Approaches to Maintaining Consistently High Quality Recycled Water in Storage and Distribution Systems

WateReuse Research Foundation

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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 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, salinity 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 increasing reliability and quality.

The Foundation's funding partners include the Bureau of Reclamation, the California State Water Resources Control Board, the California Energy Commission, and the California Department of Water Resources. Funding is also provided by the Foundation's subscribers, water and wastewater agencies, and other interested organizations.

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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 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 research topics including:

- Definition of and addressing emerging contaminants
- Public perceptions of the benefits and risks of water reuse
- Management practices related to indirect potable reuse
- Groundwater recharge and aquifer storage and recovery
- Evaluation and methods for managing salinity and desalination
- Economics and marketing of water 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 and 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 designed to assess methods of maintaining high water quality in recycled water storage and distribution systems. Focused studies of temporal and spatial variations of biological and chemical parameters in recycled water following entry into the distribution system were coupled with a review of existing treatment, disinfection, and operational practices. The study identified indicator organisms that will be useful for routine water quality monitoring, recommended practices that help protect recycled water quality through storage and distribution, and outlined areas that require further research.

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Executive Summary

Introduction

Increasing demands on limited water resources have made recycling an attractive option for stretching water supplies. Recycled water has increasingly been used for nonpotable purposes such as irrigation, toilet flushing, cooling water, and other applications. Many communities are now engaging in discussions about the possibility of using recycled water to augment potable water supplies as well, and some communities have implemented potable reuse projects.

Despite the growth of the recycled water industry, there remain some public health concerns about the potential risks of human contact with recycled water used for irrigating public and recreational areas. In addition, recycled water systems occasionally encounter aesthetic water quality issues that can impact end users and neighbors. Finally, most of the water quality testing that is performed in recycled water systems is conducted at the treatment facility where the water enters the distribution system. Little study has been done on the temporal variations in the microbiological and nutrient/chemical composition of recycled water through distribution and storage.

This study was designed to explore recycled water quality transformations from the point of entry to end users. The study team included HDR Engineering, University of Arizona (UA), United States Department of Agriculture, Agricultural Research Service (USDA-ARS), and Jacobs Engineering, along with several recycled water utilities located across the United States. The study was conducted from 2008 through 2011.

Study Overview

The WRRF-08-04 study investigated the treatment, disinfection, and operational practices that will help ensure that high quality recycled waters are maintained through storage and distribution. It focused on temporal and spatial variations of biological and chemical parameters in recycled water following entry into the distribution system. Limited information is available on potential changes in water quality past the point of compliance, and such information is crucial for establishing the public health impacts of irrigation with recycled water. The work defined water quality markers by identifying and quantifying both viral and bacterial indicator organisms, traditional and nontraditional pathogens, and nutrient and chemical constituents in the recycled water. Water quality information relating to samples collected at the point of compliance for the water reclamation treatment facilities (before recycled water enters the distribution system) was compared to that of samples collected at various time points and distances along the distribution system. An ability to identify and predict water quality changes within the system will guide remediation programs (e.g., placement of intermediate chlorine boosters), with the ultimate objective of enhancing the success of recycled water management.

The technical approach began with a literature review and collection of background information to establish a baseline of practice in the recycled water industry. The initial work developed an overview of the typical recycled water use types, water quality standards applied to recycled water systems, and a compilation of state regulations. In addition, the study team compiled information on the commonly used water recycling treatment technologies and emerging advanced treatment options tied to the targeted end-use water quality targets.

A series of case studies was conducted to support the overall project objectives. The investigative case studies began with a questionnaire to collect information on the design, operation, and environmental conditions at each utility. The study team met with each case study partner to review the causes of specific water quality issues and potential remedies.

Four recycled water distribution systems that differed by age, geographic location, class or quality of recycled water produced, and treatment train were monitored for microbial and chemical water quality. Hydraulic models were developed to estimate water age for the water quality samples collected during the study and model water quality transformations that could result from operational changes. The overall objectives were to evaluate existing water infrastructure and management, provide insight to minimize degradation through water age, and improve recycled water quality in distribution systems and storage facilities.

The research team monitored distribution system water quality by analyzing monthly grab samples for a period of 4 months to 1 year (depending on the system) from the selected sampling locations.

Microbial Water Quality

Recycled water samples were subjected to analyses for microbes that can be categorized into three groups:

- Indicator organisms, which include the traditional organisms monitored by utilities throughout the United States, including coliforms and enterococci.
- Waterborne pathogens, which are enteric organisms such as pathogenic strains of *Escherichia coli* that enter distribution systems via leakage or intrusion events. These organisms do not normally grow or regrow within distribution systems.
- Water-based pathogens, which are organisms that can live, metabolize, grow, and reproduce within distribution systems. They include bacterial species of *Legionella* and *Mycobacterium* and the amoeba *Naegleria fowleri*. In addition, bacterial species of *Aeromonas* may be considered water-based pathogens.

For all utilities, multiple recycled water samples were collected on a monthly basis at increasing distances from the source of treated water (point of compliance) at the treatment plant.

Disinfectant levels fell sharply through the distribution system, ranging from 4.60 to 0.15 mg/L at the point of compliance to <0.05 mg/L at the furthest end of the system, regardless of treatment. Averaged microbial numbers within the distribution system were negatively correlated with residual chlorine regardless of treatment technology (membrane filtration, reverse osmosis, conventional treatment). All systems that did not actively manage disinfectant (using disinfection “boosters”) in their distribution system had increasing levels of microbial activity for multiple microbial parameters assayed.

Figure ES.1 illustrates the frequency in occurrence of water-based pathogens and traditional microbial indicator organisms. Water-based pathogens, such as *Aeromonas, Legionella*, and *Mycobacterium*, were found in higher numbers in recycled water systems that did not maintain residual disinfectant in their distribution system, regardless of treatment technology. Note that *Legionella, Mycobacterium*, enterococci, amoebic activity, and male-specific or somatic coliphage were only assayed for samples collected in two of the systems.

Although water-based pathogens were detected very frequently, indicator organisms were uncommon in the chlorinated systems, and in numerous instances water-based pathogens were present in the recycled water distribution systems in the absence of indicator organisms (*E. coli*). These data question the usefulness of traditional indicators based on treatment technology. Figures ES.2 and ES.3 illustrate detailed results for a system disinfected with chlorine and a system disinfected with UV. In both systems, the levels of most microorganisms rapidly and significantly increased from the point of compliance through the first 1 or 2 miles of the distribution system. After this initial increase, microbial numbers within the distribution system remained relatively constant. In the chlorinated system, slight decreases in microbial parameters observed at the distance of approximately 12 miles were due to the presence of a chlorine booster station in the distribution system. Although the numbers of all organisms tested seemed to decrease slightly at this location, samples collected at the next sampling point downstream demonstrated that microbial numbers had readily increased to levels similar to those before the booster station.

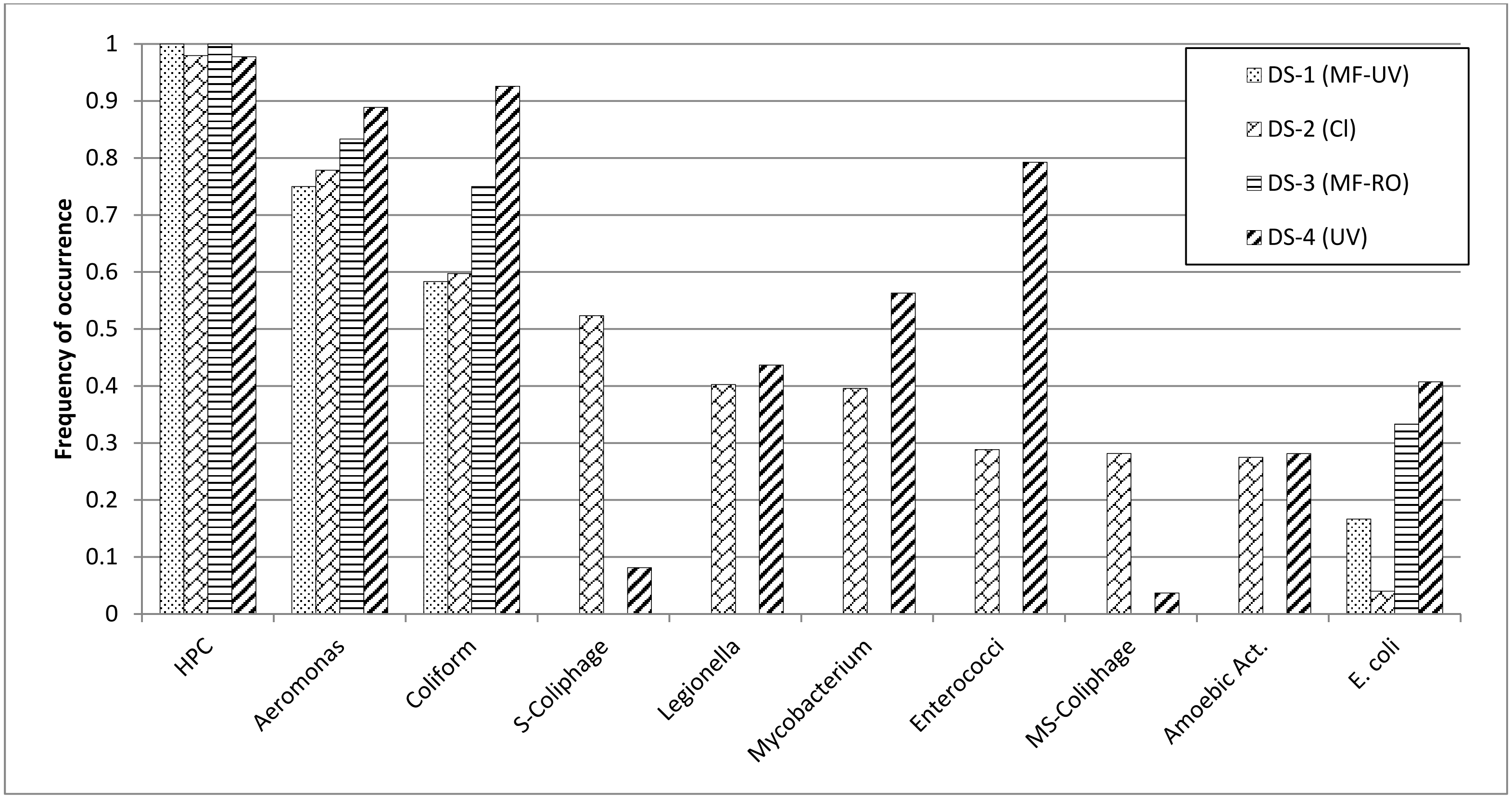


Figure ES.1. Frequency of occurrence of opportunistic pathogens, indicator bacteria, and viruses in recycled water.

Notes: DS=distribution system; MF=microfiltration; UV=ultraviolet disinfection; Cl=chlorine disinfection; RO=reverse osmosis

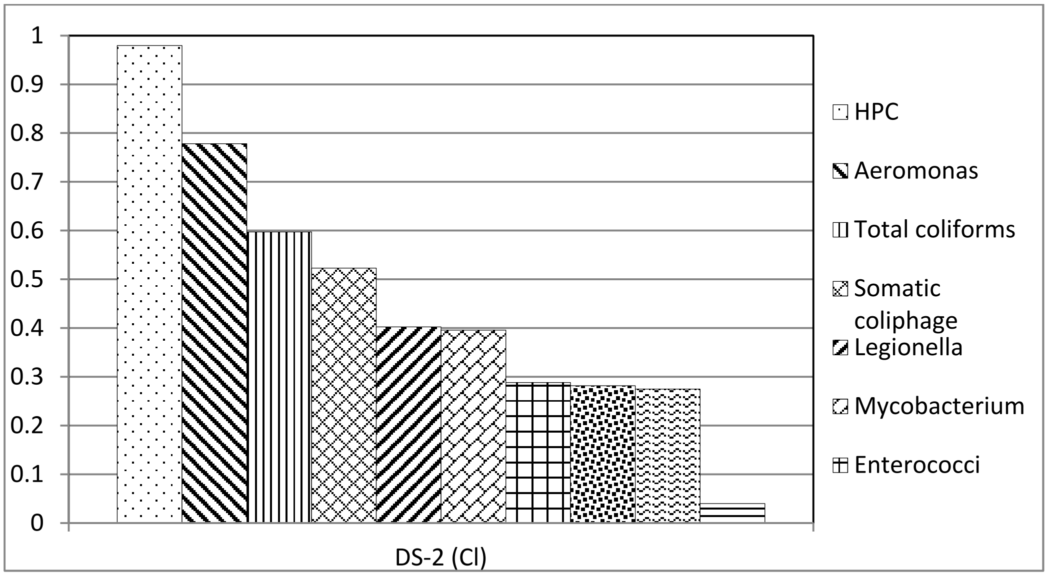


Figure ES.2. Frequency of occurrence of opportunistic pathogens, indicator bacteria, and viruses in chlorinated recycled water.

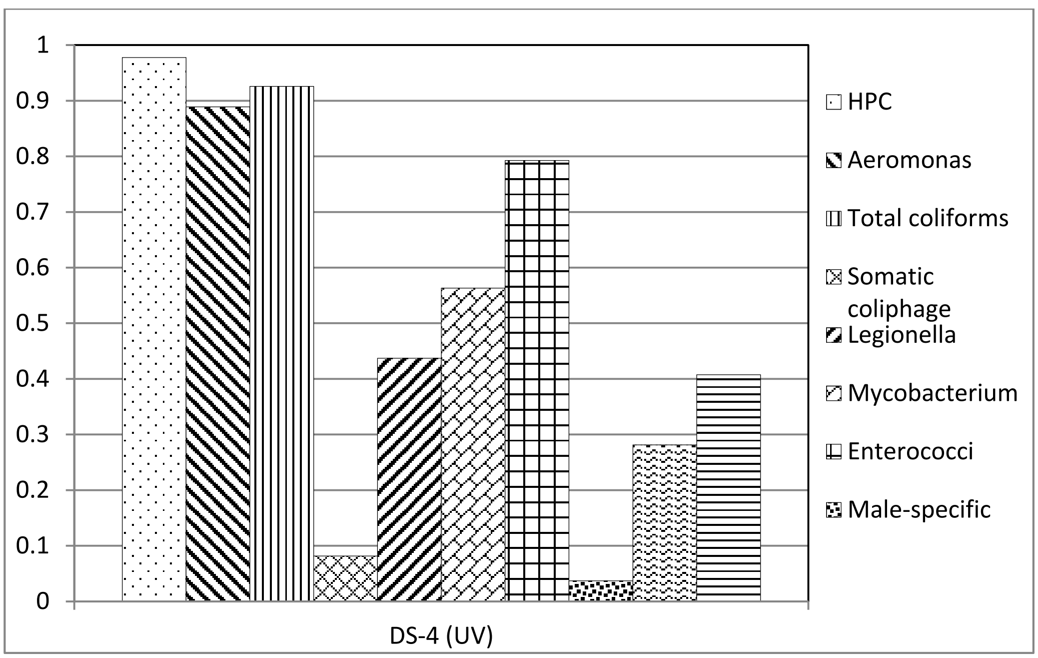


Figure ES.3. Frequency of occurrence of opportunistic pathogens, indicator bacteria, and viruses in UV-disinfected recycled water.

Chemical Water Quality

In addition to microbial water quality parameters, the chemical quality of recycled water in one distribution system was observed as a function of residence time. Nitrate-N, nitrite-N, total Kjeldahl nitrogen (TKN), and total organic carbon (TOC) did not follow any particular trend with water age, although indications that nitrification was occurring within the system were observed. Following nitrification, lower nitrate and higher alkalinity concentrations were detected at approximately 80 hours of water age, which may be due to denitrification. No other significant chemical water quality transformations were noted during this study.

Key Findings

The following key findings resulted from the WRRF-08-04 study:

- Regardless of the initial level of treatment, the microbial quality of the recycled water sampled from the utilities monitored for this research study deteriorated with increased residence time in the water distribution and storage system.
- Water-based pathogens, including *Legionella*, *Mycobacterium*, and *Aeromonas,* were routinely found in recycled waters beyond the point of compliance.
- All water-based pathogens demonstrated the ability to grow within the distribution systems. Furthermore, although water-based pathogen concentrations were reduced following chlorination boosters, pathogens showed a potential to regrow following disinfection within the distribution system.
- Fecal indicator organisms, including *E. coli* and *Enterococcus*, were rarely detected in either distribution system, suggesting that treatment effectively eliminated waterborne pathogens.
- The preceding results demonstrate that fecal indicators have no correlation with the presence of water-based pathogens within the distribution systems included in this study and are not a reliable indicator of microbial water quality.
- Amoebic activity was detected in approximately one third of all water samples collected, with frequency of detection being similar despite the variety of treatment technologies utilized by the cooperating utilities.
- During storage of reclaimed water, the microbial water quality changes over time, in correlation to the rapid dissipation of chlorine concentrations. Within a matter of days, organism levels stabilize as assimilable organic carbon (AOC) levels decrease; this suggests that an equilibrium level of available carbon is reached during growth and subsequent death of organisms.

How Does This Impact Recycled Water Utilities?

One objective for utilities to engage in this study was to determine if recycled water system managers could improve the microbial quality of the finished recycled water product by making operational changes during treatment and delivery. The results of the study confirmed that maintaining disinfectant residual is a key component to controlling microbial growth and re-growth.

The finding that fecal indicator organisms such as *E. coli* and *Enterococcus* species are only valuable in determining quality of recycled water at the point of entry, but not within the distribution system, is critical. Utility operators can consider looking at non-regulatory indicator organisms, such as *Legionella*, *Mycobacterium*, and *Aeromonas,* in the distribution system to assess microbial water quality.

The detection of water-based pathogens in water distribution systems (recycled or potable) is not novel. Many studies have determined that these organisms have an ability to thrive within water piping. The critical information not yet known is whether these organisms, present at the levels found in this study, could cause disease with human contact. A detailed risk assessment should be completed to evaluate pathogen survival outside of the distribution system (after the water is released into the environment) and the exposure (dose) of humans to the pathogen. In the absence of a risk assessment, no conclusions regarding public health risk can be drawn from the findings of this study.

Another important finding is the possible mitigation of the presence of water-based pathogens within the distribution system by reducing the TOC concentration through treatment and thereby possibly reducing the AOC fraction. Reducing the concentration of TOC can create a nutritionally stressed environment with the target goal of eliminating the nutrients for water-based pathogens, thus reducing their presence and concentration in the distributed recycled water.

The application of these findings by a utility is dependent on the uses of recycled water by the customer and the community. If the recycled water is only used for turf irrigation, the fecal indicators may be adequate to use as a measure of quality at the point of entry and within the distribution system. If the recycled water is to be used indoors or to augment potable supplies, then presence of the water-based pathogens, along with the fecal pathogens, is critical in determining the quality. Fecal indicators such as *E. coli* and *Enterococcus* need to be coupled with a non-fecal indicator to determine the presence of water-based pathogens for the utility to have a complete picture of the microbial quality. This information will assist in determining the type of treatment methods needed to eliminate waterborne and water-based pathogens in recycled water that is intended for indoor use or to augment potable supplies.

Chapter 1

Introduction

Increasing demands on limited water resources have made wastewater recycling (reclamation) an attractive option for extending water supplies. Recycled water can satisfy most water demands with adequate treatment. It has increasingly been used for non-potable purposes such as irrigation, toilet flushing, cooling water, and other applications. The reuse of reclaimed water is particularly attractive in arid climates, areas facing high growth, and those under water stress conditions.

By 2006, the United States Environmental Protection Agency (USEPA) estimated that an average of more than 1.7 billion gallons of wastewater is reused per day (Brandhuber, 2006). This represents 5 to 6% of the municipal wastewater effluent generated each day in the United States (WateReuse Association, 2011). Florida and California have the largest reuse programs, with each state reusing an average of more than 500 MGD. Reuse in Texas and Arizona also exceeds an average of 200 MGD (Brandhuber, 2006; USEPA, 2004). Water recycling programs in Arizona, California, Florida, and Texas account for about 90% of the water recycled in the country. Recycled water programs are also emerging in many other locations, including Washington, Oregon, Nevada, Colorado, New Mexico, Pennsylvania, Virginia, Georgia, and Maryland (WateReuse Association, 2011).

Public health concerns remain about the potential risks of human contact with recycled water used for irrigating public and recreational areas. In addition, recycled water systems occasionally encounter aesthetic water quality issues that can impact end users and neighbors. To date, little is known of temporal variations in the microbiological and nutrient/chemical composition of recycled water through distribution and storage after leaving treatment plants. These issues, in addition to current (and possibly erroneous) misconceptions about microbial pathogens of fecal origin in municipal effluent, will make the results of this study of prime importance to water managers considering reuse to expand their water resource portfolios.

This study investigated the treatment, disinfection, and operational practices that will help ensure that high quality recycled waters are maintained through storage and distribution. It focused on temporal and spatial variations of biological and chemical parameters in recycled water following entry into the distribution system. Limited information is available on potential changes in water quality past the point of compliance, and such information is crucial for establishing the public health impacts of irrigation with recycled water. The work defined water quality markers by identifying and quantifying both viral and bacterial indicator organisms, traditional and nontraditional pathogens, and nutrient and chemical constituents in the recycled water. Water quality information relating to water samples collected at the point of compliance for the wastewater treatment facilities (before recycled water enters the distribution system) was compared to that of samples collected at various time points and distances along the distribution system. An ability to identify and predict water quality changes within the system will guide remediation programs (e.g., placement of intermediate chlorine boosters), with the ultimate objective of enhancing the success of recycled water management.

Chapter 2

Use and Regulation of Recycled Water

2.1 Typical Recycled Water Applications in the United States

A wide variety of water demands can be supplied with properly treated recycled water. In recent years, recycled water has become an attractive option for conserving and extending available water resources. There are seven broad categories of recycled water applications in the United States.

- urban reuse
- agricultural irrigation
- industrial reuse
- environmental reuse
- recreational reuse
- groundwater recharge[1]
- indirect potable reuse[2]

Many of these reuse applications are not practiced or regulated in some states. In addition, the recycled water qualities may vary from state to state for a particular reuse application, depending on current regulations or guidelines in each state. Reuse applications and associated recycled water quality standards for 10 representative states are discussed in this section.

2.1.1 Urban Reuse

The urban reuse category covers a wide variety of applications, including landscape and golf courses irrigation, fire protection, dust control, car washing, and toilet flushing. Urban reuse can be either restricted or unrestricted depending on the recycled water quality. Generally, where public contact is likely, the recycled water requires a higher degree of treatment. At a minimum, secondary treatment with disinfection is required for all types of urban reuse. Tables 2.1 and 2.2 summarize the minimum water quality requirements for urban unrestricted reuse and restricted reuse applications.

2.1.2 Agricultural Irrigation

Agricultural irrigation is the oldest practice of recycled water use and the largest end use by volume. Depending on the type of crop, agricultural irrigation may be either unrestricted or restricted. Restricted irrigation (nonfood crops) requires less stringent treatment, whereas unrestricted irrigation (food crops) requires a very high level of treated recycled water quality. Tables 2.3 and 2.4 summarize the minimum water quality requirements for food crop (unrestricted) and nonfood crop (restricted) agricultural reuse applications.

[1]Can be either for potable or nonpotable reuse purposes. In some states this can be synonymous with indirect potable reuse.

[2]Augmentation of recycled water into the raw water supply (surface water or groundwater) for potable use.

Table 2.1. Unrestricted Urban Reuse Standards

	Arizona	California	Colorado	Florida	Hawaii	Nevada	Oregon	Texas	Utah	Washington
Treatment	secondary treatment, filtration, and disinfection	oxidized, coagulated, filtered, and disinfected	oxidized, filtered, and disinfected (Category 2)	secondary treatment, filtration, and high level disinfection	oxidized, filtered, and disinfected	secondary treatment and disinfection	oxidized, filtered, and disinfected	NS	secondary treatment, filtration, and disinfection	oxidized, coagulated, filtered, and disinfected
BOD_5	NS	NS	NS	20 mg/L $CBOD_5$ (annual avg)	NS	30 mg/L	NS	5 mg/L BOD_5 or $CBOD_5$	10 mg/L	30 mg/L
TSS	NS	NS	NS	5.0 mg/L	NS	30 mg/L	NS	NS	NS	30 mg/L
Chlorine Residual	NS	NS	NS	1 mg/L	NS	NS	NS	NS	1 mg/L	1 mg/L
pH	NS	NS	NS	6–8.5	NS	6–9	NS	NS	6–9	NS
Turbidity	2 NTU (24-hr avg)	2 NTU (24-hr avg) 5 NTU (24-hr max)	3 NTU (monthly avg)	NS	2 NTU (max)	NS	2 NTU (24-hr avg)	3 NTU	2 NTU (24-hr avg)	2 NTU (avg)
	5 NTU (max at any time)	10 NTU (max at any time)	5 NTU (max in 30 days)				5 NTU (24-hr max)		5 NTU (max at any time)	5 NTU (max)
Coliform	**Fecal**	**Total**	**Fecal**	**Fecal**	**Fecal**	**Total**	**Total**	**Fecal**	**Fecal**	**Total**
	none detectable (4 of last 7 daily samples)	2.2/100 mL (7-day avg)	126/100 mL (monthly avg)	75% of samples below detection (monthly avg)	2.2/100 mL (avg)	2.2/100 mL (7-day avg)	2.2/100 mL (7-day avg)	20/100 mL (avg)	none detectable (7-day avg)	2.2/100 mL (avg)
	23/100 mL (max)	23/100 mL (max in 30 days)	235/100 mL (max in any calendar month)	25/100 mL (max)	23/100 mL (max in 30 days)	23/100 mL (max daily)	23/100 mL (max)	75/100 mL (max)	14/100 mL (max)	23/100 mL (max)

Source: USEPA, 2004

Notes: NS=not specified; BOD=biochemical oxygen demand; CBOD=carbonaceous biochemical oxygen demand; TSS=total suspended solids

Table 2.2. Restricted Urban Reuse Standards

	Arizona	California	Colorado	Florida	Hawaii	Nevada	Oregon	Texas	Utah	Washington
Treatment	secondary treatment and disinfection	secondary–23, oxidized, and disinfected	secondary treatment and disinfection	secondary treatment, filtration, and high level disinfection	oxidized and disinfected	secondary treatment and disinfection	oxidized, and disinfected	NS	secondary treatment and disinfection	oxidized and disinfected
BOD_5	NS	NS	NS	20 mg/L $CBOD_5$ (annual avg)	NS	30 mg/L	NS	20 mg/L BOD_5 or 15 mg/L $CBOD_5$ (30-day avg)	30 mg/L (30-day avg)	30 mg/L
TSS	NS	NS	30 mg/L (max daily)	5 mg/L	NS	30 mg/L	NS	NS	NS	30 mg/L
Chlorine Residual	NS	NS	NS	1 mg/L	NS	NS	NS	NS	NS	1 mg/L
pH	NS	NS	NS	6–8.5	NS	6–9	NS	NS	6–9	NS
Turbidity	NS	NS	NS	NS	2 NTU (max)	NS	NS	NS	NS	2 NTU (avg) 5 NTU (max)
	Fecal	**Total**	**Fecal**	**Fecal**	**Fecal**	**Fecal**	**Total**	**Fecal**	**Fecal**	**Total**
Coliform	200/100 mL (avg 4 of last 7 samples) 800/100 mL (max)	23/100 mL (7-day avg) 240/100 mL (max in 30 days)	126/100 mL (monthly avg) 235/100 mL (monthly max)	75% of samples below detection 25/100 mL (max)	23/100 mL (avg) 240/100 mL (max)	23/100 mL (monthly avg) 240/100 mL (max daily)	23/100 mL (7-day avg) 240/100 mL (max)	200/100 mL (30-day avg) 800/100 mL (30-day max)	200/100 mL (7-day avg) 800/100 mL (max)	23/100 mL (avg) 240/100 mL (max)

Source: USEPA, 2004

Notes: NS=not specified; BOD=biochemical oxygen demand; CBOD=carbonaceous biochemical oxygen demand

Table 2.3. Agricultural Reuse—Food Crop Standards

	Arizona	California	Colorado		Florida	Hawaii	Nevada	Oregon	Texas	Utah	Washington
Treatment	secondary treatment, filtration, and disinfection	oxidized, coagulated, filtered, and disinfected	oxidized, coagulated, clarified, filtered, and disinfected (spray irrigation)	oxidized and disinfected (surface irrigation)	secondary treatment, filtration, and high level disinfection	oxidized, filtered, and disinfected	secondary treatment and disinfection	oxidized, filtered, and disinfected	NS	secondary treatment, filtration, and disinfection	oxidized, coagulated, filtered, and disinfected
BOD_5	NS	NS	NS	NS	20 mg/L $CBOD_5$ (annual avg)	NS	30 mg/L	NS	5 mg/L BOD_5 or $CBOD_5$ (30-day avg)	10 mg/L	30 mg/L
TSS	NS	NS	NS	NS	5.0 mg/L	NS	30 mg/L	NS	NS	NS	30 mg/L
Chlorine Residual	NS	NS	NS	NS	1 mg/L	NS	NS	NS	NS	1 mg/L	1 mg/L
pH	NS	NS	NS	NS	6–8.5	NS	6–9	NS	NS	6–9	NS
Turbidity	2 NTU (24-hr avg)	2 NTU (24-hr avg)	NS	NS	NS	2 NTU (max)	NS	2 NTU (24-hr. avg)	3 NTU	2 NTU (24-hr avg)	2 NTU (avg)
		5 NTU (24-hr max)									
	5 NTU (max at any time)	10 NTU (max at any time)						5 NTU (24-hr max)		5 NTU (max at any time)	5 NTU (max)
Coliform	**Fecal**	**Total**	**Total**	**Total**	**Fecal**	**Fecal**	**Fecal**	**Total**	**Fecal**	**Fecal**	**Total**
	none detectable (4 of last 7 daily samples)	2.2/100 mL (7-day avg)	2.2/100 mL (7-day avg)	23/100 mL (7-day avg)	75% of samples below detection (monthly avg)	2.2/100 mL (avg)	200/100 mL (30-day avg)	2.2/100 mL (7-day avg)	20/100 mL (avg)	none detectable (7-day avg)	2.2/100 mL (avg)
	23/100 mL (max)	23/100 mL (max in 30 days)	NS	NS	25/100 mL (max)	23/100 mL (max in 30 days)	400/100 mL (max daily)	23/100 mL (max)	75/100 mL (max)	14/100 mL (max)	23/100 mL (max)
		240/100 mL (max any)									

Source: USEPA, 2004

Notes: NS=not specified; BOD=biochemical oxygen demand; CBOD=carbonaceous biochemical oxygen demand; TSS=total suspended solids

Table 2.4. Agricultural Reuse—Nonfood Crop Standards

	AZ		CA	CO	FL	HI	NV	OR	TX		UT	WA
Treatment	secondary treatment and disinfection	stabilization pond, aeration, w/ or w/o disinfection	secondary–23, oxidized, and disinfected	oxidized and disin-fected	secondary treatment and basic disin-fection	oxidized, filtered, and disin-fected	secondary treatment and disinfection	oxidized and disinfected	NS	NS	secondary treatment and disin-fection	oxidized and disin-fected
BOD_5	NS	NS	NS	NS	20 mg/L $CBOD_5$ (annual avg)	NS	30 mg/L	NS	5 mg/L BOD_5 or $CBOD_5$	20 mg/L BOD_5 or 15 mg/L $CBOD_5$ (30-day avg)	30 mg/L (30-day avg)	30 mg/L
TSS	NS	NS	NS	NS	20 mg/L (annual avg)	NS	30 mg/L	NS	NS	NS	NS	30 mg/L
Chlorine Residual	NS	NS	NS	NS	0.5 mg/L	NS	NS	NS	NS	NS	NS	1 mg/L
pH	NS	NS	NS	NS	6–8.5	NS	6–9	NS	NS	NS	6–9	NS
Turbidity	NS	NS	NS	NS	NS	2 NTU (max)	NS	NS	3 NTU	NS	NS	2 NTU (avg) 5 NTU (max)

		AZ	CA	CO	FL	HI	NV	OR	TX	UT	WA	
Coliform	**Fecal**	**Fecal**	**Total**	**Total**	**Fecal**	**Fecal**	**Fecal**	**Total**	**Fecal**	**Fecal**	**Fecal**	**Total**
	200/100 mL (4 of last 7 daily samples)	1000/100 mL (4 of last 7 daily samples)	23/100 mL (7-day avg)	23/100 mL (7-day avg)	200/100 mL (30-day avg)	2.2/100 mL (avg)	200/100 mL (30-day avg)	23/100 mL (7-day avg)	20/100 mL (avg)	200/100 mL (avg)	200/100 mL (7-day avg)	23/100 mL (avg)
	800/100 mL (max)	4000/100 mL (max)	240/100 mL (max in 30 days)	NS	400/100 mL (max in 30 days)	23/100 mL (max in 30 days)	400/100 mL (max daily)	240/100 mL (max)	75/100 mL (max)	800/100 mL (max)	800/100 mL (max)	240/100 mL (max)
					800/100 mL (max at any time)							

Source: USEPA, 2004

Notes: NS=not specified; BOD=biochemical oxygen demand; CBOD=carbonaceous biochemical oxygen demand; TSS=total suspended solids

2.1.3 Industrial Reuse

Industrial reuse has increased substantially with growing populations and expanding legislation regarding water conservation and environmental compliance. In order to meet the increased demand, many major industrial facilities are using recycled water for cooling water, process/boiler-feed requirements, and flue gas scrubber utility. Table 2.5 summarizes the minimum water quality requirements for industrial reuse applications.

2.1.4 Environmental Reuse

Environmental reuse includes natural wetland enhancement and restoration, creation of artificial wetlands to serve as wildlife habitat and refuges, and stream augmentation. A review of existing reuse regulations shows only two states (Florida and Washington) that currently have regulations for environmental reuse. Table 2.6 summarizes the minimum water quality requirements for environmental reuse applications.

2.1.5 Recreational Reuse

Recreational reuse includes landscape impoundments, water hazards on golf courses, and water-based recreational reserves. This includes applications for both incidental human contact (fishing and boating) and full body contact (swimming and wading). Recreational reuse can be both restricted and unrestricted, with public access dictating the mandated recycled water quality. Generally, where public access is likely, the recycled water requires a higher degree of treatment. Tables 2.7 and 2.8 summarize the minimum water quality requirements for unrestricted and restricted recreational reuse applications.

2.1.6 Groundwater Recharge

The main objectives of groundwater recharge using recycled water are to replenish groundwater, establish saltwater intrusion barriers in coastal aquifers, provide storage of recycled water for subsequent withdrawal and use, and prevent ground subsidence (USEPA, 2004). A review of existing reuse regulations shows that four states (California, Florida, Hawaii, and Washington) have regulations for groundwater recharge for nonpotable purposes. Table 2.9 summarizes the minimum water quality requirements for groundwater recharge applications.

2.1.7 Indirect Potable Reuse

Recycled water has been used to augment surface water supply sources or recharge groundwater for public or domestic water supplies. Indirect potable reuse (IPR) involves the introduction of recycled water into the raw water supply (surface water or groundwater) for the purposes of increasing the volume of water available for potable use. A review of existing reuse regulations shows that four states (California, Florida, Hawaii, and Washington) have regulations for IPR. Table 2.10 summarizes the minimum water quality requirements for IPR applications.

Table 2.5. Industrial Reuse Standards

	Arizona	California		Colorado	Florida	Hawaii		Nevada[1]	Oregon	Texas	Utah	Washington
Treatment	NS	oxidized, coagulated, clarified, filtered, and disinfected (cooling water w/ mist)	secondary–23, oxidized, and disinfected (cooling water w/o mist)	NS	secondary treatment and basic disinfection	oxidized, filtered, and disinfected	oxidized and disinfected	secondary treatment and disinfection	oxidized and disinfected	NS (Type II)	secondary treatment and disinfection	oxidized and disinfected
BOD_5	NS	NS	NS	NS	20 mg/L $CBOD_5$ (annual avg)	NS	NS	NS	NS	20 mg/L BOD_5 (30-day avg)	30 mg/L (30-day avg)	NS
TSS	NS	NS	NS	NS	20 mg/L (annual avg)	NS	NS	NS	NS	NS	NS	NS
Chlorine Residual	NS	NS	NS	NS	0.5 mg/L	5 mg/L	0.55 mg/L	NS	NS	NS	NS	NS
pH	NS	NS	NS	NS	6–8.5	NS	NS	NS	NS	NS	6–9	NS
Turbidity	NS	2 NTU (24-hr avg) ≤ 5 NTU (24-hr max) 10 NTU (max at any time)	NS	NS	NS	2 NTU (max)	NS	NS	NS	NS	NS	NS

	Arizona	California		Colorado	Florida	Hawaii		Nevada[1]	Oregon	Texas	Utah	Washington
		Total	**Total**		**Fecal**	**Fecal**	**Fecal**		**Total**	**Fecal**	**Fecal**	**Total**
Coliform		2.2/100 mL (7-day avg)	23/100 mL (7-day avg)		200/100 mL (30-day avg)	2.2/100 mL (7-day avg)	23/100 mL (max in 30 days)		23/100 mL (7-day avg)	200/100 mL (avg)	200/100 mL (7-day avg)	23/100 mL (avg)
	NS	23/100 mL (max in | 30 days)	240/100 mL (max in 30 days)	NS	400/100 mL (max in 30 days)	23/100 mL (max in 30 days)	200/100 mL (max at any time)	NS	240/100 mL (max)	800/100 mL (max)	800/100 mL (max)	240/100 mL (max)
		240/100 mL (max at any time)			800/100 mL (max at any time)	200/100 mL (max at any time)						

Source: USEPA, 2004

Notes: BOD=biochemical oxygen demand; CBOD=carbonaceous biochemical oxygen demand; NS=not specified; TSS=total suspended solids; 1=per Nevada Administrative Code 445A.276-Reuse Categories, Category B can be used for cooling water in Industrial process, and Category C can be used as boiler feed water.

Table 2.6. Environmental Reuse—Wetlands Standards

	Arizona	California[1]	Colorado	Florida	Hawaii	Nevada	Oregon	Texas	Utah	Washington
Treatment	NS	NS	NS	advanced treatment	NS	NS	NS	NS	NS	oxidized, coagulated,| and disinfected
BOD_5	NS	NS	NS	5 mg/L $CBOD_5$ (annual avg)	NS	NS	NS	NS	NS	20 mg/L
TSS	NS	NS	NS	5 mg/L (annual avg)	NS	NS	NS	NS	NS	20 mg/L
Total Ammonia	NS	NS	NS	2 mg/L (annual avg)	NS	NS	NS	NS	NS	≤ chronic stds for fresh water
Total Phosphorus	NS	NS	NS	1 mg/L (annual avg)	NS	NS	NS	NS	NS	1 mg/L (annual avg)
Total Nitrogen	NS	NS	NS	3 mg/L (annual avg)	NS	NS	NS	NS	NS	3 mg/L TKN (annual avg)
Metal	NS	NS	NS	NS	NS	NS	NS	NS	NS	≤ surface water quality stds
Coliform	NS	NS	NS	NS	NS	NS	NS	NS	NS	2.2/100 mL (avg) 23/100 mL (max)

Source: USEPA, 2004

Notes: NS=not specified; BOD=biochemical oxygen demand; CBOD=carbonaceous biochemical oxygen demand; TKN=total Kjeldahl nitrogen; TSS=total suspended solids; 1=California does not specify treatment standards for wetlands. Treatment is based on level of human contact.

Table 2.7. Unrestricted Recreational Reuse Standards

	Arizona	California	Colorado	Florida	Hawaii	Nevada	Oregon	Texas	Utah	Washington
Treatment	NS	oxidized, coagulated, clarified, filtered, and disinfected	oxidized, coagulated, clarified, filtered, and disinfected	NS	NS	secondary treatment and disinfection	oxidized, filtered, and disinfected	NS	secondary treatment, filtration, and disinfection	oxidized, coagulated, filtered, and disinfected
BOD_5	NS	NS	NS	NS	NS	30 mg/L	NS	5 mg/L BOD_5 or $CBOD_5$ (30-day avg)	10 mg/L	30 mg/L
TSS	NS	NS	NS	NS	NS	30 mg/L	NS	NS	NS	30 mg/L
Chlorine Residual	NS	NS	NS	NS	NS	NS	NS	NS	1 mg/L	1 mg/L
pH	NS	NS	NS	NS	NS	6–9	NS	NS	6–9	NS
Turbidity	NS	2 NTU (24-hr avg) ≤ 5 NTU (24-hr max) 10 NTU (max at any time)	NS	NS	NS	NS	2 NTU (24-hr avg) 5 NTU (24-hr max)	3 NTU	2 NTU (24-hr avg) 5 NTU (max at any time)	2 NTU (avg) 5 NTU (max)
		Total	**Total**			**Fecal**	**Total**	**Fecal**	**Fecal**	**Total**
Coliform	NS	2.2/100 mL (7-day avg) 23/100 mL (max in 30 days) 240/100 mL (max at any time)	2.2/100 mL (7-day avg) 23/100 mL (max in 30 days)	NS	NS	2.2/100 mL (30-day avg) 23/100 mL (max)	2.2/100 mL (7-day avg) 23/100 mL (max)	20/100 mL (avg) 75/100 mL (max)	none detectable (7-day avg) 14/100 mL (max)	2.2/100 mL (avg) 23/100 mL (max)

Source: USEPA, 2004

Notes: NS=not specified; BOD=biochemical oxygen demand; CBOD=carbonaceous biochemical oxygen demand; TSS=total suspended solids

Table 2.8. Restricted Recreational Reuse Standards

	Arizona	California	Colorado	Florida	Hawaii	Nevada	Oregon	Texas	Utah	Washington
Treatment	secondary treatment, filtration, and disinfection (Class A)	secondary–2.2, oxidized, and disinfected	oxidized and disinfected	NS	oxidized, filtered, and disinfected	secondary treatment and disinfection	oxidized and disinfected	NS	secondary treatment and disinfection	oxidized and disinfected
BOD_5	NS	NS	NS	NS	NS	30 mg/L	NS	20 mg/L BOD_5 or 15 mg/L $CBOD_5$ (30-day avg)	30 mg/L (30-day avg)	30 mg/L
TSS	NS	NS	NS	NS	NS	30 mg/L	NS	NS	NS	30 mg/L
Chlorine Residual	NS	NS	NS	NS	NS	NS	NS	NS	NS	1 mg/L
pH	NS	NS	NS	NS	NS	6–9	NS	NS	6–9	NS
Turbidity	2 NTU (24-hr avg) 5 NTU (max at any time)	NS	NS	NS	2 NTU (max)	NS	NS	NS	NS	2 NTU (avg) 5 NTU (max)
Coliform	**Fecal**	**Total**	**Total**		**Fecal**	**Fecal**	**Total**	**Fecal**	**Fecal**	**Total**
	none detectable (avg 4 of last 7 daily samples)	2.2/100 mL (7-day avg)	2.2/100 mL (7-day avg)	NS	2.2/100 mL (avg)	2.2/100 mL (30-day avg)	2.2/100 mL (7-day avg)	200/100 mL (avg)	200/100 mL (7-day avg)	2.2/100 mL (avg)
	23/100 mL (max)	23/100 mL (max in 30 days)	NS		23/100 mL (max in 30 days)	23/100 mL (max daily)	23/100 mL (max)	800/100 mL (max)	800/100 mL (max)	23/100 mL (max)

Source: USEPA, 2004
Notes: NS=not specified; BOD=biochemical oxygen demand; CBOD=carbonaceous biochemical oxygen demand; TSS=total suspended solids

Table 2.9. Groundwater Recharge Standards

	Arizona[1]	California[2]		Colorado[1]	Florida[1]	Hawaii[1]	Nevada[1]	Oregon[1]	Texas[1]	Utah[1]	Washington[1]
Treatment	NS	oxidized, coagulated, clarified, filtered, and disinfected	secondary–reverse osmosis and advanced oxidation process	NS	secondary treatment and basic disinfection	case-by-case basis	NS	NS	NS	NS	oxidized, coagulated, filtered, and disinfected
BOD_5	NS	NS	NS	NS	NS		NS	NS	NS	NS	5 mg/L
TSS	NS	NS	NS	NS	10 mg/L		NS	NS	NS	NS	5 mg/L
Turbidity	NS	NS	NS	NS	NS		NS	NS	NS	NS	2 NTU (avg) 5 NTU (max)
TOC	NS	0.5 mg/L	0.5 mg/L	NS	NS		NS	NS	NS	NS	NS
Nitrate	NS	10 mg/L as nitrogen	10 mg/L as nitrogen	NS	12 mg/L as nitrogen		NS	NS	NS	NS	NS
Chlorine Residual	NS	NS	NS	NS	NS		NS	NS	NS	NS	1 mg/L
Coliform/Pathogens	NS	reduction of 12-log virus, 10-log *Giardia* cysts, and 10-log *Cryptosporidium* oocysts	reduction of 12-log virus, 10-log *Giardia* cysts, and 10-log *Cryptosporidium* oocysts	NS	**Fecal Coliform** 200/100 mL (30-day avg) 400/100 mL (max in 30 days) 800/100 mL (max at any time)		NS	NS	NS	NS	**Total Coliform** 2.2/100 mL (avg) 23/100 mL (max)

Sources: 1=USEPA, 2004; 2= California Department of Public Health, 2011.

Notes: BOD=biochemical oxygen demand; NS=not specified; TOC=total organic carbon; TSS=total suspended solids

Table 2.10. Indirect Potable Reuse Standards

	Arizona[1]	California[2, 3]		Colorado[1]	Florida[1]	Hawaii[1]	Nevada[1]	Oregon[1]	Texas[1]	Utah[1]	Washington[1]
Treatment	NS	oxidized, coagulated, clarified, filtered, and disinfected	secondary—reverse osmosis and advanced oxidation process	NS	advanced treatment, filtration, and high level disinfection	case-by-case basis	NS	NS	NS	NS	oxidized, coagulated, filtered, reverse-osmosis treated, and disinfected
BOD_5	NS	NS	NS	NS	20 mg/L		NS	NS	NS	NS	5 mg/L
TSS	NS	NS	NS	NS	5 mg/L		NS	NS	NS	NS	5 mg/L
Turbidity	NS	NS	NS	NS	NS		NS	NS	NS	NS	0.1 NTU (avg) 0.5 NTU (max)
TOC	NS	0.5 mg/L	0.5 mg/L	NS	3mg/L (monthly avg) 5mg/L (max)		NS	NS	NS	NS	1mg/L (monthly avg)
Total Nitrogen	NS	10 mg/L as nitrogen	10 mg/L as nitrogen	NS	10 mg/L (max annual avg)		NS	NS	NS	NS	10 mg/L (annual avg)
Chlorine Residual	NS	NS	NS	NS	NS		NS	NS	NS	NS	1 mg/L
Total Coliform/Pathogens	NS	reduction of 12-log virus, 10-log *Giardia* cysts, and 10-log *Cryptosporidium* oocysts	reduction of 12-log virus, 10-log *Giardia* cysts, and 10-log *Cryptosporidium* oocysts	NS	total coliform: not detectable in any samples		NS	NS	NS	NS	total coliform: 1/100 mL (avg) 5/100 mL | (max)
Primary and Secondary Standards	NS	NS	NS	NS	compliance with most primary and secondary standards		NS	NS	NS	NS	compliance with most | primary and secondary stds.

Sources: 1=USEPA, 2004; 2= California Department of Public Health, 2011.

Notes: BOD=biochemical oxygen demand; NS=not specified; TOC=total organic carbon; TSS=total suspended solids**;** 3=through groundwater recharge only; no surface water augmentation.

2.2 Reuse Regulations and Recycled Water Quality Standards

To date, no federal regulations exist that govern water reclamation (recycling) and reuse in the United States; however, such standards have been developed and implemented at the state government level. The lack of federal regulations and coordination between states has resulted in differing standards for recycled water across the country depending on the type of beneficial use. The process of recycling water involves multi-step treatment processes, for example, physical, chemical, and biological processes (see Chapter 3). In 1992, the EPA first developed *Guidelines for Water Reuse*, a comprehensive technical document to encourage states to develop their own regulations. Recognizing the tremendous growth in reuse, the EPA released its most recent update in September 2012.

The main purpose of federal guidelines and state regulations is to protect human health and water quality. Water reuse standards or guidelines vary with the type of application, the regional context, and the overall risk perception. The types and concentrations of constituents in recycled water depend upon the municipal water supply, the influent waste streams (i.e., domestic and industrial contributions), amount and composition of infiltration in the wastewater collection system, the wastewater treatment processes, and type of storage facilities (USEPA, 2004). The fundamental precondition for water reuse is that applications will not cause unacceptable public health risks (United Nations Environmental Programme, 2004). Therefore, microbiological parameters have received the most attention in water reuse regulations and guidelines. Because monitoring for all pathogens is not practicable, specific indicator organisms are monitored to minimize health risks (USEPA, 2004).

The World Health Organization (WHO) introduced guidance for the safe use of wastewater in 1971, updated in 2006. The WHO guidelines are relatively less restrictive than water reuse regulations and guidelines adopted by the various states (Metcalf & Eddy, 2007). The main intent of the WHO guidelines is to introduce some level of treatment of wastewater and interrupt the transmission of diseases prior to food crop irrigation. Table 2.11 provides a summary of water quality parameters of concern with approximate ranges in secondary treated sewage and reclaimed water as suggested in the EPA water reuse guidelines.

2.3 State-Level Recycled Water Regulations

The EPA views reuse as a regional issue, so water reclamation and reuse regulations have been developed and implemented at the state government level. According to the EPA (2004), 26 states have adopted reclamation and reuse regulations, 15 states have guidelines or design standards, and 9 states have no regulations or guidelines. Table 2.12 shows a summary of state reuse regulations and guidelines.

Table 2.11. Summary of Water Quality Parameters of Concern for Water Reuse

Parameter	Range in Secondary Effluents	Treatment Goal in Recycled Water	EPA Guideline
Suspended solids	5–50 mg/L	<5–30 mg SS/L	-
Turbidity	1–30 NTU	<0.1–30 NTU	2 NTU
BOD_5	10–30 mg/L	<10–45 mg BOD/L	10 mg/L
COD	50–150 mg/L	<20–90 mg COD/L	-
TOC	5–20 mg/L	<1–10 mg C/L	-
Total coliforms	<10–10^7 CFU/100mL	<1–200 CFU/100mL	-
Fecal coliforms	<1–10^6 CFU/100mL	<1–10^3 CFU/100mL	14 for any sample, 0 for 90%
Helminth eggs	<1–10/L	<0.1–5/L	-
Viruses	<1–100/L	<1/50L	-
Heavy metals	-	<0.001 mg Hg/L <0.01 mg Cd/L <0.02–0.1 mg Ni/L	-
Inorganic dissolved solids	-	>450 mg TDS/L	-
Chlorine residual	-	0.5 mg Cl/L - >1 mg Cl/L	1 mg/L
Nitrogen	10–30 mg N/L	<1–30mgN/L	-
Phosphorus	0.1–30 mg P/L	<1–20 mg P/L	-
pH	-	-	6–9

Source: USEPA, 2004

Notes: BOD=biochemical oxygen demand; Cd=cadmium; COD=chemical oxygen demand; Cl=chlorine; Hg=mercury; N=nitrogen; Ni=nickel; P=phosphorus; TDS=total dissolved solids; TOC=total organic carbon

Table 2.12. Summary of State Reuse Regulations and Guidelines

State	Regulations	Guidelines	None	State	Regulations	Guidelines	None
Alabama		•		Montana	•		
Alaska	•			Nebraska	•		
Arizona	•			Nevada	•		
Arkansas		•		New Hampshire			•
California	•			New Jersey		•	
Colorado	•			New Mexico		•	
Connecticut			•	New York		•	
Delaware	•			North Carolina	•		
Florida	•			North Dakota		•	
Georgia		•		Ohio		•	
Hawaii		•		Oklahoma	•		
Idaho	•			Oregon	•		
Illinois	•			Pennsylvania		•	
Indiana	•			Rhode Island			•
Iowa	•			South Carolina	•		
Kansas		•		South Dakota		•	
Kentucky			•	Tennessee	•		
Louisiana			•	Texas	•		
Maine			•	Utah	•		
Maryland		•		Vermont	•		
Massachusetts		•		Virginia			•
Michigan	•			Washington		•	
Minnesota			•	West Virginia	•		
Mississippi			•	Wisconsin	•		
Missouri	•			Wyoming	•		

Source: USEPA, 2004.

The lack of federal regulation has resulted in varying regulations and guidelines among states. Arizona, California, Colorado, Florida, Hawaii, Nevada, Oregon, Texas, Utah, and Washington, which will be discussed further in this chapter, have developed regulations or guidelines specifying recycled water quality and treatment requirements and the full spectrum of reuse applications that strongly encourage water reuse as a sustainable water conservation and management strategy.

2.3.1 Recycled Water Quality Regulations in Arizona

The Arizona Department of Environmental Quality (ADEQ) regulates recycled water use. Local (county) management programs have also been developed, specifically in Maricopa County. The Arizona Legislature has established reclaimed water quality standards under Arizona Administrative Code (AAC), Title 18, Chapter 11, Article 3 and reuse applications under AAC, Title 18, Chapter 9, Article 7. Arizona's Reclaimed Water Quality Standards establish five classes of reclaimed water with minimum treatment requirements and water quality criteria. Table 2.13 shows the reclaimed water quality standards as specified in the AAC.

2.3.2 Recycled Water Quality Regulations in California

The California Department of Public Health regulates recycled water use. The California Legislature has established reclaimed water quality standards and reuse applications under California Code of Regulations (CCR), Title 22, Division 4, Chapter 3. California's Reclaimed Water Quality Standards establish five classes of reclaimed water with minimum treatment requirements and water quality criteria. Table 2.14 shows the reclaimed water quality standards as specified in the CCR.

2.3.3 Recycled Water Quality Regulations in Colorado

Recycled water use is regulated by the Colorado Department of Public Health and Environment. The Colorado Legislature has established reclaimed water quality standards and reuse applications under Water Quality Control Commission, Regulation 84. Colorado Reclaimed Water Quality Standards establish three categories of reclaimed water with minimum treatment requirements and water quality criteria. Table 2.15 shows the reclaimed water quality standards as specified in Regulation 84.

2.3.4 Recycled Water Quality Regulations in Florida

The Florida Department of Environmental Protection regulates recycled water use. The Florida Legislature has established reclaimed water quality standards under Florida Administrative Code (FAC), Chapter 62-600 and reuse applications under FAC, Chapter 62-610. Florida Reclaimed Water Quality Standards establish seven types of reclaimed water with minimum treatment requirements and water quality criteria. Table 2.16 shows the reclaimed water quality standards as specified in the FAC.

Table 2.13. Recycled Water Quality Standards in Arizona

Recycled Water Class	**Treatment Process (Minimum)**	**Recycled Water Standards**							
		BOD_5	TSS	Turbidity		Microbial			Total Nitrogen
				24-hr avg	any time	Fecal Coliform		Enteric Virus	
		(mg/L)	(mg/L)	(NTU)	(NTU)	daily conc.	max conc.	Blended water	(mg/L of NO_3-N)
Class A+	Secondary treatment + filtration + nitrogen removal + disinfection	NS	NS	≤2	≤5	No detectable FC in 4 of last 7 daily samples	≤23/100 mL	No detectable enteric virus in 4 of last 7 monthly samples	5-sample geometric mean conc. <10 mg/L
Class A	Secondary treatment + filtration + disinfection	NS	NS	≤2	≤5	No detectable FC in 4 of last 7 daily samples	≤23/100 mL	No detectable enteric virus in 4 of last 7 monthly samples	NS
Class B+	Secondary treatment + nitrogen removal + disinfection	NS	NS	NS	NS	≤200/100 mL in 4 of last 7 daily samples	≤800/100 mL	NS	5-sample geometric mean conc. <10 mg/L
Class B	Secondary treatment + disinfection	NS	NS	NS	NS	≤200/100 mL in 4 of last 7 daily samples	≤800/100 mL	NS	NS
Class C	Secondary treatment (stabilization pond + aeration) + with or w/o disinfection (retention time in stabilization pond >20 days)	NS	NS	NS	NS	≤1000/100 mL in 4 of last 7 daily samples	≤4000/100 mL	NS	NS

Sources: Arizona Administrative Code (AAC), 2009;

Notes: BOD=biochemical oxygen demand; FC=fecal coliform; NO_3-N=nitrate nitrogen; NS=not specified; TSS=total suspended solids

Table 2.14. Recycled Water Quality Standards in California

Recycled Water Class	Treatment Process (Minimum)	Recycled Water Standards								
		BOD_5	TSS	Turbidity			Microbial			
				24-hr avg	24-hr max	any time	Total Coliform			Enteric Virus
		(mg/L)	(mg/L)	(NTU)	(NTU)	(NTU)	7-day avg conc.	30-day max conc.	any time max	conc.
Disinfected secondary–2.2 recycled water	Oxidized + disinfection	NS	NS	NS	NS	NS	≤2.2/100 mL	≤23/100 mL	NS	NS
Disinfected secondary–23 recycled water	Oxidized + disinfection	NS	NS	NS	NS	NS	≤23/100 mL	≤240/100 mL	NS	NS
Disinfected tertiary recycled water	Oxidized + filtration + disinfection (ct=450 mg-ml/l & 90 mins contact time, at least)	NS	NS	≤2	≤5	≤10	≤2.2/100 mL	≤23/100 mL	≤240/ 100 mL	99.999% removal of F+ MS2 bacteriophage or polio virus
Filtered wastewater	Oxidized + coagulated + filtration + disinfection	NS	NS	≤2	≤5	≤10	≤2.2/100 mL	≤23/100 mL	NS	NS
Un-disinfected secondary recycled water	Oxidized	NS	NS	NS	NS	NS	NS	NS	NS	NS

Source: California Code of Regulations (CCR)

Notes: BOD=biochemical oxygen demand; NS=not specified; TSS=total suspended solids

Table 2.15. Recycled Water Quality Standards in Colorado

Recycled Water Class	Treatment Process (Minimum)	Recycled Water Standards					
		BOD_5	TSS	Turbidity		Microbial	
				avg	Max	Fecal Coliform	
		(mg/L)	(mg/L)	(NTU)	(NTU)	avg conc.	max conc.
Category 1	Secondary treatment + disinfection	NS	≤30	NS	NS	≤126/100 mL (monthly avg)	≤235/100 mL (max in 30 days)
Category 2	Secondary treatment + filtration + disinfection	NS	NS	≤3 (monthly avg)	≤5 (max in 30 days)	≤126/100 mL (monthly avg)	≤235/100 mL (max in 30 days)
Category 3	Secondary treatment + filtration + disinfection	NS	NS	≤3 (monthly avg)	≤5 (max in 30 days)	no detectable FC in 75% of samples in 30 days	≤126/100 mL (max in 30 days)

Source: Colorado Water Quality Control Commission, 2009

Notes: BOD=biochemical oxygen demand; FC=fecal coliform; NS=not specified; TSS=total suspended solids

Table 2.16. Recycled Water Quality Standards in Florida

Recycled Water	Treatment Process (Minimum)	Recycled Water Standards													
		$CBOD_5$		Turbidity			Microbial					TOC		TOX	
		Annual Avg	TSS	Avg	Max	pH	Fecal Coliform			Total Nitrogen	Cl_2 Resi-dual	30-day avg	Max	30-day avg	Max
		(mg/L)	(mg/L)	(NTU)	(NTU)		30-day avg conc.	30-day max conc.	max conc.	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
1	Secondary treatment + low level disinfection	≤20	NS	NS	NS	6.0–8.5	NS	NS	≤2400/ 100 mL	NS	NS	NS	NS	NS	NS
2a	Secondary treatment + basic disinfection	≤20	≤20	NS	NS	6.0–8.5	≤200/ 100 mL	≤400/ 100 mL	≤800/ 100 mL	NS	0.5	NS	NS	NS	NS
2b	Secondary treatment + basic disinfection	≤20	≤10	NS	NS	6.0–8.5	≤200/ 100 mL	≤400/ 100 mL	≤800/ 100 mL	≤12	0.5	NS	NS	NS	NS
3	Secondary treatment + intermediate level disinfection	≤20	NS	NS	NS	6.0–8.5	≤14/ 100 mL	≤43/ 100 mL	≤86/ 100 mL	NS	1.0	NS	NS	NS	NS
4a	Secondary treatment + filtration + high level disinfection	≤20	≤5	NS	NS	6.0–8.5	no detectable FC in 75% of samples	NS	≤25/ 100 mL	NS	1.0	NS	NS	NS	NS
4b	Secondary treatment + filtration + high level disinfection	≤20	≤5	NS	NS	6.0–8.5	no detectable FC in 75% of samples	NS	≤25/ 100 mL	≤10	1.0	≤ 3	≤5	≤0.2	≤0.3
5	Advanced treatment + filtration + high level disinfection	≤20	≤5	NS	NS	6.0–8.5	not detectable in any samples	not detectable in any samples	not detectable in any samples	≤10	1.0	≤ 3	≤5	NS	NS

Source: Florida Administrative Code (FAC)

*Notes: C*BOD=carbonaceous biochemical oxygen demand; Cl_2=chlorine; FC=fecal coliform; NS=not specified; TOC=total organic carbon; TOX=total organic halides; TSS=total suspended solids

2.3.5 Recycled Water Quality Regulations in Hawaii

The Hawaii State Department of Health developed *Guidelines for the Treatment and Use of Recycled Water* in 2002. The guidelines establish three classes of reclaimed water with minimum treatment requirements and water quality criteria. Table 2.17 shows the reclaimed water quality standards as specified in the guidelines.

2.3.6 Recycled Water Quality Regulations in Nevada

The Nevada Division of Environmental Protection regulates recycled water use. The Nevada Legislature has established reclaimed water quality standards and reuse applications under Nevada Administrative Code (NAC), Chapter 445A.275-280. The Reclaimed Water Quality Standards establish five types of reclaimed water with minimum treatment requirements and water quality criteria. Table 2.18 shows the reclaimed water quality standards as specified in the NAC.

2.3.7 Recycled Water Quality Regulations in Oregon

Oregon Department of Environmental Quality regulates reclaimed water use. The Oregon Legislature has established the reclaimed water quality standards and reuse applications under Oregon Administrative Rules (OAR), Chapter 340, Division 55 (340-055). Reclaimed Water Quality Standards establish four types of reclaimed water with minimum treatment requirements and water quality criteria. Table 2.19 shows the reclaimed water quality standards as specified in the OAR.

2.3.8 Recycled Water Quality Regulations in Texas

The Texas Commission on Environmental Quality regulates recycled water use. The Texas Legislature has established reclaimed water quality standards and reuse applications under Texas Administrative Code (TAC), Title 30, Part 1, Chapter 210. The Reclaimed Water Quality Standards establish three types of reclaimed water with minimum treatment requirements and water quality criteria. Table 2.20 shows the reclaimed water quality standards as specified in the TAC.

2.3.9 Recycled Water Quality Regulations in Utah

The Division of Water Quality of the Utah Department of Environmental Quality regulates recycled water use. The Utah Legislature has established reclaimed water quality standards and reuse applications under Utah Administrative Code (UAC), Titles R317-1 and R317-3. The Reclaimed Water Quality Standards establish two types of reclaimed water with minimum treatment requirements and water quality criteria. Table 2.21 shows the reclaimed water quality standards as specified in the UAC.

Table 2.17. Recycled Water Quality Standards in Hawaii

Recycled Water Class	Treatment Process (Minimum)	Recycled Water Standards							
		BOD$_5$	TSS	Turbidity	Microbial				Cl$^-$ Residual
					Fecal Coliform			MS2 or Polio Virus	
		(mg/L)	(mg/L)	(NTU)	7-day median	30-day max	Any Sample Max	% Removal	(mg/L)
R 1	Oxidized+ filtration + disinfection	NS	NS	≤2	≤2.2/100 mL	≤23/100 mL	≤200/100 mL	99.999%	5.0
R 2	Oxidized + disinfection	NS	NS	NS	≤23/100 mL	≤200/100 mL	NS	NS	0.5
R 3	Oxidized	NS	NS	NS	NS	NS	NS	NS	NS

Source: Hawaii State Department of Health

Notes: BOD=biochemical organic demand; NS=not specified; TSS=total suspended solids

Table 2.18. Recycled Water Quality Standards in Nevada

Recycled Water Reuse Category	Treatment Process (Minimum)	Recycled Water Standards									
		BOD$_5$	TSS	Turbidity		pH	Microbial				Total Nitrogen
				Avg	Max		Fecal Coliform		Total Coliform		
		(mg/L)	(mg/L)	(NTU)	(NTU)		30-Day Avg	Daily Max	30-Day Avg	Daily Max	(mg/L)
Category A	secondary treatment + disinfection	≤30	≤30	NS	NS	6.0–9.0	-	-	≤2.2 CFU/ 100 mL	≤23 CFU/ 100 mL	NS
Category B	secondary treatment + disinfection	≤30	≤30	NS	NS	6.0–9.0	≤2.2 CFU/ 100 mL	≤23 CFU/ 100 mL	-	-	NS
Category C	secondary treatment + disinfection	≤30	≤30	NS	NS	6.0–9.0	≤23 CFU/ 100 mL	≤240 CFU/ 100 mL	-	-	NS
Category D	secondary treatment + disinfection	≤30	≤30	NS	NS	6.0–9.0	≤200 CFU/ 100 mL	≤400 CFU/ 100 mL	-	-	NS
Category E	secondary treatment + disinfection	≤30	≤30	NS	NS	6.0–9.0	no limit	no limit	-	-	NS

Source: Nevada Administrative Code (NAC)

Notes: BOD=biochemical organic demand; NS=not specified; TSS=total suspended solids

Table 2.19. Recycled Water Quality Standards in Oregon

Recycled Water Class	Treatment Process (Minimum)	Recycled Water Standards							
		BOD_5	TSS	Turbidity			Microbial		Total Nitrogen
				24-Hr Avg	24-Hr Max	Any Time	Total Coliform		
		(mg/L)	(mg/L)	(NTU)	(NTU)	(NTU)	median	max.	(mg/L)
Class A	oxidized+ filtration + disinfection	NS	NS	≤2	≤5	≤10	≤2.2/100 mL	≤23/100 mL	NS
Class B	oxidized + disinfection	NS	NS	NS	NS	NS	≤2.2/100 mL	≤23/100 mL	NS
Class C	oxidized + disinfection	NS	NS	NS	NS	NS	≤23/100 mL	≤240/100 mL	NS
Class D	oxidized + disinfection	NS	NS	NS	NS	NS	≤126/100 mL	≤406/100 mL	NS

Source: Oregon Administrative Rules (OAR)

Notes: BOD=biochemical organic demand; NS=not specified; TSS=total suspended solids

Table 2.20. Recycled Water Quality Standards in Texas

Recycled Water Class	Treatment Process (Minimum)	Recycled Water Standards (30-day average)							
		BOD_5	$CBOD_5$	TSS	Turbidity		Microbial		Total Nitrogen
					Avg	Max	Fecal Coliform		
		(mg/L)	(mg/L)	(mg/L)	(NTU)	(NTU)	Avg	Max	(mg/L)
Type I	NS	≤5	≤5	NS	≤3	NS	≤20 CFU/100 mL	≤75 CFU/100 mL	NS
Type II (Other than Pond System)	NS	≤20	≤15	NS	NS	NS	≤200 CFU/100 mL	≤800 CFU/100 mL	NS
Type II (Pond System)	NS	≤30	NS	NS	NS	NS	≤200 CFU/100 mL	≤800 CFU/100 mL	NS

Source: Texas Administrative Code (TAC)

Notes: BOD=biochemical organic demand; CBOD=carbonaceous biochemical organic demand; NS=not specified; TSS=total suspended solids

Table 2.21. Recycled Water Quality Standards in Utah

Recycled Water Class	**Treatment Process (Minimum)**	**Recycled Water Standards**								
		BOD_5	TSS	Turbidity		Microbial		Total Nitrogen	Cl_2 Residual	pH
				Avg	Max	Fecal Coliform				
		(mg/L)	(mg/L)	(NTU)	(NTU)	7-day median	Max	(mg/L)	(mg/L)	
Type I	secondary treatment + filtration + disinfection	≤10	≤5	≤2	≤5	none detected	≤9 /100 mL	NS	1.0	6–9
Type II	secondary treatment + disinfection	≤25	≤25	NS	NS	≤126 /100 mL	≤500/ 100 mL	NS	NS	6–9

Source: Utah Administrative Code (UAC)

Notes: BOD=biochemical organic demand; Cl_2=chlorine; NS=not specified; TSS=total suspended solids

2.3.10 Recycled Water Quality Regulations in Washington

The Washington State Department of Health developed *Water Reclamation and Reuse Standards* in 1997. The guidelines establish four classes of reclaimed water with minimum treatment requirements and water quality criteria. Table 2.22 shows the reclaimed water quality standards as specified in the guidelines.

2.4 Australian Recycled Water Regulations

With the exception of Antarctica, Australia is the driest continent on earth, and the increasing demand for water sources turned its attention to water recycling in the late 1990s. Currently, approximately 14% of Australia's wastewater is being recycled (Commonwealth Scientific and Industrial Research Organization [CSIRO], 2011). The Australian Environment Department does not have any federal regulation or guidelines governing water reuse. Guidelines governing water recycling and reuse have been developed and implemented at the state/territory government level. The Environmental Protection Authority of Victoria (EPA Victoria) provides one of the most comprehensive guidelines for recycled water quality standards and reuse applications. Table 2.23 shows reuse applications of recycled water in Australia, and Table 2.24 shows recycled water quality standards as specified in EPA Victoria's *Guidelines for Environmental Management: Use of Reclaimed Water*.

Table 2.22. Recycled Water Quality Standards in Washington

Recycled Water Class	Treatment Process (Minimum)	Recycled Water Standards							
		BOD_5	TSS	Turbidity		Microbial		Cl_2 Residual	Total Nitrogen
				Avg	Max	Total Coliform			
		(mg/L)	(mg/L)	(NTU)	(NTU)	7-Day Median	Any Sample Max	(mg/L)	(mg/L)
Class A	oxidized + coagulation + filtration + disinfection	≤30	≤30	≤2	≤5	≤2.2/100 mL	≤23/100 mL	1.0	NS
Class B	oxidized + disinfection	≤30	≤30	≤2	≤5	≤2.2/100 mL	≤23/100 mL	1.0	NS
Class C	oxidized + disinfection	≤30	≤30	≤2	≤5	≤23/100 mL	≤240/100 mL	1.0	NS
Class D	oxidized + disinfection	≤30	≤30	≤2	≤5	≤240/100 mL	NS	1.0	NS

Source: Washington Water Reclamation and Reuse Standards

Notes: BOD=biochemical organic demand; NS=not specified; TSS=total suspended solids

Table 2.23. Recycled Water Applications in Australia

Recycled Water Class	Use
Class A	Urban (nonpotable) with uncontrolled public access Agricultural: e.g., human food crops consumed raw Industrial: open systems with worker exposure potential
Class B	Urban (nonpotable) with controlled public access Agricultural: e.g., human food crops cooked/processed, grazing/fodder for livestock Industrial: systems with no potential worker exposure
Class C	Agricultural: e.g., dairy cattle grazing Industrial: e.g., wash-down water
Class D	Agricultural: nonfood crops including instant turf, woodlots, flowers

Source: EPA Victoria, 2003

Table 2.24. Recycled Water Quality Standards in Australia

Recycled Water Class	Treatment Process (Minimum)	Recycled Water Standards											
		BOD_5	TSS	Turbidity		Microbial				pH	Total Nitrogen	Total Phosphorus	Cl_2 Residual
				24-hr avg	Max	Fecal Coliform	Helminths	Protozoa	Enteric Virus				
		(mg/L)	(mg/L)	(NTU)	(NTU)	median	median	median	median		(mg/L)	(mg/L)	(mg/L)
Class A	secondary treatment + tertiary treatment + disinfection	<10	<5	<2	≤5	<10 *E. coli*/ 100 mL	<1/ L	<1/50 L	<1/50 L	6–9	<5	<0.5	1
Class B	secondary treatment + disinfection	<20	<30	NS	NS	<100 *E. coli*/ 100 mL	NS	NS	NS	6–9	<5	<0.5	NS
Class C	secondary treatment + disinfection	<20	<30	NS	NS	<1000 *E. coli*/ 100 mL	NS	NS	NS	6–9	<5	<0.5	NS
Class D	secondary treatment	<20	<30	NS	NS	<10,000 *E. coli*/ 100 mL	NS	NS	NS	6–9	<5	<0.5	NS

Source: EPA Victoria, 2003

Notes: BOD=biochemical organic demand; NS=not specified; TSS=total suspended solids

Chapter 3

Treatment and Disinfection Technologies

A wide variety of treatment technologies are available to meet the requirements of the various recycled water applications. This technology review section provides a description of these various treatment technologies and their capabilities and provides process selection recommendations for a variety of recycled water end uses.

3.1 Recycled Water Quality Requirements

Recycled water must meet certain minimum water quality requirements dictated by its anticipated end uses. As discussed in Chapter 2, end-use recycled water quality requirements are generally set by individual states, and each state has different requirements. These standards vary according to such factors as degree of human contact, irrigation of food vs. nonfood crops, potential for groundwater recharge, and IPR. Consequently, the level of treatment required for the recycled water varies according to the anticipated end use.

3.2 Conventional Treatment

Conventional wastewater treatment processes are adequate for many recycled water applications. The minimum treatment requirement includes preliminary and primary treatment as needed and biological secondary treatment to remove or stabilize suspended and dissolved organic matter. Many secondary treatment processes are available and in use throughout the world. Table 3.1 lists many of these treatment processes and the effluent quality they can achieve.

Table 3.1. Biological Secondary Treatment Process Capabilities

Process	Effluent Quality Achievable
Suspended Growth	
Aerated lagoons	BOD <45 mg/L, TSS <60 mg/L
Air-activated sludge	BOD <30 mg/L, TSS <30 mg/L
Oxygen-activated sludge	BOD <30 mg/L, TSS <30 mg/L
Attached Growth	
Trickling filters	BOD <40 mg/L, TSS <40 mg/L
Rotating biological contactors	BOD <30 mg/L, TSS <30 mg/L
Hybrid Systems	
Trickling filter (when used as a roughing filter upstream of an activated sludge process)	BOD <30 mg/L, TSS <30 mg/L
Integrated fixed film activated sludge	BOD <30 mg/L, TSS <30 mg/L

Notes: BOD=biochemical organic demand; TSS=total suspended solids

Aerated lagoons and trickling filters alone may not be appropriate for many recycled water applications because traditional secondary effluent limits of BOD <30 mg/L and total suspended solids (TSS) <30 mg/L are often not achievable. It is likely that these processes, when coupled with other processes such as secondary clarification and tertiary filtration, may be sufficient. In this chapter, biological secondary treatment refers to an activated sludge process, attached growth process, or hybrid process that achieves effluent with BOD <30 mg/L and TSS <30 mg/L. Process schematics of two biological secondary treatment processes are shown in Figures 3.1 and 3.2. Any disinfection or filtration process is added after the secondary clarifier.

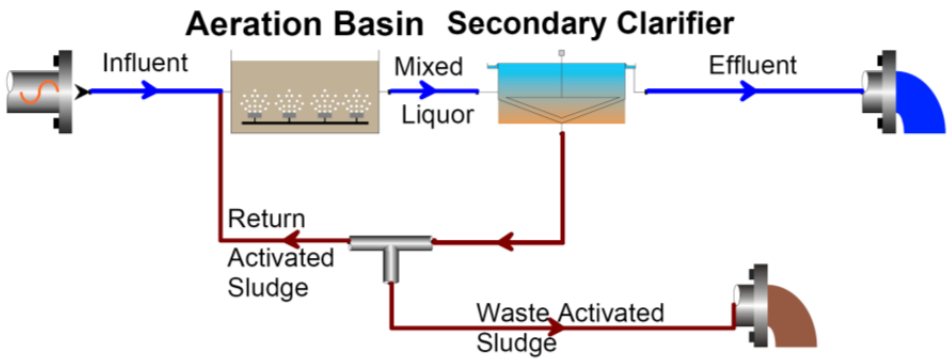


Figure 3.1. Activated sludge process schematic.

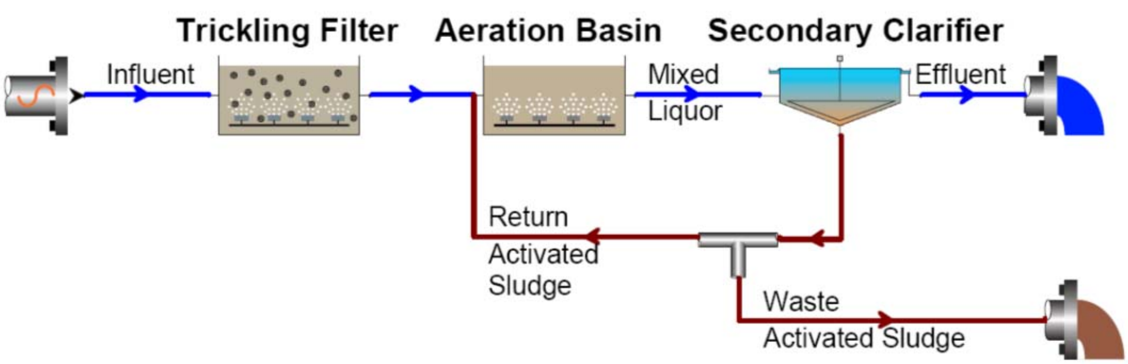


Figure 3.2. Hybrid system—roughing filter with activated sludge.

3.3 Conventional Treatment with Nutrient Removal

Many states do not require nutrient (e.g., ammonia, other nitrogen compounds, and phosphorus) removal for recycled water; however, nutrient removal is necessary for certain end uses. In particular, when used for surface impoundments, recycled water must have low levels of ammonia to avoid toxicity to aquatic life, and nitrogen and phosphorus must be low to minimize algal blooms and eutrophication. The presence of ammonia odor in double-plumbed recycled water distribution systems can be objectionable to users.

Table 3.2. Nutrient Removal Processes

Targeted Nutrient	Process	Typical Removal Levels
Ammonia	biological secondary treatment w/o nitrification	ammonia N<15 mg/L typical
	biological secondary treatment (all processes in Table 3.1 but optimized for nitrification)	ammonia N<2 mg/L
	separate secondary treatment (nitrifying trickling filter or moving bed bioreactor)	ammonia N<2 mg/L
	chemical removal (breakpoint chlorination)	ammonia N<2 mg/L
Total nitrogen	suspended or attached growth activated sludge with combined nitrification/denitrification (requires anoxic zone and internal mixed liquor recycle)	between 5 and 10 mg/L TN achievable (may require an external carbon source)
	suspended or attached growth activated sludge with separate denitrification process (denitrification tower with carbon source feed).	TN<2 mg/L
Phosphorus	biological secondary treatment	some phosphorus removal
	suspended growth activated sludge with anaerobic selector	total P<2 mg/L
	chemical removal (coagulant such as alum)	total P<0.2 mg/L

Notes: N=nitrogen; P=phosphorus; TN=total nitrogen

Ammonia can be nitrified (converted to nitrate) in oxidized wastewater as long as conditions allow adequate solids retention time to maintain a population of nitrifying bacteria. Denitrification (converting nitrate to nitrogen gas) requires an anoxic zone where nitrate and carbon are utilized by facultative bacteria as an energy and carbon source in the absence of oxygen. The Modified Ludzack Ettinger (MLE) process shown in Figure 3.3 is a popular configuration for promoting nitrification and denitrification (NdN). The internal mixed liquor return is the internal recycle that delivers nitrate to the anoxic zone for denitrification.

Phosphorus removal is often coupled with total nitrogen removal, as shown in the 5-stage Bardenpho process in Figure 3.4. The anaerobic zone is a selector for phosphorus-accumulating bacteria. These organisms remove phosphorus from the water, assimilating it into their cells. The accumulated phosphorus is ultimately purged with the waste-activated sludge.

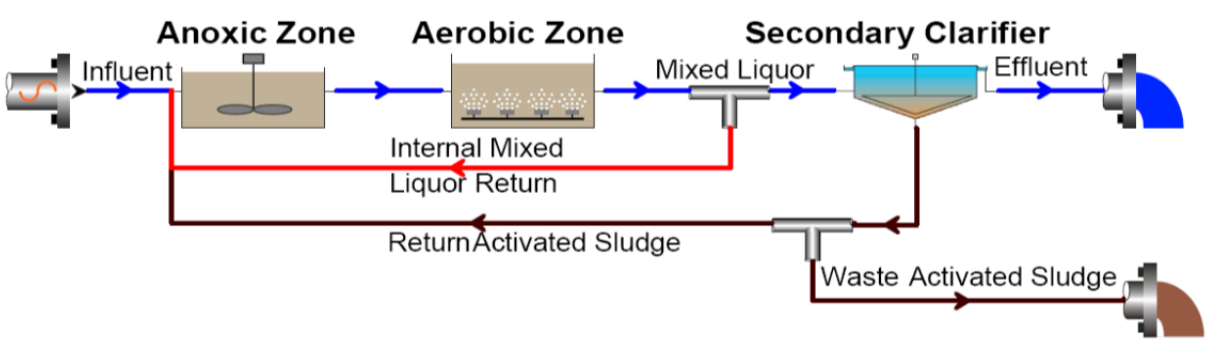


Figure 3.3. MLE process—combined nitrification and denitrification.

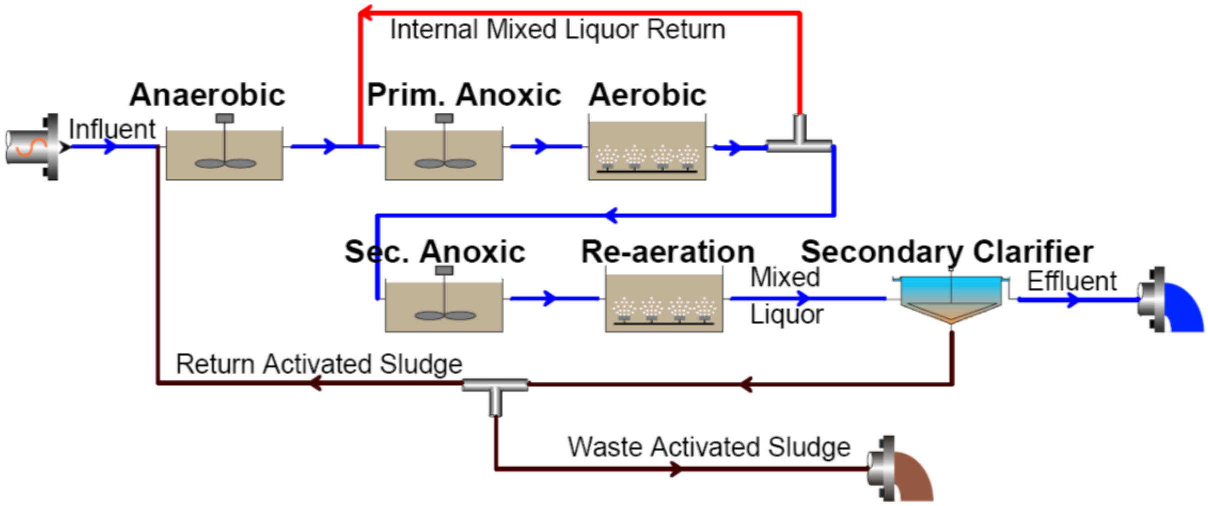


Figure 3.4. Five-stage Bardenpho (NdN and P removal).

Table 3.3. Tertiary Treatment Processes

Process	Performance
Granular media filtration	NTU<2
Cloth media filtration	NTU<2
Membrane filtration	NTU<0.1
Membrane bioreactor	NTU<0.1

3.4 Tertiary Treatment

Tertiary treatment is required to remove solids and colloids that cause turbidity (lack of transparency) in water. Generally, this is achieved by filtration processes, which must be complemented with disinfection to provide pathogen removal (see subsequent subsection on disinfection). Disinfection is often used without filtration, but the turbidity in unfiltered water may allow pathogens to escape disinfection, shielding them from disinfectants. Any recycled water use with human exposure will require both filtration and disinfection. Typically, filtration will require coagulants (see subsequent subsection on advanced treatment) and flocculants to remove the smallest particles and colloids from the water.

The level of suspended solids and turbidity removal depends upon the end-use requirements. Many tertiary technologies exist, with varied performance levels as shown in Table 3.3.

The membrane bioreactor (MBR) is unique because it uses membrane filtration in the place of secondary clarifiers and eliminates the need for a separate clarifier and filtration process in the secondary treatment scheme. Consequently, MBR treatment units are, in general, much more compact than traditional secondary treatment systems, although they are considerably more complex and may be more costly to operate. A simplified MBR process train is shown in Figure 3.5.

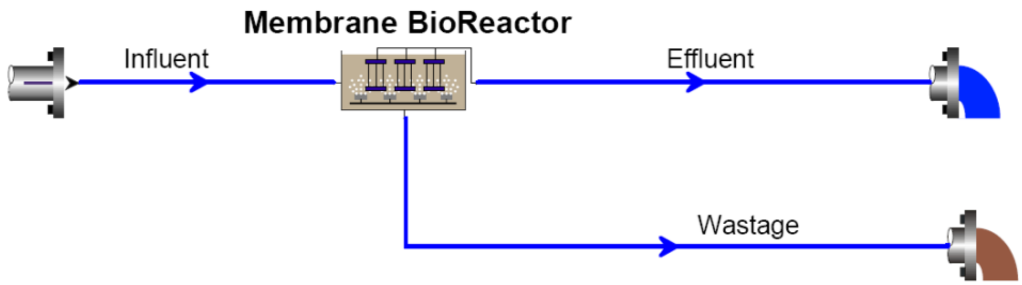


Figure 3.5. Membrane bioreactor schematic.

It is important to note that tertiary treatment will only remove solids and colloids. Dissolved constituents such as nutrients cannot be removed with tertiary filtration.

3.5 Advanced Treatment

When recycled water quality requirements exceed the capabilities of conventional and tertiary treatment processes, advanced treatment is necessary. Often specific contaminants or contaminant classes are targeted. Various advanced treatment technologies are summarized in this section.

3.5.1 Chemical Precipitation

Chemical precipitation can include processes such as coagulation and filtration with iron or aluminum salts or polymers as the coagulant or the application of a strong base such as lime to precipitate hardness-causing minerals, such as calcium and magnesium. In coagulation/filtration processes, ferrous or ferric salts or alum are applied to the water in sufficient quantities to cause iron or aluminum hydroxide flocs. These flocs remove suspended solids (SS) and other organic and inorganic materials from the treated water. The iron or aluminum sludge is removed via settling, and the supernatant is conveyed to a filtration process.

Chemical precipitation is a common process for phosphorus removal. Inorganic orthophosphate is the form of phosphorus that is removed most easily. Phosphorus is also present in the more complex polyphosphate and organic phosphate forms. Biological treatment converts most of the phosphorus to orthophosphate, so chemical precipitation is commonly implemented downstream of the biological process. Coagulated phosphorus is then removed by sedimentation, filtration, or both.

Available coagulants include lime, alum, ferric chloride, and ferrous sulfate (Water Environment Federation, 1998). A plant should select a coagulant only after adequate jar testing has determined the dose and effectiveness. To minimize chemical use, chemical phosphorus removal can be used after a biological process specifically designed for phosphorus removal, such as the 5-stage Bardenpho discussed earlier.

The application of large doses of lime to treated water can elevate the pH to levels sufficient to precipitate calcium and magnesium. This process is normally termed a softening reaction. The calcium and magnesium precipitates form sludge that separates from the water by gravity. The clear supernatant is very often conveyed to a supplemental process, such as chemical addition for pH adjustment to prevent further deposition and scaling. Both coagulation/filtration and softening can reduce total dissolved solid (TDS) levels and often many other organic and inorganic constituents in the recycled water.

3.5.2 Ion Exchange

In ion exchange (IX), water is passed through a natural or synthetic resin media. The resin media contains inorganic atoms that are exchanged for the hardness ions. The resin becomes exhausted when the ions to be exchanged have occupied all of the available inorganic sites on the resin. At this point, the resin bed must be regenerated. In order to do this, a concentrated solution of the original resin inorganic ion is circulated through the resin bed, and the exchanged ions are purged to waste. A variation on the IX process, metal ion exchange, utilizes a magnetic resin.

3.5.3 Membrane Processes

Membranes are used to remove TDS, turbidity, and very high levels of microorganisms. TDS reduction is often necessary for agricultural or turf irrigation or industrial cooling uses, depending on the quality of the source water. Often specific inorganics, such as sodium, are targeted. Elevated sodium levels can contribute to a high sodium adsorption ratio (SAR), which is contraindicative to healthy plant growth. This could render the recycled water unfit for irrigation.

Membrane technologies are superior for removing turbidity, certain organics, and microorganisms from recycled water in comparison to traditional filtration processes. When recycled water requires significant turbidity, organics, or very high microorganism reductions, membrane processes are an important tool for achieving these levels.

Membrane treatment processes rely on fine-pore synthetic or ceramic media. The level of treatment achievable is typically inversely related to the pore size of the media. In order of decreasing pore size (and increasing level of treated water quality) are the broad-based categories of microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO). Very often, membrane treatment technologies are applied in tandem; where the larger pore units are placed ahead of the finer pore units, the larger pore units effectively function as prefilter units to reduce fouling of the finer pore units. MF/RO is a common combination.

Electrodialysis is another membrane process available. According to the United States Bureau of Reclamation publication, “Managing Water in the West” (2010):

> *Electrodialysis (ED) is an electrochemical process in which ions migrate through ion-selective semipermeable membranes as a result of their attraction to two electrically charged electrodes. ED is able to remove most charged dissolved ions. Electrodialysis Reversal (EDR) is similar to ED but the polarity of the electrodes is regularly reversed, thereby freeing accumulated ions on the membrane surface. This process minimizes the effect of inorganic scaling and fouling by converting product streams into waste streams. This process requires additional plumbing and electrical controls, but increases membrane life. EDR does not require added chemicals, and eases cleaning as well.*

3.5.4 Advanced Oxidation Processes

Some compounds are not effectively removed by conventional and tertiary treatment, chemical precipitation, ion exchange, or membranes. A class of emerging contaminants, including endocrine disrupting chemicals (EDCs) and pharmaceuticals and personal care products (PPCPs), fall in this category. Although not completely understood, their potential adverse effects on public health are of growing concern and may be more widely regulated in the future. Other organic compounds, such as the family of nitrosamines, have demonstrated adverse health effects. Nitroso dimethyl amine (NDMA), a potent carcinogen formed by reaction of organic nitrogen and nitrite, is one compound of this family that has received much recent regulatory scrutiny.

Many recycled water providers are using advanced oxidation processes (AOP) to remove emerging contaminants, NDMA, and other synthetic organics with potential adverse health effects. In many cases, AOP are utilized in IPR applications. AOP relies on the synergistic application of multiple oxidants, ultraviolet (UV) light irradiation, or both to create highly active hydroxyl radicals. The most popular oxidants employed in AOP are hydrogen peroxide (H_2O_2) and ozone (O_3). Process configurations for AOP often include more than one oxidant (e.g. UV/H_2O_2, UV/O_3, H_2O_2/O_3, and $UV/H_2O_2/O_3$), as it has been shown that the effective oxidizing power of hydroxyl radicals is much higher than either O_3 or H_2O_2 alone.

3.5.5 Riverbank Filtration

Riverbank filtration (RBF) utilizes the natural filtration capacity of the soils and alluvial sediments between a river bed and adjacent recovery well fields. The process is often used for potable water but is also used as part of an overall treatment scheme to recycle water from effluent-dominated streams or recharge basins. Water in the stream or basin percolates into the ground, where biological and chemical processes in soils remove organic and inorganic contaminants, whereupon the treated water is recovered by wells that reach into the water table. The distance between the river bank and the recovery wells (and hence the available residence time in the subsurface strata) must be adequate to remove turbidity, pathogens, and solids. Favorable hydrogeological properties of the soils and sediments are also necessary for successful treatment and economical well productivity. When hydrogeological conditions are appropriate, RBF requires only recovery wells, pumps, and piping. This can be much less costly than tertiary filtration.

3.5.6 Constructed Wetlands

Constructed wetlands (CW) are artificial wetland systems that mimic natural wetlands to remove contaminants from the water. CW can be either free surface or subsurface wetlands. Free surface wetlands (FSW) flow above ground and provide habitat for fish, birds, and other wildlife but must be carefully managed to avoid mosquito production and algal blooms. Subsurface wetlands or vegetated submerged bed (VSB) wetlands flow below ground in a gravel media. Subsurface wetlands avoid the problems with algae and mosquitoes.

Various contaminant removal mechanisms are present in wetlands, including sedimentation, filtration, adsorption, volatilization, biological uptake, biodegradation, and photolysis (USEPA, 2000). SS can be removed via sedimentation because of the slow movement of water through the wetland. Subsurface wetlands provide filtration for additional solids removal. Adsorption of contaminants onto sediments or biomass allows sequestration of contaminants. Biological uptake achieves this as well. Biodegradation is driven by autotrophic or heterotrophic bacteria suspended in the water, attached to plants, or within the soils. Depending on the depth of the sediment or thickness of the biofilm, aerobic, anoxic, or anaerobic conditions exist. FSW have large surface areas exposed to sunlight, which promotes photolysis of contaminants. An added benefit of CW technology is its inherent ability to create wildlife habitat and provide recreational value even as it treats the water for recycling.

CW is becoming an attractive final polishing step for recycled water. A typical example of a successful CW is the joint U.S. Army Corps of Engineers and City of Phoenix Tres Rios

Environmental Restoration Project at the Regional 91st Avenue Wastewater Treatment Plant. The Tres Rios CW has been in operation since 2000.

3.5.7 Granular Activated Carbon Adsorption

Granular activated carbon (GAC) can efficiently remove organic compounds from water. The water is passed through a bed of GAC media, much like a filter. GAC is essentially charcoal that has been activated at very high temperatures. Activation creates billions of tiny pores in the carbon that produce large amounts of active surface area. Organic compounds in the water adsorb onto the carbon and are thus removed from the bulk stream. When all available adsorption sites are filled, the GAC is spent and must be reactivated. GAC is often used to help reduce the formation of disinfection byproducts by removing the organic precursors. GAC will also remove many troublesome synthetic organics found in recycled water.

3.5.8 Summary of Advanced Treatment Applications

Table 3.4 summarizes the various advanced treatment processes and their application in recycled water treatment.

Table 3.4. Advanced Treatment Processes Summary

Process	Technology	Applications
Adsorption	Granular Activated Carbon	Dissolved Organics Removal
Advanced oxidation	UV/H_2O_2, UV/O_3, H_2O_2/O_3, and $UV/H_2O_2/O_3$	NDMA, EDCs, PPCPs, and other natural and synthetic organics removal
Chemical precipitation	iron or aluminum salt or polymer coagulation or lime softening	organics, inorganics, SS, hardness, or TDS removal
Constructed wetlands	free surface wetlands subsurface wetlands	organics, inorganics, and nutrient removal
IX	fixed bed IX or magnetic resin IX	inorganics, organics removal
Membrane treatment	MF, UF	SS, turbidity, microorganism removal
	NF, RO, MF/RO	turbidity, microorganism, TDS removal
	electrodialysis, electrodialysis reversal	TDS removal
Riverbank filtration	riverbank filtration	SS, turbidity, microorganism removal

Notes: EDC=endocrine disrupting compounds; H_2O_2=hydrogen peroxide; IX=ion exchange; MF=membrane filtration; NF=nanofiltration; NDMA=nitroso dimethyl amine; O_3=ozone; PPCP=pharmaceutical and personal care products; RO=reverse osmosis; SS=suspended solids; TDS=total dissolved solids; UF=ultrafiltration; UV=ultraviolet

3.5.9 Advanced Treatment Case Studies

Several case studies are presented to illustrate how advanced treatment technologies are being implemented for water recycling. The trend among all case studies is the multiple barrier approach to treat water destined for IPR.

3.5.9.1 Scottsdale Arizona Water Campus Water Reclamation Plant

The Water Campus Water Reclamation Plant (WRP) combines conventional activated sludge, tertiary filtration, MF/RO, and AOP (soon to be implemented with UV/O_3) to meet its recycled water requirements. Depending on the season, WRP effluent is used for irrigation or recharged to the aquifer. During the summer, most of the effluent is delivered to golf courses for irrigation. The WRP uses MF/RO as needed to reduce TDS and sodium, which are particularly detrimental for turf irrigation. During the winter, the WRP recharges the aquifer through vadose-zone injection wells. Because the aquifer may ultimately become a potable water aquifer, the city has implemented a multiple barrier approach. The MF/RO process effectively removes any pathogens that may have escaped disinfection. The AOP process is designed to remove EDCs and NDMA.

3.5.9.2 San Diego Advanced Water Purification Facility Demonstration Project

An advanced water purification facility is currently planned to augment San Diego's water supply (City of San Diego, 2013). This project will treat recycled water from the North City Water Reclamation Plant (NCWRP) and deliver the treated water to the San Vicente Reservoir to augment surface water inflows. This treatment scheme is typical of an IPR approach. NCWRP effluent is disinfected tertiary recycled wastewater, and the advanced water purification facility will include MF, RO, and AOP (see Figure 3.6). This combination provides multiple barriers to protect public health.

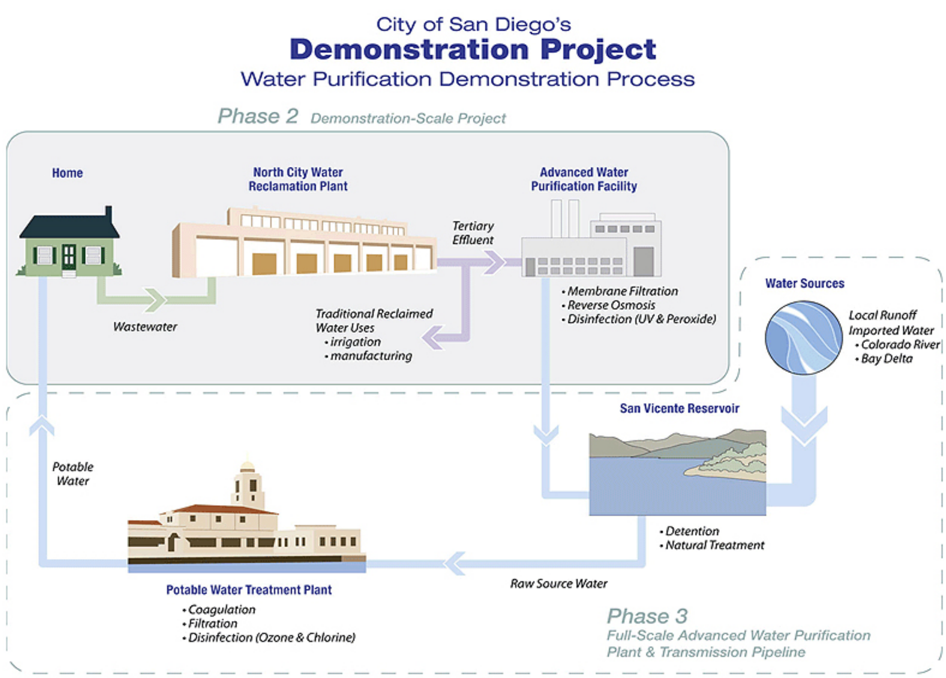


Figure 3.6. San Diego advanced water purification facility demonstration project schematic.

3.5.9.3 Aurora Water Prairie Waters Project

Aurora, CO, is augmenting its surface water supplies by tapping into the South Platte River as an indirect source for potable water. A large percentage of water in the South Platte originates from the Denver Metro Water Reclamation District treatment facilities and contains industrial and agricultural runoff. Aurora is implementing a multiple barrier approach. South Platte water is first treated through RBF as it is pumped from a well field along the river. It is further treated through aquifer recharge and recovery. The water is pumped to recharge basins and percolates into the ground a second time and is recovered from the wetlands with a second well field. This water is delivered to an advanced treatment facility that employs precipitation softening, biological filtration, GAC filtration, and UV/H_2O_2 advanced oxidation. Aurora chose to not include membranes in the process because membranes, particularly RO, waste a significant portion of the water (20%) as a waste brine stream. The Aurora well field and recharge basins are shown in Figure 3.7.

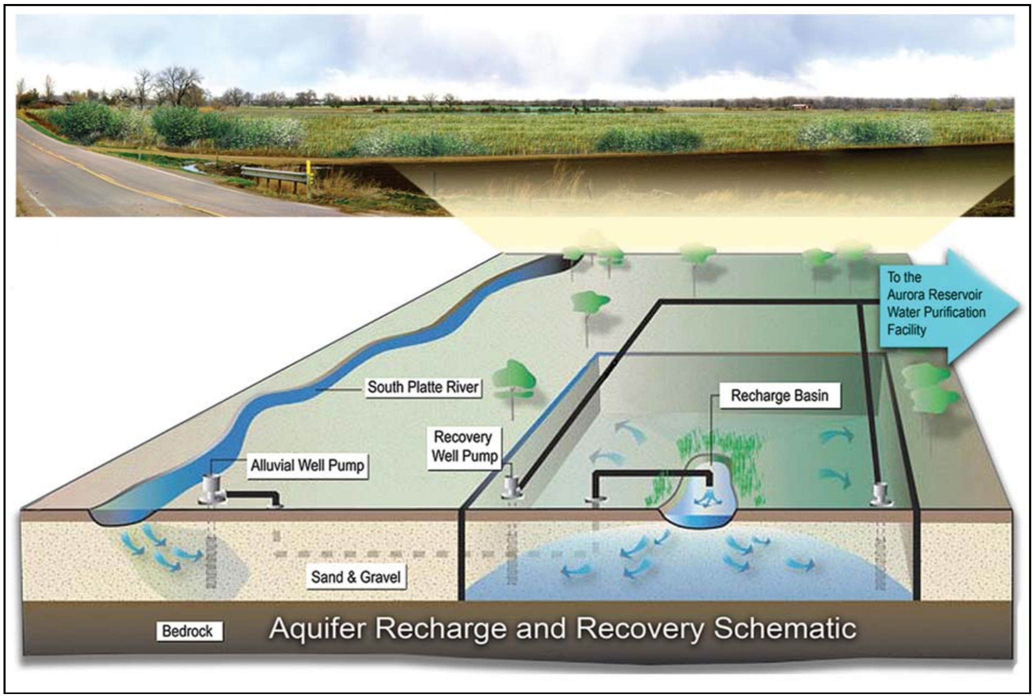


Figure 3.7. Aurora aquifer recharge and recovery schematic.

3.6 Disinfection Technologies

Pathogens are a class of microorganism contaminants with potential adverse human health effects. Disinfection is typically used to deactivate pathogens, and five types of disinfection have gained favor in recent years. These include combined chlorine, free chlorine, chlorine dioxide, ozone, and UV light. The effectiveness of these treatments is assessed in the following figure published in *Water Treatment Principles and Design* (Crittenden, 2005). Figure 3.8 illustrates the required product of the concentration or intensity and the reaction time (Ct and It) for inactivation of a range of pathogens.

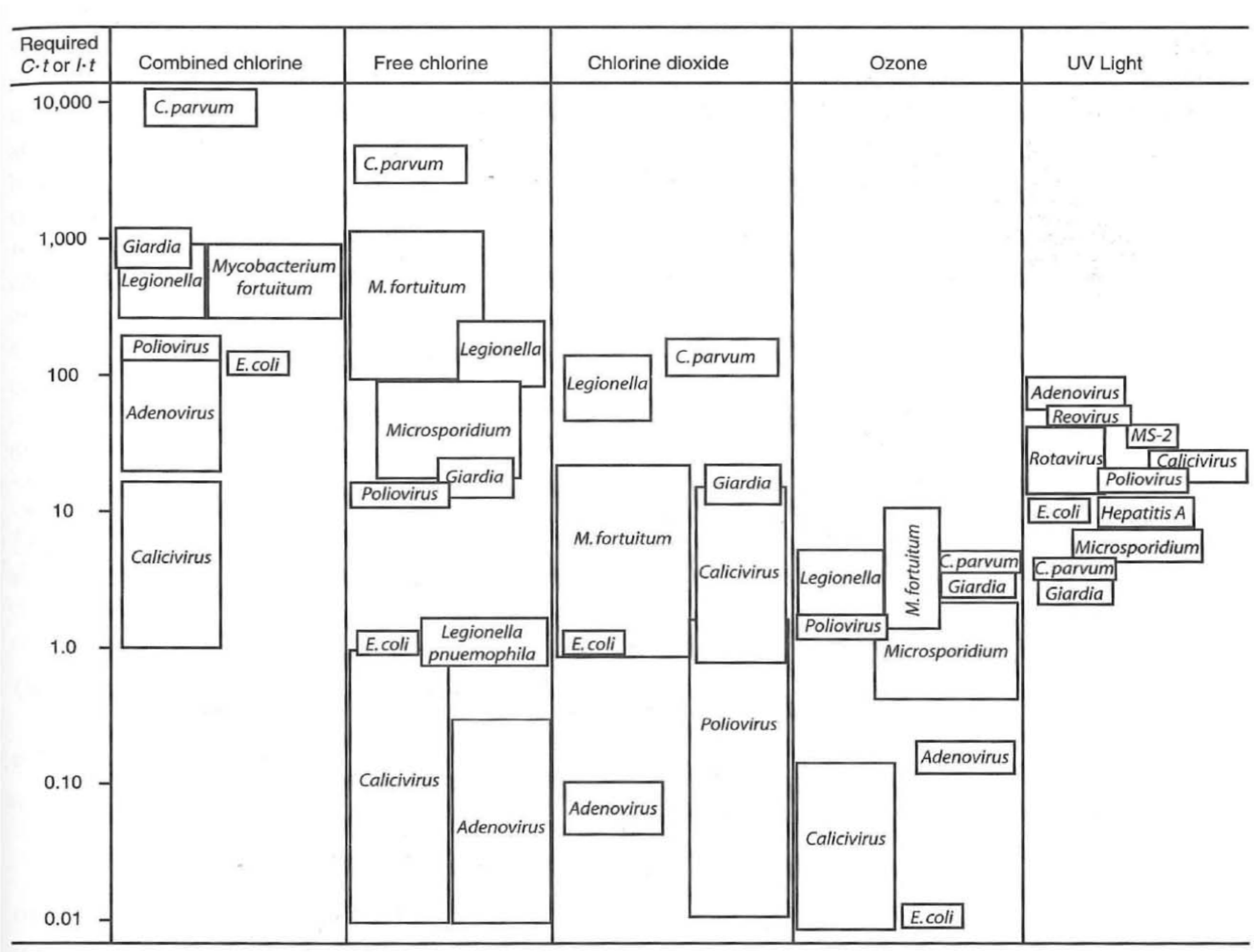


Figure 3.8. Disinfection requirements for 99% pathogen inactivation.

Figure 3.8 suggests that chlorine-based disinfection requires higher dosage for parasites such as *Cryptosporidium parvum*, whereas O_3 and UV light require a lower dose. The dose requirement alone should not dictate which disinfection to use; other important factors to consider include the creation of chemical byproducts, residual disinfectant stability, capital and operational cost, upstream treatment requirements, operation, and safety. Table 3.5 lists the five disinfection processes and discusses these factors.

Table 3.5. Characteristics of Five Common Disinfectants

Disinfectant	Chemical Byproducts	Residual Stability	Capital and Operating Costs	Upstream Treatment Requirements	Operation and Safety
Combined chlorine	traces of THMs and HAAs	most stable residual	low capital and operating cost	source of ammonia required	chlorine gas and sodium hypochlorite solutions are hazardous
Free chlorine	THMs and HAAs	stable residual	low capital and operating cost	secondary treatment only	same as combined chlorine
Chlorine dioxide	chlorite and chlorate ions	stable residual	high operating costs	secondary treatment only	chlorine and chlorite powder are hazardous
Ozone	bromate	no residual; small reactors subject to short circuiting	relatively high capital and operating costs (electricity)	tertiary treatment necessary	avoids hazardous chemicals
UV	none	no residual; small reactors subject to short circuiting	relatively high capital and operating costs (electricity)	tertiary treatment necessary	avoids hazardous chemicals

Notes: HAA=halo acetic acid; THM=trihalomethane; UV=ultraviolet

Disinfection is arguably the most important process for recycled water, and many factors should be considered when selecting a process. If the recycled water reaches a potable aquifer, disinfection byproducts from chlorine may pose a problem. In addition, residual is needed to prevent growth of pathogens or nuisance biofilms in the recycled water distribution system. Often a single technology cannot meet the process needs, and more than one process is used. Because O_3 or UV do not provide chlorine residual in the recycled water distribution system, chlorine is commonly added at downstream chemical injection stations or reservoirs to provide supplemental disinfection.

3.7 Application of Treatment Technologies

The end use of recycled water determines which upstream treatment processes are necessary. In some cases, recycled water standards may be more lenient than the associated wastewater treatment discharge permit levels. In other cases, the recycled water treatment train must include significant advanced treatment. Table 3.6 summarizes various uses of recycled water and suggested treatment processes to reach the required water quality.

Table 3.6. Treatment Process and Water Quality Summary

Use	Process Train	Water Quality*
Irrigation		
Food crops where water contacts edible portion	Conventional treatment with tertiary filtration and disinfection	Disinfected tertiary
Landscape irrigation with public access	Same as previous	Same as previous
Food crops where water does not contact edible portion	Conventional treatment with disinfection	Disinfected secondary–2.2
Landscape irrigation with controlled public access	Conventional treatment with disinfection	Disinfected secondary–23
Pasture irrigation for milk production	Conventional treatment with disinfection	Disinfected secondary–23
Crops not eaten by humans, pasture irrigation	Conventional treatment	Un-disinfected secondary
Impoundments		
Unrestricted public access	Conventional treatment with tertiary filtration and disinfection	Disinfected tertiary
Restricted public access	Conventional treatment with disinfection	Disinfected secondary–2.2
Decorative landscape impoundments without fountains	Conventional treatment with disinfection	Disinfected secondary–23
Industrial Cooling		
Cooling tower or spray generating equipment	Conventional treatment with tertiary filtration and disinfection	Disinfected tertiary Potentially advanced treatment for TDS or hardness removal
Without cooling tower or mist producing equipment	Conventional treatment with disinfection	Disinfected secondary–23 Potentially advanced treatment for TDS or hardness removal
Indirect Potable Reuse		
Reservoir augmentation	Conventional, tertiary, and advanced treatment	Site specific
Groundwater recharge	Conventional, tertiary, and advanced treatment	Site specific
Other Purposes		
Flushing toilets Priming drains Industrial process water that may contact workers Structure fire protection Decorative fountains Water for backfill around potable piping Snow making Car washing Boiler feed water Nonstructural fire fighting Water for backfill, including around nonpotable piping Mixing concrete Dust control Cleaning roads and sidewalks Industrial process water that does not contact workers Water used to flush sanitary sewers	Conventional treatment with tertiary filtration, advanced treatment, and disinfection Conventional treatment with advanced treatment and disinfection Conventional treatment	Disinfected tertiary Disinfected secondary–23 Un-disinfected secondary

Notes: *=as defined by California Title 22, see Table 2.14; TDS=total dissolved solids

Evaluation of treatment and disinfection processes for water recycling depends upon the end use and specific contaminant removal requirements. Often conventional treatment is adequate, but as TDS and emerging contaminant removal become necessary, advanced treatment is needed. The technologies for producing excellent reuse water are available; the challenge for the reuse community is selecting and combining processes to provide this treatment efficiently, safely, and cost effectively.

Chapter 4

Recycled Water System Case Studies

The research team conducted a series of case studies to support the overall study objectives. The investigative case studies began with a questionnaire to collect information on the design, operation, and environmental conditions at each utility. The study team met with each case study partner to review the causes of specific water quality issues and potential remedies. Sampling was also conducted at select locations to support the analyses presented in Chapter 5.

The case studies targeted utilities from different regions of the United States where the usage of recycled water is widely practiced. In the selection process, attention was given to a broad range of treatment technologies, storage and distribution system sizes, operational schemes, source water qualities, and types of end use.

4.1 Typical Recycled Water Operations

Recycled water is distributed with a dual-piping network that keeps recycled water pipes (light purple) completely separate from potable water pipes. Distribution storage is required to provide a balance between production and demand of recycled water; recycled water systems tend to have wider swings in seasonal demand than typical potable systems. Storage requirements can be either short- or long-term, with short-term storage usually ranging from 1 day to 1 week. Long-term storage is usually provided because of seasonal variation between production and demand of recycled water.

Literature reviews have shown that long residence time in distribution and storage systems leads to degradation of water quality, regrowth of microorganisms, nitrification, odor problems (USEPA, 2002), and biofilm formation (Narasimhan et al., 2005). Numerous recent and current research projects involve the factors that affect the reclaimed water quality in the distribution and storage systems. These factors can be categorized as physical, chemical, and biological (Metcalf & Eddy, 2007).

Potable water is subject to relatively minor changes in quality in distribution and storage systems when compared to recycled water. Recycled water usually contains a higher amount of organic matter (Drewes and Fox, 1999), which reacts with chlorine and results in depletion of the disinfectant residuals (Ryu et al., 2005). High carbon contents (TOC, dissolved organic carbon [DOC], AOC, biodegradable dissolved organic carbon [BDOC]) in recycled water also serve as nutrients for bacterial growth (Jjemba et al., 2010; Liu et al., 2002; LeChevallier et al., 1996; Escobar et al., 2001). Ammonia in recycled water reacts with chlorine and forms chloramines, which is a less effective disinfectant than chlorine. Therefore, the combined effects of high nutrient levels and low disinfectant residuals, along with changes in physical and chemical parameters of recycled water, initiate microbial growth in the distribution systems (Ryu et al., 2005; Kirmeyer et al., 2001). As a result, maintaining the quality of the treated recycled water as it moves through storage and distribution systems can be challenging.

Water age can be reduced by distribution system flushing, increasing storage tank turnover, reducing storage volume, changing operational methods, and eliminating dead zones (Kirmeyer et al., 2000). Numerous research projects have shown that a well-calibrated hydraulic model can be used for macroevaluation of water age in the distribution system (Wilkes, 2008) and determine the optimal point of flushing, flushing frequency, and rates. Routine monitoring of indicator parameters of recycled water quality includes chlorine residual, dissolved oxygen (DO), temperature, turbidity, indicator organisms, and pH. Current research aims at developing a target matrix of recycled water quality parameters to maintain consistently high recycled water in storage and distribution systems.

4.2 Recycled Water Case Study Overview

Recycled water contains a large microbial community and high levels of nutrients; therefore, recycled water quality changes over time as it travels through the distribution system from the point of production to the end users (Icekson-Tal et al., 2003). Recycled water distribution systems may encompass vast networks of pipes and long-term seasonal storage tanks, which increases the potential for extensive biofilm growth where bacterial pathogens can reside (Icekson-Tal et al., 2003; Oregon Department of Environmental Quality, 2009). Variations in treatment, operational, or environmental conditions also impact recycled water quality. The quality of recycled water is generally monitored at the points of entry to distribution systems to assess compliance; however, it is seldom monitored in the distribution system. Therefore, the water quality transformations that occur during distribution and storage are as yet not well characterized.

4.2.1 Case Study Approach

The research team developed a questionnaire (provided as Appendix A) to gather information on reuse types, utility and treatment descriptions, distribution system and storage descriptions, and water quality monitoring. The research team targeted the following utilities for the case studies:

- City of Scottsdale, AZ. Southwest region representation, focus on evaluation of RO treatment
- Dublin San Ramon Services District, CA. Northern California representation, past water quality issues during winter
- East Bay Municipal Utility Department, CA. Northern California representation, indoor recycled water usage
- City of Westminster, CO. Central location representation, long-term storage in the distribution system during winter
- Trinity River Authority, TX. Central location representation, long-term open seasonal storage
- Hillsborough County, FL. East coast representation, past water quality concerns

In addition to the case studies listed previously, extensive water quality sampling and hydraulic modeling were performed at Tucson Water (AZ) and Global Water Resources (Maricopa, AZ) recycled water systems in support of the study objectives (see Chapter 5).

The questionnaire was distributed electronically to each utility to obtain initial input, followed by research team site visits. After receiving input from the case study utilities, the research team selected two of the systems for water quality sampling to supplement the data collected from Tucson Water and Global Water Resources. This effectively allowed the study team to measure the impacts of a wider variety of treatment and disinfection practices. Sampling points within the case study systems were selected based on end-usage types and distance from treatment/source.

4.2.2 Sampling Procedures and Laboratory Analyses

The research team developed detailed sampling and laboratory procedures as part of the case study process (Appendix B). Water quality in the case study distribution systems was monitored by analyzing monthly grab samples for a period of 4 months from the selected sampling locations. Table 4.1 shows the selected parameters and preferred method for analyses for measuring distribution system water quality.

4.3 Case Study Descriptions

4.3.1 City of Scottsdale Water Reclamation Facility

The City of Scottsdale Water Reclamation Facility (WRF), located at the Scottsdale Water Campus, treats wastewater using a combination of conventional and advanced wastewater treatment technologies, including MF and RO. The recycled water is used to irrigate golf courses and recharge groundwater aquifers through vadose-zone recharge wells.
The rationale for selecting the City of Scottsdale included:

- Combination of conventional and advanced treatment technologies
- Includes groundwater recharge end use
- Customer-driven desired water quality

4.3.1.1 Background and Utility Description

Scottsdale's primary 20-MGD WRF, located at the Water Campus, uses conventional treatment technology to treat wastewater for irrigation of golf courses associated with the city's Reclaimed Water Distribution System (RWDS). The WRF includes an activated sludge process with biological nutrient removal, followed by tertiary treatment and disinfection, which provides Arizona Class A+ recycled (reclaimed) water. A portion of the Class A+ recycled water is further treated through the Advanced Water Treatment (AWT) facility for groundwater recharge through a series of vadose-zone wells surrounding the Water Campus. The AWT consists of MF, RO, and post-treatment stabilization (WateReuse Association, 2009).

Table 4.1. Common Analyses and Methods

Analysis	Type	Method	Bottle Type	Preservative	Hold Time	Notes
Aeromonas	micro	EPA 1605	sterile 1-L polypropylene	sodium thiosulfate	30 hours	Transport on ice separate from other sample types.
Alkalinity	inorganic	SM 2320B	500-mL plastic	none	14 days	-
Ammonia	inorganic	EPA 350.1	125-mL plastic	sulfuric acid	28 days	-
Coliform, fecal	micro	SM 9222-D	sterile 1-L polypropylene	sodium thiosulfate	6–24 hours	Transport on ice separate from other sample types.
Coliform, total	micro	SM 9222-B	sterile 1-L polypropylene	sodium thiosulfate	6–24 hours	Transport on ice separate from other sample types.
Dissolved organic carbon	organic	SM 5310C	125-mL amber glass	none	28 days	-
E. coli enzyme substrate coliform test	micro	SM 9223B	125-mL sterile IDEXX	sodium thiosulfate	6 hours	Transport on ice separate from other sample types.
Heterotrophic plate count	micro	SM 9215C	sterile 1-L polypropylene	sodium thiosulfate	24 hours	Transport on ice separate from other sample types.
Nitrate/nitrite	inorganic	EPA 353.1	125-mL plastic	sulfuric acid	28 days	-
Total dissolved solids	inorganic	EPA 160.1/ SM 2540C	500-mL plastic	none	7 days	-
Total Kjeldahl nitrogen	inorganic	EPA 351.2	125-mL plastic	sulfuric acid	28 days	-
Total organic carbon	organic	SM 5310C	40-mL amber glass	sulfuric acid	28 days	-
Total suspended solids	inorganic	EPA 160.2/ SM 2540D	1-gallon plastic	none	7 days	-

Notes: Microbiological sample bottles (polypropylene) were filled to the line with ample headspace, using sterile sampling technique. Septum cap vials were filled with zero headspace.

Recycled water is conveyed to Reservoir B (8 MG) located at the Water Campus, which serves as a forebay for the distribution system pumps. The city provides reclaimed water to 20 golf courses with a total demand of 14 MGD. Raw Central Arizona Project (CAP) water is also available to a limited number of golf courses (Golf Club of Scottsdale and Desert Mountain North and South). During the late fall (September) and spring (May) time periods, when the golf courses are over-seeding their turf, recycled water with a total sodium content of less than 125 mg/L is required. The city provides a blend of raw CAP water with recycled water from Reservoir B to meet the salinity target.

The golf course users recently approached the city expressing a desire to receive year-round recycled water with a total sodium content of less than 125 mg/L (WateReuse Association, 2009). In order to achieve this year-round goal and minimize the dependency on CAP raw water, Scottsdale is currently constructing an expansion of the AWT to bring its capacity up to 20 MGD, which would match the treatment capacity of the WRF. This expansion will enable the city to provide water of the required salinity level, less than 125 mg/L, to the golf courses year-round and reduce the dependency on CAP water for nonpotable uses.

4.3.1.2 Operation, Storage, and Distribution System Description

The residence time of treated effluent in Reservoir B is less than half a day. The RWDS (see Figure 4.1) is approximately 28 miles in total length and has four booster stations, with the first located at Reservoir B.

- **Site 96:** Located at Reservoir B at the Water Campus, the facility consists of 9 200 HP constant speed pumps and 1 variable speed pump. Water is not static in the system except during periods of significant rainfall when there is no demand from the golf courses. This station supplies Site 97 and the golf courses beyond, as well as the Silverleaf, DC Ranch, and Gray Hawk North and South turnouts, directly.
- **Site 97:** Located at Pima Road and Los Gatos Drive, this station is supplied from Site 96. This is an inline pump station consisting of 6 200 HP constant speed pumps and 1 200HP variable speed pump. Site 97 supplies Site 98 as well as the Desert Highlands and Troon East golf course turnouts.
- **Site 98:** Located at Pima Road and Dynamite Boulevard, this station is supplied from Site 97. This is an inline pump station consisting of 6 200 HP constant speed pumps and 1 200 HP variable speed pump. Site 98 supplies Site 99 as well as the Terravita, Boulders North, Boulders South, Estancia, Troon North, Whisper Rock Upper, and Whisper Rock Lower golf course turnouts.
- **Site 99:** Located at Pima Road and Cave Creek Road, this station is supplied from Site 98. This is the final RWDS station. It consists of 3 100 HP constant speed pumps, 2 100 HP variable speed pumps, and 1 0.05-MG coated steel reservoir that acts as a buffer for the inline pump stations and temporary storage to keep the supply line from the inline pump stations full when the system is offline. Site 99 supplies Legend Trail, Desert Mountain, and Mirabel Club.

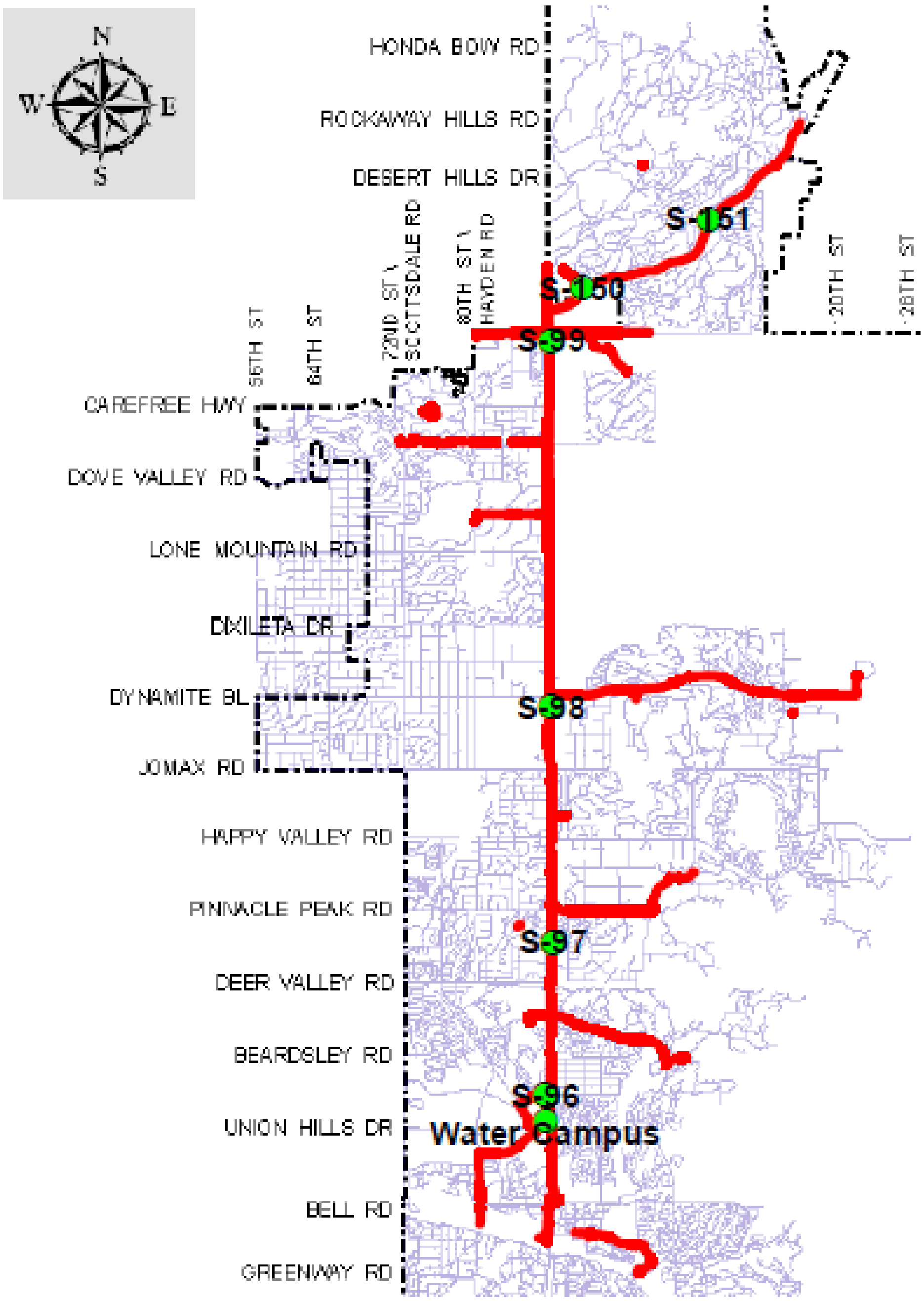


Figure 4.1. Scottsdale RWDS pipeline and booster stations.

Source: City of Scottsdale

The distribution system booster stations are inline with essentially no storage. The city can move recycled water at a very high volume through the existing 36-inch RWDS line. It takes less than 6 hours to move water from Reservoir B to the farthest part of the system. Because of the high volume and lack of storage, there is generally low water age in the RWDS. The city operates the system based on a demand set point. Summer and winter operations of the RWDS are generally the same, except for recycled water demands. Unlike many recycled water systems, higher usage has been observed during the winter months compared to the summer months because of the high number of winter residents in the Scottsdale area. Demand depends on time of day, and daily variations tend to be greater than seasonal variations.

4.3.1.3 Compliance Monitoring

Under normal conditions, the city only tests recycled water quality at Reservoir B, not in the distribution system. Water quality parameters such as TDS, residual chlorine, turbidity, nitrate, nitrite, ammonia, phosphorus, pH, fecal coliform, and others are monitored twice daily (day and night samples). In addition to the water quality parameters, the city also monitors Langelier index for corrosion potential.

4.3.1.4 Sampling Locations for the Case Study

Because the city does not have a water age issue, it was decided by the research team that sampling from the end users will not be required. The following sampling locations were selected for the RWDS pipeline to monitor parameters as stated in Table 4.1 for 4 months starting from October 2010:

- WRF plant effluent (Reservoir B influent)
- Reservoir B effluent or Site 96 booster pump station
- Site 97 booster pump station
- Site 98 booster pump station
- Site 99 booster pump station

Sampling results for Scottsdale and other case study locations are included in the general discussion of Chapter 5.

4.3.2 Dublin San Ramon Services District

The San Ramon Valley Recycled Water Program (SRVRWP) is a water-recycling project jointly sponsored by the Dublin San Ramon Services District (DSRSD) and the East Bay Municipal Utility District (EBMUD). DERWA (DSRSD EBMUD Recycled Water Authority) is a Joint Powers Authority wholesaler formed in 1995 between DSRSD and EBMUD to supply recycled water to DSRSD and EBMUD to serve their respective service areas. The Water Recycling Plant (WRP) consists of two separate treatment processes, either sand filtration or MF, to produce recycled water (DERWA, 2009). The reclaimed effluent is used to irrigate schoolyards, parks, roadway medians, and golf courses.

The rationale for selecting DSRSD included:

- Use of both conventional and AWT technologies
- Buried and aboveground storage tanks
- Long-term storage up to 21 days during off-peak demand

4.3.2.1 Background and Utility Description

The wastewater treatment plant (WWTP), located at the Regional Wastewater Treatment Facility, has a maximum capacity to process 17.0 MGD of wastewater (average dry weather flow) and is the source of secondary effluent that is further processed by the WRP. Depending on demand, the secondary effluent either passes through the sand filtration or the MF system. The sand filtration system has a capacity of 9.7 MGD and is used during summer months when the demand is high; the MF system has a capacity of 3.0 MGD and is used during winter months when the demand is low (DERWA, 2010). Both systems are highly automated with continuous monitoring. The sand filtration process uses chlorinated secondary effluent and includes sedimentation/flocculation, sand filtration, and UV-disinfection steps. The MF process uses un-disinfected secondary effluent and includes 0.1 to 10 µm pore MF membranes followed by UV disinfection.

Recycled water from the WRP is conveyed to the Pump Station R1 wet well, and sodium hypochlorite is added at a dose of 5 ppm as residual disinfectant. The Pump Station R1 wet well serves as a forebay for the distribution system pumps. DSRSD provides reclaimed water to residential and commercial irrigation customers, with a summer 2011 peak day demand of 5.98 MGD. DSRSD has been having challenges with water quality in the winter, notably the loss of residual disinfectant that was due to nitrification. In order to resolve this issue, the recycled water is drained back to the WWTP for treatment. In addition, algae causes turbidity problems throughout the entire plant. The sources of algae are facultative sludge lagoons and effluent storage basins. The strategy for algae remediation is to drain the basins down overnight and then refill during the day.

4.3.2.2 Operation, Storage, and Distribution System Description

DSRSD provides recycled water to customers through the DERWA and DSRSD recycled water distribution system (see Figure 4.2). The DSRSD recycled water distribution system is approximately 55 miles in total length. DERWA and DSRSD operate five pump stations for recycled water distribution.

- **Pump Station R1:** Located at the WRP and supplies recycled water to reservoir R100 and pressure zone R1.
- **Pump Station R20:** Supplies recycled water to reservoir R20 and pressure zone R20.
- **Pump Station R200B:** Supplies recycled water to reservoir R200 and pressure zone R200.
- **Pump Stations R300 and R300B:** Supply recycled water to reservoir R300 and pressure zone R300.

The DERWA distribution system includes 2 4.5-MG reservoirs, and DSRSD separately operates two additional recycled water reservoirs connected to the system.

- **Reservoir R20:** 1.5 MG capacity, buried concrete reservoir
- **Reservoir R100:** 4.5 MG capacity, buried concrete reservoir
- **Reservoir R200:** 4.5 MG capacity, buried concrete reservoir
- **Reservoir R300:** 0.45 MG capacity, welded steel tank

Water age in the reservoirs varies seasonally. During peak demands (summer), the water age varies between 1 and 3 days. During off-peak demand or winter months, the water age can range up to 21 days. In order to maintain recycled water quality, DSRSD chlorinates at the reservoirs with sodium hypochlorite at a dose of 7 ppm to maintain the target Cl^- level of 5 mg/L. Along with seasonal variation, diurnal variation exists for recycled water demand.

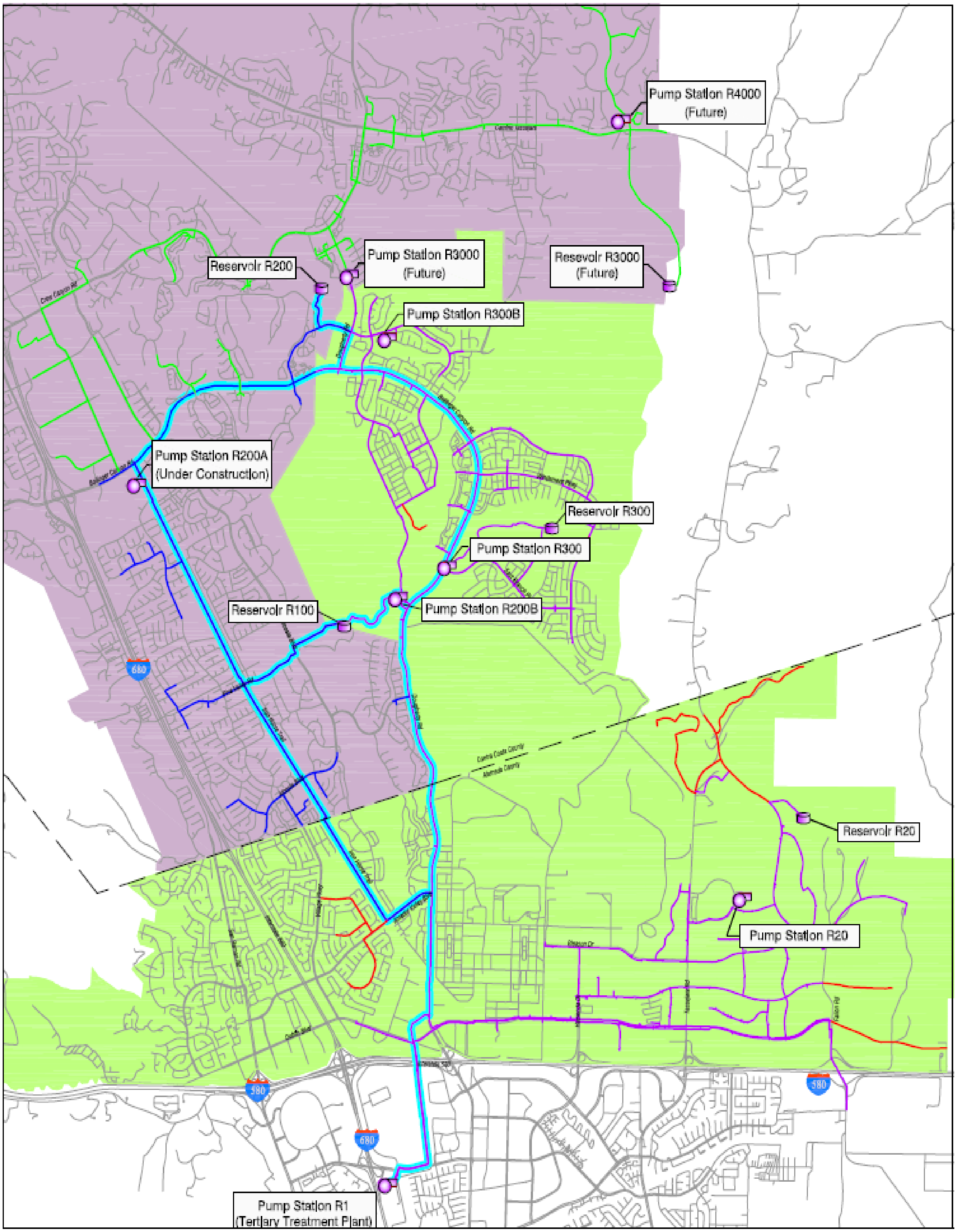


Figure 4.2. DERWA recycled water distribution system.

Source: [DERWA, 2009]()

4.3.2.3 Compliance Monitoring

DSRSD routinely performs recycled water sampling and testing at distribution system and storage tank locations. Water quality parameters such as TDS, DO, conductivity, residual chlorine, alkalinity, turbidity, nitrate, nitrite, ammonia, TSS, pH, and total and fecal coliform are monitored three times a week to daily.

4.3.2.4 Sampling Locations for the Case Study

The following three sampling locations were selected for the DSRSD system to monitor parameters as stated in Table 4.1 for 4 months starting from October 2010:

- WRP plant effluent
- Reservoir R20
- Reservoir R200

4.3.3 East Bay Municipal Utility District

East Bay Municipal Utility District (EBMUD) in California supplies more than 9 MGD of recycled water to various end users from several water reclamation facilities/sources such as North Richmond Water Reclamation Plant (NRWRP), San Ramon Valley Recycled Water Program (SRVRWP), East Bayshore Reclaimed Water Project (EBRWP), and EBMUD WWTP. The water recycling processes vary from secondary level to tertiary level of treatment using conventional and advanced treatment processes. EBMUD provides recycled water to numerous sites for irrigation, commercial, and industrial uses.

The rationale for selecting EBMUD included:

- Use of conventional and AWT technologies
- Industrial uses such as cooling towers and boiler feed water
- Indoor uses such as toilet flushing

4.3.3.1 Background and Utility Description

The NRWRP is EBMUD's first major project to produce recycled water for an industrial application. With a design capacity of 5.4 MGD, it is one of the larger industrial cooling water reuse projects in the nation. NRWRP receives secondary effluent from nearby West County Wastewater District and provides tertiary treatment of sand filtration and disinfection. The recycled water is delivered to three cooling towers located at the Chevron Richmond Refinery. Currently, approximately 4.2 MGD of recycled water is being used in the cooling towers.

EBMUD expanded its industrial recycled water program by implementing the Richmond Advanced Recycled Expansion (RARE) recycled water project at the Chevron Richmond Refinery. The RARE project will produce approximately 3.5 MGD of very high quality recycled water for boiler makeup water. The facility receives secondary effluent from West County Wastewater District and provides advanced treatment including MF and RO. Currently, the Chevron Richmond Refinery uses a total of approximately 7.5 MG of recycled water each day.

The SRVRWP also serves part of EBMUD’s recycled water needs. Currently, EBMUD receives 0.9 MGD of recycled water and, at build-out condition, the volume of recycled water will be approximately 2.4 MGD for irrigation customers in portions of Blackhawk, Danville, and San Ramon.

The EBRWP is a multiphased project located at EBMUD's WWTP in Oakland, CA. EBRWP provides recycled water to customers within the cities of Alameda, Albany, Berkeley, Emeryville, and Oakland, including the disadvantaged community of West Oakland. With a build-out capacity of 2.88 MGD, the EBRWP is now producing 0.4 MGD of recycled water. The plant receives disinfected secondary effluent from the EBMUD WWTP and provides advanced treatment including MF and disinfection. Treated effluent will be used to irrigate landscape, flush toilets, restore wetlands, and for industrial purposes. The Shorenstein Building (located at 555 City Center) and the second floor of EBMUD's administration building have been retrofitted with copper and PVC piping, respectively, to use recycled water for toilet flushing.

EBMUD's WWTP treats approximately 75 MGD of municipal wastewater. It produces secondary effluent through an activated sludge process with biological nutrient removal, followed by disinfection. Approximately 6.6 MGD of the treated secondary effluent is being reused at the WWTP for various purposes, including equipment wash-down, mixing chemicals, and landscape irrigation.

4.3.3.2 Operation, Storage, and Distribution System Description

As discussed previously, EBMUD supplies recycled water treated at several facilities. The total length of EMBUD reclaimed waterline is 65 miles within its service area. The treated effluent from the RARE project is conveyed to a 2-MG steel storage tank with a maximum of 12 hours residence time, which is then supplied to boilers at the Chevron Richmond Refinery. The EBRWP effluent will also be conveyed to a 1.5-MG steel storage tank, which will serve as a forebay for the distribution system pumps. No residual chlorine is maintained at the distribution system. EBMUD currently provides recycled water to 57 customer sites within its service area for landscape irrigation. In general, irrigation customers use the highest amount of recycled water during summer months.

4.3.3.3 Compliance Monitoring

Under normal conditions, EBMUD only performs recycled water sampling and testing at the EBRWP outflow, not in the distribution system. Water quality parameters such as DO, residual chlorine, alkalinity, turbidity, nitrate, nitrite, ammonia, pH, and total coliform are monitored. In addition to the water quality parameters, EBMUD is conducting a corrosion study to assess the effect of recycled water from EBRWP on various piping materials. This study will determine whether the recycled water can be supplied to customers for interior uses such as toilet and urinal flushing. Results of the corrosion study were pending as of the writing of this report

4.3.3.4 Sampling Locations for the Case Study

Four sampling locations were selected for the EBMUD system; however, the utility experienced budget and manpower cuts during the course of the study and decided not to collect and analyze samples for the project.

4.3.4 City of Westminster Reclaimed Water Treatment Facility

The City of Westminster Reclaimed Water Treatment Facility (RWTF) in Colorado treats effluent from the Big Dry Creek Wastewater Treatment Facility (BDCWWTF). The two facilities are located on the same property. Effluent from the BDCWWTF is conveyed to the RWTF at times when the influent wet well has available capacity. Any surplus effluent from the BDCWWTF is discharged into Big Dry Creek. The city's recycled water is used to irrigate golf courses, parks, and commercial and public grounds.

The rationale for selecting Westminster included:

- Long-term distribution system storage during off-peak demand
- Previous recording of water quality issues (algae and salinity)

4.3.4.1 Background and Utility Description

The existing RWTF has a current capacity of 6 MGD. The city reached its maximum recycled water demand of 6 MGD in 2008; therefore, Westminster is currently implementing expansion of the RWTF to 10 MGD. The recycled water system has an ultimate goal of 3500 acre-feet per year of demand at build-out. The RWTF receives secondary effluent from the BDCWWTF and provides tertiary-level treatment to generate water suitable for irrigation use. The BDCWWTF process includes an activated sludge process with phosphorus, nitrogen, and biological nutrient removal, followed by UV/chlorine disinfection. The disinfected secondary effluent receives further treatment at the RWTF through coagulation and sand filtration, followed by chlorine disinfection at a dose of 1 to 8 ppm. Excess secondary effluent is dechlorinated (if disinfected by chlorine) before being discharged into Big Dry Creek. Figure 4.3 shows the treatment schematic for Westminster RWTF.

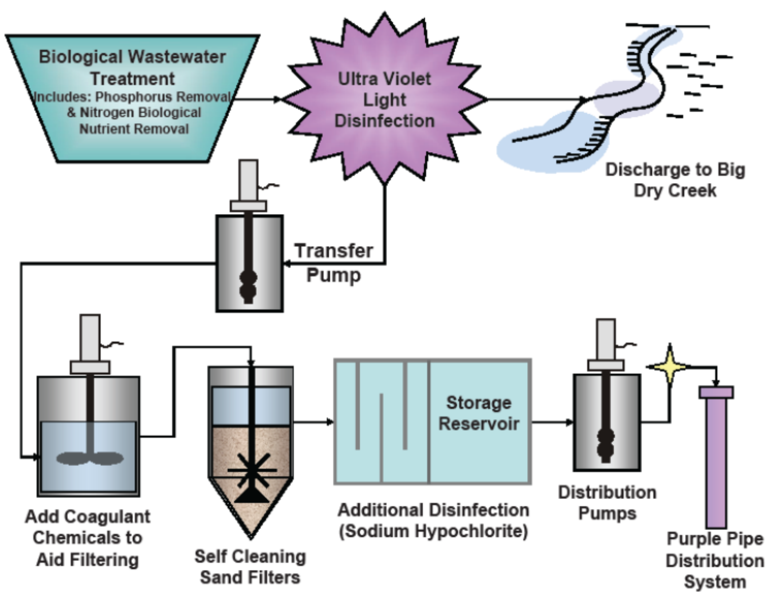


Figure 4. 3. Westminster water reclamation schematic.
Source: City of Westminster

Treated effluent from the RWTF is conveyed first to a 0.5-MG reservoir located downstream of the chlorine contact chamber. A 0.17-MG clear well receives flow from the reservoir and serves as a forebay for the distribution system pumps. The city provides reclaimed water to 85 customers. Raw water from Standley Lake is also available to the city in order to meet peak demand.

4.3.4.2 Operation, Storage, and Distribution System Description

The current system has 0.67 MG of storage available at the plant site. The residence time of recycled water in the reservoir is less than 1 day. The recycled water system is currently a two-zone system with high=pressure requirements to deliver recycled water from the plant to the furthest customer. The distribution pumps provide 175 psi at the discharge header at the plant. The goal is to have a minimum of 70 psi in the distribution system.

Flow rates are based on demand. The city's reclaimed water transmission and distribution system (RWTDS) is 26 miles long and consists of service lines (8- to 10-inch-diameter), feeder mains (12- to 18-inch-diameter), and transmission mains (18- to 30-inch-diameter). Pipe materials vary within the system. There are no intermediate or inline booster pumps on the reclaimed water distribution system. The distribution system also includes a 210,000-gallon painted steel standpipe located at the Westminster City Hall Complex, which is the highest point in the system. No other online storage is available in the distribution system, except for storage provided by the customer, located on the customer's land, and operated independently of the city's system.

The reclaimed water plant only operates March 15 to November 15. Peak demands occur in the middle of summer. Because the water is utilized for irrigation, customers use more water in the peak of summer when the weather is hot and dry. Although the RWTF is not operated during winter months, the distribution system stays charged/pressurized all winter, with water stored in the standpipe, and encounters water age issues. At the beginning of each spring, Westminster drains and cleans the entire reclaimed water facility but not the distribution system. Therefore, the customers receiving reclaimed water in early spring may receive poor water quality that could contain algae, an issue that could be attributed to water aging through the winter season.

4.3.4.3 Compliance Monitoring

The city samples and tests the recycled water effluent from the RWTF but not in the distribution system. On occasion, the city tests water quality within its customer’s storage facility, but this is not done on a regular basis. Water quality parameters such as TDS, residual chlorine, alkalinity, turbidity, nitrate, nitrite, ammonia, TSS, pH, *E. coli*, and phosphorus are monitored. Turbidity and pH are monitored daily, *E. coli* is monitored twice per week, and other parameters are monitored once a week. No sampling was conducted specifically for this study because of utility budget constraints.

4.3.5 Central Regional Wastewater System, Trinity River Authority

The Central Regional Wastewater System (CRWS) operated by the Trinity River Authority (TRA) in Texas treats municipal wastewater to produce high quality recycled water. Recycled water from the CRWS is conveyed to TRA’s reclaimed water pipeline and discharged into a series of open channels and small manmade lakes in the Los Colinas area of the Dallas–Fort Worth metroplex.

The rationale for selecting TRA included:

- Multiple open-surface reservoirs.
- Closed and open channel distribution system.

4.3.5.1 Background and Utility Description

TRA's CRWS receives wastewater from 21 customer agencies including the cities of Dallas, Arlington, Irving, and Grand Prairie. Arlington is the largest contributor. TRA owns a system of large-diameter interceptors longer than 200 miles. TRA takes possession of the wastewater after it enters the interceptors.

CRWS provides complete treatment for monthly average flows of 162 MGD and daily maximum flows of 335 MGD. The treatment processes include an activated sludge process with BOD, SS, and ammonia nitrogen removal, followed by filtration and chlorine disinfection. The chlorine dose is typically between 1.1 and 1.5 mg/L to meet a requirement of 1 mg/L for 20 minutes.

4.3.5.2 Operation, Storage, and Distribution System Description

CRWS is the largest urban water reuse program in Texas, capable of providing 17 MGD of recycled water to the Las Colinas canals, as well as irrigation for numerous area golf courses with an average demand of 2 MGD. CRWS has multiple open reservoirs (Figure 4.4).

Figure 4.4. Open reservoirs at the Central Regional wastewater system.

Source: Trinity River Authority

The detention time in these reservoirs is unknown. TRA's reclaimed water distribution system consists of an 11-mile, 30-inch-diameter pipeline. This pipeline delivers water to a series of open channels and small manmade lakes in the Los Colinas area that lead to Lago de Claire, Bobcat Lake, or Lake Remle. Recycled water is not delivered on a continuous basis. The pipeline is sometimes shut down for several weeks at a time for construction of other facilities. Recycled water is delivered on demand by the Dallas County Utilities and Reclamation District (DCURD).

TRA operates the pipeline, but as soon as recycled water leaves the pipeline it becomes the responsibility of DCURD, which is solely responsible for operating the reuse system using a network of open channels, lakes, creeks, and raw water pumps/pipelines. As TRA's responsibility for the reuse water ends essentially at the end of this pipe, and TRA's permit compliance point is at the inlet to the pipe, no data are available on the recycled water quality in the distribution system.

4.3.6 Hillsborough County

As a part of its water conservation efforts, Hillsborough County, FL, developed an aggressive recycled water program, which is jointly sponsored by the Northwest and South-Central Recycled Water Systems. The Northwest Recycled Water System includes recycled water produced at four regional WWTPs: the Van Dyke WWTP, Dale Mabry Advanced Wastewater Treatment Plant (AWWTP), the Northwest Regional Water Reclamation Facility (NWRWRF), and the River Oaks AWWTP. All of these plants are located in the northwest portion of Hillsborough County. The South-Central Recycled Water System includes recycled water produced at three regional WWTPs: the Falkenburg AWWTP and Valrico AWWTP, located in Central Hillsborough County, and the South County AWWTP, located in South Hillsborough County. The recycled water is used for industrial purposes and to irrigate schoolyards, parks, roadway medians, residential houses, and golf courses.

The rationale for selecting Hillsborough County included:

- Combination of conventional and AWT technologies
- Buried and aboveground storage tanks
- Extensive distribution system, approximately 320 miles of pipeline

4.3.6.1 Background and Utility Description

The WWTPs located within the Northwest Recycled Water System have a maximum capacity of 37.7 MGD.

- Van Dyke WWTP provides advanced secondary wastewater treatment with a bar screen headworks, two extended aeration oxidation ditches, two final clarifiers, shallow and deep bed filters, and a chlorine contact chamber with a permitted design capacity of 1.7 MGD. The existing recycled water system includes pumping facilities and approximately 8 miles of recycled water transmission and 20 miles of distribution main.

- Dale Mabry AWWTP has a permitted design capacity of 6.0 MGD. Treatment at the Dale Mabry AWWTP consists of oxidation ditch systems with chemical addition and denitrification filters for additional nutrient removal. The flow is screened and degritted at the headworks and mixed with return activated sludge in a conditioner basin for a short, anoxic contact time. Large-diameter connecting pipes direct the flow to the two oxidation ditches. Alum is added to the oxidation ditch effluent for phosphorus removal. The clarifier effluent passes through the denitrification deep bed, dual-media filters and activated carbon columns and then the chlorine contact chambers for high level disinfection and post-aeration. Effluent in excess of reclaimed water demands is dechlorinated by addition of sulfur dioxide gas and then flows through a gravity outfall pipe to Brushy Creek. Recycled water is provided to more than 3000 single-family households from this AWWTP.

- NWRWRF AWWTP has a permitted design capacity of 10.0 MGD. Pretreatment is achieved with a bar screen at the headworks and a grit chamber. Pretreated wastewater then flows to the advanced treatment or Bardenpho system, which includes a five-stage biological reactor for removal of organic pollutants and nutrients (nitrogen and phosphorus). The five stages consist of fermentation, first anoxic, aeration, second anoxic, and re-aeration tanks/basins. Following clarifiers, the waste stream then flows through deep bed, dual-media filters and receives high level disinfection in the chlorine contact chamber. The existing recycled water system includes approximately 50 miles of reclaimed water transmission mains and 40 miles of distribution mains.

- The River Oaks AWWTP has a permitted design capacity of 10.0 MGD. Primary treatment is provided by a headworks with two mechanically cleaned bar screens and two primary sedimentation tanks. Secondary treatment is provided by an activated sludge process with a series of three aeration tanks followed by three secondary sedimentation tanks. Sodium aluminate is added to the primary effluent stream for phosphorus removal. A suspended growth denitrification process provides AWT. Methanol is added to the secondary effluent and processed through denitrification and final sedimentation tanks, followed by deep bed filtration, post-aeration, and chlorination to complete the advanced treatment process. Recycled water is provided to approximately 4450 single-family households from this AWWTP.

The WWTPs located within the South-Central Recycled Water System have a maximum capacity of 28.5 MGD.

- Both the Falkenburg and Valrico AWWTPs have permitted design capacities of 12.0 MGD each and identical treatment processes. The preliminary stage removes sand, grit, rags, and other solid debris. The biological process in the secondary treatment train removes conventional organic pollutants and converts ammonia and organic nitrogen compounds into nitrate. Advanced treatment includes a biological process to convert nitrate into nitrogen gas, a chemical process to remove phosphorus, and a physical process to filter additional suspended materials prior to UV disinfection. Recycled water is provided to approximately 25,000 single-family households from the combined Falkenburg and Valrico AWWTPs.

- The South County AWWTP has a permitted design capacity of 4.5 MGD and operates based on the Kruger Bardenpho process. This process incorporates biological nitrification/denitrification, deep bed, dual-media filters for nitrogen removal, biological phosphorus conditioning with sodium aluminate addition for polishing, and chlorination for disinfection. Recycled water is provided to approximately 7000 single family households from this AWWTP.

4.3.6.2 Operation, Storage, and Distribution System Description

The existing combined Northwest Recycled Water System consists of 38 MGD of firm, high service pumping capacity, 54 MG of aboveground and pond storage, and approximately 200 miles of recycled water distribution pipeline (see Figure 4.5). The Van Dyke WWTP pumps recycled water at high pressure from an on-site, 6-MG aboveground tank to the distribution system. Approximate water age in the tank is 1 to 3 days. An on-site lined storage pond (1.68 MG) can provide 1 day of storage. The Dale Mabry AWWTP has two on-site, 5-MG aboveground tanks and a pump station to deliver recycled water. NWRWWRF's high service pump station delivers the recycled water from two 2 5-MG and one 3-MG, on-site, aboveground storage tanks through a 36-inch transmission main to reuse applications. The River Oaks AWWTP has one on-site, 5-MG, aboveground tank for recycled water distribution. In addition to on-site storage tanks, the Northwest reclaimed water system consists of six additional aboveground storage tanks providing approximately 18 MG of storage.

The existing combined South-Central Recycled Water System consists of 48.5 MGD of firm, high service pumping capacity, 51 MG of aboveground and pond storage, and approximately 120 miles of recycled water distribution pipeline (see Figure 4.6). The Falkenburg AWWTP pumps recycled water at high pressure from two on-site, 5-MG, aboveground tanks to the distribution system using two pump stations. The Valrico AWWTP has four on-site, 5-MG, aboveground tanks and a pump station to deliver recycled water. South County's high service pump station delivers the recycled water from two 6-MG, on-site, aboveground storage tanks to reuse applications. In addition to on-site storage tanks, the South-Central Reclaimed Water System consists of one 5-MG and one 4-MG aboveground storage tank at Lithia and Summerfield, along with pump stations. Maximum pumping pressure for both the systems is 100 psi, and a minimum distribution main pressure of 45 psi is maintained for residential and commercial customers. A minimum pressure of 35 psi is required for storage facilities of major users.

The recycled water demand shows a diurnal variation along with seasonal variation, with high demand during summer and dry months. Tanks and ponds are currently used for recycled water storage to manage short-term demand variations; there is no long-term storage of recycled water for the Hillsborough County systems.

4.3.6.3 Compliance Monitoring

Under normal conditions, Hillsborough County performs recycled water sampling and testing at the plant outflow only, not in the distribution system or storage tanks. Water quality parameters such as residual chlorine, TDS, TSS, nitrate, nitrite, ammonia, and pH are monitored. The county does not monitor for microbial water quality parameters in the plant effluent. No sampling was performed specifically for this research study.

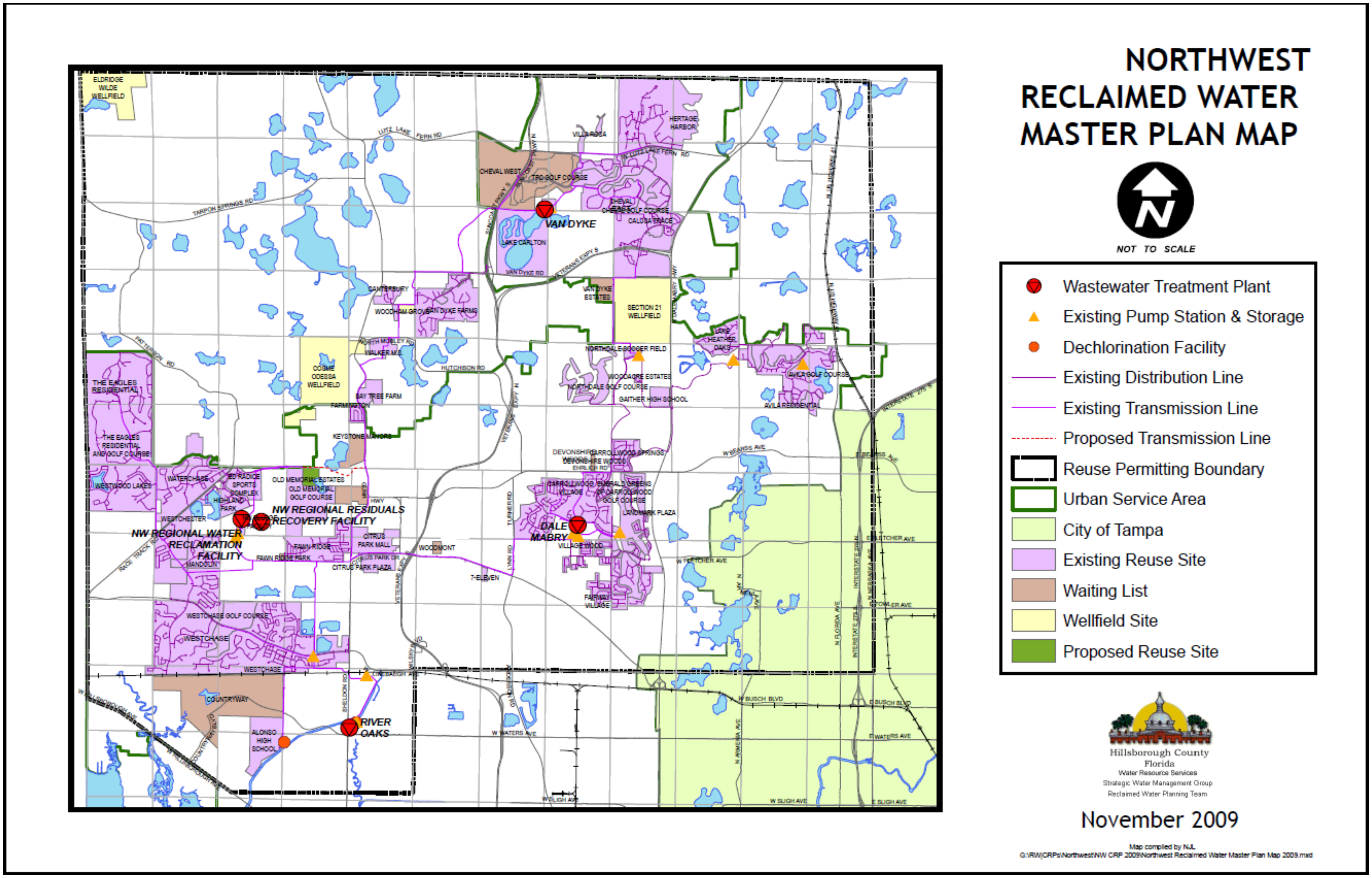


Figure 4.5. Northwest recycled water system map.

Source: Hillsborough County

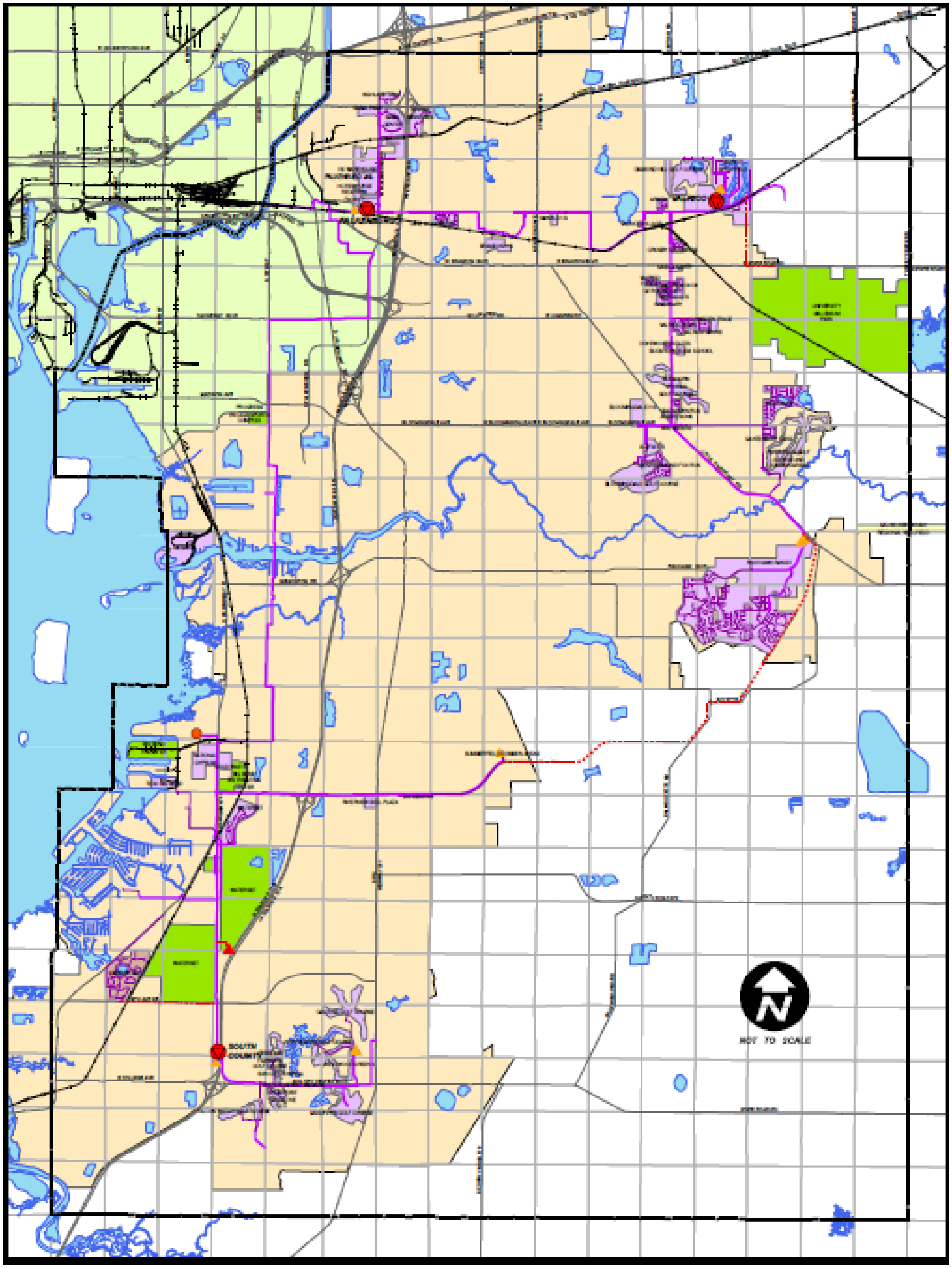


Figure 4.6. South-Central recycled water system map.
Source: Hillsborough County

Chapter 5

Recycled Water Quality in Distribution Systems

In this study, four recycled water facilities that differed by age, geographic location, class or quality of recycled water produced, and treatment train were monitored for microbial and chemical water quality. The overall objective was to evaluate existing water infrastructure and management, provide insight to minimize degradation due to water age, and improve recycled water quality in distribution systems and storage facilities.

5.1 Study Approach

The research team monitored distribution system water quality by analyzing monthly grab samples for a period of 4 months (case study locations) to 1 year (DS-2 and DS-4) from the selected sampling locations. Table 5.1 shows the selected parameters and methods for analyses used to monitor distribution system water quality.

Recycled water samples were subjected to analyses for microbes that can be categorized into three groups:

- Indicator organisms, which include the traditional organisms monitored by utilities throughout the United States, including coliforms and enterococci.
- Waterborne pathogens, which are enteric organisms such as pathogenic strains of *E. coli* that enter distribution systems via leakage or intrusion events. These organisms do not normally grow or regrow within distribution systems.
- Water-based pathogens, which are organisms that can live, metabolize, grow, and reproduce within distribution systems. They include bacterial species of *Legionella* and *Mycobacterium* and the amoeba *Naegleria fowleri*. In addition, bacterial species of *Aeromonas* may be considered a water-based pathogen.

Table 5.1. Microbial Analyses with Associated Methods and Bottles (DS-2 and DS-4 Systems*)

Analysis	Type	Method	Bottle Type	Preservative	Holding Time	Notes***
Aeromonas	micro	EPA 1605	sterile 1-L polypropylene	sodium thiosulfate	30 hours	Transport on ice separate from other sample types
Amoebic activity	micro	internal method**	sterile 1-L polypropylene	sodium thiosulfate	6–24 hours	Transport on ice separate from other sample types
Coliform, fecal	micro	SM 9222-D	sterile 1-L polypropylene	sodium thiosulfate	6–24 hours	Transport on ice separate from other sample types
Coliform, total	micro	SM 9222-B	sterile 1-L polypropylene	sodium thiosulfate	6–24 hours	Transport on ice separate from other sample types
E. coli enzyme substrate coliform test	micro	SM 9223B	125-mL sterile IDEXX	sodium thiosulfate	6 hours	Transport on ice separate from other sample types
Enterococci	micro	SM 9230C (MF)	sterile 1-L polypropylene	sodium thiosulfate	30 hours	Transport on ice separate from other sample types
Enterococci	micro	EPA 1600 (Enterolert)	sterile 1-L polypropylene	sodium thiosulfate	30 hours	Transport on ice separate from other sample types
Heterotrophic plate count	micro	SM 9215C	sterile 1-L polypropylene	sodium thiosulfate	24 hours	Transport on ice separate from other sample types
Legionella	micro	SM 9260J	sterile 1-L polypropylene	sodium thiosulfate	6–24 hours	Transport on ice separate from other sample types
Male-specific and somatic coliphage	micro	EPA 1602	sterile 1-L polypropylene	sodium thiosulfate	48 hours	Transport on ice separate from other sample types
Mycobacterium	micro	SM 9260M	sterile 1-L polypropylene	sodium thiosulfate	24 hours	Transport on ice separate from other sample types

Notes: Microbiological sample bottles (polypropylene) were filled to the line with ample headspace, using sterile sampling technique; *=Monitoring of systems DS-1 and DS-3 followed the protocols listed in Table 4.1; **=Amoebic activity methods were excerpted from Anon (1990); ***=See Appendix B, Table B.1.

5.2 Systems and Sampling Locations

For all utilities, multiple recycled water samples were collected on a monthly basis at increasing distances from the source of treated water (point of compliance) at the treatment plant. Treatment technologies utilized by the public or private utilities evaluated in this study are outlined in Table 5.2. These technologies were described in detail in Chapter 3.

Table 5.2. Treatment Technologies for Systems with Distribution System Sampling

Identifier	Location	Tertiary Treatment	Disinfection
DS-1	Dublin San Ramon Services District	MF (winter) or sand filters (summer)	UV
DS-2	City of Tucson Water	dual media filters, recharge/recovery, or MBR	Cl_2
DS-3	Scottsdale	MF/RO	AOP
DS-4	Global Water Resources	filtration	UV*

Notes: AOP=advanced oxidation process; Cl=chlorine; MBR=membrane bioreactor; MF=microfiltration; RO=reverse osmosis; UV=ultraviolet; *=Global Water Resources began to add a chlorine residual, post-UV, approximately 8 months into the study.

5.2.1 Dublin San Ramon Services District (DS-1)

As described in Chapter 4, DSRSD has two primary treatment systems: an MF system used during low demand periods and a sand filtration system used during the higher demand season (see Table 5.2). The water quality data collected for this research study were obtained during the low demand season; therefore, they reflect the MF treatment process. The following three sampling locations were monitored in the DSRSD system for this research study:

- WRP plant effluent
- Reservoir R20
- Reservoir R200

5.2.2 Tucson Water (DS-2)

Tucson Water, a public water utility, serves approximately 775,000 people in a 350-square-mile area. Tucson has a conventional water/wastewater distribution infrastructure. The Tucson Water system provides tertiary treatment of secondary effluent derived from Pima County Regional Wastewater Reclamation Department (PCRWRD) facilities to produce water of sufficient quality to be used for landscape irrigation and certain industrial uses. The system includes more than 100 miles of transmission pipelines and serves almost 13,000 acre-feet per year of recycled effluent to about 600 customers, including multiple golf course facilities, parks, schools, industrial sites, and certain residential sites. Tucson Water's reclaimed water system serves to meet approximately 8% of its total water demand. This reuse of effluent reduces groundwater pumping and conserves higher quality water sources for potable supply.

5.2.2.1 Operation, Storage, and Distribution System Description

The secondary effluent that is received from Pima County's treatment facilities is either filtered through the dual-media filtration system at the Tucson Reclaimed Water Treatment Plant or recharged in a number of facilities. The recharge facilities include the Sweetwater Recharge Facilities (SRF), the Santa Cruz River Managed Underground Storage Facility (Santa Cruz Phase I), and the Lower Santa Cruz River Managed Recharge Project (Santa Cruz Phase II; Tucson Water, 2003). Although all of these facilities are essential to the successful operation of the Recycled Water System, the SRF are the core supply source, providing high water quality, system reliability, and a beneficial public amenity. In addition to the dual-media filtration plant and the various recharge facilities, PCRWRD also operates a 3-MGD MBR scalping plant that discharges directly into Tucson Water's recycled water distribution system.

Product water from the Reclaimed Water Treatment Plant is usually blended with water recovered from the extraction wells to manage turbidity. Under the Wastewater Reuse Permit, turbidity at the point of compliance has to be 5 NTU or lower. The filters at the plant can effectively remove approximately 50% of the turbidity measured in the secondary effluent, but this can often exceed 5 NTU. The stored water that is removed through the extraction wells consistently has a low turbidity. The blending of recovered water and plant effluent continues to be an effective strategy to remain within the compliance limits. During various times of the year, the ratio of blended water put into the distribution system varies based on water demand and water quality requirements.

5.2.2.2 Sampling Locations

The Tucson Water reclaimed water distribution system is shown on Figure 5.1, with sampling locations highlighted. Locations were selected based on communications with the project team and the utility. Sampling locations highlighted in blue were collected on a monthly basis, whereas samples highlighted in red were collected every other month. A total of 17 sample locations were originally selected; however, after the onset of the project, two locations were identified as not in service and dropped from the sampling regime. Table 5.3 provides the locations and distance in miles from the origin or reclaimed water facility.

5.2.3 Scottsdale Water Reclamation Facility (DS-3)

The Scottsdale Water Reclamation Facility (WRF) is described in Chapter 4. Treatment includes a combination of conventional and AWT technologies (Table 5.2). The following sampling locations were monitored for this research study:

- WRF plant effluent (Reservoir B influent)
- Reservoir B effluent or Site 96 booster pump station
- Site 97 booster pump station
- Site 98 booster pump station
- Site 99 booster pump station

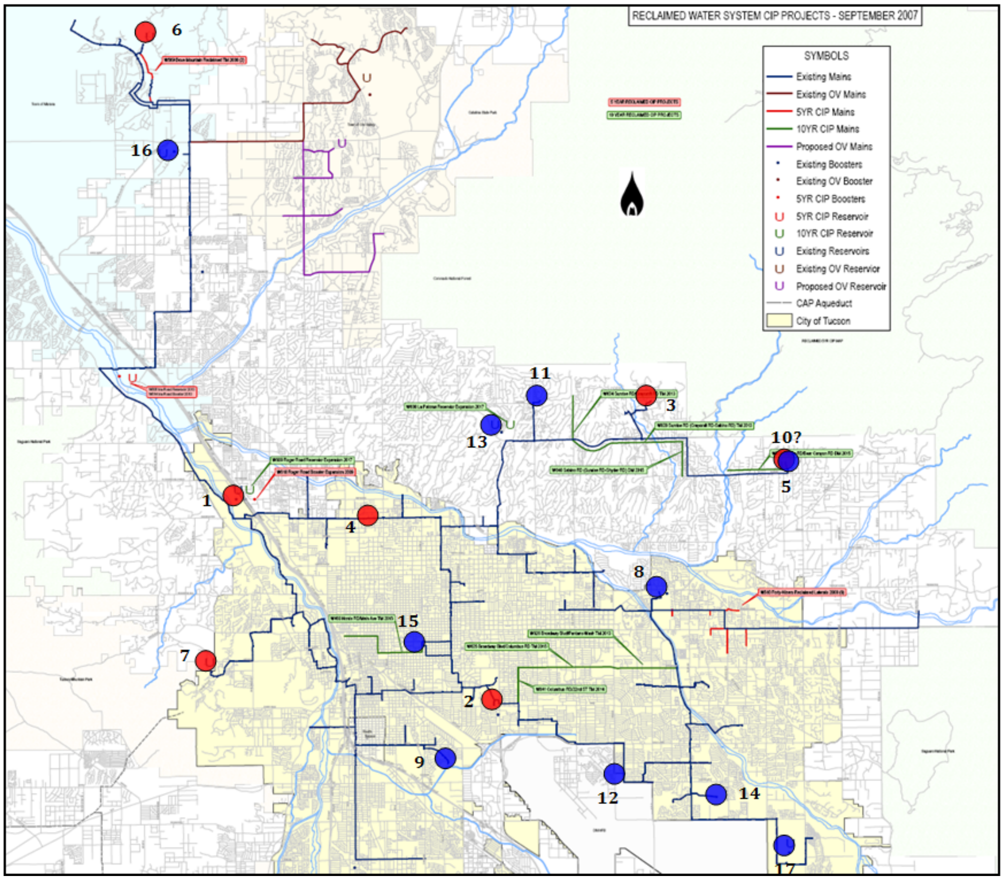


Figure 5.1. Tucson Water recycled water distribution system.

Table 5.3. Tucson Water Sample Locations

Location ID	Location	Distance (miles)
1	Recycling Facility	Origin
2	Rillito Downs	5.05
3	Starr Pass	7.19
4	University of Arizona	9.11
5	La Paloma	9.65
6	Kino	11.61
7	Skyline	11.65
8	Reid Park	11.74
9	Udall	14.35
10	Thornydale	14.35
11	Ventana Golf Course	14.7
12	Davis Monthan	17.26
13	Sabino Springs	18.52
14	Fred Enke	21.48
15	Houghton	24.71

5.2.4 Global Water Resources (DS-4)

Global Water Resources (GWR) operates investor-owned utilities focused on rapidly growing, new service areas. It is known for the deployment of recycled water, along with potable water, throughout its service areas. In the City of Maricopa (incorporated in 2003), the company serves approximately 16,000 connections. Recycled water is collected, treated, and redistributed through 8- to 24-inch-diameter pipe systems within the service area. Treatment of the recycled water relies on UV rather than chlorine injection; however, 8 months into this study GWR began to chlorinate following UV treatment. In addition, GWR relies on open ponds as retention storage for recycled water. The recycled effluent is used to irrigate golf courses and municipal parklands, fill lakes and reservoirs, and operate water features within the community.

5.2.4.1 Operation, Storage, and Distribution System Description

The Global Water Center in Maricopa, AZ, a dual-plumbed facility, was employed for the evaluation of microbial water quality. This facility is provided Arizona Class A+ recycled water from the Global Water–Palo Verde Utilities Company Water Reclamation Facility (WRF). This LEED Silver–certified building provides many open access points for the direct evaluation of biofilm development and recycled water quality. Further, the recycled water for this facility can be subjected to numerous post-treatment processes at the Recycled Water Test Facility located at the WRF. This testing facility has sensors for pH, oxidation-reduction potential (ORP), turbidity, pressure, and flow.

GWR provides recycled water to numerous lakes in Maricopa. The recycled water distribution and storage system contains pressure and flow sensors that were used to validate a hydraulic model for water delivery. Detailed sampling occurred at both the inlet to the distribution system and the discharges to four lakes in the city. Data from additional sampling from the lakes (separate project) will be utilized to characterize the degradation of water quality in open-air storage.

5.2.4.2 Sampling Locations

A total of five locations were selected for sampling (Table 5.4). Figure 5.2 depicts the sampling locations for the GWR recycled water distribution system. GWR utilizes a series of aboveground retention basins or “lakes” for storage of the recycled water prior to its use. Outlets to these lakes were selected as sampling locations for the accessibility of sampling ports and the necessity of collecting water quality data prior to storage.

Table 5.4. Global Water Resources Sample Locations

Location ID	Location	Distance (miles)
1	Recycling Facility	Origin
2	Rancho El Dorado	0.55
3	Homestead	2.12
4	Pacana Park	2.47
5	Sorrento	7.6

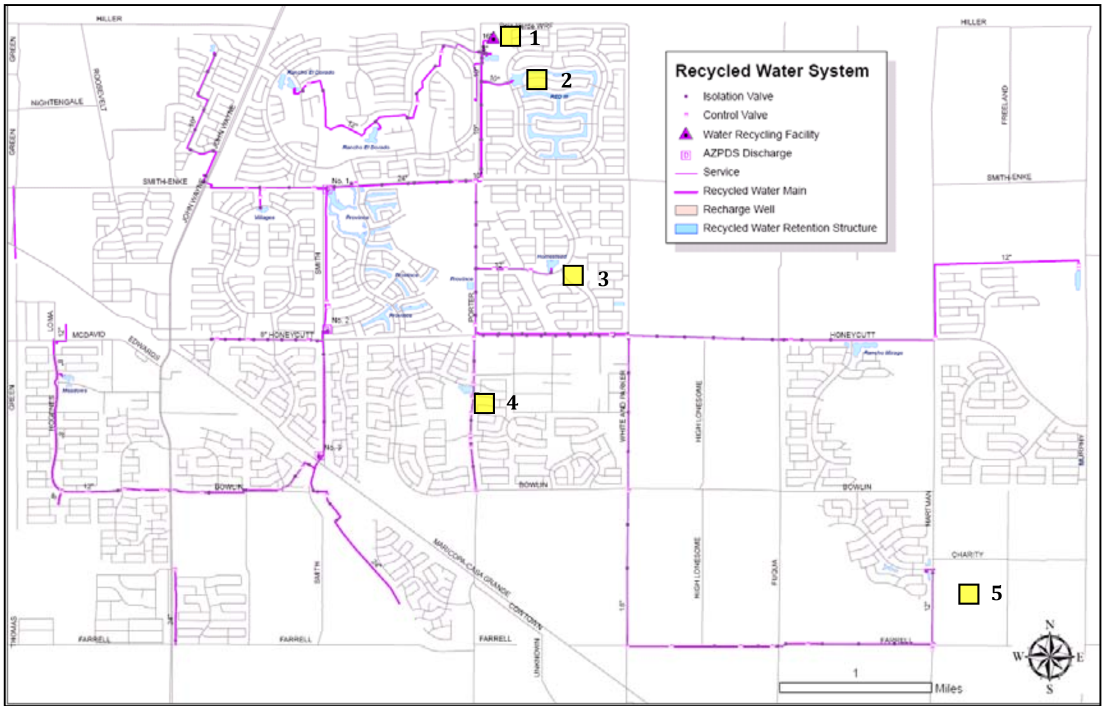


Figure 5.2. Global Water Resources recycled water distribution system.

5.3 Microbial Water Quality Observations

Over the sampling period, water samples for microbial analyses were collected from discrete locations along the distribution systems. Because these locations differed with respect to distance from the source, the effect of water age or distribution residence time on microbial water quality could be inferred. For the purposes of this report, the following sections will outline preliminary microbial results for the four distribution systems evaluated in this study (DS-1, DS-2, DS-3, and DS-4) and provide overall observations comparing each system. It should be noted that data collected for DS-2 and DS-4 were provided by the UA/USDA project team, whereas data collected for DS-1 and DS-3 were provided by individual utility partners.

Substantial variations were observed in the four recycled water distribution systems evaluated. Figure 5.3 presents the residual chlorine levels observed at the point of compliance (effluent) for each of the facilities as well as a midpoint and the end point or furthest monitored point within each distribution system. It should be noted that only two of the four facilities, DSRSD (DS-1) and Tucson Water (DS-2), actively manage disinfectant residual within their distribution system. This management includes periodic monitoring and the utilization of booster stations to adequately dose disinfectant levels within the system. The remaining facilities included in this study, although they may add disinfectant at the point of compliance, do not actively maintain chlorine residual or monitor microbial water quality beyond the point of compliance.

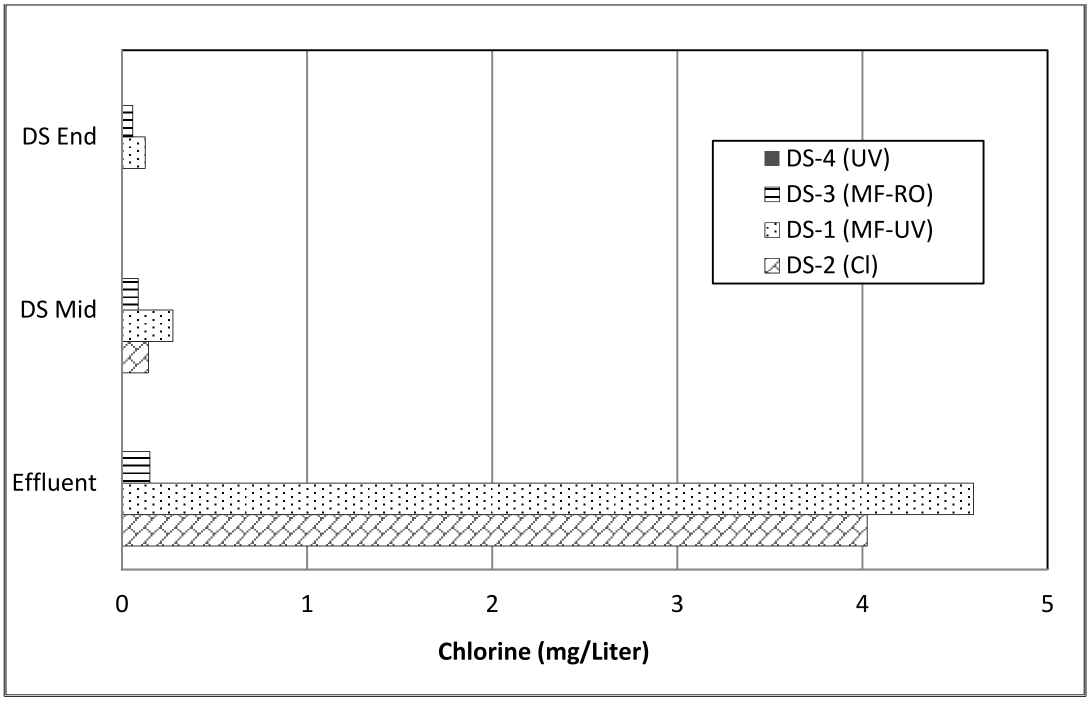


Figure 5.3. Dissipation of free chlorine in recycled water distribution systems.

Disinfectant levels fell sharply through the distribution system, ranging from 4.60 to 0.15 mg/L at the point of compliance to <0.05 mg/L at the furthest end of the system, regardless of treatment. Averaged microbial numbers within the distribution system were negatively correlated with residual chlorine; regardless of treatment technology (membrane filtration, RO, conventional treatment), all systems that did not actively manage disinfectant in their distribution system had increasing levels of microbial activity for multiple microbial parameters assayed. Table 5.5 describes the numbers of microorganisms in treated effluents and their numbers following regrowth in the distribution system; it shows microbial numbers at the point of compliance (effluent) as well as at the furthest distance sampled in each system.

Figure 5.4 illustrates the frequency in occurrence of water-based pathogens and traditional microbial indicator organisms. Water-based pathogens, such as *Aeromonas, Legionella*, and *Mycobacterium*, were found in higher numbers in recycled water systems that did not maintain residual disinfectant in their distribution system regardless of treatment technology. *Legionella, Mycobacterium*, *Enterococci*, amoebic activity, and male-specific or somatic coliphage were only assayed for samples collected in DS-2 and DS-4.

Although water-based pathogens were detected very frequently, indicator organisms were uncommon in the chlorinated systems, and in numerous instances water-based pathogens were present in the recycled water distribution systems in the absence of indicator organisms (e.g., *E. coli*). These data question the usefulness of traditional indicators based on treatment technology. Figures 5.5 and 5.6 illustrate the Tucson Water (DS-2) and GWR (DS-4) recycled water distribution systems in greater detail. In both systems, the levels of most microorganisms rapidly and significantly increased from the point of compliance through the first 1 or 2 miles of the distribution system. After this initial increase, microbial numbers within the distribution system remained relatively constant. In Figure 5.5, slight decreases are seen at the distance of approximately 12 miles in the DS-2 system because of a chlorine booster station. Although the numbers of all organisms tested seem to decrease slightly at this location, samples collected at the next sampling point of 14.35 miles demonstrated that microbial numbers readily increased to levels similar to those before the booster station. Trends for the GWR system are detailed in Figure 5.6.

Table 5.5. Concentrations of Microorganisms in Treated Effluents and Their Regrowth in the Distribution Systems*

			CFU/100 mL (mean±standard error)					
Organism	**Location**		**Effluent**			**DS End**		
Aeromonas spp.	DS-1	DSRSD	2.49E+02	±	3.07E+02	7.12E+01	±	1.38E+02
	DS-2	TW	1.15E+02	±	3.45E+02	4.52E+02	±	2.24E+02
	DS-3	Scottsdale	3.67E+03	±	6.35E+03	6.17E+03	±	7.75E+03
	DS-4	GWR	4.50E+01	±	9.27E+01	3.72E+03	±	5.09E+03
E. coli	DS-1	DSRSD	1.50E+00	±	1.91E+00	0.00E+00	±	0.00E+00
	DS-2	TW	0.00E+00	±	0.00E+00	1.43E-01	±	3.78E-01
	DS-3	Scottsdale	0%	±	-	75%	±	-
	DS-4	GWR	2.19E-01	±	4.46E-01	3.23E+00	±	4.37E+00
Enterococci	DS-1	DSRSD	-		-	-		-
	DS-2	TW	1.43E-01	±	3.63E-01	1.30E+00	±	1.12E+00
	DS-3	Scottsdale	-		-	-		-
	DS-4	GWR	1.26E+00	±	1.94E+00	1.16E+02	±	2.25E+02
HPCs	DS-1	DSRSD	1.51E+05	±	1.90E+05	2.52E+06	±	3.22E+06
	DS-2	TW	4.23E+05	±	1.10E+06	5.35E+07	±	5.20E+07
	DS-3	Scottsdale	2.90E+01	±	9.54E+00	7.14E+02	±	6.10E+02
	DS-4	GWR	2.06E+07	±	8.12E+07	3.76E+07	±	4.53E+07
Legionella spp.	DS-1	DSRSD	-		-	-		-
	DS-2	TW	7.14E+01	±	2.67E+02	1.65E+03	±	3.52E+03
	DS-3	Scottsdale	-		-	-		-
	DS-4	GWR	3.13E+01	±	1.25E+02	2.52E+03	±	4.00E+03
Mycobacterium spp.	DS-1	DSRSD	-		-	-		-
	DS-2	TW	2.64E+01	±	6.03E+01	2.17E+01	±	4.20E+01
	DS-3	Scottsdale	-		-	-		-
	DS-4	GWR	1.07E+00	±	4.01E+00	2.98E+02	±	7.13E+02
Total coliform	DS-1	DSRSD	6.25E+01	±	5.49E+01	1.00E+00	±	2.00E+00
	DS-2	TW	4.21E+00	±	9.61E+00	1.56E+01	±	1.54E+01
	DS-3	Scottsdale	25%	±	-	100%	±	-
	DS-4	GWR	6.91E+00	±	1.04E+01	2.15E+03	±	3.86E+03

Notes: DSRSD=Dublin San Ramon Service District; GWR=Global Water Resources; HPC=heterotrophic plate count; TW=Tucson Water; *=Scottsdale reported total coliform and *E. coli* as presence or absence; therefore the % positives are displayed in the table.

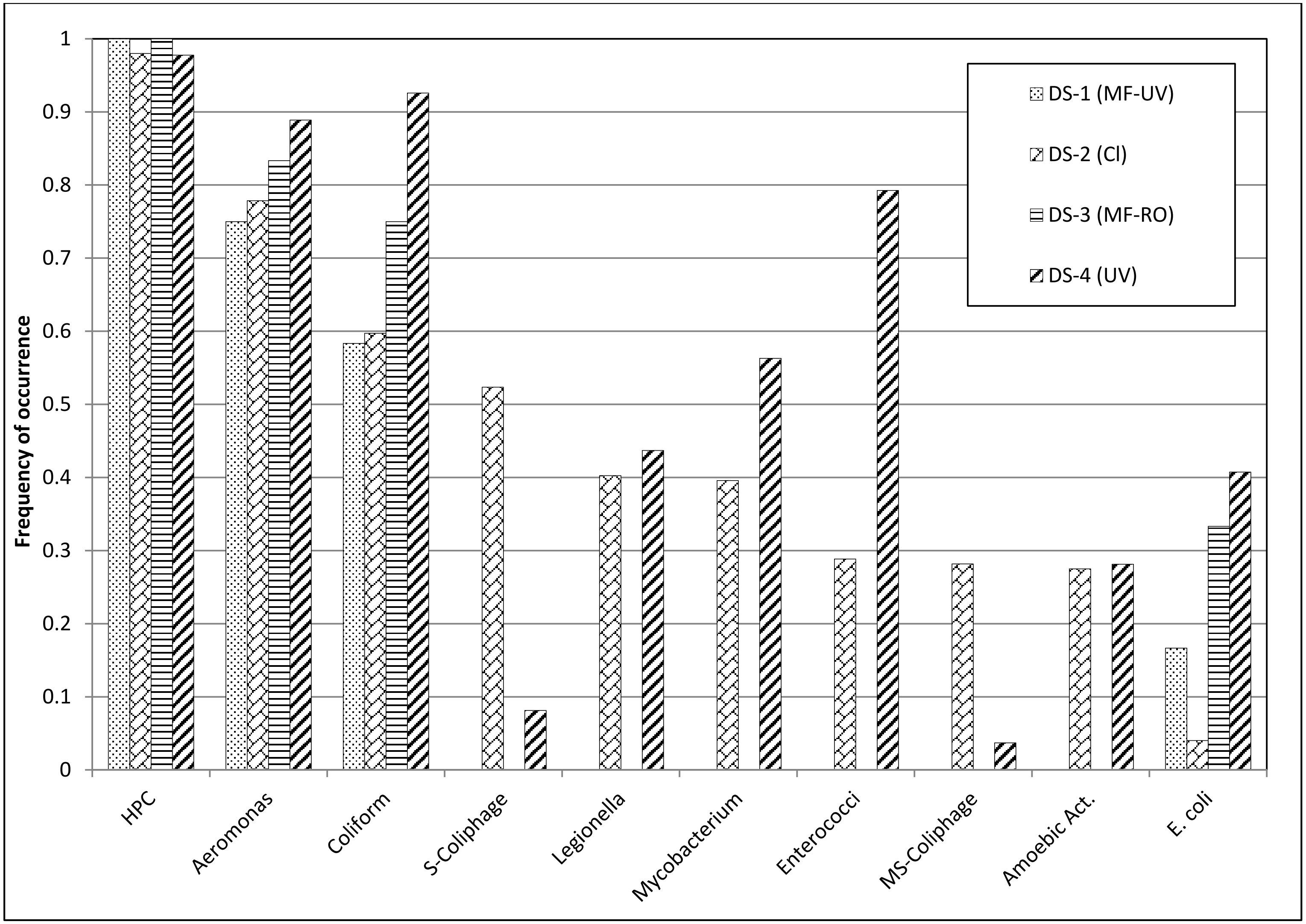


Figure 5.4. Frequency of occurrence of opportunistic pathogens and indicator bacteria and viruses in recycled water.

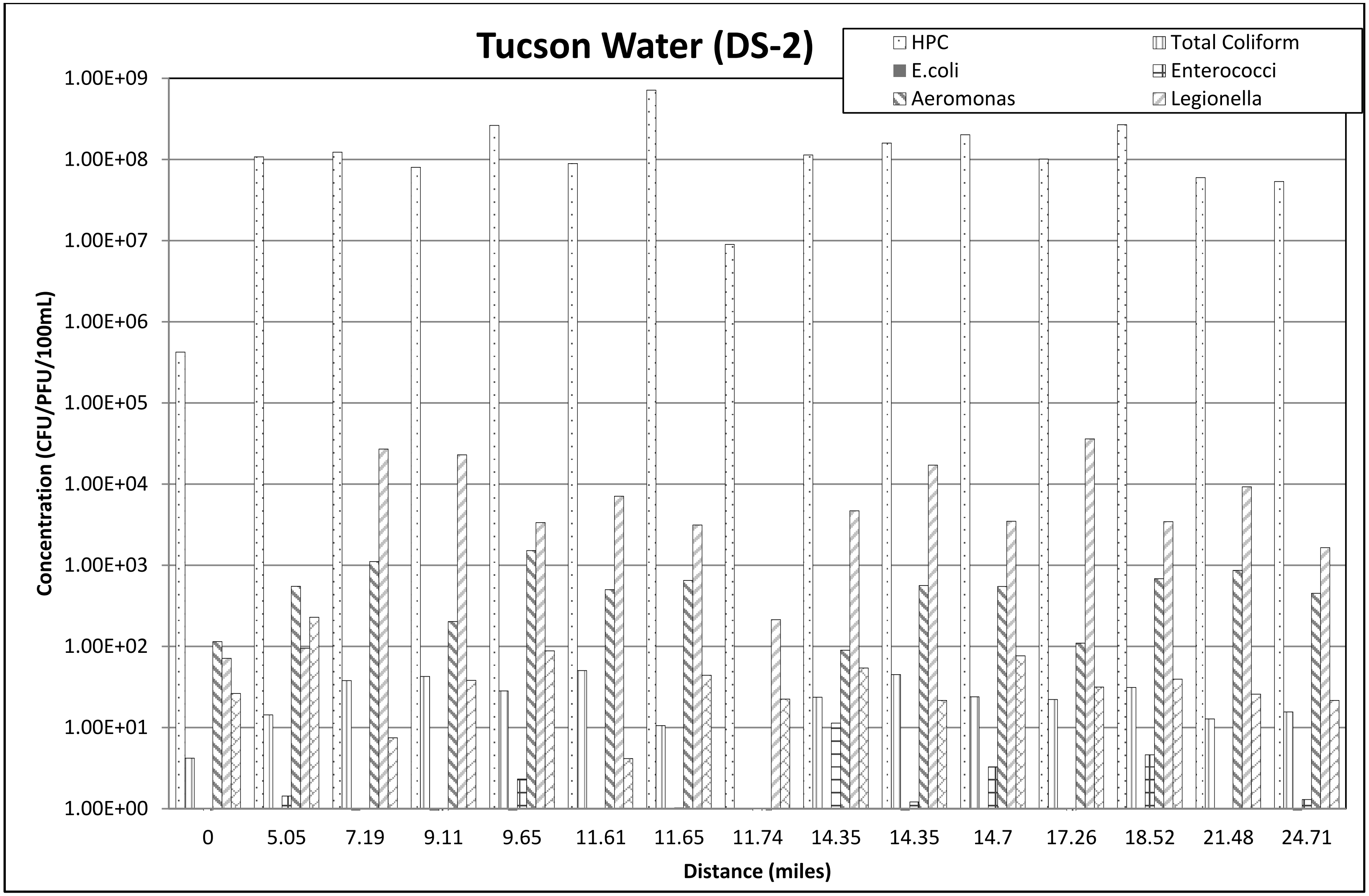


Figure 5.5. Averaged microbial numbers in the Tucson Water recycled water distribution system.

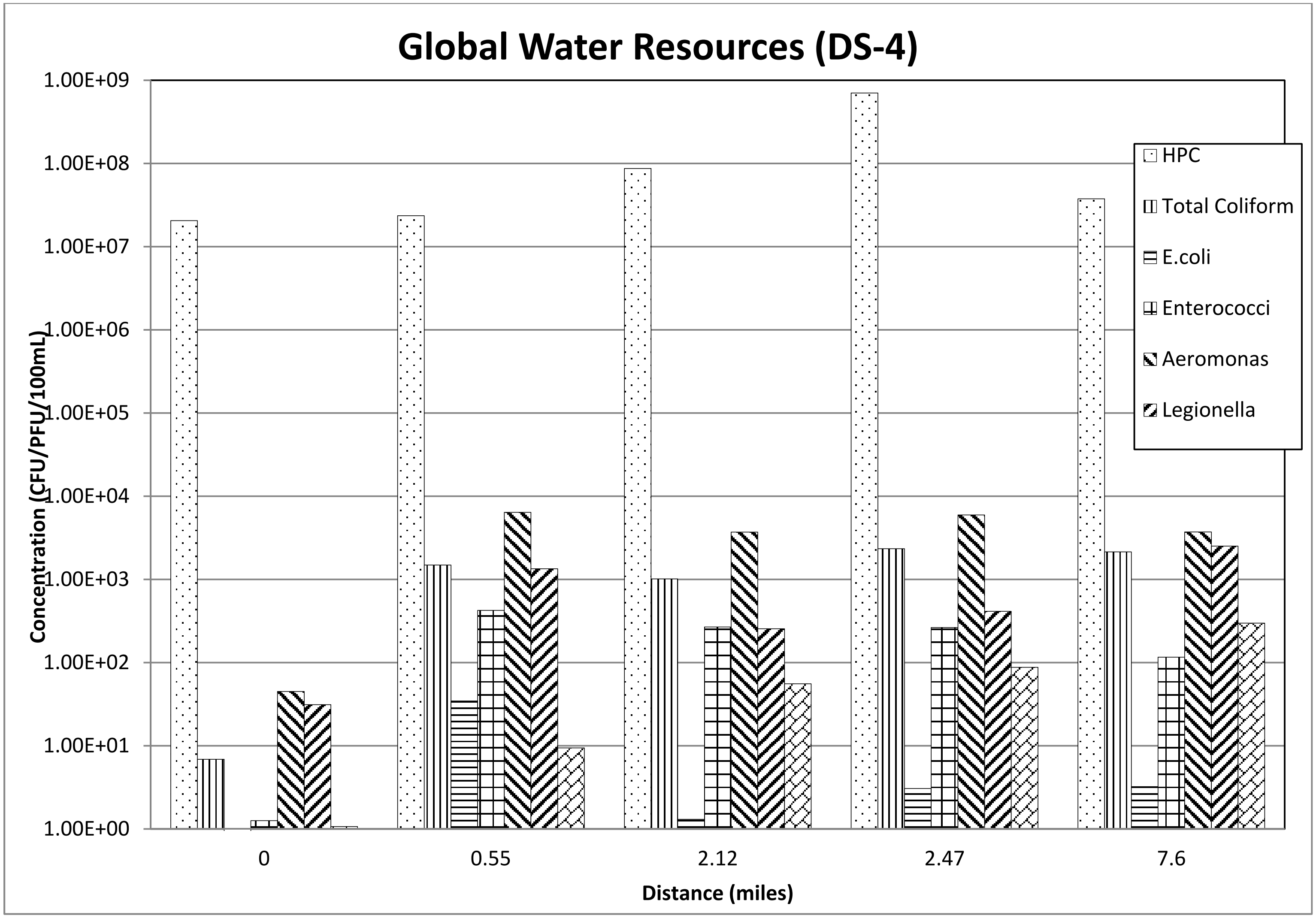


Figure 5.6. Averaged microbial numbers in the Global Water Resources recycled water distribution system.

Figure 5.7 shows the microbial water quality from the DS-2 treatment system that utilized chlorine as a disinfectant. Analogous data for the DS-4 treatment system that utilized UV as a disinfectant is shown in Figure 5.8. These figures illustrate frequency in occurrence of all microorganisms tested averaged over all sampling locations and time points.

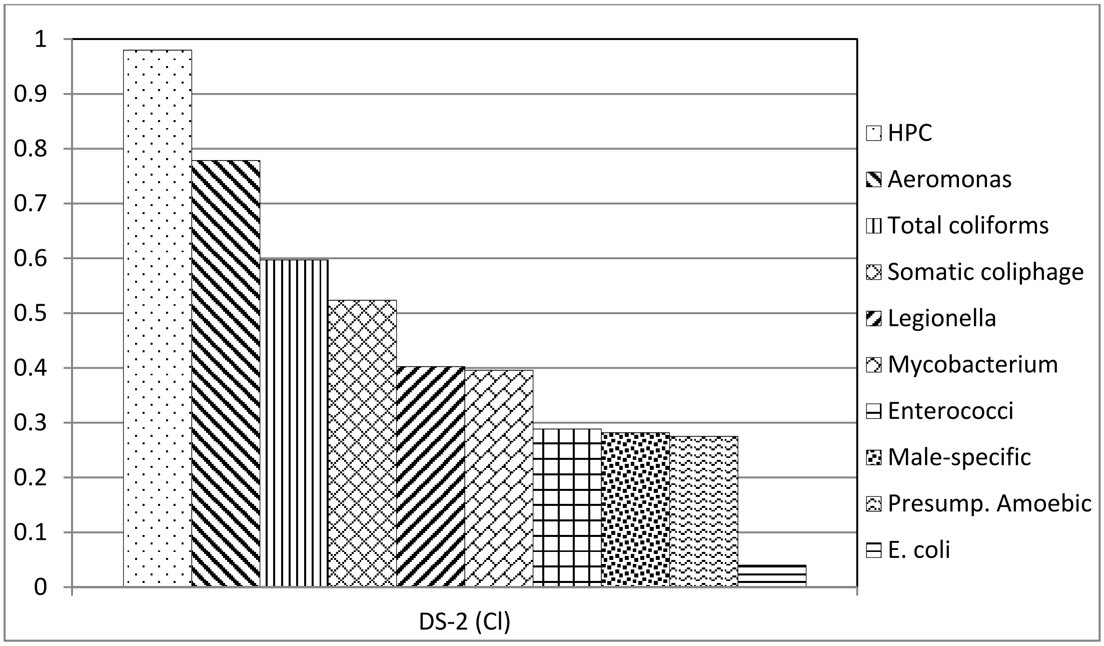


Figure 5.7. Frequency of occurrence of opportunistic pathogens and indicator bacteria and viruses in chlorinated recycled water.

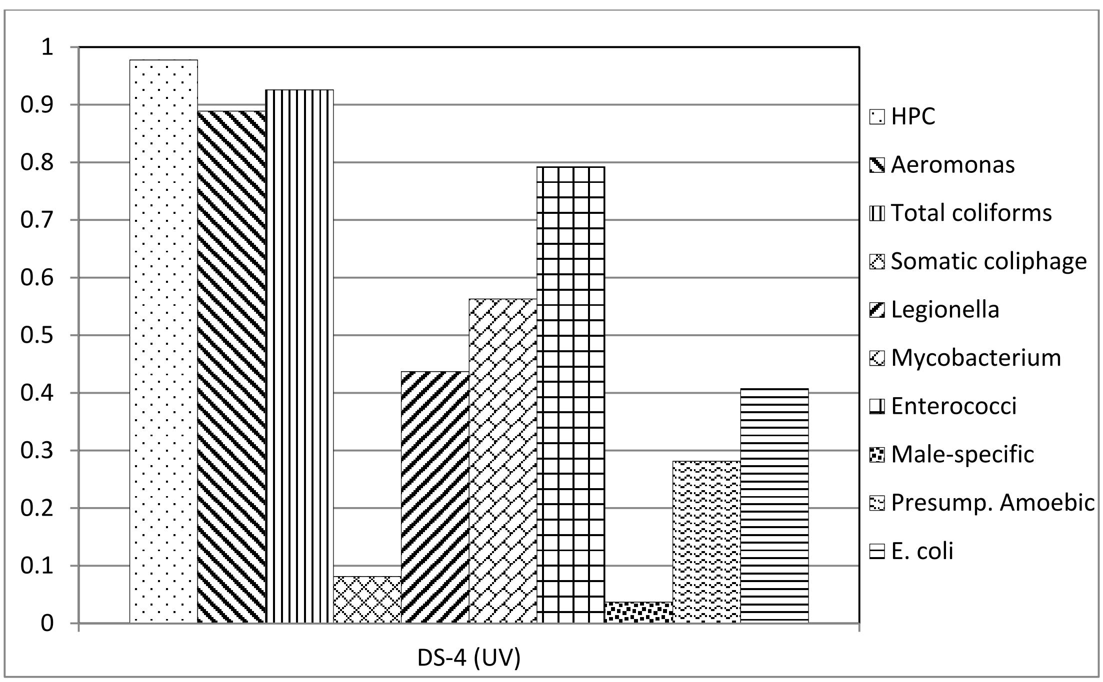


Figure 5.8. Frequency of occurrence of opportunistic pathogens and indicator bacteria and viruses in UV-disinfected recycled water.

Traditional indicator organisms such as *E. coli* were rarely detected or only detected at very low frequency in both systems. Furthermore, water-based pathogens were detected on occasions where currently used indicators of microbial water quality were not, suggesting that *E. coli* and fecal coliform concentrations, which are traditionally used for compliance monitoring, may not accurately represent microbial water quality from a risk assessment/public safety perspective.

Total coliform indicator organisms were detected at lower concentrations and frequency in the chlorinated system (DS-2) than the UV system (DS-4). The indicator *E. coli* was only found at low concentrations and frequency in both systems. In the UV-disinfected system, *Enterococci* were found at levels one order of magnitude greater than the chlorinated system. For the chlorinated system, all mean indicator concentrations were less than 10^2 per 100 mL, whereas all values were generally $\leq 10^3$ per 100 mL for the UV system.

The water-based pathogens, *Aeromonas, Legionella,* and *Mycobacterium* spp., were routinely found in samples collected from both systems. In the chlorinated system, *Legionella* was found in the highest concentrations, with levels increasing with water age, distance, or both. Approximately 5 miles from the source, *Legionella* concentrations were $\approx 10^2$/100 mL, increasing to $\approx 10^4$/100 mL after 7 miles and remaining at that level throughout the remainder of the distribution system. A similar increase in microbial numbers with water age was found for *Aeromonas,* with values reaching $\approx 10^3$/100 mL. *Mycobacterium* was found at fairly constant concentrations, albeit at lower levels than the other pathogens. Overall, there were numerous instances where water-based pathogens were relatively high in number in the absence of the indicator organisms (*E. coli*). This is not wholly unexpected given that traditional indicators used for monitoring by utilities only indicate fecal waterborne contaminants, and numerous studies have found no relation between fecal indicators and water-based pathogens (Carter et al., 1987; Baggi et al., 2001; Jjemba et al., 2010). It is of interest that the injection of chlorine at the 11.7-mile booster station in DS-2 had only a temporary effect on indicator and pathogen concentrations. This may suggest an adaptation to the environmental conditions including resistance to chlorine; in other words, only resistant species survived.

In the UV system (DS-4), *Aeromonas* was found at the highest concentrations; however, trends show that whereas *Legionella* and *Mycobacterium* were initially found at lower concentrations, with increased water age concentrations of both organisms increased, approaching similar values to those seen for *Aeromonas*. The pathogen level increase with water age is presumably due to the ability of the water-based pathogens to grow and reproduce within the water environment. Documentation of water-based pathogens in other studies of recycled waters was recently reported in Jjemba et al. (2010).

Table 5.6. Amoebic Activity from DS-4 and DS-2 Recycling Facilities

Recycling Facility	Number Sampled	Number Positive	% Positive
DS-4 (UV)	134	38	28.3%
DS-2 (Cl)	140	42	30.0%

Notes: Cl=chlorine; UV=ultraviolet

Data on amoebic activity show that similar incidence levels were found in both recycled waters evaluated in this study. This is of interest because a relationship between the presence of amoebae and water-based pathogens has been reported (Thomas and Ashbolt, 2011). The growth of *Legionella* within *Acanthomoeba* has been well documented (Declerck et al., 2009), suggesting the potential for the incidence of amoebic activity to be used as an indicator for water-based pathogens. In this study, data from the DS-2 and DS-4 systems did not show strong correlations between amoebic activity and the presence of *Legionella*. Data on amoebic activity are summarized in Table 5.6. Microbiological work within the DS-2 system has isolated the pathogenic amoeba *Balamuthia* in previously collected biofilm samples (personal communication, Tucson Water, 2009). *Balamuthia* is a free-living amoeba known to cause amoebiasis in humans, in particular the condition known as granulomatous amoebic encephalitis. *Balamuthia* has not been definitively isolated in nature, but it is believed to be distributed throughout the temperate regions of the world. Work is currently being performed with collected isolates to identify the species of amoeba found in each distribution system.

The finding of water-based pathogens in reclaimed water distribution systems is not unexpected. *Legionella* spp. and *Aeromonas* spp. have frequently been isolated from domestic and hospital water supplies, even after chlorination (LeChevallier et al., 1982; Kuhn et al., 1997; Leoni et al., 2005). *Aeromonas* spp. have been shown to survive in mineral water for more than 100 days (Brandi et al., 1999), whereas *Legionella* have been isolated from groundwater supplies (Costa et al., 2005). These comparisons with drinking water supplies are not meant to negate the gravity of isolation of pathogens in reclaimed water systems but do illustrate that control of water-based pathogens is a problem ubiquitous to all water delivery systems, regardless of source or quality.

5.4 Preliminary Microbial Conclusions

For microbial water quality data collected in the distribution systems, the following preliminary conclusions are identified:

- Microbial water quality within all systems deteriorated with increased residence time in the water distribution system; however, increased numbers of organisms occurred during the initial residence period within the systems. Beyond this initial increase, microbial numbers remained relatively constant, suggesting that maintenance populations become established with growth and cell death compensating each other.

- Water-based pathogens were detected in all systems, and concentrations increased with water age, indicating growth of the organisms similar to pathogen growth patterns found in potable water systems.

- Fecal indicator organism concentrations were low, and *E. coli* was rarely detected.

- Fecal indicators were not correlated with water-based pathogen incidence or concentrations. This suggests that current indicators may not accurately represent the quality of recycled water from a risk perspective and highlights the need for the establishment of new indicators for water-based pathogens.

- Rechlorination of the distribution system did not reduce the concentrations of either pathogens or indicators significantly, suggesting that chlorine-resistant organisms had survived. Although some die-off occurred, rapid dissipation of residual chlorine proved problematic and allowed for growth and regrowth of pathogens and indicators.

- Amoebic activity was detected in approximately one third of all samples from systems tested; however, no correlations were found between amoebic activity and the presence of any of the indicators or between amoebic activity and *Legionella, Mycobacterium*, or *Aeromonas*, suggesting that water conditions promoting the growth of amoebae may differ from those promoting pathogen and indicator regrowth.

5.5 Chemical Parameter Observations

In addition to microbial water quality parameters, the chemical quality of recycled water in the distribution system for Tucson Water was observed as a function of residence time. See Chapter 6 for discussion of the hydraulic modeling effort that generated the residence time information for use in interpreting the chemical parameter data. Figures 5.9 through 5.14 depict a gradual decrease in SAR and its constituents, salinity (TDS), and alkalinity (as bicarbonate) with water age past 20 hours of residence time at the Skyline sampling location. The Ventana East and Sabino locations did not follow any particular trend for these parameters, although some spikes in concentration for the above parameters were observed around 80 hours of residence time. The optimal quality of agricultural irrigation water has an SAR less than 4.4 (Ayers, 1985). The Tucson Water sampling locations did not exceed this level, even with extended residence time (water age). Most reclaimed water from urban areas is slightly saline. The TDS concentration in recycled water for Tucson Water varies from approximately 600 to 750 mg/L, and historical data show that the average TDS concentration in Tucson's potable water is approximately 450 mg/L (Tucson Water, 2011). This supports claims in the literature that residential use of water may add approximately 200 to 400 mg/L dissolved salts (Lazarova et al., 2004).

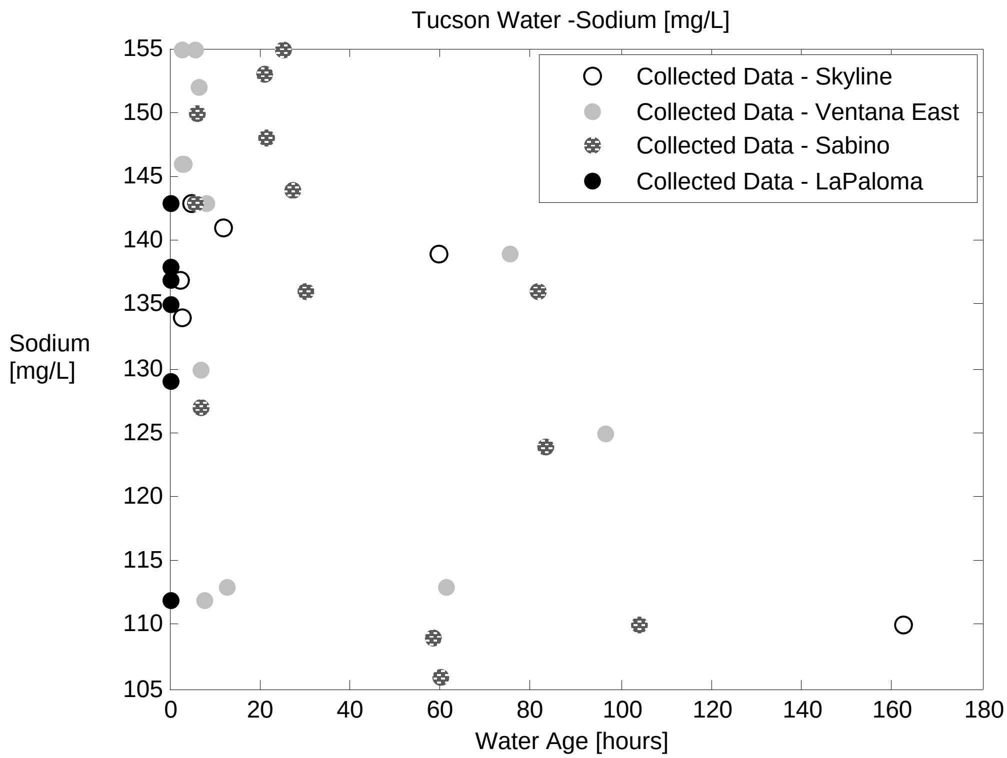


Figure 5.9. Sodium concentration in Tucson Water distribution system.

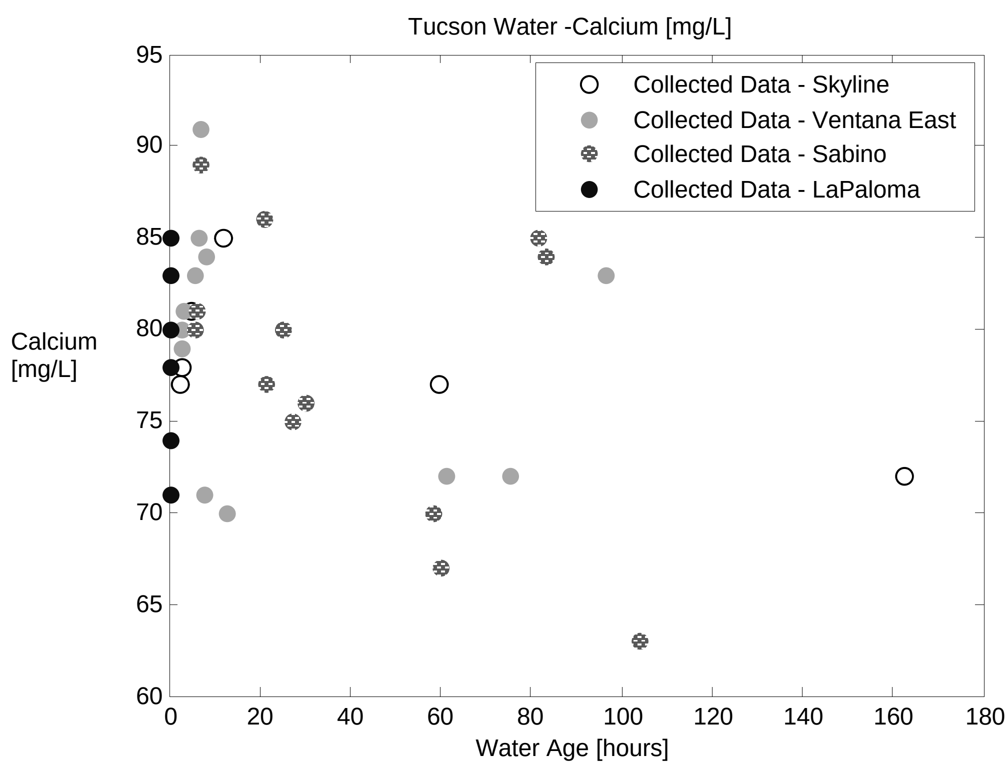


Figure 5.10. Calcium concentration in Tucson Water distribution system.

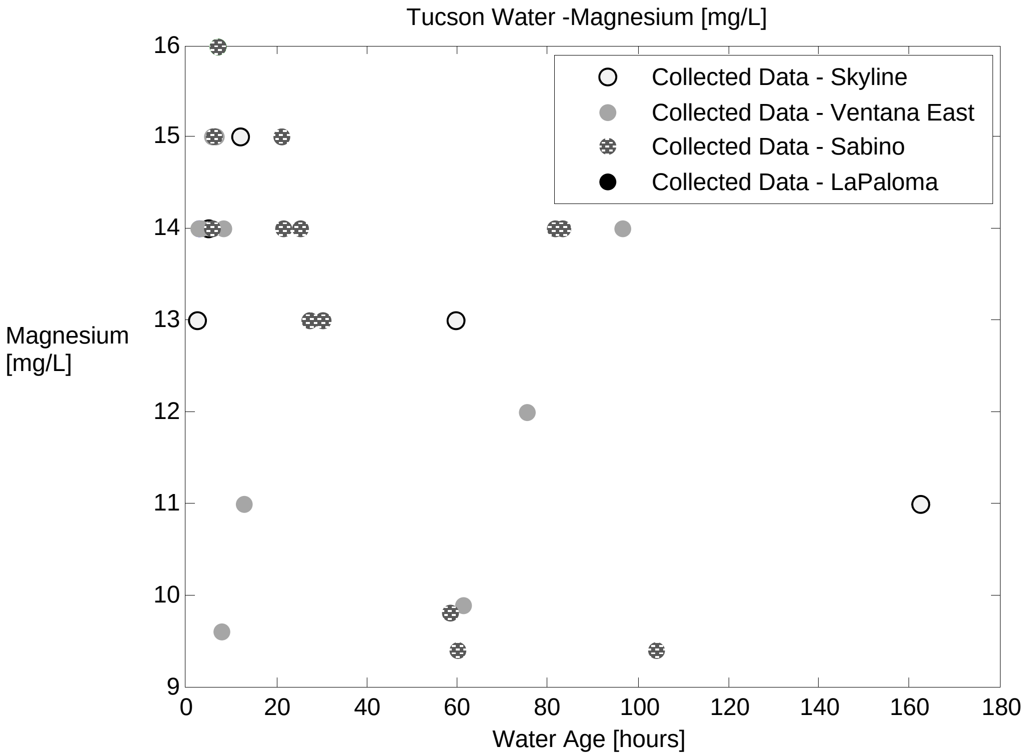


Figure 5.11. Magnesium concentration in Tucson Water distribution system.

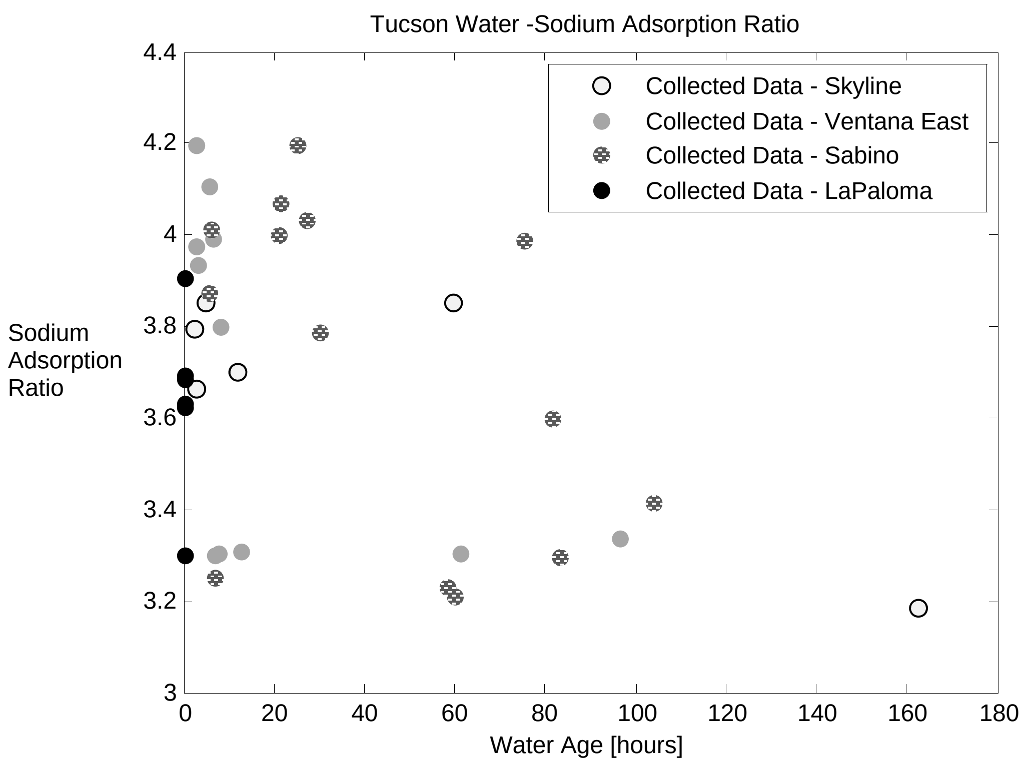


Figure 5.12. SAR in Tucson Water distribution system.

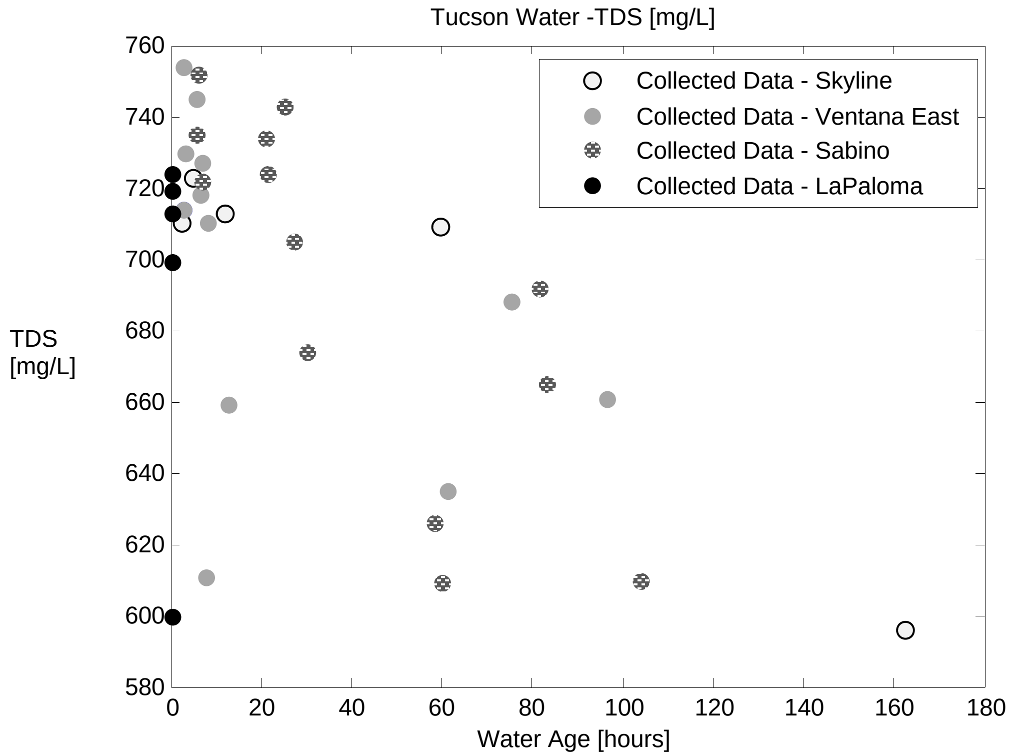


Figure 5.13. TDS concentration in Tucson Water distribution system.

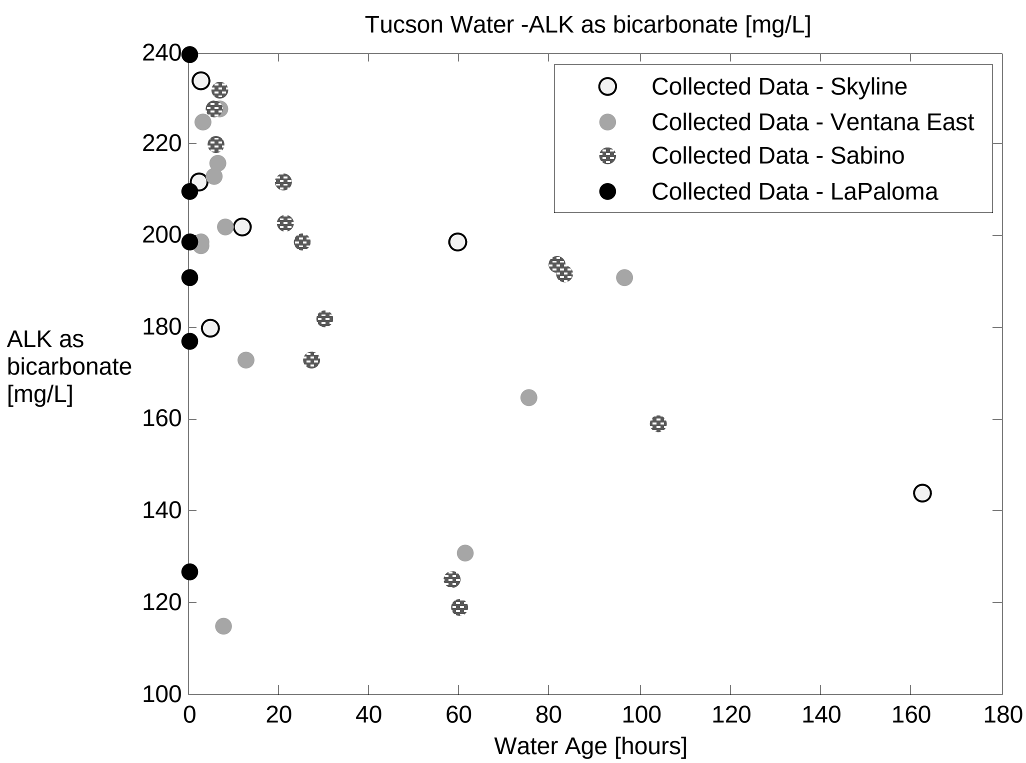


Figure 5.14. Alkalinity in Tucson Water distribution system.

Figures 5.15 through 5.18 display observed nitrate-N, nitrite-N, TKN, and TOC concentrations for the sampling locations that do not follow any particular trend with water age. Significant nitrate concentrations at the Ventana East and Sabino locations at 60 hours of water age were due to nitrification, resulting in decrease/dissipation of nitrite and TKN concentrations.

Following nitrification, lower nitrate concentrations and higher alkalinity concentrations were detected (Figure 5.14) at the Ventana East and Sabino locations at approximately 80 hours of water age; this may be due to denitrification. Higher concentrations of nitrate and consequently lower concentrations of nitrite and TKN were observed at 85 and 100 hours of water age at Sabino and Ventana East, respectively. This may also be attributed to nitrification.

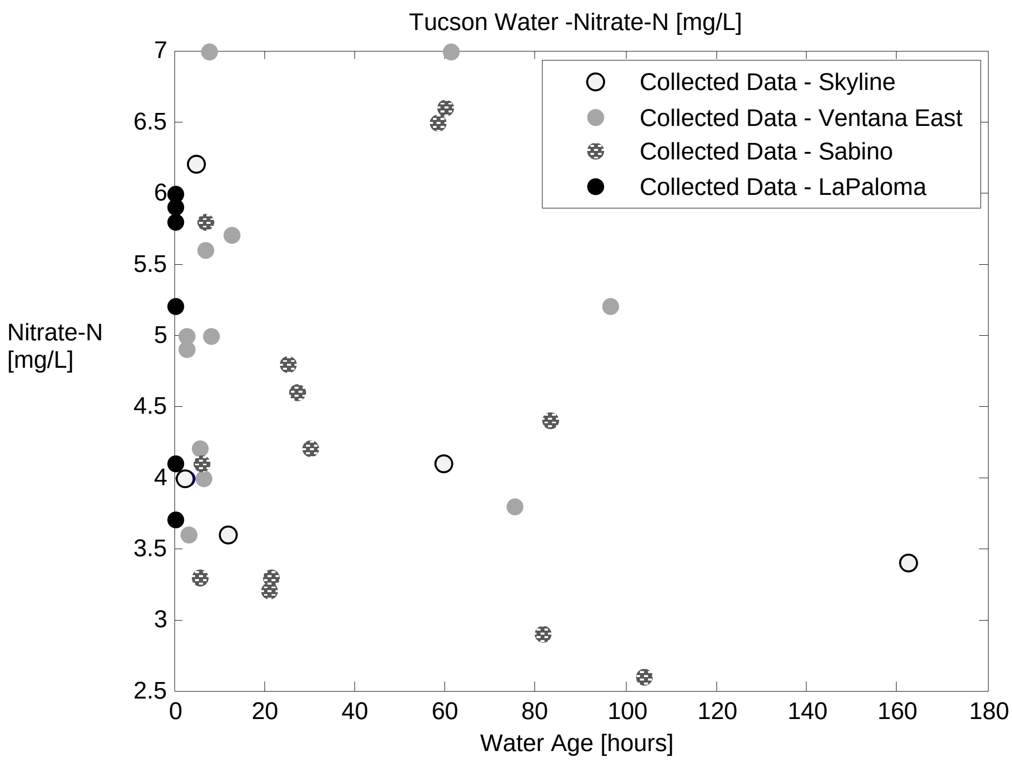


Figure 5.15. Nitrate-N concentration in Tucson Water distribution system.

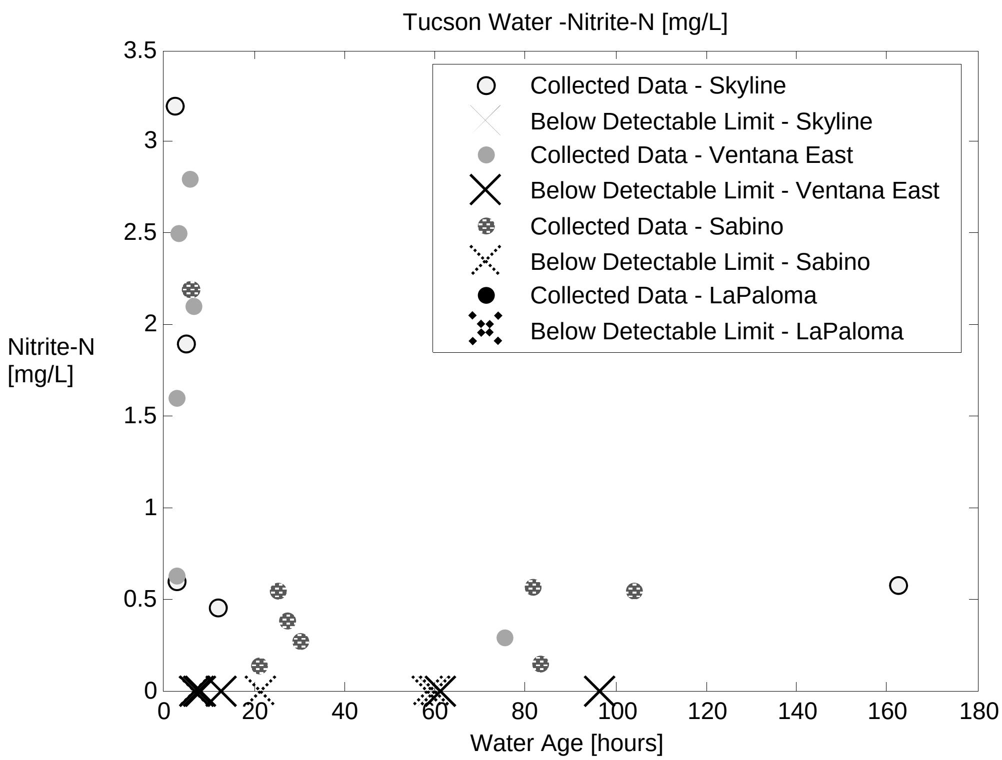


Figure 5.16. Nitrite-N concentration in Tucson Water distribution system.

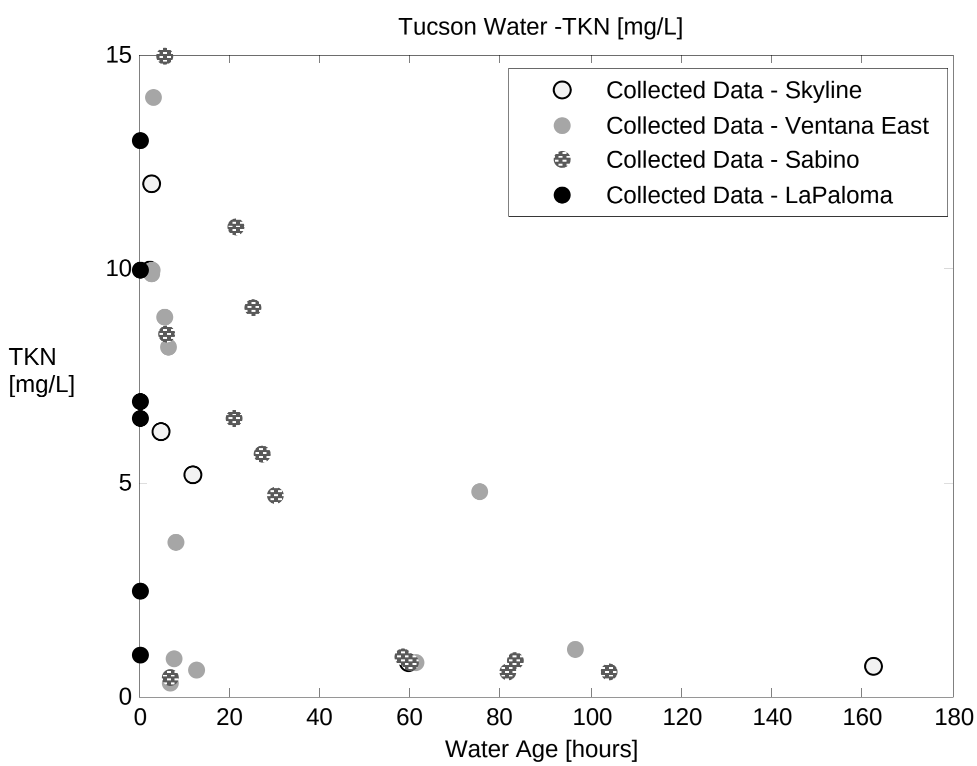


Figure 5.17. TKN concentration in Tucson Water distribution system.

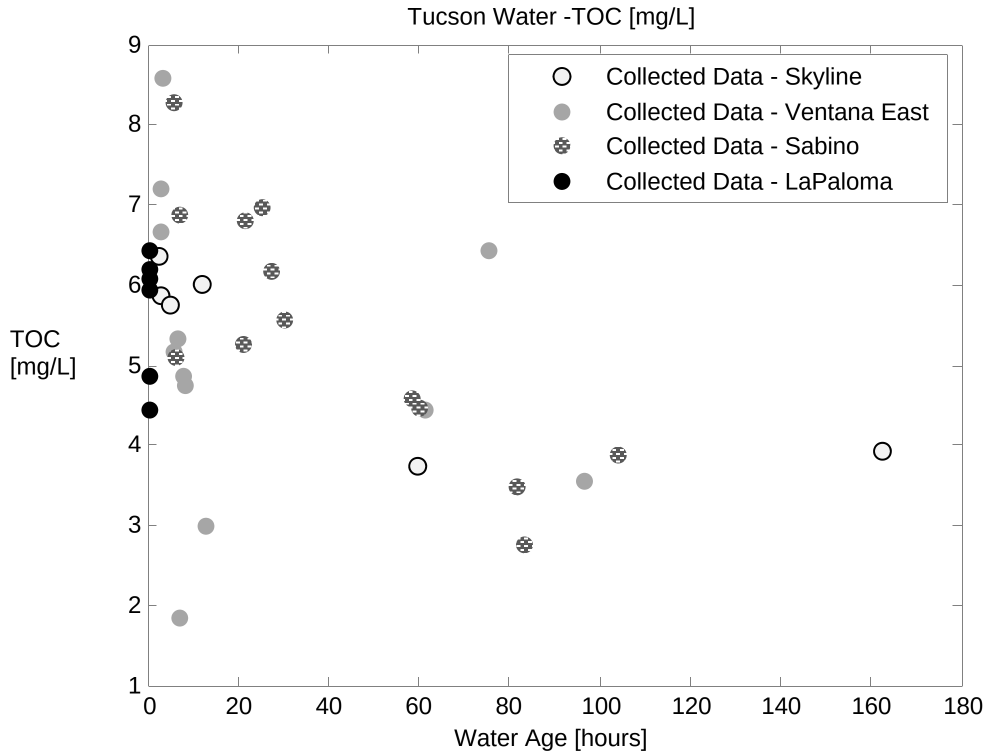


Figure 5.18. TOC concentration in Tucson Water distribution system.

5.6 Preliminary Chemical Parameter Conclusions

Previous studies have shown that salinity and SAR may have impacts on nitrification, where nitrification decreases with increased salinity and SAR and vice versa (Quanzhong and Guanhua, 2009). The figures in this chapter show that lower salinity and SAR values were observed during nitrification at 60 hours of water age for Ventana East and Sabino locations. Lower SAR values were also observed at these locations when nitrification occurred at the 85- and 100-hour water ages.

Microbial mineralization of TKN, followed by the first reaction of nitrification (bio-oxidation), produces a large amount of strong acid, which may cause reductions of alkalinity (Ghannoum and O'Toole, 2004). Low alkalinity (Figure 5.14) was observed at 60 hours of water age (Ventana East and Sabino), which may be attributed to bio-oxidation of TKN.

Denitrification processes use organic (heterotrophic denitrification) or inorganic (autotrophic denitrification) carbon and therefore raise alkalinity (Rijn et al., 2006). Figures 5.14 and 5.18 show increases in alkalinity at the Ventana East and Sabino locations and decreases in TOC at the Sabino location, along with denitrification at 80 hours of water age. High concentrations of TOC at the Ventana East location during the denitrification process (80 hours) show that the denitrification process may be autotrophic.

Chapter 6

Recycled Water Quality in Storage

6.1 Introduction

Storage reservoirs are primarily used to balance seasonal demands generated by a variety of urban reuse scenarios. The storage of recycled water in open lagoons can affect the microbial quality of recycled water; algal bloom is often a significant problem in open reservoirs. Recycled water can also be stored in enclosed storage tanks, but there are few data on the overall water quality of recycled water following storage. Potential problems that may arise when storing recycled water for short, intermediate, or long terms can include, but are not limited to, increases in odor; turbidity; color; and regrowth and survival of microorganisms, including potential opportunistic pathogens.

6.2 Methods

This study included efforts to monitor microbial and chemical quality of stored recycled water as a function of residence time. Utilities are considering increased storage to enhance their water resource portfolio at various times throughout the year. In water-stressed regions, such as the semi-arid Southwest, water demand during the winter months may decrease; therefore, recycled water may remain stored in the distribution system for extended periods of time.

In order to evaluate the effects of long-term storage on recycled water quality, one bench-scale and two field-scale studies were conducted using recycled water of two qualities. In the bench-scale study, two classes of recycled water, Arizona Class A and A+, were stored in two 10-L containers and monitored for chemical and microbial quality for a period of 7 days. Class A and A+ water qualities in the state of Arizona are similar to California Title 22, with the + referring to denitrification to a level less than 10 mg/L nitrate nitrogen (NO_3-N). The rationale for the bench-scale study was to establish an optimal sampling regime for the subsequent field-scale studies.

The study was repeated twice in the field with larger volumes of recycled water stored in two 946-L (250-gallon) tanks (Figure 6.1). The first field-scale study was monitored for a period of 5 months from September 2010 through January 2011. The second field-scale study of stored recycled water started in April 2011 and continued through June 2011. During the second field-scale study, intensive monitoring was conducted every 2 hours for the first 48 hours. This was done in order to provide detailed water quality information to the research team for accurate microbial model calibration discussed in later chapters.

Figure 6.1. Field study storage reservoirs.

6.3 Observations: Field Study No. 1

Results from the first field study showed rapid dissipation of residual chlorine within 24 hours of storage for both Class A and Class A+ water qualities. This result was similar to both the bench-scale study and the second field-scale study in that residual chlorine was negligible within very short retention times (hours). Figure 6.2 outlines the rapid decline of residual chlorine after storage observed in the bench-scale storage experiments. This rapid dissipation was also observed during both field-scale studies.

Table 6.1 outlines the averaged values and standard deviations of chemical, physical, and microbial water quality parameters monitored during the first field phase of this study. Parameters (microbial, chemical, or physical) that are in bold text indicate those that seem to show significant differences between water quality classifications Class A or Class A+.

Total coliform bacteria were observed in Class A water; however, waterborne pathogens such as *E. coli* and *Enterococci* were negligible during the duration of the study. In Class A water, *Aeromonas* was detected on only one occasion at Day 35. *E. coli* was not detected, and heterotrophic plate counts (HPCs) remained constant in the range of 10^7 to 10^8 CFU/100mL. HPCs in Class A+ water increased 4 orders of magnitude after 7 days of storage from 10^5 to 10^9 CFU/100mL, and *Aeromonas* increased several orders of magnitude. A similar increase in *Aeromonas* was not found in the Class A water, suggesting that conditions in the Class A+ water were selective for growth of this species. Significant decreases in TOC and NO_3^- during the same time period in Class A+ water may have resulted from *Aeromonas* activity, as this microbial group has shown the ability to respire NO_3^- (Lee and Welander, 1996; Abdalla et al., 2011). Growth conditions in Class A water were enhanced for the indicator species (total coliform, *Enterococci*) compared to the Class A+ water, suggesting the presence of a fundamental chemical difference between the two waters, one that resulted in enhanced growth of a potential pathogen in Class A+ water. This phenomenon warrants further investigation.

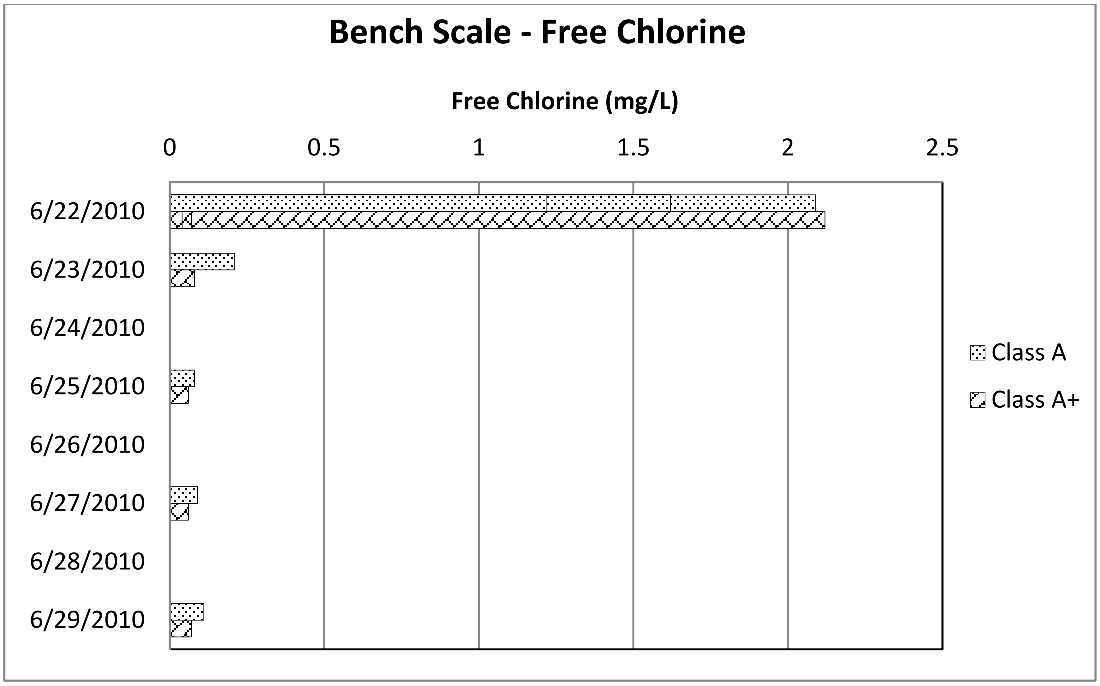


Figure 6.2. Residual free chlorine in bench-scale storage.

As with microbial water quality, Class A chemical water quality also changed as storage duration increased. All ammonium within the Class A water dissipated to essentially zero within 24 hours. Significant nitrite concentrations were detected during Days 1 through 29, but following this period nitrite was converted to nitrate via the second reaction of nitrification, resulting in enhanced nitrate concentrations.

TOC concentrations remained between approximately 2 and 10 mg/L for much of the storage period and averaged 6.87 mg/L throughout the duration of Class A storage. By the end of the Class A storage period (>100 days), the TOC concentration had dropped to 2.9 mg/L.

Similarly, AOC in Class A stored water values generally decreased as storage duration increased, most likely because of loss of available carbon as CO_2 during microbial respiration (Figure 6.3). No significant correlations were found between AOC and HPCs in the storage tanks; however, this does not discount the hypothesized relationship. The HPC is an estimate of the viable heterotrophic bacteria in water samples and, although accepted as a standard technique, has been shown to underestimate heterotrophic growth because of the inability of the bacterial medium to support all heterotrophic growth equally and the presence of viable but nonculturable bacteria within the water sample (Nollet, 2007). The averaged value of AOC in stored Class A water measured 0.40 mg/L and was similar to values obtained in Class A+ stored water of 0.39 mg/L.

Table 6.1. Field Study No. 1 Storage Tank Average Water Quality Results

Field Study No. 1 Parameters	Class A		Class A+	
	Average	**STDEV**	**Average**	**STDEV**
***Aeromonas* (CFU/100mL)**	**6.88E-01**	**2.50E+00**	**2.34E+03**	**6.13E+03**
Alkalinity (mg/L)	171.41	9.43	132.58	6.22
Assimilable organic carbon (mg/L)	0.40	0.22	0.39	0.23
E. coli (MPN/100mL)	<1	<1	<1	<1
Electrical conductivity (ms/cm)	1.25	0.09	0.95	0.05
***Enterococcus* (MPN/100mL)**	**3.00E-01**	**4.83E-01**	**<1**	**<1**
Free Cl_2 (mg/L)	0.02	0.09	0.01	0.05
HPC (CFU/100mL)	9.65E+08	2.05E+09	2.78E+08	4.90E+08
NH_4-N (mg/L)	0.25	0.92	0.12	0.12
NO_2-N (mg/L)	**5.53**	**3.97**	**0.00**	**0.00**
NO_3-N (mg/L)	8.95	3.92	4.78	0.22
pH	7.36	0.35	7.48	0.26
Temperature (° C)	25.68	6.66	25.83	7.12
Total Cl_2 (mg/L)	0.03	0.13	0.01	0.06
Total coliform (MPN/100mL)	**9.70E+01**	**9.93E+01**	**3.63E+00**	**4.67E+00**
Total dissolved solids (mg/L)	**801.08**	**57.09**	**609.00**	**34.96**
Total nitrogen (mg/L)	**14.02**	**0.87**	**5.14**	**0.22**
Total organic carbon (mg/L)	6.87	5.11	6.37	3.99

Notes: Cl=chlorine; HPC=heterotrophic plate count; NH_4-N=ammonium; NO_2-N=nitrite nitrogen; NO_3-N=nitrate

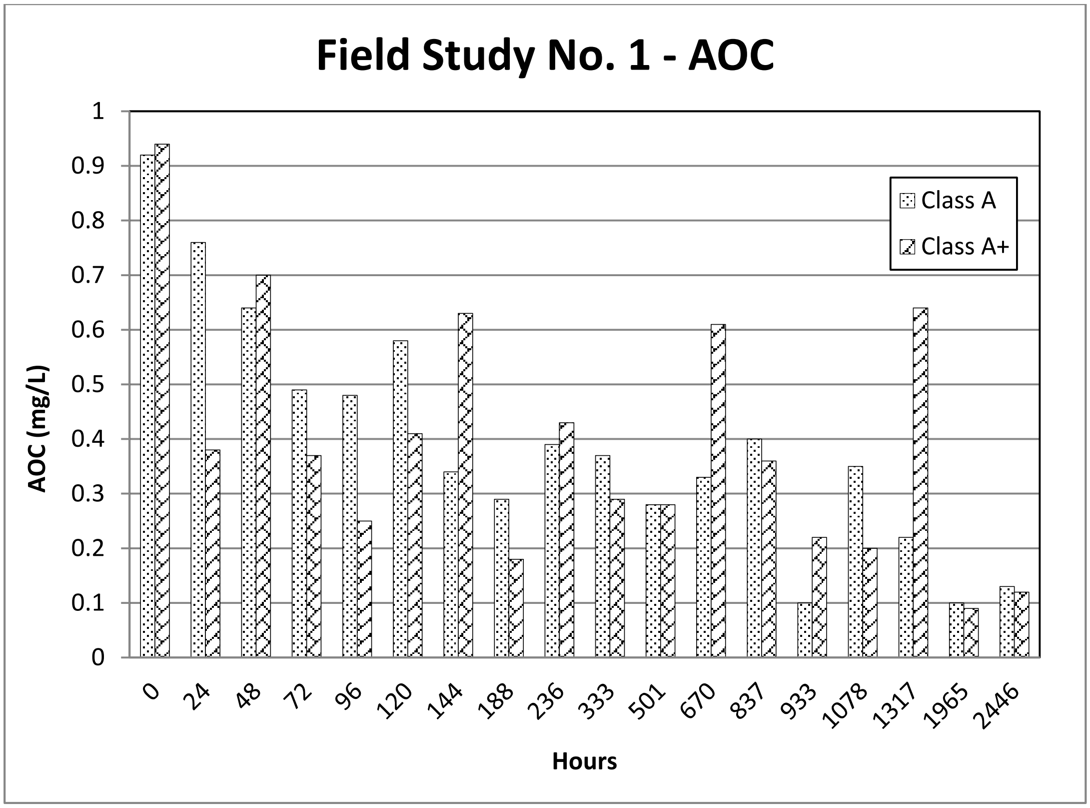


Figure 6.3. Assimilable organic carbon (AOC) concentrations during storage.

Total nitrogen concentrations in Class A water remained fairly constant throughout the storage period, as demonstrated in Figure 6.4.

In Class A+ water, chemical changes during storage were also observed; however, in contrast to Class A, ammonium (NH_4-N) and nitrogen dioxide (NO_2) values were negligible throughout the total storage period. Nitrate and total nitrogen concentrations both remained constant throughout the storage period and averaged 4.78 and 5.14 mg/L (Figure 6.5). Trends for TOC and AOC were similar to those seen in Class A water, with very little significant differences between the two stored waters over time. Microbial results for Class A and Class A+ waters are provided in Figures 6.6 and 6.7.

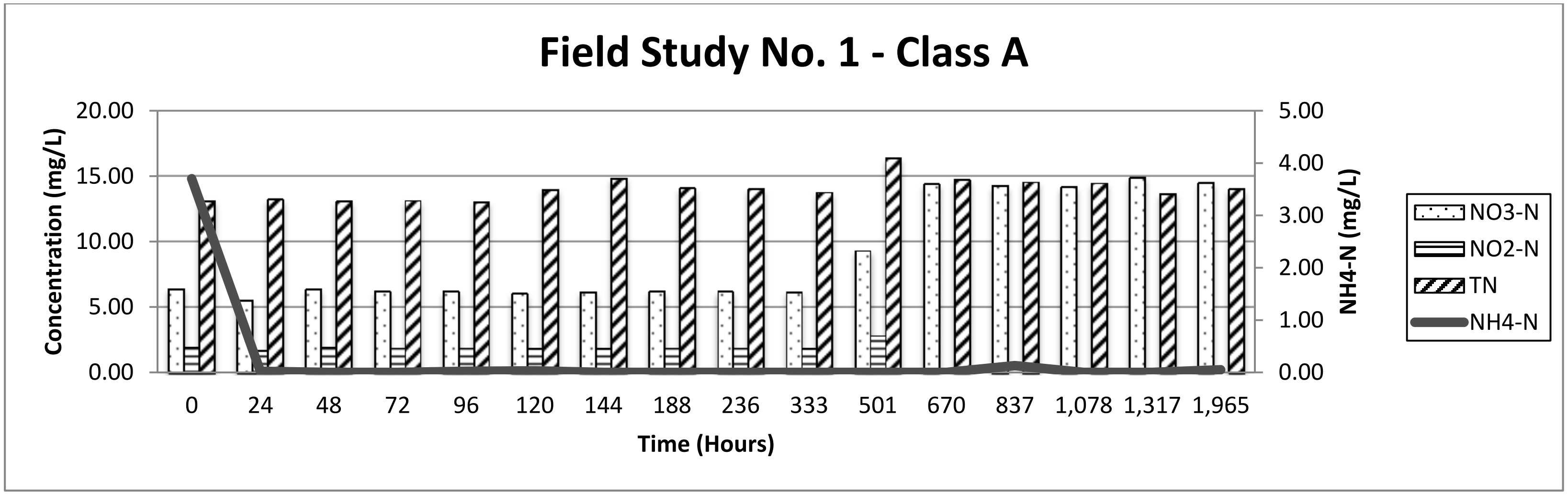


Figure 6.4. Nitrogen species concentrations during storage, Class A.

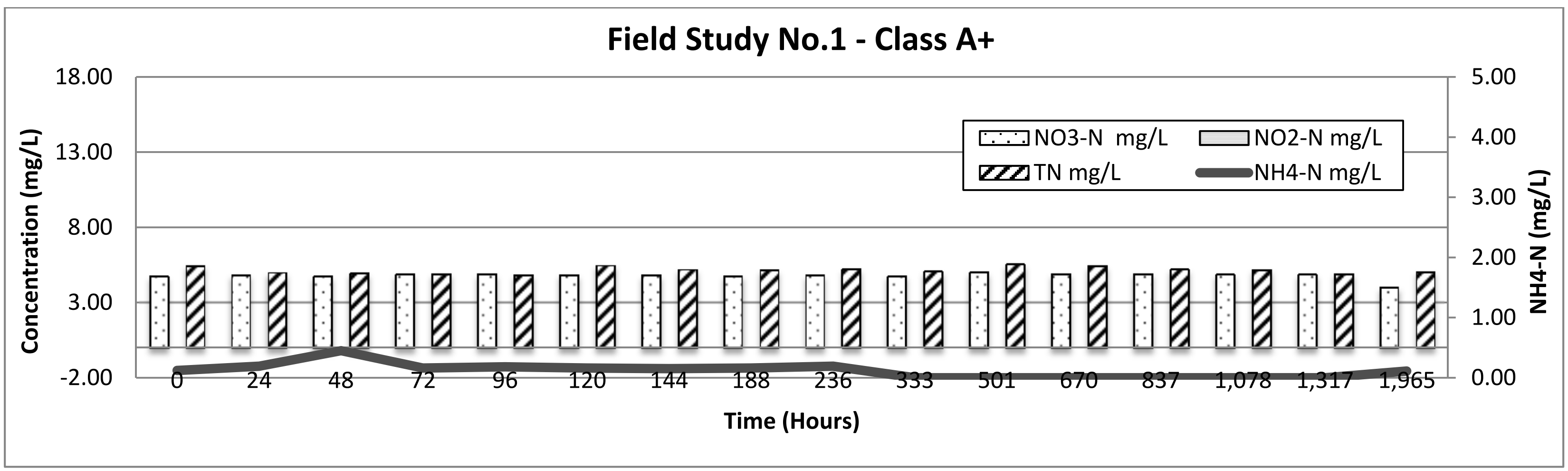


Figure 6.5. Nitrogen species concentrations during storage, Class A+.

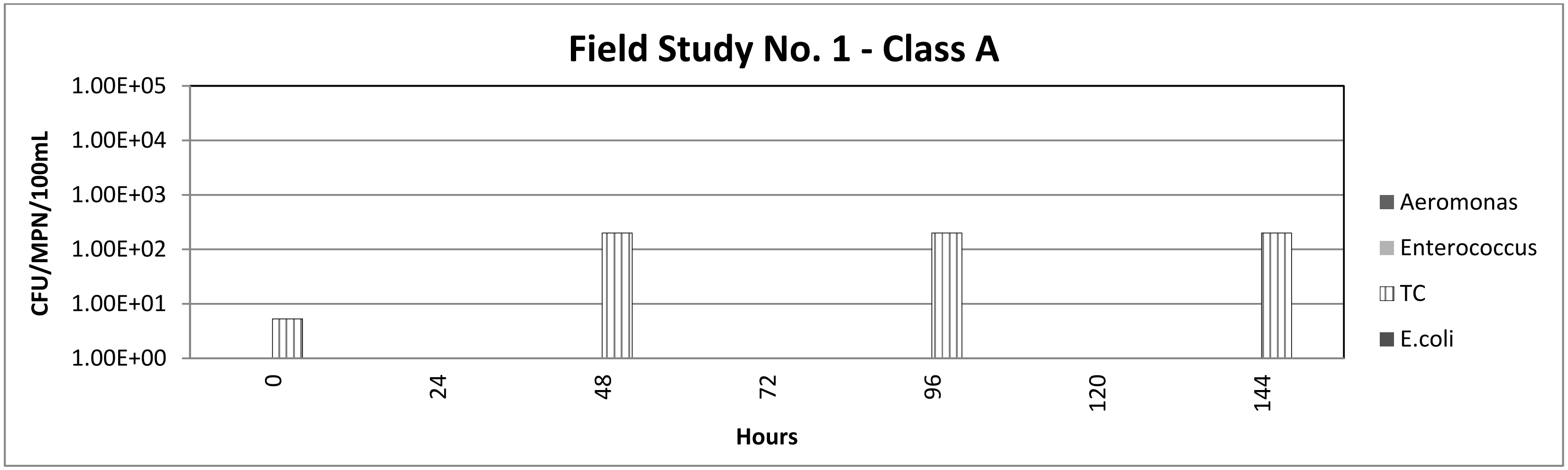


Figure 6.6. Water quality changes during Field Study No. 1 storage (Class A).

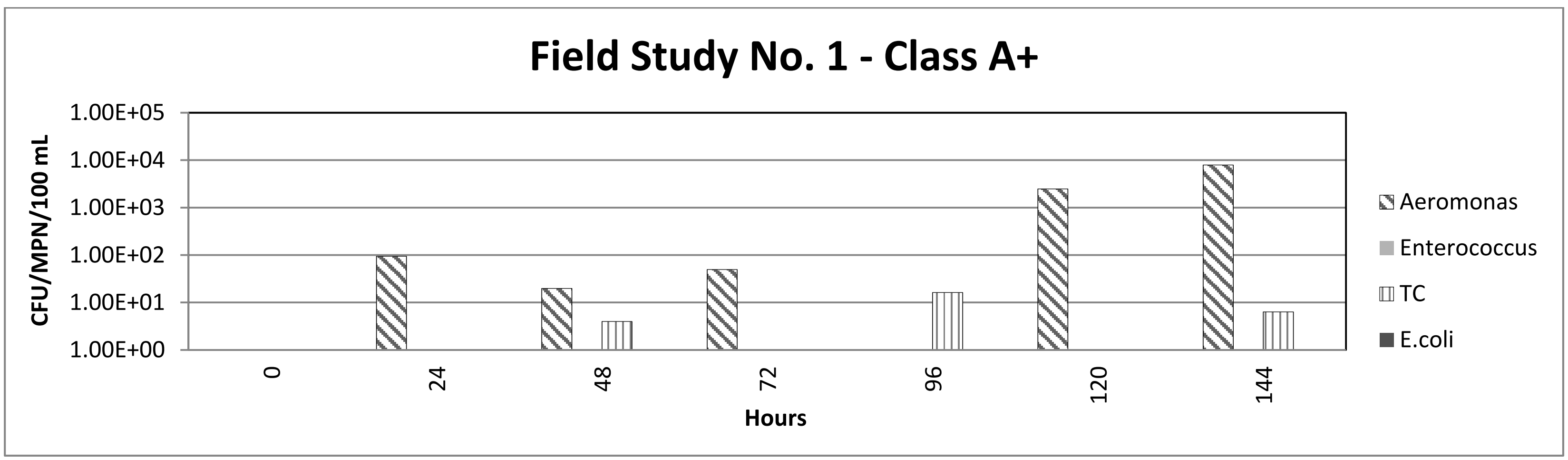


Figure 6.7. Water quality changes during Field Study No. 1 storage (Class A+).

6.4 Observations: Field Study No. 2

The goal of repeating the storage tank field study was to gather data from a replication of the initial observations of microbial and chemical water quality associated with stored recycled water. The storage tank study was repeated approximately 4 months following the initial study (April to June) and monitored for indicator bacteria, waterborne and water-based pathogens, and chemical parameters. Intensive sampling was done every 2 hours during the first 48 hours of the study in order to provide detailed short-term water quality data on key parameters such as chlorine and AOC concentrations, which may control microbial populations. Obtaining such data may allow for superior models to be developed that predict the influence of residence time on microbial water quality. Because of the complexity of the assay, *Aeromonas* was only monitored every 6 hours during the first 48 hours, and thus we were unable to determine the presence of the same sharp increase in *Aeromonas* concentrations over 7 days, a pattern found in Field Study No. 1.

Averaged values and standard deviations of chemical and microbiological parameters monitored for Class A and Class A+ stored recycled water are provided in Table 6.2. Parameters in bold are those that show significant differences between the two stored classes of water.

Table 6.2. Storage Tank Average Water Quality Results

	Class A		**Class A+**	
Field Study No. 2 Parameters	**Average**	**STDEV**	**Average**	**STDEV**
Aeromonas (CFU/100mL)	2.29E+01	5.11E+01	6.82E-02	3.20E-01
Alkalinity (mg/L)	174.32	8.21	126.02	3.00
Assimilable organic carbon (mg/L)	1.48	1.11	1.30	0.88
E. coli (MPN/100mL)	<1	<1	<1	<1
Electrical conductivity (ms/cm)	1.26	0.02	1.03	0.01
Enterococcus (MPN/100mL)	1.86E+01	5.51E+01	9.82E+00	4.06E+01
Free Cl_2 (mg/L)	0.01	0.03	0.01	0.01
HPC (CFU/100mL)	1.58E+08	5.30E+08	1.10E+08	2.01E+08
NH_4-N (mg/L)	0.05	0.04	0.05	0.04
NO_2-N (mg/L)	9.32	3.90	0.22	0.58
NO_3-N (mg/L)	4.80	3.00	5.34	0.15
pH	7.19	0.26	7.94	0.46
Temperature (° C)	24.89	2.39	25.27	1.95
Total Cl_2 (mg/L)	0.02	0.04	0.02	0.04
Total coliform (MPN/100mL)	1.03E+01	1.56E+01	1.61E+00	1.77E+00
Total dissolved solids (mg/L)	806.21	10.32	661.86	3.11
Total nitrogen (mg/L)	14.52	0.58	6.01	0.29
Total organic carbon (mg/L)	5.13	1.07	5.43	2.78

Notes: Cl=chlorine; HPC=heterotrophic plate count; NH_4-N=ammonium; NO_2-N=nitrite nitrogen; NO_3-N=nitrate

As stated previously, the second field-scale study involved more intensive sampling during the first 3 days of storage to ascertain microbial and chemical shifts during short-term storage. As in Phase 1, results showed rapid dissipation of residual chlorine within 24 hours of storage for both water qualities, A and A+. The average temperatures were similar for both stored classes of recycled water and ranged from 23 to 30° C. The pH of Class A reclaimed water tended to be neutral throughout the sampling period, whereas Class A+ was slightly alkaline. Indicator organisms (*E. coli*) were absent in both classes of stored reclaimed water. Total coliform levels were slightly higher in Class A when compared to Class A+ water.

HPCs were consistently in the range of 10^7 to 10^9 CFU/100mL for Class A. In contrast to Class A+, HPC levels were initially 10^4, but following rapid growth increased to 10^7 CFU/100mL within 4 days of storage. Following this, HPC levels for both waters were similar, showing enhanced growth after 32 hours of storage. These results were similar to those obtained from the previous phase of the storage study and suggest that seasonal changes in recycled water quality did not affect levels of HPC bacteria in storage systems.

It is interesting to note that HPC populations were correlated with AOC levels in both Class A and Class A+ storage tanks. After 32 hours of storage, HPC populations within Class A water increased by one order of magnitude. In exactly this same time period, the AOC level increased by more than 100% (Figure 6.8). Similarly for Class A+ water, after 32 hours of storage the AOC level increased significantly just as the HPC levels increased by two orders of magnitude. It appears that initial storage conditions may have stimulated degradation of TOC levels in the water (highly plausible, given that a measurable Cl_2 residual existed). TOC degradation may have increased AOC, which in turn acted as a substrate for heterotrophic bacterial growth. Many oxidative processes have been shown to contribute to increased AOC presence in water, but the presence of oxidants (e.g., H_2O_2) was not measured in this study.

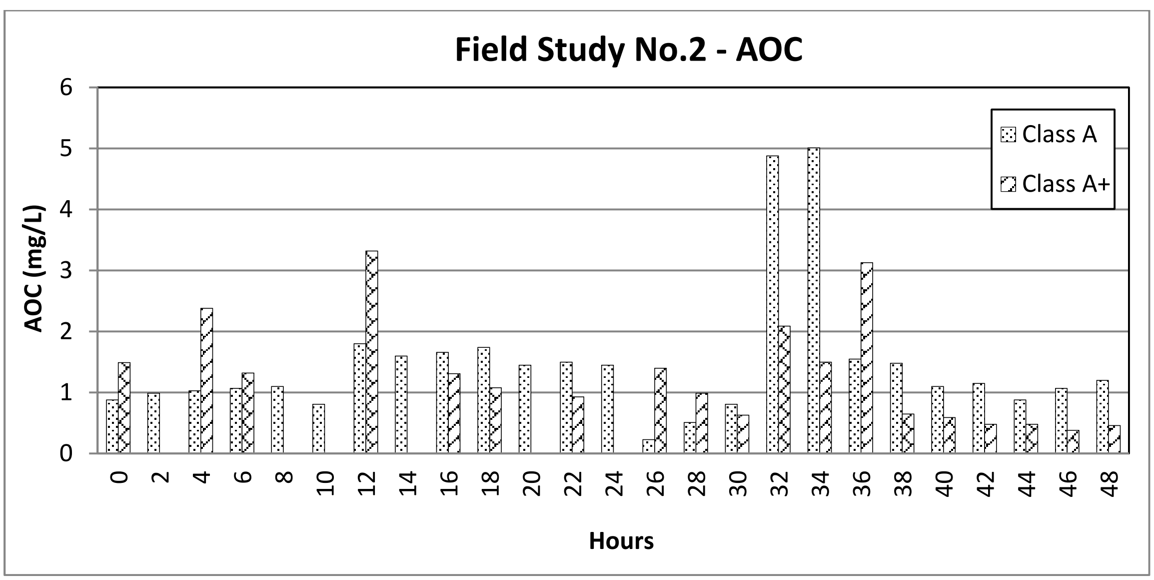


Figure 6.8. Assimilable organic carbon (AOC) concentrations during storage.

Aeromonas was occasionally found in Class A water but at levels significantly lower than those found in the first storage tank study. Also, in contrast to the first study, *Aeromonas* was found in negligible concentrations in Class A+ water in the second storage tank study. As previously stated, however, *Aeromonas* levels were measured in the second study over only 48 hours, unlike the first study, in which they were assessed over several weeks. Therefore, comparative assessments of *Aeromonas* levels between the two studies cannot be made.

The chemical quality of Class A+ water changed with the duration of storage. Nitrite levels were less than the detection limit in the majority of samples collected. Measurable nitrite was only detected between 120 and 408 hours of storage, after which nitrite was converted to nitrate via microbial nitrification, similar to the trends observed during the first storage tank study. In Class A, higher levels of nitrite were observed initially, approximately three times higher than initial nitrite levels observed in the first storage tank study. Reasons for the higher nitrite in the second study are unknown, but, as in the first study, nitrite levels were reduced gradually until they were completely converted to nitrate, as indicated by the high levels of nitrate towards the end of the study due to nitrification.

TOC levels in Class A water remained fairly constant throughout the study, whereas in Class A+ TOC levels dropped throughout the monitoring period from 14.0 to 3.8 mg/L. The average of the total nitrogen concentrations was higher for Class A than for Class A+, as shown in Table 6.2. This is acceptable because there is no nitrogen maximum for Class A reclaimed water as stipulated by the Arizona Department of Environmental Quality.

Charts of Class A nitrogen species, Class A+ nitrogen species, Class A microbial data, and Class A+ microbial data are provided on Figures 6.9, 6.10, 6.11, and 6.12, respectively.

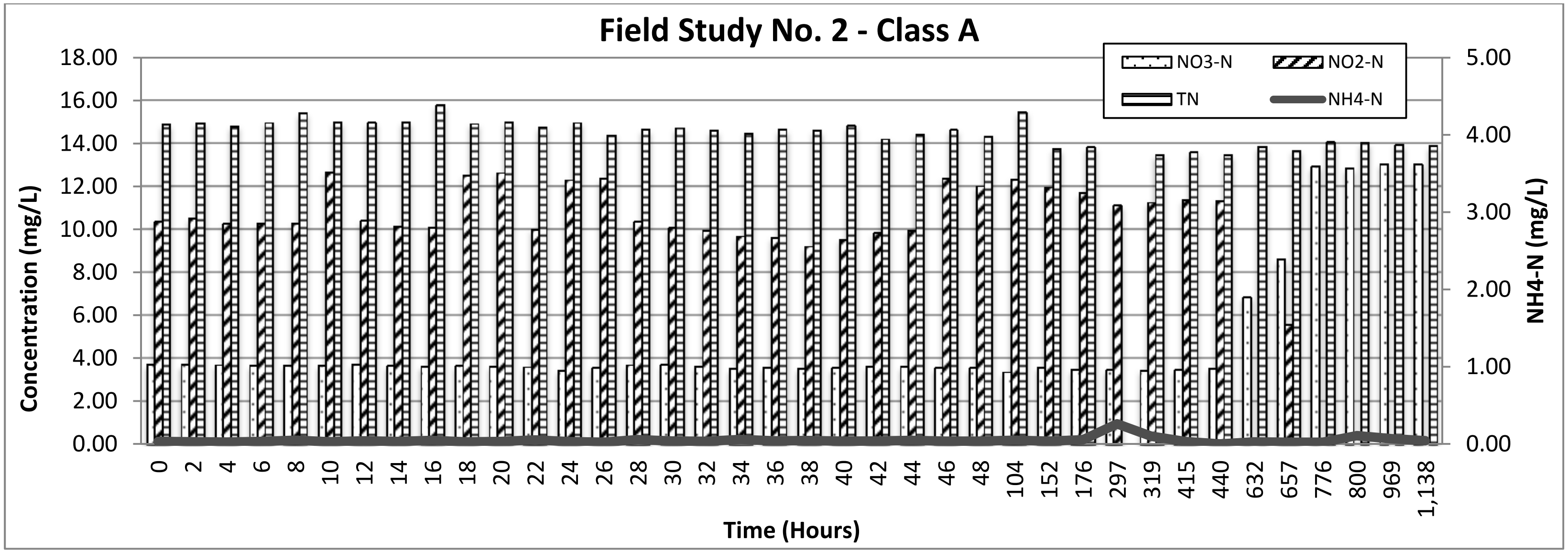


Figure 6.9. Nitrogen species concentrations during storage, Class A.

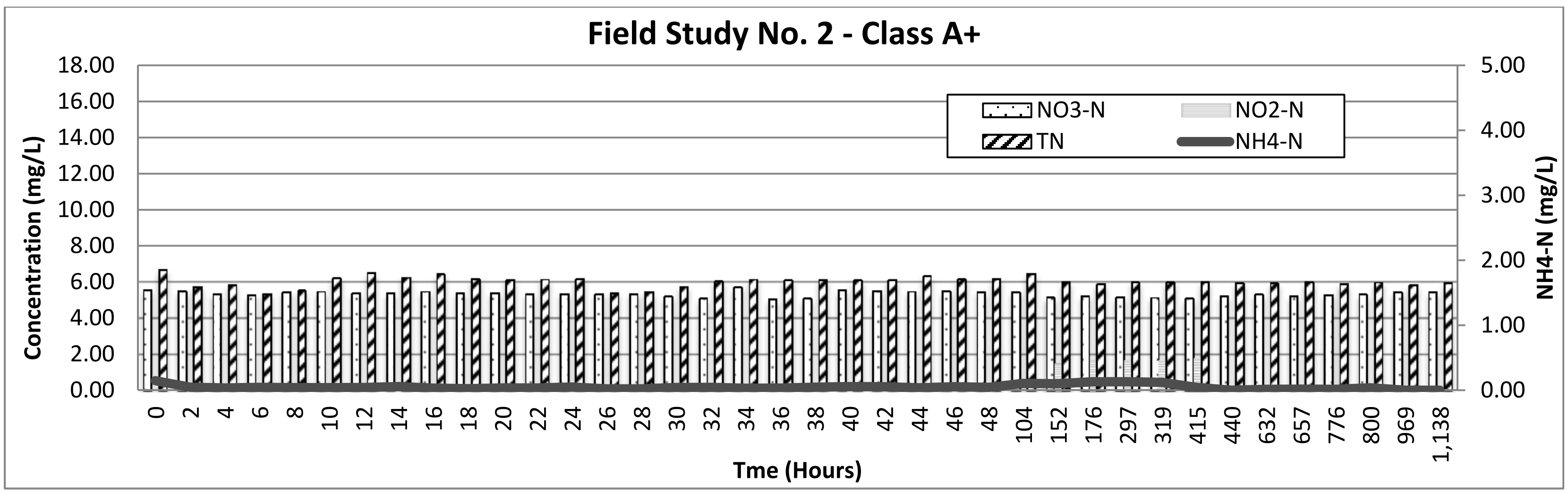


Figure 6.10. Nitrogen species concentrations during storage, Class A+.

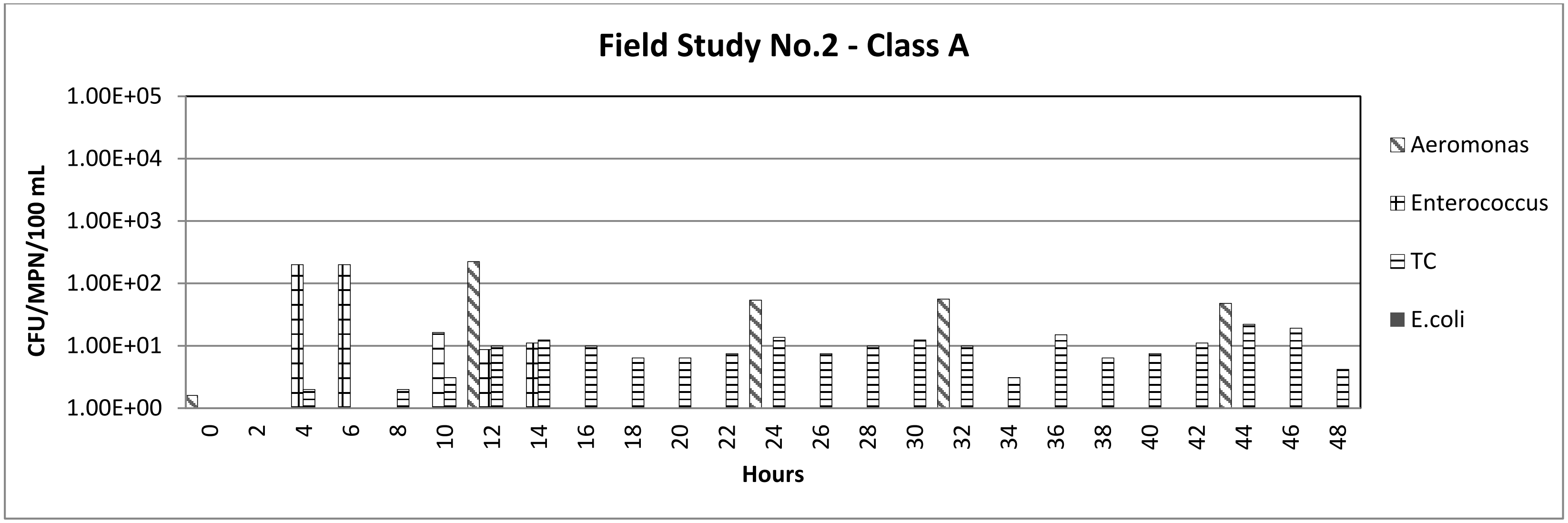


Figure 6.11. Water quality changes during Field Study No. 2 storage, Class A.

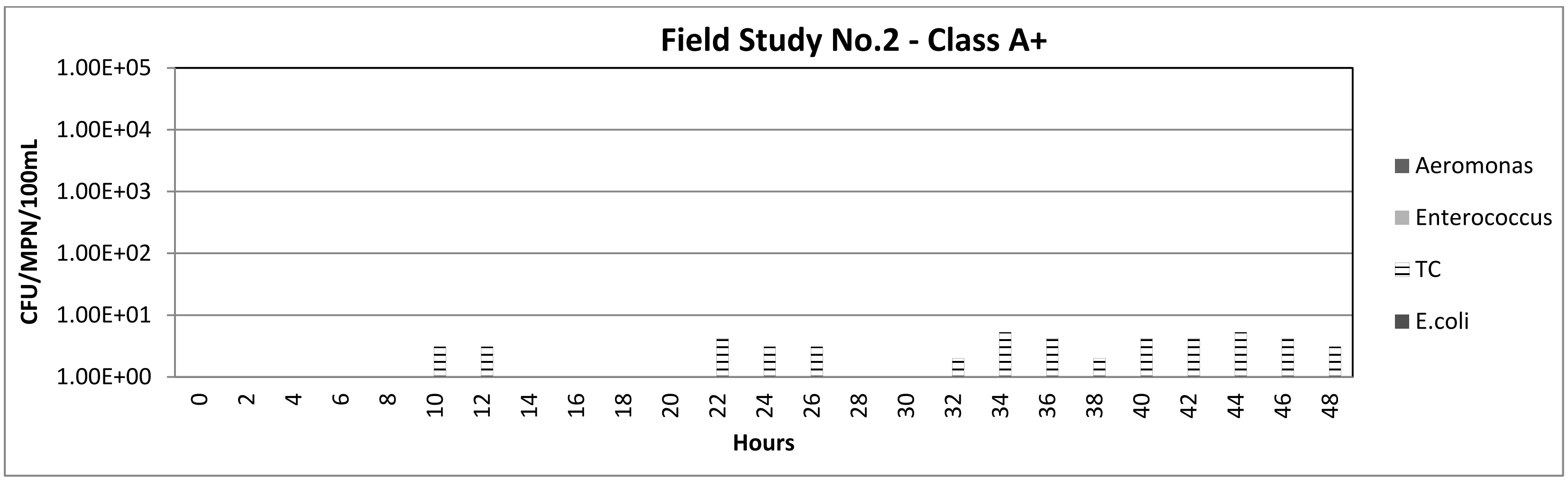


Figure 6.12. Water quality changes during Field Study No. 2 storage, Class A+.

6.5 Microbial Growth and Regrowth

For the purposes of this report, microbial concentrations have been plotted through144 hours (6 days) for the first field study and 48 hours for the second field study. Microbial concentrations seem to fluctuate within the first 48 hours until the initial pseudo-equilibrium phase of microbial growth is reached, with greater fluctuations seen in Class A water than Class A+ water. This initial fluctuation may be due to competition of microbial populations until those ideally suited for storage conditions out-compete others, at which point the increase of microbial populations (biomass) seems to follow the conventional growth curve until the stationary phase is reached and die-off begins. This phenomenon was seen after 6 days of storage in both field-scale studies, where levels of microbial parameters monitored seem to reach equilibrium in both tanks and begin to decline in concentration for the duration of the study.

This trend was seen in both qualities of recycled water regardless of initial treatment. Because this trend was seen in both field studies and water qualities, our team hypothesizes that there may be an optimal storage holding time under which conditions fluctuate between acceptable and unacceptable water quality and back again. Figure 6.13 represents this scenario. Because initial recycled water quality varies so greatly between treatment facilities, additional evaluation may be needed to establish appropriate best management practices that include minimum and maximum holding/residence times for various recycled water qualities in order to optimize recycled water use and short- and long-term storage. We foresee recommendations for increased residence time to allow for microbial biomass decline or the reintroduction of disinfectant to the storage reservoir after a certain residence time has passed. It is also important to note that short- and very long-term storage are not necessarily detrimental to water quality, as demonstrated in Figure 6.13, but increased awareness is needed to determine where along the growth curve any individual recycled water storage lays.

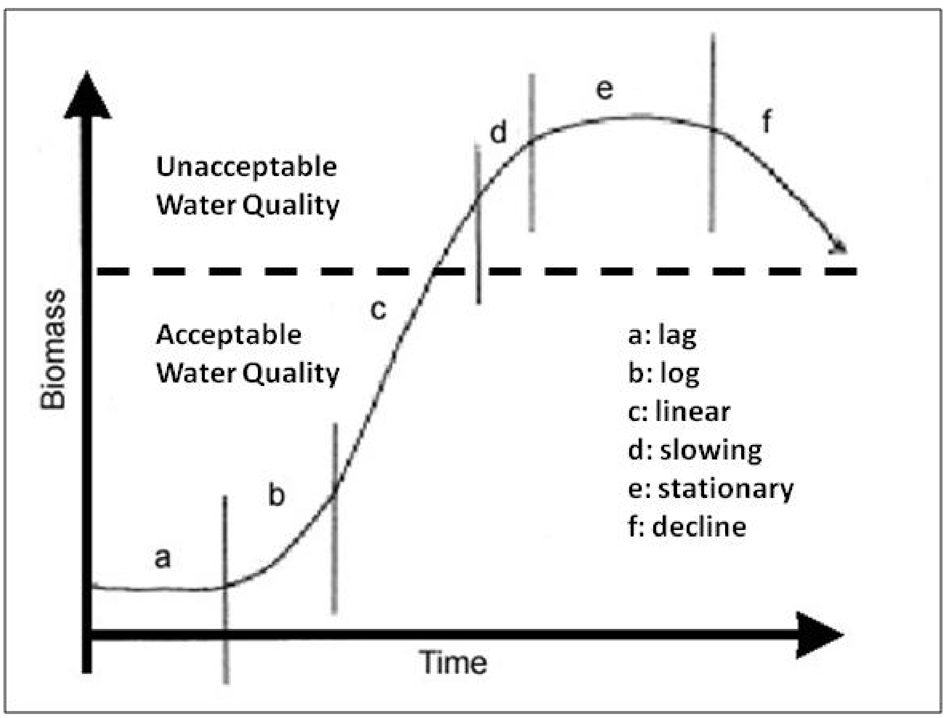


Figure 6.13. Microbial growth curve for recycled water storage scenario.

6.6 Microbial Diversity: Storage Tanks

In addition to the cultural microbial analyses and chemical assessments of water quality on samples pulled from storage tanks, the research team utilized measurements of microbial diversity to assess community-level changes over time. Because they are at the bottom of the food chain, changes in microbial communities are often a precursor to changes in the health and viability of any given environment, and shifts in overall microbial diversity or species richness may provide insight into controls that may reduce degradation in water quality during storage.

To measure community-level microbial diversity, the study team utilized the Biolog EcoPlate™, a 96-well plate containing 31 carbon sources. Utilization of the carbon sources by the microbial community within a water sample is assessed over time, resulting in a characteristic reaction pattern, a "metabolic fingerprint" that can rapidly and easily provide a vast amount of information.

Inoculation of the EcoPlate was performed on water samples collected from both storage tanks at 9 time points over 36 days following the filling of the tanks. Undiluted tank water samples were pipetted directly into each well of the microplate (150 µL sample per well). Plates were incubated at room temperature (~25° C) and analyzed once every 24 hours for a total of 4 days. Analysis was performed using a plate-reading spectrophotometer (absorbance wavelength: 590 nM). Metabolic capability of the microbes within the water sample was visualized by development of purple color within each well, which occurs in response to carbon dioxide production as the microbes utilize the carbon source and begin to respire.

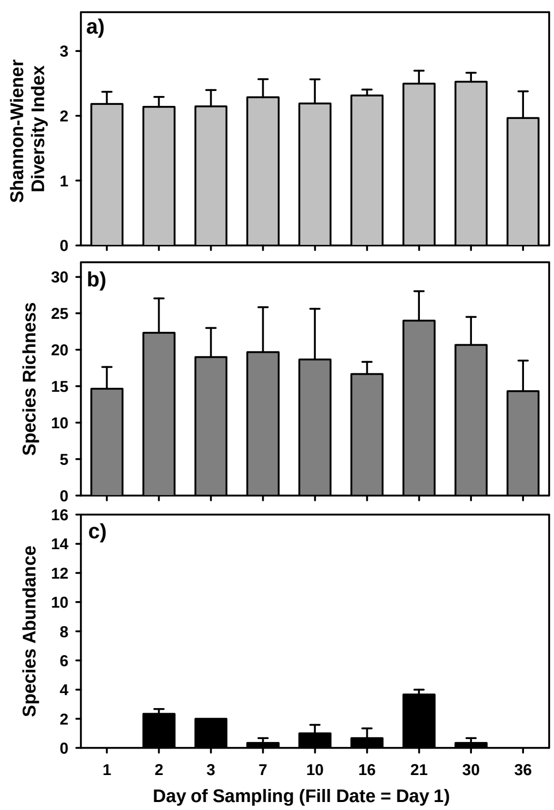
The community profile included the following measures:

- Shannon-Wiener Diversity Index, a measurement that accounts for the richness (total number of wells displaying purple coloration) and evenness of the distribution of wells displaying a color change. The index assumes that the proportion of individual microbial groups within a water sample indicate their importance to diversity. A higher diversity index implies that within the microbial community there is an increased amount of diversity.
- Species richness, the total number of wells showing purple coloration (total number of microbial groups utilizing that substrate). As a result of the plate layout, containing 31 different carbon substrates, species richness can range from 0 to 31. This measurement does not take into account the proportion and distribution of each microbial group.
- Species abundance**,** the number of individuals per microbial group within a community (assessed using the relative level of purple coloration response). Two communities may contain equal species richness but differ in abundance. For example, each community may contain 10 microbial groups, but in one community all groups show equal coloration between the 10 wells, indicating that the groups are equally common, whereas in the second community one well shows distinctly greater color development, indicating that this group significantly outnumbers the other nine.

Temporal patterns in diversity differed between the Class A+ (Figure 6.14) and Class A (Figure 6.15) quality recycled municipal wastewater. The Class A+ water showed little difference in diversity over the 36-day storage period. Species richness showed only limited variability, indicating that few shifts in net activity by microbial groups occurred over time. Species abundance measurements were very low, indicating that the activities contributing to species diversity and richness were dominated by only a very few microbial groups.

One exception to the patterns described above occurred on Day 21 (Figure 6.14), when increases in diversity, richness, and abundance were all recorded. Microbial sampling noted a sharp increase in *Enterococcus* within the sampling tank on this date. These results suggest that, following 3 weeks of storage, conditions conducive to microbial growth occurred. Data from previous storage tank experiments show increases in total nitrogen and AOC following 21 to 28 days of Class A+ water storage. Though steady reductions in indicator microorganisms were found in the weeks prior, it is possible that on or around Day 21 a threshold was reached whereby indigenous microbial populations in the storage tanks could not utilize nutrients released by dying biomass quickly enough to prevent buildup. The increasing levels of nutrients could conceivably have stimulated the growth of additional communities that had up to that point been inhibited by competition for limited nutrients.

The Class A water showed very similar patterns in diversity, species richness, and species abundance over the 36-day storage period (Figure 6.15). All three parameters were highest during the first 3 days of water storage and thereafter displayed a steady decline. Species abundance measurements were sufficiently high to suggest that microbial populations were sufficiently diverse to efficiently utilize the excess nutrients resulting from microbial die-off and thus no spikes were noted in the latter stages of the storage experiment.



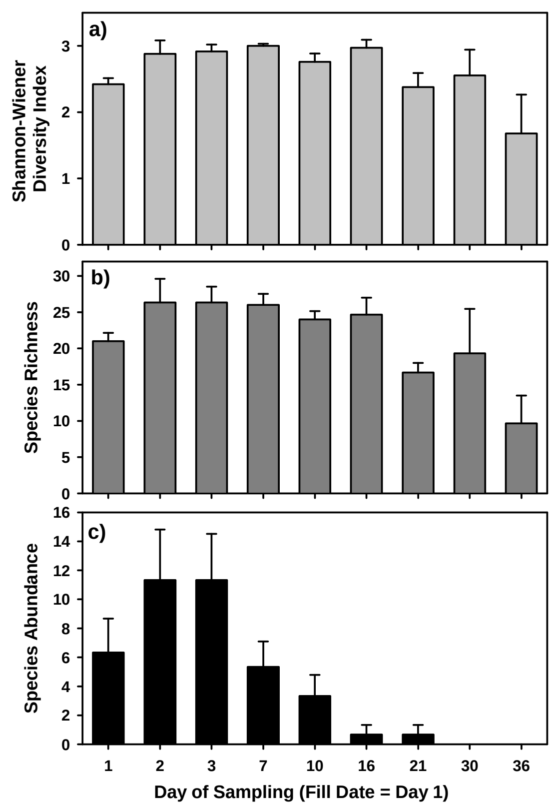


Figure 6.14. (Left) Measurements of diversity index (a), species richness (b), and species abundance (c) over 36 days from tanks filled with tertiary treated, Class A+ recycled water.

Figure 6.15. (Right) Measurements of diversity index (a), species richness (b), and species abundance (c) over 36 days from tanks filled with tertiary treated, Class A recycled water.

Statistical analyses of the diversity parameters show that the Shannon-Wiener Diversity Index for the Class A+ samples (Figure 6.14) was positively correlated with *Enterococcus* (r=0.809; p=0.008) over the 9 sampling dates of the 36-day experiment. Within the Class A tank, species abundance was positively correlated with *Aeromonas* (r=0.794; p=0.019), which showed the same pattern of increase from Days 1 through 3, followed by a gradual decline (Figure 6.15).

When measuring microbial diversity utilizing EcoPlate analysis, results describe the relationship of individual microbial groups of varying subspecies (all using the same substrate) within a water sample. In the use of these measurements, there are some underlying assumptions that may or may not be valid for the water tank study:

1. All groups utilizing a single carbon substrate are equally different. This is not necessarily true; development of a deep purple color in a well could result from a single microbial species displaying a high carbon substrate usage or from multiple microbial groups contributing to a high substrate usage.

2. Carbon substrate usage is equal to species importance. In health-based assessments of water quality, this may not be true. A high population of nonpathogenic microbes is not as important as a population that may be limited in number but able to cause human disease. This issue is common in water quality monitoring, which uses assessments of indicator microorganisms that often have no relative correlation with pathogens.

Despite these potential limitations, the microbial diversity measurements within the storage tanks reveal several intriguing patterns. All of the measured components of species diversity (diversity index, richness, and abundance) respond differently to various environmental conditions. Of key interest are the patterns in species richness and abundance that appear similar to the patterns in total carbon and nitrogen over the same time period, most notably in the Class A water (Figure 6.15), providing evidence that carbon and nitrogen are controlling heterotrophic microbial populations in the storage tanks. The data shown are preliminary, but additional work examining how diversity measures change over time may allow researchers to identify critical time points at which remediation efforts may be applied most effectively to stored reclaimed water.

Chapter 7

Applicability of Analytical Methods

7.1 Molecular Confirmation

Historically, cultural methods have been highly successful for isolating and identifying opportunistic pathogens from drinking water; however, past work by the research team raised concerns over the applicability of selected cultural media to accurately identify and quantify indicator microorganisms and pathogens in the recycled water matrix (McLain and Williams, 2008; McLain et al., 2011). Therefore, in order to better understand the applicability of cultural methods as well as confirm our results, the research team selected approximately 10% of *Legionella* spp. and *Mycobacterium* spp. isolates for molecular confirmation.

Legionella spp. were analyzed using Standard Method 9260 (Standard Methods, 1998). In brief, 100 mL of the recycled water sample was filtered through a 0.45 µm pore size nitrate cellulose membrane, and the filter was then aseptically submerged in a 10 mL phosphate buffer. The buffer was vortexed for 30 seconds and an aliquot of 0.1 mL mixed with an equal amount of acid (i.e., HCl–KCl, pH 2.2). The mixture was incubated at room temperature for 15 minutes and then 0.1 mL of a KOH–KCl base added to neutralize the acid. An aliquot of 0.1 mL (and its dilutions) was then introduced onto buffered charcoal yeast extract (BCYE) plates supplemented with Legionella Agar Enrichment (BD Difco, MD), which primarily contains cysteine, an essential amino acid for *Legionella* spp. PAV supplement (Remel, KS), which contains Polymyxin B, Anisomycin, and Vancomycin, was also added. The plates were incubated at 35° C, and growth was monitored for up to 1 week. Randomly selected presumptive *Legionella* spp. colonies (approximately five colonies from each plate) were streaked on BCYE without any cysteine (NHS, 2007). Failure to grow in the absence of cysteine was regarded as presumptive for *Legionella* spp.

Approximately 10% of colonies that were presumptively positive were selected for molecular confirmation by Polymerase Chain Reaction (PCR) using *Legionella*-specific primers LEG-225 (5'AAGATTAGCCTGCG TCCGAT) and LEG-858 (5' GTCAACTTATCGCGTTTGCT) targeting the 16S rRNA gene. The amplification resulted in a DNA fragment of approximately 654 bp, enabling genetic analysis to determine the diversity of the detected *Legionella.* Speciation work is ongoing. Our research team has archived approximately 56 isolates for PCR confirmation and species identification through cloning and sequencing. Approximately 46% of isolates identified as positive for *Legionella* by cultural methods have been confirmed by PCR (Figure 7.1). Upon visualization of the PCR product, presence of a DNA fragment of 654 bp indicated positivity for *Legionella*. The confirmatory analysis also allowed for identification of seasonal shifts in performance of the *Legionella*-specific medium of concern from past findings of nearly 100% failure of selective media for identification of *E. coli* in reclaimed water (McLain and Williams, 2008; McLain et al., 2011).

Mycobacterium spp. was enumerated by initially decontaminating a known aliquot of the collected water sample with cetylpyridinium chloride (CPC) to a final concentration of 0.005% to avoid overgrowth of nontarget organisms. Although most Gram-negative bacteria are susceptible to CPC, *Mycobacterium* is relatively resistant. The CPC-treated sample was then filtered (0.45 µm pore size) and the filter mounted onto Middlebrook 7H10 agar plates and incubated up to 21 days at 35° C. Representative colonies with a variety of morphological appearances ranging from smooth opaque, smooth transparent, or tan irregularly shaped were subjected to acid-fast staining as described by Seeley et al. (1991) with carbol-fuchsin/Zeihl-Neelsen (Ricca Chemical Company, Arlington, TX) and counterstaining with a 1% methylene blue solution. The cells from colony smears that retained a characteristic red color under microscopy were scored as *Mycobacterium* spp.

For a subset of the samples, *Mycobacterium* positive colonies were selected for molecular confirmation. PCR combined with restriction enzyme analysis has been widely used in identifying *Mycobacterium* spp. in environmental samples, targeting the heat shock protein 65 (hsp65 gene; Jjemba et al. 2010). Primers Tb11 (ACCAACGATGGTGTGTCCAT) and Tb12 (CTTGTCGAACCGCATACCCT), which represent the hsp65 gene, were used in molecular confirmation. A total of 79 samples were selected for molecular confirmation. Of isolates selected as presumptive positive for *Mycobacterium* spp., 100% were confirmed by molecular methods stated previously, demonstrating that cultural methods seem to be robust for recycled waters evaluated in this study.

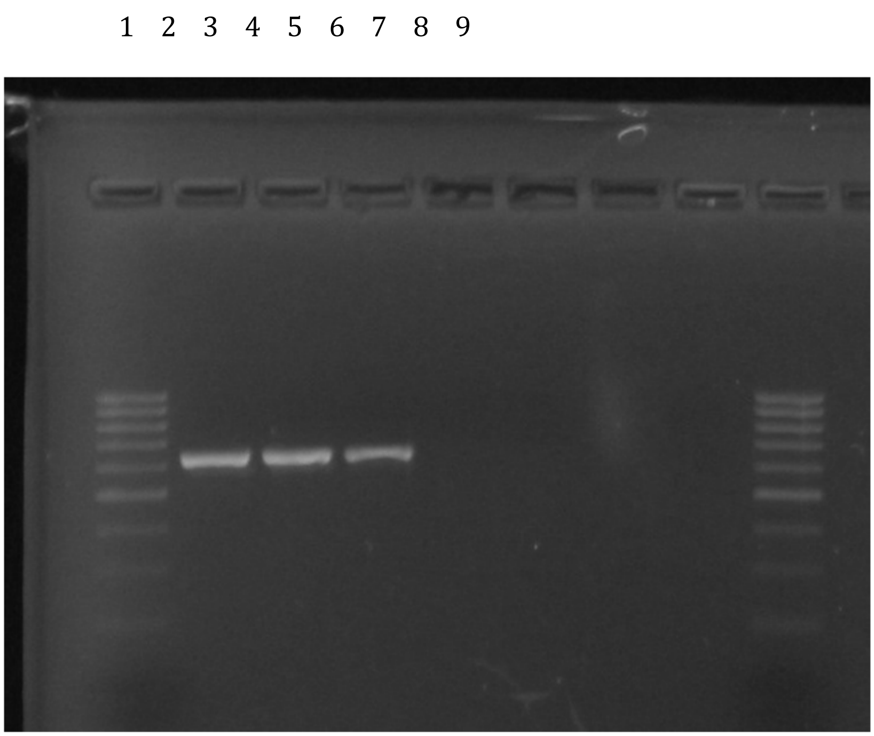


Figure 7.1. Results of confirmatory PCR for *Legionella*.

Notes: Lanes 1 and 9: 100 bp DNA ladder; Lane 2: positive control *Legionella* (ATCC 33152); Lanes 3–4: Legionella isolates from recycled water samples; Lane 8: negative control (nontemplate control**).**

7.2 False-Positive Method Evaluation for Recycled Water

The key to an effective management program for water quality is to ensure that the program is accurate and repeatable. The parameters of the quality monitoring programs must have well-established test methods with well-understood statistical accuracy (avoid false positives). Such testing is of heightened importance for treated wastewater effluents, where water quality is assessed under a permitted system in which a high false-positive rate could result in unnecessary waste of disinfectant, an increase in the release of disinfection byproducts into the environment, or an erroneous violation of a discharge permit. For this reason, membrane filtration methods utilized to enumerate select fecal indicators (*E. coli* and *Enterococcus*) were tested for the presence of false positives and false negatives.

The necessity of confirmation work arises from our previous studies showing elevated false-positive rates in *E. coli* isolated from recycled water retention ponds (33.3%) and in point-of-compliance samples from treatment facilities (48.8%). False-positive *E. coli* in storm flows (4.0%) agreed closely with USEPA technical literature (McLain et al., 2011). Sequencing of false-positive isolates confirmed that most were, like *E. coli*, of the family Enterobacteriaceae. False-positive identification rates were inversely related to air temperature, suggesting that seasonal variations in water quality influence *E. coli* identification. Knowledge of factors contributing to failure of chromogenic media will lead to manufacturer enhancements in media quality and performance and ultimately increase the accuracy of future water quality monitoring programs.

7.2.1 Methods

All water samples were analyzed for *E. coli* and total enterococci using membrane filter techniques in conjunction with USEPA Methods 1604 (*E. coli*) and 1600 (*Enterococcus*). For enumeration of *E. coli*, filters were placed onto 60 mm Petri plates with prepared MI Agar with cefsulodin added at 5 mg/L^{-1} to inhibit growth of Gram-positive organisms and selected noncoliform Gram negatives. *Enterococcus* was isolated on m-Enterococcus agar, and all plates were incubated at 37 °C for 24 to 36 hours before counting dark blue or bright red/mauve colonies (presumptive for *E. coli* and *Enterococcus*). Select blue, red, and colorless colonies (from MI agar, for identification of false-negative *E. coli*) were collected from each plate for confirmatory PCR.

Colonies remained frozen at -20 °C until regrowth and molecular analysis. Confirmation of isolates was performed by PCR using primers specific for the *sfm*D gene encoding a putative outer membrane export protein common to all known *E. coli* or primers targeting the 23S rRNA gene of *Enterococcus.* Each PCR run included positive and negative control tubes, with template *E. coli* (ATCC #25922) or *Enterococcus* (ATCC #29212) as positive controls and nuclease-free water as a template for the negative control. Upon visualization of the PCR product, presence of a DNA fragment of 106 base pairs indicated positivity for *E. coli*, whereas *Enterococcus* was identified by the presence of a 71-base pair PCR product.

7.2.2 Results

A total of 472 isolates were analyzed by PCR to assess the accuracy of the agar media in identification of *E. coli* and *Enterococcus* (Table 7.1). No error was detected in the identification of *Enterococcus* on m-Enterococcus agar or in the false-negative identification of *E. coli* on MI agar. False-positive identification rates for *E. coli* were found to be 38.5%; 70 of 182 colonies showing dark blue color were not confirmed as *E. coli* by PCR.

Earlier work by our group showed that false-positive identification rates of *E. coli* were higher in seasons of cooler air temperature (McLain and Williams, 2008; McLain et al., 2011). The present work did not show the same trend, as false-positive rates showed no correlation to air temperature ($p = 0.767$). Rather, false-positive rates in this work were strongly correlated with HPC ($p = 0.091$); with average HPCs for false-positive samples equal to 7.4×10^7, and those for samples with confirmed *E. coli* equal to 4.6×10^7. This indicates that an overabundance of background flora may be inhibiting the agar's ability to correctly identify *E. coli*. Current work is under way to identify additional water quality parameters that correlate with false-positive rates.

Table 7.1. Results of PCR Identification of False-Positive and False-Negative Isolates

Target Group	Morphology	Total Isolates Analyzed	Confirmed Identity	Error Rate
E. coli	dark blue colonies (MI agar)	182	112	38.50%
E. coli	colorless colonies (MI agar)	124	124	no error
Enterococcus	dark red colonies (m-Enterococcus agar)	116	116	no error

Chapter 8

Water Age and Recycled Water Quality

The goals of this portion of the project were to model water age and quality transformations within the distribution system. Many recycled water distribution systems are operated sporadically as a result of intermittent irrigation demands. This, in tandem with the typical branched configuration of the distribution systems, results in water that may remain stationary in pipes for some time. Therefore, distances from sources may not be a true indicator of time spent in the system. Through water age estimation, it may be possible to gain a more fundamental understanding of water quality changes that may occur over time.

In addition to water age modeling, we have modeled concurrent microbial water quality changes in the networks. By representing the bulk microbial and some chemical transformations, greater sensitivity can be achieved in our examinations of the effects of management decisions on water quality. Such management alternatives can include changes in treatment, additional chlorine dosing, and altering demand patterns.

8.1 Methods

This section begins with a general discussion of a published microbial water quality model that has been applied for the two distribution systems that have extensive water quality data (D-2 and D-4). The water age and model calibration work is then presented for the two systems.

Water age estimation presented unique problems in each system. D-2 is a pressurized system in which water only moves from the tank source to demand locations based on system withdrawals. All flow meters were not functional during the study, and additional estimation analyses were necessary to allocate demands and their timing.

Flow in the D-4 system, on the other hand, moves in both directions and is not fully pressurized at all times. This complex pattern required each parcel of sample water to be individually backtracked to the source by following flow patterns in reverse order. The resulting water age estimates are satisfactory for our purposes. In addition, however, a generalized computer code to model this process was partially completed to fine-tune water age estimates and is described at the end of this section.

With accurate water movement patterns, equivalent hydraulic models were formulated for each system for each time period in EPANET, the industry standard water distribution quality model. Its extension, EPANET-MSX (Multi-Species EXtension), was then applied to represent the complex microbial model noted previously.

The water distribution quality model includes bulk and wall reaction/interactions and parameters associated with each component. The D-2 system tank data are only affected by bulk reactions, so these parameters are isolated and estimated from that data set. Class A water is provided to the D-2 system, so its bulk parameters are provided to the model, and the wall reaction coefficients are then calibrated.

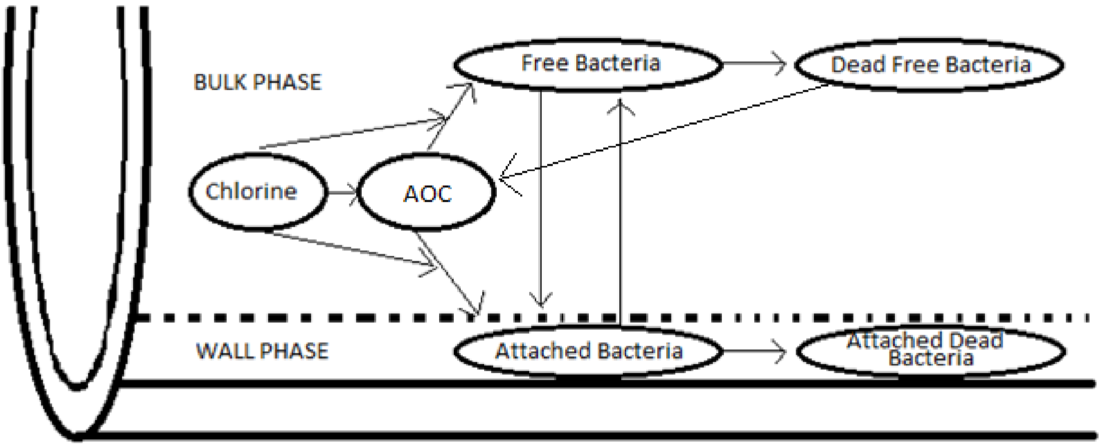


Figure 8.1. Conceptual diagram of chemical species and physical phases within a pipe.

In all cases, the modeling focus is HPCs. Reactions for individual microbial species are not possible because the relative contribution of a species in terms of utilization of substrate is not possible to determine. Results combining water quality sampling and water age are presented in the next section.

8.2 Microbial Model

Chemistry within the pipe network is mathematically defined with respect to two phases: a mobile bulk phase and an immobile wall phase. Constituents located in the bulk phase move with the average velocity of the water, which is determined from the system hydraulics. The wall phase species are attached to the inside surface of the pipe and are stationary. Bacterial growth within a distribution network is fueled by organic substrates and inhibited by disinfectants present in the water. Bacterial concentrations in the bulk flow of water are also affected by deposition and detachment to and from the biofilm. In this model, Cl_2, AOC, and bacteria all exist in the bulk phase. Bacteria also exist in the wall phase, composing the biofilm lining the pipe surface. A diagram of the hypothesized interaction between species and phases is presented in Figure 8.1.

The free bacteria concentration in the bulk flow is a function of the concentration of substrate (AOC), disinfectant (chlorine), and attached bacteria. That is, the reaction of one constituent is dependent on the concentration of another, necessitating a system of differential equations to define such interactions. Zhang et al. (2004) and Munavalli and Kumar (2004) successfully applied Monod kinetics in order to model the process of chlorine-inhibited microbial regrowth during transportation from the treatment facility to the far-reaching branches of the pipe network. The following model, similar to the previous works, is presented here:

$$\frac{dX_b}{dt} = (\mu_b - k_d - k_{dep})X_b + k_{det}UA_vX_a \qquad (1)$$

$$\frac{dX_a}{dt} = (\mu_a - k_d - k_{det}U)X_a + k_{dep}A_vX_b \qquad (2)$$

$$\mu_i = \mu_{i,max}\left(\frac{AOC}{AOC + k_s}\right) \qquad when\ Cl_2 < Cl_{2,ti} \qquad (3a)$$

$$\mu_i = \mu_{i,max}\left(\frac{AOC}{AOC + k_s}\right) exp\left(-\frac{Cl_2 - Cl_{2,ti}}{Cl_{2,c}}\right) \ when\ Cl_2 > Cl_{2,ti} \quad (3b)$$

$$\frac{dAOC}{dt} = -\left(\frac{1}{Y_g\beta}\right)\left[\left(\mu_b - k_{ly}k_d\right)X_b + \mu_a A_v X_a\right] \qquad (4)$$

$$\frac{dCl_2}{dt} = -k_b Cl_2 - k_w A_v \qquad (5)$$

The time rate of change of free bacteria (X_b) is determined by Equation 1 utilizing the specific growth rate (μ_b), bacterial mortality rate (k_d), and detachment (k_{det}) and deposition (k_{dep}) rates from and to the wall phase. Likewise, the derivative of attached bacteria (X_a) with respect to time is given in Equation 2. The term $\mu_{i,max}$ in Equation 3 is the maximum growth rate of bacteria. The subscript i refers to either a or b for attached or bulk phase.

As seen in Equations 3a and 3b, microbial growth and mortality are impacted by other species in the water. Specifically, AOC is the concentration of assimilable organic carbon, and k_s is the Monod half-saturation constant for AOC/substrate consumption. In addition, Cl_2 is the concentration of chlorine and $Cl_{2,ti}$ and $Cl_{2,c}$ are the threshold and characteristic chlorine concentrations. When the Cl_2 level is below the threshold for free or attached bacteria, chlorine has no effect on the growth rate.

Hydraulic conditions also affect the reactions. These factors are introduced through the velocity (U) and the surface area per unit volume (A_v) that are determined during the extended period simulation of the system hydraulics. A_v is used to convert between areal density of the wall phase and volumetric concentration of the mobile phase.

In addition to AOC and Cl_2 influencing microbial activity, they also are impacted by those and other reactions. The concentration of AOC is determined by the rate presented in Equation 4. Y_g represents the growth yield coefficient of bacteria, β is a unit conversion factor, and k_{ly} is the fraction of dead bacteria converted to AOC after lysis. Chlorine decay is modeled as first order with respect to the bulk phase and zero order with respect to the wall. The corresponding coefficients from Equation 5 are $k_b$and k_w.

Because degradation of quality is a function of the water age and local pipe velocities, it is important to couple the microbial analysis with the network hydraulics. EPANET has a built-in capability to track and monitor the transport of a single constituent. Accompanied by the MSX software addition, EPANET can analyze multiple constituents that chemically interact with one another. EPANET-MSX allows the user to define bulk species that are transported with the average velocity of the water and immobile wall species. The Lagrangian approach is used to discretize water volumes that travel with the bulk flow (Shang and Rossman, 2007).

EPANET and EPANET-MSX only consider advective transport. Although some research tools are under development, no model represents diffusion processes when water is stagnant or moving at low velocity, as occurs in reclaimed systems. Given the scale of this transport mechanism, the uncertainties in temporal demand patterns, and the expected lack of abrupt water quality changes that would necessitate molecular-scale movement modeling, this process is not considered in this study.

8.3 Tucson Water (DS-2) Reclaimed Water System Modeling

The previous model is a general formulation that is appropriate for all data sets collected in this study. To determine model parameters, we isolate calibration between tank and system data; both of which can be modeled in EPANET-MSX. Tank waters are not strongly influenced by wall reactions, so bulk parameters are estimated with these data. Bulk parameters from the Class A storage tank experiment are then applied in the Tucson Water distribution system, and the wall parameters are calibrated from that data set. Given the relatively few data points, all data are used for calibration rather than completing a preferred, split-sample analysis to verify model accuracy. As noted earlier, water demand modeling was needed to fill gaps in the withdrawal data prior to the system calibration exercise. Water age estimates were also provided from that analysis.

8.3.1 Bulk Parameter Calibration

Microbial (i.e., HPC) and chemical data from the first phase of the Class A storage tank experiment were used to calibrate the bulk parameters from Equations 1 through 5. Tank hydraulics are represented by a single-cell tank that was completely mixed over a 30-day extended period simulation. EPANET-MSX does not consider wall species in a tank based on the assumption that the volume to surface area ratio is large enough that the wall species can be neglected. Without wall interactions, the tank model's governing equations simplify to Equations 6 through 8 with Equation 3a or 3b; all of which only contain parameters for the bulk species components and reactions.

$$\frac{dX_b}{dt} = (\mu_b - k_d)X_b \qquad (6)$$

$$\frac{dAOC}{dt} = -\left(\frac{1}{Y_g\beta}\right)(\mu_b - k_{ly}k_d)X_b \qquad (7)$$

$$\frac{dCl_2}{dt} = -k_b Cl_2 \qquad (8)$$

The HPC microbial data set is used as X_b. HPCs were chosen because they were present in most of the samples above detectable limits and are an indicator of overall microbial activity.

Eight parameters, k_b, $\mu_{b,max}$, k_d, k_s, k_{ly}, Y_g, $Cl_{2,c}$, and $Cl_{2,tb}$ were calibrated using the tank model. The parameter unit, range, and calibrated values are listed in Table 8.1. The range of values was determined by considering the maximum and minimum values reported in the literature. The first-order chlorine decay coefficient was determined explicitly from the Roger Road data.

For a given set of values for the eight parameters, solution of Equations 3a or 3b and 6 through 8 is a time series of AOC, Cl_2, and X_b. These values can be compared to the corresponding values measured at discrete times from water samples. The calibration goal is for the model to equal the measured values. This objective is quantified as the sum of the normalized error sum of the squared differences between the measured and model-predicted values of AOC and log (X_b).

Table 8.1. Bulk Parameters in Microbial Model

Bulk Parameter	Symbol	Unit	Range	Calibrated Value	
				Class A	Class A+
First-order kinetic constant for bulk chlorine decay	k_b	h^{-1}	N/A	0.123	0.123
Maximum free bacteria growth rate	$u_{b,max}$	h^{-1}	0.03–0.70	0.126	0.168
Bacterial mortality rate	k_d	h^{-1}	0.002–0.060	0.035	0.051
Monod half-saturation coefficient	k_s	mg C/L	0.05–1.20	1.154	1.107
Fraction of dead biomass converted to AOC after lysis	k_{ly}	mg/mg	0.05–0.95	0.868	0.888
Growth yield coefficient for bacteria	Y_g	mg/mg	0.05–0.90	0.863	0.119
Characteristic chlorine concentration	$Cl_{2,c}$	mg/L	0.05–0.50	0.486	0.489
Chlorine threshold for free bacteria	$Cl_{2,tb}$	mg/L	0.01–0.10	0.085	0.078

Notes: AOC=assimilable organic carbon; C=carbon; Cl=chlorine

To automate this process, an optimization model was applied. Here, MATLAB's Genetic Algorithm (GA) optimization tool (MATLAB version 7.10.0, R2010a. Natick, MA, The Mathworks, Inc., 2010) was linked to EPANET-MSX. The GA generates and evolves sets of parameter values to minimize the objective function noted previously. The allowable range of the parameter values that could be searched by the GA was limited to those listed in Table 8.1.

In this phase of the tank experiment, samples were taken every 24 hours for the first week. For the Class A tank, the residual chlorine dropped below detectable limits between 24 and 48 hours, meaning only two data points were recorded. For the Class A+ tank, chlorine was decayed completely before 24 hours. Because the only chlorine information available for this system was from the Class A tank, the k_b value calculated for Class A was also applied to Class A+.

Figures 8.2 and 8.3 compare the calibrated model (solid line) to the measured values (open circles) for the two tank studies. The curve fit lines generally fit the trend around the scatter of data points for all constituents in both tanks, increasing our confidence in the parameter estimates. Optimal model parameters are listed in Table 8.1. Parameter values tend toward the higher range of reported values. Although the two waters are produced by significantly different types of treatment, the microbial growth parameters are similar, with the exception of Y_g.

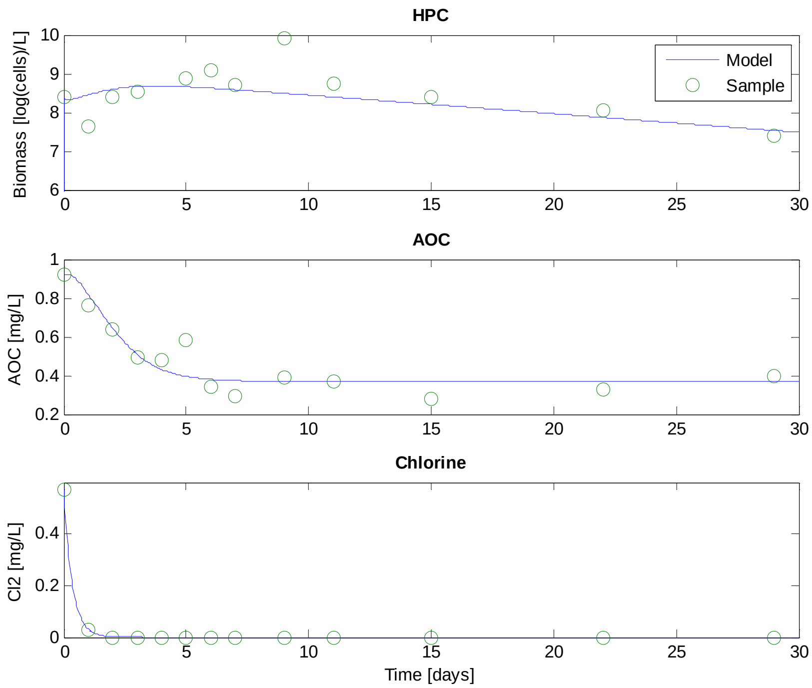


Figure 8.2. Class A experimental and model results for Phase 1 of the tank study: HPC (top), AOC (middle), and chlorine (bottom).

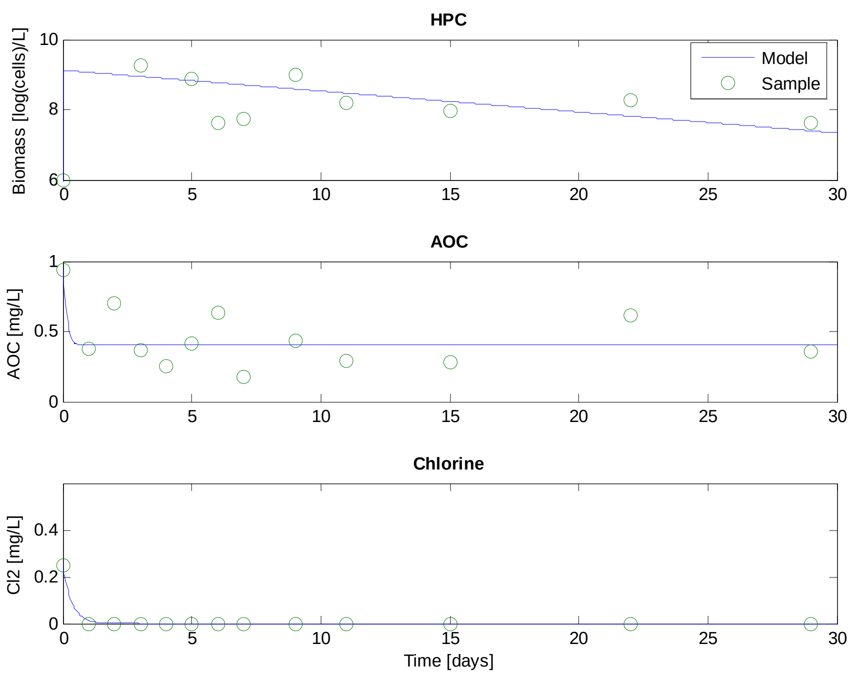


Figure 8.3. Class A+ experimental and model results for Phase 1 of the tank study: HPC (top), AOC (middle), and chlorine (bottom).

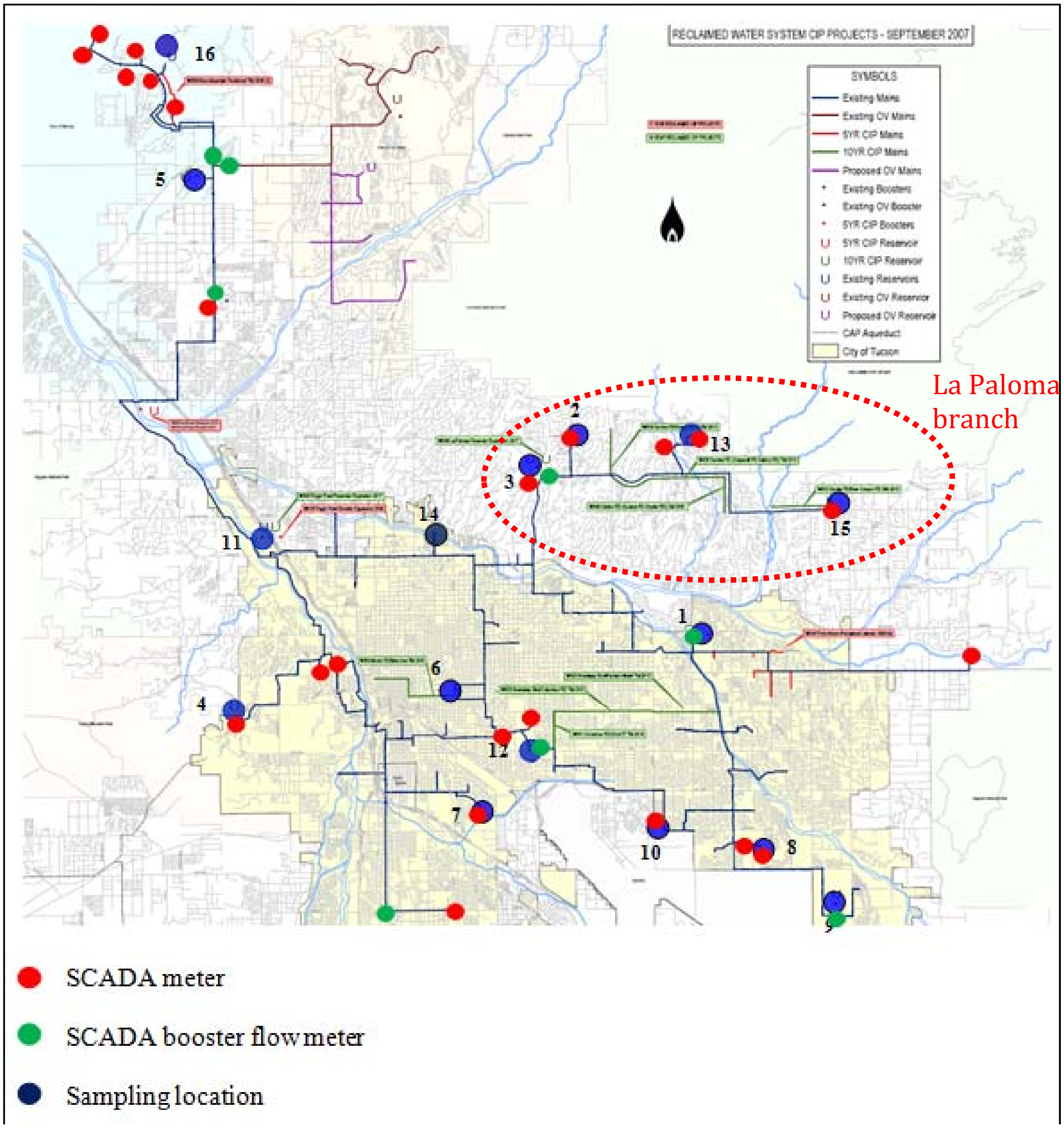


Figure 8.4. Map of Tucson Water's reclaimed water distribution system.

8.3.2 Tucson Water Reclaimed Water System Overview

The modeling focus of the Tucson Water reclaimed water network is a long branch that runs from La Paloma reservoir and booster station to the end of the line at Sabino Springs (Arizona National Golf Course). This section is circled in red on Figure 8.4. Along this transmission main, there are four major consumers that account for more than 90% of the total demand leaving La Paloma reservoir. A time history of flows, pressures, and reservoir levels was obtained from Tucson Water's Supervisory Control and Data Acquisition (SCADA) system; however, flow meters on one branch of the system were not operational during the study period. Therefore, the record for these withdrawals was reconstructed using a mass balance of inflow to all withdrawals. Some error results from the unmetered minor users along this branch, which were lumped into the unknown branch demands. The hydraulic model formulation including the demand analyses is presented herein, followed by the water quality modeling of this system.

8.3.3 Demand Data Preparation

As noted, demand data from Tucson Water's SCADA system was the basis of the hydraulic and water quality simulation model, EPANET and EPANET-MSX. Table 8.2 summarizes the available system data provided by Tucson Water. In addition to monthly summaries from a separate flow meter, SCADA data were measured and recorded whenever a change was detected (minimum readings at 1 minute to 1 hour). EPANET requires a regular time step, however; therefore, the first step in data modification was to generate data with a consistent 1-minute time step.

During this transformation step, it was determined that flow data for Sabino Springs did not match its monthly billing data. The flow meter was malfunctioning for some time periods, signal dropping and latching. Fortunately, reliable pressure data were available for the same location, and a close relationship was identified between flow and pressure. Therefore, periods of dropped signals were flagged, and those flows were replaced with estimates based on the outlet pressure measurements.

Table 8.2. Available Data Sets from SCADA System

Location	Data	Unit	Description
La Paloma	flow rate	GPM	
	pressure	lb/in^2	
	chlorine	mg/L	
Skyline	flow rate	GPM	
Ventana West	flow rate	GPM	
	pressure	lb/in^2	
Ventana East	flow rate	GPM	*flow meter malfunction*
Sabino Springs	flow rate	GPM	*does not match monthly billing records*
	pressure	lb/in^2	

Notes: Monitoring period: November 1, 2009 through October 31, 2010 (1 year); data measured every time there is a change (1 min<Δt<1 hr)

In addition, the Ventana East flow meter was not operational. Because all major locations were measured except for this location, Ventana East demands were computed based on a mass balance across the system. This balance neglects the flow to other users during periods when flow is provided to Ventana East.

The following steps summarize the demand preparation procedures:

- Step 1: Convert original data sets for uniform time step, Δt=1 min (original SCADA data sets were measured whenever there was a change in flow and pressure)

- Step 2: Recover Sabino Springs flow data based on outlet pressure. Figure 8.5 provides the reconstructed data for June 2010. The blue blocks indicate the withdrawals for those periods, and the gray areas mark times of no demand.

- Step 3: Recover Ventana East (VE) flow data based on a systemwide mass balance or:

$$Q_t^{VE} = Q_t^{La\ Paloma} - Q_t^{skyline} - Q_t^{VW} - Q_t^{sabino}$$

Figure 8.6 shows a representative period of record for the final reconstructed flows/demands at each location (June 19–24, 2010).

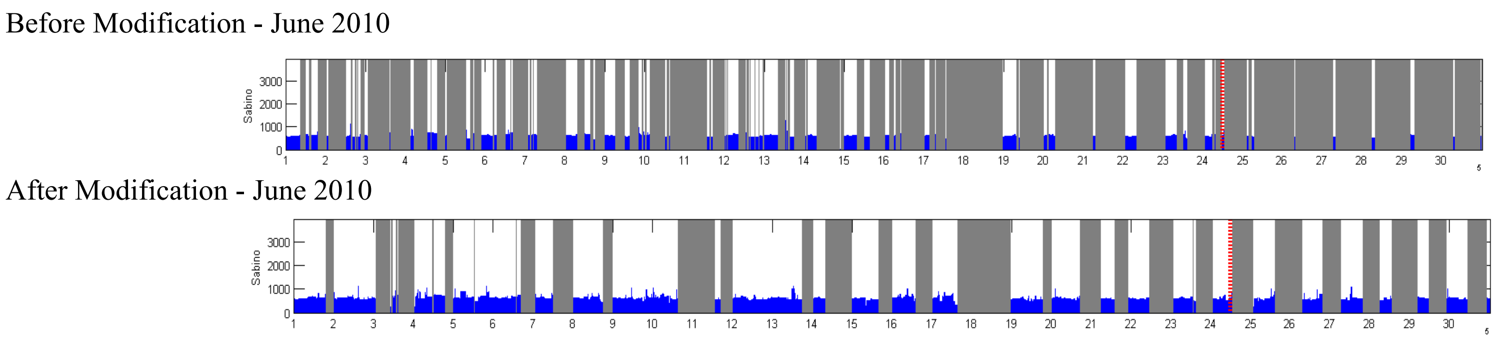


Figure 8.5. Reconstructed flow data for Sabino Springs location.

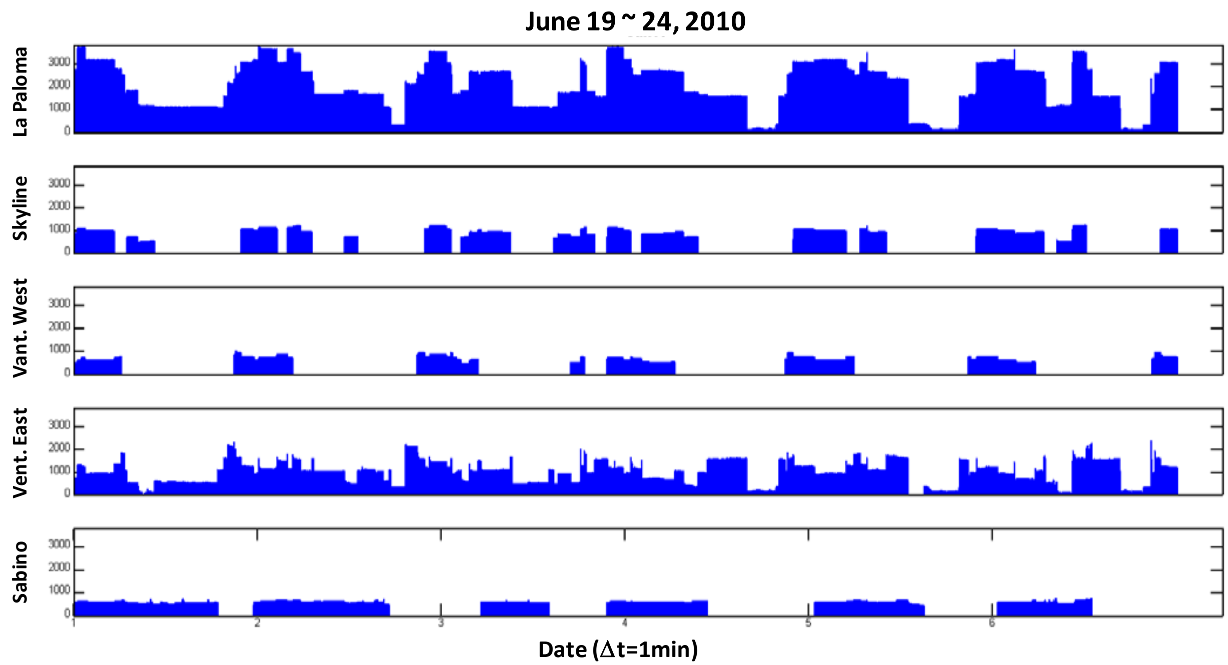


Figure 8.6. Reconstructed flow data for La Paloma branch locations.

8.3.4 Hydraulic and Water Quality Modeling

Tucson Water provided the pipe data for the system listed in Table 8.3, which corresponds to the link and node representation in Figure 8.7. With the reconstructed demand data sets, 18 hydraulic simulation models were constructed in EPANET. The 18 sets correspond to the water quality sampling events and are long enough to encompass the period from when water samples entered the network to when they were extracted.

When executed as an independent hydraulic and water quality model, EPANET provides the flow rates, velocities, and consequently the water ages (residence time in the system) of each water sample from each location. As seen in Figure 8.8, water ages for the most distal point (Sabino Springs) are generally longest, but at times water remains in some branches for a longer period before delivery, particularly during winter months. This result clearly shows the need to evaluate water age over simple distances when considering water quality in this system.

Table 8.4 lists the various water quality sampling times and model simulation period lengths. Figure 8.9 is a plot of HPC versus water age for this system. Similar to the storage tank experiment data, HPC concentrations slightly decrease with time and appear to reach an equilibrium.

Table 8.3. La Paloma Reclaimed Network Pipe Data

Pipe ID	Length [ft]	Diameter [in.]
1	1027	24
2	2984	16
3	5681	12
4	5486	16
5	9974	16
6	2787	16
7	1017	16
8	1235	12
9	3273	16
10	18,042	12
11	9057	8

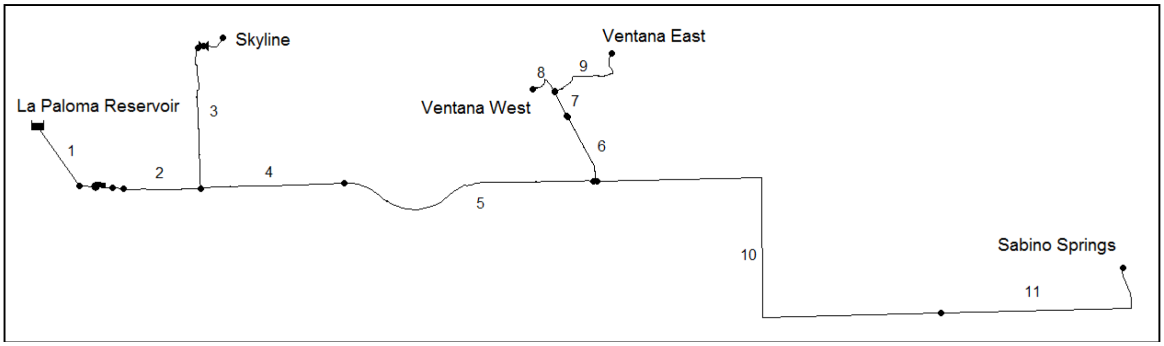


Figure 8.7. Pipe layout for La Paloma branch.

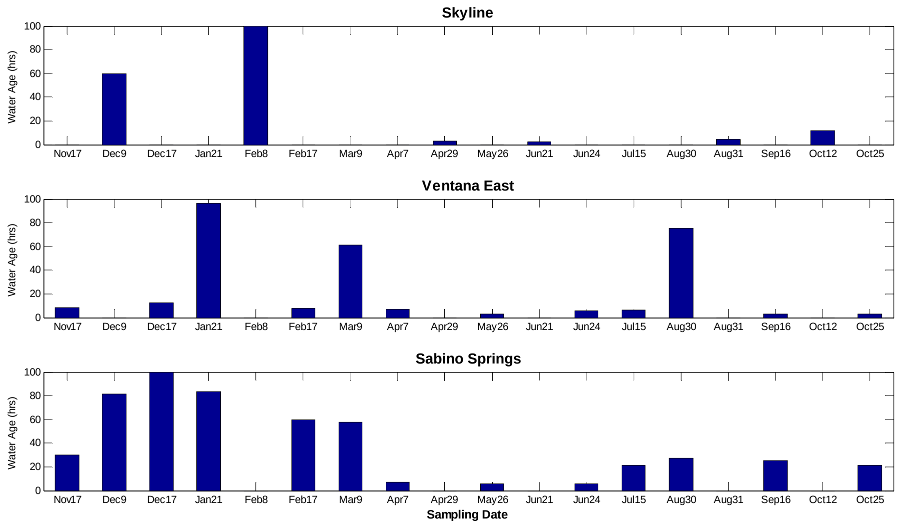


Figure 8.8. Water age for three sampling locations for all periods.

*Note***.** Zero values indicate no sample taken during the given period.

Table 8.4. Specifications for the Hydraulic Models

ID	Sampling Location	Sampling Date/Time	Model ID	Simulation Period
1	Ventana East Sabino Springs	11-17-2009 / 09:48AM 11-17-2009 / 10:42AM	Nov	11/16–11/17, 48hrs
2	Sabino Springs Skyline La Paloma	12-09-2009 / 11:15AM 12-09-2009 / 09:55AM 12-09-2009 / 09:30AM	Dec1	12/05–12/09, 120 hrs
3	Ventana East Sabino Springs	12-17-2010 / 09:43AM 12-17-2010 / 10:20AM	Dec2	12/13–12/17, 120 hrs
4	Ventana East Sabino Springs	01-21-2010 / 09:20AM 01-21-2010 / 10:20AM	Jan	01/16–01/21, 144 hrs
5	Skyline La Paloma	02-08-2010 / 09:47AM 02-08-2010 / 09:20AM	Feb1	02/01–02/08, 192 hrs
6	Ventana East Sabino Springs	02-17-2010 / 09:25AM 02-17-2010 / 10:10AM	Feb2	02/15–02/17, 72 hrs
7	Ventana East Sabino Springs	03-09-2010 / 09:55AM 03-09-2010 / 10:40AM	Mar	03/06–03/09, 96 hrs
8	Ventana East Sabino Springs	04-07-2010 / 10:40AM 04-07-2010 / 11:30AM	Apr1	04/06–04/07, 48 hrs
9	Skyline La Paloma	04-29-2010 / 10:05AM 04-29-2010 / 09:35AM	Apr2	04/28–04/29, 48 hrs
10	Ventana East Sabino Springs	05-26-2010 / 09:00AM 05-26-2010 / 09:45AM	May	05/25–05/26, 48 hrs
11	Skyline La Paloma	06-21-2010 / 09:35AM 06-21-2010 / 09:10AM	Jun1	06/20–06/21, 48 hrs
12	Ventana East Sabino Springs	06-24-2010 / 10:28AM 06-24-2010 / 11:16AM	Jun2	06/23–06/24, 48 hrs
13	Ventana East Sabino Springs	07-15-2010 / 08:35AM 07-15-2010 / 09:25AM	Jul	07/14–07/15, 48 hrs
14	Ventana East Sabino Springs	08-30-2010 / 08:37AM 08-30-2010 / 09:29AM	Aug1	08/27–08/30, 96 hrs
15	Skyline La Paloma	08-31-2010 / 08:25AM 08-31-2010 / 08:53AM	Aug2	08/30–08/31, 48 hrs
16	Ventana East Sabino Springs	09-16-2010 / 11:05AM 09-16-2010 / 10:15AM	Sep	09/15–09/16, 48 hrs
17	Skyline La Paloma	10-12-2010 / 11:15AM 10-12-2010 / 10:46AM	Oct1	10/11–10/12, 48 hrs
18	Ventana East Sabino Springs	10-25-2010 / 11:10AM 10-25-2010 / 12:21AM	Oct2	10/24–10/25, 48 hrs

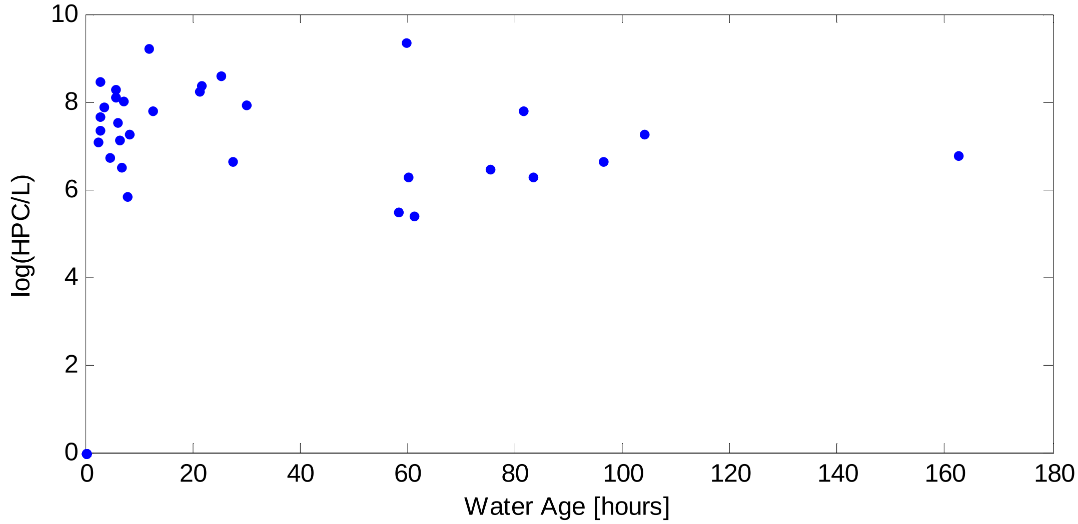


Figure 8.9. HPC concentration versus water age independent of sampling location.

To examine the changes of specific constituents, the hydraulic conditions were linked with EPANET-MSX to solve Equations 1 through 5 in order to capture wall effects on water quality during transport. The source of the water entering La Paloma reservoir is the Roger Road Water Recycling Facility. This recycled water travels about 10 miles through the system before reaching La Paloma. As best estimates, the bulk parameters calibrated for the Class A tank were applied. The wall parameters were then calibrated by linking MATLAB's genetic algorithm to EPANET-MSX as described for the tanks in the previous section. Because AOC was not measured during the distribution system sampling, the objective function was to minimize the sum of the squared error between the measured and computed HPC concentrations. The resulting values for the wall parameters are listed in Table 8.5.

Calibration results are presented in Figures 8.10 and 8.11 for HPC and chlorine. The three bars for each sample indicate the measured and modeled result, considering and not considering the wall reactions. Generally, wall reactions did not significantly affect HPC concentrations; however, more notable differences in chlorine concentrations are evident when wall effects are neglected. As might be expected, these differences occur in samples that have shorter travel times (Figure 8.11).

Table 8.5. Wall Parameters in Microbial Model

Wall Parameter	Symbol	Unit	Range	Calibrated Value
Maximum attached bacteria growth rate	$\mu_{a,max}$	h^{-1}	0.03–0.70	0.3901
First-order kinetic constant for detachment	k_{det}	h^{-1}	0.005–1.50	1.3937
First-order kinetic constant for deposition	k_{dep}	$h^{-1}(m/s)^{-1}$	0.015–1.50	0.1390
Zero-order kinetic constant for wall chlorine	k_w	$mg/m^2/h$	10–100	98.5673
Chlorine threshold for attached bacteria	$Cl_{2,ta}$	mg/L	0.01–0.50	0.0436

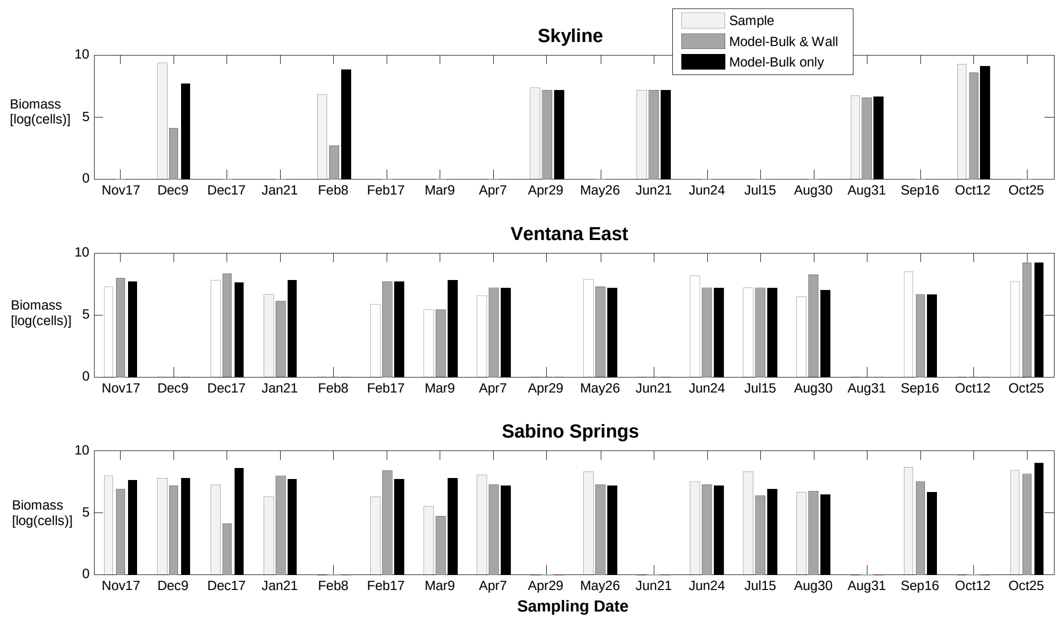


Figure 8.10. Measured and computed log (HPC) concentration for three sampling points and events.
Note: Zero concentrations are periods when no samples were taken.

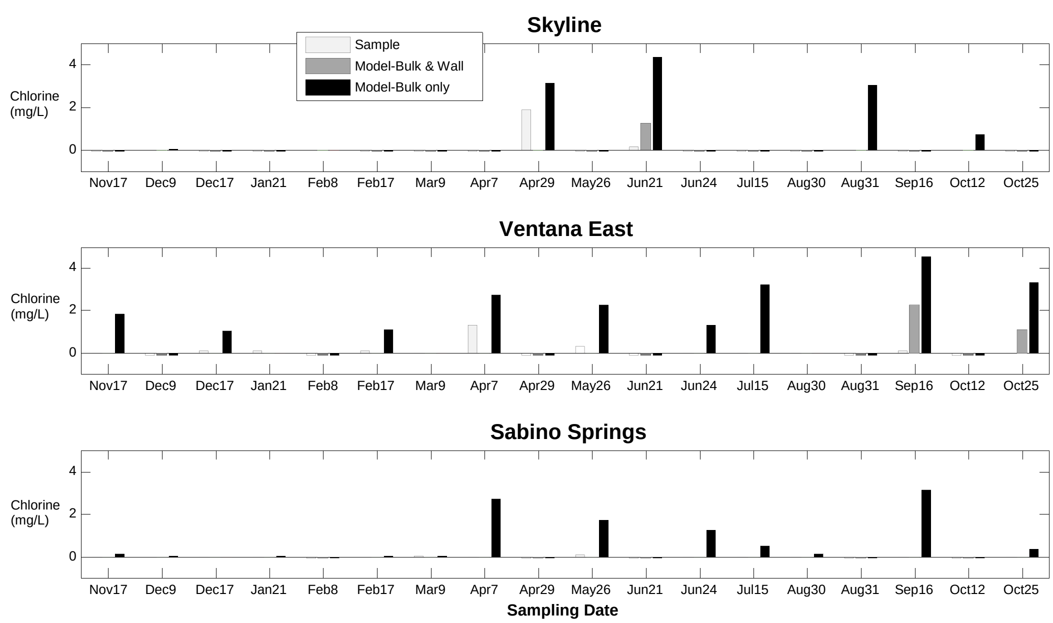


Figure 8.11. Measured and computed chlorine concentration for three sampling points and events.
Note: Zero concentrations are periods when no samples were taken.

8.4 Global Water Resources (DS-4) Recycled Water System Modeling

8.4.1 System Configuration

The lake system served by GWR in Maricopa, AZ, comprises existing and planned lakes including Cobblestone, Villages, Province, Rancho Eldorado (RED) III, Homestead, Glennwilde, Rancho Mirage, and Sorrento. Figure 8.12 and Table 8.6 present the reclaimed water infrastructure and list the properties used to construct the hydraulic model.

In this system, there are a limited number of demand locations, all of which are accounted for in the SCADA system. This provides a complete mass balance over a 24-hour time period. The recycled water system is fed from the Palo Verde Water Reclamation Facility. The recycled water pump station consists of three American Turbine 15-M-200 1760 RPM 50 HP pumps in parallel, equipped with variable frequency drives (VFDs). The current operation requires the VFD to maintain a constant level in the wet well (from which the pumps draw). The plant operators have indicated that the pumps are currently below their capacity, with system pressures ranging from 12 to 25 feet.

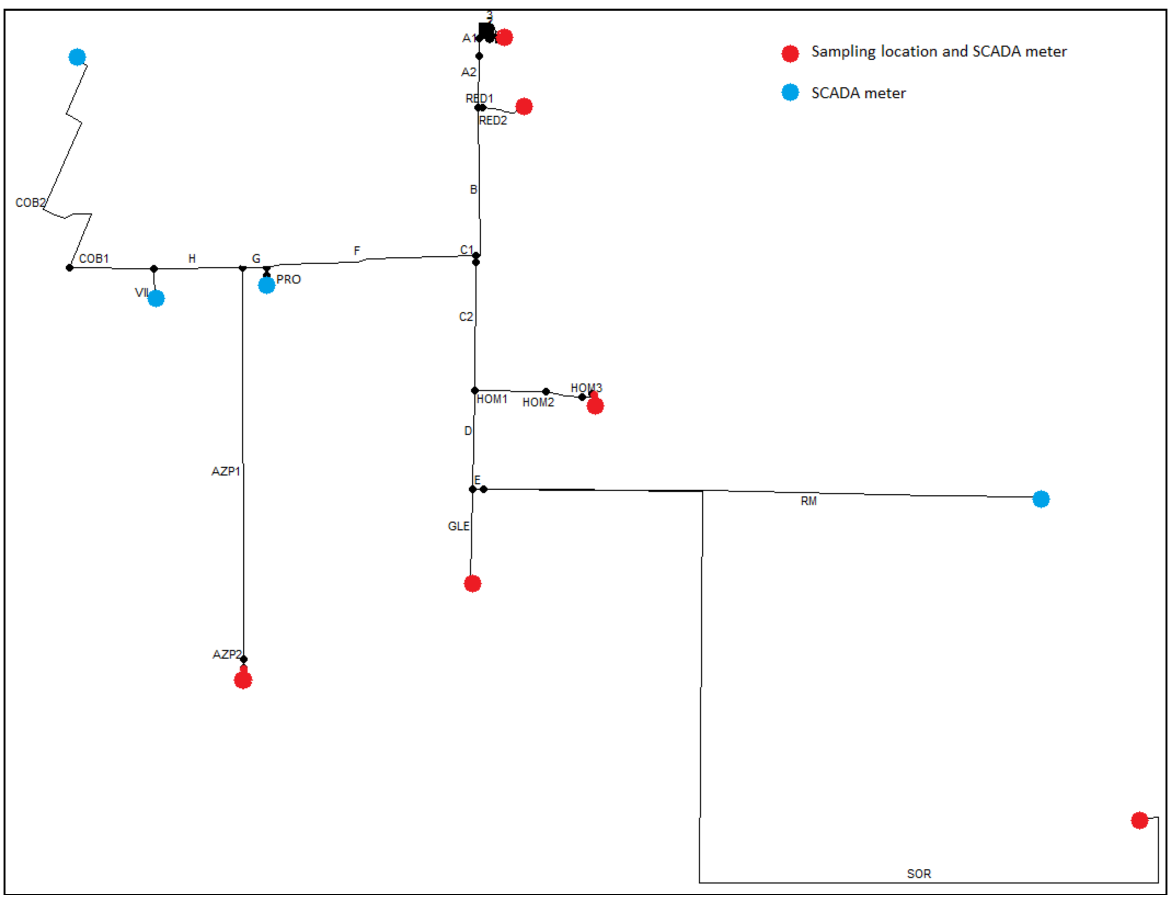


Figure 8.12. Pipe layout for Global Water Resources reclaimed network.

Table 8.6. Global Water Reclaimed Network Pipe Data

Pipe ID	Length [ft]	Diameter [in.]
A1	497	16
A2	1250	24
B	3564	24
C1	28	24
C2	3032	18
D	2214	18
E	137	18
F	4900	24
G	283	24
H	2320	16
RED1	18	24
RED2	1153	10
HOM1	2664	12
HOM2	1212	8
HOM3	110	12
GLE	2404	8
RM	10,809	12
SOR	29,440	12
PRO	94	16
AZP1	9376	24
AZP2	139	16
VIL	756	16
COB1	2288	16
COB2	5791	12

8.4.2 Hydraulic Modeling

The available water distribution network models calculate hydraulics and water quality under pressurized conditions. Under those conditions, when a valve is switched open, water is immediately available and flows through the valve. Potable water distribution systems and many recycled water networks, including the Tucson Water Recycled Water System, operate under pressure.

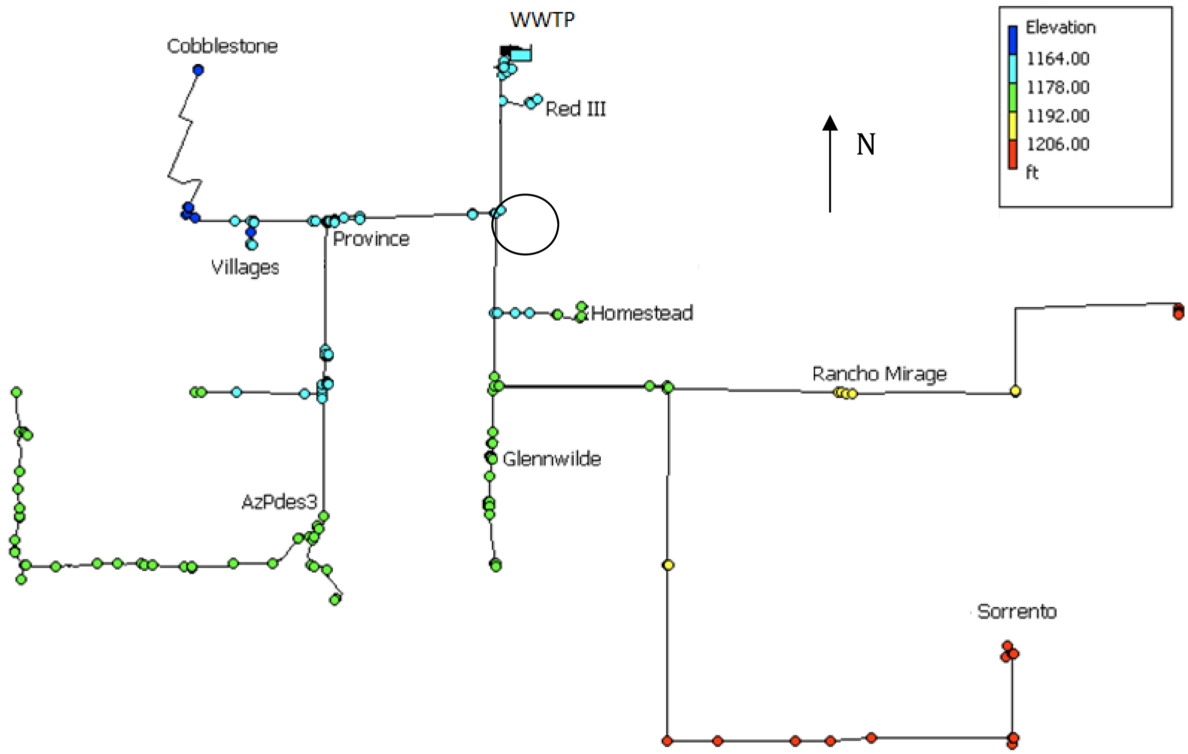


Figure 8.13. Global Water Resources nodal elevations.

The pipes in the GWR network, however, are not continuously charged. The GWR network behaves in a way similar to a sewer system, with gravity-driven flow downhill and pumps required to drive flow uphill when necessary. Water can enter the network and fill the system without discharging flow. Conversely, pipes may drain toward a point of lower elevation. Approximate system elevations are provided in Figure 8.13 to illustrate that when water is being delivered to locations at lower elevations, such as Cobblestone, Villages, or Province, the pipes at higher elevations are either draining or already empty.

For every sampling event, samples were collected in the same sequence: Palo Verde Water Reclamation Facility, Sorrento, Glennwilde, Homestead, and REDIII. The 24-hour demands for a typical winter sampling day are shown in Figure 8.14. During the winter, the lake demands are low, and the majority of the reclaimed water is discharged to the local wash at the AZPDES-3 location.

During GWR sampling events, two samples were taken from each discharge location. The first sample ("first flush") is collected immediately as soon as flow reaches the outlet. The line is then flushed of hydraulically "old" water, and a "new" water sample ("steady state") is collected after about 30 minutes. For some of the longer network branches, the total volume of water discharged between the first flush and steady state samples was insufficient to completely discharge stagnant water that had been in the pipe for a long period before the sampling event.

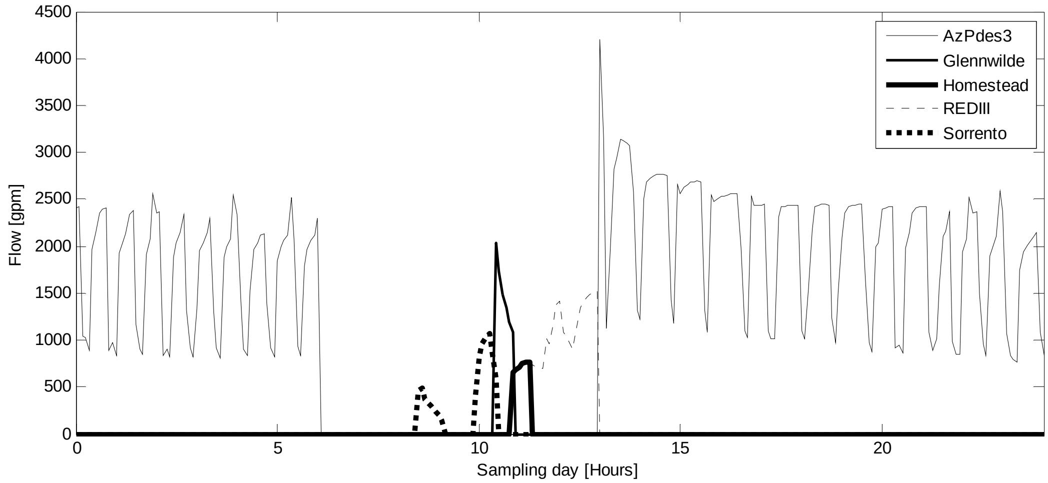


Figure 8.14. Demands for a typical sampling event (winter).

For example, Figure 8.14 shows a discharge pattern for one sampling event. The AZPDES-3 point varies as the wet well is filled and emptied. At about 6:00 am, when the AZPDES-3 valve is closed, its discharge goes to zero, and the valve at the highest elevation discharge point, Sorrento, is opened. No releases are made from the system until approximately 9:00 am, when water has completely filled the pipe leading to Sorrento and the flow is exiting through that valve. Flow returns to zero in response to pump operations at the WWTP.

The second sample is taken after pumps begin operating again. Our preference was for this sample to transit the full system from the WWTP to Sorrento during a single day; however, because AZPDES-3 is at a higher elevation than the WWTP, water partially filled many pipes in the network. Therefore, the sampled water may have been in the pipe south of the circled node for a long period of time. Determining the source of each sample required a manual process.

8.4.3 First-Order Travel Time Estimation

The first step in modeling an unpressurized system in EPANET (which assumes the system is pressurized) was to determine if the volume of collected sample was delivered directly from the wastewater treatment facility or if there were periods of stagnation and reverse flow. This was accomplished by calculating the volume of water being discharged and comparing it to the volumetric capacity of the branch. If the demand volume was greater than the total volume of the branch, the water from that sampling period was delivered from the source during the sampling period.

The hydraulics of these truly steady-state cases were modeled in EPANET by moving the water through the network based on SCADA-derived demand patterns in order to determine the water age, or hydraulic retention time, at the time the sample was collected.

When the steady-state conditions did not occur, times of flow, drainage (reverse flow), and stagnation were determined. An equivalent hydraulic model was then created in EPANET. The location of the sample volume at the beginning of the sampling period was determined from the initial levels in the pipe and the withdrawal pattern. Beginning at the start of the sampling period, this discrete volume was tracked back to the WWTP following the flow pattern in reverse.

An equivalent EPANET pipeline was then generated for each sample volume. Segments in the equivalent pipe were added for each flow condition. Forward flow used the real pipe diameter and demand as occurred in the network. Stagnation periods were represented by setting all the demands beyond the discrete volume equal to zero. Reverse flow was accounted for by calculating the velocity and distance that the volume moved (toward the WWTP). In the equivalent model, a length of pipe was added (in the forward direction) by the computed length and a demand applied to result in the desired velocity. This approach was taken for all samples over all sampling periods.

To provide some perspective on travel times, Figure 8.15 plots the log (HPC) value against water age for the GWR samples. At times, water remains in this system for 10 to 12 days during periods of low demand. Further, it is notable that the HPC appears to increase in the very short term after leaving the WWTP and decay slightly over time, reaching or nearly reaching an equilibrium condition.

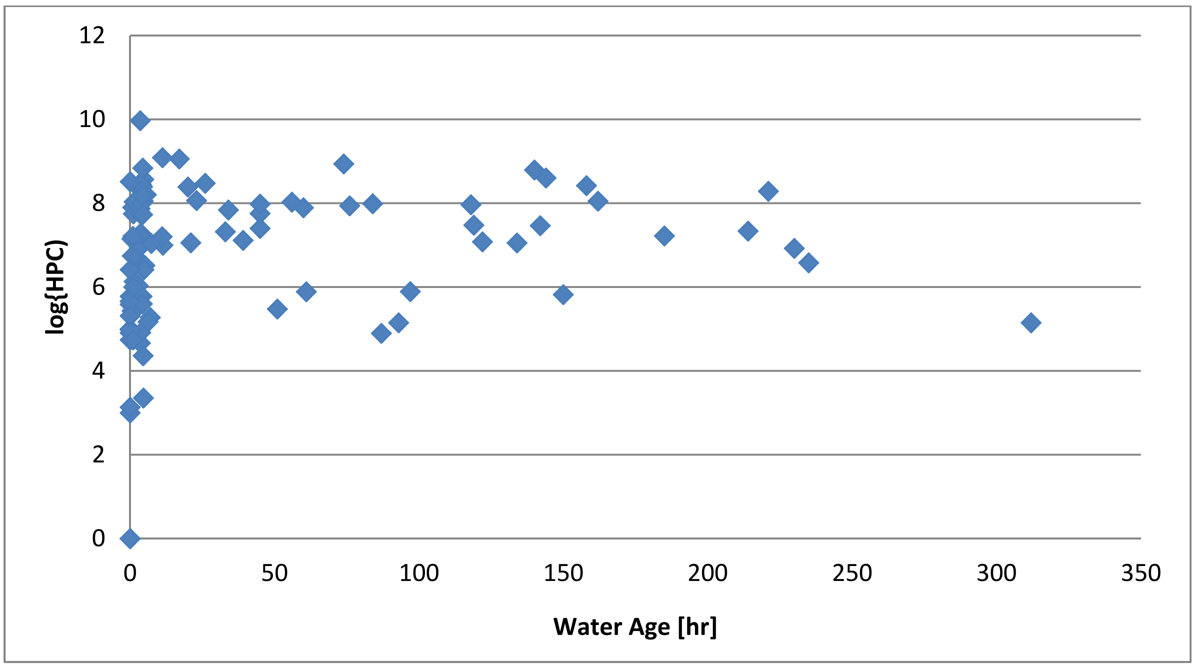


Figure 8.15. Log (HPC) versus water age.

8.4.4 Water Quality Modeling

For the GWR system, chemical and microbial data were not collected for a storage tank; as a result, bulk model parameters could not be calibrated separately from the wall parameters as in the Tucson Water system. Using the same optimization approach as for Tucson Water, the optimization problem was formulated to determine the full parameter set of bulk and wall decay coefficients; however, because of the size of the problem and limited measured values, no acceptable solution was found.

8.4.5 Finite Volume Modeling Approach

The parcel tracking approach described as the first-order estimates is likely sufficiently accurate for this system given the relative small changes in HPC at longer retention times. At lower water ages, the approach may result in inaccuracies because of the relatively flat slopes in the pipes. An alternative modeling approach was explored and formulated to overcome these weaknesses, but we do not expect a significant change in results or any change in our conclusions.

The model deliverables that are computed at each time step are: the flow rate in each pipe segment, the pressure head at each node, the system's water surface elevation, the total volume of water in each pipe (percent full), the incremental pipe volume change, and the water age or Hydrologic Retention Time (HRT). As in the first-order estimate, water age will be used to determine the fate of various constituents based on their specific, individual reaction rates and the relative concentrations of other species present in the water. The target networks to be modeled are complex on the basis of flow provisions because the system operations permit both pressurized plug flow and unpressurized open channel flow. At each location within the network, the type of flow is imposed by the topographic configurations, the geometry, and the connectivity of pipes and outlets.

With the proper data input, the code can be used to simulate a historical event in order to predict the quality of water delivered to the end users over a designated time period. First, the physical geometry of the network must be explicitly defined. This requires the user to input pipe lengths and diameters, start and end nodes, and Manning's roughness value. The lengths and diameters are used to determine the total pipe volumes, whereas the start and end nodes reflect the link connectivity.

To obtain the system's topographic information, it is necessary to input the elevations corresponding to each node. For pressure head calculations, equations relating the total dynamic head to the flow capacity must be characterized in the model input as pump curves. After the network geometry is laid out, the code requires explicit declaration of the inlet flow rates from the WWTP clear well, as well as a history of the valve positions. This time series data are retrieved from the utility's database of SCADA entries. The time series data must be adjusted to reflect a constant time step, Δt, specified by the modeler. Finally, the premodeling, initial conditions of the system must be known. That is, the user must identify the existing water surface elevation and, for each pipe, determine the current volumetric capacity percentage.

8.4.6 Model Assumptions and Limitations

The accuracy of a computer model is greatly dependent on the validity of the assumptions and approximations made by the mathematical, physical, and chemical description of the subject model. In this model, the assumptions incorporated into code affect the output hydraulics and water quality predictions.

The first assumption is that the water surface elevations in unpressurized flow are governed by gravity. When under plug–flow conditions, it is assumed that there is only a single phase present in the pipe, meaning there is no trapped air or air gaps. The model also neglects the effects of axial and longitudinal dispersion. It is assumed that water travels in volume parcels discretized by the Lagrangian modeling approach and that mixing between the parcels is insignificant; that is, each has its own properties.

8.4.7 Plug–Flow Hydraulics

When the system is pressurized and water is being pumped uphill, the pipe flows are determined by a mass balance around each node and an energy balance for each pipe, beginning at the distribution system inlet. If the current pipe is empty or partially full, the incoming water will remain in the pipe, increasing the total volume of water in the pipe, until the water surface elevation rises above the pipe's invert elevation at the outlet. Further increases in the water surface elevation will cause flow to reach the next pipe(s) before the previous pipe is completely full. The pipe filling schematic provided in Figure 8.16 demonstrates this concept based on the geometry and slopes of the pipes.

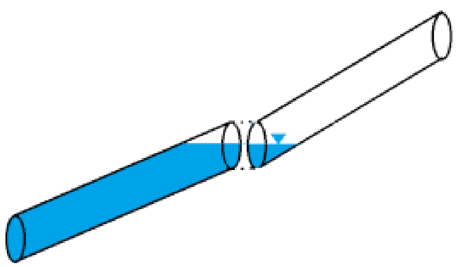


Figure 8.16. Pipe filling schematic.

Conservation of energy is used to determine the system pressures. Hazen-Williams Equation 9 is implemented in the model to account for the head loss occurring in the pipes.

$$h_f = K_u \left(\frac{Q}{C_{HW}}\right)^{1.852} \frac{L}{D^{4.87}} \quad (9)$$

8.4.8 Open Channel Flow Hydraulics

The governing equations for unsteady flow of water through a network are the conservation of mass (10) and the conservation of momentum (11).

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \quad (10)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial (Q^2 / A)}{\partial x} + gA\frac{\partial H}{\partial x} + gAS_f + gAh_L = 0 \quad (11)$$

The friction slope, S_f, in Equation 11 is defined by the Manning formula and given in Equation 12.

$$S_f = \frac{n^2 V|V|}{k^2 R^{4/3}} \quad (12)$$

The continuity relationship at the junction of pipes is shown in Equation 13, where *Astore* is the surface area of the node and *As* is the surface area of the water in each pipe connected to the node. Figure 8.17 establishes the geometric relationship between adjacent conduits, whereas Equation 10 relates changes in hydraulic head at the node with respect to time. In this model, the nodes are assumed to have zero storage area (Astore=0) and the conduits are directly connected to one another.

$$\frac{\partial H}{\partial t} = \frac{\sum Q}{Astore + \sum As} \quad (13)$$

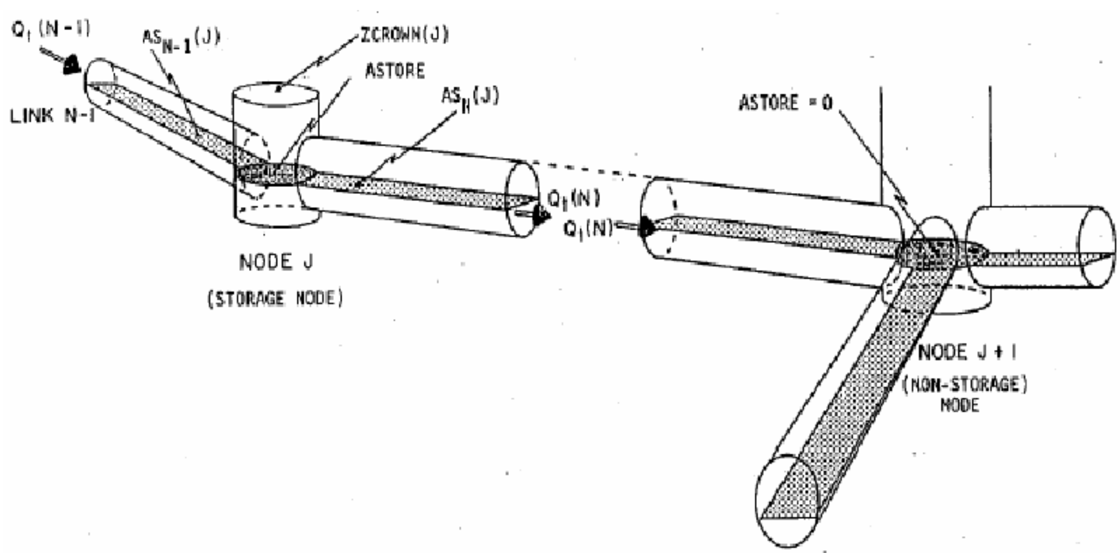


Figure 8.17. Node–link representation of a drainage system in EPA SWMM.
Source: Roesner et al, 1992

Equations 10, 11, and 13 are solved numerically by converting them into a set of finite difference formulas used to calculate the flow in each pipe and head at each node for time t + Δt, using the values calculated at the previous time step. The flow rate at each time step is given by Equations 14 through 18.

$$Q_{t+\Delta t} = \frac{Q_t + \Delta Q_{gravity} + \Delta Q_{inertial}}{1 + \Delta Q_{friction} + \Delta Q_{losses}} \quad (14)$$

$$\Delta Q_{gravity} = g\overline{A}(H_1 - H_2)\Delta t / L \tag{15}$$

$$\Delta Q_{inertial} = 2\overline{V}(\overline{A} - A_t) + \overline{V}^2(A_2 - A_1)\Delta t / L \tag{16}$$

$$\Delta Q_{friction} = \frac{gn^2 |\overline{V}| \Delta t}{k^2 \overline{R}^{4/3}} \tag{17}$$

$$\Delta Q_{losses} = \frac{\sum_i K_i |V_i| \Delta t}{2L} \tag{18}$$

The head at each node is calculated from Equations 19 and 20.

$$H_{t+\Delta t} = H_t + \frac{\Delta Vol}{\left(Astore + \sum As\right)_{t+\Delta t}} \tag{19}$$

$$\Delta Vol = 0.5\left[\left(\sum Q\right)_t + \left(\sum Q\right)_{t+\Delta t}\right]\Delta t \tag{20}$$

A second-order Runge-Kutta method is executed to numerically solve Equations 14 and 19 at each time step. When the flow through a relatively empty pipe reaches the minimum elevation of the conduit, the water accumulates, filling the end pipe and increasing the local, detached water surface. Water continues to flow downhill in an open channel fashion until the local water surface rises significantly to reach the water surface elevation of the pumped water. When this takes place, the pipes are assumed to be fully charged, and plug–flow dominates. Figure 8.18 represents the transition to open channel flow where water begins to flow downhill and accumulate at the bottom of the conduit.

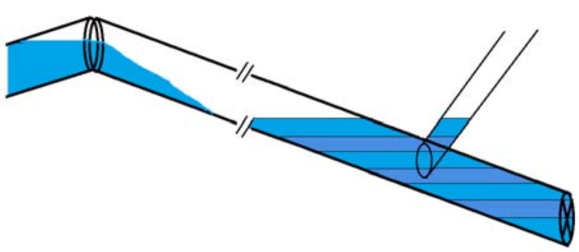


Figure 8.18. Open channel pipe schematic.

8.5 Modeling Results

For the Tucson Water distribution system, Figures 8.19 through 8.21 for *Legionella, Mycobacterium,* and *Aeromonas,* respectively display various water-based pathogen concentrations with respect to water age. Figures 8.22 through 8.24 show the waterborne pathogens as a function of water age. Plots are given for coliforms, *E. coli,* and *Enterococcus*. Figures 8.25 through 8.27 and 8.28 through 8.31 are plots for the GWR network for the same set of water-based and waterborne pathogens. During the project sampling period, GWR began injecting chlorine as a disinfectant. Data for all periods are plotted together because no distinguishable difference was noted between the two periods. *E. coli* concentrations are representative of the lack of difference between pre- and post-chlorination periods (Figures 8.29 and 8.30). These results demonstrate that water-based and waterborne pathogens are present in reclaimed water distribution systems regardless of the treatment level.

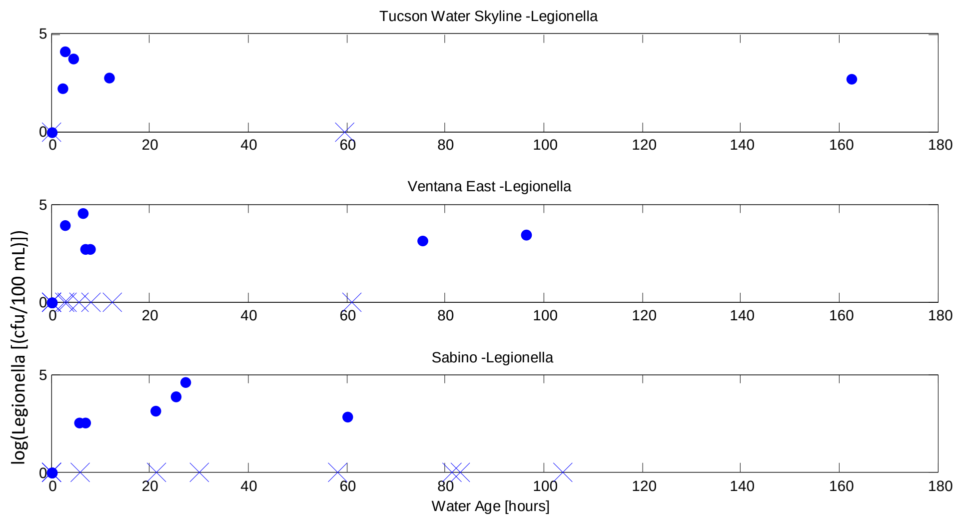


Figure 8.19. Water-based pathogens versus water age—*Legionella*—for various sampling points in the Tucson Water system.

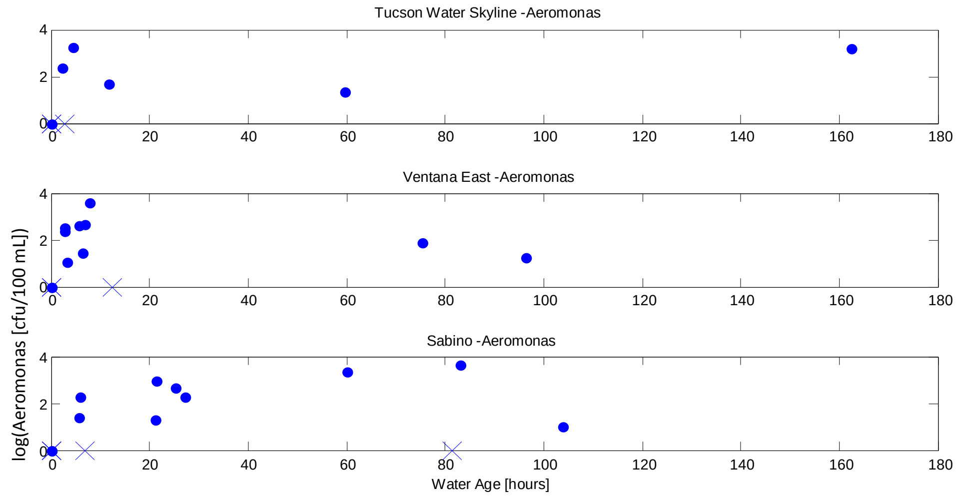


Figure 8.20. Water-based pathogens versus water age—*Aeromonas*—for various sampling points in the Tucson Water system.

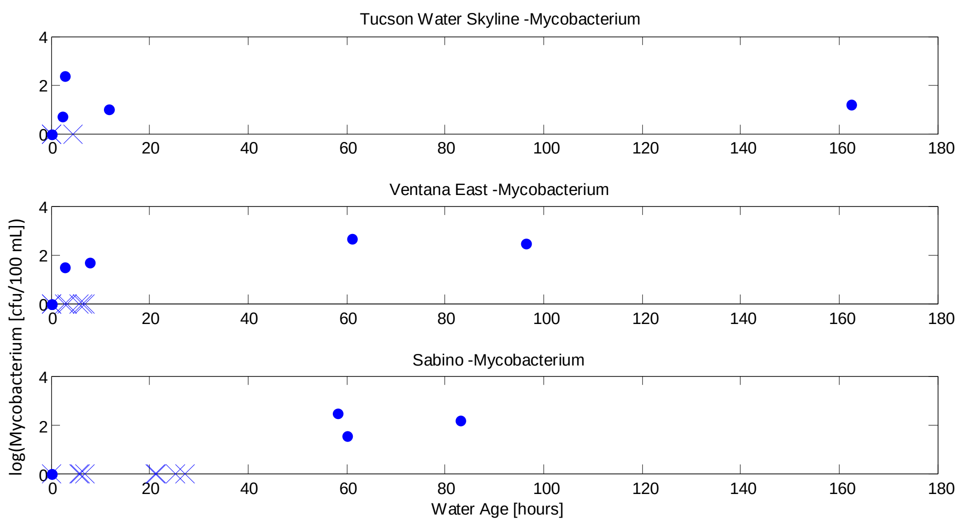


Figure 8.21. Water-based pathogens versus water age—*Mycobacterium*—for various sampling points in the Tucson Water system .

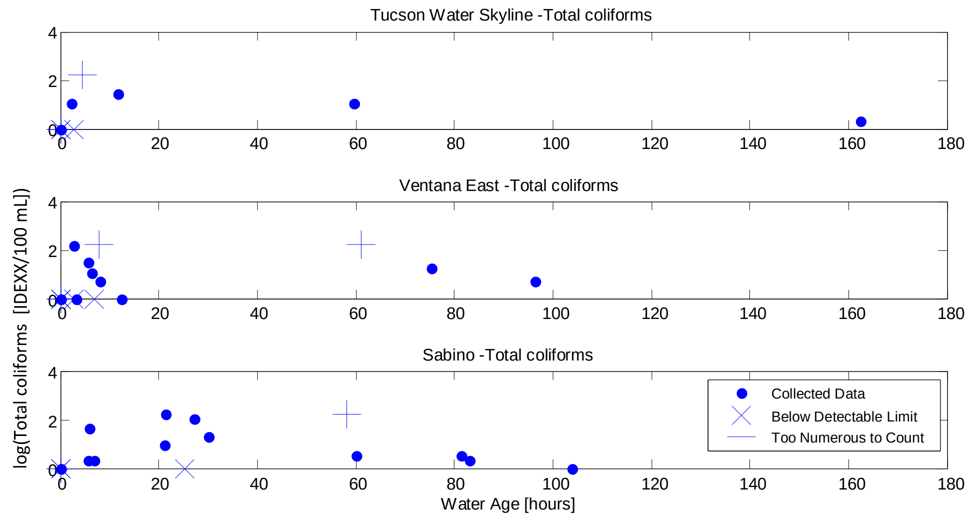


Figure 8.22. Waterborne pathogens versus water age—total coliforms—for various sampling points in the Tucson Water system.

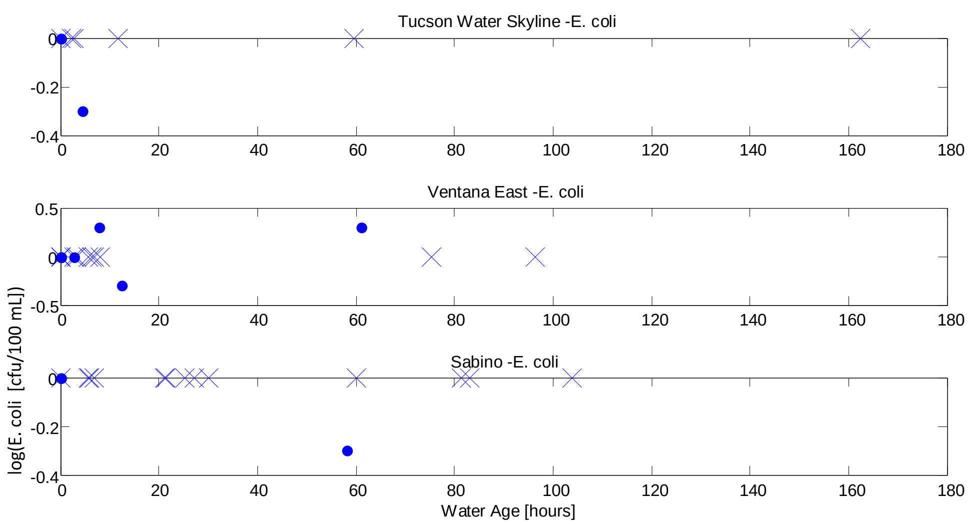


Figure 8.23. Waterborne pathogens versus water age—*E. coli*—for various sampling points in the Tucson Water system.

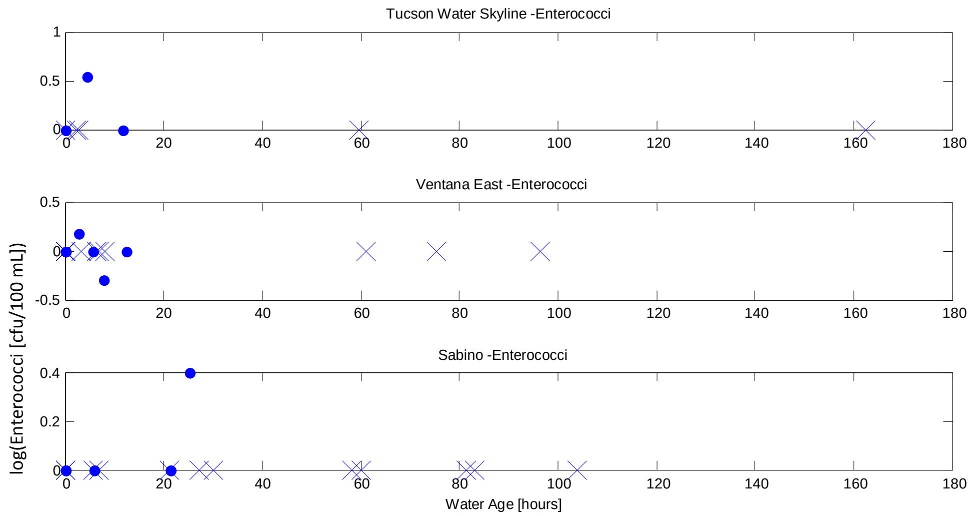


Figure 8.24. Waterborne pathogens versus water age—*Enterococci*—for various sampling points in the Tucson Water system.

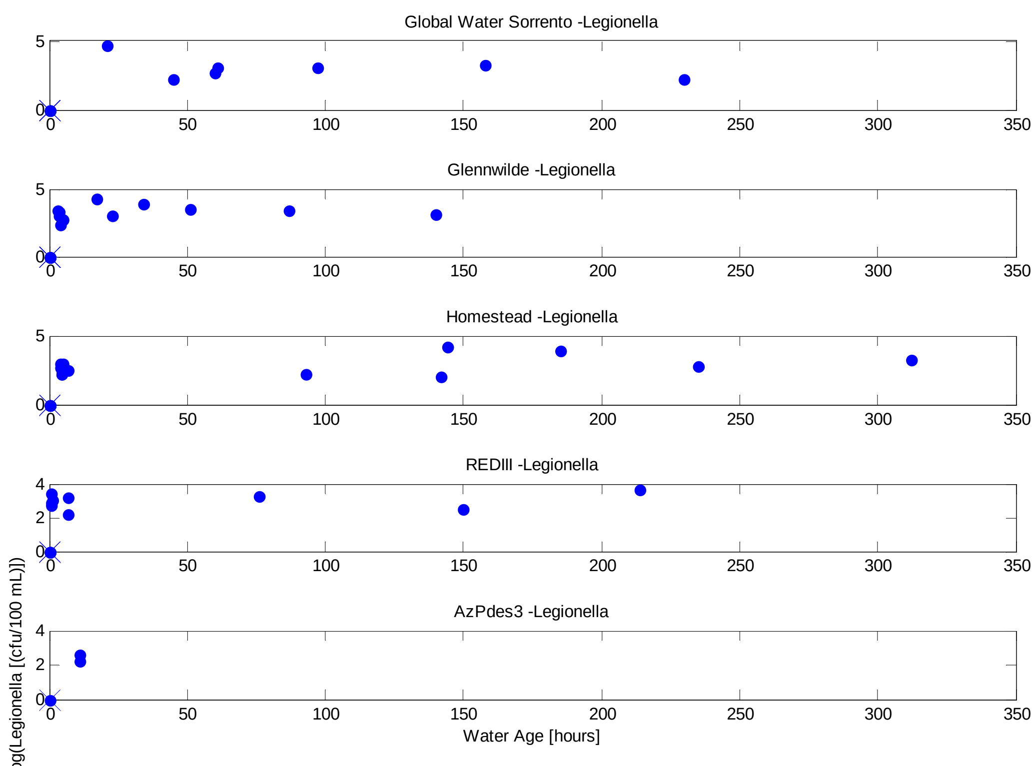


Figure 8.25. Water-based pathogens versus water age—*Legionella*—for various sampling points in the Global Water Resources system.

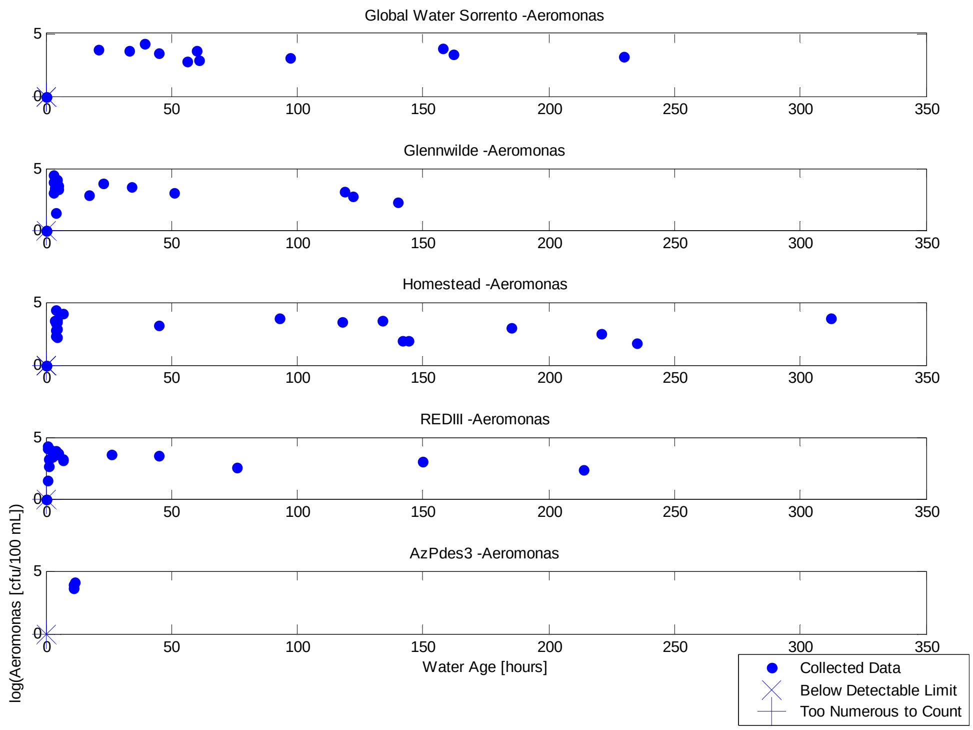


Figure 8.26. Water-based pathogens versus water age—*Aeromonas*—for various sampling points in the Global Water Resources system.

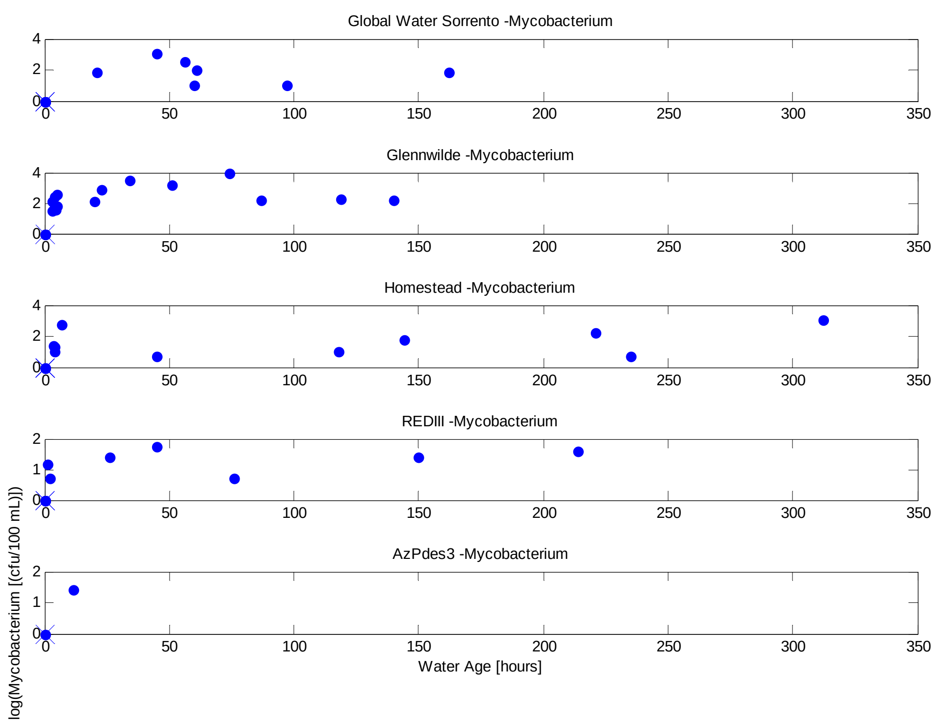


Figure 8.27. Water-based pathogens versus water age—*Mycobacterium*—for various sampling points in the Global Water Resources system.

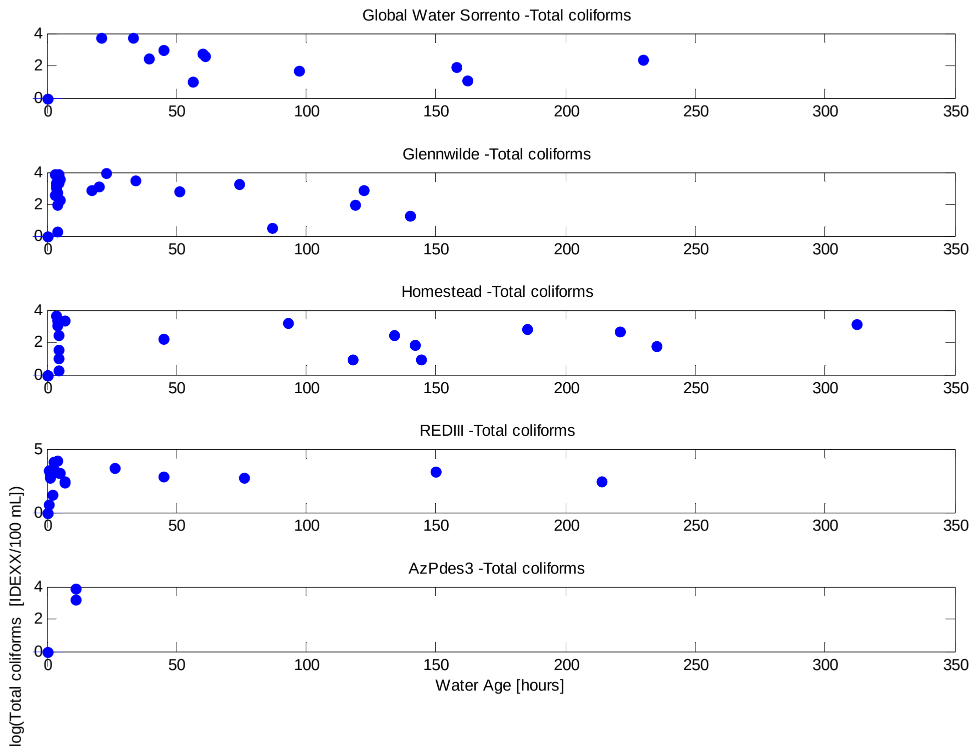


Figure 8.28. Waterborne pathogens versus water age—total coliform—pre- and post-chlorination for various sampling points in the Global Water Resources system.

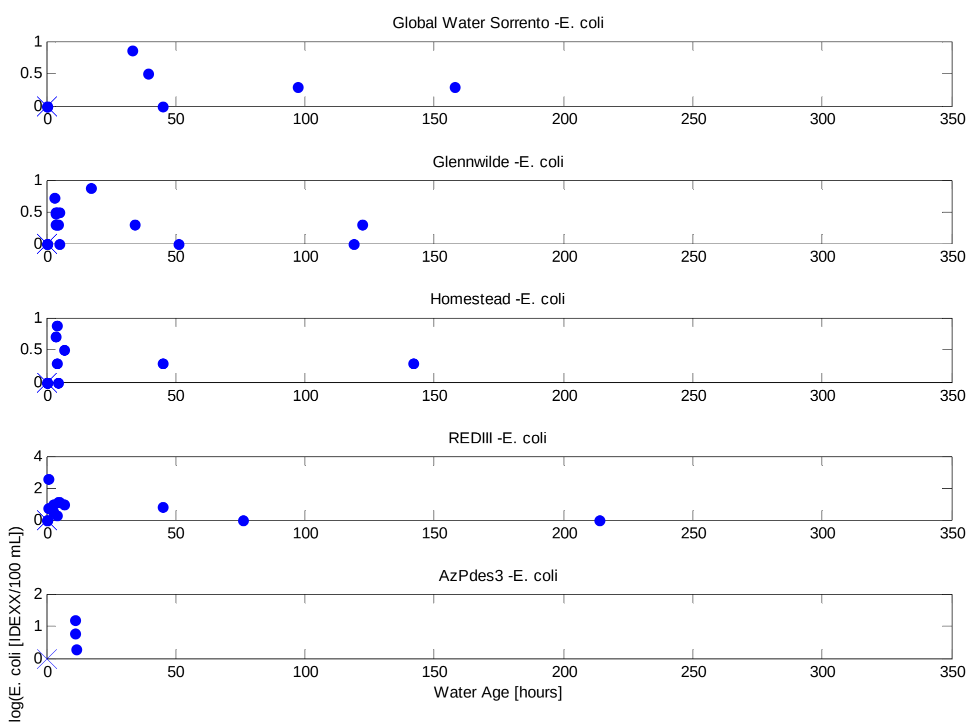


Figure 8.29. Waterborne pathogens versus water age—*E. coli*—prechlorination for various sampling points in the Global Water Resources system.

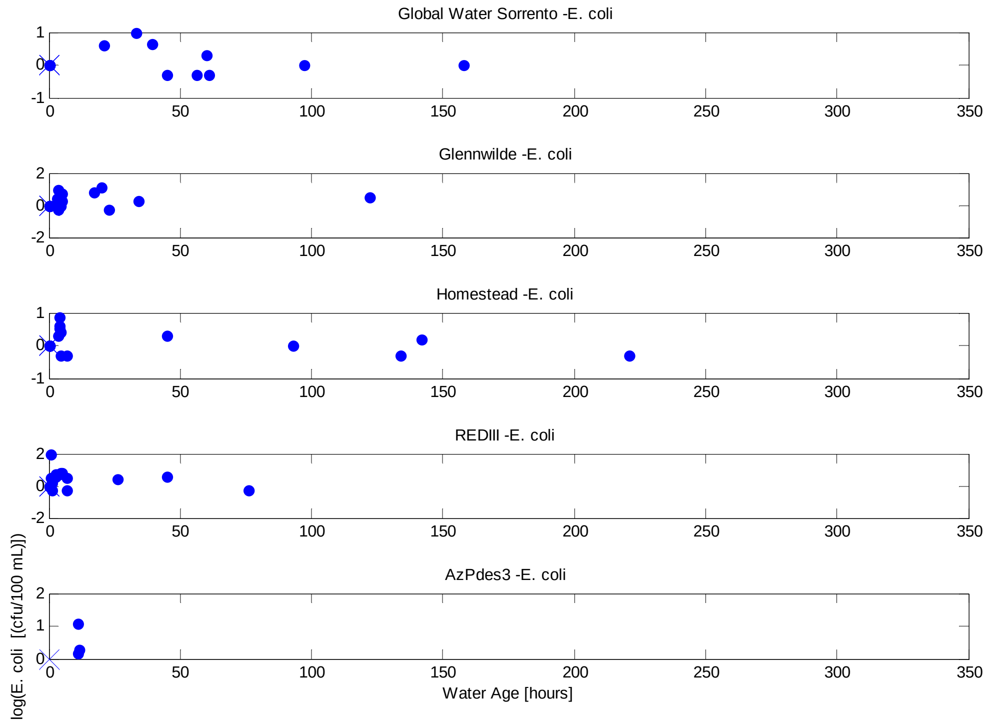


Figure 8.30. Waterborne pathogens versus water age—*E. coli*—post-chlorination for various sampling points in the Global Water Resources system.

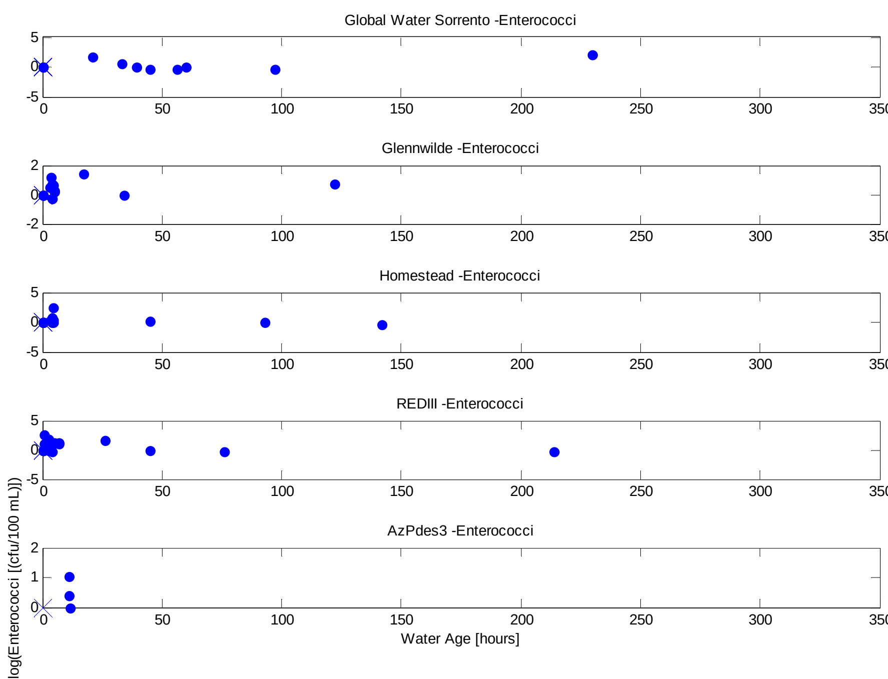


Figure 8.31. Waterborne pathogens versus water age—*Enterococci*—pre- and post-chlorination for various sampling points in the Global Water Resources system.

8.6 Sensitivity Analysis

8.6.1 Opportunities for Reclaimed Water Distribution System Management Using Modeling

One benefit of a system model is its ability to simulate alternative scenarios and examine possible outcomes. Here, we examine two management scenarios: increased disinfection levels and alternative wastewater treatment on water quality in the Tucson Water system. Before discussing the results, caveats on interpreting model results must be mentioned. These results are extrapolations of the models to new states that are beyond the range of calibrated conditions. As such, they are intended to be general indicators of possible levels of changes.

8.6.2 Changes in Wastewater Treatment—Bulk Parameter Sensitivity

Studies were completed for two reclaimed water qualities, Class A and A+, and bulk water parameters were determined for each water quality. The Tucson Water model study area was selected because it was a reasonably isolated area that could be well monitored. It was supplied with Class A water. To examine the potential benefits of a higher level of treatment, the distribution system model was executed using the bulk parameters obtained from the Class A+ tank study. The wall parameters were assumed to be the same as for Class A water. Summer (July) and winter (February) periods were modeled with demand patterns shown in Figures 8.32 and 8.33.

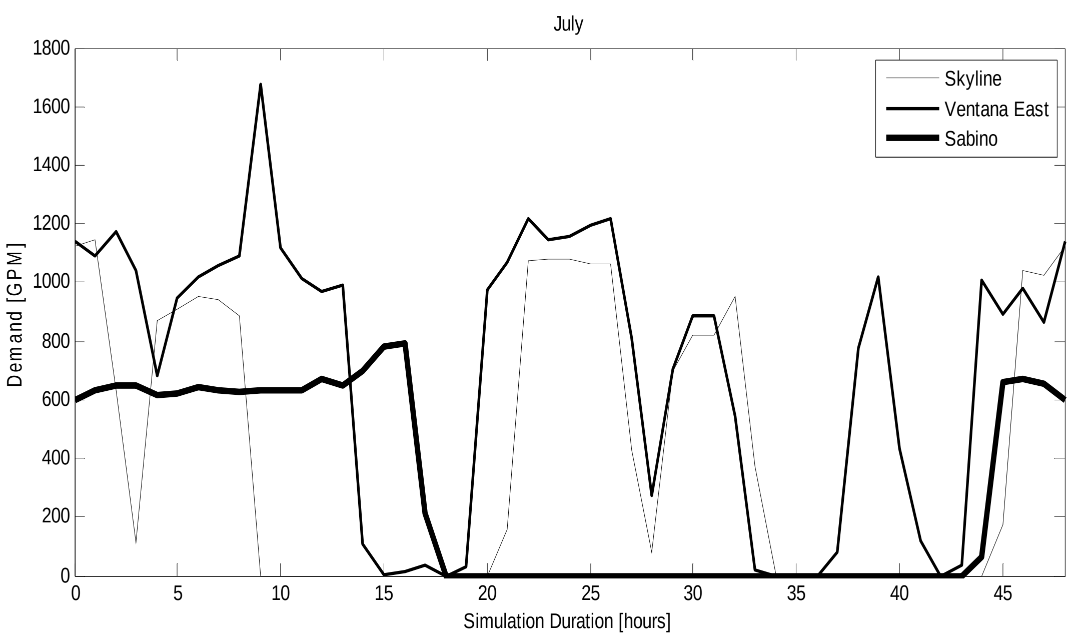


Figure 8.32. Summer 48-hour demand patterns for La Paloma branch.

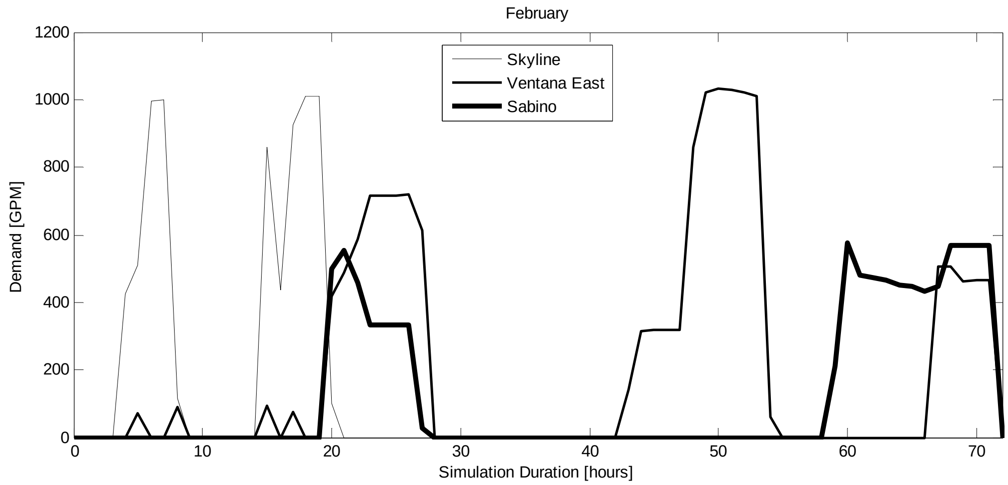


Figure 8.33. Winter 72-hour demand patterns for La Paloma branch.

Results shown in Figures 8.34 and 8.35 suggest that the initial Class A+ water quality will be evidenced after travel through the distribution system; however, given the variations in demands, and thus water age, the benefits vary by season. The benefits of using Class A+ in winter with that season's longer retention times is greater (about a 14% decrease in log [HPC]) than the benefit of using such water in summer (about a 7% reduction).

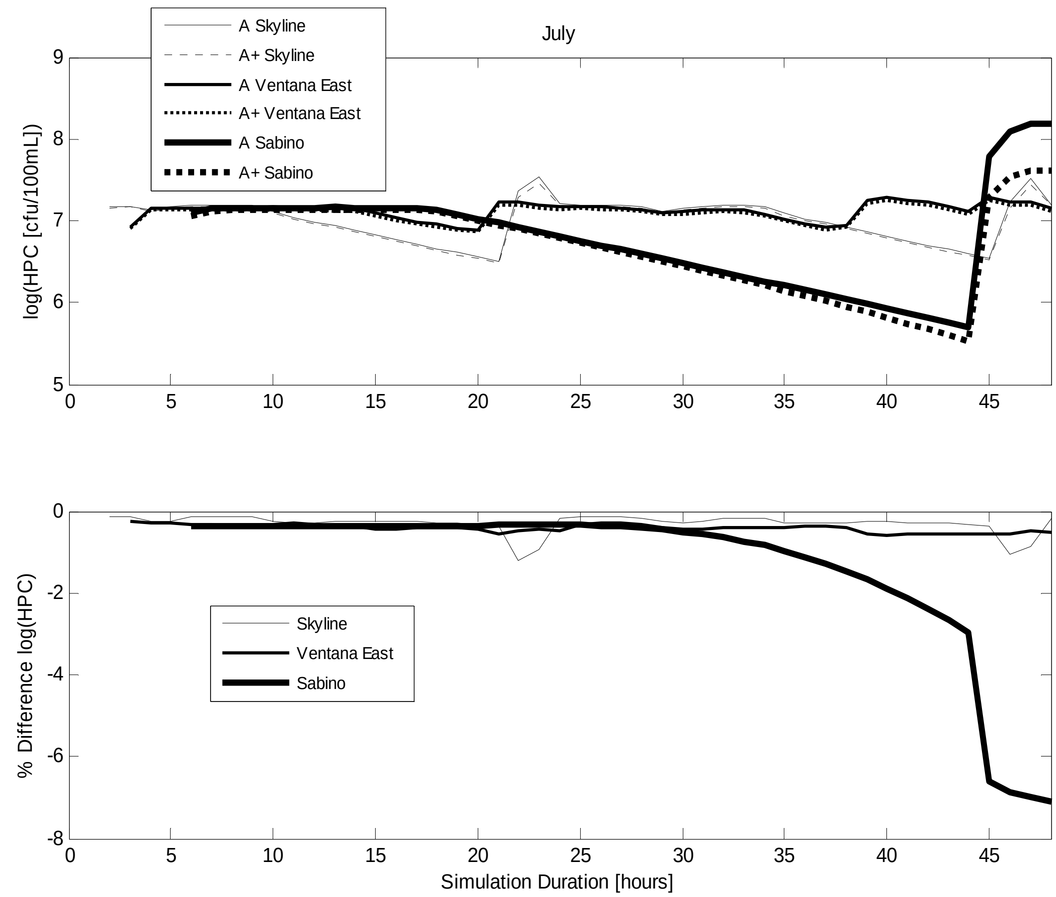


Figure 8.34. Summer comparison (top) of Class A and Class A+ log (HPC) and percent difference (bottom) in log (HPC) for Skyline, Ventana East, and Sabino.

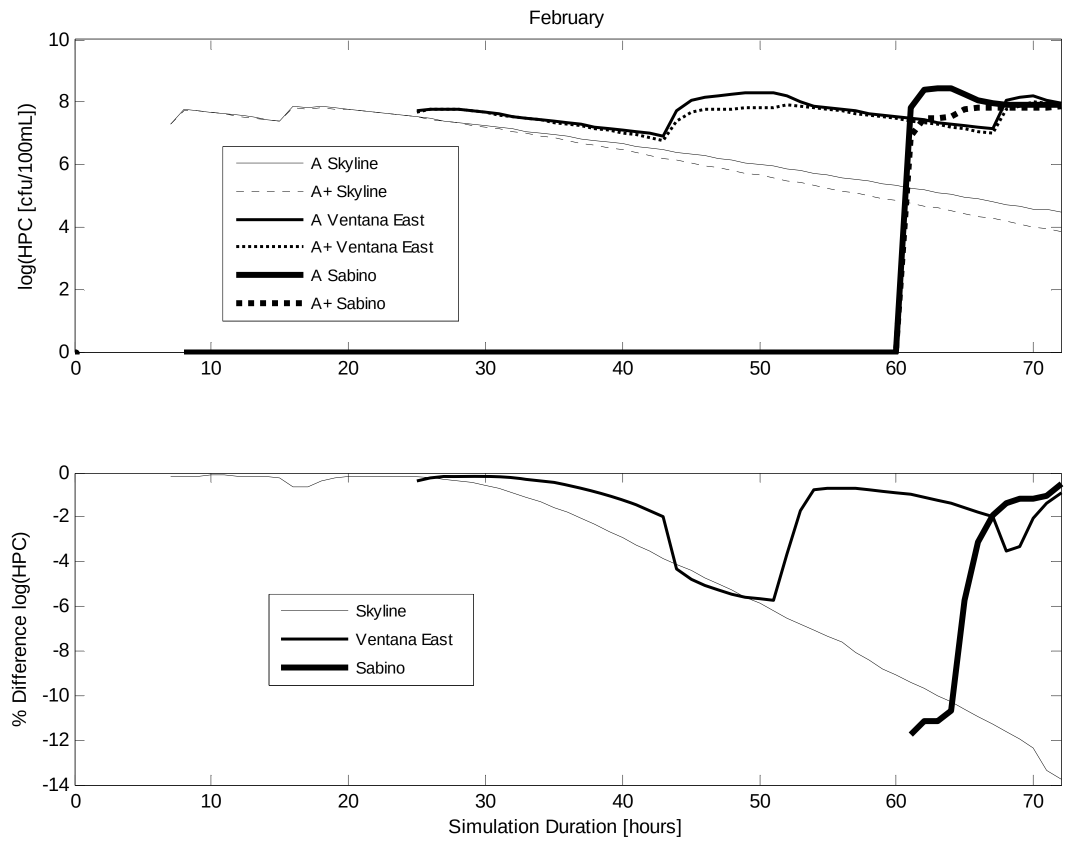


Figure 8.35. Winter comparison (top) of Class A and Class A+ log (HPC) and percent difference (bottom) in log (HPC) for Skyline, Ventana East, and Sabino.

The parameter that differs the most between Class A to Class A+ water is Y_g, the growth yield coefficient for bacteria. Y_g decreases from 0.863 (Class A) to 0.119 mg biomass/mg substrate in Class A+. This difference implies that more AOC must be consumed to sustain the same levels of HPC in Class A+ waters. As a result, AOC concentrations are reduced in Class A+ water (Figures 8.36 and 8.37), and the difference is greater in winter months.

These results suggest that advanced treatment does have an impact on downstream water quality. Some uncertainties exist because of the relatively small sample size used for tank model calibration. Further, because data were unavailable for wall reaction rates, the values obtained from Class A water were used; however, results generally indicated that the wall parameters had less influence on HPC compared to the bulk parameters (see Tucson Water modeling section). Field testing is justified based on this modeling work and also in order to support such work. Development of a field sampling plan is recommended for the region of the Tucson Water system that receives the Class A+ water to improve these model estimates and, more importantly, determine the benefits of additional treatment.

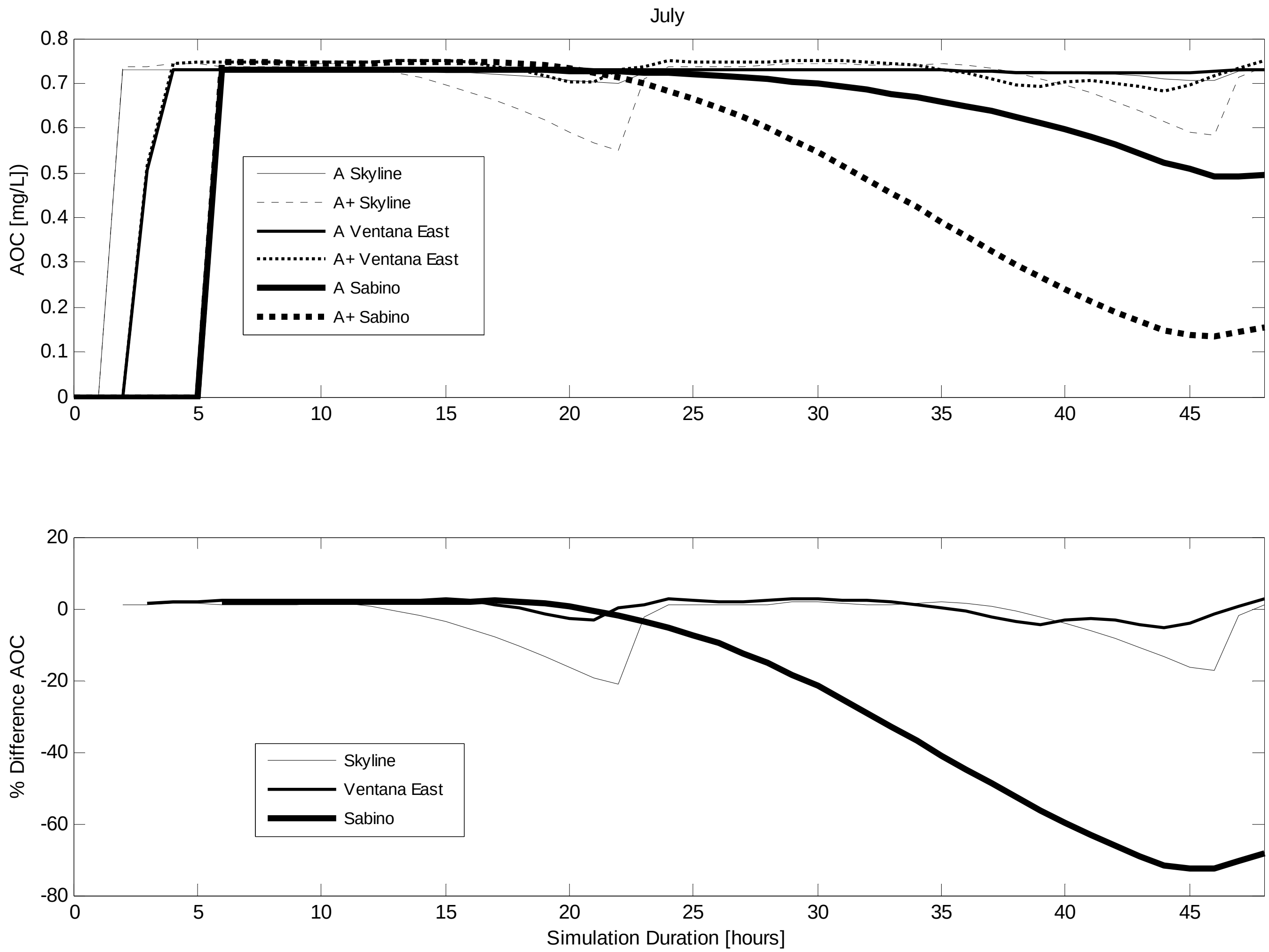


Figure 8.36. Summer comparison of Class A and Class A+ AOC (top) and percent difference in AOC (bottom) for Skyline, Ventana East, and Sabino.

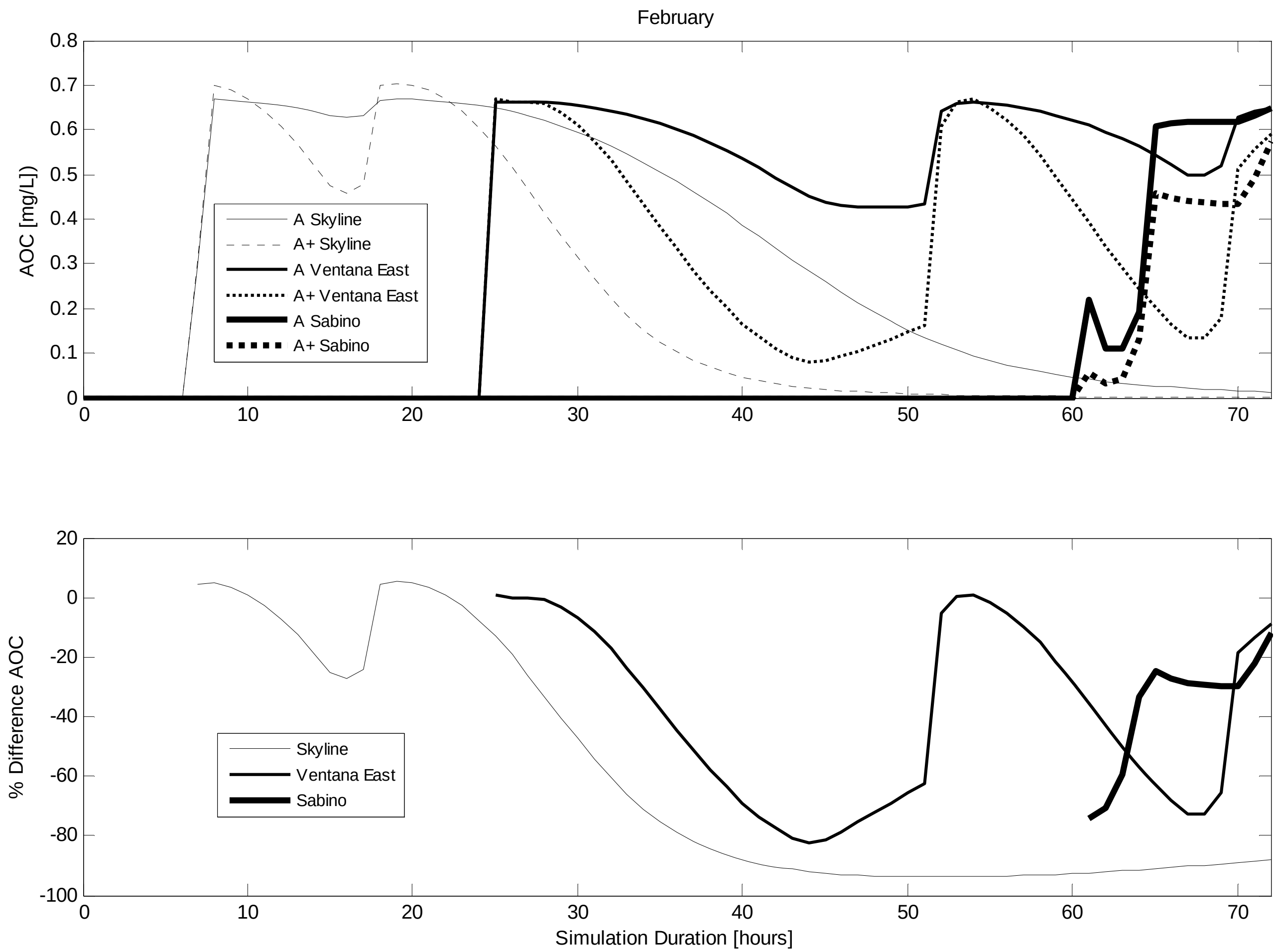


Figure 8.37. Winter comparison of Class A and Class A+ AOC (top) and percent difference in AOC (bottom) for Skyline, Ventana East, and Sabino.

8.6.3 Chlorine Injection Rates

To assess the benefit of increasing disinfection levels, a sensitivity analysis was performed on La Paloma branch of the Tucson Water network to determine the sensitivity of HPC to the initial chlorine concentration. Figure 8.38 shows the demands for Skyline, Ventana East, and Sabino over a 48-hour period. The original conditions had a chlorine injection rate upon leaving the pumping station of 3.33 mg/L. The calibrated EPANET-MSX model was simulated for initial chlorine dosages that were increased by 50, 100, 150, 200, 250, and 300%. The results are displayed in Figures 8.39 through 8.43.

Increasing the initial chlorine concentration affects locations close to the dosing point; however, the effect on HPC levels is minimal. With a 300% increase in chlorine, the greatest reduction of HPC is less than 2% of log (HPC). It is apparent that as demands increase the chlorine concentrations in the system are positively impacted, but this trend has little effect on HPC levels. Under lower demands, the slight decreases in HPC are noted. This analysis suggests that increasing the chlorine levels would not significantly improve water quality with respect to HPCs.

As noted in the introduction to this section, these results are extrapolations of the model to new conditions. Under the present conditions for which the model has been calibrated, the impact of chlorine appears to be quite limited, so parameter estimates related to chlorine are likely to be highly uncertain and may underestimate the sensitivity of disinfection in this system. As such, we recommend follow-up field studies to determine more precisely the impact of varying disinfection dosages.

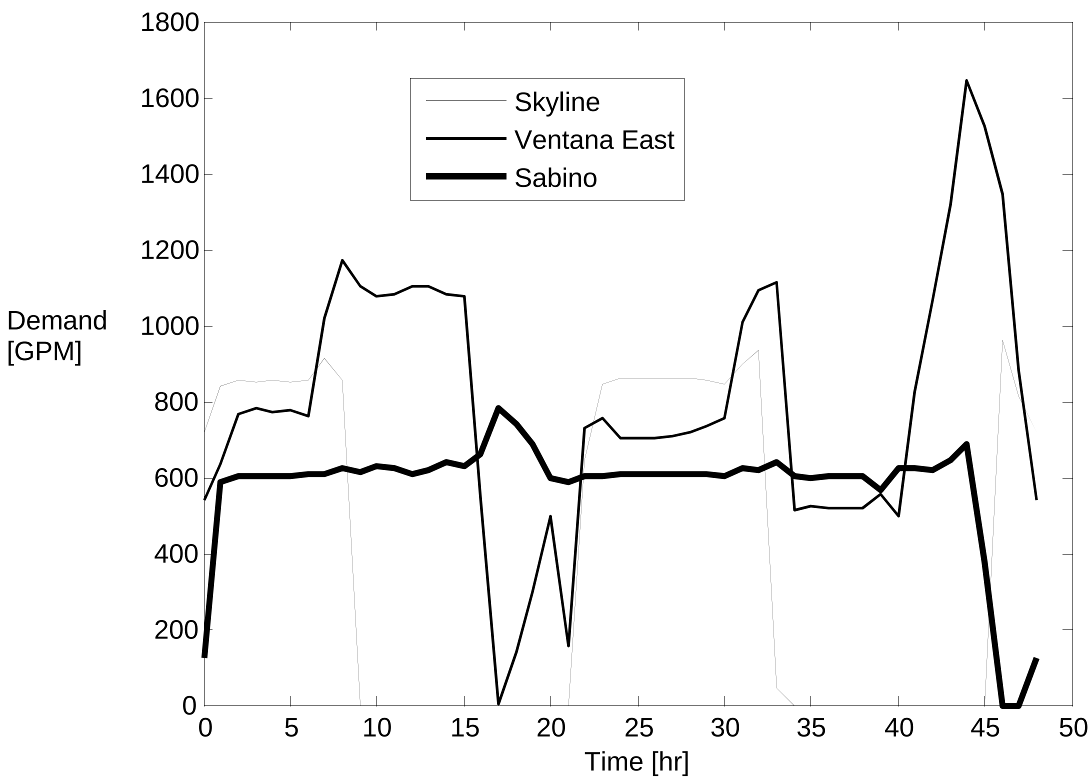


Figure 8.38. Demand patterns for sensitivity analysis.

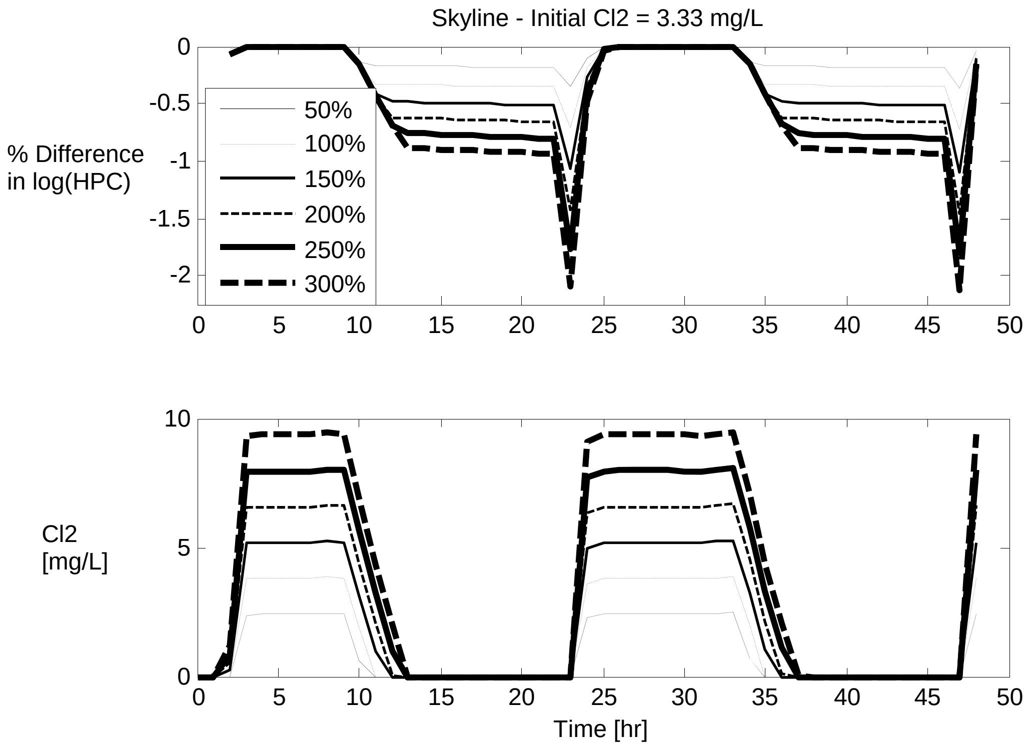


Figure 8.39. Skyline: Percentage difference in log (HPC) values (top) and chlorine concentration (bottom).

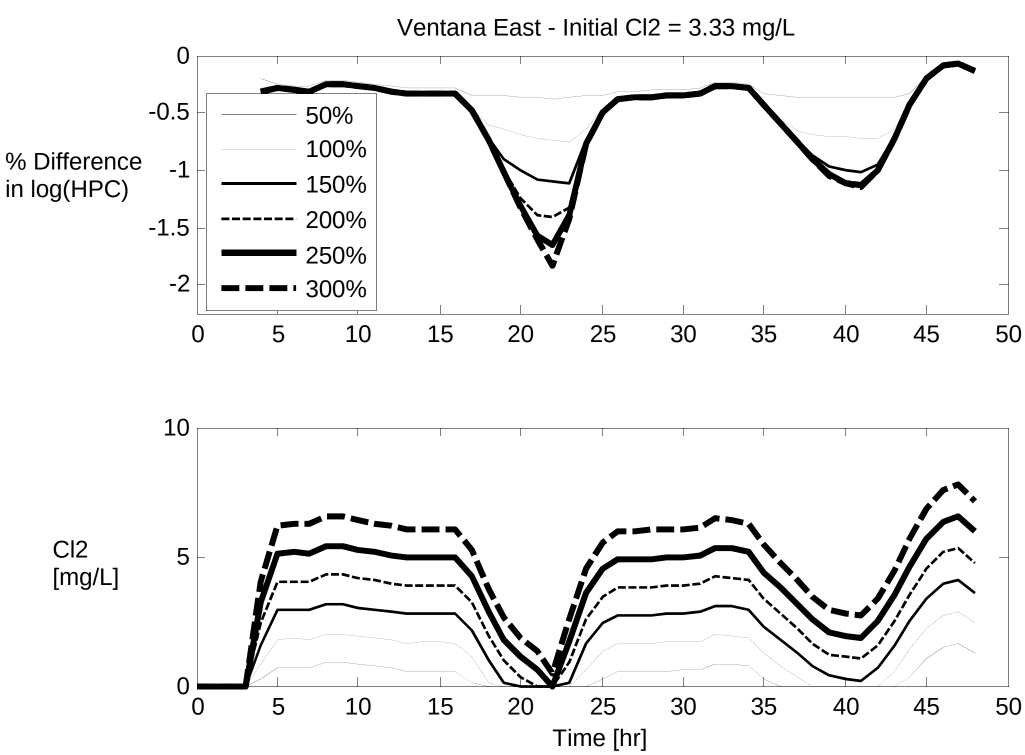


Figure 8.40. Ventana East: Percentage difference in log (HPC) values (top) and chlorine concentration (bottom).

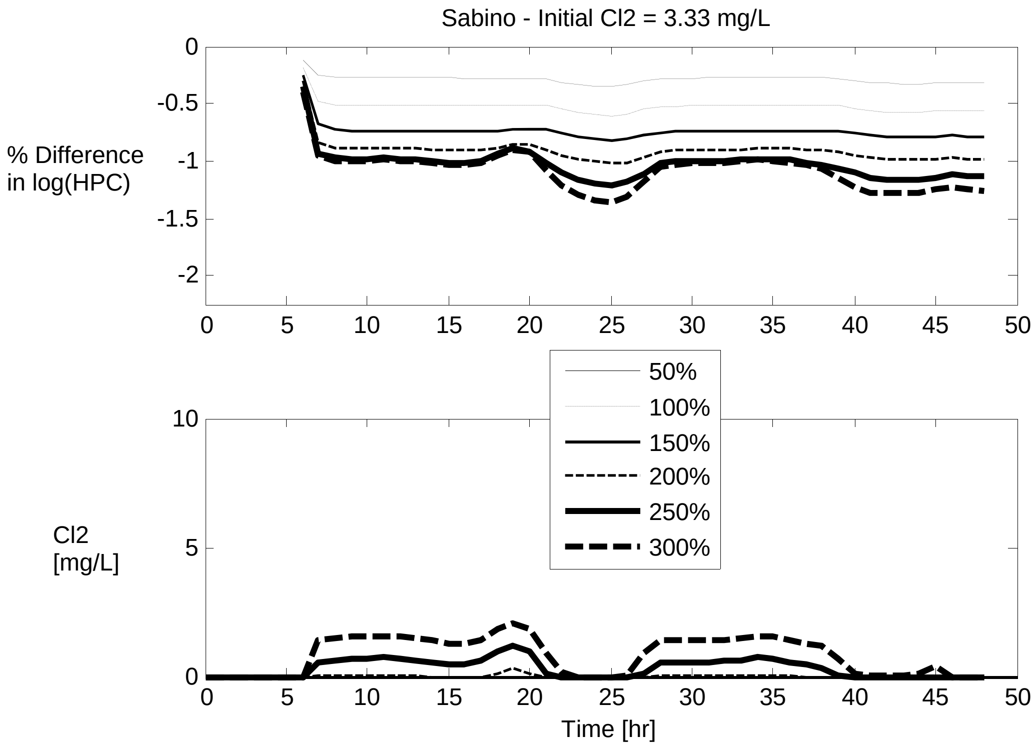


Figure 8.41. Sabino: Percentage difference in log (HPC) values (top) and chlorine concentration (bottom).

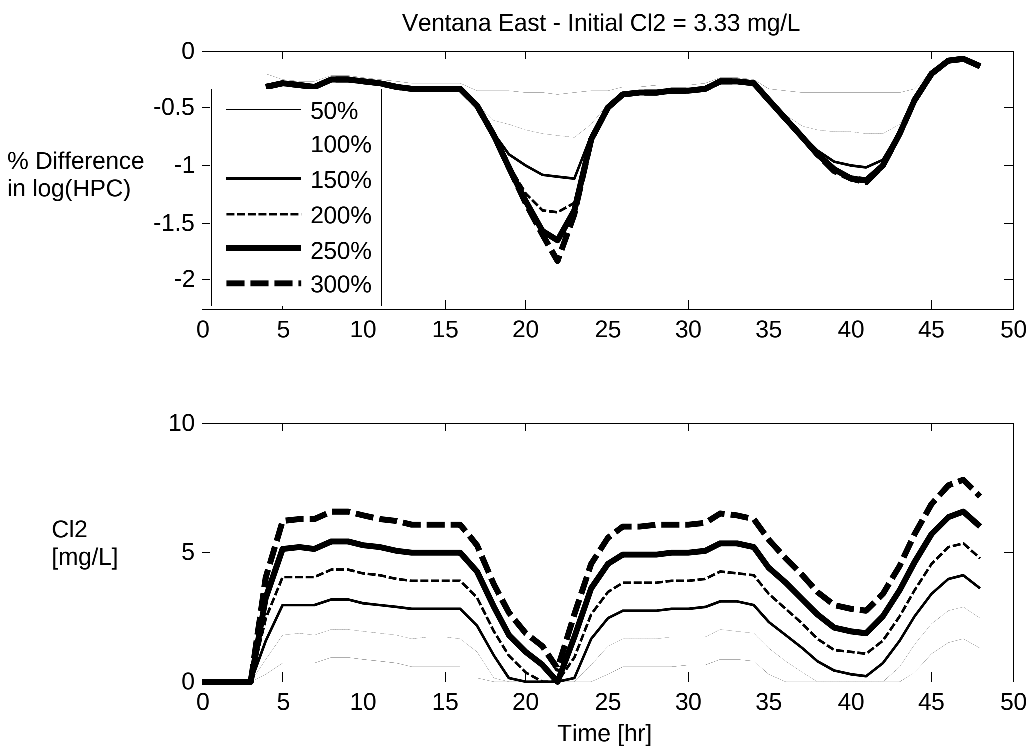


Figure 8.42. Ventana East: Percentage difference in log (HPC) values (top) and chlorine concentration (bottom).

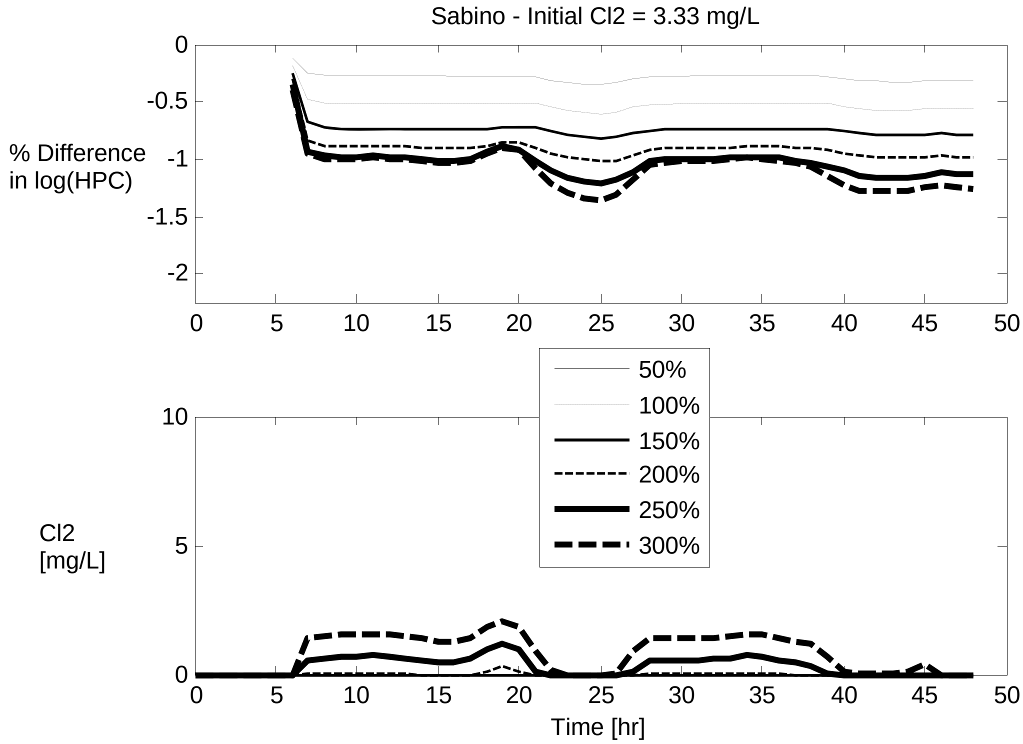


Figure 8.43. Sabino: Percentage difference in log (HPC) values (top) and chlorine concentration (bottom).

Chapter 9

Conclusions

This study explored the water quality transformations that occur during recycled water distribution and storage. It was divided into five phases involving a questionnaire, case studies, storage tank experiments, distribution system sampling, and hydraulic modeling.

9.1 Key Findings

- Regardless of the initial level of treatment, the microbial quality of the recycled water sampled from the utilities monitored for this research study deteriorated with increased residence time in the water distribution system.

- Water-based pathogens, including *Legionella*, *Mycobacterium*, and *Aeromonas,* were routinely found in recycled waters beyond the point of compliance.

- All water-based pathogens demonstrated the ability to grow within the distribution systems. Furthermore, although water-based pathogen concentrations were reduced following chlorination boosters, pathogens showed a potential to regrow following disinfection within the distribution system.

- Fecal indicator organisms, including *E. coli* and *Enterococcus*, were rarely detected in either distribution system, suggesting that treatment effectively eliminated waterborne pathogens.

- The preceding results demonstrate that fecal indicators have no correlation with the presence of water-based pathogens within the distribution systems included in this study and are not a reliable indicator of microbial water quality.

- Amoebic activity was detected in approximately one third of all water samples collected, with frequency of detection being similar despite the variety of treatment technologies utilized by the cooperating utilities.

- During storage of reclaimed water, the microbial water quality changes over time in correlation to the rapid dissipation of chlorine concentrations. Within a matter of days, organism levels stabilize as AOC levels decrease; this suggests that an equilibrium level of available carbon is reached during growth and subsequent death of organisms.

- One marked difference in the microbial water quality of stored Class A versus Class A+ water was an increased frequency of detection of *Aeromonas* in Class A+ water; however, this only occurred in the first replicate storage tank study and was not observed in the second study. The reasons for this are not clear and warrant further investigation.

9.2 Utility Perspective

An objective for utilities to engage in this study was to determine if recycled water system managers could improve the microbial quality of the finished recycled water product by making operational changes during treatment and delivery. The results of the study confirmed that maintaining disinfectant residual is a key component to controlling microbial growth and regrowth.

The key finding was that fecal indicator organisms such as *E. coli* and *Enterococcus* spp. are only valuable to determine quality of the recycled water at the point of entry but not within the distribution system. The fecal indicator organisms are eliminated by the use of chlorine without regrowth within the distribution system. Therefore, utility operators must look at nonregulatory indicator organisms, such as *Legionella*, *Mycobacterium*, and *Aeromonas,* in the distribution system. These microorganisms, including heterotrophic bacteria, are found in the distributed recycled water regardless of the original treatment processes or the presence of total chlorine.

It must be stressed that these findings of water-based pathogens in water distribution systems (reclaimed or potable) is not novel. Many studies have determined that these organisms have an ability to thrive within water piping (e.g., Alonso et al., 2006; Jjemba et al., 2010). The critical information not yet known is whether these organisms can cause disease through human contact with this water. To determine this, a detailed risk assessment must be done. Such a risk assessment would include factors such as pathogen survival outside of the distribution system (after the water is released into the environment) and the exposure (dose) of humans to the pathogen. Dose is a very important piece of information, as a pathogen such as *Legionella* is considered nontoxic at levels below 10^3 CFU/L but dangerous at levels exceeding 10^6 CFU/L (International Energy Agency, 2001). We must stress that, in the absence of a risk assessment, no conclusions regarding public health risk can be drawn from the findings of this study.

An important finding is the possible mitigation of the presence of water-based pathogens within the distribution system by reducing the TOC concentration through treatment and thereby possibly reducing the AOC fraction. Reducing the concentration of TOC can create a nutritionally stressed environment with the target goal of eliminating the nutrients for these water-based pathogens, thereby reducing their presence and concentration in the distributed recycled water. Specific removal of the AOC fraction (via ozone and biological-activated carbon (BAC), for example, or biologically active sand filters) may help mitigate water-based pathogens also.

The application of these findings by a utility is dependent on the uses of recycled water by the customer and the community. If the recycled water is only used for turf irrigation, the fecal indicators may be adequate to use as a measure of quality at the point of entry and within the distribution system. If the recycled water is to be used indoors or as a source for potable reuse, then the microbial quality of the water-based pathogens, along with the fecal pathogens, is critical in determining the quality. In this scenario, fecal indicators such as *E. coli* and *Enterococcus* need to be coupled with a nonfecal indicator to determine the presence of the water-based pathogens for the utility to have the complete picture of the microbial quality. This information will assist in determining the type of treatment methods needed to eliminate waterborne and water-based pathogens in recycled water that is intended for indoor or potable use. Additional studies in this area will assist utilities that are developing potable reuse strategies to better understand the microbial quality and dynamics in recycled water.

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Appendix A

Case Study Questionnaire

WateReuse Research Foundation Project #08-04

Approaches to Maintain Consistently High Quality Recycled Water in Storage and Distribution Systems

Case Study General Questionnaire

Section 1: Utility General Information

1. Utility Name:____

   ____

2. Street Address:____

   City: ______________________State: ______ Zip Code: __________

Section 2: Utility Contact Information

1. Contact Person's Name:______________________________________
2. Title:____
3. Street Address:____

   City: ______________________State: ______ Zip Code: __________

   Phone: _______________ E-mail:_______________________________

4. Does Research Team Have Permission for a Site Visit at the Facility?

   ☐ No ☐ Yes   If Yes, Any Preferred Time: _____________________

Section 3: Utility Recycled Water Production Information

1. Type of Utility:

   ☐ Only Production ☐ Only Distribution ☐ Production & Distribution

2. System Capacity (MGD):__________________________
3. Actual Production Capacity (AF/YR):___________________
4. Influent Water Type *(Check all that apply)*:

☐ Agricultural Return Flow ☐ Storm Water ☐ Municipal Wastewater
☐ Industrial Wastewater ☐ Brackish Water ☐ Poor Quality Groundwater
☐ Other, Please Specify ___________________________________

5. Does the System Include Blending as Part of its Operation? If Yes, Describe Blend Water(s), Reason(s) for Blending, and any Diurnal, Seasonal, or other Blend Considerations ____
____
____
____
____
____
____
____

6. Treatment Technologies *(Check all that apply)*:

Treatment Process	Process Description	Sizes and/or Design Capacities
☐ Pretreatment		
☐ Primary Treatment		
☐ Organics Removal		
☐ Nitrogen Removal		
☐ Phosphorus Removal		
☐ Secondary Solids Removal		
☐ Tertiary Treatment		
☐ Advanced/Membrane		
☐ Disinfection		
☐ Solids Handling		

7. Can You Provide Process Schematic and Site Layout of the Treatment Facility?

☐ No ☐ Yes If Yes, Please Attach to this Questionnaire

8. Any Historical Seasonal Recycled Water Flow Data through the Facility Available?

☐ No ☐ Yes If Yes, Please Attach to this Questionnaire

9. Can You Provide a Copy of the Basis of Design Report for the Treatment Facility?

☐ No ☐ Yes If Yes, Please Attach to this Questionnaire

Section 4: Distribution System Information

1. Total Length of Recycled Water Distribution Pipe (miles): ________________
2. Recycled Water Distribution Pipe Size and Material: ____________________
3. Can You Provide Recycled Water Distribution System Map?

   ☐ No ☐ Yes If Yes, Please Attach to this Questionnaire

4. Can You Provide Recycled Water Distribution System Model, if any?

   ☐ No ☐ Yes If Yes, Please Attach to this Questionnaire

5. Please Specify Typical High & Low System Pressures, Historical Flow Rates and Typical Water Age in the Distribution System ______________________

   ____
   ____
   ____
   ____
   ____
   ____

6. Distribution System Pumping Facilities *(Check all that apply)*:

Pumping Facilities	No. of Pumps	Type of Pumps	Pump Capacity (gpm)	Design Flow (gpm)	Design TDH (ft)
☐ Distribution System Pumping Facilities at the Treatment Facility		☐ Fixed ☐ VFD			
☐ Intermediate Recycled Water Booster Stations		☐ Fixed ☐ VFD			

7. Recycled Water Storage*(Check all that apply)*:

   ☐ None ☐ Aquifer Storage/Recovery for Later Distribution

☐ Covered Storage ☐ Open Storage

☐ Concrete Reservoir ☐ Steel Reservoir

☐ Lined Earthen Reservoir ☐ Unlined Earthen Reservoir

☐ Distribution System Storage

☐ On-Site Storage, Please Specify Type________________________________

☐ Off-Site Storage, Please Specify Type________________________________

☐ Other, Please Specify ____

8. Recycled Water Age at the Storage Facility *(Check all that apply)*:

☐ Not Applicable

☐ Operational (Diurnal) Storage: _____ Hours

☐ Seasonal Storage: _____ Mo ____ Days

- ☐ Short Term Storage: _____ Mo ____ Days
- ☐ Long Term Storage:
  - ☐ Peak Demand: ___ Mo ____ Days, What Time of the Year? _________
  - ☐ Off Peak Demand: ___ Mo ____ Days, What Time of the Year? _______

☐ Other, Please Specify ______________________________

____

____

9. Please Specify Number of Recycled Water Storages, Storage Capacity, Storage Configuration, Materials and Water Age: ________________________________

____

____

____

____

____

____

10. Any Additional Treatment of Recycled Water after Storage before Sending to End Users? ____

____

____

____

____

____

11. Intermediate Cl_2 Boosting:

☐ None

☐ Yes, Locations ____________________________; Residual Cl_2 ________ mg/L

<u>Section 5: Operation, Compliance and Recycled Water Quality</u>

1. Can You Provide Copies of the Recycled Water Treatment, Distribution and End Usage Permits?

☐ No ☐ Yes   If Yes, Please Attach to this Questionnaire

2. Target Recycled Water Quality Goals at the Treatment Facility *(Check all that apply)*:

☐ pH __________ ☐ TSS_____________
☐ TDS __________ ☐ Temperature_______
☐ DO __________ ☐ Turbidity__________
☐ Conductivity_______ ☐ TOC/DOC_________
☐ Cl_2 Residual_______ ☐ Nitrogen species (NO3, NO2, Ammonia, TKN)_____
☐ Alkalinity__________ ☐ HPC (Heterotrophic Plate Count)______________
☐ Coliform__________ ☐ Others, Please Specify _____________________

3. Actual Recycled Water Quality at the Treatment Facility *(Check all that apply)*:

☐ pH __________ ☐ TSS_____________
☐ TDS __________ ☐ Temperature_______
☐ DO __________ ☐ Turbidity__________
☐ Conductivity_______ ☐ TOC/DOC_________
☐ Cl_2 Residual_______ ☐ Nitrogen species (NO3, NO2, Ammonia, TKN)_____
☐ Alkalinity__________ ☐ HPC (Heterotrophic Plate Count)______________
☐ Coliform__________ ☐ Others, Please Specify _____________________

4. Target Recycled Water Quality Goals at End User *(Check all that apply)*:

☐ pH __________ ☐ TSS_____________
☐ TDS __________ ☐ Temperature_______
☐ DO __________ ☐ Turbidity__________

☐ Conductivity_______ ☐ TOC/DOC_________
☐ Cl_2 Residual_______ ☐ Nitrogen species (NO3, NO2, Ammonia, TKN)____
☐ Alkalinity__________ ☐ HPC (Heterotrophic Plate Count)______________
☐ Coliform__________ ☐ Others, Please Specify ____________________

5. Actual Recycled Water Quality at End User *(Check all that apply)*:

☐ pH ___________ ☐ TSS_____________
☐ TDS __________ ☐ Temperature_______
☐ DO ___________ ☐ Turbidity__________
☐ Conductivity_______ ☐ TOC/DOC_________
☐ Cl_2 Residual_______ ☐ Nitrogen species (NO3, NO2, Ammonia, TKN)____
☐ Alkalinity__________ ☐ HPC (Heterotrophic Plate Count)______________
☐ Coliform__________ ☐ Others, Please Specify ____________________

6. Target Recycled Water Quality Goals at Storage Facility *(Check all that apply)*:

☐ pH ___________ ☐ TSS_____________
☐ TDS __________ ☐ Temperature_______
☐ DO ___________ ☐ Turbidity__________
☐ Conductivity_______ ☐ TOC/DOC_________
☐ Cl_2 Residual_______ ☐ Nitrogen species (NO3, NO2, Ammonia, TKN)____
☐ Alkalinity__________ ☐ HPC (Heterotrophic Plate Count)______________
☐ Coliform__________ ☐ Others, Please Specify ____________________

7. Actual Recycled Water Quality at Storage Facility *(Check all that apply)*:

☐ pH ___________ ☐ TSS_____________
☐ TDS __________ ☐ Temperature_______
☐ DO ___________ ☐ Turbidity__________
☐ Conductivity_______ ☐ TOC/DOC_________
☐ Cl_2 Residual_______ ☐ Nitrogen species (NO3, NO2, Ammonia, TKN)____
☐ Alkalinity__________ ☐ HPC (Heterotrophic Plate Count)______________
☐ Coliform__________ ☐ Others, Please Specify ____________________

8. Any Water Quality Issues with Portion(s) of the Distribution System those are Downstream of a Pressure-Reducing Valve? ______________________________

____

____

____

9. Do You Make any Environmental Discharge in Addition to Supplying Recycled Water for End Use? If so, What is that Discharge, Under What Conditions, and with What Water Quality Requirements?

____

____

____

____

____

____

10. Are You Willing to Share Water Quality Data with the Research Team?

☐ No ☐ Yes If Yes, Please Attach to this Questionnaire

11. Do You Monitor Recycled Water Quality Regularly?

☐ No ☐ Yes, Frequency of Monitoring______________________

12. Points of Sample Collection *(Check all that apply)*:

☐ Influent Water ☐ Effluent Water

☐ Distribution System ☐ End User

☐ Storage Tank ☐ Others, Please Specify _________________

13. Do You Monitor Recycled Water For *(Check all that apply)*:

☐ Not Applicable ☐ pH

☐ TDS ☐ TSS

☐ DO ☐ Temperature

☐ Conductivity ☐ Turbidity

☐ Cl_2 Residual ☐ TOC/DOC

☐ Alkalinity ☐ Nitrogen species (NO3, NO2, Ammonia, TKN)

☐ *Aeromonas hydrophila* ☐ HPC (Heterotrophic Plate Count)

☐ Coliform ☐ Others, Please Specify _________________

14. Please Describe Sampling Procedure ______________________________

15. Please Describe Lab Analysis Protocol

16. Any Water Quality Issues or Problems? How it was Addresses/Resolved? Any Short Term or Long Term Solution?

17. If Funding is Available, What would be the Ideal System You Wish to Have?

18. If Funding is Available, What would be the Operator's Wish to Improve Operations?

19. Are You Willing to Collect and Analyze Samples for the Research Team?

☐ No ☐ Yes

20. Is Your Lab Capable of Analyzing the Followings per Attached Protocol?

☐ pH ☐ TDS

☐ TSS ☐ DO

☐ Temperature ☐ Conductivity

☐ Turbidity ☐ Cl_2 Residual

☐ TOC/DOC ☐ Alkalinity

☐ Coliform ☐ Nitrogen species (NO3, NO2, Ammonia, TKN)

☐ *Aeromonas hydrophila* ☐ HPC (Heterotrophic Plate Count)

21. If Your Lab is Not Capable of Analyzing all the Above Parameters, Are You Willing to Collect and Send Samples to the Research Team per Attached Protocol? ☐ No ☐ Yes

22. Any "Best Practice" Implemented to Ensure High Quality Recycled Water?

Section 6: End User Information

1. Please Specify Number & Types of End Users and Recycled Water Requirements for Each ____
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2. Any Seasonal Variation in Usage Pattern? ____________________________
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3. Any Seasonal Variation in Demand Pattern? ____________________________
____
____

4. Any Issues with Water Quality Produced vs End User Expectations? _________

Appendix B

Sampling and Analysis Plan

The research team decided to monitor the distribution system water quality by analyzing monthly grab samples for a period of 4 months from the selected sampling locations. Table B.1 shows the selected parameters and preferred method for analyses to be monitored for distribution system water quality.

Preparation for Field Sampling

The following safety measures and equipment are recommended for field sampling by the research team:

- Safety items
- Vehicle safety cone: ensures vehicle visibility and allows operator to walk around vehicle. (Follow all administrative directives and regulations for safe vehicle operation.)
- Steel-toe safety shoes
- Safety vest
- Safety glasses
- Disposable latex or nitrile gloves
- Drinking water to prevent dehydration
- Hand sanitizer
- Hard hat
- Calibrated field meters
- pH/EC/temperature multimeter
- Chlorine/turbidity meter, with free and total chlorine DPD reagent pillows
- Chlorine analyzer, with free and total chlorine DPD reagent pillows
- Turbidity meter
- Dissolved oxygen meter
- Other required items
- Ice chest with ice
- Sample bottles
- Chain of Custody (CoC) forms
- Field data sheets
- Cell phone
- Telephone lists
- Employee ID and gas card
- Vehicle gas key
- Plastic bucket and hand tools (pliers, screwdrivers)
- Paper towels
- DI water
- Bleach solution
- Flushing hose
- Sun block lotion
- Wire brush

Table B.1. Common Analyses and Methods

Analysis	Type	Method	Bottle Type	Preservative	Holding time	Notes
Aeromonas	micro	EPA 1605	sterile 1-L polypropylene	sodium thiosulfate	30 hours	transport on ice separate from other sample types
E. coli–enzyme substrate coliform test	micro	SM 9223B	125-mL sterile IDEXX	sodium thiosulfate	6 hours	transport on ice separate from other sample types
Total coliform	micro	SM 9222-B	sterile 1-L polypropylene	sodium thiosulfate	6–24 hours	transport on ice separate from other sample types
Fecal coliform	micro	SM 9222-D	sterile 1-L polypropylene	sodium thiosulfate	6–24 hours	transport on ice separate from other sample types
Heterotrophic plate count	micro	SM 9215C	sterile 1-L polypropylene	sodium thiosulfate	24 hours	transport on ice separate from other sample types
Total suspended solids	inorganic	EPA 160.2/ SM 2540D	1-gallon plastic	none	7 days	-
Total dissolved solids	inorganic	EPA 160.1/ SM 2540C	500-mL plastic	none	7 days	-
Alkalinity	inorganic	SM 2320B	500-mL plastic	none	14 days	-
Total organic carbon	organic	SM 5310C	40-mL amber glass	sulfuric acid	28 days	-
Dissolved organic carbon	organic	SM 5310C	125-mL amber glass	none	28 days	-
Ammonia	inorganic	EPA 350.1	125-mL plastic	sulfuric acid	28 days	-
Total Kjeldahl nitrogen	inorganic	EPA 351.2	125-mL plastic	sulfuric acid	28 days	-
Nitrate/nitrite	inorganic	EPA 353.1	125-mL plastic	sulfuric acid	28 days	-

Note: Microbiological sample bottles (polypropylene) are to be filled to the line with ample headspace, using sterile sampling technique. Septum cap vials are to be filled with zero headspace.

Sampling Procedure for Dedicated Taps

The following procedures are recommended:

- Inspect and clean dust or loose debris.
- Place bucket under tap to prevent soil erosion.
- Open tap fully to perform a high volume flush for a minimum of 5 gallons.
- Reduce flow to a pencil-thin stream and flush for 4 minutes.
- Analyze free chlorine with the chlorine analyzer and turbidity with the turbidity meter or both parameters with the chlorine/turbidity meter.
- Measure remaining field parameters: dissolved oxygen, temperature, pH, and conductivity.
- Record field parameter data and CoC information.
- Collect microbiological sample first in 1-L/125-mL sterile, polypropylene bottles, using sterile sampling technique.
- Collect samples for additional parameters. Refer to Table B.1 for list of analyses with corresponding referenced methods, bottle types, preservatives, and additional information.

Sampling Procedure for Nondedicated Taps

The following procedures are recommended:

- Spray hose bib with 250 mg/L chlorine solution.
- Attach flushing hose, if needed, to control erosion and mud.
- Flush with tap wide open for 1 minute and a minimum of 5 gallons. Use a longer flush if necessary to assure representative water from the main.
- Close tap, remove hose from hose bib.
- Spray hose bib again with 250 mg/L chlorine solution.
- Brush hose bib and hose bib threads.
- Spray hose bib threads generously to rinse off any dislodged particles.
- Open tap wide open for a minimum of 5 seconds.
- Reduce flow to a solid pencil stream for sampling (estimated 0.8 to 1.5 gpm).
- Analyze free chlorine with the chlorine analyzer and turbidity with the turbidity meter or both parameters with the chlorine/turbidity meter.
- Measure remaining field parameters: dissolved oxygen, temperature, pH, and conductivity.
- Record field parameter data and CoC information.
- Collect microbiological sample first in 1-L/125-mL sterile, polypropylene bottles, using sterile sampling technique.
- Collect samples for additional parameters. Refer to Table B.1 for list of analyses with corresponding referenced methods, bottle types, preservatives, and additional information.

Sterile Technique Microbiological Sampling

The following procedures are recommended:

- Perform required flushing of sampling location to ensure representative sample.
- Collect microbiological sample bottles first, before other types.
- Open the sealed sample bottle cap, being careful to not touch the lip of the bottle or the threads of the lid to the tap or with your hands.
- The bottle contains sodium thiosulfate preservative; do not rinse the bottle.
- Do not allow water to splash into the lid.
- To fill, tilt the bottle at about a 45^{o} angle into the stream.
- Fill bottle to the line with ample headspace.
- Screw the cap on tightly and record sample information on label.
- Place microbiological sample bottles in a separate ice chest from other environmental samples.
- Microbiological samples are transported on ice under darkened conditions, and have a holding time of 6 to 30 hours (see Table B.1).

Practical Solutions for Water Scarcity




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