Ozone
- o Other, please specify

4 Indicate storage type (check all that apply)
- o Open
- o Closed
- o Underground
- o Aboveground

5 Indicate typical storage time (in days)

6 Is there additional treatment before distribution? If yes, please describe Yes No
Additional comment

7 Indicate miles of distribution system pipeline
- o 5 miles or less
- o 6-10 miles of pipes
- o More than 10 miles of pipes

8 Indicate your distribution system configuration (check all that apply)
- o Branched
- o Looped
- o Multiple pressure zones

9 Indicate the end-use(s) of the reclaimed water (check all that apply)
- o Landscape irrigation
- o Fodder crop irrigation
- o Produce crop irrigation
- o Industrial uses
- o Groundwater recharge
- o Groundwater injection
- o Recreational water body
- o Other, please specify

10 List your top three issues or challenges with reclaimed water distribution system storage, water quality, operations, management, or customer satisfaction

Appendix B

Phone Interview

Phase II - Phone Interview Questionnaire for Quality, Operational and Management Practice Issues for Reclaimed Water Systems

Questions marked with an asterisk (*) are mandatory.

1 * Please tell us about yourself

Utility Name

State or Country (if outside US)

Contact Name

Contact Phone Number

Contact E-Mail Address

GENERAL SYSTEM INFORMATION

2 Indicate what year your system was initially commissioned.

3 Specify the type of reuse.

4 Can you provide a system schematic?

Additional Comment

5 Indicate the type of biological treatment process that is employed.

AS
SBR
RBC
Lagoon
MBR
Other, please specify

6 Indicate what disinfection process(es) is / are used in the treatment plant.

Chlorine
Chloramines
UV
Ozone
Other, please specify

7 Is there any filtration before disinfection? If so, what type (e.g., cloth, sand, GAC, etc.)?

8 Provide basic information on the design of the reclaimed water distribution system.

Type of pipe material
Length of pipe (units)
What do you do to limit the number of dead ends?
Valves in system (frequency, composition of material, etc.)
Booster stations
Re-disinfection locations

Availability of a hydraulic model

9 Provide information on main breaks.

Do you collect information about main breaks (provide units (e.g., x / 100 miles))?

Do you do any leak detection in the system?

10 Provide information on distribution system / storage problems you encounter.

Utility perspective (design, operational, monitoring, maintenance, etc.)

Do you have leakage problems?

Customer perspective (complaints, safety concerns - perceived or otherwise, demand - supply issues)

How do you address these complaints / concerns / demand - supply issues?

WATER QUALITY MONITORING

11 Think about the major water quality or aesthetic issues experienced by your system.

What are the major aesthetic issues (e.g., color, turbidity, odor) experienced by your system?

What are the

major microbial issues experienced by your system?

Are there other water quality issues (e.g., snails) that you are experiencing?

Do you have practices in place to remediate any of these issues?

If so, how effective are they?

Can you provide existing protocols for addressing these issues?

12 Think about the parameters you monitor for.

What parameters do you monitor in the plant effluent?

What parameters (including location and frequency) are monitored for in order the distribution sytem?

Are there any requirements to monitor the distribution system?

13 What do you do to restore any of these monitored parameters when they get out of range? Can you provide protocols for addressing these adjustments?

14 What action do you take when you receive complaints on water quality from your customers?

Industrial customers

Residential customers

OPERATIONS

15 If hydraulic pressure is measured in the system:

List the typical hydraulic pressure and range

Indicate how you respond to pressures outside of your acceptable range

16 What operations do you perform to mitigate water effect from dead ends?

17 How often do you exercise the valves?

18 What measures do you have in place related to cross connection control?

19 If the system has a flushing program:

Indicate the frequency

Indicate how the flushed water is handled

Indicate if there is a flushing protocol that addresses velocities, duration, etc.

20 Indicate how water age is managed to meet different demands (seasonal) patterns.

How large is your storage?

What is your winter production?

What is your summer production?

Do you ration water to manage demand / supply?

21 How do you promote turnover in your reservoir?

22 Think about cleaning of your storage facilities:

How frequently is there cleaning of storage?

Do you have a practice in place for cleaning?

What method is used (e.g., chemical, jetting, scrapping, etc.)

23 Do you have training programs / workshops in place for any of these operations? If so, how often are they conducted?

MANAGEMENT

24 Do you have management practices in place for:

Strategic planning (infrastructure growth)	
Managing customer relations	
Managing regulatory compliance issues	
Investing in technology (e.g., SCADA, collection and dissemination of the information (LIMS), written SOPS specifically for DS, etc.)	
Other	

25 Think about the costs of producing reclaimed water.

Is the cost of producing reclaimed water fully covered by its production cost?	
Do you meter your reclaimed water customers?	
Do you know the relative cost of reclaimed water to potable water?	

MOVING FORWARD

26 Documented BMPs are critical tools for success.

Does your facility have any specific BMPs you would be willing to share with us for this study?	

Have you identified any specific BMPS that you would like to have at your facility?

What would be the best way for you to access BMPs that you are looking for?

27 Are you interesting in having us visit your facility? If so, would you be willing to allow us to collect samples from your distribution system?

Additional Comment

SUBMIT

Appendix C

Table C.1. Utilities Selected to Advance to Next Phase Based on a Cluster Analysis and an Aggregate Point System

Cluster unit	Plant code	Filtration media[1, 2, 3]	Type of issues raised through questionnaire[4]	Numeric score[5]	Selected for phone interview
1	*CO-1*	*Large AS utility with open reservoir; long branched or looped distribution system. Disinfects with UV or UV and chlorine*	*Water quality, Customer, Operational*	*8*	*CO-1 WA-4*
	WA-4		*Infrastructure, Customer, Cost*	*8*	
2	FL-2	Large AS utility with open reservoir; long branched distribution system. Disinfects with chlorine	Capacity/Supply, Cost, Capacity/Supply	NA	
3	*AZ-2*	*Large AS (or AS + SBR for AZ-2). Open aboveground reservoir. Have long distribution systems with multiple pressure zones. Disinfects with chlorine and UV. AZ-2 has post-storage disinfection but CO-4 does not. Both have a long distribution systems with multiple pressure zones*	*Infrastructure, Infrastructure, Regulations*	*9*	*AZ-2*
	CO-4		*Infrastructure, Infrastructure*	*4*	
4	*CA-1*	*Very large AS utility with filtration media with open reservoir. Disinfects with UV or (for AZ-7) UV + chlorine. Both have a long branched distribution system. CA-1 conducts post-storage disinfection*	*Water quality, Operational, Customer*	*8*	*CA-1*
	AZ-7		*Water quality, Customer, Infrastructure*	*5*	
5	*CO-2*	*Very large BAF utility with filtration media with open reservoir. Disinfects with chlorine. Both have a long branched distribution system. CO-2 has underground reservoir whereas FL-11 has an open reservoir*	*Infrastructure, Customer, Operational*	*7*	*FL-11*
	FL-11		*Operational, Operational*	*8*	
6	CA-7	Very large utility with open reservoir with long branched and looped distribution system. Disinfects with chlorine	Water quality, Capacity/Supply, Infrastructure	NA	
7	*AZ-6*	*Very large AS with either lagoon (AZ-6) or BNR (FL-1 Utility). Both have a covered reservoir (underground for AZ-6) and a long looped distribution system (branched in some areas for FL-1 Utility). Both use chlorine as disinfectant*	*Customer, Infrastructure, Water quality*	*5*	*FL-1*
	FL-1		*Capacity/Supply, Capacity/Supply*	*12*	

Cluster unit	Plant code	Filtration media[1, 2, 3]	Type of issues raised through questionnaire[4]	Numeric score[5]	Selected for phone interview
8	FL-13	Very large AS utility with above and underground reservoirs Long distribution system. Uses chlorine disinfestations. Also has a filtration medium	Customer, Regulations, Cost	NA	
9	*TX-1*	*Very large AS (or AS+RO for CA-5) utility with a closed aboveground reservoir (TX-1 has an underground reservoir also). Have a filtration medium and disinfect with chlorine, UV, and (for TX-1) O3. Conduct post-storage disinfection. Have long branched distribution systems with multiple pressure zones*	*Water quality, Infrastructure, Capacity/Supply*	*9*	*CA-5*
	CA-5		*Regulations, Cost*	*12*	
10	FL-6	Very large AS utilities with filtration medium. Both have open and closed aboveground reservoirs. Both have long branched and looped distribution systems. FL-6 conducts post-storage disinfection and FL-12 has multiple pressure zones	Operational, Infrastructure, Infrastructure	NA	
	FL-12		Operational, Workforce	NA	
11	CA-9	Very large utility with filtration medium. Disinfects with chlorine. Has both open and closed, aboveground and underground reservoirs. Has a long branched and looped distribution system with multiple pressure zones	Water quality, Water quality, Water quality	NA	
12	TX-4	Very large AS utility with filtration medium. Disinfect with chlorine. Have open and (for CA-13) a closed reservoir. Both have long branched distribution system with multiple pressure zones	Cost, Cost, Cost	NA	
	CA-13		None reported	NA	
13	*FL-5*	*Very large A2O utility with A2O with a closed aboveground reservoir. Disinfects with chlorine and UV. Has a long branched distribution system*	*Customer, Customer, Customer*	*NA*	*FL-5*
14	*TX-3*	*Very large AS utility with filtration media. Have closed aboveground reservoir. TX-3 disinfects with chlorine (even) post storage. Both have a long branched distribution system*	*Customer, Operational, Operational*	*8*	*TX-3*[6]
	CA-12		*Regulations, Customer, Customer*	*10*	
15	*CA-4*	*Very large AS utility with coagulation and clarification. Uses filtration media and disinfects with chlorine. Has a closed above and underground reservoirs as well as a long branched distribution system*	*Water quality, Regulations, Infrastructure*	*NA*	*CA-4*

Cluster unit	**Plant code**	**Filtration media[1, 2, 3]**	**Type of issues raised through questionnaire[4]**	**Numeric score[5]**	**Selected for phone interview**
16	*FL-3*	*Large AS utility with filtration media and disinfect with chlorine. Closed reservoir (aboveground for FL-3). Long looped distribution system*	*Customer, Operations, Regulations*	*13*	*FL-8*
	FL-8		*Customer, Capacity/Supply, Cost*	*14*	
17	*CA-6*	*Large utility with filtration media and disinfect with chlorine. Closed aboveground reservoir. Long branched distribution system with multiple pressure zones*	*Capacity/Supply, Water quality, Infrastructure*	*NA*	*CA-6*
18	*AZ-9*	*Large AS (or AS+NR for S. CA-1) utility with filtration media and disinfect with chlorine. Open and closed reservoir (aboveground for FL-16 and underground for AZ-9).S. CA-1 has both underground and aboveground reservoirs. Long branched distribution system*	*Water quality, Water quality*	*4*	*FL-16*
	FL-10		*Customer, Infrastructure, Capacity/Supply*	*9*	
	FL-16		*Capacity/Supply, Miscellaneous*	*15*	
19	FL-15	Large AS utility with filtration media. Has open and closed aboveground reservoirs. Disinfects with chlorine. Has a long and branched distribution system.	Capacity/Supply, Operational, Infrastructure	NA	
20	*NC*	*Mid-size AS utility with filtration medium. Disinfects with chlorine and UV. Has an aboveground reservoir and a long branched distribution system*	*Cost, Customer*	*NA*	*NC*
21	*CA-15*	*Mid-size AS utility with filtration medium. Disinfects with chlorine. Has a closed aboveground reservoir and a medium branched distribution system. CA-15 system has multiple pressure zones*	*Operational, Infrastructure*	*NA*	*ID[7]*
	ID		*Infrastructure, Capacity/Supply, Operational*	*NA*	
22	*FL-4*	*Very large (FL-4) or extremely large (Aus-1) AS (AS+RO for Aus-1) utility. Uses filtration media. Has closed aboveground reservoir. The distribution system is medium length, branched and looped. Disinfect with chlorine (or chlorine and UV for Aus-1)*	*Infrastructure, Infrastructure*	*NA*	*FL-4[8]*
	Aus-1		Infrastructure, Cost, Infrastructure		
23	*TX-2*	*Extremely large AS (or AS+RBC for TX-2) utility. Use filtration media. Has closed or (for Orange County) open and closed*	*Water quality, Workforce, Customer*	*12*	*TX-2*

Cluster unit	Plant code	Filtration media[1, 2, 3]	Type of issues raised through questionnaire[4]	Numeric score[5]	Selected for phone interview
	FL-14	*aboveground reservoirs. The distribution system is long and looped (or branched and looped for FL-14). TX-2 distribution system has multiple pressure zones. Disinfect with chlorine. Post-storage disinfection is practiced*	*Infrastructure, Infrastructure, Operational*	*6*	
24	*VA*	*Extremely large AS with coagulation, clarification and lime treatment utility with filtration media. Disinfect with chlorine. Has open aboveground reservoir. Has a short looped distribution system with multiple pressure zones*	*Water quality, Operational, Cost*	*NA*	*VA*
25	AZ-1	Very large AS utility. Disinfect with chlorine even post-storage. Has open aboveground reservoir and a medium-sized distribution system	Regulations, Workforce, Cost	NA	
26	*AZ-3*	*Mid-size SBR (AZ-3) or AS+BNR (AZ-8) utility with filtration media. Have open aboveground reservoir and a short branched distribution system. Disinfects with chlorine even post-storage*	*None reported*	*0*	*AZ-8*
	AZ-8		*Cost, Capacity/Supply*	*11*	
27	*WA-3*	*Mid-size MBR with an open aboveground reservoir and a short branched distribution system. Disinfects with chlorine*	*Regulations, Workforce*	*NA*	*WA-3*
28	*CO-5*	*Mid-size AS (or AS+MBR for AZ-11) with an open (and for AZ-11) aboveground reservoir and a short branched distribution system. Disinfects with chlorine and UV*	*Customer, Customer, Cost*	*9*	*CO-5*
	AZ-11		*None reported*	0	
29	FL-7	Mid-size AS utility with filtration media and a closed reservoir. Disinfects with chlorine and has a short branched distribution system	None reported	NA	
30	*WA-1*	*Small AS (or AS+MBR for WA-1) utility with filtration media. Have aboveground open (or for CA-14, open and closed) reservoir and a short branched distribution system. For WA-1, post-storage disinfection is practiced*	*Water quality*	*2*	*CA-14*
	CA-14		*Water quality, Operational*	*6*	
31	*NV*	*Mid-size AS utility with filtration media. Has underground open reservoir and a short distribution system. Disinfects with chlorine and UV and conducts post-storage disinfection*	*Water quality*	*NA*	*NV*

Cluster unit	Plant code	Filtration media[1, 2, 3]	Type of issues raised through questionnaire[4]	Numeric score[5]	Selected for phone interview
32	AZ-5	Extremely large lime/soda ash utility with filtration media. Disinfects with chlorine and has an open underground reservoir. The distribution system is small and branched	Water quality, Operational, Water quality	NA	
33	*CA-2*	*Large lagoon treatment utility with filtration media and an open reservoir. Has a short branched distribution system*	*Regulations*	*NA*	*CA-2*
34	*SC*	*Large AS with (in the case of CA-19 a filter media). Have an open reservoir and a short distribution system which in the case of CA-19 is branched. Disinfect with chlorine*	*Infrastructure*	*NA*	*SC*[9]
	CA-19		*Water quality*	NA	
35	WA-5	Large SBR with a filter medium. Disinfects with chlorine and UV. Has a short branched distribution system	Regulations	NA	
36	*AZ-4*	*Large AS with open reservoir and a short (and in the case of AZ-4) a branched distribution system. AZ-4 also disinfects post-storage.*	*None reported*		*AZ-4*[10]
	AZ-10		None reported		
37	*CA-8*	*Very large (CA-8) or small (CO-3) AS+SBR utilities with open reservoirs and a short branched distribution system. The reservoir for CA-8 is aboveground. CO-3 has a filter media and disinfects with UV*	*Cost*	*5*	*CA-8*
	CO-3		*Infrastructure, Customer, Water quality*	*5*	*CO-3*
38	*WA-2*	*Small AS+MBR (WA-2) or BNR (CA-10) utilities. Latter has a filtration medium whereas WA-2 has a covered reservoir and disinfects with chlorine and UV even at post-storage. CA-10 only uses chlorine (no post-storage treatment). Both have underground storage and a medium length branched distribution system*	*Infrastructure, Water quality, Infrastructure*	*4*	*CA-10*
	CA-10		*Infrastructure, Regulations, Water quality*	*10*	
39	FL-9	Large utilities (AS+RO for CA-17) whereas FL-9 has a filtration medium. Disinfect with chlorine. Have closed (or in the case of CA-17, a closed and open aboveground) reservoirs. The distribution system is medium size and branched	Customer, Infrastructure	NA	
	CA-17		Infrastructure, Operational, Cost	NA	
40	*CA-18*	*Large MBR utility with closed reservoir and a medium size*	*Water quality*	*NA*	*CA-18*

Cluster unit	Plant code	Filtration media[1, 2, 3]	Type of issues raised through questionnaire[4]	Numeric score[5]	Selected for phone interview
		branched distribution system. Disinfect with UV; some post-storage treatment			
41	*CA-3*	*Extremely large utility with closed reservoir and long branched distribution system. Disinfects with chlorine*	*Regulations, Cost, Water quality*	*NA*	*CA-3*
42	CA-11	Large utility with aboveground and in the case of CA-11, a closed reservoir. Has a long looped (CA-11) or long branched (CA-16) distribution system	Customer, Workforce, Cost	NA	
	CA-16		Water quality, Infrastructure, Infrastructure	NA	
43	Aus-2	Very large AS + lagoon (Aus-2) or mid-sized AS (TX-11) utility system. Former disinfects with chlorine and UV whereas the latter uses only UV. Aus-2 has a short distribution system	Customer	NA	
	TX-11		None reported	NA	
44	TX-10	Mid-size utility system with an aboveground reservoir	None reported	NA	
45	TX-9	Small utilities; the former has a short branched distribution system. No additional information was provided about the latter	None reported	NA	
	AZ-12		None reported	NA	

Notes:
[1]For size: EL = Extremely large (≥10^{10} GPY); VL = Very large (10^9 GPY); L = Large (10^8 GPY); MS = Midsize (10^7 GPY); S = Small (≤10^6 GPY)
[2]AS = activated sludge; MBR = membrane bioreactor; RO = reverse osmosis; CLA = clarification; CO = coagulation; BNR = biological nutrient removal; BAF = Biological aerated filtration; RBC = rotating biological contactor; SBR = sequential batch reactor; A2O = aerobic/anoxic/oxic
[3]S = short DS (≤5 miles); M = medium length DS (6-10 miles); L = long DS (>10 miles of pipeline)
[4]Same issue/problem category may be listed more than once for same utility. For example AZ-2 reported two infrastructure-related issues and one regulations issue.
[5]For each cluster with ≥2 utilities, frequency of issue/problems provided by respondents were used to develop the score, whereby infrastructure (22%), water quality (17.6%), customer (17.6%), operations (11.1%), cost (10.5%), capacity/supply (8.5%), regulations (7.8%), workforce (3.3%), and miscellaneous (1.3%) issues/problems had a score of 1, 2, 2, 4, 5, 6, 7, 8, and 9, respectively. **Italicized utilities were candidates the phone interview.** The utility with the higher cumulative score was selected (unless otherwise noted). Both utilities in cluster 1 and 37 were selected as they had the same score.
[6]Overruled the numeric score to explore the post-treatment process conducted by the TX-3 distribution system.
[7]Favored, as it is the only respondent from Idaho (ID).
[8]Favored, as there are no plans to include nondomestic utilities beyond the initial questionnaire phase.
[9]Favored, as it is the only respondent from South Carolina (SC).
[10]Selected because it has post-storage treatment and did not report any issue/problem with storage or distribution systems.

Appendix D

Table D.1. Additional Characteristics of Interviewed Utilities

Utility	Pressure Booster Stations	Hydraulic Model	Main Breaks	Limiting Dead End?	Leak Detection?
CO-1	Yes (1)	Yes. InfoWater (by Innovyze)	None in last four years	No. Have one loop and two dead ends	Yes. Monitored once a year using acoustics
WA-4	Yes (1)	No	No	Not limited at all.	No
AZ-2	Yes (4)	No (potable and wastewater departments use H2OMAP)	No (New system)	No	No
CA-1	Yes (approx. 45)	Yes	No (only one this year)	Terminate into pond	Yes
FL-11	Yes (2)	No	Yes (No data provided)	No dead ends as pipe delivers directly to golf course, i.e., open flow delivery water level or directly to non-residential entity	No
FL-1	Yes (3)	Yes (WaterGem)	None	No (high usage and velocity)	Yes (all employees)
CA-5	Yes (3)	Yes (Synergee)	Yes (rare; one or two per year; collected in SWIMS i.e. Sewer & Water Infrastructure Management System)	Terminate into well	Yes (crew)
FL-5	No	No	No breaks	No	No
TX-3	Yes (one temporary)	Yes (EPANET)	No (so infrequent)	No	No (monitor pressure drop)
CA-4	Yes (4)	Yes	Yes (Not many)	Continuous (high usage)	No
NC	Yes (1)	Yes	No (New system)	Looped	Yes (SCADA)
ID	Yes (1)	Yes	Yes (None)	Yes (Looped)	No; only monitor pressure

Utility	Pressure Booster Stations	Hydraulic Model	Main Breaks	Limiting Dead End?	Leak Detection?
FL-4	None	Yes. Wonderwave	Yes. Had 2 in 6 years whereby one was due to a construction accident	No. Have some loops and dead ends as customers get added	No; only noticed if excess pumping is required
TX-2	Yes (three main boosters and several other subsidiary boosters)	Yes. InfoWater	No	Looped system with no dead ends	No
VA	Not applicable	No (have one for wastewater collection system)	Not applicable	Not applicable	Not applicable
AZ-8	No	No	Yes; a couple per year	No dead ends	Yes; monitoring for leaks or loss of fluid is requires because system crosses U.S. waterway (intermediate stream)
CO-5	No	No (depends on the hydraulic profile provide on the distribution system schematic)	None	None (straight transmission pipe)	No
CA-14	No	Yes, WaterCAD V8 under CA-14 Co District 1 Recycles water Hydraulic Model	No	Have three dead ends	No; only monitored at construction using pressure gauges
NV	Yes (three, i.e., Durango Hills Main Pumping Station, Cheyenne Booster Pumping Station, and Rampart Booster Pumping Station)	Yes. H20 Map is used extensively.	No	None (Looped system)	No
CA-2	Yes (two, i.e., one on the north course and one on the south course)	No	Not had any	None	No
SC	No	No	Yes. One main break	No dead ends (linear system)	No
CA-8	No	No (Gravity)	None	Standpipes with meters at delivery points	No
CA-10	Yes (2)	No	Average of one per year	Have four dead ends	No

Utility	Pressure Booster Stations	Hydraulic Model	Main Breaks	Limiting Dead End?	Leak Detection?
CA-18	No	No	No; only one owing to construction breach	No	No (Monitor pressure drop)
CA-3	Yes (5)	Yes. ID Modeling with InfoWater	Yes, five since system in place. Had one last year	Yes, as there has to be a customer at the end of the line or else it is not built. Despite this strategy, system has a few dead ends	No

Appendix E

Table E.1. Monitoring Requirements

Utility	Parameters Determined		Remedies to Restore Out of Range Parameters
	Effluent	**Distribution System and Requirement**	
CO-1	Meeting secondary effluent (category II) requirements i.e., *E. coli*, TSS, turbidity	None (monitoring not required)	Pump shutoff automatically if out of range. For turbidity, turn off distribution until things are back within range after process adjustment and cleaning to get rid of settled material.
WA-4	Total N, coliform, turbidity, DO, CBOD, pH, chlorine residual, coagulant used	Chlorine residual at discharge end into a lake (monitoring not required)	Shut down production process to remedy problem (usually owing to total coliform). Shut down system if chlorine in the reservoir is <0.5 ppm; no delivery until adjusted.
AZ-2	Bacteria, metals, TDS as per NPDES list	Chlorine residual, coliform (monitoring not required unless you are discharging from the plant)	Make adjustments at treatment plant or source. One golf course monitors TDS + fertilizers to enhance greens.
CA-1	BOD (three times/week), NFR, (pH, turbidity, TSS, coliform; daily for each), (PO_4, NH_3; three times/week for each), NO_3, priority pollutants (i.e,, VOC, EPA-priority pollutants; quarterly), metals (quarterly)	No monitoring in the DS unless there is an issue. Only time monitored is when we discharge but does not include discharging into the geyser but rather into receiving water. Monitor DATASON (i.e., DO, pH, temp, EC) every 15 min (using SCADA) (No monitoring required except where/when discharging)	N/A
FL-11	N, P, TSS, turbidity, NO_3, fecal coliform, *Giardia*, *Cryptosporidium*	Measure water quality parameters in on- and offsite lakes (monitoring not; but required to monitor groundwater)	Inject the reclaimed water into deep well instead of delivery to lakes.
FL-1	BOD, suspended solids, TN, TP, pH, chlorine residual and fecal coliforms continuously or four times/week. Also approx. 40 other constituents as part of FL requirements	None (monitoring not required)	Divert to reeds if turbidity exceeds 2 NTUs
CA-5	The Water Quality Laboratory (WQL) monitors North City effluent weekly for total and fecal coliform, pH, total and free chlorine residual, temperature and total dissolved solids. Others include a whole range of nutrient, metals and organic compounds (provided an extensive list)	The Water Quality Laboratory (WQL) monitors seven North City distribution sites for total and fecal coliform, pH, total and free chlorine residual, temperature, total suspended solids, total dissolved solids, ammonia (as N), nitrate, and nitrite. Three distribution sites and the two storage tanks (Meanly Dr. and Poway) are monitored weekly. Two other distribution sites are monitored monthly. The two storage tanks and a distribution site located between them are also monitored weekly for HPC (heterotrophic plate count) bacteria (monitoring not required)	Evaluate monitoring data from Water Quality lab (weekly) vs. procedure
FL-5	Fecal coliform, TSS, TRC (i.e., residual chlorine), turbidity, pH, total P, NO_3, NO_2, NH_3, TKN (continuously or weekly). Also metals (monthly) and priority pollutants (annually)	None (monitoring not required)	For pH, turbidity, and TRC falling outside the range, have to reject capability in both plants and instead send to the wetland to recover
TX-3	Chlorine (requirement for detectable levels; no specific concentration); turbidity of <3 NTU; fecal coliform	Have online residual monitoring at elevated storage tank but not reported and/or deliberately monitored/checked.	Work with operators to take supplemental samples and increase chlorination. No protocol but sample three times/week and

Utility	Parameters Determined		Remedies to Restore Out of Range Parameters
	Effluent	**Distribution System and Requirement**	
	requirement	(monitoring suggested but not required).	tracking parameters to meet permit requirements. No standard
CA-4	DO, coliform, NTU, chlorine residual (8mg/L leaving plant and approx. 2mg/L, at end of the system), flow rate, priority pollutants (two times/year), NH_3, nitrate and nitrogen.	Periodically randomly test for coliforms and residual in the distribution system (monitoring not required).	Adjustments, e.g., residual, increase usage, aluminum sulfate, or polymer (to decrease turbidity, microsand to treat sand filter)
NC	BOD, pH, TSS, NH_3, fecal coliform	Chlorine, turbidity, pH, conductivity (through SCADA); monitoring is part of the permit specifications; records kept but are not required to submit	If know the solution, problem is fixed. Otherwise, the reclaimed water is dumped into a river and tank filled with potable water (delivered through a candy cane delivery backup system in place) maintaining customer demand
ID	A lot of parameters, i.e., BOD, TSS, TN, NH3, NO_3, NO_2, TP, pH, TDS, total coliform, *E. coli*, turbidity, transmittance	None; monitoring not required	Look at the issue and address, e.g., TN high by adding a C-source changing anoxic zones; P by pursuing BNR; look at high turbidity and add polymer
FL-4	Turbidity, pH, chlorine residual, TSS, coliform	Chlorine residual, TSS at screens/filters (monitoring not required)	Make process control adjustments
TX-2	BOD (regulatory standard is 5 mg/L but we aim at 2 mg/L), turbidity (reg requirement is 3 NTU; we attain <1 NTU), fecal coliform (reg is <20; we attain <2/100 mL), TDS, TSS, sodium adsorption ratio (SAR), residual chlorine, sodium carbonate, pH	Chlorine residual (aim at 1 mg/L by feeding approximately 50 lb/day to entire system) (monitoring not required; done owing to self-imposed needs).	If at the plant, water is not distributed; if in distribution system, use potable water to supplement and meet reclaimed water needs
VA	(1) Industrial users via pretreatment program permits; (2) product water via NPDES permit; (3) stormwater discharge permit; (4) general permit to meet Chesapeake Bay nutrient management standards; (5) U.S.EPA 503 program for biosolids; (6) SDWA at water reclamation plant and potable water plant; (7) plant process control monitoring	(1) EDCs and PPCPs on reuse product water and potable water; (2) comprehensive watershed and reservoir monitoring program	Take corrective action as needed
AZ-8	All under the permit to prevent degradation of stream and includes NO_3, NO_2, NH_3-N, coliforms, *E. coli*	Golf course blends with groundwater to irrigate; monitor groundwater wells for N, P, heavy metals, runoff from golf course (compare samples from upstream with those from downstream; monitoring distribution system is not required	For coliform and *E. coli*, review disinfection procedure; if P, review chemical addition of $Al(SO_4)_3$ for P removal; if N, review biological activity needs method
CO-5	*E coli*, nutrients, such as inorganic N to calculate N-loading on the fields; also SAR, P	None; monitoring not required; tested or *E. coli* on holding ponds in past and densities were comparable to those in effluent)	If *E. coli* densities are out of range, UV and chlorine doses are increased; may also decrease the feed rate through the filter (e.g, from 1000 down to 800 gal).
CA-14	Under Title 22, monitor for chlorine residual, total and fecal coliform, inorganics (as by permit) oil and grease, TSS, TDS, sulfide, chloride, NO_3, NO_2, NH_3, chromium 6, priority pollutants, radioactivity	Chlorine residual (in reservoir); monitoring not required	Make process adjustments such as return rate; if problem is associated with metals, a pretreatment process is included
NV	Per the NDEP permit, the WRC monitors flow, BOD, TSS, total coliform, pH, total nitrogen as N, nitrate +	Total and free chlorine, TDS, and pH are monitored continuously at our reservoir (monitoring not required)	For disinfectant: adjust chlorine levels to maintain 1 ppm total chlorine from the main pumping station. For TDS. being a

Utility	Parameters Determined		Remedies to Restore Out of Range Parameters
	Effluent	**Distribution System and Requirement**	
	nitrite as N, total Kjeldahl nitrogen as N, total ammonia as N; NTU and total chlorine are also monitored but not required per permit		satellite plant, bypasses influent flow during the night/early morning to avoid taking peak TDS flow
CA-2	Turbidity, pH, chlorine residual (instrumental for all three), TSS, TDS, sodium chloride, NO_3, TKN, and coliform using the fermentation tube method. For water to the ranch, also observe waste discharge requirements (WDR)	None; have measure coliforms in ponds in the past and saw no difference compared to levels in effluent, so discontinued. (Only flow monitoring required)	For turbidity: djust the coagulant (following jar testing). For pH: Add NaOH. For chlorine residual: Increase the dose as needed (e.g, to 8 ppm).
SC	BOD, TSS, NO_3, DO, pH, fecal coliform. Low coliform limit by site is 14-43, i.e., 14 monthly average and 43 daily maximum	Monitoring wells (three courses have 29 monitoring wells) every 6 months to depth of water table, conductivity, pH, total P, NH_3, chloride, NO_3, alkalinity. Yes, monitoring required semi-annually as per permit	No limit specified. Isolated incident in the past at one well with high nitrate (>10 mg/L)
CA-8	Nitrate, electrical conductivity, BOD, TSS, Na, K	Flow; monitoring not required	Discharger controls
CA-10	Turbidity (0 to 2 NTU) and chlorine residual (5 to 20 ppm).	No; monitoring not required	Coliform/*E. coli*: Shut plant down and drain reclaimed water chlorine contact channel back to Wastewater Treatment Plant then restart the plant, and increase chlorine feed while taking grab samples to check on chlorine feed. Turbidity: keep filter system operating and diverting filter effluent back to the plant until chemical and flow adjustments are made to bring turbidity back into range.
CA-18	Coliform, enterococci, turbidity, BOD, pH, TDS, chlorine, boron, TON, and EPA screen, i.e., pesticides, VOC, metals, disthylate, hexavalent chromium, NDMA, UV transmittance, UV dose, methyl blue active substance, total hardiness, total P. Mostly quarterly but some are semi-annual	Not directly, but have 10 groundwater monitoring wells for total coliform, fecal coliform, pH, enterococci, MBAS, nitrate, NH3-N, NO2-N, organic nitrogen, TDS, boron, sulfate, BOD, pesticides, and metals quarterly; have data for 10 years; monitoring of DS is not required	Measures to restore (basically modifying plant process) only taken if BOD, DO, all four types of nitrogen, sulfate, and coliforms are out of range
CA-3	Chlorine (CT), (see WQ table on Web site)	None. Once it leaves the plant; it has met Title 22 monitoring not required	Troubleshoot (i.e., assess process control)

Appendix F

Table F.1. Practices to Control Cross-Connection and Manage Flushing

Utility	Cross-Connection Control	Flushing
CO-1	(1) Onsite inspections annually; (2) Don't allow potable water running/flowing through reclaimed water nearby; (3) All sites have backup potable water; (4) Backflow preventers required when using potable water	Water is continuously flowing
WA-4	(1) Cross-connection control plan requires double valve at any site with reclaimed water; (2) use of purple pipe minimizes connection potable with reclaimed water	Not flushed except by draining (blowing out water) over winter to avoid over-freezing
AZ-2	(1) Maintain separation distances; (2) maintain separate trenches: (3) purple pipe and signage: (4) testing (pressure) when fill system	No
CA-1	(1) Annual inspection (urban areas); (2) require having pressure reducing valve on potable system (checked annually); (3) Annual cross-connection test (for dual system owners)	No (unless disposing reclaimed water back to sewer)
FL-11	Under permit requirements, actively evaluate sites for cross-connection by monitoring specific conductivity (reclaimed water has specific conductivity that is distinctively different from potable water)	No
FL-1	(1) All users have a state-required backflow prevention system; (2) full-time cross-connection inspector; (3) periodically use consultants to test all parts which might be affected	No, except for new mains flushed to get 3 ft or higher
CA-5	(1) Conduct random and annual inspections; (2) conduct quadrennial pressure tests; (3) each potable service has a backflow to limit any contamination to the one site; (4) customers have to go through plan review where the purveyor and DEH have to review physically inspect; (5) conduct shutdown tests	No, cannot put reclaimed water into storm drain. Can drain into the sewer.
FL-5	Goal is to inspect all connection every 2 years but all behind to approximately one-third annually	No
TX-3	(1) RW customers have double check valve to prevent backflow; (2) maintain a pressurized system; (3) meet state mandate separation of 4 in. on potable side; (4) Backflow preventers on each site with reclaimed water; (5) regular inspection of preventers by a third (independent) party every year (certification required to continue supply); (6) Purple pipe, purple sprinkler heads and signs	No (release discouraged by city and state)
CA-4	(1) Backflow preventers (2) Conduct cross connection tests	No but system has areas/users with continuous use or flow into ponds
NC	Require annual professional inspection and permit to continue using reclaimed water	Frequency is as needed depending on water quality based on SCADA; flushed into river or back into sewer; velocity is not checked
ID	(1) Backflow preventers on all connections; (2) conduct site surveys; (3) conduct annual regulated test; (4) review and approval of reclaimed water connection applications	Annually back into the sewer
FL-4	(1) Backflow preventers at user site; (2) Instilling or permitting process calls to make ensure no cross connection	No; despite having hydrants in the system
TX-2	(1) Annual inspection of each customer (dye test conducted); (2) backflow devices also tested annually; (3) for inaccessible properties (because of security systems), customer has to provide annual certified inspection report verifying cross-connection control	System designed with spots for connecting reclaimed to sewer to facilitate flushing. spots have air relief valves in some parts and provide a physical connection to the sewer
VA	Not applicable	Not applicable
AZ-8	(1) Have a gap between reclaimed water supply system and drinking water system; (2) backflow preventer	One flushing station but not used as the systems is scoured

Utility	Cross-Connection Control	Flushing
	in chlorine	with chlorine
CO-5	(1) Backflow preventers at the community park near the playground with a holding pond to collect; (2) distance separations; (3) backflow preventers annually inspected before supplying reclaimed water	No
CA-14	(1) Have leak detection; (2) annual user inspection; (3) annual shutdown test	No
NV	Each customer must have a cross-connection control survey conducted on their property annually. Survey conducted by a certified cross-connection control company.	No
CA-2	Purple pipe system with no cross-connection; setup dedicated lines for wastewater facility for process water which reduces contact with potable water through air gap	No
SC	All lines on GIS for both potable and RW, so clearly know where they are with no possibility of cross-connection	No
CA-8	Purple pipe distinction	No
CA-10	(1) Air gaps and backflow devices; (2) reclaimed water systems is totally separate; (3) conduct surveys every year to physically check for cross-connection	No
CA-18	Annual cross-connection control program run by county	Automatic through irrigation (every night); also discharge to replenish groundwater
CA-3	(1) Cross-connection test conducted before approval. If any changes are made, application resubmitted; (2) have four years of dual appliance; only one cross-connection control a year	No flushing as cannot discharge reclaimed water

Appendix G

Table G.1. Strategic Planning by Reclaimed Water Utilities

Utility	Infrastructural Growth	Technological Investments
CO-1	Not planning of growing at this time	Have SCADA, open/close user sites from plant, monitor water level from/into the pond, lab with LIMS data reported back remotely, written SOPs (Lab and operations)
WA-4	Yes, driven by budget to do different projects; city handles growth as production of RW is part of a comprehensive plan to reduce use of potable water (supported through engineering)	Under sewer treatment budget with SCADA on the production side. Customers have the irrigation system (Maxcom)
AZ-2	Do a lot planning, e.g., where to recharge reuse, who gets to reuse; lots of changes because of stage of growth; making changes to places where it is needed and finding the money to do it; no recharge if groundwater is shallow; only deeper groundwater; town council, town manager, and engineer involved	No SCADA system and not yet invested. Only present in the potable water system.
CA-1	Yes, water supply section	Have good SCADA system, which gives real-time monitoring for discharge to changes. Computerized lab system.
FL-11	Continuously looking to future for meeting demand; currently, only water contracts obligated and increasing customer base requires increasing wastewater; looking at strategically meeting permit criteria and conducting long-term budget planning	Have active SCADA system and GIS. Lab is up-to-date on LIMS system. Our weakest area is written SOPs.
FL-1	Yes, master utility plan for each utility system, capital improvement program (5–10 years)	SCADA distribution control. Data acquisition and control system. Lab has LIMS system and SOPs
CA-5	Yes, a Recycled Water Master Plan is required by city council every 5 years to maximize reuse; also, recently completed reclaimed water to look at reducing flow of water into the ocean, i.e., a long-range water resources plan (sent link about this)	Constantly upgrading SCADA system to make sure we have the latest technology available for all staff. Do have a water purification demonstration project, an indirectly potable reuse 1 MGD which directly supplies the reclaimed water distribution system. It has been active for 1 year
FL-5	City has strategic initiative but not focused on reclaimed water; aimed at groundwater recharge. Recharge capability governs the strategic planning; main strategy is to use groundwater recharge	Have SCADA for operation and data, LIM system for lab; software available to detect pressure issues
TX-3	Master plan to handle growth	Investing in automatic pumping system to minimize manpower requirements. SCADA on potable side and we have the same aspiration for reclaimed water system
CA-4	Feasibility study for capital equipment	Have a SCADA system since day one; helps out as it is the main eyes for the system
NC	Yes. Follow AWWA's effective utility management with list of tenets and	SCADA and SOPs

Utility	Infrastructural Growth	Technological Investments
	elements of planning vision, strategic vision to cost–benefit analysis. New lines go in for everybody's benefit to reduce load on potable water	
ID	Yes, know what system can do only targeting commercial and large winter users along our corridor	Invest in treatment prediction and reuse is part of facility; cost is more expensive. Have extremely hard P limitation and wastewater treatment standardization of the reclaimed water because it is hard to treat to reduce required
FL-4	Yes, tied to new housing developments	Beginning process of investing in SCADA system; it will be for the sewer side for the start but not reclaimed water system
TX-2	Yes, well invested in engineering, modeling, attorneys, and planning for future development and meeting potential customer needs	Operations investing in efficiency with no planning of expansion but rather on maintenance. Have SCADA system and the lab uses up-to-date methods
VA	Not provided	Yes, heavily [i.e., integrated SCADA, LIMS, DCS, enterprise resource planning (ERP), software asset management systems, process models, and GIS]
AZ-8	Yes, expanding system to incorporate four areas onboard with 600,000 GPD (full production); cannot fully meet golf course requirements during summer; monitor effluent quality and efficiency (headworks modification)	Small system but expanding technology to enhance process; do not go into production overnight so SCADA is not best way to go but have alarm system; operational 8 h/day, 7 days/week; try to keep operational staff/trained for technical background
CO-5	Requires lots of capital investment and therefore not actively exploring growth; if add more customers, likely to run into water rationing issues balanced against water rights	Got simple system monitored with SCADA for pond levels know how much to pump; set not to over-pump; alarms to indicated high level in the ponds; auto-pumps (on/off); lab equipment/technology typical need for *E. coli* IDEXX; turbidity measured continuously (with time stamps); continuous report whether flow or not
CA-14	Yes and have reclaimed water master plan and urban management plan	SCADA and some O&M SOPs used for facility and reservoir operations
NV	Yes, no details provided	Yes, we collect data though SCADA and have operations guidance documents for the pumping stations.
CA-2	Yes, have an integrated water master plan with reclaimed water as a component; recently adopted a policy of reclaimed water use on residential lawns for new developments and industrial parks	Facilities monitored by instrumentation, i.e., programmable logic controller (PLC), which is a base layer of SCADA and manual controls that send an alarm to alert of discrepancies
SC	No, maximum growth has been attained and no plans are in place for future growth	Have SCADA for lagoon monitoring pumps, lagoon levels so they do not overflow, start/stop pumps; have SOPs for lab to monitor water daily as required by the state
CA-8	Wastewater Treatment Master Plan, Sewer System Master Plan	SCADA control in place
CA-10	Yes, includes water supply and conservation planning as well as budgeting infrastructure growth	Reclaimed water system on SCADA; have SOPs
CA-18	Do not know as we are contract operators and do not own the system	Have SCADA and written SOPs
CA-3	Would like to have strategic plan but budget limitations do not allow that	System feeds on distribution control system (DCS) stored in data control base; have written SOPs about control shutdowns

Appendix H

Table H.1. Reclaimed Water Utilities' Customer Relations and Regulatory Compliance

Utility	Customer Relations	Regulatory Compliance
CO-1	Onsite visits and meetings	Inspections
WA-4	Have user agreements, whereby intended use is spelled out based on regulations with possibility of discontinuation/termination if misused; under those agreements, staff members are also supposed to train their customers about reclaimed water	Observed under sewer plant National Pollutions Discharge Elimination Systems (NPDES) permits
AZ-2	Planning to handle customer relations	Extensive
CA-1	Yes. If having issues with users, e.g., farmers user meetings, urban users; also in contact with park users (at Llano) and school districts	Document all runoff more than 1000 gal from the system in contact, irrigation, runoff, etc., requires notification to regulatory board; city is part of water reuse association
FL-11	In touch with customers daily	Try to keep track of ongoing regulation, especially how to meet the prospective requirement for numeric plant system in the offing
FL-1	Yes, commercial	Permit checklist every month to ensure compliance with permit requirements
CA-5	Nature of permits around visits, respond to inquiries for reclaimed water, safety, irrigation issues, use of reclaimed water in school yards, parks, etc.	Division Environmental Plan constantly updating regulatory agencies for any changes in operations, staffing and new facilities; three branches, i.e., wastewater, distribution system, and business meet frequently with regulators
FL-5	City has a conservation person and a Web site link to her to ask any questions about reclaimed water; does it for all types of water	Addressed through permit renewals
TX-3	Hands on with customers; fewer large volume customers in design and expansion not hard to control	Yes, one staff member deals with and follows regulation developments including their maintenance
CA-4	Customers are trained as they come online; have two cities and two power plants for which we are in good communication with each other, including through webcast information	Environmental compliance through engineering and staff
NC	Meet with citizen advisory councils (CACs)/subdistricts at meetings; also outreach through Web site and videos (e.g., see You-Tube about biosolids in Raleigh, NC)	Legal counsel to address issues we like (national and state government affairs committee) and stakeholders in rulemaking
ID	Relations with the Parks Department and commercial car wash	Onsite professional laboratory
FL-4	Managed as those for potable water and sewer collection	Yes, through permits
TX-2	In-house programs and through the Web site	Water quality effluent meeting permits tied to discharge permits for the plant
VA	Not provided	Not provided

Utility	Customer Relations	Regulatory Compliance
AZ-8	Have good repertoire; staff are in direct contact with internal and external customers through monthly newsletter, online, Web site, financial status updates, etc.	Have every 5 years to satisfy NPDES permits although some of the requirements are questionable; were under consent order in the past but have kept in compliance since
CO-5	City is the only customer and the needed contact with the city administration is maintained	File annual report with state; if any user problems inspection before reuse season begins, take care of deficiencies; NOVs taken care of in 30 days or less to avoid state getting involved or else supply cutoff
CA-14	Maintained strictly as for the potable (treated) water in terms of supply, usage, and application	Mainly dealing with Reuse Water Control Board (RWCB) for issuing permits and oversight; also California Department of Public Health (CDPH) provides oversight for users, cross-connection control, public health
NV	Yes (no details provided)	No
CA-2	Maintain normal day-to-day communication with the country clubs and ranch	Required to submit monthly report (e-mail) to the state; permit refers to waste discharge guidelines and specifies what needs to be done to attain them
SC	In contact with customers on a daily basis; no charge for the water and not viewed as customers but rather opportunity to get rid of effluent; reclaimed water is not viewed as a product for sale and charging money only for deep well water usage	Members of associations that deal with reclaimed water, which represents our interest; the associations are part of the South Carolina Water Quality Association
CA-8	No	No
CA-10	Yes (no details provided)	Yes, regulatory compliance issues through the Regional Water Quality Control Board (RWQCB), we have a full-time person in charge of communicating regulatory issues
CA-18	Managers have gone through the California State University program on water utility management	Part of California State University certification program
CA-3	Yes, sending notices to customers about water quality, shutdowns, etc.	Yes, complies with state and local requirements, e.g., NDMA issue and the need to avoid irrigation of locations near aquifer and potable water sources

Appendix I

Table I.1. Detailed Distribution System and Storage Problems at 25 Utilities[1]

Utility Name	Distribution System / Storage Problems Encountered		How Are They Addressed?	What are the Major Aesthetic Issues?
	Utility Perspective	Customer Perspective		
CO-1	No operational storage in the system; provide 3 days of storage to users; pump in real time.	Send survey once a year; like communication; only complaint is sometimes they cannot do certain things but they get all water they need	Talking at least once a month; e-mail regularly	Storage ponds get mossy sometimes; especially occurs in July/August (peak demand time)
WA-4	Cost of providing reclaimed water is high compared to selling price. Trying to provide people and politicians with estimate but they still believe RW can/should be cheaper	Don't like the great variations in demand, i.e., high demand in summer compared to limited supply; supply is in relation to intake, which mostly limits supply in summer	(1) Communicating with customers to reduce watering during high demand season; actively encourage conservation during drought conditions; (2) supplement with potable water at an extra cost (not always desirable by customers)	Algae growth problems sometimes; all RW goes into a nonrecreational impoundment lake (no odors), which also collects rain water
AZ-2	No problems yet because reclaimed water it goes to limited places	TDS of reclaimed water is higher (TDS is a problem in potable water too); surface water is 600, whereas for effluents it is 800; high TDS affects greens as >800 is a problem for turfgrass. TDS is 1600 at one place and could be an issue for ryegrass. Solution by one client is to blend 50:50 with reclaimed water/surface water. Bermuda grass can withstand high TDS but not ryegrass	Take note but in planning will consider blending source water with reclaimed water in the future or using RO	TDS is the main issue; another one is turbidity
CA-1	(1) Biggest operational challenge is storing lots of water in lined ponds;(2) as reclaimed water level gets low (in summer) algal growth occurs; (3) Maintaining ponds is a challenge involving mowing, maintaining levees. etc.; in spring time have to check electrical, pumping, parts, repair, etc.; (4) low pressure (system with booster to maintain pressure)	No safety concern; installed a large (24 in. diameter) main without enough customers (community garden) on the new plant side. The longer detention time led to odor issues	(1) To control odor, drained the low flow volumes into the sewer; (2) as part of outreach, conduct a users' meeting in spring to go over storage and give a summer outlook to the farmers; farmers get the reclaimed water for free (new users are beginning to be charged) and enjoy a cheap uninterrupted supply; priority (highest to lowest) is to power plant > urban users > agricultural use	(1) Odor was the only issue at dead end (resolved by allowing flow to drain into the sewer); (2) algal growth in late summer; no concern about turbidity as system uses drip irrigation
FL-11	(1) Insufficient storage during significant wet weather; (2) distribution pumping and timing changed to add more flow capacity (customized); (3) potential implementation of numeric criteria by FL requiring for example 1.4 mg N, which could cause	Not received complaints about water quality; work hand in hand with golf course managers; receive questions as to whether reclaimed water can be used in local community gardens	Considering enlarging storage lakes but space is an issue	None

Utility Name	Distribution System / Storage Problems Encountered		How Are They Addressed?	What are the Major Aesthetic Issues?
	operational challenges			
FL-1	(1) Storage not enough; (2) during peak demand (April/May) demand exceeds supply; could augmented if had additional storage capacity	Perception that reclaimed water is more corrosive	Get in touch with commercial customers to understand their issue; corrosion index done on RO vs. potable water but difference is small irrespective of the type of water; cases of corrosion in small (dia. ≤2 in.) black steel pipes were few and far between	Producing high-quality effluent without color, odor, turbidity or hardiness; has higher chloride level (chloride intolerant plants impacted with approx. 120 mg/L); however, most plants are not impacted
CA-5	(1) Some of the valves not holding during shutdowns, covered with AC pavement, too deep and covered with dirt inside the valve cans, or incorrectly located compared to as-built drawings; (2) insufficient storage capacity creating operational problems in case of plant upsets, such as high turbidity, high TDS, TSS, and low chlorine residuals; (3) Inadequate SCADA level transmitters (minor problem); (4) pumps not operating properly (minor problem); (5) Inability to supply to customers during repairs; (6) lack of pumping flexibility as currently have 600HP pumps but plan to install smaller pumps for use when demand goes down	Past customer complaints in recycled water: (1) no chlorine residual; (2) high TDS; (3) low pressure; (4) inadequate supply; (5) high chlorine smell; (6) yellowish color of recycled water	These complaints have been addressed by dealing with the specific customer at the site and by providing education and training for site supervisors; operations staff is in continuous contact with the plant staff to resolve any problems with nondelivery and plant upsets; staff from all divisions meet on weekly and monthly basis to coordinate and monitor recycled water quality, testing, and maintenances issue; operations staff implement periodic maintenance schedule of the entire system and constantly monitor storage tanks levels through SCADA system. Decrease TDS by electrodialysis, blending, or magnetizing by ionic; typical TDS is 1050–1150 but can reduce to 800–900 ppm; also concentrating using RO	The only aesthetic issues that come up from time to time are sign placement locations at some sites; customers from time to time prefer to limit the amount of recycled water signs on site; regulators require a certain number of signs, i.e., purple pipe signs, but customers may prefer toning the numbers down; also, customers see more yellowing in toilets and urinals
FL-5	Need to loop system to avoid dead ends; have pressure issues; potential; approx. 10 years ago had study done for valve actuators but not funded	Yes. Phone calls about the supply because supplies in recharge areas require people to go on reclaimed water if they live in this critical area; pressure issues from high consumption dead end lines with several low/min (supply is there but pressure is not enough)	Pressurizing the line from one end to take care of the pressure; pressure resolved by pressurizing from both ends; any connection request sent to engineer to see whether reclaimed water is available; ordering irrigation hours adjustment	Water spots on vehicles/windows from (high) TDS; the spots are carried over to cars during irrigation

Utility Name	Distribution System / Storage Problems Encountered		How Are They Addressed?	What are the Major Aesthetic Issues?
TX-3	(1) Insufficient storage is inadequate; (2) chlorination control and a lack of residual in the distribution system (rule is to have "detectable" levels in effluent and the plant aims for 2mg/L in the effluent to attain 1mg/L in the distribution system)	Lower quality assumed and no concern about turbidity, odor, or bacteria as use is mostly at night (nobody around), flushing toilets, etc.; customer concern only about outages; concern more about outage than quality	To design additional storage to follow potable water, i.e., 2000 gal/connection; not initially applied because of small number of customers; will adapt the Ten State Standards (GLUMRB, 2012) for storage, i.e., average daily use; also to look at Texas Drinking Water Standards Rule (Section 290); activate field crew to deal resolve outage; check water levels to address cause of outage	Chlorination control (minor as there are no complaints); elevated storage tank tablet system; get chlorine smell, corrosion of metal components, e.g., piping, equipment (no corrosion of tank)
CA-4	Low pressure	No	Constant communication with customers; pressure could be because of pump tripping, which sets the alarm for us to reset	Smell of irrigation water at the beginning when the site has been out of service, with stagnant water.
NC	(1) Water quality degradation; (2) different usage patterns; (3) chlorine dissipation; (4) oxidation of pipes; (5) discoloration	(1) Chillers do not get as many cycles compared to potable water owing to high conductivity of RW (e.g., with RW chillers for refrigeration give five cycles compared to seven with potable water; (2) discoloration from pipes	Flush potable water into RW near location where chillers are used as to blend, diluting the conductivity	Color, high conductivity, chlorine, and pH
ID	Not enough storage now; before that, had ponds and algal growth; because of algal growth, 1 MG at the park CT450 required 4.5 mg/L with fish dying; fishing/game concerned	Biggest issue is being dependent on the plant; if have high turbidity, the plant shuts down and is, therefore, deemed by customers as unreliable in performance	Backup source for irrigation (secondary irrigation source)	Occurrence of high total nitrogen early spring coming off winter field applications (runoff); attaining and staying within 2 NTU is a challenge sometimes
FL-4	Lack of ability to exercise hydrants as they are near the right of way, which cannot be wetted with reclaimed water, as such wetting is prohibited under discharge permit	One major user complained about debris in the system/water	Debris problem fixed by putting backflow preventers at all service line intakes	Although users are mainly not impacted, utility notices some blocked screens, which restrict flow creating high differential pressure.
TX-2	Majority of customers use reclaimed water for irrigation in summer which puts a lot of seasonal demand in summer compared to winter months	(1) Long application process before connection; process involves assessing pressure needs, quality needs, preconnection inspections, etc.; all of these are expensive and time-consuming to prospective customers but have to be done to ensure right fit; (2) interruption of service in case of line breaks or maintenance (i.e., out of service)	Try to offer advance notice of line interruptions	Degradation during long storage in tanks.; customers know not to let water sit for long but again usage is as needed all year around; usage just happens to be less in winter and likely to sit in storage for longer during that time
VA	Positive perspective	Yes, water purveyor wants more during drought and does not like diversion to consumptive non-potable reuses	Delicately as they tend to be politically driven	Managing nutrients
AZ-8	More storage is needed as when have monsoon, customers do not need much of	Perception that reclaimed water is too expensive as we wrestle with the question of how much to	Have a monthly newsletter about billing, system repairs, production,	Total N, P, cyanide production from chlorination

Utility Name	Distribution System / Storage Problems Encountered		How Are They Addressed?	What are the Major Aesthetic Issues?
	the RW; under those circumstances, utility has to come up with emergency discharge plan to river, so discharging is a lot in winter	charge. To meet class A+ standard, the water has to be treated well; an expensive process.	improvements done, and efficiency	
CO-5	Have a single system with a problem of getting elevation in ponds; programmable logic control (PLC) for pond elevation going out to extent that valves at community park are not opening or closing	Customer is City of CO-5 for use on golf courses; any complaint could be golfers not opting to reuse; surrounding home owners complain of signs and sometimes twist the signs to hide the sign's message (i.e., that reclaimed water is used); instances of people taking valves off to water their yards (vandalizing/unauthorized to use on their lawns); others complain of community park begin slow in accepting RW but eventually coming around to accepting to use it; acceptability still low	Have not been active in public education but when called to explain that it is secondary treated and disinfected twice do so; may engage them in the future, starting off with in-house employees educated to over-irrigate and showing them what is happening	Algal growth in secondary treated and storage sites. No concern about salts or pathogens. Most concern is about nutrients and algae
CA-14	Tank levels cannot supply to the lake, thus requiring pumping, which adds expense an causes problems in case of power failure	None	Getting type of pressure control, SCADA control to engineer a better control system	Color
NV	None, this system was designed to be a closed system with no storage.	(1) Occasionally we receive water quality questions from the general public on the recycled water we deliver; (2) conducts maintenance on system from time to time or experience operational issues that temporarily prevent supplying flow to customers	(1) Inform the public about the water quality and permitting requirements of the water by NDEP; the WRC produces the highest category of recycled water permitted by NDEP (Category A per NAC 445A.2762); as permitted, public access to the area of use is not controlled and human contact with the treated effluent can reasonably be expected to occur. Further annual cross-connection surveys are required by all customers to ensure separation between the potable and recycled systems; (2) we plan and schedule maintenance where the customer typically never sees an issue with delivering flow; during operational issues we work very closely with our customers to keep them informed of the issue and ultimately deliver the flow they request	None

Utility Name	Distribution System / Storage Problems Encountered		How Are They Addressed?	What are the Major Aesthetic Issues?
CA-2	Have holding basin before transferring to golf courses as required by Regional Water Quality Control Board (RWQCB), which has been very stringent on runoff of reclaimed water; reclaimed water is still regarded as WW, so a zero discharge policy/permit; no entry into storm drain is permitted, which causes a big operational issue	(1) Irrigation procedures because of runoff restrictions; (2) perception from public that it is "dirty" water; (3) odors	(1) Country club has had to redesign system to reduce aerosolized spray incidents, runoff and storage levels observed for no spillage commitments: (2) drain the ponds at end of each season so no water stays; providing fresh supplies every season reduces odor	Stagnation in distribution system creating odor; holding ponds develop algae
SC	Have a 9 Ac Ft pond for storage in winter but need more storage	Not enough water as we treat approx. 100 MG but need 300 MG.	Supplement with deep well groundwater which is higher in salts; however, customers prefer reclaimed water to the salty groundwater	Have algae in lagoons
CA-8	Storage is in 320 acres of ponds, annual reports due for application to land	Not enough water to meet full demand.	Ration delivery equally to all customers	None
CA-10	(1) Steel pipes are very corrosive and expensive; (2) need for additional storage; (3) pump station in a vault relying on pressure, which is challenging and involves a lot of work	(1) Pressure is not guaranteed (e.g., in case of a power failure) and not enough booster, which reduces reliability of the system; (2) Limited time to irrigate, which limits use to only at night to minimize contact with customers/general public	(1) Looking for additional storage; (2) switch to laminar flow noncorrosive, e.g., PVC 900 instead of steel; (3) cathodic protection of the system	Color and odor
CA-18	Unique subsurface drip irrigation system, which follows drip design specifications and monitoring	Type (cultivar) of Bermuda grass used not very good for strip irrigation—rye grass is more desirable; (2) water generated is low in N and high salt content; (3) design system needs to consider how to fertilizer with N and K	Landscape management practice of less mowing (or mowing at a higher height) recommended through the landscapers; plant has a fulltime agronomist	Color issues at end of the system. Otherwise no issues before that as system is subsurface or directly injected into groundwater aquifer
CA-3	Built for diverting flow to irrigation system and thus has a flow cap; shifted to supplementing potable water and, thus, a change in use, which requires additional storage; agricultural to industrial base changes	Complaints about (1) hard water (cooling towers); (2) high salt content; (3) pressure too high damaging sprinkler heads and nozzles; (4) Ground level settlement over 100 years due to groundwater pumping	(1) Use pressure regulator; (2) add chemicals (proprietary but generally containing sulfuric acid) to control hardness; also use of antiscaling agents and biocides; RW reduced need for GW (reduced ground level settlement)	Color, hardness, alkalinity

Notes:
[1]The highlighted text represents significant responses or cues used to develop a quantitative score in Table I.4.

Table I.2. Detailed Distribution System and Storage Problems at 25 Utilities[1]

Utility	Major Microbial Issues Experienced by System	Any Other Water Quality Issues Experienced	Remediate Strategies (and Effectiveness)	Protocol(s) Available?	Parameters Monitored	
					In the Plant Effluent	In Storage or Distribution System (Is Monitoring of Systems Required?)
CO-1	None. No regrowth in the system	None	Mossy ponds dealt with by building screens (8 ft × 8 ft box) at **the intake** (very effective)	Yes	Meeting secondary effluent (category II) requirements i.e., *E. coli*, TSS, turbidity	None (monitoring not required)
WA-4	None	No	Aeration for preventing algae. System has a diffuser (effective)	Run by different entity (customer)	Total N, coliform, turbidity, DO, CBOD, pH, chlorine residual, coagulant used	Chlorine residual at discharge end into a lake (monitoring not required)
AZ-2	One plant is new and operating at smaller volumes; have microbial issues, i.e., high microbial counts (stream discharge than Class A owing to low volume); monitor daily	Starting to see fluoride high in system because source >0.20 (that discoloration). if >4.0 cannot serve it but this comes to WW, it increases (WW is not allowed to exceed 4.0 => degrade aquifer getting close => blend; arsenic is another problem => arsenic treatment is in the source—if not treated that is reflected in the RW; unlike potable water where limit is 10 ppb, loose arsenic standard for RW	Blending (effective)	Address them as they occur	Bacteria, metals, TDS as per NPDES list	Chlorine residual, coliform (monitoring not required unless you are discharging from the plant)
CA-1	No	Snails	Yes. (1) For odor, allowed RW to drain into the sewer; (2) for algal growth, clean filters more often; (3) Snails successfully controlled by post-disinfection with sodium hypochlorite at a dose of 3 mg/L (quite effective)	No	BOD (three times/week), NFR, [pH, turbidity, TSS, coliform; daily for each], [PO_4, NH_3; three times/week for each], NO_3, priority pollutants (i.e, VOC, EPA-priority pollutants; quarterly), metals (quarterly)	No monitoring in the DS unless there is an issue; only time monitored is when we discharge but does not include discharging into the geyser but rather into receiving water; monitor DATASON (i.e., DO, pH, temp, EC) every 15 min (using SCADA); no monitoring required except where/when discharging

Utility	Major Microbial Issues Experienced by System	Any Other Water Quality Issues Experienced	Remediate Strategies (and Effectiveness)	Protocol(s) Available?	Parameters Monitored	
					In the Plant Effluent	In Storage or Distribution System (Is Monitoring of Systems Required?)
FL-11	RW system has been in effect since 1986; no microbial issues throughout that period	System of RW flowing to lakes has been invaded by turtles and catfish (invasive species), which can obstruct the flow through strainers and meters.	Completely redesigning our pumping system to increase efficiency; a very direct engagement with customers, which limits the number of people because we deal with commercial customers (effective).	Yes	N, P, TSS, turbidity, NO3, fecal coliform, *Giardia*, *Cryptosporidium*	Measure WQ parameters in on- and offsite lakes; monitoring not required, but required to monitor groundwater
FL-1	None. Coupon studies showed no evidence of bacterial growth even if no chlorine residual because completely nitrify/denitrify and decrease P levels; no bacterial growth	Meets primary and secondary drinking water standards and decreased *Giardia* sp./*Cryptosporidium* sp.	Live with chloride issue consider alternative measure of disinfection because of saving pool, laundry, swim parks, dishwashers; think of UV as alternative; considering treatment plant UV but expensive; no regulatory drivers		BOD, suspended solids, TN, TP, pH, chlorine residual, and fecal coliforms continuously or four times/week. Also approx. 40 other constituents as part of FL requirements	None (monitoring not required)
CA-5	Low free chlorine residuals between plant (City of Potay) and the tank, i.e., the ability to maintain a significant total and free chlorine residual in the Scripps Ranch-Poway branch of the North City distribution system	None that the city is aware of	Site supervisor classes for staff and new employees and education program continues to grow		The Water Quality Laboratory (WQL) monitors North City effluent weekly for total and fecal coliform, pH, total and free chlorine residual, temperature and total dissolved solids; others include a whole range of nutrient, metals, and organic compounds (provided an extensive list)	The Water Quality Laboratory (WQL) monitors seven North City distribution sites for total and fecal coliform, pH, total and free chlorine residual, temperature, total suspended solids, total dissolved solids, ammonia (as N), nitrate, and nitrite. three distribution sites and the two storage tanks (Meanly Dr. and Poway) are monitored weekly; two other distribution sites are monitored monthly; the two storage tanks and a distribution site located between them are also monitored weekly for HPC (heterotrophic plate count) bacteria; monitoring not

Utility	Major Microbial Issues Experienced by System	Any Other Water Quality Issues Experienced	Remediate Strategies (and Effectiveness)	Protocol(s) Available?	Parameters Monitored	
					In the Plant Effluent	In Storage or Distribution System (Is Monitoring of Systems Required?)
						required
FL-5	No. Effluent test for *Giardia/Crypto*; get some hits but within compliance for fecal coliform (tested four times/week)	No	Protocols to pressurize the system at both ends when possible to deal with pressure issue (very effective)	Provided (e-mailed after interview)	FC, TSS, TRC (i.e., residual chlorine), turbidity, pH, total P, NO_3, NO_2, NH_3, TKN (continuously or weekly). Also metals (monthly) and priority pollutants (annually)	None (monitoring not required)
TX-3	None	No	Building a ground storage tank. To control chlorination; changing by adding a mixer in the tank; flow-based but not continuous; will change to continuous chlorine feed + mixing in tank; expected to work	Addition of a mixer with consultation of process engineering and operators	Chlorine (requirement for detectable levels; no specific concentration); turbidity of <3 NTU; FC requirement	Have online residual monitoring at elevated storage tank but not reported and/or deliberately monitored/checked; monitoring suggested but not required
CA-4	None. Random testing in system	Soil sampling for TDS but not a problem; cooling towers TDS range is 800ppm but recirculate fewer cycles	Ongoing study to provide additional treatment to reduce TDS (e.g., RO, blending; ongoing study)	Not yet	DO, coliform, NTU, chlorine residual (8 mg/L leaving plant and approx. 2 mg/L, at end of the system), flow rate, priority pollutants (twice a year), NH3, nitrate, and nitrogen	Periodically randomly test for coliforms and residual in the DS (monitoring not required)

Utility	Major Microbial Issues Experienced by System	Any Other Water Quality Issues Experienced	Remediate Strategies (and Effectiveness)	Protocol(s) Available?	Parameters Monitored	
					In the Plant Effluent	In Storage or Distribution System (Is Monitoring of Systems Required?)
NC	None at the moment; no extensive monitoring of microbial as water is for urban uses; state has introduced tiers for food-related applications: Tier 2 (the highest quality) has to meet certain coliphage, *E. coli* and clostridium standards; our product is probably Tier 2 but not regularly tested as we are non-agricultural	Snails in the treatment process	Chlorination controlled snails when adapted dual barrier disinfection (very effective)	Yes	BOD, pH, TSS, NH_3, fecal coliform	Chlorine, turbidity, pH conductivity (through SCADA); monitoring is part of the permit specifications; records kept but are not required to submit
ID	Have had one total coliform exceedence for entire time	None	Continuously monitoring chlorine residual; if <2 ppm automatically adds chlorine to tank. Chlorine added downstream of analyzer (where you add chlorine is a big deal); keep storage tank mixing; 800 GPM pump constantly mixing rate for entire content of 0.5 MG storage tank (effective)	Not sure	A lot of parameters i.e., BOD, TSS, TN, NH3, NO3, NO2, TP, pH, TDS, total coliform, *E. coli*, turbidity, transmittance	None (monitoring not required)
FL-4	None; have high chlorine residuals (6 ppm), which controls microbes	No	Periodically clear the screens as part of maintenance (effective)	Yes	Turbidity, pH, chlorine residual, TSS, coliform	Chlorine residual, TSS at screens/filters; monitoring not required
TX-2	Algal growth if stored for long	No	Turnover quickly from ponds (effective)	Yes	BOD (regulatory standard is 5 mg/L but we aim at 2 mg/L), turbidity (reg requirement is 3 NTU; we attain <1 NTU), fecal coliform (reg is <20; we attain <2/100mL), TDS, TSS, sodium adsorption ratio (SAR), residual chlorine, sodium carbonate, pH	Chlorine residual (aim at 1 mg/L by feeding approx. 50 lb/day to entire system); monitoring not required; done because of self-imposed needs

Utility	Major Microbial Issues Experienced by System	Any Other Water Quality Issues Experienced	Remediate Strategies (and Effectiveness)	Protocol(s) Available?	Parameters Monitored	
					In the Plant Effluent	In Storage or Distribution System (Is Monitoring of Systems Required?)
VA	Yes	Very	If desired; rather complex		(1) Industrial users via pretreatment program permits; (2) product water via NPDES permit; (3) stormwater discharge permit; (4) general permit to meet Chesapeake Bay nutrient management standards; (5) EPA 503 Program for biosolids; (6) SDWA at water reclamation plant and potable water plant; (7) plant process control monitoring	(1) EDCs and PPCPs on reuse product water and potable water; (2) comprehensive watershed and reservoir monitoring program
AZ-8	Not a lot when chlorination system is working properly; no *Giardia* or *Cryptosporidium* detected	Occurrence of midge flies especially in filters	Midge flies controlled/treated with chemicals (quite effective, as flies are sterilized)	Yes	All under the permit to prevent degradation of stream; include NO_3, NO_2, NH_3-N, coliforms, *E. coli*	Golf course blends with groundwater to irrigate; monitor groundwater wells for N, P, heavy metals, runoff from golf courses (compare samples from upstream with those from downstream); monitoring DS is not required
CO-5	None for what we monitor	(1) Filter accumulates filter flies; we get some snails in WW plant but they are not problematic; snails => not concerned; (2) algae are treated by subcontractor with CuSO4 or some noncopper algaecide	Provide another storage pond for additional storage (effective)		*E coli*, nutrients, such as inorganic N, to calculate N-loading on the fields; also SAR, P	None (monitoring not required; tested or *E. coli* on holding ponds in past and densities were comparable to those in effluent)
CA-14	No	No	Fast consumption (mixed results)	Not applicable	Under Title 22, monitor for chlorine residual, total and fecal coliform, inorganics (as by permit) oil and grease, TSS, TDS, sulfide, chloride, NO_3, NO_2, NH_3, chromium 6, priority pollutants, and radioactivity	Chlorine residual (in reservoir); monitoring not required

Utility	Major Microbial Issues Experienced by System	Any Other Water Quality Issues Experienced	Remediate Strategies (and Effectiveness)	Protocol(s) Available?	Parameters Monitored	
					In the Plant Effluent	In Storage or Distribution System (Is Monitoring of Systems Required?)
NV	None	None	Not applicable	Not applicable	Per the NDEP permit, the WRC monitors flow, BOD, TSS, total coliform, pH, total nitrogen as N, nitrate + nitrite as N, total Kjeldahl nitrogen as N, total ammonia as N are monitored. NTU and total chlorine are also monitored but not required per permit	Total and free chlorine, TDS, and pH are monitored continuously at our reservoir; monitoring not required
CA-2	None	Surface weed (duckweed) and water fern (azolla)	Fountains to mix water, pump to recirculate keeps odor down. Also herbicides to control duckweed and azolla. The irrigation system intake is several feet below the surface to avoid algae and weeds, which mostly float on surface (very effective).	No formal (written) protocols available, as mostly use historical knowledge	Turbidity, pH, chlorine residual (instrumental for all three), TSS, TDS, sodium chloride, NO_3, TKN, and coliform using the fermentation tube method; for water to the ranch, also observe waste discharge requirements (WDR)	None (have measure coliforms in ponds in the past and saw no difference compared to levels in effluent; so discontinued); only flow monitoring required
SC	No	None	Golf courses hire company to eradicate algae using chemicals (effective)	Golf course’s responsibility	BOD, TSS, NO_3, DO, pH, fecal coliform. Low coliform limit by site is 14-43, i.e., 14 monthly average and 43 daily maximum	Monitoring wells (three courses have 29 monitoring wells) every 6 months to depth of water table, conductivity, pH, total P, NH3, chloride, NO3, alkalinity; yes, monitoring required semi-annually as per permit
CA-8	Undisinfected	No.	Not applicable		Nitrate, electrical conductivity, BOD, TSS, Na, K	Flow (Monitoring not required)
CA-10	Bacteria counts can increase with improper or complete backwashes of filter media	None	Proper backwashing (effective)	No	Turbidity (0 to 2 NTU) and Chlorine residual (5–20 ppm).	No; monitoring not required

Utility	Major Microbial Issues Experienced by System	Any Other Water Quality Issues Experienced	Remediate Strategies (and Effectiveness)	Protocol(s) Available?	Parameters Monitored: In the Plant Effluent	Parameters Monitored: In Storage or Distribution System (Is Monitoring of Systems Required?)
CA-18	Test for coliforms weekly at furthest point; no hits of more than 2.2. fcu/100mL	Stagnant water breeding mosquitoes	Yes. Provided three ponds to absorb standing water (very effective)	Yes, can share	Coliform, enterococci, turbidity, BOD, pH, TDS, chlorine, boron, TON, and EPA screen, i.e., pesticides, VOC, metals, disthylate, hexavalent chromium, NDMA, UV transmittance, UV dose, methyl blue active substance, total hardiness, total P; mostly quarterly but some are semi-annual	Not directly but have 10 groundwater monitoring wells for total coliform, fecal coliform, pH, enterococci, MBAS, nitrate, NH3-N, NO2-N, organic nitrogen, TDS, boron, sulfate, BOD, pesticides, and metals quarterly; have data for 10 years; monitoring of DS not required
CA-3	(1) Regrowth of bacteria; (2) occasionally have slime	None	Use line to rid of redundancy (effective). Problem is in winter when flows are low.	Yes, have a resourceful Web site	Chlorine (CT), (see WQ table on Web site)	None. Once it leaves the plant, it has met Title 22; monitoring not required

Notes:
[1]The highlighted text represents significant responses or cues used to develop a quantitative score in Table I.4.

Table I.3. Detailed Distribution System and Storage Problems at 25 Utilities[1]

Utility	Flushing Frequency	Flushed Water Handling (and Flushing Details)	Flushing Protocol (Frequency, Velocity, etc.)	Promoting Turnover in Reservoir	Reservoir Cleaning Frequency	Cleaning Practice and Method
CO-1	No. Continuously flowing	Not applicable	Not applicable	Intake is on opposite side from outlet	Done as needed (only once when maintenance was needed)	Not applicable
WA-4	Not flushed except by draining (blowing out water) over winter to avoid over-freezing	Not applicable	Not applicable	Not promoted	Never	Not applicable
AZ-2	No flushing program (will have more with more hydraulics); flush by using	Not applicable	Not applicable	(1) Used within few days, thus, rapid turnover; (2) no plant storage but users have storage	Not applicable	Not applicable
CA-1	No formal flushing program; rather a disposal practice	Back to sewer supply	Not applicable	Stored in spring; used up in summer; thus maintain an annual empty out by end of irrigation season	Ponds are never cleaned; sump pumps are cleaned every 2 years; other (e.g., geyser) are by inspection	Yes, use tractor and truck to vacuum the silt (geyser) or tractor to scoop up the silt
FL-11	No	Not applicable	Not applicable	Lakes designed specifically for RW storage in sequential order with level of linear flow	Open surface water lakes are cleaned with vegetation management plan (i.e., removal of vegetation)	As needed by mechanically removing the vegetation
FL-1	No	Not applicable	Flush new mains to get 3 ft/s or higher	1.5 days storage at the most (rapid turnover)	Inspected every 3–4 years; not had any cause for cleaning; divers or robotic camera used	Not applicable
CA-5	No, as cannot put RW into storm drain; if >50,000 gal, have to drain into sewer than storm drain, which goes to the bay and ocean	Not applicable	Not applicable	Manage what volumes are treated	Annually	Yes, a set of standards and procedures are in place for cleaning tanks and reservoirs with dive teams; jetting and scraping silt/solids
FL-5	No	Not applicable	Not applicable	Series of 7 ponds with pump in one pond to a single tank. Ponds are shallow and get into pattern late fall and late summer drain wetland because of high demand.	Never cleaned; had prices on inspection but not done at the tank	No
TX-3	No flushing program on purpose. State and city discourage release of RW	Not applicable	Not applicable	Pump starts and stops; run until tanks are full or stop when full, so based on elevation in tanks	Biannual (same people who maintain potable system tanks manage our storage cleaning)	Potable water protocol is used; cleaning is by spraying down

Utility	Flushing Frequency	Flushed Water Handling (and Flushing Details)	Flushing Protocol (Frequency, Velocity, etc.)	Promoting Turnover in Reservoir	Reservoir Cleaning Frequency	Cleaning Practice and Method
					too	
CA-4	No formal program, but irrigation users have large reservoirs that ensure continuous use/flow	Not applicable	Not applicable	Continuous use	Tank cleaned every 5 years; at one of the golf courses, a new reservoir (just a year) with continuous mixing (by design); the other golf course tank is cleaned once every 3 years	Yes, by vacuuming out (work done by a contractor)
NC	Frequency is as needed depending on water quality based on SCADA	Into river or back into reuse system	Duration depends on the numbers and velocity is not checked	Rule of thumb is 2 days in smaller tank and 3 days in large tank; reduce the pump levels to stay within these levels	Once every 7 years	Contractor uses scraping, possibly combined with chemicals
ID	Annually	Back to sewer	Yes (no details provided)	Pump mixing, which turns the water; drained every winter and cleaned	Every winter	Drained back to plant and hosed with potable water
FL-4	No, despite having hydrants in the system	Not applicable	Not applicable	No deliberate turnover promotion	As needed	Yes, using jetting
TX-2	There are spots in the system for connecting reclaimed to sewer to facilitate flushing; spots have air relief valves in some parts and provide physical connection to the sewer	Into sewer	None provided	Through operational adjustments: in summer we fill up reservoirs at a higher elevation; in winter the floats are set lower	Every 5 years	Yes, through contractors whose divers vacuum out sediments and inspect spots for integrity
VA	Not applicable	Not applicable	Not applicable, as there is no distribution system; however, the reservoir flushes with large runoff events	Drinking water reservoir provides some longitudinal mixing along normal plug flow path; less mixing occurs in summer during thermal stratification and low flows; more significant mixing and flushing during high flow meteorologically induced events	Never been dredged	No

Utility	Flushing Frequency	Flushed Water Handling (and Flushing Details)	Flushing Protocol (Frequency, Velocity, etc.)	Promoting Turnover in Reservoir	Reservoir Cleaning Frequency	Cleaning Practice and Method
AZ-8	One flushing station but no need as scoured with chlorine	Recovered and sent back to the plant	Not applicable	(1) Golf course maintain levels by pulling water from the bottom; (2) golf course has two ponds that are interconnected; move water from one to the other	Onsite reservoir is cleaned once every 2 years by draining the water; golf course clay-lined reservoir has not been cleaned in 15 years (had sediments before then)	Divert water to equilibration tank by pumping down; cleaning is by high-pressure water washing
CO-5	No	Not applicable	Not applicable	Intake is at bottom of reservoir so turning over; one pond has aerators but some may have stagnation	Very frequently; reservoir at the community park modified liner and cleaned in 2006; have holding pond cleaned out 2 years ago	Yes, by drying out and shoveling the sediments
CA-14	No flushing	Not applicable	Not applicable	Level controls are set lower in winter and set higher in summer; winter reservoir is approximately 3 days' worth, whereas winter consumption is approx.1 day's worth	Every 2 years	Same as potable system by jetting and scraping
NV	None	None	None	Has 1–2 MG reservoir from which all customer demand is supplied; winter average daily demand is approximately 2.8 MGD; water is rapidly used, i.e., have a "pass through" system from plant through to the customers' ponds	As needed; divers have inspected the reservoir and found very little silt accumulation	Yes, divers vacuum reservoir floor.
CA-2	No	Not applicable	Not applicable	Produced as needed and sent out right away	Equilibration basin cleaned at end of the season (Oct 15) and again at the beginning of the season (April 15); natural lake at the country clubs are not cleaned	Empty out to second pond and then fire hosing
SC	No	Not applicable	Not applicable	Just from demand–supply	Never	Not applicable
CA-8	Not applicable	Not applicable	Not applicable	Natural only	Not applicable	Not applicable
CA-10	No	Not applicable	Not applicable	Not applicable (no reservoir)	Not applicable	Not applicable

Utility	Flushing Frequency	Flushed Water Handling (and Flushing Details)	Flushing Protocol (Frequency, Velocity, etc.)	Promoting Turnover in Reservoir	Reservoir Cleaning Frequency	Cleaning Practice and Method
CA-18	Flushing is automatic when irrigating every night	Discharged to replenish groundwater supply	No (not applicable)	Continuous discharge through irrigation and groundwater recharge	Annually	SOP for superchlorination (thus chemical treatment)
CA-3	No flushing as cannot discharge reclaimed water	Not applicable	Not applicable	Try to use as much as reservoir has in a day; fill cycle/drain cycle on daily basis	2–3 years	Yes, by vacuuming

Notes:
[1]The highlighted text represents significant responses or cues used to develop a quantitative score in Table I.4.

Table I.4. Detailed Distribution System and Storage Problems at 25 Utilities[1]

Utility	Does your facility have any specific BMPs you would be willing to share with us for this study?	Have you identified any specific BMPS that you would like to have at your facility?	What would be the best way for you to access BMPs that you are looking for?	Interested in site visit and willingness to provide samples from the distribution system?	Cumulative points from Tables 1–4 (Site visits to the highest 10)
CO-1	Yes, the reclaimed water state regulations	No	Talking to others such as state reuse coordinator and calling other peers	Yes, with authorization from supervisors as CO-1 aspires to be "the best in industry"	1+1+1+0=3
WA-4	None	System construction should have solid set of specifications (e.g., lessons from places, such as CA, where reclamation has gone on for longer time)	Electronic	Yes	3+1+0+1=4
AZ-2	Do not have, but if had, would be willing to share; each system has permit, operators measured for boosters; tend to operate RW as if it was a potable system; have BMPs but not written to control cross contamination	Would if get access, especially as system expands; fairly new system with few users, although that is going to change	Internet, e-mail (electronic)	Yes. welcome to visit especially when we expand the system	2+3+1+0=6
CA-1	Yes. SOPs for doing things such as (1) discharge control overview, (2) pump station overview, (3) on-farm station overview, (4) sampling info SOPs, (5) SOPs for handling sodium hypochlorite, (6) what to do with contaminated plant effluents,i.e., those that do not meet standards, (7) chemical spill, (8) confined space access	No	Electronic	Yes	3+2+2+1=8
FL-11	No specifically written BMPs but managing surface lakes and managing customers are good BMPs we practice	Education of the public (ours is engaged but we are curious what others are doing)	Presentation WateReuse conference and through the webinar	Tentatively yes but that will depend on what parameters you are to be determined.	0+1+3+2=6
FL-1	Chlorine levels approx. × 10 compared to potable water => determining source using digital test strips to test in the field to determine whether RW of potable water (approx. 10–15mh/L range HACH, e.g., to look for leaks	No	Attend workshop and seminar on RW and related issues	Probably okay if remains anonymous	2+2+2+1=7
CA-5	Yes, stormwater BMP provided	ISO program called Water Treatment Division Environmental Plan	Best is hard copy (binders); online is okay too	Out of purview but can collaborate	2+0+1+1=4
FL-5	Provided a customized BMPs for pressurizing system at both ends	Maintenance system, e.g., flushing, looking for WQ problems (what to look for: system turnover and chlorine dissipation)	Electronic	Yes and are looking forward to the report from this study	3+1+1+2=7

Utility	Does your facility have any specific BMPs you would be willing to share with us for this study?	Have you identified any specific BMPS that you would like to have at your facility?	What would be the best way for you to access BMPs that you are looking for?	Interested in site visit and willingness to provide samples from the distribution system?	Cumulative points from Tables 1–4 (Site visits to the highest 10)
TX-3	(1) Tanks turnover (pump start/stop); (2) low volume storage compared in demand to minimize detention times	Future needs for distribution system monitoring (not from manufacturers' perspective)	Look at potable water quality sector as a guide, because it has been around for long and has already solved most problems (we can learn from them); we should have a lot of synergy between the two	Yes and can collect and analyze samples as you specify, collect and send or host study personnel to collect and take samples; have done so for various projects	2+1+1+2=6
CA-4	Generally permit lists the BMP and we provide a report every 4 years; more frequent are the inspections	No	E-mail/Electronic	Possibly (subject to discussions with Engineering)	2+2+0+0=4
NC	Yes, snails remediation	Pipeline understanding potable and nonpotable and what they can do to educate employees about cross connection and about the product	Factsheets or brochures (in as few words as you can) that refer to technical manual	Okay, as long as results are anonymous	2+2+1+3=8
ID	No	No	AWWA; network system plugged in with other cities in the Pacific Northwest	Yes	2+0+2+0=4
FL-4	No	Currently have 5–9 customers (golf courses); as system becomes more integral to city and we get residential customers, issues of spills and leaks will be inevitable and central to our system management challenges	Online	Possibly	4+2+0+1=7
TX-2	Cross connection control program	Have one main type of customer (irrigation); if we could find more lines of customers would be good to address unused capacity in fall through spring	Personal e-mail/Internet	Yes	0+1+1+2=3
VA	Have many strategies developed over the last 3–4 decades of operation. I am willing to discuss what might be of interest for this study	Those identified as having merit have most likely been put in place; one recently surfaced is how to manage revisions/modifications with regard to documenting them for operations, maintenance, and design reason	Via freely available online resources from a reliable and trusted source that are published on the Worldwide Web/Internet	Not applicable, as there is no reclaimed water distribution system	1+0+0+0=1
AZ-8	(1) Chemical treatment of midge flies; (2) try to ensure quality and talent to maintain as workforce ages by bringing in people who are interested (not written but practiced)	Security for infrastructure and equipment; working on more training for people and outsourcing to other service entities	Internet; also conferences by AWWA and AWQC	Yes	2+3+5+2=12

Utility	Does your facility have any specific BMPs you would be willing to share with us for this study?	Have you identified any specific BMPS that you would like to have at your facility?	What would be the best way for you to access BMPs that you are looking for?	Interested in site visit and willingness to provide samples from the distribution system?	Cumulative points from Tables 1–4 (Site visits to the highest 10)
CO-5	No	Need more public outreach for use of reuse e.g., annual basis	E-mail; have shared information with others about inspection	Yes, and have worked on similar requests from the University of Colorado without a problem; have to minimize staff's' time used to collect samples though	3+1+2+1=7
CA-14	No	No	Look at other agencies in the county (call them)	Yes	0+1+2+0=3
NV	No	No	E-mail, official document; online	No	0+1+0+0=1
CA-2	(1) Joint operations plan (provided); (2) Maintaining high (8 ppm) chlorine residual in the distribution system	No	Publications by WateReuse or WEF	Yes as it is a public agency; can also see other RW systems nearby once in the area (e.g., El Dorado Irrigation District, and City of Roseville)	4+2+2+1=9
SC	None	No	E-mail/Internet	Yes	2+2+0+0=4
CA-8	No.	No, driven by recurring problems	Use of a consultant	Yes	2+0+0+0=2
CA-10	No	No	Online	Not sure	4+1+0+0=5
CA-18	Yes; relate to O&M for subsurface drip irrigation	Monitor TOC, provide fertilization for site and additives to reclaimed water to enhance plant nutrient needs and prevent compacting of the turf	Publish a book on BMPs	Yes	4+2+3+2=11
CA-3	(1) Plants tolerant to high salts; (2) No over-irrigation by following our guidelines detailed on the Web site	Industrial use, e.g., cooling tower application	E-mail/Internet	Yes	3+2+0+2=7

Notes:
[1]The highlighted text represents significant responses or cues used to develop a quantitative score.

Appendix J

Table J.1. Specific Management Practices Presented by 25 Utilities Interviewed

BMP Code*	Utility	Problem or Issue Identified	Category	Solution from Utilities	Solution from Literature
A	FL-11	Lack of storage, especially during wet weather	Infrastructure	Considering enlarging lakes but space is an issue	Link production to consumption using decision support system (DSS) software to optimize pumping, transmission and storage (Joksimoric et al., 2008);
	FL-1	Lack of storage; demand exceeds supply	Infrastructure		
	TX-3	Lack of storage	Infrastructure	Will adapt the Ten State Standards (GLUMRB, 2012) for storage	
	WA-4	System construction specifications	Infrastructure	Use lessons learnt from long-term users, e.g., in CA	
B	CA-10	Steel pipes are very corrosive and expensive	Infrastructure/water quality	Switch to laminar flow noncorrosive, e.g. PVC 900 and cathodic protection of the system	Corrosion monitoring (waterandwastetesting.com); use of less corrosive chloramine versus chlorine; minimize sulfide-formation (Miller and Mancl, 1997); use anticorrosion agents
C	AZ-8	Customer perceptions	Customer	Monthly newsletter about billing, system repairs, production, improvements done, and efficiency	Customer training and awareness of reclaimed water benefits and shortfalls
	CO-5	Customer perceptions	Customer		
	CA-2	Customer perceptions	Customer		
	FL-11	Public outreach/education	Customer	Civic engagement	
D	AZ-2	TDS	Water quality/operation	Blending with surface water	Modeling mass balance of TDS using Water Quality Analyst model; minimizing “salt pickup”; use of reverse osmosis (RO); adapting KCl-based softeners or portable exchanger softener
	CA-5	TDS	Operation	Decrease TDS by electrodialysis, blending, or magnetizing by ionic	
	NV	High TDS	Operation	Satellite plant bypasses influent flow during the night/early morning to avoid picking peak TDS flow	
	NC	Chillers do not get as many cycles compared to potable water because of high conductivity (TDS) of reclaimed water	Operation	Flush potable water into reclaimed water near location where chillers are used as to blend, diluting the conductivity	
	CA-3	Hard water (cooling towers	Operation/water quality	Add chemicals (proprietary but generally containing sulfuric acid) to control hardness	
E	WA-4	Algae	Operation	Aeration	Commercial mixed use of reservoirs, e.g., with floating solar panels, tapping algae for biofuel production (water-energy nexus);
	CO-5	Algae	Water quality	Algae are treated with CuSO4 or some noncopper algaecide	

BMP Code*	Utility	Problem or Issue Identified	Category	Solution from Utilities	Solution from Literature
	TX-2	Algae	Water quality	Turnover quickly	low nutrients (especially N and P); filtration (80–100 µ); ultrasonication, dissolved air floatation (DAF), ozoflotation (Benoufella et al., 1994).
	CA-1	Algae	Operation	Cleaned filters more often	
	CA-2	Algae	Operation	Pump to recirculate water	
	CO-1	"Mossy" storage ponds	Water quality	Screens (8 ft × 8 ft box) at the intake	
F	CA-1	Snails	Water quality	Snails successfully controlled by post-disinfection with sodium hypochlorite at a dose of 3 mg/L	
	NC	Snails	Water quality	Chlorination controlled snails when adapted dual barrier disinfection	
G	AZ-8	Develop midge flies especially in filters	Water quality	Midge flies controlled/treated with chemicals (quite effective as flies are sterilized)	
H	TX-3	Regrowth of bacteria	Water quality	Redisinfection	Optimal location of disinfectant boosters using booster disinfectant design analysis (BDDA) software (Uber et al., 2003); minimizing intermittent flow patterns; aeration to keep dissolved oxygen above 5 mg/L (Rimer and Miller, 2012); reduce AOC; use multiple disinfectant barriers.
	TX-3	Distribution system monitoring	Water quality/operation	Synergy with potable water	
	CA-2	Odor	Water quality	Drain reservoirs at end of season	
	FL-4	Inability to flush	Water quality		
I	VA	Nutrients	Water quality		Avoid algaecides when algal growth is intense; adjust to ≥pH 9 to precipitate heavy metals (Ayers et al., 1994)
	CA-18	Water is low in N and high in salt	Water quality		
J	FL-11	Cross-connection control	Water quality	Monitoring specific conductivity (reclaimed water has specific conductivity that is distinctively different from potable water)	Monitor cross-connection events with three-dimensional fluorescence excitation-emission matrices (EEM) (Hambly et al., 2010)
K	FL-11	Promoting turnover	Operation/ water quality	Reclaimed water reservoirs designed in sequential order with level of linear flow	Flushing distribution systems altering the valving of the network; flushing onto green areas already permitted to use reclaimed water; downsizing mains (i.e., downstream declining pipe diameter); adjusting pumping schedules altering system configuration
	CO-1	Promoting turnover	Operation	Intake and outlet are on opposite sides of each other	
	AZ-8	Turnover promotion	Operation/ water quality Water quality	Two interconnected reservoirs, which are aerated; supply into the distribution system draws water from the bottom of the reservoir; interconnection moves water from one reservoir to the other	
	CO-5	Promoting turnover	Operation	Intake is at bottom of reservoir to help with turning over	
	CA-5	Promoting turnover	Operation/water quality	Produce just enough reclaimed water to meet the needs of the day (i.e., production-on-demand model)	
L	FL-5	Pressure	Operation	Pressurizing from both ends	Use of resilience index (RI) in pipe diameter, layout, and water demand to maintain a pressurized system (Baños et al.,
	CA-4	Pressure	Customer	Constant communication with customers; pressure could be because of pump tripping, which sets the alarm for us	

BMP Code*	Utility	Problem or Issue Identified	Category	Solution from Utilities	Solution from Literature
				to reset	2011; Lamaddalena et al., 2012; Hung and Kim, 2012); use of other appropriate models, e.g., EPANET-MSX
	CA-14	Pressure	Operation	Getting a better engineered SCADA control system	
M	ID	High turbidity	Operation/water quality	Shut down and switch to backup source for irrigation	Manage color by maintaining pH7–9
	CA-2	High turbidity	Operation/water quality	Adjust the coagulant following jar testing	
	CA-10	Turbidity	Operation	Keep filter system operating and diverting filter effluent back to the plant until chemical and flow adjustments are made to bring turbidity back into range	
	FL-4	Debris in the system/water	Water quality	Putting backflow preventers at all intakes to service line	
	CA-5	Color	Water quality		
N	WA-4	Demand greater than supply	Supply and demand	Conservation	Modeling (e.g., Poisson rectangular pulse model) to characterize the intensity and duration of water demand
	SC	Demand greater than supply	Operation	Supplement with deep well groundwater	
	CA-8	Demand greater than supply	Operation	Ration delivery equally to all customers	
	FL-5	Smoothed demand vs. supply	Operation	Store excess in wetland; tapped into to meet demand	

Notes: *A = optimizing reclaimed water storage; B = minimizing the impact of reclaimed water corrosivity; C = improving customer perception; D = managing reclaimed water TDS; E = controlling algae in reclaimed water reservoirs and distribution systems; F = managing snails and other macroorganisms in reclaimed water; G = managing reclaimed water-associated midge flies; H = minimizing regrowth, odor, and biofilms in reclaimed water systems; I = handling nutrients and heavy metals in reclaimed water; J = rapid monitoring of cross-connection control; K = managing reclaimed water age to enhance quality and operational bottlenecks; L = ensuring pressure sustaining reclaimed water systems; M = staying within reclaimed water turbidity targets; N = navigating the operational challenges to streamline reclaimed water supply and demand hoops.




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