Final Report

STATE OF TECHNOLOGY OF WATER REUSE

Prepared For:
Texas Water Development Board
P.O. Box 13231, Capitol Station
Austin, Texas 78711-3231

TEXAS WATER DEVELOPMENT BOARD

STATE OF TEXAS
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8/31/10

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August 2010

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... because water is precious

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In addition to her significant technical contribution, Margaret Nellor also assisted in the coordination, editing and revisions of the document.

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Table of Contents

List of Figures

List of Tables

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1. Executive Summary

Texas has a long history of successful planned water reuse projects dating back, in some cases, several decades. More recently, as a result of the Texas Water Development Board state water planning process and the increased difficulty and expense of developing new surface or groundwater supplies, water reuse has become a significant water management strategy for many entities throughout the state. The purpose of this document is to review the state of technology associated with implementation of water reuse projects. The review covers the following general topics:

- The types of beneficial uses of reclaimed water;
- Water quality requirements for beneficial uses of reclaimed water and some of the anticipated challenges to meet those requirements;
- Source control approaches to prevent undesirable chemicals or concentrations of chemicals from entering a wastewater management system;
- Treatment technologies for the production of safe, reliable reclaimed water that address pathogens, nutrients, trace metals, salts, and organic chemicals, including priority pollutants, pharmaceuticals, endocrine disrupting chemicals, and ingredients in personal care products;
- Water quality monitoring of reclaimed water to insure that public health and the environment are protected;
- Approaches for assessing human health effects and related studies of using reclaimed water for potable reuse;
- Ecological issues that are being evaluated related to the presence of endocrine disrupting chemicals;
- The inter-relationship between energy and water and the use of reclaimed water;
- Public acceptance and outreach models for use of reclaimed water;
- The multiple barrier approach for potable reuse;
- Technology gaps and future needs;
- Ongoing water reuse research programs; and
- Case studies of exemplary water reuse projects to illustrate the application of many of the technologies and approaches discussed.

This document not only provides a valuable reference for entities and individuals interested in obtaining detailed information on topics related to water reuse, but also illustrates the wide range and significant volume of research that has been focused on water reuse in recent years. Continued support of this research is critical to further advancement of water reuse as a water management strategy in Texas, the United States and internationally.

2. Introduction

The importance of efficiently using existing water supplies is becoming increasingly evident as populations continue to grow and sources of new supply become more difficult to acquire. Water reuse, the practice of taking water that has already been used and using it again for a beneficial purpose, is a key component of water supply efficiency. Typically this practice uses reclaimed water (or reclaimed wastewater), which is domestic or municipal wastewater which has been treated to a quality that makes it suitable for a beneficial use.

The Texas Water Development Board, through the project "Advancing Water Reuse in Texas," has committed to developing a series of documents to record the history of reuse in Texas, summarizing the state of technology with respect to water reuse, and developing an agenda of priority research needs that will help to advance the implementation of water reuse projects included in the state Water Plan. This document comprises the second in this series.

2.1. Purpose of document

The purpose of this document is to review the state of technology associated with implementation of water reuse projects. The primary topics to be addressed include:

- Identification of beneficial uses
- Water quality issues and associated regulatory requirements
- Source control (from industrial sources discharging to wastewater treatment systems)
- Treatment technologies
- Monitoring
- Human health issues
- Ecological issues
- Energy and sustainability issues
- Public acceptance and outreach
- Multiple barriers for potable reuse
- Ongoing water reuse research

In addition, case studies of exemplary projects are presented to illustrate the application of many of the technologies and approaches discussed.

2.2. Background

The Texas Water Development Board was created in 1957 by action of the state legislature to oversee the creation of plans to conserve and develop the water resources of Texas. This action came after a particularly devastating drought struck the state in the early to mid 1950s. The importance of water reuse was recognized early by west Texas communities as treated wastewater became an established source of water for irrigation and industrial process needs. While reuse was prominently identified in early Texas water plan documents, it stayed primarily in the background until after the year 2000 when rapid population growth, reservoir build-out, and drought conditions again placed focus on more efficient use of a limited available supply.

2.3. Importance of water reuse for Texas

In Texas and elsewhere, the availability of water is dictated by climate, geography, and geology. Eastern Texas benefits from substantial regular rainfall that keeps rivers and streams running and aquifers replenished. Central Texas depends on both groundwater and surface water to supply its needs. Reservoir construction has harnessed an extremely variable rainfall source, providing storage to sustain the supply during times of drought. The minimal rainfall in western Texas has led to almost exclusive dependence on groundwater wells for its water supply.

Increasing demands from a rapidly growing population are putting a severe strain on these historical water sources. Groundwater in many areas is being withdrawn at rates that cannot be naturally replenished, and sites for new reservoirs are becoming increasingly difficult to acquire. Ground subsidence from groundwater over-harvesting in the Houston area is increasing the potential for flooding. Water reuse is one of the tools available to increase water use efficiency by reclaiming growing supplies of highly treated wastewater.

2.4. Water reuse in current Texas Water Plan

Water for Texas 2007, the most recent statewide plan published by the Texas Water Development Board, summarizes expectations for growth of water reuse in Texas (TWDB, 2007). Water reuse from current permits and existing infrastructure is expected to grow slightly from 359,117 acre-feet per year (320 million gallons per day) in 2010 to 372,120 acre-feet per year (332 million gallons per day) by 2060. With the addition of new water management strategies to existing supplies, water volumes available from reuse are projected to be 800,000 acre-feet per year (714 million gallons per day) in 2010 and increase to 1,630,000 acre-feet per year (1,455 million gallons per day) by 2060. A majority of the water supply attributed to water reuse involves indirect potable reuse projects. Successful implementation of water reuse projects will depend on using sound science and appropriate technology, which can be justified and defended to the citizens they serve.

2.5. Overview of key technology issues

Many of the key technology areas related to water reuse focus on ensuring adequate water quality for the intended beneficial use of the water. Protection of human health and the environment is a primary goal of technology development related to water quality. Other key issues relate to energy usage, sustainability and public perception and are highlighted below.

- *Identification of constituents of concern for the intended uses of the reclaimed water and associated regulatory requirements.* Many constituents are known to have potential human health-related and/or ecological-related impacts and are currently regulated. However, there is a growing list of "constituents of emerging concern," many being detected at very low levels, for which potential impacts on human health and the environment are less understood. The extent to which these constituents need to be addressed and regulated and how their presence in reclaimed water impacts public perception and treatment/energy requirements is currently a key area of focus in the water reuse community.

- *Source water control.* Contaminants discharged to wastewater management systems from industries and businesses can often be controlled by implementing and policing an effective pretreatment program. Using appropriate technology to capture contaminants, such as toxic metals, at their industrial source can be a cost effective and efficient method of keeping these constituents out of the reclaimed water supply. Source control can also include programs that minimize the commercial use of constituents of concern or otherwise reduce their introduction into industrial waste streams or that seek less troublesome substitutes for constituents of concern. For example, "drug take-back" programs seek to reduce the introduction of pharmaceutical products into the wastewater systems.

- *Treatment technologies.* Application of the appropriate treatment technologies for the production of safe, reliable reclaimed water is one of the keys to operating any water reuse system. Appropriate treatment technology will depend on the intended use of the water, the associated water quality requirements and goals, and the cost of implementation.

- *Ecological impacts.* Water reuse, particularly surface water augmentation, has the potential to impact ecosystems. However, ecological impacts comprise a broader issue that will ultimately have to be addressed by all wastewater dischargers, regardless of whether reuse is practiced.

- *Monitoring*. A key component of ensuring a safe water source is a reliable monitoring program to confirm that constituents of concern are maintained within acceptable limits and environmental and health impacts are controlled.

- *Energy and sustainability*. Water and energy have a very intertwined relationship, which is becoming more evident as both resources become increasingly scarce. Implementation of water reuse projects can be energy-efficient, particularly in cases where reclaimed water does not require the application of advanced treatment and the source of reclaimed water is relatively close to the intended use. Furthermore, it may be easier and less expensive to remove contaminants associated with wastewater prior to discharge when they are present at higher concentrations, than to remove more diluted contaminants from source water during drinking water treatment. However, many treatment technologies used for water reuse projects, such as reverse osmosis or other membrane processes, are very energy-intensive and have requirements for disposal of concentrated treatment byproducts. Development of sustainable energy-efficient technologies and linking the appropriate technology to the desired quality of reclaimed water will be key elements of advancing the implementation of water reuse projects.

- *Public acceptance and outreach.* Where public contact with reclaimed supplies is expected, an information program is needed to raise public awareness. While health and safety are key elements of public education, promoting the understanding that water reuse is part of the overall water cycle and helps to improve the efficiency and sustainability of our current use of water supplies is also extremely important. In many communities, the public is not well informed about the sources of their water supply and their limitations, so a public awareness program can be used to improve the public's overall understanding of the water cycle in general; namely, that all water is reused in the environment, either intentionally or unintentionally and its implications for their community specifically. A public awareness program also provides an opportunity to call attention to the fact that people can have an impact on water quality by controlling their use of household chemicals including herbicides and pesticides and disposing of pharmaceuticals through means other than the sanitary sewer.

3. Beneficial uses of reclaimed water

Texas law defines the beneficial use of reclaimed water to be the economic use of domestic or municipal wastewater, which has been treated to a suitable quality for a specific use that takes the place of potable and/or raw water that would otherwise be needed from another source.[1] The Texas Water Plan (TWDB, 2007) identifies two types of water reuse: 1) direct reuse and 2) indirect reuse. Direct reuse is the use of reclaimed water that is piped directly from the wastewater treatment plant to the place where it is used. Indirect reuse is the use of reclaimed water that is placed back into a river or stream and then diverted further downstream to be used again. Within these two broad categories of water reuse there are a number of specific non-potable and potable uses that can be applied. Potable reuse refers to the planned use of reclaimed water to augment drinking water supplies while non-potable reuse refers to the planned use of reclaimed water for purposes other than to augment drinking water supplies.

3.1. Types of uses

The general categories of non-potable reuse that are practiced in the United States are: 1) urban irrigation and non-irrigation uses; 2) industrial uses; 3) agricultural uses; 4) environmental and recreational uses; and 5) other non-potable uses. Some states allow reclaimed water to be used for potable reuse via water supply augmentation of groundwater and surface water. Each type of use is generally reliant on specified water quality requirements that are based on protection of public health and the environment. Typically, requirements are structured so that the higher the degree of potential public contact or the potential for environmental degradation, the more stringent the applicable requirements will be. A summary of the different types of uses is presented in Table 1 and discussed in the following sections. Specific case studies are presented in Section 15.

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[1] See Texas Administrative Code, Title 30, Section 210.3

Table 1. Beneficial uses of reclaimed water

General Category	Applications
Non-potable urban irrigation	Cemeteries Golf courses Greenbelts Industrial parks Public parks School yards Residential and other lawns Roadway medians and plantings
Other non-potable urban uses	Air conditioning cooling water Commercial car wash Commercial laundries Decorative fountains and water features Driveway and tennis court washdown Fire protection Sewer flushing Snow melting Toilet and urinal flushing
Industrial	Boiler feedwater Cooling water Equipment washdown Fire protection Heavy construction (dust control, concrete curing, fill compaction, and clean-up) Process water
Agricultural irrigation	Commercial nurseries Food, fiber, fodder, and seed crops Frost protection Silviculture Sod farms
Recreation and environmental uses	Artificial lakes and ponds Fisheries Snowmaking Stream flow augmentation Wetlands enhancement
Groundwater subsidence credits	
Indirect potable reuse	Barriers against brackish or seawater intrusion Groundwater replenishment Surface water augmentation
Direct potable reuse	Blending with treated drinking water

(Source: Metcalf & Eddy, 2007)

3.1.1. Urban

Urban opportunities for water reuse are varied and are subject to a range of water quality requirements as discussed in Section 4. In Texas, regulations allow for reclaimed water to be piped directly to sites where it can be used for:

- Residential irrigation, including landscape irrigation at individual homes;
- Irrigation of public parks, golf courses, school yards, athletic fields, cemeteries, and freeway medians;
- Water impoundments provided for storage or scenic value;
- Fire protection in internal sprinklers or external fire hydrants;
- Toilet or urinal flush water; and
- Maintaining ponds for recreational activities.

Figure 1. Waterchase Golf Course, Fort Worth, TX; irrigated with reclaimed water. (Source: City of Fort Worth)

Many urban uses are seasonal or event specific, such as landscape irrigation and fire protection, and thus do not utilize reclaimed water at a constant rate throughout the year.

Water quality requirements and operational controls placed on landscape irrigation projects generally differ based on the area being irrigated, its location relative to populated areas, and the extent of public access or use, such as contact with the water or ingestion of soil or turf (particularly by children). Landscape irrigation frequently occurs in areas where unrestricted public access can occur, and thus treatment and use area restrictions are required to minimize exposure to microbial pathogens in reclaimed water. This issue becomes less important in areas with limited or no public access. For some types of urban irrigation, there may be requirements for tolerable levels of dissolved ions to protect the irrigated plants or turf.

More recently, reclaimed water irrigation uses have received additional scrutiny with regard to potential degradation of underlying groundwater by salts and nutrients. In addition, concerns have been raised about chemicals of emerging concern, such as pharmaceuticals, ingredients in personal care products, and endocrine disrupting compounds, and in reclaimed water used for irrigation that might migrate to groundwater underlying irrigation sites or accumulate in soil or turf.

3.1.2. Industrial

Industrial uses of reclaimed water include both cooling water and process water, such as pulp and paper manufacturing, chemical manufacturing, textile production, and petroleum and coal development/production. Texas regulations currently authorize the use of reclaimed water for cooling tower makeup water. Specific water quality requirements will vary by industrial application, with some processes necessitating the application of additional treatment technologies to match exact water quality needs. For example, some industrial processes within the electronics industry will require water of nearly distilled purity that can be supplied with reclaimed water treated using membrane filtration, while a paper manufacturer may establish specific color requirements. Because industries tend to use reclaimed water at a constant rate through the year, they provide good opportunities for year-round use of reclaimed water.

While water quality requirements and treatment will be industry specific, use of reclaimed water for cooling is a significant use where total dissolved solids, hardness, ammonia, silica, and dissolved oxygen are specific concerns due to scaling or corrosion in pipes or heat exchangers. Residual organic matter and nutrients may contribute to biological growth in heat exchangers and cooling towers. Microorganisms can also induce corrosion or fouling and can present a potential health risk to employees.

3.1.3. Agricultural

Similar to urban reuse, direct agricultural reuse opportunities are also dictated by water quality requirements. Texas regulations allow for reclaimed water to be used for:

- Irrigation of food crops;
- Irrigation of pastures;
- Irrigation of sod farms;
- Irrigation of feed crops; and
- Silviculture.

The major human health concern associated with using reclaimed water for agricultural irrigation is the potential for food crop contamination by microbial pathogens, particularly for foods eaten raw. Pathogens can survive on plants and in soil for extended periods of time. Thus, if reclaimed water is used for food crops not treated to destroy pathogens, the crops should be commercially processed in a manner that will destroy pathogens prior to being distributed for human consumption. Water salinity, particularly chloride and sodium concentration, is another important factor in determining whether reclaimed water can be used for agricultural irrigation. As salinity increases in irrigation water, the probability for certain soil, water, and cropping problems increases (Ayres and Westcott, 1976) unless irrigation water is properly applied and managed (also see Section 6.1.4). Plants tend to vary widely with respect to their tolerance to salinity, and provision of adequate soil drainage and irrigation management practices will help alleviate potential problems associated with the salinity of irrigation water. As with urban irrigation uses, the use of reclaimed water for agricultural irrigation has recently received additional scrutiny with regard to potential degradation of underlying groundwater by salts and nutrients. The uptake of organic chemicals through roots or foliage has been raised as a potential issue. Nasir and Batareh (2008) found that plants irrigated with wastewater had different uptakes and translocation behavior for polynuclear aromatic hydrocarbons, polychlorinated biphenyls, chlorinated benzenes, and phenols. These chemicals may be present in reclaimed water depending on the raw wastewater source, type of treatment, and sensitivity of the method used to analyze samples. They can be of health concern at very low concentrations (such as parts per billion or lower). Most are man-made chemicals that are subject to source control (see Section 5) or product bans, with the exception of polynuclear aromatic hydrocarbons, which are formed during incomplete combustion of coal, oil, gas, wood, garbage, or other organic substances. Herklotz et al. (2010) looked at the potential uptake and accumulation of four human pharmaceuticals in cabbage and Wisconsin Fast Plants and found that the pharmaceuticals were detected in the roots and leaves of the plants. Additional information on the significance of pharmaceuticals in reclaimed water is discussed in Section 8.6. Weber et al. (2006) conducted a hypothetical modeling assessment on the risks of chloroform, pyrene, and 1,1,2-trichloroethane via uptake through food grown in irrigated soil. The results showed that for these compounds the resulting health risk was acceptable ranging from 10^{-6} to 10^{-7} for each compound.

3.1.4. Environmental and recreational

Environmental reuse includes applications such as wetlands enhancement and restoration, the creation of wetlands for wildlife habitat and refuges, and stream augmentation to enhance aquatic and wildlife habitat as well as to maintain the aesthetic value of water courses. Recreational applications can include a broad range of landscape impoundments from water hazards on golf courses to large recreational impoundments that can be used for fishing, boating, swimming, or wading. In cases where the augmentation or enhancement is accomplished via a direct discharge of treated wastewater to a water body considered to be a "water of the United States," the requirements imposed will be based on meeting state water quality standards. Water quality standards are defined to consist of the designated uses for the water body and the applicable water quality criteria, which can be both numeric and narrative. Water quality requirements applied to a project will also vary depending on the degree of contact for recreation (such as full body or partial body contact), the type of wildlife being protected, and the potential for a pollutant to bioaccumulate in fish tissue. Some reuse systems incorporate constructed wetlands to polish treated effluent for discharge into waters used for potable supplies. These systems not only provide treatment to remove residual nutrients and pathogens, they also provide habitat to support wildlife and natural plant populations and associated recreational opportunities for the human population.

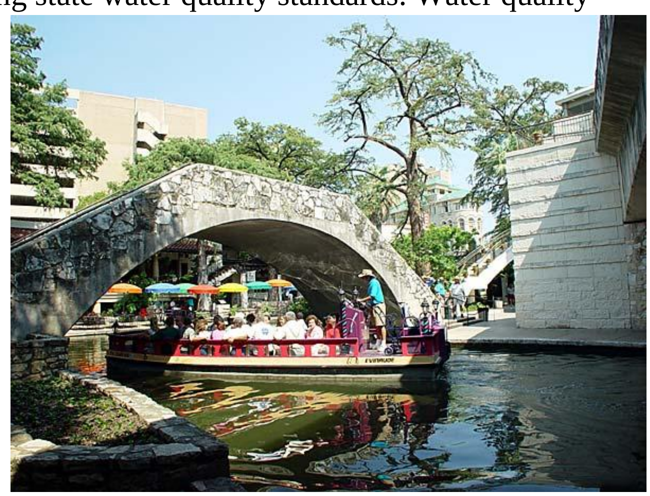

Figure 2. Reclaimed water use in San Antonio, Texas (Source: photohome.com)

Texas regulations authorize the use of reclaimed water for maintenance of recreational impoundments or natural water bodies where wading or fishing takes place as well as impoundments or natural water bodies with no direct human contact.

More recently, concerns have been raised about the use of reclaimed water for environmental and recreational uses due to the potential human and ecological health effects of constituents of emerging concern found in reclaimed water. One key example is feminization of fish, which has received significant media attention. This issue regarding potential ecological effects is not unique to reclaimed water. Constituents of emerging concern can be found in all surface waters, wastewater, and reclaimed water if the number of analytes is large enough and the analytical detection limits are low enough. Additional information on this topic is presented in Sections 6 and 9.

3.1.5. Other non-potable urban uses

There are a variety of other non-potable uses of reclaimed water that do not fit exactly into the first four categories. For example, Texas regulations allow for reclaimed water to be used for soil compaction and dust control. Other possible uses include:

- Ornamental nurseries;
- Decorative fountains;
- Consolidation of backfill material around pipelines;
- Mixing concrete;
- Cleaning roads, sidewalks, and outdoor work areas;
- Flushing sanitary sewers;
- Commercial laundries;
- Commercial car washes;
- Snow making; and
- Equipment washing.

Water quality requirements for these uses tend to focus on control of pathogens.

3.1.6. Groundwater subsidence credits

In Texas, it may be possible to use reclaimed water to obtain groundwater subsidence credits. State regulations allow subsidence districts to control groundwater withdrawals. For example, Fort Bend Subsidence District developed a groundwater reduction plan that requires all public water suppliers to decrease groundwater withdrawals by 30 percent by 2013 and 60 percent by 2025. For this example, each user must identify a method of meeting this goal to avoid paying a disincentive fee. Some users are considering the use of reclaimed water as an option, with the incentive for conversion linked to obtaining a subsidence credit that is established by the applicable regional subsidence district (Vandertulip and Shepard, 2006).

3.1.7. Potable supply augmentation via indirect potable reuse

Reclaimed water can also be used to augment potable water supplies. Indirect potable reuse is the planned augmentation of a drinking water source with reclaimed water with an environmental buffer. Environmental buffers include assimilation/blending of the reclaimed water with the surface water or groundwater that is being augmented, natural attenuation that can occur as reclaimed water percolates through soil (for groundwater recharge) or *in situ*, and time for attenuation to occur as reclaimed water is stored (underground or in surface reservoirs) prior to use. In contrast, many communities take water from rivers or other surface waters that receive wastewater discharges. Other communities use groundwater influenced by land disposal of wastewater or septage. The practice of diverting raw water supplies downstream of wastewater discharges is often called incidental or unplanned potable reuse.

Examples of indirect reuse projects include managed aquifer recharge and supplementing water supply reservoirs. There are a number of specific uses of reclaimed water for managed aquifer recharge including:

- Augmenting potable or non-potable supply aquifers;
- Creating barriers against brackish or sea water intrusion ;
- Providing storage of reclaimed water for subsequent retrieval and reuse; and
- Controlling or preventing ground subsidence.

Managed aquifer recharge can be accomplished by surface application of reclaimed water, such as the use of spreading or percolation basins, or by sub-surface application such as injection wells or dry wells. Infiltration and percolation of reclaimed water provides additional polishing via physical, chemical, and biological treatment that occurs as the reclaimed water moves from the surface to the underlying aquifers (soil aquifer treatment). Additional attenuation may occur as the water moves through the aquifer system.

Surface augmentation of potable supplies with reclaimed water can be accomplished using different treatment schemes ranging from membrane separation and disinfection to wetland polishing. These projects use environmental buffers (blending, natural attenuation, and time of storage) to provide additional barriers.

In the United States, planned indirect potable reuse has been practiced for more than 50 years. Drewes and Khan (in press) have summarized a number of the various indirect potable reuse projects that have been implemented in the United States and abroad, as shown in Table 2. Specific case studies are presented in Section 15.

Table 2. Summary of indirect potable reuse projects

Project / location	Type of indirect Reuse	Reclaimed water use (mgd)[a]	Start-up date	Current status
Montebello Forebay Groundwater Recharge Project, Los Angeles County, CA	Groundwater recharge via surface spreading basins	44	1962	Ongoing
Upper Occoquan Service Authority, VA	Surface water augmentation	54	1978	Ongoing
Water Factory 21, Orange County, CA	Seawater barrier via direct injection	16	1976	Terminated 2004
Hueco Bolson Recharge Project, El Paso, TX	Groundwater recharge via direct injection	10	1985	Ongoing
Clayton County Water Authority, GA	Surface water augmentation	17.5	1985	Ongoing
West Coast Basin Barrier Project, Los Angeles County, CA	Seawater barrier via direct injection	12.5	1993	Ongoing
Gwinnett County, GA	Surface water augmentation	48	1999	Ongoing
Scottsdale Water Campus, AZ	Groundwater recharge via direct injection	14	1999	Ongoing
Toreele Reuse Plant, Wulpen, Belgium	Groundwater recharge via infiltration ponds	1.8	2002	Ongoing
NEWater, Bedok, Singapore	Surface water augmentation	8.5	2003	Ongoing
NEWater, Seletar, Singapore	Surface water augmentation	6.4	2003	Ongoing
Essex & Suffolk Water Langford Recycling Scheme, United Kingdom	Surface Water Augmentation	10.6	2003	Ongoing
Alamitios Barrier Project, Los Angeles, CA	Seawater barrier via direct injection	3	2005	Ongoing
Chino Basin Groundwater Recharge Project, San Bernardino County, CA	Groundwater recharge via surface spreading basins	18	2005	Ongoing
Dominguez Gap Barrier Project, Los Angeles, CA	Seawater barrier via direct injection	5	2006	Ongoing
NEWater, Ulu Pandan, Singapore	Surface water augmentation	32	2007	Ongoing
Groundwater Replenishment System, Orange County, CA	Groundwater recharge via direct injection and spreading basins	70	2008	Ongoing
Western Corridor Project, Southeast Queensland, Australia	Surface water augmentation into drinking water reservoir	62	2008	Ongoing

Project / location	Type of indirect Reuse	Reclaimed water use (mgd)[a]	Start-up date	Current status
Loudoun County Sanitation Authority, VA	Surface water augmentation	11	2008	Ongoing
Arapahoe County/Cottonwood, CO	Groundwater recharge via surface spreading	9	2009	Ongoing
Prairie Waters Project, Aurora, CO	Groundwater recharge via riverbank filtration	50	2010	Ongoing

(Source: Drewes and Khan, in press, with some additions and updates)

a. Million gallons per day (mgd).

Health and regulatory issues for potable reuse projects are typically more complex than those encountered in non-potable reuse projects and take into consideration both acute and chronic effects related to pathogens and trace constituents. Indirect potable reuse projects that utilize a water of the United States for surface augmentation or managed aquifer recharge will also need to protect the designated uses of those water bodies and any applicable water quality criteria, as well as comply with any anti-degradation policies for surface water and/or groundwater. Although there are examples of this practice in the state, Texas regulations have not been established for the use of reclaimed water for potable supply augmentation. Information on applicable water reuse regulations is presented in Section 4.

In 1998, the National Research Council released a review of the viability of augmenting drinking water with reclaimed water (NRC, 1998). Specific concerns that were identified include the following:

- Disinfecting reclaimed water may create different and often unidentified disinfection byproducts than those found in conventional water supplies;
- Only a small percentage of the organic compounds in drinking water have been identified, and the health effects of only a few of these have been determined;
- The health effects of mixtures of two or more of the hundreds of compounds in any reclaimed water used for potable purposes are not easily characterized; and
- The whole process relies on technology and management.

While these issues are not insurmountable, they illustrate the need to acknowledge that complex health and regulatory issues related to public health, water quality, and environmental protection must be evaluated and accommodated in potable reuse projects. Many of these concerns are common to drinking water and thus are not unique to reclaimed water. The National Research Council is currently conducting a study that is evaluating the role of reclaimed water in addressing future water demands, including an updated review of non-potable and potable reuse. The report will be available in 2011.

3.1.8. Direct potable reuse

Direct potable reuse is typically defined as the introduction of reclaimed water either directly into the potable water system downstream of a water treatment plant or into the raw water supply immediately upstream of a water treatment plant (Metcalf & Eddy, 2007). Other than one case in the 1950's in Chanute Kansas during an emergency drought (Metzler et al., 1958), this practice has not been adopted by or approved for any water system in the United States. The only existing project in the world, which started in 1968, is located in Windhoek, Namibia. The impetus for the Windhoek project was the region's limited water availability due to climate. The project provides 35 percent of the Windhoek drinking water supply by adding highly treated reclaimed water directly into the water distribution network. Windhoek has managed to overcome public perception with positive and proactive marketing.

Beginning in 2009, a number of activities have been initiated related to the potential for direct reuse in the United States based on the premise that technology has advanced to the point that direct reuse may be a safe and cost effective option to pursue. The WateReuse Association and WateReuse California are investigating the feasibility of direct potable reuse. The California Urban Water Agencies, National Water Research Institute, and WateReuse California held a two-day workshop on April 26-27, 2010, involving technical experts, regulators (including the California State Water Resources Control Board and the California Department of Public Health), and other policy makers to identify information gaps that need to be filled related to the development of regulations for direct potable reuse. Discussion by workshop participants was be informed by two white papers that were presented at the workshop. The first, sponsored by the National Water Research Institute, focused on regulatory issues and public health (Crook, 2010). The other white paper was sponsored by WateReuse California and focused on public and political acceptance of direct reuse in California (Nellor and Millan, 2010). Discussions at the workshop addressed these topic areas: treatment, water quality management, monitoring, regulations, risk assessment, and public acceptance. The participants developed a set of highest priority issues and action items that will be assembled by WateReuse California for later review by the workshop participants. This information will be turned into a work plan that will address each issue, possible funding sources, and timing for implementation.

Direct reuse faces a number of challenges related to public acceptance, regulatory acceptance, and public health concerns, and technology, which are summarized in Table 3.

Table 3. Challenges to direct potable reuse

Categories	Challenges
Public acceptance	Educational and psychological obstacles
	Perception of unclean source water
	Loss of environmental/psychological barrier
	Trust of technology/utilities/government
	Acceptance issues associated with faith
	Terminology
	Leadership
Regulatory acceptance / public health concerns	Lack of established regulations
	Process performance/quality
	Public health concerns
	Reliability – risk of failure
	Loss of environmental barrier
	Loss of time to respond to problems

Categories	Challenges
Technology	Process reliability Disposal of treatment residuals Corrosion control Real time monitoring

(Sources: Dishman et al., 1989; WateReuse California, 2009.)

4. Water quality requirements by use

Most reuse programs operate within a framework of regulations that must be addressed in planning and implementing projects. Because of differing environmental conditions from region to region across the country, and since different end uses of the reclaimed water require different levels of treatment, universal water quality, treatment, and operational standards do not exist for reclaimed water.

4.1. Federal regulations and guidelines

Currently, water reuse in the United States is governed by individual state regulations and guidelines as there are no national regulations or guidance in place. In this context, regulations (or criteria) refer to enforceable rules adopted by federal agencies or states, while guidance (or guidelines) refer to non-enforceable advice or recommended actions by federal agencies or states.

The U.S. Environmental Protection Agency published guidelines in 1992 and 2004 (U.S. EPA, 2004). The guidelines are currently in the process of being updated. The 2004 guidelines include chapters on the different types of reuse applications, technical issues is planning water reuse systems, legal and institutional issues, funding, public involvement programs, and water reuse outside of the United States. The guidelines also present and summarize state water reuse regulations and guidance, with supporting information, for the benefit of utilities and regulatory agencies. The document is intended to be solely informational and does not impose legally-binding requirements on the U.S. Environmental Protection Agency, states, local or tribal governments, or members of the public.

4.1.1. Clean Water Act

A water reuse project that involves a discharge to a water of the United States must comply with federal and state requirements pursuant to the Clean Water Act and applicable state law. These include technology based requirements (for secondary treatment) and compliance with the state's water quality standards. Water quality standards consist of designated uses of surface water bodies (such as recreation, drinking water supply, and wildlife habitat) and the applicable water quality criteria to protect the uses. The U.S. Environmental Protection Agency establishes recommended numeric water quality criteria for protection of human health via 1) recreation, 2) drinking water and eating fish, and 3) for eating fish; and for protection of aquatic life. The criteria for protection of human health (by ingestion of water and fish and ingestion of fish) are based on a cancer risk of 10^{-6} and take into account bioaccumulation of chemicals in fish tissue

(U.S. EPA, 2009a). A cancer risk of 10^{-6} (or 1 in a million) implies a likelihood that up to one person, out of one million equally exposed people would contract cancer if exposed to a contaminant at a specific concentration over 70 years (an assumed lifetime). The U.S. Environmental Protection Agency numeric water quality criteria do not take cost or technical achievability into consideration. States can adopt these criteria or more stringent criteria into their own standards, and have an obligation to review and update them every three years during what is known as the triennial review process. States adopt both numeric and narrative criteria, which are typically established for bacterial indicators, priority pollutants, minerals, toxicity, and nutrients. For drinking water uses, the state criteria typically include drinking water standards and numeric criteria for priority pollutants. Water quality standards also include anti-degradation provisions for surface waters whereby states adopt policies to prevent the deterioration of existing levels of water quality or protection of “high quality” waters.

There are cases where Clean Water Act requirements can be more stringent than federal drinking water standards. The key is how the water body is designated. For example, water quality criteria for priority pollutants in California were adopted in the California Toxics Rule strictly based on the U.S. Environmental Protection Agency’s recommended criteria. The California criteria for protection of human health for the trihalomethanes consist of specific criterion for dichlorobromomethane, chlorodibromomethane, and bromoform. For chloroform, the U.S. Environmental Protection Agency elected to reserve its decision on numeric criteria for chloroform and therefore did promulgate chloroform criteria in the final rule.[2] The sum of the three trihalomethane criteria is 5.26 µg/L. In cases where reclaimed water is discharged to a drinking water supply, such as a surface augmentation project, a limit for each of the trihalomethanes could potentially be included in the permit for such projects if there is reasonable potential to exceed the criteria. This Clean Water Act-based requirement is considerably more stringent than the current total trihalomethane drinking water maximum contaminant level of 80 µg/L. For Texas, the most stringent surface water criterion for total trihalomethanes for protection of human health is currently 100 µg/L; however as part of the ongoing triennial review, the Texas Commission on Environmental Quality is proposing that the criterion be set at 80 µg/L.

Another example where Clean Water Act-based requirements can be more stringent than drinking water standards is N-nitrosodimethylamine. The California Toxics Rule water quality criterion for protection of human health is 0.00069 µg/L. There is no drinking water standard for N-nitrosodimethylamine; however the California Department of Public Health has adopted an advisory Notification Level of 0.01 µg/L, which has been used to establish the treatment performance levels in the draft groundwater recharge regulations discussed in Section 4.2.1. In cases where reclaimed water is discharged to a drinking water supply, such as a surface augmentation project, a limit of 0.00069 µg/L for N-nitrosodimethylamine could potentially be included in the permits based on the water quality criterion established at the 10^{-6} risk level if there is reasonable potential to exceed the criterion. In contrast, the current and proposed Texas

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[2] The 2009 U.S. Environmental Protection Agency’s recommended water quality criteria for the trihalomethanes for protection of human health have been updated for consideration by states for inclusion in water quality standards. The criteria are: 5.7 µg/L for chloroform, 4.3 µg/L for bromoform, 0.4 µg/L for chlordibromomethane, and 0.55 µg/L for dichlorobromomethane (U.S. EPA, 2009a).

water quality standards do not currently include a criterion for N-nitrosodimethylamine for protection of public health.[3]

For indirect potable reuse projects facing these types of requirements, it may be possible to obtain a dilution credit for the determination of an effluent limitation; however, it would depend on the water body and approval by the state. It may also be possible to obtain a site-specific objective or variance from the criterion. An indirect potable reuse project would have to consider how these regulatory "off-ramps" would impact public acceptance of the project.

One area that is in transition and that could impact a reuse project that uses a water of the United States relates to nutrients and integration of treatment to remove nutrients. The first issue is ammonia. The U.S. Environmental Protection Agency has developed recommended water quality criteria that are pH and temperature dependent, and have been adopted by most states. However, it is likely that ammonia criteria will become more stringent over time. The U.S. Environmental Protection Agency has recently released draft recommended national criteria for ammonia that are more stringent than the existing criteria. The proposed criteria now provide for protection of freshwater mussels. The net result is that if freshwater mussels are present (or have the potential to be present) in a water body, the applicable ammonia criteria are more stringent. For example, at pH 8 and a temperature of 25° centigrade, the chronic criterion for protection when mussels are present is 0.26 mg/L in comparison to 1.8 mg/L when mussels are absent.

With regard to other nutrient regulation, in 2001 the U.S. Environmental Protection Agency released recommended ecoregional criteria for nitrogen and phosphorus with the goal of having states adopt the criteria into their standards by 2004.[4] These criteria were very stringent and were based on concentrations found at references sites. As an example, for the xeric west, the total nitrogen criterion for lakes was 0.51 mg/L and for phosphorus was 0.172 mg/L. The schedule for state adoption of criteria was extended; however, in lieu of proceeding to adopt criteria, many states have elected to use the implementation of the Total Maximum Daily Load program to control nutrients. Under this scenario, states can use narrative criteria for nutrients to list waters as impaired under sections 301(a) and 303(d) of the Clean Water Act and then develop and implement reduced nutrient loads using Total Maximum Daily Loads.

Currently, Texas has no numerical criteria for nutrients in the Texas Surface Water Quality Standards. Nutrient controls do exist in the form of narrative criteria, watershed rules, and anti-degradation considerations. The Texas Commission on Environmental Quality screens phosphorus, nitrate nitrogen, and chlorophyll monitoring data as a preliminary indication of areas of possible concern for the Clean Water Act section 303(d) listings of impaired water bodies. On June 30, 2010, the Texas Commission on Environmental Quality adopted the 2010 Texas Surface Water Quality Standards that included site-specific numeric nutrient criteria for chlorophyll a. The adopted standards and implementation procedures as are not effective for Clean Water Act purposes until they have been approved by the U.S. Environmental Protection

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[3] A proposed criterion has also not been included in the current triennial review of the state standards. However, the Texas Water Code allows criteria to be established for chemicals not specifically listed in the standards based the most recent numerical criteria adopted by the U.S. Environmental Protection Agency and a cancer risk of 10^{-5}. For N-nitrosodimethylamine, this would be 0.0069 µg/L in comparison to the 10^{-6} risk level of 0.00069 µg/L.

[4] See http://www.epa.gov/waterscience/criteria/nutrient/ecoregions/index.html.

Agency. It is expected that new nutrient criteria will result in Texas utilities being required to provide additional nutrient removal to comply with their Texas Pollution Discharge Elimination System Permits. This situation will certainly be a factor in treatment required for indirect potable reuse projects. It may also encourage non-potable reuse if utilities elect to lower treatment costs by eliminating or reducing surface water discharges and shifting to direct reuse.

There are two other ongoing programs that may have additional impacts on the status of future nutrient standards for states, including Texas.

- The first is the U.S. Environmental Protection Agency's Draft Strategy for Protecting and Restoring the Chesapeake Bay. It is a top-down, federally-led approach to solving water quality problems and will establish mandates on state and local governments. It is anticipated that the strategy will require municipal and industrial dischargers to install enhanced nutrient removal technology. The U.S. Environmental Protection Agency has told stakeholders that it intends to use its Chesapeake Bay activities as a model for other watersheds throughout the country.

- The second is the development of nutrient criteria in Florida, which is taking place under a consent decree between the U.S. Environmental Protection Agency and environmental groups pursuant to a lawsuit that challenged Florida's narrative nutrient criteria. The criteria, which articulated acceptable levels of phosphorus and nitrogen based on visible algal blooming, were deemed inadequate for protecting water quality within the state. As part of the settlement agreement to the lawsuit, the U.S. Environmental Protection Agency committed to establishing numeric criteria for lakes and flowing waters by October 2010. The draft criteria were released on January 14, 2010.[5] There are a number of important aspects to the proposed criteria that could establish precedents for how nutrient criteria are set around the country, and could potentially present challenges for the nutrient criteria under consideration for adoption in Texas. First, the criteria for lakes and the criteria for springs and clear streams are set using the "stressor-response" approach, which was criticized by the U.S. Environmental Protection Agency's Science Advisory Board's Nutrient Committee in 2009. Second, the criteria for rivers and streams and the criteria for canals were set using a "reference condition" approach, which was used to set the "ecoregional" criteria in 2001 and will likely result in many waters being listed as impaired even though no adverse impacts to designated uses have been shown. Third, the proposed criteria for rivers and streams include a specific formula to make the levels more restrictive based on possible impacts to downstream lakes and estuaries. This approach is considered to be the federal application of anti-degradation provisions, and in essence reduces the reference condition values by at least 50 percent, resulting in very stringent criteria. Fourth, the U.S. Environmental Protection Agency is proposing to establish new "restoration water quality standards" for impaired waters in Florida. Under this approach, interim goals would be set as part of the water quality standards, to be achieved over certain time periods, recognizing that the new final criteria may not be feasible to meet for a long period of time (if ever). It is anticipated that similar lawsuits, and approaches to nutrient criteria and restoration standards will begin to appear in many other states.

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[5] See http://www.epa.gov/waterscience/standards/rules/florida/prepub.pdf.

Another important water quality issue to address for water reuse is the application of whole effluent toxicity requirements in wastewater. The Texas Commission on Environmental Quality is being challenged by the U.S. Environmental Protection Agency with regard to the application of whole effluent toxicity limitations in wastewater permits. The U.S. Environmental Protection Agency wants Texas to include whole effluent toxicity limitations in new permits or only after one failure of a sub-lethal toxicity test. There is scientific disagreement over the validity of applying limits and undertaking toxicity evaluation related to sub-lethal effects, such as body mass and length. The 2010 Texas Surface Water Quality Standards and implementation procedures use representative data for a five-year period of whole effluent toxicity testing and best professional judgment to make a determination whether a permit should include a limit for whole effluent toxicity. It remains to be seen if the U.S. Environmental Protection Agency will approve or disapprove of the adopted standards and procedures. The U.S. Environmental Protection Agency's approach could potentially impact the type of treatment to be applied to surface augmentation projects using reclaimed water.

There are also three important evolving activities involving Clean Water Act authority related to endocrine disrupting chemicals that may be of importance for water reuse projects.

- First, the Center for Biological Diversity has petitioned the U.S. Environmental Protection Agency to establish water quality criteria for endocrine disrupting chemicals under section 304(a) of the Clean Water Act based on harm to wildlife and humans. The U.S. Environmental Protection Agency can deny or act on the petition.
- Second, the Center for Biodiversity has asked the Nevada Division of Environmental Protection to 1) include Las Vegas Wash, Las Vegas Bay, and Lake Mead on the state's list of impaired waters pursuant to section 303(d) of the Clean Water Act, due to pollution from endocrine disrupting chemicals, and 2) establish Total Maximum Daily Loads for these pollutants to protect water quality and the designated uses of the water bodies. The Center for Biodiversity is contending that the presence of endocrine disrupting chemicals has impaired beneficial uses based on one of the state's narrative criterion, which specifies that waters be free from "deleterious substances attributable to domestic or industrial waste or other controllable sources at levels or combinations sufficient to be toxic to human, animal, plant or aquatic life or in amounts sufficient to interfere with any beneficial use of the water." The request is in response to the state's call for information in support of the development for the Nevada 2008-2010 Integrated Report (the Clean Water Act section 303(d) list and the section 305(b) water quality report). If this request is granted, the impairment designation would have ramifications by placing controls on existing discharges and prohibiting new discharges, and sets a precedent for any reuse project that discharges to a water of the United States.
- The U.S. Environmental Protection Agency has developed a white paper detailing the technical issues and recommendations that will serve as the basis for modifying the 1985 guidelines for deriving water quality criteria specifically to address constituents of emerging concern.[6] This action can be considered the initial step the U.S. Environmental Protection Agency must take to develop aquatic life water quality criteria that ultimately

[6] See http://www.epa.gov/waterscience/criteria/library/sab-emergingconcerns.pdf.

when recommended would be adopted by states. These criteria would impact any reuse project that discharges to a water of the United States.

Groundwater is not regulated under the Clean Water Act, but by individual states. Subject to state law, states may also adopt water quality criteria and anti-degradation policies for protection of groundwater, which can be applied to reclaimed water projects that have the potential to impact groundwater. State groundwater criteria typically include drinking water maximum contaminant levels and criteria for salts (see Section 4.2). With regard to application of anti-degradation policies to groundwater, one example is California which has adopted a Recycled Water Policy (SWRCB, 2009) that requires the statewide development of salt/nutrient management plans for groundwater basins and specifies how to apply state anti-degradation policy for landscape irrigation and groundwater recharge projects regarding impacts on groundwater quality. Texas has adopted a statutory policy of non-degradation of groundwater as discussed further in Section 4.2.

4.1.2. Safe Drinking Water Act

Potable reuse projects (and some non-potable reuse projects) include requirements to meet drinking water standards adopted by states under the Safe Drinking Water Act.

The Safe Drinking Water Act allows the U.S. Environmental Protection Agency to promulgate national primary drinking water standards specifying maximum contaminant levels for each contaminant present in a public water system with an adverse effect on human health, taking into consideration cost and technical feasibility. Maximum contaminant levels have been established for approximately 90 contaminants in drinking water.[7] In cases where the maximum contaminant levels cannot be feasibly ascertained, the U.S. Environmental Protection agency may elect to identify and establish a schedule of “treatment techniques” preventing adverse effects on human health to the extent feasible.

Drinking water maximum contaminant levels are established in two steps. First, the U.S. Environmental Protection Agency establishes maximum contaminant level goals, which are the maximum levels of a contaminant in drinking water at which no known or anticipated adverse effect on the health of persons would occur, and which allow an adequate margin of safety. These have been historically set at zero for microbial and carcinogenic contaminants. Once the maximum contaminant level goal is established, the U.S. Environmental Protection Agency determines the feasible maximum contaminant level or treatment technology level that may be achieved with the use of the best available technology and treatment techniques, and taking cost into consideration.

On March 22, 2010, the U.S. Environmental Protection Agency released a new strategy for drinking water standards development (U.S. EPA, 2010). The shift in drinking water strategy is organized around four key principles: 1) to address contaminants as a group rather than one at a time so that enhancement of drinking water protection can be achieved cost-effectively; 2) to foster development of new drinking water treatment technologies to address health risks posed

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[7] For a current list of maximum contaminant levels, see http://www.epa.gov/safewater/contaminants/index.html.

by a broad array of contaminants; 3) to use the authority of multiple statutes to help protect drinking water; and 4) to partner with states to share more complete data from monitoring of public water systems.

The Safe Drinking Water Act includes a process that the U.S Environment Protection Agency must follow to identify and list unregulated contaminants that may require a national drinking water regulation in the future. This process requires the periodic publication of a list of contaminants called the Contaminant Candidate List. The U.S. Environmental Protection Agency must then decide whether to regulate at least five or more contaminants on the list. The list is also used by the U.S. Environmental Protection Agency to prioritize research and data collection efforts to help the agency determine whether it should regulate a specific contaminant. In September 2009, the U.S. Environmental Protection Agency published the final version of the third Contaminant Candidate List. The list contains 104 chemicals or chemical groups, including pesticides, disinfection byproducts, chemicals used in commerce, waterborne pathogens, pharmaceuticals, steroid hormones, and biological toxins.[8] Thus, pharmaceuticals and steroid hormones have the potential to be selected for development of future drinking water standards.

As part of the Safe Drinking Water Act, the U.S. Environmental Protection Agency administers the Underground Injection Control program that could apply to an indirect potable reuse project that augments groundwater, depending on how the program is implemented by an individual state. The federal program has categorized injection wells into five classes, only one of which (Class V) applies to groundwater recharge projects. Under the existing federal regulations, Class V injection wells are "authorized by rule," which means they do not require a federal permit if they do not endanger underground sources of drinking water and comply with other program requirements. For Texas, the Texas Commission on Environmental Quality is the permitting administrator for Class V wells. Applicants must submit an authorization form to the commission; however, it may not be necessary in all cases to apply for an injection well permit in Texas.

4.2. Texas regulations

In Texas, the use of reclaimed water is governed by the Texas Commission on Environmental Quality (Title 30, Chapter 210 of the Texas Administrative Code) and the Texas Surface Water Quality Standards (Title 30, Chapter 307 of the Texas Administrative Code). These regulations establish quality, design, and operational requirements for the beneficial use of reclaimed water.

Prior to using reclaimed water, a provider must obtain an "authorization for use" from the Texas Commission on Environmental Quality pursuant to Chapter 210. Chapter 321, Subchapter P establishes the authorization procedures, general design criteria, and operational requirements for reclaimed water production at a site other than a permitted domestic wastewater treatment facility.

[8] For the list of contaminants see http://www.epa.gov/safewater/ccl/ccl3.html.

The Texas regulations for non-potable reuse (Chapter 210) sub-categorize reclaimed water into Type I and Type II uses, with specific water quality standards as presented in Table 4. Type I use includes irrigation or other uses in areas where the public may be present during the time when irrigation takes place or other uses where the public may come in contact with the reclaimed water. Type II use includes irrigation or other uses in areas where the public is not present during the time when irrigation activities occur or other uses where the public would not come in contact with the reclaimed water.

This table reflects changes to the regulations, which went into effect in 2009, that allow reclaimed water providers to select either the currently required fecal coliform or the new requirement for Texas Pollutant Discharge Elimination System domestic permits, *Escherichia coli* or *Enterococci* as the indicator organism for disinfection. All three bacteria can be used to demonstrate disinfection efficacy. This flexibility allows the provider to choose the most convenient, most cost effective bacteria test for its facility.

The reuse regulations also contain:

- General requirements including prohibitions for spray irrigation of raw food crops, degradation of groundwater quality, and overflows from storage ponds (except during rain events or when authorized by a permit).
- Storage requirements that require lining of storage ponds.
- Irrigation use area requirements including control of application rates, determining irrigation demands, and conducting audits of users for compliance with regulations.
- Design criteria regarding designation and protection of reclaimed water hose bibs and faucets, horizontal separation of reclaimed water piping from potable water piping and sewers, and construction of reclaimed water distribution system and storage tanks.

Texas currently has no specific water quality regulations that pertain to indirect use of reclaimed water.

For the Hueco Bolson Recharge Project in El Paso, Texas, the advanced treated reclaimed water must meet primary drinking water standards and requirements set by the Texas Commission on Environmental Quality's prior to injection (Crook, 2007). The extracted water is mixed with other well water and chlorinated prior to distribution to customers.

For surface water augmentation projects using reclaimed water, the current approach in Texas uses a blending/retention time concept to address constituents of emerging concern (Alan Plummer Associates, 2004). This approach is based on the use of percent reclaimed wastewater content (percent blend) and detention time as a measure of potential exposure to contaminants that may have human health effects. The use of these indicators is based on the assumption that natural degradation and dilution are important factors in reducing the quantities of potentially harmful contaminants in the water supply. Based on experience from existing projects, an average blend limit of approximately 30 percent combined with a 1-year average minimum

Table 4. Summary of Texas reuse requirements

	Type I	Type II	
Allowable Uses	Irrigation or other uses where public may be present during use: • residential irrigation • urban irrigation • fire protection • edible food crops • irrigation of pasture for milking animals • recreational impoundments • toilet flushing • Any Type II uses	Irrigation or other uses where the public is not present during use: • irrigation of sod farms • silviculture • irrigation of highway medians • irrigation of remote sites • irrigation of sites protected by walls or fences • irrigation of sites not used during times of irrigation (cemeteries, golf courses, etc) • irrigation of processed food crops • irrigation of animal feed crops • soil compaction or dust control for construction • cooling tower makeup • irrigation at wastewater treatment plants	
Water Quality Standards	**All**	**Other than Pond**	**Pond**
BOD_5[a]	5 mg/L[b]	20 mg/L[b]	30 mg/L[b]
$CBOD_5$[c]	5 mg/L[b]	15 mg/L[b]	
Turbidity	3 NTU[b,d]		
Fecal coliform or *E. coli*[e]	20 CFU/100 mL[f,g]	200 CFU/100 mL[g]	200 CFU/100 mL[g]
Fecal coliform or *E. coli*	75 CFU/100 mL[h]	800 CFU/100 mL[h]	800 CFU/100 mL[h]
Enterococci	4 CFU/100 mL[g]	35 CFU/100 mL[g]	35 CFU/100 mL[g]
Enterococci	9 CFU/100 mL[h]	89 CFU/100 mL[h]	89 CFU/100 mL[h]

a. Five-day Biochemical Oxygen Demand (BOD_5).

b. 30-day average.

c. Five-day Chemical Oxygen Demand (COD_5)

d. Nephelometric Turbidity Units (NTU).

e. *Escherichia coli (E. coli).*

f. Colony Forming Units (CFU).

g. 30-day geometric mean.

h. Maximum single grab sample.

detention time have been used as "rule-of-thumb" guidance for determining the maximum quantities of reclaimed water that can be used to augment the supply.[9] However, there may be some latitude for variation from these criteria, particularly with the use of multiple barriers and implementation of appropriate advanced wastewater or water treatment.

For a water reuse project that discharges to a water of the U.S., such as a surface water augmentation project, requirements will be imposed to comply with the Texas Surface Water Quality Standards in Chapter 307. They include 1) general narrative criteria that apply to all waters in the state; 2) the state Anti-degradation Policy for surface waters that are defined as being of intermediate, high, or exceptional quality; and 3) specific numerical criteria. The numeric criteria have been developed for 39 toxic pollutants (expressed as maximum in-stream concentrations) to protect aquatic life and for 65 toxic pollutants for protection of public health via human consumption of fish and drinking water.[10] For protection of human health, the Texas Water Code allows criteria to be established for chemicals not specifically listed in the regulations, based on the most recent numerical criteria adopted by the U.S. Environmental Protection Agency and a cancer risk of 10^{-5}. The state standards also include provisions for biomonitoring. Any significant toxicity observed during biomonitoring must then be evaluated and eliminated. Appendix A of Chapter 307 of the Texas Administrative Code contains specific numeric criteria for chloride, sulfate, total dissolved solids, dissolved oxygen, pH, and temperature by specific water body segments.[11]

Surface water bodies in the state (river basins, bays, and estuaries) have been divided into segments based on regional hydrologic and geologic diversity, which are referred to as classified or designated segments. Segments are listed and defined in the Texas Surface Water Quality Standards.

Of significance for indirect potable reuse, domestic water supply consists of two use subcategories: 1) public water supply and 2) aquifer protection, which is specifically defined as segments capable of protecting the Edwards Aquifer. Drinking water maximum contaminant levels and toxic criteria apply to these use subcategories. Also important to reuse is the aquatic life use, which is divided into five subcategories: 1) limited aquatic life, 2) intermediate aquatic life, 3) high aquatic life, 4) exceptional aquatic life, and 5) oyster waters. The Texas Surface Water Quality Standards include specific numeric criteria for toxic pollutants for protection of aquatic life.

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[9] These percent blend and detention time limits are based on review of regulations in other states, levels of treatment being applied and known percent blend/detention time conditions experienced in unplanned and planned projects within Texas.

[10] See http://info.sos.state.tx.us/pls/pub/readtac$ext.TacPage?sl=R&app=9&p_dir=&p_rloc=&p_tloc=&p_ploc=&pg=1&p_tac=&ti=30&pt=1&ch=307&rl=7, http://info.sos.state.tx.us/fids/30_0307_0006-4.html, http://info.sos.state.tx.us/fids/30_0307_0006-5.html, http://info.sos.state.tx.us/fids/30_0307_0006-6.html, for the list of site specific uses and criteria.

[11] http://info.sos.state.tx.us/fids/30_0307_0010-6.html.

Not all surface waters have been assigned site specific criteria. Unclassified waters are those smaller water bodies that have not had a site specific analysis performed in order to set site specific standards. Unclassified waters are protected by general aquatic life standards, which apply to all surface waters in the state.

Texas has just amended its surface water standards. The standards and accompanying implementation procedures must be approved by the U.S. Environmental Protection Agency before they go into effect.[12] The new standards include changes to:

- The general criteria;
- Toxics criteria to incorporate new data on toxicity effects (for example the total trihalomethane criterion for protection of human health is proposed to be 80 µg/L; the existing criterion is 100 µg/L.);
- Toxics criteria to provide clarity to the basic requirements for toxicity effluent testing (see Section 4.1 related to the whole effluent toxicity testing discussion);
- Additional categories of recreational uses and more definition on assigning recreational uses; and
- New site specific nutrient criteria (for chlorophyll a) that will be used to confirm if a water body is attaining the nutrient criteria (see Section 4.1 related to the nutrient discussion).

Texas has adopted three overarching principles to guide state groundwater management: 1) the policy of non-degradation of groundwater quality established in the state's Groundwater Goal and Policy[13]; 2) stakeholder and regionally based planning for ground and surface water; and 3) local control of groundwater quantity management through groundwater conservation districts. The goal for non-degradation does not mean zero contaminant discharge. Discharges of pollutants, disposal of wastes, and other regulated activities must be conducted in a manner that will maintain present uses and not impair potential uses of groundwater or pose a public health hazard. State law empowers groundwater conservation districts to adopt and carry out management plans, rules, and permits for the conservation, preservation, and protection of groundwater and the prevention of the waste of groundwater in their jurisdictions. Fifty-one districts have adopted management plans that set out the goals of the individual districts consistent with state law and the regional and state water plans (TGCP, 2003).

The Texas Groundwater Protection Committee has developed a water quality classification system for groundwater that guides the state's groundwater protection programs. Under the groundwater classification system, four classes are defined based on quality as determined by total dissolved solids content. Since the legislatively mandated goal of non-degradation guides groundwater programs, the state has not developed specific standards for pollutant discharges to groundwater (TGCP, 2003).

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[12] See http://www.tceq.state.tx.us/assets/public/permitting/waterquality/attachments/standards/2010ip_rtcfinal.pdf and http://www.tceq.state.tx.us/assets/public/legal/rules/rule_lib/adoptions/RG-194.pdf.

[13] See Texas Water Code Section 26.401.

The ramifications of this framework in relation to the use of reclaimed water for groundwater recharge are uncertain, but will need to be addressed for a project early in its planning process.

4.2.1. Comparison of Texas regulations to other state regulations

As of November 2002, a survey conducted of all 50 states found that 25 states had adopted regulations regarding the reuse of reclaimed water, 16 states had guidelines or design standards, and 9 states had no regulations or guidelines (U.S. EPA, 2004).[14] A summary of the 2002 inventory by type of use is presented in Table 5.

Table 5. Number of states with regulations or guidelines in 2002 for each type of reuse application

Type of reuse	Number of states
Unrestricted Urban	28
Irrigation[a]	28
Toilet Flushing[a]	10
Fire Protection[a]	9
Construction	9
Landscape Impoundment[a]	11
Street Cleaning	6
Restricted Urban[a]	34
Agricultural (Food Crops) [a]	21
Agricultural (Non-food Crops) [a]	40
Unrestricted Recreational[a]	7
Restricted Recreational	9
Environmental (Wetlands)	3
Industrial[a]	9
Groundwater Recharge (Non-potable Aquifer)	5
Indirect Potable Reuse	5

(From U.S. EPA, 2004, Table 4.2)

a. This use is specifically allowed under Title 30, Chapter 210 of the Texas Administrative Code; however for Type I uses, the regulations allow for other similar activities where the potential for unintentional human exposure may occur.

The 2002 survey also concluded that the regulations and guidelines varied significantly from state to state in terms of 1) the reuse applications covered (most states did not have regulations that covered all potential uses); 2) the specific treatment and use area requirements applied to projects (some states had more stringent or comprehensive requirements than other states); 3) the basis of setting the requirements (some regulations may be risk-based while others may be based on research, experience, existing applications and achievability)[15]; and 4) the specific objectives

[14] It should be noted that some of the "reuse" regulations are directed at land disposal of effluent, but for this document were counted in this category.
[15] In many cases the actual basis for the regulations or guidelines may not be specified or fully understood, or they are based on what other states are practicing.

of the regulations/guidelines (some regulations are intended to promote water reuse as a resource while some are developed to provide a disposal alternative for discharges of wastewater to surface water). The WateReuse Research Foundation is preparing a white paper, which will be published in 2010, that is assessing potential alternatives to achieve national consistency in the quality and safety of reclaimed water produced through reuse, including the development of regulations/criteria, guidelines, industry "standards" or voluntary standards of practice, and other options.

As an example, regulations for unrestricted urban use for Arizona, California, Florida, Hawaii, Nevada, Texas, and Washington are shown in Table 6.

Table 6: Comparison of state regulations for unrestricted non-potable urban reuse

	Arizona	California	Florida	Hawaii	Nevada	Texas	Washington
Treatment	Secondary treatment, filtration, disinfection	Oxidized, coagulated, filtered, disinfected	Secondary treatment, filtration, high-level disinfection	Oxidized, filtered, disinfected	Secondary treatment, disinfection	NS	Oxidized, coagulated, filtered, disinfected
BOD_5	NS[a]	NS	20 mg/L $CBOD_5$	NS	30 mg/L	5 mg/L	30 mg/L
TSS[b]	NS	NS	5.0 mg/L	NS	NS	NS	30 mg/L
Turbidity							
Avg	2 NTU	2 NTU	NS	NS	NS	3 NTU	2 NTU
Max	5 NTU	5NTU	NS	2 NTU	NS	NS	5 NTU
Coliform	Fecal	Total	Fecal	Fecal	Fecal	Fecal[c]	Fecal
Avg	ND[d]	2.2/100 mL (7-day)	75% ND[f]	2.2/100 mL (7-day)	2.2/100 mL	20/100 mL[g]	2.2/100 mL
Max	23/100 mL	23/100 mL[e]	25/100 mL	23/100 mL[e]	23/100 mL	75/100 mL[h]	23/100 mL
Enterococci							
Avg	NS	NS	NS	NS	NS	4 CFU/100 mL[g, i]	
Max	NS	NS	NS	NS	NS	9 CFU/100 mL	

(Source: Updated from U.S. EPA, 2004, Table 4.3)

a. Not specified by state regulations.
b. Total suspended solids (TSS).
c. Or *Escherichia coli* per current Texas regulations.
d. Below detection (ND).
e. In 30 days.
f. 75 percent (%) of the samples below detection.
g. 30-day geometric mean.
h. Single sample.
i. Colony forming units (CFU).

As of 2009, eight states had developed regulations and/or guidance for indirect potable reuse:

- California: narrative statements in the reuse regulations that allow for approval of groundwater recharge projects on a case-by-case basis and draft regulations with specific requirements for groundwater recharge by surface spreading and injection;
- Florida: regulations for recharge, indirect potable reuse, salinity barriers, canal recharge, aquifer storage and recovery;
- Hawaii: narrative recharge guidelines that offer guidance on a case-by-case basis;
- Idaho: recharge regulations;
- Virginia: narrative indirect potable reuse regulations that allow projects on a case-by-case basis;
- New Hampshire: regulations and guidelines;
- Massachusetts: regulations; and
- Washington: guidelines for groundwater recharge by surface spreading and injection.

California has developed a comprehensive framework as part of its August 2008 draft groundwater regulations, which are summarized in Table 7.

Table 7. California August 2008 draft groundwater recharge regulations - summary of reclaimed water requirements

Parameter	Surface applications	Subsurface applications
Pathogenic Microorganisms		
Filtration	≤ 2 NTU	
Disinfection	450 CT mg-min/L at all times with 90 min. modal contact time, based on peak dry weather design flow <u>or</u> 5-log virus inactivation[a]; and ≤ 2.2 total coliform per 100 mL	
Retention time[b]	6 months	
Regulated Contaminants		
Drinking Water Standards	Meet all drinking water standards (except nitrogen) in reclaimed water. For primary drinking water standards (except perchlorate), compliance based on running annual average of quarterly samples; for perchlorate, running 4-week average.[c] For secondary drinking water standards, compliance is based on annual sample. For disinfection byproducts, compliance can be determined after soil aquifer treatment.	
Total Nitrogen	• For projects in operation for 20 years with no Reclaimed Water Contribution (RWC)[d] increase, at a level specified by the California Department of Public Health; • For new projects or increased RWC, ≤5 mg/L in reclaimed water or the reclaimed water and dilution water before or after application; or, • For new projects or increased RWC, the reclaimed water or combination of reclaimed water and dilution water must meet 10 mg/L, with specified levels for nitrite, nitrate, ammonia, organic nitrogen, dissolved oxygen, BOD	
Unregulated Contaminants		
TOC[e] Filtered Wastewater	TOC ≤ 16 mg/L in any portion of the filtered wastewater not subjected to RO[f] treatment	

Parameter	Surface applications	Subsurface applications
TOC in reclaimed water	• RO and AOP[g] treatment as needed to achieve: TOC ≤ (0.5 mg/L)/RWC (new project or increased RWC at existing project) • Compliance point is in reclaimed water or in reclaimed water after soil treatment not impacted by dilution (no blending) • TOC_{max} limits can be increased (above the TOC equation) pending approval for projects in operation > 10 years and have met provisions including health evaluations and peer review	• 100 percent RO and AOP treatment for the entire wastestream & TOC ≤ (0.5 mg/L)/RWC (new project or increased RWC at existing project) • TOC_{max} limits can be increased (above the TOC equation) pending CDPH approval for projects in operation > 10 years and have met provisions including health evaluations and peer review
RWC_{max} Initial	Up to 20 percent disinfected tertiary Up to 50 percent w/ RO & AOP	Up to 50 percent w/ RO & AOP[e]
Increased RWC_{max}	Subject to additional requirements	

a. The virus log reduction requirement may be met by a combination of removal and inactivation.

b. Must be verified by a tracer study.

c. The 4-week average applies if the MCL is exceeded in the quarterly sample, and then the average of the quarterly sample and verification sample.

d. Reclaimed water contribution (RWC), which is defined as the quantity of reclaimed water applied at the recharge site divided by the sum of the reclaimed water applied at the site and authorized dilution water.

e. Total organic carbon (TOC).

f. Reverse osmosis (RO).

g. Advanced oxidation (AOP) must achieve at a minimum a 1.2 log N-nitrosodimethylamine reduction and 0.5 log 1,4-dioxane reduction, whether the compounds are present or not.

h. The requirement for AOP for all subsurface applications ≤ 50 percent is under deliberation.

There are a number of other key provisions of the draft California groundwater regulations that are important for planning and implementation of projects:

- A project sponsor must conduct quarterly monitoring of the reclaimed water and down-gradient monitoring wells for the U.S. Environmental Protection Agency's priority pollutants, and for chemicals with state notification levels, or other chemicals that the California Department of Public Health has specified based on the specific conditions of a project. The draft regulations also require annual monitoring of reclaimed water for constituents that indicate "the presence of municipal wastewater." The selection is based on the specific conditions of a project and a constituent's ability to characterize the presence of pharmaceuticals, endocrine disrupting chemicals, personal care products, and other indicators of municipal wastewater, and the availability of a test method for a constituent.

- A project sponsor must administer an aggressive source control program that evaluates the fate of contaminants through the wastewater and reclaimed water treatment systems; source investigations and contaminant monitoring that focus on specified contaminants; an outreach program to industrial, commercial, and residential communities; and an up-to-date inventory of contaminants.

- The project sponsor must have an operations plan for operations, maintenance, and monitoring.
- Prior to operating, the project sponsor must collect at least two samples from the approved monitoring wells.
- The project sponsor must provide an engineering report.
- The project sponsor must conduct a source water evaluation for dilution water per the California-Nevada Section of the American Water Works Association watershed sanitary survey handbook, or other California Department of Public Health approved evaluation.
- The project sponsor must have an approved plan to provide an alternative source of domestic drinking water or an approved treatment system if the recharge project causes a producing drinking water supply to not meet drinking water standards or is degraded so that it can no longer be used as a safe source of drinking water.

The draft regulations allow for a project to use an alternative if it can be demonstrated that it provides the same level of protection to public health and has been approved by the California Department of Public Health. The approval of alternatives typically involves review and sanction by an expert panel.

California law allows for augmentation of drinking water reservoirs with reclaimed water provided that the Department of Public Health 1) performs an evaluation of the technology used to treat the reclaimed water and finds that after treatment the water poses no threat to public health, and 2) holds three public hearings in the area where the water will be served. There are no specific regulations that have been developed by the California Department of Public Health for surface water augmentation with reclaimed water; however, any discharge of reclaimed water into a reservoir would be regulated under the state's National Pollutant Discharge Elimination System. In 1996, "A Proposed Framework for Regulating the Indirect Potable Reuse of Advanced Treated Reclaimed Water by Surface Water Augmentation in California" was developed by the California Potable Reuse Committee, a group of educators, engineers, and scientists. This guidance document included recommendations for authorizing surface water augmentation projects including the following:

- Approved advanced reclaimed water treatment processes have been applied.
- All relevant water quality standards are achieved.
- The highly purified reclaimed water is retained in a surface storage reservoir for sufficient time before treatment in a surface water treatment plant prior to distribution.
- Downstream drinking water treatment plant operations will not be negatively impacted.
- Multiple barriers are erected for removal of pathogenic microorganisms and toxic chemicals.

In 2009, the California State Water Resource Control Board adopted a Recycled Water Policy (regulations) using a collaborative stakeholder process. The Policy, which addresses the use of reclaimed water for landscape irrigation and groundwater recharge and is intended to facilitate reuse, includes provisions that:

- Specify water recycling mandates to increase the use of reclaimed water in California by 200,000 acre-feet per year by 2020 and by an additional 300,000 acre-feet per year by 2030.
- Provide direction for streamlining water reuse permits.
- Mandate the development of salt/nutrient management plans for all groundwater basins in the state.
- Provide provisions on how to demonstrate compliance with state anti-degradation requirements.
- Create an expert panel to develop recommendations for monitoring constituents of emerging concern (see Section).
- Include incentives for the use of reclaimed water and stormwater.

4.3. International guidelines for water reuse

To generate a nationally consistent approach to the management of health and environmental risks from water recycling, Australia has developed a suite of documents that make up the Australian Guidelines for Water Reuse. The guidelines were developed by the National Health and Medical Research Council in collaboration with the Natural Resource Management Ministerial Council. Phase 1 of the guidelines cover non-potable uses; additional documents have been developed in Phase 2 for the use of reclaimed water to augment drinking water supplies and managed aquifer recharge. The guidelines build upon a risk management framework as detailed in the 2004 Australian Drinking Water Guidelines (Health and Medical Research Council, Natural Resource Management Ministerial Council, 2004). The framework provides generic guidance based on 12 elements that form a structured and systematic approach for the management of water quality from catchment to consumer, to assure its safety and reliability, rather than relying on verification monitoring. By replacing “drinking” with “reclaimed” these elements apply in exactly the way to the framework for reclaimed water quality. Management of water resources in Australia is the responsibility of the states, rather than the federal government. Thus, the guidelines are not mandatory and have no formal legal status. However, their adoption provides a shared national objective and allows states and/or local jurisdictions to independently adopt them or to use their own legislative and regulatory tools to refine them into their own guidelines. To date, all of the state health regulators have taken and implemented the guidelines either in their entirety or with some minor modifications.[16]

The United Kingdom’s Framework for Developing Water Reuse Criteria was commissioned by the United Kingdom Water Industry Research Limited, the Water Research Foundation, and the WateReuse Research Foundation. It consists of a framework developed by an international committee of experts as part of a two-day workshop that took place in April 2004 (UKWIR, 2004). The framework is related to the Australian Guidelines in that it takes a risk management approach as a guide for reuse. The framework includes an overarching component and detailed components for specific uses based on varying levels of treatment. The overarching component

[16] Personal communication from Adam Lovell, Water Services Association of Australia, July 31, 2009.

consists of identifying hazards, barriers to hazards, and management tools, and verification by independent third parties. Unlike the Australian framework, this approached includes verification monitoring. The United Kingdom framework has not been formally adopted for use.

The World Health Organization has published three sets of guidelines on water reuse for agriculture and aquaculture (WHO, 2006a; WHO, 2006b; WHO, 2006c). The 2006 guidelines are the most recent publications and provide basic information on health risks of using wastewater, excreta, and greywater, and how to set health based targets by quantifying the risk and developing pathogen reduction targets. They are designed to protect the health of farmers (and their families), local communities, and product consumers. They are meant to be adjusted to take into consideration national sociocultural, economic and environmental factors. The guidelines are not mandatory and have no formal legal status.

5. Source control

A critical component of any water reuse program is to develop and implement an effective industrial source control program as the first barrier to preventing undesirable chemicals or concentrations of chemicals from entering a wastewater management system. Pollutants in industrial wastewater may compromise municipal treatment plants' processes or contaminate the nation's waters. To protect municipal treatment plants and the environment, the Clean Water Act established the National Pretreatment Program, which requires industrial dischargers to use treatment techniques and management practices to reduce or eliminate the discharge of harmful pollutants to sanitary sewers. The term "pretreatment" refers to the requirement that nondomestic sources discharging wastewater to publicly owned treatment works control their discharges, and meet limits established by the U.S. Environmental Protection Agency, the state, or local wastewater authority on the amount of pollutants allowed to be discharged. Limits may be met by the nondomestic source through treatment, pollution prevention techniques (product substitution recycle and reuse of materials), or best management practices (for some pollutants).

The National Pretreatment Program objectives are to:

- Prevent industrial facilities' pollutant discharges from passing through municipal wastewater treatment plants untreated;
- Protect treatment plants from the threat posed by untreated industrial wastewater, including explosion, fire, and interference with the treatment process; and
- Improve the quality of effluents and sludges so that they can be used for beneficial purposes.

Wastewater authorities must adopt ordinances, issue permits to industries, monitor industrial discharges for compliance with federal and locally-established limits/requirements, and take enforcement actions when violations occur.[17] The U.S. Environmental Protection Agency has

[17] All publicly owned treatment works with flows greater than 5 million gallons per day must establish pretreatment programs. The U.S. Environmental Protection Agency or state may require that a publicly owned treatment works with a design flow of 5 million gallons per day or less develop a pretreatment program.

established technology-based numeric effluent guidelines for 56 categories of industry. The Clean Water Act sections 301(d), 304(b), 304(g), 304(m), and 307(b) require the U.S. Environmental Protection Agency to annually review its effluent guidelines and pretreatment standards and to identify potential new categories for pretreatment standards. Recommendations are presented in a Preliminary Effluent Guidelines Program Plan. The 2010 Plan includes a strategy for the development of best management practices for unused pharmaceutical disposal at hospitals and other health care facilities. As noted in the 2010 Plan, this strategy is intended to eliminate the inconsistent messages and policies regarding "flushing" of drugs to municipal sewer systems that have been issued by the U.S. Environmental Protection Agency, U.S. Food and Drug Administration, and the White House Office of National Drug Control Policy. The U.S. Environmental Protection Agency hopes to have the best management practices finished in October 2010.

Wastewater management agencies are required to establish local limits for industries as needed to comply with National Pollutant Discharge Elimination System permits and to prevent discharges into sewerage systems that inhibit or disrupt treatment processes, or the uses/disposal of treated wastewater.

It is important to note that expectations regarding pollution prevention and source control must be realistic. Pollution prevention programs will be effective in achieving reductions if the following conditions can be met:

- The pollutant can be found at measurable levels in the influent and collection system.
- A single source or group of similar sources accounting for most of the influent loading can be identified, such as the source's relative contributions to the mass loading and concentration of a pollutant or pollutants. The portion of the total influent source that is identified and considered controllable must be greater than the reduction in pollutant levels needed.
- The sources are within the jurisdiction of the agency to control (or significant outside support/resources are available). For example, industrial sources are more easily controlled because industries are regulated and required to meet sewer use permit requirements, while residential sources are not within the legal jurisdiction of publicly owned treatment works and, therefore, voluntary behavioral changes must be accomplished. If a pollutant source is a commercial product, such as mercury thermometers or lindane head lice remedies, it may not be within the local agency's power to ban or restrict the use of the product. To be effective, the use of a product must be restricted on a regional, statewide, or national basis.

For agencies implementing indirect potable reuse projects, source control programs may go beyond the minimum federal requirements. Many agencies have developed local or statewide "no drugs down the drain programs"[18] and/or drug take-back programs. For example in Texas, the San Antonio Water System has developed a collection program for un-used medications. Other agencies have included additional program elements to enhance their pollution prevention efforts. For example, to meet permit conditions imposed by the California Department of Public Health, the Orange County Sanitation District, which provides reclaimed water to the Orange County Water District for the Groundwater Replenishment System Project, has instituted

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

additional program elements that build on the agency's traditional source control program. They consist of a pollutant prioritization scheme that includes chemical fate assessment for a broad range of chemicals; an outreach program for industries, businesses, and the public; and a toxics inventory that integrates a geographical information system and chemical fact sheets. The Orange County Sanitation District successfully used its source control program to reduce the discharge of N-nitrosodimethylamine and 1,4-dioxane from industries into its wastewater management system.

Oregon is establishing rules that set trigger levels for pollutants that will require any municipal wastewater facility with a dry weather design flow capacity of 1 million gallons per day or more to develop toxics reduction plans for listed priority persistent pollutants if any of the pollutants are found in their effluent above the trigger levels set by the rule. The December 2009 proposed rule includes numeric effluent concentration values or trigger levels for each of the 118 "priority persistent pollutants" for which a drinking water maximum contaminant level has not been adopted, but that the Oregon Environmental Quality Commission has determined by rule should be included in a permitted facility's toxic pollutant reduction plan. The list is divided into two categories: 1) pollutants that persist in the environment, and 2) pollutants that accumulate in animals. All of the pollutants on the list have the potential to cause harm to human health or aquatic life. Some are known carcinogens and others are believed to disrupt endocrine functions. The list includes both well studied pollutants that people have worked to reduce for many years, and those for which little information exists. Municipal wastewater utilities will compare the results of wastewater effluent monitoring against these trigger levels for each applicable treatment facility. Where effluent concentrations of a pollutant on the list exceed the trigger level, the facility will be required to develop a toxics reduction plan by July 2011 aimed at reducing levels of that pollutant in their discharge. The Oregon Department of Environmental Quality consulted with a Science Peer Review Panel to develop the list of pollutants and triggers.[19] The state plans to recommend that the Oregon Environmental Quality Commission adopt the rule at the commission's June 16, 2010 meeting.

6. Treatment technologies

Application of the appropriate treatment requirements for the production of safe, reliable reclaimed water is one of the keys to operating any water reuse system. Treatment requirements will vary based on:

- Constituents of concern in reclaimed water.
- The type of use.
- Degree of public exposure.
- Potential impacts on water quality (surface and groundwater) and the environment.
- Applicable state regulations and guidelines.

[19] See http://www.deq.state.or.us/wq/SB737

Historically, water reuse treatment has focused on protection of public health by: 1) reducing or eliminating concentrations of pathogenic bacteria, parasites, and enteric viruses in the reclaimed water, 2) controlling chemical constituents in reclaimed water, and/ or 3) limiting public exposure (contact, inhalation, ingestion) to reclaimed water. Reclaimed water projects may vary significantly in the level of human exposure incurred, with a corresponding variation in the potential for health risks. Where human exposure is likely in a reuse application, reclaimed water should be treated to a high degree prior to its use. Conversely, where public access to a reuse site can be restricted so that exposure is unlikely, a lower level of treatment may be satisfactory, provided that worker safety is not compromised.

While it must be acknowledged that raw wastewater may pose a significant risk to public health, it is equally important to point out that current treatment technologies allow water to be treated to almost any quality desired. For many uses of reclaimed water, appropriate water quality can be achieved through conventional, widely practiced treatment processes. Reclaimed water is generally considered to be treated wastewater that has received, at a minimum, secondary-level treatment and basic disinfection at a wastewater treatment facility. There are four stages of wastewater treatment: primary, secondary, tertiary, and advanced treatment. During primary treatment, suspended solids are removed by screening and settling. The water is then subjected to secondary treatment where biological decomposition reduces complex organic material into simpler forms. The water is separated from any remaining organic material and then either disinfected (often by chlorination) and directly discharged or reused. Some facilities add tertiary treatment, such as nutrient removal or filtration, prior to disinfection. Finally, some facilities utilize advanced treatment, such as membrane separation or advanced oxidation.

Wastewater parameters that may be required to be removed or reduced during treatment consist of:

- Pathogens;
- Nutrients;
- Trace metals;
- Salts;
- Organic chemicals, including priority pollutants, pharmaceuticals, endocrine disrupting chemicals, and ingredients in personal care products.[20]

6.1. Constituents of concern

This section provides a broad overview of microbial and chemical constituents that could be present in reclaimed water. Currently, the universe of regulated constituents is fairly small and may not be applied to all uses of reclaimed water. It is comprised of:

[20] In this document, we have used the term "constituents of emerging concern" to describe this group of organic chemicals.

- Drinking water maximum contaminant levels for microorganisms, disinfectants, disinfection byproducts, inorganic chemicals, organic chemicals, and radionuclides.[21]
- Secondary drinking water standards.[22]
- Water quality criteria for inorganic and organic chemicals for priority pollutants.[23]
- Water reuse criteria for microorganisms and treatment performance measures.

To put this in perspective, it is illustrative to look at two U.S. Environmental Protection Agency prioritization efforts for regulating constituents in water. The first effort is the U.S. Environmental Protection Agency's Candidate Contaminant List 3 for drinking water. This is a list of contaminants that are currently not subject to any proposed or promulgated national primary drinking water regulations, that are known or anticipated to occur in public water systems, and which may require regulation under the Safe Drinking Water Act. To develop the most recent list, the U.S. Environmental Protection Agency started with nearly 26,000 substances, which were narrowed down to a list of 116 candidates (104 chemicals or chemical groups and 12 microbiological contaminants). The list includes, among others, pesticides, disinfection byproducts, chemicals used in commerce, waterborne pathogens, pharmaceuticals, and biological toxins. The second effort is the U.S. Environmental Protection Agency's Endocrine Disruptor Screening Program, which was created to screen more than 87,000 pesticides, chemicals, and environmental contaminants for their potential effect on estrogen, androgen and thyroid hormone systems.[24] Of this total, the first group of chemicals to be tested for endocrine effects consists of 67 pesticide active ingredients and High Production Volume chemicals used as pesticide inert ingredients. Information garnered from these efforts, occurrence data, and production and use of chemicals is used to prioritize which constituents should be targeted for further monitoring and research.

6.1.1. Pathogens

The potential transmission of infectious disease by pathogenic agents is the most common concern associated with reuse of treated municipal wastewater. The presence and concentration of pathogens in treated wastewater varies depending on infection patterns in the community tributary to the wastewater management system and the type of treatment and disinfection processes applied to the wastewater. The majority of microorganisms of concern in reclaimed water are bacteria as shown in Table 8.

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[21] See http://www.epa.gov/safewater/contaminants/index.html.
[22] Ibid.
[23] See http://www.epa.gov/waterscience/criteria/wqctable/nrwqc-2009.pdf.
[24] See http://www.epa.gov/endo/pubs/edspoverview/development.htm.

Table 8. Most cited organisms in peer reviewed literature in relation to potential presence in reclaimed water

Organism	Percent of results	Genera	Examples of diseases and symptoms
Bacteria	68	Coliform[a]	N/A
		Aeromonas	Gastroenteritis and bacterial septicemia
		Alcaligenes	Urinary tract infections and meningitis
		Bacillus	Anthrax and food poisoning
		Bacteroides	Variety of infections in the body
		Campylobacter	Diarrhea/gastroenteritis
		Citrobacter	Neonatal meningitis and, perhaps, gastroenteritis
		Clostridium	Gas gangrene, tetanus, botulism, pseudomembranous colitis and food poisoning
		Enterococcus	Endocarditis, urinary tract infections, abdominal infection, cellulitis, and wound infection as well as concurrent bacteremia
		Escherichia	Diarrhea and urinary tract infections
		Helicobacter	Diarrhea/gastroenteritis; can lead to hemolytic uremia syndrome
		Legionella	Legionnaires' disease
		Mycobacterium	Tuberculosis and leprosy
		Photobacterium	Fish pathogen
		Pseudomonas	Skin and soft tissue infections, respiratory infections, urinary tract infections and bacteremia
		Salmonella	Diarrhea/gastroenteritis and typhoid fever
		Shigella	Diarrhea/gastroenteritis
		Staphylococcus	Skin and ear infections
		Streptococcus	Strep throat, scarlet fever, impetigo, cellulitis and toxic shock syndrome
		Vibrio	Gastroenteritis and cholera
		Yersinia	Plague
Virus	13	Enterovirus	Meningitis, paralysis, rash, fever, myocarditis, respiratory disease, diarrhea
		Hepatitis A	Infectious hepatitis
		Norovirus	Diarrhea/gastroenteritis
		Rotavirus	Diarrhea
Fungi	10	*Aspergillus*	Pulmonary, sinus or ear infections
		Cunninghamella	Pulmonary infections
		Prototheca	Skin lesions and http://www.ncbi.nlm.nih.gov/pubmed/17428884
Protozoa	6	*Cryptosporidium*	Acute diarrhea, fatal for immunocompromised individuals
		Giardia	Chronic diarrhea
Helminthes	3	*Trichuris*	Whipworm

(Source: Metcalf & Eddy, 2007; Bukhari et al., 2009; http://lib.bioinfo.pl/meid:22587; http://www.cehs.siu.edu/fix/medmicro/clost.htm; http://www.merk.com;

http://www.ncbi.nlm.nih.gov/pubmed/12102234; http://www.textbookofbacteriology.net/streptococcus.html; http://www.cdc.gov; http://www.medscape.com/viewarticle/409748_2; http://www.ncbi.nlm.nih.gov/pubmed/17428884)

a. Though not a genera, coliform is included because of wide usage in water literature; coliform is an indicator organism and as such is not pathogenic, but is used to estimate the presence of pathogens.

The ability to routinely measure specific pathogens in treated wastewater is limited by the availability of reliable and sensitive analytical methods. Consequently, there is very little specific pathogen data available and surrogate parameters, such as coliforms, must still be used to characterize desired treatment levels. The advent of newer, molecular-based analyses, particularly polymerase chain reaction, may be much more sensitive, but more work is needed to link results and organism viability before these methods can be used for compliance monitoring or risk assessment. Thus, compliance for pathogens (as contained in most state regulations) is based on coliform concentrations; Texas regulations establish limits and allow reclaimed water providers to select either fecal coliforms, *Escherichia coli* or *Enterococci* as the indicator organism for demonstrating compliance with disinfection requirements.

Most bacteria associated with waterborne diseases, including typhoid fever, cholera, bacillary dysentery and gastroenteritis, are considered to be relatively susceptible to chemical disinfection practices, such as chlorination and chloramination, and thus can be effectively controlled by wastewater reclamation processes (Metcalf & Eddy, 2007).

Viruses typically are more resistant to environmental stresses than many bacteria are, although some viruses persist for only a short time in municipal wastewater. Numerous studies have used viruses as model organisms to determine the fate of microorganisms because viruses can be more resistant to disinfection than bacteria and small in size, which makes them least removed by filtration (Bukhari et al., 2009). Viruses can persist in a variety of environments including on inert surfaces (Mahl and Sadler, 1975), soils (Vaugh et al., 1978), and in some reclaimed waters (U.S. EPA, 2004). Studies of soil aquifer treatment of filtered disinfected effluent, using bacteriophage as a tracer, have shown that a 7-log reduction in bacteria can occur within approximately 100 feet of travel through the subsurface (Fox et al., 2001).

Cryptosporidium and *Giardia* are the most common enteric protozoan parasites agents associated with reported waterborne disease outbreaks (Hrudey and Hrudey, 2007). In water and wastewater, protozoa may produce cysts or oocysts that aid in their survival. As a result, some of these organisms, including *Cryptosporidium* are highly resistant to chlorine disinfection and must generally be controlled by other means, such as filtration, ultraviolet radiation, ozone oxidation, membrane filtration, soil aquifer treatment, or riverbank filtration (Drewes and Khan, in press). Methods to evaluate protozoa are hampered by the inability to differentiate viable and infectious cysts from non-infectious cysts.

Algal growth in reclaimed water systems can cause serious aesthetic problems, can increase turbidity, can be associated with odors related to hydrogen sulfide production, and can impact the delivery of water through sprinklers and drip irrigation emitters (Bukhari et al., 2009). High algal concentrations can favor the proliferation of sulfate-reducing bacteria that transform sulfate to hydrogen sulfide creating odors and potentially causing corrosion (Miller and Mancl, 1997). Freshwater blue-green algae have the potential to produce toxins, such as microcyctins, nodularins, cylindrospermopsin, and saxitoxins, many of which are hepatotoxic and some are neurotoxic (Bukhari et al., 2009; Dewes and Khan, (in press)).

6.1.2. Nutrients

Treated municipal effluents may contain nitrogen and phosphorus in concentrations that can present issues for water reuse. For non-potable reuse projects, nutrients can lead to algal growth that causes maintenance issues in distribution and storage systems, and can lead to conditions that favor formation of odors. Nitrogen present in reclaimed water may also cause groundwater degradation where reclaimed water is used for agricultural or landscape irrigation. For indirect potable reuse projects, nitrogen in reclaimed water could result in degradation of groundwater or surface water. For surface water augmentation projects, eutrophication of drinking water reservoirs due to phosphorus may be of concern by causing nuisance levels of algae and aquatic vegetation, toxic algae, low dissolved oxygen levels, imbalance of aquatic species, aesthetic issues, and formation of organohalides during drinking water disinfection (Walker, 1983; Metcalf & Eddy, 2007). Thus, nutrient removal may be necessary for projects depending on the use and site specific requirements that must be met.

6.1.3. Trace metals

Trace metals in municipal wastewater can originate from industries and domestic uses of water. Pretreatment programs have substantively reduced the discharge of metals whereby most water reclamation facilities can meet drinking water standards for metals in the influents to their treatment plants. In addition, conventional secondary biological treatment is effective at removing metals via adsorption to solids. In some cases, metals concentrations in the final effluent can exceed water quality criteria for protection of aquatic life, particularly for copper. The primary source of copper is leaching from residential copper plumbing caused by corrosive water conditions. In some cases, even pollution prevention strategies, such as the addition of corrosion control chemicals to the water supply, have not obtained the reductions needed to comply with water quality criteria for protection of aquatic life (WERF, 2000). For situations where a reuse application involves discharge to a water of the United States and copper compliance cannot be obtained through conventional means, possible resolutions range from changing the state plumbing code to allow for the use of plastic rather than copper piping, seeking regulatory relief via a change to a water quality standard, or providing additional treatment.

6.1.4. Salts

Salts are ionic compounds containing the cations sodium, boron, calcium, magnesium, and potassium, and the anions bicarbonate, carbonate, chloride, nitrate, phosphate, sulfate, and fluoride. Salts are commonly measured by water quality parameters that measure combinations of ions, such as total dissolved solids and electrical conductivity. All domestic, commercial, and industrial uses of public water supplies have the potential to increase the salt concentrations in municipal wastewater. The minerals may come from homes and businesses through routine use of water, from regeneration of automatic water softeners, or from the water supply itself. Some agencies have sought to control the use of automatic softeners in industries and homes. Industrial softeners can be controlled through pretreatment programs. The ability of a wastewater agency to restrict the use of residential automatic softeners is often limited by state law and/or is difficult to implement due to the public's desire to use softeners and the influence of the water conditioning industry. Salts are of concern for water reuse projects since they can potentially degrade surface or groundwater quality or conflict with water quality needs for industries. Salts also can have impacts on plants or turf based on the guidelines shown in Table 9.

Table 9. Water quality guidelines for irrigation

Issue	Related constituents	Units	No problems	Increasing problems	Severe problems
Salinity[a]	Total dissolved solids	mg/L	< 750	750 - 3,000	> 3,000
Permeability	Total dissolved solids	mg/L	> 500	500 - 200	< 200
Specific ion toxicity	Sodium absorption ratio	Ratio	< 3	3.0 - 9.0	> 9.0
	Chloride	mg/L	< 142	142 - 355	> 355
	Boron	mg/L	< 0.5	0.5 - 2.0	2.0 - 10
Specific ion toxicity from foliar absorption	Sodium	mg/L	< 69	> 69	N/A[c]
	Chloride	mg/L	< 106	> 106	N/A
Miscellaneous	Ammonia/Nitrate[b]	mg/L	< 5	5 - 30	> 30
	Bicarbonate	mg/L	< 90	90 – 520	> 520
	pH	pH units	6.5 - 8.46	< 6.5 or > 8.46	N/A

(Source: Ayres and Westcott, 1976)

a. Plants vary in tolerance to salinity.

b. For sensitive crops.

c. Not applicable (N/A).

For some indirect potable reuse projects, the application of dilution, nanofiltration, and/or other types of membrane treatment may be required to remove salts to meet water quality standards or other site specific requirements.

6.1.5. Organic chemicals

The organic chemical content of reclaimed water has historically caused concern as a potential source of chronic human health effects, especially carcinogenic, mutagenic, or teratogenic responses to long-term exposure to low concentrations, or a source of adverse effects to aquatic life and wildlife. Examples of organic chemicals that can be present in treated reclaimed water are presented in Table 10.

Table 10. Examples of organic chemicals that may be present in reclaimed water

Category	Examples
Surfactants	Linear alkylbenzene sulphonates, Alkane ethoxy sulphonates
Industrial products byproducts	Bisphenol A, Chlorinated benzenes, Ethylenediaminetetraacetic acid, Polychlorinated biphenyls, Polyaromatic hydrocarbons
Volatile organics	Carbon tetrachloride, Methylene chloride, Trichloroethylene, Tetrachloroethylene, Toluene
Pesticides or their metabolites	Atrazine, Chlordane, Diazinon, Dichloro-diphenyltrichloroethane, Lindane, Pyrethroids
Algal toxins	Cylindrospermopsin, Microcystins
Disinfection byproducts	Chlorate, Chlorite, Formaldehyde, Haloacetic acids, Nitrosomines, Trihalomethanes
Pharmaceutical residues	Analgesics (Ibuprofen, Naproxen), Antibiotics (Cephalexin, Amoxicillin, Sulfamethoxazole), Beta blockers (Atenolol), Cholesterol lowering (Simvastatin, Gemfibrozil), Epileptic seizures (Carbamazepine, Primidone), Oral contraceptives (Ethinylestradiol), Sedatives (Temazepam),
Estrogenic and androgenic hormones	17β-estradiol, Estrone, Testosterone
Personal care products	N,N-diethyltoluamide, Triclosan, Tris(2-chloroethyl) phosphate

(From Drewes and Kahn, in press, Table 16-4)

Traditionally, organic matter has been measured using surrogates such as biochemical oxygen demand, chemical oxygen demand, and total organic carbon. Although these constituents have no direct health significance, they are used to monitor the efficacy of existing treatment processes or to evaluate new organics removal methods. Some states use total organic carbon as a surrogate for controlling "unknown" organic chemicals for regulation of indirect potable reuse projects.

The overall load of organic chemicals in water can be more specifically quantified in terms of the dissolved organic carbon concentration, which is comprised of natural organic matter (originating from drinking water), soluble microbial products (generated during biological wastewater treatment), and small concentrations of a very large number of individual organic chemical contaminants (Drewes and Fox, 2000). These contaminants include industrial and household chemicals (pesticides, personal care products, preservatives, surfactants, flame retardants, and perfluorochemicals), chemicals excreted by humans (pharmaceutical residues and steroidal hormones), and chemicals formed during wastewater and drinking water treatment processes (disinfection byproducts) (Drewes and Khan, in press). Chemical contaminants may be present in reclaimed source waters, or may be formed as byproducts or metabolites via chemical or biological transformation during wastewater collection and treatment. Pretreatment programs have historically focused on the 126 priority pollutants, which are primarily of industrial origin.[25] As a result, the majority of these compounds, with the exception of metals, are typically below analytical detection levels in treated wastewater.

Additionally, as analytical methods are modified to permit the detection of very low levels of contaminants (at nanograms per liter or less), more compounds will be found. It is important to acknowledge that it is not feasible to identify all potential organic chemicals in reclaimed water. Moreover, the ability to detect a compound does not necessarily translate to human or ecological health concerns.

Trace organics that can be found in treated wastewater include:

- Anionic surfactants, which are used in commercial and domestic detergent products. Conventional wastewater treatment can effectively reduce the concentrations of these compounds to the micro-gram per liter level (Drewes et al., 2009). Treatment for reclaimed water may need to be directed at deriving concentrations that are not of ecologic concern.
- Synthetic industrial chemicals, such as plasticizers and heat stabilizers, biocides, epoxy resins, bleaching chemicals and byproducts, solvents, degreasers, dyes, chelating agents, polymers, polyaromatic hydrocarbons, polychlorinated biphenyls, and phthalates (Drewes and Khan, in press). Biological treatment can significantly reduce these contaminants in reclaimed water to levels usually below drinking water standards (Trenholm et al., 2008); however many of these chemicals lack water quality standards.
- Volatile organic compounds such as solvents. Many of the most common compounds are addressed through pretreatment programs. Even so, some compounds, such as perchloroethane and trichloroethane, once in groundwater as a result of industrial contamination have very limited sorptive retardation and negligible, if any, attenuation (Rivett et al., 2001). Thus, they are considered to be conservative and may need to be addressed as part of a water reuse program (Drewes and Khan, in press).
- Pesticides and insecticides. These compounds can enter municipal wastewater systems in a number of ways including stormwater influx, use of pet shampoos, washing fruits and vegetables, and use of insecticide repellants and washing human skin (Drewes and Khan, in press). Pesticides are created to be resistant to environmental stresses and to be toxic to weeds and pests, and thus may need to be addressed as part of a water reuse program, depending on the constituent and concentration.
- Pharmaceuticals (and their active metabolites). More than 3,000 pharmaceuticals are currently approved for prescription use in the United States and thousands of other compounds are approved for over the counter use, are used as ingredients in personal care products, or are used as adjuncts in the formulation of these other materials (Bruce et al., in press). The primary route by which these compounds enter wastewater treatment systems is by excretion of human feces and urine. Secondary routes include disposal of unwanted medicines, and bathing, washing, and laundering (Daughton and Ruhoy, 2009).

[25] See 40 Code of Federal Regulations at 401.15.

These activities release compounds remaining on skin from use of high-content dermal applications or from excretion to skin via sweating. The presence of pharmaceutical compounds in water and wastewater has been of significant concern for the last decade, including public reactions to reconnaissance surveys conducted by researchers such as the U.S. Geological Survey. Specific concerns have not been raised for most classes of drugs, but issues regarding potent endocrine disrupting compounds, aquatic toxicity, and the spread of antibacterial resistance could have significant ecological implications (Ternes et al., 2004). While there are no definitive requirements or guidance on how to manage these compounds for water reuse applications, they are typically only present at very low concentrations (in the part per trillion level or lower).

Guo et al. (2010) looked at the occurrence, fate and transport of pharmaceuticals and personal care products and other organic wastewater contaminants in three major drinking water sources in California, including the impact of wastewater discharges, many of which meet California standards for reuse of water for unrestricted recreation and landscaping. Of the 126 samples analyzed for the project, one surface water source had no detectable levels of any of the analytes evaluated. All other samples had one or more analytes detected at or above the corresponding method reporting level. The five most frequently detected chemicals were caffeine (stimulant), carbamazepine (anti-convulsant), primidone (anti-convulsant), sulfamethoxazole (antibiotic), and tris(2-chloroethyl) phosphate (flame retardant). At the sample sites upstream of wastewater treatment plant discharges in all three watersheds, the concentrations of selected pharmaceuticals and personal care products, except for caffeine, were low (i.e., ≤ 13 ng/L), pointing to wastewater discharges as the primary contributing source. Caffeine represented an exception, with other potential sources such as urban runoff and plants that produce caffeine.

Another study that is currently underway, sponsored by the Water Environment Research Foundation, is assessing the environmental risks of using reclaimed water for golf course turf irrigation by looking at the fate of pharmaceuticals, personal care products, and endocrine disrupting chemicals that may be present in reclaimed water. This study will be completed in 2011.

With regard to new drugs in production, Fox et al., 2009 looked at trends in the future manufacture and distribution of pharmaceutical and personal care products by analyzing information on the research, development, production, and utilization of pharmaceutical compounds. This work has identified over 2,000 pharmaceutical agents within the research and development pipeline that may reach approval. Of this group, the top 10 therapeutic categories were cancer, central nervous system, infectious disease, cardiovascular, diabetes and metabolic, pulmonary, pain/inflamation, blood diseases, gastrointestinal, and dermatologic categories shown in Figure 3.

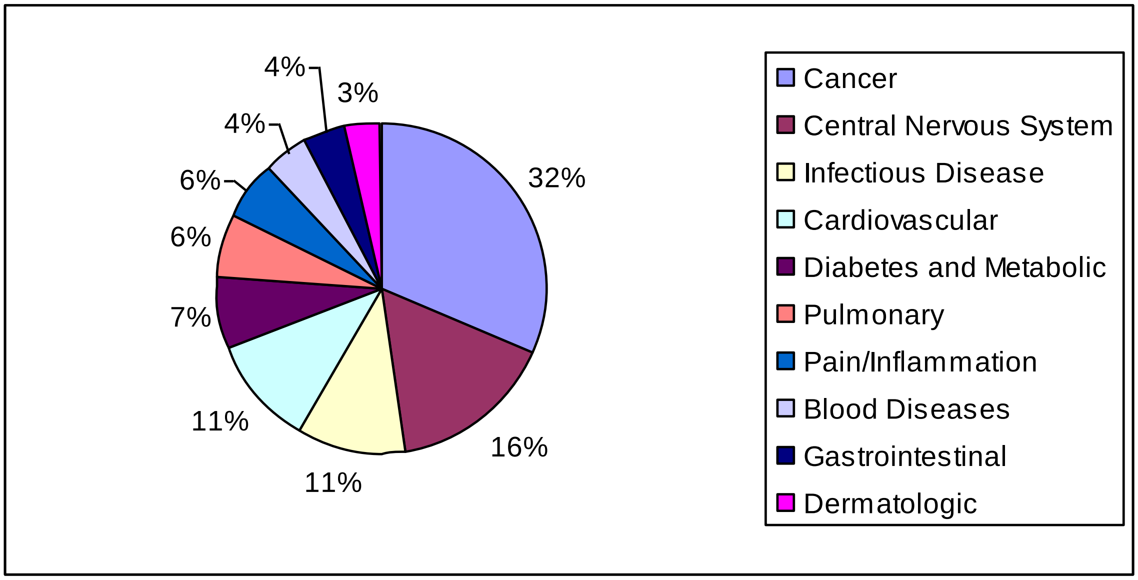

Figure 3. Top 10 drug categories in production (Fox et al., 2009; Nellor et al., 2009)

One of the big trends in this group of pharmaceuticals is the production of oral chemotherapy agents. Another trend is pegylation, the process by which polyethylene glycol chains are attached to another molecule, normally a drug or therapeutic protein to enhance the delivery of therapeutic agents. This modification shields the drug thereby allowing it to remain in the body for a longer time period, and thus it is used to treat individuals within therapeutic ranges for a longer period of time. The Persistence Bioconcentration Toxicity Profiler was used to estimate the persistence of the target compounds during wastewater treatment and soil aquifer treatment by estimating half-lives in water. The results indicated that over 90 percent of these compounds are compounds are not potentially persistent.

- Endocrine disrupting chemicals. Hundreds of chemicals, including certain personal care products and hormones (natural and manmade), have been purported to be endocrine disrupting chemicals based on a variety of different criteria (WHO, 2002; IEH, 2005). The water resource community and public have become increasingly aware of reproductive disorders reported in fish, reptiles, and amphibians collected from waters in the United States. Research has shown that endocrine disrupting chemicals present in wastewater effluent can induce feminization of fish, usually characterized by an increase in the production of the protein vitellogenin, which is an essential precursor for egg production in fish, or other conditions such as alterations in sex hormone levels, and development of intersex conditions (Snyder et al., 1999; Falconer et al., 2006; Sumpter and Johnson, 2008). The compounds present in reclaimed water that may be of significance are the steroid hormones and nonylphenol and related compounds. Other potential endocrine disrupting chemicals are usually present in low concentrations in reclaimed water (Bruce et al., (in press)). There are no definitive requirements or guidance on how to manage these compounds for water reuse applications.

- Anti-bacterial agents. These chemicals, such as triclosan, are commonly used in a number of household products including toothpaste, deodorants, detergents, and soaps. Triclosan has been frequently detected in wastewater effluents (Trenholm et al., 2008). There are no definitive requirements or guidance on how to manage these compounds for water reuse applications.
- Perfluorochemicals. This is a family of manmade chemicals that have been used for decades to make products that resist heat, oil, stains, grease, and water. Common uses include nonstick cookware, stain-resistant carpets and fabrics, as components of fire-fighting foam, and other industrial applications. Perfluorochemicals are potentially toxic to aquatic life. They have been found in water and wastewater (Schultz et al., 2006; Plumlee, et al., 2008). In 2009, the U.S. Environmental Protection Agency issued Provisional Health Advisory water values for perfluorooctanoic acid (0.4 µg/L) and perfluorooctane sulfonate (0.2 µg/L) in response to the potential for leaching of these compounds into groundwater from land application of biosolids (U.S. EPA, 2009b). The health advisories are guidance values and provide technical information on health effects, analytical methodologies, and treatment technologies associated with drinking water contamination. Perfluorochemicals have been determined to be ubiquitous contaminants in wastewater outfalls and serve as a source to "down-stream" drinking water supplies (Quinones and Snyder, 2009).
- Disinfection byproducts. These compounds are formed by reactions between disinfectants and other constituents in wastewater. Of particular significance for water reuse are the trihalomethanes and haloacetic acids, which are regulated under the drinking water standards program. These particular compounds can be formed during disinfection with free chlorine in the absence of ammonia (or when ammonia is present in low concentrations). N-nitrosodimethyamine is another important disinfection byproduct that is formed during chloramination of wastewater (Sedlak et al., 2005). It has become the key parameter used to design advanced oxidation systems for some indirect potable reuse projects. Studies have shown that some of the precursors to N-nitrosodimethyamine formation can originate from industrial discharges and from the use of polymers for solids removal and foam control during wastewater treatment (Neisses, et al., 2003; Sedlak, et al., 2005). The principal precursor is dimethylamine, either the nascent compound or the functional group on polymers or resins (Najm and Trussell, 2001). Ozone treatment of reclaimed water may result in the formation of several groups of disinfection byproducts such as bromate and aldehydes (Wert et al., 2007). Bromate is a suspected human carcinogen and some aldehydes, including formaldehyde and acetaldehyde, have been classified as probable human carcinogens (2006, Quiñones et al.). Bromate formation may be hindered by the presence of ammonia (Snyder, 2008).

6.2. Treatment mechanisms

The level of treatment and specific treatment mechanism required for individual water reclamation facilities vary according to the specific reuse application and associated water quality requirements. The simplest systems involve solid/liquid separations processes and disinfection, while more complex systems involve combinations of different unit processes that apply multiple barriers through physical, chemical, and biological treatment, as well various management techniques (Adin and Asano, 1998). In addition to the liquid stream treatment unit processes, a method for handling treatment residuals must also be considered. There will be an incremental increase in total residuals to be handled with each successive unit process that is added to the treatment train, and for some systems residuals will include brine wastes. Information on the different treatment mechanisms is presented in this section.

6.2.1. Physical/Chemical

Physical/chemical treatment pertains to any of the mechanical or chemical processes used individually or in combination to modify the quality of reclaimed water. Some of these treatment methods are used to produce tertiary reclaimed water (such as coagulation/flocculation and filtration) while others are considered to be advanced treatment processes (such as membrane separation and chemical oxidation) Examples of these processes and applications for removing specific pollutants are presented in Table 11.

Table 11. Physical/chemical treatment processes for water reuse

Process	Description	Target
Chemical		
Coagulation/flocculation	A chemical (coagulant) is added to water to produce flocs of suspended particulate matter and to precipitate other contaminants, such as heavy metals, phosphorus, and organics. Chemicals used for coagulants include alum, ferric chloride, lime, polymers, polyaluminum chloride, polyelectrolytes, polymer flocculants, and various prehydrolyzed aluminum or iron salts. Separation of flocs can be accomplished using sedimentation, filtration, dissolved-air flotation, low-pressure membranes (microfiltration/ultrafiltration), or a combination of any one of these technologies.	Metals; phosphorus; organics; pathogens
Ion exchange	Ion exchange is a reversible chemical reaction wherein an ion (an atom or molecule that has lost or gained an electron and thus acquired an electrical charge) from solution is exchanged for a similarly charged ion attached to an immobile solid particle. These solid ion exchange particles are either naturally occurring inorganic zeolites or synthetically produced organic resins.	“Hardness” ions; nutrients; metals; perchlorate
Electrodialysis	Electrodialysis is a membrane process that uses electric current, rather than pressure, as its driving force. When direct current is applied to two electrodes submersed in water, an electrical charge is transferred through the liquid. The electrical charge is carried by the ionic species in solution, mainly the dissolved salts. One electrode becomes the cathode, which is negatively charged. The other electrode becomes the anode, which is positively charged. Because un-like charges attract, positively charged cations in solution migrate toward the cathode and negatively charged anions migrate	Salts

Process	Description	Target
	toward the anode.	
Chemical oxidation using chlorine (free and combined), chlorine dioxide, ozone, hydrogen peroxide, titanium dioxide, or peracetic acid *(Combinations of these are called Advanced Oxidation - see Section 6.3)*	A process in which oxidizing chemicals are added to water that directly react with the constituents in water. Reduction-oxidation (or redox) reactions take place when an oxidant is added to water and electrons are transferred from the reductant to the oxidant. The constituent that gains electrons (oxidant) is reduced. The constituent that looses electrons is oxidized and referred to as the reducing agent. Ideally, no residue of oxidant should remain after treatment is completed that impacts toxicity, particularly if a surface water discharge is involved.	Odor control; hydrogen sulfide control; color; inorganics (manganese, iron, sulfate, cyanide); trace organics; algae *Also achieves disinfection via pathogen destruction (see Section 6.2.4)*
Photolysis using ultraviolet radiation	Ultraviolet radiation photolysis is the process by which chemical bonds of the contaminants are broken by the energy associated with UV[a] light. When UV photons enter a medium (water, for example), they are both transmitted and absorbed by the medium and its constituents (dissolved species including organic and inorganic substances). A contaminant molecule will undergo the photolysis reaction if the molecules in water are capable of absorbing UV photons (measured by the contaminant's molar absorption coefficient) and if the energy holding the chemical bonds in the molecule together is less than the energy of the UV photons absorbed. For reclaimed water, UV photolysis is used as a method of advanced treatment to remove trace organic compounds that pass through membrane separation such as N-nitrosodimethylamine.	Trace organics[f] *Also achieves disinfection via pathogen destruction (see Section 6.2.4)*
Physical		
Depth filtration	A treatment system that involves the removal of particulate material suspended in a liquid by passing the liquid through a filter bed comprised of granular or compressible filter media (such as anthracite). Types of filters include upflow, downflow, pulsed bed, and traveling bridge. They can be operated under gravity or pressurized flow regimes. This is one of the most common treatment methods used for reclaimed water (following secondary treatment) and is applied to allow for more effective disinfection, as a pretreatment step for subsequent unit processes, and to remove chemically precipitated phosphorus (when this process is used).	Suspended solids; pathogens; phosphorous (as part of chemical treatment)
Surface filtration	A treatment system that involves the removal of particulate material suspended in a liquid via mechanical sieving by passing the liquid through a thin septum. Materials include cloth fabrics and synthetic materials. This filtration method is being used now as an alternative to granular media filters.	Suspended solids; pathogens

Process	Description	Target
Membrane filtration (microfiltration and ultrafiltration)	A treatment system that passes liquid through semi-permeable membranes to exclude particles ranging in size from 0.005-2.0 µm. MF[b] and UF[c] are differentiated based on pore size (> 50 ηm for MF and 2-50 ηm for UF). The principle types of membranes are tubular, hollow fiber, spiral wound, plate and frame, and cartridge. There are two basic flow patterns: 1) outside in; and 2) inside- out. These systems are being used for reclaimed water applications in place of depth filters and/or as pretreatment for subsequent unit treatment processes.	Suspended solids; pathogens; organics; nutrients
Dissolved air flotation	A treatment process that attaches air bubbles to particulate matter to provide buoyancy so the particles can be removed by skimming. For water reuse, this treatment has been primarily used for pond water containing algae and particles that are difficult to remove by sedimentation.	Algae; particulate matter
Air stripping	A treatment system that removes compounds from water by forcing an airstream through the water and causing the compounds to evaporate. Air stripping is typically accomplished by pumping water to the top of a tower packed with media and falls by gravity downward in a film layer along the packing surfaces. Air is blown into the base of the tower and flows upward, contacting the large surface area for mass transfer of volatile contaminants from the water into the air. The resulting air stream typically must be treated prior to release to the environment. For ammonia, removal treatment involves raising the pH to covert the ammonium ion to ammonia gas.	Ammonia; volatile organics; carbon dioxide
Membrane separation (nanofiltration and reverse osmosis)	RO[d] and NF[e] occur when a pressure greater than the osmotic pressure is applied to a solution bound by a semi-permeable membrane. In this scenario, pure water will be driven by the pressure from the more concentrated solution to the other side of the membrane and the membrane acts as a barrier to solutes. Permeate (product) water passes through the membrane and has reduced solute concentrations. A reject flow stream (retentate) is produced that contains salts and other constituents rejected by the membrane process. RO operates at pressures over 10 bar and can remove monovalent ions in the range of 98-99 percent; NF operates at pressures in the range of 5-10 bar and can remove monovalent ions in the range of 50-90 percent. Membrane separation is used for advanced treatment process for indirect potable reuse projects and industrial applications. For uses where salt removal in the 50-90 percent range is needed, NF is attractive since it produces less brine waste and uses	Salts; organics

Process	Description	Target
	less energy.	
Adsorption	Adsorption is used for the removal of substances that are in solution by accumulating them on a solids phase. Treatment is accomplished using an adsorbent material that involves passing a liquid to be treated trough a bed of adsorbent material held in a reactor or blending the adsorbent material into unit process followed by sedimentation. It is primarily used for the continuous removal of organics or as a barrier for prevention against the breakthrough of organics from other unit processes. Polar low molecular weight compounds have a lower adsorption affinity. The principle types of sorbents are activated carbon, granular ferric hydroxide, and activated aluminum. For carbon, after its adsorptive capacity has been reached, it needs to be regenerated or replaced. This can be a limitation for using carbon based on the logistics of transporting material and the disposal of waste carbon (treated as a hazardous waste).	Organics; nitrogen; sulfides; metals; odors

(Sources: Metcalf & Eddy, 2007; WEF/AWWA, 2008)

a. Ultraviolet radiation (UV).

b. Microfiltration (MF).

c. Ultrafiltration (UF).

d. Reverse osmosis (RO).

e. Nanofiltration (NF).

f. UV alone (without hydrogen peroxide) is only effective for compounds that have high quantum yields like N-nitrosodimethylamine. At germicidal doses or a magnitude higher, trace organics removal is marginal.

6.2.2. Biological

Biological treatment utilizes microorganisms in reactors to feed on dissolved and colloidal matter, and can be conducted under aerobic, anoxic/aerobic, and anaerobic/aerobic conditions as shown in Table 12.

Table 12. Types of biological treatment processes for water reuse

Name	Type	Use
Aerobic Processes		
Activated sludge	Flow through suspended growth	BOD[a] and TSS[b] removal; nitrification
Sequencing batch reactor	Batch suspended growth	BOD and TSS removal; nitrification
Trickling filter and submerged attached growth packed-bed reactor	Attached growth	BOD and TSS removal; nitrification
Trickling filter/activated sludge	Hybrid suspended and attached growth	BOD and TSS removal; nitrification

Name	Type	Use
Anoxic/aerobic processes		
Modified Ludzack-Ettinger	Flow-through suspended growth	Denitrification
Sequencing batch reactor	Batch suspended growth	Denitrification
Upflow and downflow packed bed reactors and fluidized bed reactors	Attached growth	Denitrification
Anaerobic/aerobic processes		
Phoredox and anaerobic ammonium oxidizing process	Suspended growth	BOD and TSS removal; phosphorus removal
Sequencing batch reactor	Batch suspended growth	Phosphorus removal
Membrane bioreactors	Biological and membrane systems	BOD, TSS, colloidal solids, and phosphorus removal; nitrification; denitrification

(Source: Metcalf & Eddy 2007)

a. Biochemical oxygen demand (BOD).

b. Total suspended solids (TSS).

In suspended growth processes, the microorganisms used for treatment are maintained in liquid suspension by mixing and aeration to maintain aerobic conditions. In attached growth processes, a medium (fixed packing, rotating disks, and granular media) is used to which the microorganisms attach and form a biofilm, come into contact with the liquid, and oxidize the organic matter.

For some water reuse applications, biological treatment is used to remove nitrogen and phosphorus. Conventional activated sludge treatment only removes about 30 percent or less of nitrogen and thus additional treatment may be needed to reduce total nitrogen to lower concentrations (Metcalf & Eddy, 2007). In reclaimed water, nitrogen may be present in both ionic and non-ionic forms. Nitrogen removal can be accomplished biologically by applying a two step process known as nitrification/denitrification that uses either suspended or attached growth processes. A well operated biological nitrogen removal process would be expected to produce an effluent with negligible amounts of ammonia, less than 5 mg/L of nitrate and nitrite, and less than 1 mg/L of organic nitrogen (Drewes and Khan, in press). Some systems can achieve nitrate and nitrite concentrations from 1 to 2 mg/L (Jeyanayagam, 2005).

Phosphorus removal may also be required in cases where aquatic growth or biofouling may be of concern. It can be achieved biologically using different types of combined anaerobic/aerobic processes to remove phosphorus followed by precipitation and filtration to remove any residual orthophosphate (if necessary). Sedlak (1991) and Krasner et al. (2008) have reported typical phosphorus concentrations in biological nutrient systems designed to treat nitrogen and phosphorus in the range of < 0.1 to 0.6 (Drewes and Kahn, in press) mg/L. Some systems can achieve phosphorus concentrations of 0.1 mg/L and particulate phosphorus following solids removal less than 0.05 mg/L (Jeyanayagam, 2005).

Membrane bioreactors are another option for providing enhanced organics, solids, and nutrient removal by combining biological treatment with an integrated membrane system. A recent survey of vendors indicated that a 250 percent increase in membrane bioreactor installations has occurred between 2004 to 2008 (Decarolis et al., 2009). The general types of membrane bioreactors are external pressure driven membranes, integrated submerged membranes, external submerged membranes, and external submerged rotating membranes. Membranes are typically hollow fiber or fixed plates. These systems offer advantages for water reuse treatment because they produce a high quality of water and have a small footprint. The membrane pore size can range from 0.04 to 0.4 µm, resulting in highly clarified product water low in biochemical oxygen demand, suspended solids, turbidity, and bacteria similar to clarified secondary effluent that has been treated using microfiltration (Metcalf & Eddy, 2007). Membrane bioreactors can also be used to remove nutrients.

The Water Environment Research Foundation is currently conducting a research study entitled "Trace Organic Compounds Removal during Wastewater Treatment - Categorizing Process by their Efficacy in Removal of a Suite of Indicator Trace Organic Compounds." The overall goal of the study is to measure and predict the removal of trace organics (primarily constituents of emerging concern) with different physical/chemical properties during conventional wastewater treatment, including biological treatment. Detailed objectives include identification of suitable trace organics to characterize treatment performance; determination of full-scale wastewater treatment plant mass balances of the selected trace organics to better understand fate and transport; development of functional relationships between critical process parameters and trace organic removal efficiencies for various conventional unit operations; and development of a strategy and model to describe and predict trace organic removal efficiencies. The results of the project should be available in 2012.

6.2.3. Natural systems

Different natural treatment systems, such as bank filtration, aquifer recharge and recovery, soil aquifer treatment, or wetlands have been applied in many countries throughout the world to improve the quality of reclaimed water. Considering their low carbon footprint and energy needs, there is now renewed interest in these methods. Natural treatment systems provide attractive alternatives to other forms of treatment because they are robust and, if properly designed and operated, provide a comprehensive, sustainable treatment of multiple contaminants present in wastewater. These systems are also used to purify surface waters used for drinking water that have been impaired by wastewater discharge. Natural treatment systems rely on natural phenomena comprising different physical, chemical and biological removal mechanisms taking place during passage through a surface water body or subsurface environment for the improvement of water quality. Fono et al. (2006) evaluated the attenuation of a suite of wastewater-derived contaminants in the Trinity River under conditions when wastewater effluent accounted for nearly the entire flow of the river over a travel time of approximately 2 weeks. Concentrations of ethylenediamine tetraacetate, gemfibrozil, ibuprofen, metoprolol, and naproxen all decreased between 60 percent and 90 percent as the water flowed downstream. Biotransformation, rather than photolysis, was the key attenuation mechanism. Studies conducted in the Santa Ana River in southern California, an effluent dominated stream, have shown that photolysis was a key attenuation mechanism for three pharmaceuticals, with removals ranging from 63 to 100 percent over 7 miles of river flow (Gurr et al., 2006).

The suitability and performance of such natural treatment systems, however, depend on multiple factors, such as flow conditions and morphology of a surface water body; hydrogeological conditions of the subsurface; source water quality; process conditions applied; and water quality goals to be achieved by the treatment. Natural treatment processes can be classified into surface and subsurface systems. Natural surface systems include natural or constructed wetlands as well as surface reservoirs.

6.2.3.1. Subsurface Systems

Managed aquifer recharge is defined as the infiltration or injection of a source water, such as river or lake water, reclaimed water, or urban stormwater, into an aquifer under controlled conditions with the intention of storage and/or treatment of water and in some cases with the intention to augment drinking water supplies. Water can be introduced into the aquifer by a number of methods including infiltration via basins or galleries, or by use of injection wells. The use of managed aquifer recharge has the potential to provide benefits for water resources and environmental management as it can augment quantity as well as improve the quality of water. There are different managed aquifer recharge systems designed to increase the quantity and improve the quality of water. Managed aquifer recharge systems for water quality improvement or water treatment include:

- Bank filtration (river or lake);
- Artificial recharge and recovery; and
- Soil aquifer treatment.

Indirect potable reuse projects that employ vadose zone infiltration, which is also known as soil aquifer treatment, normally apply tertiary wastewater treatment prior to infiltration whereas groundwater injection projects usually employ secondary or tertiary treatment followed by integrated membrane systems consisting of microfiltration and reverse osmosis, and in some cases advanced oxidation processes (Drewes and Khan, in press). The process of surface spreading has the added benefit of additional constituent removal due to transformation in the basin via volatilization and photodecomposition and during subsequent percolation, in the form of physical filtration, adsorption to soil particles, microbial biotransformation, and dilution with native groundwater (Fox et al., 2001; Snyder et al., 2004; Fox et al., 2006; Benotti and Snyder, 2009; Rodriguez et al., 2009). Natural attenuation is an attractive option because it requires no chemical inputs and does not create a waste stream for disposal. The recent detection of a variety of chemicals in municipal wastewater effluents has raised concern about the potential presence of trace organic chemicals and associated adverse health effects in water produced by indirect potable reuse systems (Focazio et al., 2008; La Farre et al., 2008; Mompleat, et al., 2009; Wells, et al., 2009).

Several mechanisms are responsible for improvement of water quality during travel through subsurface systems, where the water is subject to a combination of physical, chemical and biological processes, such as 1) filtration, 2) solution-precipitation, 3) ion exchange, 4) sorption desorption, 5) complexation, 6) redox reactions, 7) microbial biodegradation, and 8) dilution, all of which significantly improve water quality (Kuehn and Mueller, 2000; Hiscock and Grischek, 2002; Drewes, 2009). Water quality improvements during managed aquifer treatment include removal of organic matter, removal of suspended solids and odorous compounds, reduction and inactivation of pathogens, reduction of nitrogen species, and attenuation of trace organic chemicals.

Soil aquifer treatment is a managed aquifer recharge as well as wastewater treatment technology which, in combination with other available "above-ground" wastewater treatment technologies, can produce reclaimed water of acceptable quality for indirect potable reuse (Snyder et al., 2005; Fox et al., 2006). It is a low cost and appropriate option for wastewater reclamation. It is also considered appropriate for replenishment of underground water to avoid exhaustion of groundwater resources and lowering of groundwater levels. Furthermore, artificial recharge of groundwater basins with reclaimed water subject to soil aquifer treatment contributes to the sustainability of surface water and groundwater resources within the context of integrated water resources management (Rodriguez et al., 2009). Soil aquifer treatment has been practiced in different parts of the world using primary, secondary and tertiary effluents from wastewater treatment (Fox et al., 2001; Nema et al., 2001). Furthermore, different pretreatment and post-treatment methods have been applied together with soil aquifer treatment in order to produce water quality suitable for the intended use.

Water quality improvements are a key benefit of subsurface treatment. Removal of nitrogen species in reclaimed water through nitrification/denitrification often occurs during travel through the subsurface, as does the reduction in the concentration of dissolved organic carbon through biological processes. Phosphates and metals can also be removed but are retained in the soil by adsorption. In an indirect potable reuse system, the residual humic substances present in effluent organic matter may impart color and may serve as a precursor to disinfection byproducts if extracted water is chlorinated upon recovery, while the nitrogen rich soluble microbial products present in effluent organic matter may represent a precursor to nitrogenous disinfection byproducts (Krasner et al., 2008). In addition to concerns about bulk effluent organic matter, there are various effluent derived trace organic chemicals, including endocrine disrupting compounds, pharmaceutically active compounds, and ingredients in personal care products that are present in reclaimed water (Snyder et al., 2004). Research has demonstrated that subsurface treatment is efficient in transforming biodegradable trace organic chemicals (Drewes et al., 2003; Snyder et al., 2004, Rauch-Williams et al., in press).

6.2.3.2. Constructed Treatment Wetlands

There are two general types of constructed treatment wetlands: surface flow and subsurface flow wetlands. A surface flow wetland is very similar to a natural marsh wetland with respect to vegetation and hydrologic regimes. Water flows above ground through an area containing aquatic plants. For a subsurface flow wetland, water flows below ground through a gravel and/or soil media bed with aquatic plants growing above the media and the plants' root systems growing into the media.

The treatment mechanisms that occur in the two types of constructed treatment wetlands vary. Often, a specific contaminant may be affected by two or more mechanisms. This may occur simultaneously or sequentially, depending upon the type of contaminant and its locations within the wetland (Wallace and Knight, 2006). In surface flow wetlands, treatment includes physical processes (such as settling and volatilization), chemical processes (such as absorption, photolysis, and chemical precipitation), and biological processes (such as microbial degradation and plant uptake) (Wallace and Knight, 2006). In subsurface flow wetlands, treatment processes also include physical, chemical, and biological mechanisms. The subsurface wetland media may also provide more surface area for microbial growth and microbial biofilters (Wallace and Knight, 2006).

In the case of the surface flow constructed treatment wetlands, which can treat large quantities of water, key design and operating considerations include hydraulic and mass loading rates, hydraulic residence time, water depth, plant density, and flow distribution. Thermal effects and oxygen transfer into the water column are also important. Aquatic plants play a key role in the successful treatment performance of surface flow constructed treatment wetlands as they provide the surface area and carbon source to support the microbial functions. Subsurface flow constructed treatment wetlands are better suited for treating small volumes of water. Therefore, they are generally not considered to be a viable process for large volumes of reuse water. Key design and operation considerations for subsurface constructed treatment wetlands are the type and depth of media, the hydraulic loading rate, and the hydraulic detention time. Constructed wetlands are also prone to hydraulic short circuiting and thus flow paths must be managed. In addition, wetlands often require active management (such as harvesting or removal of plants).When compared to surface flow constructed treatment wetlands, subsurface constructed treatment wetlands are less dependent on aquatic plants to sustain their treatment processes (Wallace and Knight, 2006).

For water reuse applications, constructed treatment wetlands are typically used to provide polishing treatment following treatment at a conventional wastewater treatment facility for constituents such as biochemical oxygen demand and nutrients, and/or serve as a as one treatment barrier within a multiple barrier system for indirect potable reuse projects. Treatment performance is site specific (Kadlec and Wallace, 2009). Other constituents, such as metals and pathogens have been shown to be removed through the wetland treatment processes (Gersberg et al., 1989; Williams et al., 1995; Hench et al., 2003; Kadlec and Wallace, 2009). For pathogens, despite marked reductions, the concentrations may not comply with final discharge limits for receiving bodies of water. Wildlife can also contribute pathogens to wetlands effluents. The effectiveness of constructed wetlands for removing hormones and pharmaceuticals can vary. For hormones including 17β-estradiol and 17α-ethinyl estradiol, removals in test cells ranged from 36 percent (Gray and Sedlak, 2005) up to 99.9 percent (Alan Plummer Associates, Inc., et al., in press). For the Alan Plummer Associates Inc. study, estrone was not removed, while Gary and Sedlak (2005) observed elevated levels of estrone due to biotransformation, as it is a metabolite of 17α-ethinyl estradiol. Park et al. (2009) evaluated removals of pharmaceuticals in constructed wetlands. The results showed fairly good removal for some compounds (atenolol, naproxen, and triclosan) and medium to low removal for other compounds (sulfamethoxazole, dilantine, carbamazepine, diazepam and triclosan). Additional research is needed to develop a better understanding of the treatment mechanisms, their effectiveness in the reduction of wastewater derived organic compounds, and other constraints on applying constructed wetlands to water reuse projects (Park et al., 2009).

Another important feature of constructed wetlands is that they provided added value related to public perception, wildlife habitat, and recreational and educational opportunities. Furthermore, the use of constructed treatment wetlands as a component of indirect potable reuse projects in Texas has been very instrumental in gaining regulatory and public support for the projects.

In some parts of the country, wetlands have been shown to play a major role in the production and export of methylmercury, which is a potent neurotoxin that affects both humans and wildlife. While mercury pollution is a global problem, it is of special concern in areas where coal combustion emissions or legacy mining activities result in increased mercury levels in ecosystems. In Texas, mercury transport via air pollution is the major contributor to mercury water body impairments in Texas (TCEQ, 2009), which will require both interstate and international cooperation to identify mercury sources and solutions for addressing air emissions. In the meantime, the state of Texas has implemented controls on mercury emissions and discharges from wastewater point sources that will continue to reduce contribution. Thus, discharges from constructed wetlands to reservoirs could be subject to regulatory controls for mercury. Potential management tools that can be used for mitigation of biologically available methylmercury in constructed wetlands include devegetation (Windham-Myers et al., 2009), and the addition of iron to wetland sediments (Mehrotra et al., 2003; Mehrotra and Sedlak 2005; Sedlak and Ulrich, 2009). These results have laid the groundwork for future studies to evaluate the efficacy of an iron amendment at the field scale, which could demonstrate that this technique is a viable landscape-scale control on methylmercury production in wetlands.

6.2.4. Disinfection

Disinfection is the treatment of wastewater for the destruction of pathogens. Another term that is sometimes also used in describing the destruction of microorganisms is sterilization. Sterilization is the destruction of *all* microorganisms. While disinfection indicates the destruction of pathogens, no attempt is made in wastewater treatment to obtain sterilization. However, disinfection procedures properly applied to wastewater will result in a quality of reclaimed water that is safe for its intended use.

There are chemical and physical processes that can be used for disinfection. Chlorine and hypochlorite salts (sodium and calcium) are the most commonly used disinfectants at water reclamation plants. When chlorine or hypochlorite salts are added to water, two reactions take place: 1) hydrolysis to form hypochlorous acid and 2) ionization to convert hypochlorus acid to hypochlorite ion. The total quantity of hypochlorus acid and hypochlorite ion present in water is called free chlorine. The distribution of the two species is important because hypochlorus acid the more effective disinfectant. Wastewater can contain ammonia (even after treatment), which reacts with hypochlorus acid to form chloramines. Chloramines also serve as disinfectants, but are slow reacting. When chloramines are the only disinfectants, the measured chlorine residual is defined as combined chlorine. Breakpoint chlorination is the process whereby enough chlorine is added to react with all oxidizable substances in the water such that if additional chlorine is added is will remain as free chlorine. Disinfection can form disinfection byproducts such as trihalomethanes using free chlorine or N-nitrosodimethylamine using combined chlorine.

Ultraviolet radiation is also used for disinfection of reclaimed water. The germicidal portion of the ultraviolet radiation band is between 200 to 320 nm, with wavelengths between 255 to 265 nm considered to be the most effective (Metcalf & Eddy, 2007). UV radiation is produced using lamps containing mercury vapor and are categorized by internal operating parameters as either low presssure/low intensity, low pressure/high intensity, and medium pressure/high intensity systems.

Ozone has also been used as a disinfectant for reclaimed water. Ozone is typically produced by radiochemical reaction by electrical discharge (Metcalf & Eddy, 2007). Ozone is a highly reactive oxidant. Bacterial kill occurs because of cell wall disintegration. It is also effective at virus inactivation, and may be more effective than chlorine.

A comparison of the advantages and disadvantages of ultraviolet disinfection in comparison to chemical disinfection are presented in Table 13.

Table 13. Advantages and disadvantages of ultraviolet disinfection over chemical disinfection

Advantages	Disadvantages
Effective at inactivating most bacteria, viruses, spores and cysts	Dosage must be sufficient to inactivate certain organisms
Eliminates the need to manage toxic, hazardous, or corrosive chemicals	Organisms sometimes amenable to reverse the destructive effects
Might not generate harmful residuals (such as disinfection byproducts)	Preventive maintenance is more intensive
Can be less labor intensive to operate	Must be designed to account for turbidity and suspended solids in wastewater that can reduce the transmittance of the ultraviolet radiation
Uses shorter contact times	Does not provide a disinfectant residual, which may be a disadvantage where a residual is desirable
Requires less space for equipment and process	
Does not require de-chlorination for releases to the environment	

Source (U.S. EPA, 2007)

A recent survey indicated 75 percent of United States publicly owned treatment works use chlorine based disinfectants (Leong et al., 2008). Ultraviolet light and ozone are also used. Some water reuse programs are combining multiple disinfectants such as chlorine and ultraviolet light due to benefits such as disinfection of a wider range of pathogens, improved reliability through redundancy, reduced disinfection byproducts, and potential cost savings (Munakata et al., 2009). There can be a delicate balance between pathogen removal and creation of disinfection byproducts when using chlorine or ozone as previously discussed. In addition, chlorine in the form of sodium hypochlorite has the potential to increase total dissolved solids in reclaimed water.

In general, chemical disinfection is conducted using a dedicated reactor taking into consideration contact time and hydraulic efficiency, concentration of the disinfectant, temperature, the type of organism, the reclaimed water quality (primarily turbidity), and the upstream treatment processes (Metcalf & Eddy, 2007). Disinfection requirements for the use of reclaimed water vary by state. For example, California water reuse regulations define disinfection (for reuse applications where a total coliform limit of 2.2/100 mL is specified) in terms of a 450 mg-min/L concentration and contact time, based on a peak dry weather modal contact time of 90 minutes. It should be noted that lower concentration/contact times may be effective for destruction of bacteria and viruses, but may have little or no impact on protozoan parasites. Concentration/contact times as high as 6,000 to 7,200 mg-min/L have resulted in 1.0 to 1.7 log inactivation of *Cryptosporidium* (Korich et al., 1990; Venczel et al., 1997).

Based on potential safety and security concerns regarding chlorine and the potential for production of disinfection byproducts, there is increased interest in alternative disinfectants. Leong et al. (2008) estimates that 21 percent of the United States publicly owned treatment works use ultraviolet light for disinfection. This form of disinfection is highly effective against chlorine resistant protozoa such as *Cryptosporidium* (for example 3 to greater than 4 log inactivation with doses of 5 to10 mJ/cm^2), and 4 log inactivation of various bacteria at doses of 2 mJ/cm^2 to less than 8 mJ/cm^2 (Bukhari et al., 2009). For viruses, higher ultraviolet light doses (27 mJ/cm^2 to greater than 100 mJ/cm^2) may be required to achieve 4 log reductions. Adenoviruses, which are susceptible to free chlorine, are more resistant to ultraviolet light (Munakata et al., 2009). Ultraviolet light disinfection is instantaneous and no disinfectant residuals are maintained in the treated reclaimed water, which may lead to microbial re-growth issues where the reclaimed water is distributed for reuse applications (Jjemba et al., 2009).

The combination of physical and chemical treatment results in incremental removal of pathogens as shown in Table 14.

Table 14. Removal of coliforms by unit process

Process	Log removal
Coarse screens	0 – 0.7
Fine screens	1.0 – 1.3
Grit chambers	1.0 – 1.4
Plain sedimentation	1.4 – 2.0
Chemical precipitation	1.6 - 1.9
Trickling filters	1.9 - 2.0
Activated sludge	1.9 - 3.0
Depth filtration	0 –-1.0
Microfiltration	2 - >4
Reverse Osmosis	>4 - 7
Disinfection with chlorine	4 - 6

(Source: Metcalf and Eddy, 2007; Table 11-4)

Other types of physical treatment facilities can provide additional removal of pathogens. Membrane bioreactors can remove up to 5 logs of *Escherichia coli* and *Enterococci*; 1.7 logs of enterovirus; and 1.0 log of norovirus (Bukhari et al., 2009). Membrane separation processes, via their small pore size, can remove various microbes. Microfiltration in combination with reverse osmosis can achieve 2 to 6 logs of bacterial virus removal, and greater than 7 logs removal of oocysts based on research done by the Orange County Water District, Singapore Public Utilities District, and the City of San Diego, California. Microfiltration and reverse osmosis are also capable of removing viruses.

Advanced oxidation systems also provide substantive levels of disinfection. The Trojan UVPhox system installed at the West Basin Municipal Water District, California has been validated to achieve a minimum inactivation of 4 logs of bacterial virus per reactor with a minimum ultraviolet radiation dose of 115 mJ/cm^2. With four reactors on line, the West Basin system can achieve a theoretical 16-log inactivation.

6.2.4.1. Distribution System Issues

For the most part, regulation of reclaimed water quality for non-potable reuse is focused on treated effluent quality and not at the use application. However, biodegradable material and nutrients remaining in reclaimed water have the potential to contribute to the formation of biofilms in distribution systems that can lead to regrowth of microorganisms and cause operational and aesthetic issues (such as odors). Several researchers have detected opportunistic pathogens, including *Legionella* and *Mycobacterium*, in reclaimed distributions systems (Pang and Liu, 2006; Jjemba et al., 2009). Biofilm can also clog irrigation systems. The WateReuse Research Foundation is sponsoring a project that will identify best management practices to assist reclaimed water agencies in maintaining high water quality in reclaimed water storage and distribution systems.

6.3. Advanced Oxidation

Advanced oxidation processes have been defined as water treatment oxidation processes that involve the generation of highly reactive intermediates (radicals), especially the hydroxyl radical. They can be used to destroy trace organics and microorganisms in reclaimed water. Advanced oxidation processes are characterized by a variety of radical reactions that involve combinations of chemical agents (ozone, hydrogen peroxide, transition metals, or metal oxides) and auxiliary energy sources (ultraviolet radiation, electronic current, g-radiation, and ultrasound). Examples of advanced oxidation processes include ozone/ hydrogen peroxide, ozone/ hydrogen peroxide/ultraviolet radiation, hydrogen peroxide/ultraviolet radiation, Fenton's reactions (iron/ hydrogen peroxide, photo-Fenton, or iron/ozone), titanium dioxide/ultraviolet radiation, ozone/titanium dioxide, and ozone at elevated pH (Snyder et al., 2003, Ikehata et al., 2006; Metcalf & Eddy, 2007).

Advanced oxidation processes have been found to be particularly effective for removal of refractory trace organics such as pesticides, chlorinated organics, and certain taste and odor compounds (Rosario-Ortiz et al., 2010). Advanced oxidation processes utilize the transient formation of hydroxyl radicals to degrade carbon-carbon and other chemical bonds. The range of byproducts formed is a function of the nature of the organic matter present and the relative susceptibility of specific bonds for radical attack. Accordingly, a large number of unidentified low molecular weight products are expected to be formed during advanced oxidation of complex solutions.

The performance of an advanced oxidation process is affected by such water quality parameters as pH, total organic carbon, and other chemical species that can act as initiators, promoters, or inhibitors of the chain reaction process. Carbonates and bicarbonates are powerful radical inhibitors, and the efficiency of the advanced oxidation process will decrease quickly with increasing alkalinity. Generally, advanced oxidation processes work well if the alkalinity is low (less than100 mg/L calcium carbonate). Consequently, in some waters, it may be necessary to adjust the pH or even to use softening treatment before the advanced oxidation process. High levels of natural or effluent organic matter can also increase scavenging of hydroxyl radicals, making application of advanced oxidation processes less effective and less economical in these conditions.

For potable reuse projects the most commonly used processes are:

- Hydrogen peroxide /ultraviolet radiation.
- Ozone/hydrogen peroxide.
- Ozone/ultraviolent radiation.

However, for the majority of organic contaminants, ozone alone will provide excellent oxidation. The addition of peroxide is likely warranted only in the case of the most resilient organic contaminants, such as flame retardants (Snyder et al., 2006; Wert et al., 2009). In addition to organics removal and disinfection, the advantages and disadvantages of the three processes are presented in Table 15.

Table 15. Advantages and disadvantages of advanced oxidation processes used for potable water reuse

Advanced oxidation process	Advantages	Disadvantages
Hydrogen peroxide/ultraviolet radiation (UV)	Hydrogen peroxide is stable and can be stored on site	Fouling of UV lamps, high energy process, need special UV reactors
Ozone/hydrogen peroxide	Can treat water with poor UV light transmission, does not require special UV reactors, volatile organics will be stripped from the ozone contractor (and may require treatment)	Ozone must be produced at the point of use and can be an expensive and inefficient process, high energy process, achieving the correct dosages may be difficult, ozone off-gas must be removed, can form undesirable disinfection by products
Ozone/ultraviolet radiation	Easier to control ozone dosage, UV absorbs more UV light that an equivalent dose of hydrogen peroxide, volatile organics will be stripped from the process (and may require treatment)	Ozone must be produced at the point of use and can be an expensive and inefficient process, using ozone and UV to produce hydroxide is inefficient compared to just using hydroxide, high energy process, need special UV reactors, ozone off-gas must be removed, can form undesirable disinfection by products

Source (Metcalf & Eddy, 2007; Wert et al., 2007; Trenholm et al., 2008)

Since it usually takes a combination of two technologies to create the hydroxyl radical, the efficacy of each individual technology should be evaluated based on the specific application, water quality, constituents to be treated, and cost.

6.4. Concentrate management

For many reuse applications that require removal of dissolved salts and organics, membrane separation processes, such as nanofiltration and reverse osmosis, are utilized (see Section 6.3.1). The use of membrane separation processes results in the generation of a concentrated waste stream, the concentrate fraction, as a byproduct of the purification process. It typically represents about 15 percent of the total flow treated. The concentrate is also often called brine retentate or reject water. It contains elevated concentrations of total dissolved solids and other. Other residuals resulting from membrane treatment that are important for management include wash water and waste chemical cleaning solutions since they can be either acidic or basic and may contain detergents, surfactants, or other pollutants. The management of concentrate is a significant challenge for reuse projects based on cost and limited options for disposal.

The key issues that must be addressed in the management of concentrate include: 1) volume, 2) characteristics including constituents of concern, and 3) environmental classification and regulations (Tchobanoglous, et al., 2009).

The principal objective in concentrate management is to minimize the volume that must ultimately be disposed of by recovering recyclable materials and reducing the water content of the residuals. Other considerations include minimizing environmental impacts and meeting discharge requirements established by regulatory agencies.

The methods for concentrate management include:

- Disposal to surface waters. This is considered to be the most common disposal method (Metcalf & Eddy, 2007). Salt concentrations may present compliance issues depending on the receiving water and applicable standards.
- Ocean discharge. This option is used by facilities located in coastal areas with access to ocean outfalls. There may be pollutants present in the brine (such as ammonia and metals) that may present discharge compliance issues, even with allowable mixing zones.
- Disposal to high salinity groundwater. This option may be allowed, depending on state regulations, in aquifers that are brackish or have been eliminated as a potential source of drinking water. There may be pollutants present in the brine that present discharge compliance or anti-degradation issues.
- Disposal to a wastewater collection system. The feasibility of this option would depend on the regulatory requirements applicable to the wastewater treatment plant (its ultimate receiving water and pertinent standards) and the source control requirements administered by the wastewater agency for discharges to sewerage systems. Cost may be another issue if the agency applies connection or service charge fees to such sewerage system discharges.

- Land application. The feasibility of this option would depend on the site specific conditions of the location in terms of underlying groundwater quality, permeability of the soil, concentration of the retentate, and other factors.
- Pond evaporation. This option requires large amounts of land even in arid regions. Ponds may have to be constructed using natural or synthetic liners to protect underlying groundwater.
- Deep well injection. This option could be used by facilities that may be located in areas with access to abandoned oil and gas well fields. The wastes are injected into porous subsurface formations in areas where there is no communication with potable groundwater supplies. The discharge would have to comply with underground injection regulations. Preliminary calculations indicate that approximately one well is necessary to inject 0.1 million gallons per day of brine waste into the subsurface environment (MWH, 2003).

Other options that have been considered include crystallization/landfilling, creation of wetlands, and creation of aquaculture (Sethi et al., 2006, Metcalf & Eddy, 2007).

A significant amount of research is underway evaluating concentrate management for water reuse and desalination applications, focusing on concentrate minimization and beneficial reuse (Voutchkov, 2009). The Texas Water Development Board has sponsored an extensive applied research initiative related to brackish groundwater desalination that is directed at advancing technologies for low-cost concentrate management, including 1) the Vibratory Shear Enhanced Process (patented membrane filtration technology), 2) anti-scalant deactivation, 3) precipitation and electrodialysis, and 4) silica reduction in using lime and vibratory shear enhanced processing.

6.5. Decentralized systems

Decentralized wastewater management is defined as the collection, treatment, and reuse of wastewater at or near the point of generation (Metcalf & Eddy, 2007). Examples include treatment systems for the collection, treatment, and dispersal/reuse of wastewater from individual homes, clusters of homes, isolated communities, industries, or institutional facilities, at or near the point of waste generation. Septic and neighborhood cluster systems are included among the types of treatment practices utilized.

Decentralized systems can be fully independent from centralized wastewater systems or, in the case of satellite systems, have a connection to the centralized wastewater collection system for the discharge of solids and excess flow. The primary advantage of decentralized and satellite systems with respect to water reuse is the ability to produce the reclaimed water near the point of application, obviating the need for extensive collection and distribution infrastructure systems (Tchobanoglous et al., 2009). Thus, they are most commonly used in semi-urban, rural, and remote areas. Some centralized wastewater management systems create scalping or satellite plants that siphon off water within sewersheds for treatment and localized reuse.

Satellite and decentralized systems can experience the same operational and regulatory issues as centralized systems. They also are subject to other issues, including increased influent variability, minimal staff or staffing skills for process control, monitoring and maintenance staffing issues, and special considerations for residuals management and odor control (Tchobanoglous et al., 2009).

The key issues and challenges facing decentralized systems include 1) a lack of awareness and limited experience with technology options, 2) limited design information available for implementation, 3) the need for an optimization model of infrastructure configuration, 4) development and guidance on improved systems for monitoring and control of remote processes, and 5) the need to develop and apply processes that can produce a reclaimed water with minimal operator attention and skill reliably (Tchobanoglous et al., 2009). The Water Environment Research Foundation has established a dedicated research program for decentralized treatment systems.

6.6. Treatment applications by use

Information on anticipated treatment schemes for different reuse categories is presented in Table 16, and includes recommended treatment and principal removal functions (by pollutant) and other potential treatment and management methods that might apply.

Table 16. Treatment applications for specific uses

Type of use	Recommended treatment	Principal removal function	Other potential management/treatment	Principal removal function
Urban				
Landscape irrigation	- Biological	- Organic matter & suspended solids	- Biological nutrient removal	- Nitrogen and/or phosphorus
			- Irrigation application rate	- Nutrients and salts
	- Physical (filtration)	- Particulate matter	- Use area requirements (buffer zones, signs, drying time, etc.)	- Pathogens
	- Disinfection	- Pathogens		
Storage & recreational impoundments	- Biological	- Organic matter & suspended solids	- Biological nutrient removal	- Nitrogen and/or phosphorus
	- Physical (filtration)	- Particulate matter		
	- Disinfection	- Pathogens		
Fire protection	- Biological	- Organic matter & suspended solids		
	- Physical (filtration)	- Particulate matter		
	- Disinfection	- Pathogens		
Urinal flushing	- Biological	- Organic matter & suspended solids		
	- Physical (filtration)	- Particulate matter		

Type of use	Recommended treatment	Principal removal function	Other potential management/treatment	Principal removal function
	- Disinfection	-Pathogens		
Industrial				
Cooling	- Biological - Physical (filtration) - Disinfection	- Organic matter & suspended solids - Particulate matter - Pathogens	- Nitrification -Biological nutrient removal -Buffer zones	- Ammonia - Nutrients - Pathogens
Processing	- Biological - Physical (filtration) - Disinfection	- Organic matter & suspended solids - Particulate matter - Pathogens	- Site specific	- Industry specific water quality requirements
Agricultural				
Raw food crop irrigation	- Biological - Physical (filtration) - Disinfection	- Organic matter & suspended solids - Particulate matter - Pathogens	- Biological nutrient removal - Application rate - Use area requirements (buffer zones, signs, drying time, etc.)	- Nitrogen and/or phosphorus - Nutrients and salts - Pathogens
Processed food crop irrigation	- Biological - Disinfection	- Organic matter & suspended solids - Pathogens	- Biological nutrient removal - Application rate - Use area requirements (buffer zones, signs, drying time, etc.)	- Nitrogen and/or phosphorus - Nutrients and salts - Pathogens
Fodder & fiber crop irrigation	- Biological - Disinfection	- Organic matter & suspended solids - Pathogens	- Biological nutrient removal - Application rate - Use area requirements (buffer zones, signs, drying time, etc.)	- Nitrogen and/or phosphorus - Nutrients and salts - Pathogens
Silviculture	- Biological - Disinfection	- Organic matter & suspended - Pathogens		
Environmental and Recreational				
Wetlands	- Biological - Disinfection	- Organic matter & suspended - Pathogens	- Site specific depending on designated use, applicable water quality criteria, reasonable potential to exceed standards, and anti-degradation	- Range from nutrients to priority pollutants
Stream augmentation	- Biological - Disinfection	- Organic matter & suspended - Pathogens	- Site specific depending on designated use, applicable water quality criteria, reasonable potential to exceed standards, and anti-degradation	- Range from nutrients to priority pollutants

Type of use	Recommended treatment	Principal removal function	Other potential management/treatment	Principal removal function
Landscape impoundments (no contact)	- Biological - Disinfection	- Organic matter & suspended - Pathogens	- Site specific depending on designated use, applicable water quality criteria, reasonable potential to exceed standards, and anti-degradation - Signage	- Range from nutrients to priority pollutants - Pathogens
Landscape impoundments (contact)	- Biological - Physical (filtration) - Disinfection	- Organic matter & suspended solids - Particulate matter - Pathogens	- Site specific depending on designated use, applicable water quality criteria, reasonable potential to exceed standards, and anti-degradation	- Range from nutrients to priority pollutants
Other Non Potable Uses				
Vary	- Biological - Disinfection	- Organic matter & suspended - Pathogens	- Physical (filtration)	- Particulate matter
Potable Reuse				
Groundwater recharge by surface spreading above potable aquifers	- Biological - Physical (filtration) - Disinfection - Natural systems (soil aquifer treatment, riverbank filtration)	- Organic matter & suspended solids - Particulate matter - Pathogens - Dissolved organics, pathogens, nutrients	- Wetlands - Advanced treatment (adsorption, membrane separation, chemical processes (electrodialysis or ion exchange) - Advanced oxidation - Required underground retention time - Blending with water of non-reclaimed origin	- Nutrients - Salts, trace metals, trace organics, nutrients - Pathogens and trace organics - Pathogens and time to respond to possible problems - Trace organics
Groundwater recharge by direct injection or dry wells into potable aquifers	- Biological - Physical (filtration) - Disinfection - Advanced treatment (can include carbon adsorption, microfiltration, ultrafiltration, reverse osmosis, ion exchange)	- Organic matter & suspended solids - Particulate matter - Pathogens - Particulates, salts, trace metals, trace organics, nutrients	- Advanced oxidation - Required underground retention time - Blending with water of non-reclaimed origin	- Pathogens and trace organics - Pathogens and time to respond to possible problems - Trace organics
Augmentation of surface supplies	- Biological[a]	- Organic matter & suspended solids	- Wetlands - Advanced oxidation	- Nutrients - Pathogens and trace organics

Type of use	Recommended treatment	Principal removal function	Other potential management/treatment	Principal removal function
	- Physical (filtration) - Disinfection	- Particulate matter - Pathogens - Dissolved organics, pathogens, nutrients - Particulates, salts, trace metals, trace organics, nutrients	- Required underground retention time - Blending with water of non-reclaimed origin - Advanced treatment (adsorption, membrane separation, chemical processes such as electrodialysis or ion exchange)[b]	- Pathogens and time to respond to possible problems - Trace organics
Direct potable reuse	To be determined		To be determined	

a. For projects in Texas, surface augmentation projects use advanced secondary treatment that is capable of producing reclaimed water with low biochemical oxygen demand (5 mg/L) and phosphorus (1 mg/L), sometimes followed by treatment though constructed wetlands.

b. The application of advanced treatment is state specific. Some states require advanced treatment, while others may only require advanced treatment as necessary to meet surface water quality standards.

7. Monitoring

Water quality monitoring is an important component of reclaimed water projects to insure that public health and the environment are protected. Typically reclaimed water monitoring (and compliance with regulatory requirements) is conducted at the water reclamation plant before reclaimed water is distributed for use. For indirect potable reuse projects, additional monitoring may be required. For groundwater recharge projects or salt intrusion barriers, monitoring may be required using lysimeters, monitoring wells, and/or groundwater production wells. For reservoir augmentation projects, monitoring may be required for surface water and treated drinking water. Typical monitoring programs focus on parameters with numeric water reuse criteria, including biochemical oxygen demand, turbidity, and pathogens or pathogen surrogates (such as coliform, *E. coli*, and *Enterococci*). Depending on the project and state permitting procedures, monitoring can also include parameters, such as salts, minerals, and constituents with maximum contaminant levels, to determine if the designated uses of receiving waters, both groundwater and/or surface water, are being protected. Real-time online monitoring is desirable, but with the exception of monitoring for surrogates such as total organic carbon and electrical conductivity, may not be achievable with existing analytical technology (Crook, 2010).

7.1. Monitoring for Chemicals of Emerging Concern

Recent attention has been focused on monitoring strategies for new classes of chemicals, such as pharmaceuticals, current use pesticides, and industrial chemicals, collectively referred to as chemicals of emerging concern. In February 2009, the California State Water Resources Control Board adopted a Recycled Water Policy that created an expert panel to develop recommendations for monitoring chemicals of emerging concern in reclaimed water used for indirect potable reuse via surface spreading; indirect potable reuse via subsurface injection into a drinking water aquifer; and urban landscape irrigation. The panel was charged with addressing the following questions:

- What are the appropriate constituents to be monitored in recycled water, and what are the applicable monitoring methods and detection limits?
- What toxicological information is available for these constituents?
- Would the constituent list change based on level of treatment?
- If so, how? What are the possible indicators (i.e., surrogates) that represent a suite of chemicals of emerging concern?
- What levels of CECs should trigger enhanced monitoring in recycled, ground, or surface waters?

The panel issued its final report in June 2010 (Drewes et al., 2010a), which included four specific products:

1. A conceptual framework for determining which chemicals of emerging concern to monitor. The panel recommended four monitoring categories:

   Health-based Indicators. Since thousands of chemicals potentially are present in reclaimed water and information about these chemicals is rapidly evolving, the panel developed a transparent framework to guide the prioritization of chemicals for monitoring. The framework includes four steps for identifying health-based indicators:
   - Compiling occurrence data (a "measured environmental concentration") in the reclaimed water used for a project. To be conservative, the panel elected to use secondary or tertiary reclaimed water as the source of the occurrence data even for use applications that apply advanced treatment.
   - Developing a "monitoring trigger level" based on toxicological relevance (see Section 7.2).
   - Comparing occurrence with the trigger level such that any chemical where the ratio of the occurrence and trigger level was greater than one, was prioritized for monitoring.
   - Screening the priority health-based indicators to ensure robust analytical methods are available.

   Performance-based Indicators. These are chemicals that characterize the performance of individual unit processes. An indicator compound represents certain physicochemical and biodegradable characteristics of a family of trace organic constituents. The indicator compounds are relevant to fate and transport of broader classes of chemicals and provide a conservative assessment of removal during treatment. Additional information on indicator compounds is provided in Section 7.3.

   Performance-based Surrogates. A surrogate parameter is a quantifiable change of a bulk parameter such as total organic carbon, ammonia, or conductivity, that can measure the performance of individual unit processes (often in real-time) or operations in removing trace organic compounds and/or assuring disinfection. Surrogates and indicators are intended to evaluate removal of chemicals that are known to exist but cannot be quantified. Additional information on surrogate compounds is provided in Section 7.3.

Bioanalytical Screening. The use of bioassays is recommended to characterize chemicals for which occurrence and toxicological information is presently unavailable. This category of compounds is designated as "unknown unknowns". The panel recommended further development of bioanalytical screening methods before screening can be reliably undertaken. Additional information on bioassays is provided in Section 7.4.

2. Application of the framework to identify a list of chemicals that should be monitored during the next three years. The list of recommended compounds is provided in Appendix B.

3. A sampling design and approach for interpreting results from the monitoring programs. The panel recommended a multi-phase approach for implementing the monitoring program and interpreting the resulting data (see Appendix B). The approach involves the use of multiple tiers to provide a flexible, adaptable response to increase or decrease monitoring based on the initial results, thereby providing a cost-effective means for incremental information gathering. Should compounds be consistently present at high levels, additional evaluations or actions may be warranted, such as source control or treatment. The panel also recommended strict sampling and laboratory measurement quality assurance guidelines.

4. Priorities for future improvements in monitoring and interpreting data. The panel considers the science of investigating chemicals of emerging concern to be in its early stages and recommended that the State Water Board undertake several activities that would greatly improve both monitoring and data interpretation for reclaimed water management. These activities include: i) developing and validating better analytical methods to measure chemicals of emerging concern in reclaimed water; ii) encouraging the development of bioanalytical screening techniques that allow better identification of the "unknown unknown" chemicals; and iii) developing a process to predict likely environmental concentrations of chemicals of emerging concern based on production, use and environmental fate, as a means for prioritizing chemicals on which to focus method development and toxicological investigation. These investigations should be conducted with guidance and review by an expert panel.

In addition to these recommendations, the panel recommended that the State Water Board develop a process to rapidly compile, summarize, and evaluate monitoring data as they become available. The panel further recommended that the State Water Board establish an independent review panel that could provide periodic review (every three to five years) of the proposed selection approach, reuse practices, and environmental concentrations of ongoing monitoring efforts, particularly as data from the monitoring programs become available.

7.2. Health-based indicators

Drewes et al. (2010a) used the methodologies of Snyder et al. (2010) to develop screening level human health risk-based criteria for chemicals of emerging concern potentially present in reclaimed water. Snyder et al. (2010) devised a simple, conservative approach for the development of health risk-based guidelines for chemicals of emerging concern that selects the lowest calculated level (most protective of human health) from several possible risk assessment schemes that consider the most sensitive toxicological endpoint (therapeutic dose, no observed adverse effect level, lowest observed adverse effect level, carcinogenicity) divided by appropriate uncertainty factors. The proposed approach consists of the following steps:

1. If the chemical is a pharmaceutical, select the lowest value from among comparison values derived using the following processes:
    a. Divide the therapeutic dose (on a milligram per kilogram body weight basis, based upon range of doses and age groups for which the chemical is prescribed) by a default uncertainty factor of 3,000; divide by an additional uncertainty factor of 10 if the compound is either a non-genotoxic carcinogen or an endocrine disrupting compound. A non-genotoxic carcinogen produces cancer by mechanism other than gene damage.
    b. Divide the literature-based no observed adverse effect level by a default uncertainty factor of 1,000 or the lowest observed adverse effect level by a default uncertainty factor of 3,000; divide by an additional uncertainty factor of 10 if the compound is either a non-genotoxic carcinogen or an endocrine disrupting chemical.
    c. If the compound is a genotoxic carcinogen and tumor incidence data are available, develop a slope factor and establish a comparison value assuming a *de minimis* cancer risk of 1 in 1,000,000.
    d. If the compound is a genotoxic carcinogen and no tumor incidence data are available, use the lower of the virtually safe dose derived using the method of Gaylor and Gold (1998) or the threshold of toxicological concern. The threshold of toxicological concern is the value below which there would be no appreciable risk to human health based on chemical structure.
2. If the chemical is not a pharmaceutical and either a literature-based no observed adverse effect level or lowest observed adverse effect level can be identified or the chemical is a genotoxic carcinogen, set guidelines based on toxicological data following (b), (c), and (d), above.
3. If the chemical is not a pharmaceutical, but does not have either a literature-based no observed adverse effect level or lowest observed adverse effect level or there is no evidence it is a genotoxic carcinogen, derive a screening level based on the threshold of toxicological concern.

Based on the occurrence data and toxicological thresholds reviewed, the State Water Board's expert panel recommended four chemicals of emerging concern as health-based indicators for monitoring groundwater recharge projects using reclaimed water (surface spreading and sea water intrusion barriers): N-nitrosodimethylamine, 17beta-estradiol, caffeine, and triclosan. No health-based indicators were recommended for landscape irrigation projects using reclaimed water because none of the candidate chemicals exceeded the threshold for monitoring priority. This was largely attributable to higher monitoring trigger thresholds because of reduced water ingestion in a landscape irrigation settings compared to drinking water. A summary of the indicators is presented in Appendix B.

7.3. Performance-based indicators and surrogates

In municipal wastewater effluents, the majority of non-traditional chemical contaminants are typically present at low concentrations (for example at concentrations less than 300 ηg/L) and most analytical methods are optimized to detect only a few compounds at a time. As a result, the effort required to perform a comprehensive analysis of all of the detectable chemical contaminants is infeasible for all but the most sophisticated analytical laboratories.

Engineered or natural treatment systems can be used to control trace organic chemicals in potable reuse systems employing physical, chemical, and biological processes to remove or transform the compounds. Published research on the mechanisms through which treatment processes act indicates that it should be possible to predict the extent of removal for specific compounds (termed *indicators*) exhibiting similar properties provided that those properties determine the behavior of the compound in the treatment process (Snyder et al., 2003; Bellona et al., 2004; Snyder et al., 2006; Deborde and von Gunten, 2008; Benotti et al., 2009; Dickenson et al., 2009). Furthermore, the removal of specific compounds or families of compounds with closely related properties may be correlated with the removal of other routinely measured compounds or operational parameters (termed *surrogates*) that can be monitored continuously, for example, conductivity and ultraviolet absorbance (Drewes et al., 2008; Wert et al., 2009).

Recent efforts have identified useful combinations of surrogate parameters and indicator compounds to monitor the removal efficiency of various advanced processes employed by treatment plants engaged in indirect potable water reuse programs (Drewes et al., 2008; Dickenson et al., 2009). In this context, a surrogate is a quantifiable parameter that can serve as a performance measure of treatment processes that relates to the removal of specific contaminants. Surrogate parameters provide a means of assessing water quality characteristics of treatment processes without conducting difficult trace contaminant analysis.

The approach of using a surrogate measure, such as total organic carbon or conductivity, and a limited list of trace organic indicator chemicals may be a reasonable way to circumvent the significant costs associated with the analysis of all the possible chemicals of concern if the analytes monitored are good predictors of the contaminants of concern (Drewes et al., 2008; Trenholm et al., 2009). Ultimately, a monitoring system adopted for a water reuse project may include a combination of approaches that balances costs, reliability, and sample turnaround times. For example, a monitoring system might employ direct measurement of a broad suite of compounds during the initial start-up of a system followed by annual monitoring of indicators and weekly measurement of surrogates. Some surrogates, such as conductivity, can be measured on-line. The ultimate goal is that monitoring by using a combination of indicator and surrogate parameters will ensure the absence or significant reduction of unknown and potentially harmful contaminants, thus ensuring a quality of reclaimed water that is suitable for its intended use.

Proper removal is ensured as long as the treatment process of interest is operating according to its technical specifications. It is therefore necessary to define for each treatment process the operating conditions under which proper removal is to be expected. Predetermined changes of surrogate and indicator parameters can be utilized to define normal operating conditions according to specification for a given treatment process. However, it is important to remember that each monitoring approach will be site-specific depending on the source water being treated and the treatment processes used.

The State Water Board's expert panel (Drewes et al., 2010a) recommended four chemicals of emerging concern as performance-based indicators for monitoring groundwater recharge projects using reclaimed water (surface spreading and sea water intrusion barriers): N,N-Diethyl-meta-toluamide, gemfibrozil, iopromide and sucralose along with certain surrogate parameters (such as ammonia, dissolved organic carbon, conductivity), which differed by the type of reuse practice (see Appendix B). For irrigation applications using reclaimed water, the panel recommended that monitoring emphasis be placed only on the use of surrogate parameters that can demonstrate that the treatment processes employed are effective in removing chemicals of emerging concern: turbidity, chlorine residual, and coliform (see Appendix B).

7.3.1. Indicator/surrogate framework

One example of an indicator/surrogate framework classifies potential indicator compounds into four removal categories (Drewes et al., 2008; Drewes et al., 2010b):

- "Good removal (greater than 90 percent)";
- Two groups of "intermediate removal (between 50 to 90 percent and between 25 to 50 percent);" and
- "Poor removal (less than 25 percent)."

This rating of indicators into removal categories of individual unit processes is dependent upon the physicochemical and biodegradable properties of the compounds. Whether the proposed degree of removal is achieved will depend upon operational conditions of the treatment process. The most sensitive compounds to assess the performance of a specific treatment process will be those that are partially removed under normal operating conditions. Thus, a system failure will be indicated by poor removal of indicator compounds classified in the categories "good removal (greater than 90 percent)" and "intermediate removal (50 to 90 percent)," while normal operating conditions will be indicated by partial or complete indicator compound removal.

The framework is a conservative approach designed to ensure proper removal of identified and unidentified trace organic contaminants and to detect failures in system performance.

Assessing system performance of individual unit processes comprising an overall treatment train is distinguished into two phases: piloting/start-up and full-scale operation/compliance monitoring. In order to apply the surrogate/indicator framework to a given or proposed treatment train, first operational boundary conditions of treatment processes need to be identified, ensuring the performance of each unit process according to their technical specifications. During a piloting/start-up phase for each unit process, the surrogate or operational parameters that demonstrate a measurable removal (differential) under normal operating conditions ($\Delta X = [X_{in} - X_{out}]/X_{in}$) need to be identified. In parallel, an occurrence study should be performed confirming that the indicator compounds occur at high enough concentrations in the feedwater to measure removal. During piloting or start-up of a new treatment process, challenge or spiking tests can be conducted with select indicator compounds to determine the removal differential ΔY under normal operating conditions. For these tests, five to 10 indicator compounds from the treatment category classified as “good removal” should be selected. For the full-scale operation, the operational boundary conditions and removal differential ΔX and ΔY for selected surrogate and operational parameters and indicator compounds should be confirmed. To ensure the proper performance of each full-scale unit operation, key surrogate and operational parameters should be measured on a regular basis. While it is implied that proper performance of the full-scale treatment train will ensure appropriate removal of wastewater-derived organic contaminants, the key indicator compounds (three to six) for each unit process and/or the overall treatment system should be monitored at frequencies on the order of semiannually or annually. The individual steps to develop a surrogate/indicator monitoring framework are summarized in Table 17.

Table 17. **Application of surrogate/indicator framework to an overall treatment train**

	Surrogate parameters	**Indicator compounds**
Piloting and/or start-up		
Step 1	Define operational conditions for each unit process comprising the overall treatment train for proper operation according to technical specification	
Step 2	For each unit process, select surrogate parameters that demonstrate a measurable change under normal operating conditions and quantify this differential $\Delta X_i = \lvert(X_{i,in}-X_{i,out})\rvert$	Conduct occurrence study to confirm the detection ratio[a] of viable indicator compounds is larger than 5 in the feed water of each unit process
Step 3		Conduct challenge or spiking study with select indicator compounds (5-10) during pilot- or start-up to determine the removal differentials under normal operating conditions $\Delta Y_i = (Y_{i,in}-Y_{i,out})/Y_{i,in}$
Step 4	Select viable surrogate and operational parameters for each unit process	Select 3-6 indicator compounds from categories classified as “Good removal”

Full-scale operation/compliance monitoring

Step 5	Confirm operational conditions of full-scale operation and removal differential □ X_i for selected surrogate and operational parameters	
Step 6	**Operational monitoring**: Monitor differential □ X_i of select surrogate and operational parameters for each unit process or/and the overall treatment train on a regular basis (daily, weekly)	**Verification monitoring**: Monitor differential □ Y_i of selected indicator compounds for each unit process or/and the overall treatment train semi-annually/annually

a. The detection ratio is defined as the ratio between the median concentration and the limit of quantification. The limit of quantification is the minimum concentration or amount of an analyte that a method can measure with a specified degree of precision.

7.3.2. Indicator compounds for surface spreading operations

Using the framework proposed by Drewes, specific indicator compounds identified during earlier studies for indirect potable reuse surface spreading operations are listed in Table 18 (Drewes et al., 2008; Drewes et al., 2010b); surrogate parameters that can be used to measure proper performance of surface spreading operations are presented in Table 19.

Table 18. Treatment removal categories for indicator compounds of surface spreading systems[1]

Good removal (>90%)		Intermediate removal (90–50%)	(50–25%)	Poor removal (<25%)
Acetyl cedrene[b]	Indolebutyric	TCEP[1]		Carbamazepine[1]
Atenolol[c,1]	Iopromide[1]	TCPP[1]		Primidone[1]
Atorvastatin[b,1]	Isobornyl acetate[b]		TDCPP[1]	
Benzophenone[1]	Meprobamate[1]		Dilantin[1]	
Benzyl acetate[c]	Methyl dihydrojasmonate[c]			
Benzyl salicylate[d]	Methyl ionine[d]			
Bisphenol A[1]	Methyl salicylate[c]			
BHA[1]	Metoprolol			
Bucinal[d]	Musk ketone[b]			
Caffeine[1]	Musk xylene[b]			
DEET[1]	Naproxen[1]			
Diclofenac[1]	NDMA			
EDTA	Nonylphenol			

Good removal (>90%)		Intermediate removal (90–50%)	Intermediate removal (50–25%)	Poor removal (<25%)
Erythromycin[1]	OTNE[b]			
Estrone	Propranolol			
Fluoxetine[1]	Propylparaben[c]			
Galaxolide[b,1]	Sulfamethoxazole[1]			
Gemfibrozil[1]	Terpineol[b]			
Hexyl salicylate[d]	Tonalide[b]			
Hexylcinnamaldehyde[b]	Triclocarban[b]			
Hydrocodone[1]	Triclosan[1]			
Ibuprofen[1]	Trimethoprim[1]			

(Source: Drewes et al., 2008; Drewes et al., 2010b)

Operating conditions: 1) no dilution with native groundwater; 2) used partially nitrified treated wastewater with an extensive vadose zone (greater than 100 feet); subsurface travel time greater than 2 weeks; 3) used nitrified/denitrified treated wastewater with a shallow vadose zone (less than 10 feet); subsurface travel time: greater than 2 months.

1. Percent removals (%) based on Drewes et al., 2008 and Drewes et al., 2010b; note, removal of compounds with no superscript was verified through peer reviewed data.

a. N-Diethyl-meta-toluamide (DEET); Ethylenediaminetetraacetic acid (EDTA); Iso-E-Super® (OTNE); ris(2-carboxyethyl)phosphine (TCEP); Tris(chloroisopropyl)phosphate(TCPP); Tris(1-chloro-2-propyl) phosphate (TCPP); Butylated hydoxyanisole (BHA).

b. Removal estimate is based upon log D being greater than 3.0 (pH 7).

c. Removal is estimated as fast biodegradation on the basis of a BioWin prediction.

d. Removal estimate is based upon log D being greater than 3.0 (pH 7) and upon fast biodegradation on the basis of a BioWin prediction.

Table 19. Sensitive surrogate parameters identified for different treatment categories

Mechanism	Treatment process	Surrogate for performance assessment
Biodegradation	SAT[a]	BDOC[d]; DOC[e]; UVA[f]; TOX[g]; ammonia; nitrate; fluorescence
Physical separation	RO[b]	Conductivity; boron
	NF[c]	Calcium; magnesium

Source (Drewes et al., 2008; Drewes et al., 2010b)

a. Soil aquifer treatment (SAT).

b. Reverse osmosis (RO).

c. Nanofiltration (NF).

d. Biodegradable dissolved organic carbon (BDOC).

e. Dissolved organic carbon (DOC).

f. Ultraviolet absorbance (UVA).

g. Total organic halide (TOX).

7.3.3. Indicator compounds for direct injection projects using high-pressure membranes

Using the framework proposed by Drewes (Drewes et al., 2008; Drewes et al., 2010b), projects that use reclaimed water for direct injection into a potable aquifer might require more advanced treatment above ground, such as treatment through high-pressure membranes. Table 20 summarizes viable indicator compounds using reverse osmosis.

Table 20. Treatment removal categories for indicator compounds of reverse osmosis systems[a]

Good removal (>90%)				Intermediate removal		Poor removal (<25%)
				(90–50%)	(50–25%)	
Indolebutyric acid[b]	Dichlorprop	Isobutylparaben[b]	Propranolol		Chloro-form	
Acetaminophe	Diclofenac	Ketoprofen	Propylparab		NDMA	
Acetyl cedrene[b]	Dilantin	Mecoprop	Salicylic acid			
Atenolol	EDTA[d]	Meprobamate	Simvastatin hydroxy			
Atorvastatin	Erythromycin–H_2O	Methyl dihydrojasmonat	Sulfamethox azole			
Atorvastatin (o-hydroxy)	Estriol	Methyl ionine[b]	TCEP[f]			
Atorvastatin (p-hydroxy)	Estrone	Methyl salicylate[b]	TCPP[g]			
Benzyl	Fluoxetine	Metoprolol	TDCPP[h]			
Benzyl salicylate[b]	Galaxolide	Musk ketone	Terpineol[b]			
Bisphenol A	Gemfibrozil	Musk xylene[b]	Tonalide[b]			
Bucinal[b]	Hexyl salicylate[b]	Naproxen	Triclocarban[b]			
Butylated hydroxyanisol	Hexylcinnam-aldehyde[b]	Nonylphenol	Triclosan			
Caffeine	Hydrocodone	Norfluoxetine	Trimethopri			
Carbamazepin	Ibuprofen	OTNE[e]				
Ciprofloxacin[b]	Iopromide	Phenylphenol[b]				
DEET[c]	Isobornyl acetate[b]	Primidone				

a. Removal percentages (%); operating conditions: recovery: 80%; permeate flux: ~12 gfd or 20 LMH; pH = 6.5. Removal of compounds with no footnote was verified through peer-reviewed literature data or experimental data generated during this study.

b. Removal estimate is based upon molecular weight being greater than 150 g/mol.

c. N-Diethyl-meta-toluamide (DEET).

d. Ethylenediaminetetraacetic acid (EDTA).

e. Iso-E-Super® (OTNE).

f. Tris(2-carboxyethyl)phosphine (TCEP).

g. Tris(chloroisopropyl)phosphate (TCPP).

h. Tris(1-chloro-2-propyl) phosphate (TCPP).

Potential surrogate parameters for reverse osmosis treatment are previously listed in Table 19.

7.3.4. Monitoring framework for soil aquifer treatment

Following the steps outlined in Table 17, a viable surrogate parameter for a soil aquifer treatment operation could be biodegradable dissolved organic carbon or the difference in ammonia, nitrate, dissolved organic carbon, or ultraviolet absorbance measurements prior to and after a spreading operation (Table 19). During a piloting study or start-up of a full-scale facility, these measurement differentials would be determined. As an example, certain indicator compounds representing different biodegradability levels are suggested in Table 21 to be considered in performance-monitoring efforts.

Table 21. Monitoring framework for soil aquifer treatment systems[a]

Monitoring level	Good removal (>90%)	Intermediate removal (90 < x < 50%)	Intermediate removal (50 < x < 25%)	Poor removal (<25%)
Piloting/start-up	Ammonia			
	Nitrate			
	DOC[b]			
	Fluorescence			
	BDOC[c]			
	Gemfibrozil			Primidone
	DEET[d]			
	Iopromide			
	Meprobamate			
Full-scale operation/ compliance monitoring	Ammonia			
	UVA[e]			
	TOC[f]			

a. Percent (%) removals; conditions: travel time in subsurface greater than 4 weeks; predominant redox conditions: oxic followed by anoxic; dilution: 0%.

b. Dissolved organic carbon (DOC).

c. Biodegradable dissolved organic carbon (BDOC).

d. N-Diethyl-meta-toluamide (DEET).

e. Ultraviolet absorbance (UVA).

f. Total organic carbon (TOC).

During piloting or start-up, the expected removal differentials for these indicators need to be determined. Monitoring for a compound that behaves conservatively during soil aquifer treatment, such as primidone or carbamazepine, can provide an organic wastewater tracer that allows an assessment of dilution with native groundwater. If the observed removal of the select indicator compounds falls outside the expected removal category, the process is not properly designed or working and adjustments must be considered. If the indicator compound differentials confirm the proposed removal categories, monitoring for the expected removal differential of selected surrogate compounds will ensure proper removal of wastewater-derived organic compounds during this operation. During full-scale operation, it is necessary only to ensure that the select surrogate parameter differential is achieved.

7.3.5. Monitoring framework for high-pressure membrane treatment

Following the steps outlined in Table 17, a viable surrogate parameter for a reverse osmosis operation could be the differential in conductivity, total organic carbon, and boron measurements prior to and after reverse osmosis treatment. During a piloting study or start-up of a full-scale facility, these measurement differentials will be determined. As an example, certain indicator compounds representing different solute properties are suggested in Table 22 for consideration in performance-monitoring efforts for reverse osmosis operations.

Table 22. Monitoring framework for reverse osmosis systems[a]

Monitoring level	Good removal (>90%)	Intermediate removal (90 < x < 50%)	Intermediate removal (50 < x < 25%)	Poor removal (<25%)
Piloting/start-up:	Conductivity			
	TOC[b]			
	Boron			
	Caffeine		NDMA[d]	
	DEET[c]			
	Meprobamate		Chloroform	
	Acetaminophen			
Compliance monitoring	Conductivity			
	Boron			

a. Percent (%) removal; dilution 0%.
b. Total organic carbon (TOC).
c. N-diethyl-meta-toluamide (DEET).
d. N-nitrosodimethylamine.

During piloting or start-up, the expected removal differentials for these indicators need to be determined. If the observed removal of the selected indicator compounds falls outside the expected removal category, the process is not properly designed or working and adjustments must be considered. If the indicator compound differentials confirm the proposed removal categories, monitoring for the expected removal differential of selected surrogate compounds will ensure proper removal of wastewater-derived organic compounds during this operation. During full-scale operation, it is necessary only to ensure that the key surrogate parameter differential is achieved.

7.4. Bioassays

Bioassays are tests performed using live cell cultures or mixtures of cellular components in which the potency of a chemical or water concentrate is tested based on its effect on a measurable parameter, such as inhibition or the induction of a response (including carcinogenicity and mutagenicity). For unknown chemicals that may be unknowingly released into the environment and for which there are currently no known methods for their quantification, biological monitoring or chemical screening methods could be used to quantify effects/equivalents or identify unknown chemicals and thus may offer an additional safeguard for human health or ecological health (Drewes et al, 2010a). The main advantage of bioassays is that they are able to detect the presence of chemicals based on their bioactivity rather than on their detection by analytical chemistry. An added benefit of bioassays is they can be used to measure synergistic, additive, and antagonistic interactions between compounds that may be present in a mixture. There are both *in vivo* and *in vitro* assays that have been developed, which can also be linked with analytical chemical methods to identify potential toxicants; *in vivo* bioassays are conducted using whole organisms while *in vitro* bioassays are conducted at the cellular level. Bioassays have advantages and disadvantages and robust, reproducible and high throughput assays need to be developed (Hartung & Daston, 2009; Drewes et al., 2010a). Full implementation of bioassay screening methods is believed to be several years away (Drewes et al., 2010a).

The U.S. Environmental Protection Agency work on bioassays has focused on compounds that interfere with estrogen, androgen and thyroid hormone responses. As part of its Endocrine Disruptor Screening Program, the U.S. Environmental Protection Agency is using screening level bioassays to prioritize an estimated 87,000 chemicals for risk assessments.[26] Bioassays have been used as screening tools for identifying chemicals of concern in reclaimed water or mixtures of chemicals and for assessing treatment performance as discussed in Section 8.4. At the present time, bioassays are limited in their ability to predict effects in humans and other organisms and additional research is needed to improve their utility for water reuse applications (Snyder, 2009).

8. Human health issues

A primary consideration of the use of reclaimed water is the potential for human health impacts via contact or ingestion. Crook (2005) collected information on the use of reclaimed water for irrigation of parks, playgrounds, athletic fields, and school grounds in the United States, and reported that while there have been no documented adverse health effects to children or others,

[26] See http://www.epa.gov/endo/.

public concerns over the safety of the practice can occasionally arise. Most concerns relate to the potential for disease transmission to children from pathogens or health effects related to exposure to chemical contaminants from incidental ingestion of water or soil or contact with turf. Many of the concerns are unfounded and often based on lack of information, misinformation, or general fears about the use of reclaimed water.

Over the past 30 years, a number of studies have specifically evaluated the public health risks of water reuse. Most sought to analyze and compare the toxicological properties of reclaimed water to those of drinking water; some included epidemiological and risk assessment components. When discussing health issues, it is important to do so in a risk management context.

8.1. Risk management

Risk management is the identification, assessment, and prioritization of risks followed by coordinated and economical application of resources to minimize, monitor, and control the probability and/or impact of unfortunate events or to maximize the realization of opportunities (Charnley et al., 1997). There are four steps in risk assessment: hazard identification, dose–response assessment, exposure assessment, and risk characterization. In each step, scientists address key questions with the goal of completely understanding a hazard's seriousness and scope.

- In the hazard identification step, researchers evaluate the types of health effects that the contaminant of concern can cause. Such effects may range from 1) subtle, reversible physiological changes to 2) acute illness to 3) cancer. This step establishes the contaminant's health endpoint of concern and includes discussions on the data types, quality, and uncertainties in the evaluation.
- In the dose response assessment step, researchers quantify the magnitude of the health effect with respect to exposure. For example, a cancer-slope factor allows researchers to estimate the probability of cancer occurring based on contaminant exposure. For non-carcinogenic endpoints, the reference dose is a "bright line" exposure level below which no adverse health effect is believed to occur; it cannot be used to estimate probabilities of risk. Dose response values include a number of conservative health assumptions, so they may yield an upper bound to risk estimates when the true risk is probably lower or zero.
- In the exposure assessment step, researchers provide a site-specific description of the plausible amounts of a contaminant that people can receive. This assessment takes into consideration the locations and amounts of the contaminant; its movement and attenuation through the environment; the nature, routes, and frequency of possible human contact with the contaminant; and the numbers and types of people exposed.
- In the risk characterization step, researchers combine the toxicological and exposure analyses to describe the nature, magnitude, and significance of any health risks. The quantitative expression of risk can include both the average risk and the range of risks, based on the range of exposures anticipated.

The U.S. Environmental Protection Agency has developed a series of risk assessment guidelines for various endpoints (including carcinogenicity, neurotoxicity, reproductive toxicity, and mutagenicity), as well as guidelines on dealing with exposure assessment and chemical mixtures.[27] Many states also have developed risk assessment approaches for setting standards and regulating contaminants.

8.2. Hazard Analysis and Critical Points Systems

For microbial pathogens and many trace organics, it is not yet practical to routinely and continuously monitor their presence in reclaimed water. The Hazard Analysis and Critical Control Points System was developed as an engineering means of controlling microbial hazards in consumed food. The Hazard Analysis and Critical Control Points System and Water Safety Plans (as developed by the World Health Organization based on the Hazard Analysis and Critical Control Points System) have been widely adopted world-wide as a mechanism for regulating water treatment operations. New Zealand, Iceland, Swiss and Australian water sectors have developed formalized, systematic "catchment to consumer" water quality risk management systems based around Hazard Analysis and Critical Control Points Systems (CAC, 2003). The Australian Guidelines for Water Recycling include all of the Hazard Analysis and Critical Control Points System principles and preliminary steps within its risk management framework. The Singapore NEWater project uses Hazard Analysis and Critical Control Points System as part of its quality assurance system for its indirect potable reuse schemes.

The system consists of a two-part technique: 1) an analysis that identifies hazards and their severity and likelihood of occurrence; and 2) identification of critical control points and their monitoring criteria to establish controls that will reduce, prevent, or eliminate the identified hazards. It consists of 12 specific elements:

- Define the scope of the hazard analysis;
- Set up a multi-disciplinary team;
- Perform detailed analyses of the process;
- Obtain information on raw materials and process conditions;
- Produce detailed flow diagrams;
- Perform hazard analysis and prioritize hazards in order of importance and probability of occurrence;
- Identify critical control points for each hazard;
- Specify criteria for each critical control point;
- Identify the means of monitoring critical control points to ensure control;
- Identify actions to be take if tolerances are exceeded;
- Document all control and monitoring procedures; and
- Train personnel involved in the process.

The WateReuse Research Foundation is sponsoring a study to investigate and develop an approach for managing and monitoring microbial water quality of reclaimed water through the Hazard Analysis and Critical Control Points process, and in particular its applicability and benefits for water reuse programs in the United States.

[27] See http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=22567.

8.3. Epidemiology

A limited number of ecological epidemiology studies have specifically evaluated the public health implications of direct and indirect potable reuse. Ecologic studies rely on exposure and outcome data for groups rather than individuals. The diseased persons in a given ecologic study may not be the most exposed individuals, but this cannot be determined. Nor is information on important risk factors (such as smoking, alcohol consumption, and occupational/environmental exposure that might affect disease incidence) typically available or controllable in the analysis. Other confounding factors for the analysis can include population migration in and out of the study areas and the use of bottled water or point of use devices. A summary of the relevant epidemiology projects and related studies is presented in Table 23. A summary of the statistical results for the various studies have been provided in a report by Gutteridge Haskins and Davey Pty Ltd (2001).

Table 23. Summary of water reuse epidemiology studies

Project	Project description	Studies/results
Montebello Forebay Groundwater Recharge Study, Los Angeles County, CA (Nellor, et al., 1984; Sloss et al., 1996; Sloss et al. 1999)	Reclaimed water has been used as a source of replenishment since 1962; other replenishment sources are imported river water (Colorado River and State Project water) and local storm runoff. Water is percolated into the groundwater using two sets of spreading grounds. From 1962 to 1977, the water used for replenishment was disinfected secondary effluent. Filtration (dual-media or mono-media) was added later to enhance virus inactivation during final disinfection. During this time period, the amount of reclaimed water spread annually averaged 27,000 acre-feet per year (24 million gallons per day), which was 16 percent of the inflow to the groundwater basin. At that time an arbitrary cap of 32,700 acre-feet per year (29 million gallons per day) of reclaimed water had been established. In 1987, the project was allowed in increase the amount of reclaimed water to 50,000	The studies have looked at health outcomes for 900,000 people that received some reclaimed water in their household water supplies in comparison to 700,000 people in a control population. Three sets of studies have been conducted: 1) the 1984 Health Effects Study, which evaluated mortality, morbidity, cancer incidence, and birth outcomes for the period 1962-1980; 2) the 1996 Rand Study, which evaluated mortality, morbidity, and cancer incidence for the period 1987-1991; and 3) the 1999 Rand Study, which evaluated adverse birth outcomes for the period 1982-1993. *Health Effects Study (1962-1980):* the epidemiological studies focused on a broad spectrum of health concerns that could potentially be attributed to constituents in drinking water. Health parameters evaluated included: mortality (death from all causes, heart disease, stroke, all cancers and cancers of the colon, stomach, bladder and rectum); cancer incidence (all cancers, and cancers of the colon, stomach, bladder, and rectum); infant and neonatal mortality; low birth weight; congenital malformations; and selected infectious diseases (including Hepatitis A and *Shigella*). Another part of the study consisted of a telephone interview of adult females living in reclaimed water and control areas. Information was collected on spontaneous abortions and other adverse reproductive outcomes, bed-days, disability-days, and perception of well-being. The survey was able to control for the confounding factors of bottled water usage and mobility. The study included a component that could be considered a "reverse" risk assessment where a computer simulation model was used to determine the concentration of four chemicals (dinitrotoluene, heptachlor, polychlorinated biphenyls, and phthalate esters) that would have to be present to see cancer,

Project	Project description	Studies/results
	acre-feet per year (45 million gallons per day). The current permit allows for a maximum reclaimed water contribution of 35 percent based on a five-year running average.	cancer of the rectum, cancer of the liver, and congenital malformations. The concentrations necessary were substantively greater than concentrations observed in the water samples tested. *Rand (1987–1991):* the study evaluated cancer incidence (all cancers, and cancer of the bladder, colon, esophagus, kidney, liver, pancreas, rectum, stomach); mortality (death from all causes, cancer, cancer of the bladder, colon, esophagus, kidney, liver, pancreas, rectum, stomach, heart disease, cerebrovascular disease); and infectious diseases (including *Giardia*, Hepatitis A, *Salmonella*, *Shigella*). *Rand (1982–1993):* the evaluation focused on two types of adverse birth outcomes: a) prenatal development and infant mortality (including: low birth weight (full term only), low birth weight (all births), very low birth weight, preterm birth, infant mortality); and b) birth defects (all defects, neural tube defects, other nervous system defects, ears, eyes, face, neck defects; major cardiac defects, patent ductus arteriosus, other cardiac defects, and respiratory system defects; cleft defects, pyloric stenosis, intestinal artesias, other digestive system defects; limb, other musculoskeletal, integument and all other defects; chromosomal syndromes and syndromes other than chromosomal). The results from these three studies found that after almost 30 years of groundwater recharge, there was no association between reclaimed water and higher rates of cancer, mortality, infectious disease, or adverse birth outcomes.
Total Resource Recovery Project, City of San Diego (Western Consortium for Public Health, 1996; NRC, 1988)	This is a proposed surface water augmentation project that would utilize advanced treated reclaimed water to supplement the San Vicente raw reservoir water (current drinking water supply). The project and treatment system are currently being re-evaluated.	Baseline reproductive health and vital statistics data were assembled. The reproductive data were collected from telephone interviews of 1,100 women. Vital statistics data were collected on mortality, birth outcomes, and infectious disease. Data were also collected on neural tube birth defects from 1979 – 1985.
Windhoek, South Africa – direct reuse (Isaacson and Sayed, 1988)	This is a direct reuse project. At the time the studies were conducted, the reclaimed water was treated using sand filtration and granular activated carbon, and the reclaimed water was added to drinking water supply system. The treatment system for this project has been revised since this work	The study, which was conducted for the period 1976–1983, looked at cases of diarrheal diseases. For the Caucasian population of similar socio-economic status studied, disease incidence was marginally lower in persons supplied with reclaimed water than those with water from conventional sources. Incidence rates were significantly higher in black populations, all of whom received conventional water only. Age-specific incidence rates in children of the various ethnic groups also showed differences characteristically associated with socio-economic stratification. It was concluded that

Project	Project description	Studies/results
	was conducted.	the consumption of reclaimed water did not increase the risk of diarrheal diseases caused by waterborne infectious agents.
Chanute, Kansas (Metzler et al., 1958)	Emergency use of reclaimed water during a drought for 150 days during 1956-57. The Neosho River was dammed below the outfall of the sewage treatment plant and the treated effluent backed up to the water intake. The impounding acted as waste stabilization and water was chlorinated prior to service. The use ended when heavy rains washed out the temporary dam. The river water source already contained wastewater prior to this event.	An epidemiology study showed fewer cases of stomach and intestinal illness during the period reclaimed water was used than the following winter when Chanute returned to using river water.

Recently (but not yet published), researchers in Australia compared illness rates (acute gastroenteritis, skin or respiratory conditions) between two communities: one supplied with reclaimed wastewater and the other that used conventional drinking water (Ryan, 2009). The researchers examined almost 36,000 patient records over two years and found no differences in illness rates for the two communities.

8.4. Quantitative Relative Risk Assessments

Quantitative relative risk assessments have been conducted for some indirect potable reuse projects. This type of evaluation does not assess the absolute risk from ingesting water at the tap, but relative risk based on water quality comparisons. This approach eliminates much of the uncertainty associated with the exposure-assessment elements of standard quantitative risk assessments. Estimating situational exposure can create a high degree of uncertainty because there is no direct method of determining the uptake of chemicals in the study population's drinking water supply that originated in reclaimed water. The approach also limits the effects of many confounding factors (such as bottled water use, smoking, and diet) that affect exposure assessment.

A quantitative relative risk assessment was conducted for the Orange County Water District's Groundwater Replenishment System (EOA, 2000). For this study, existing chemical and microbiological data were used to compare the relative risk of using reclaimed water that had undergone treatment by reverse osmosis for replenishment, to other sources of replenishment water: 1) the Santa Ana River[28]; and 2) Colorado River and State Water Project (imported

[28] At times of the year, the Santa Ana River is comprised almost entirely of wastewater from upstream discharges.

waters). For non-carcinogenic risk, the hazard index for each water matrix was below one, which is considered the threshold for potential health effects, with the advanced treated reclaimed water lower than the Santa Ana River water and the imported waters. For carcinogenic risks, the risk levels were lower for the advanced treated reclaimed water and imported waters in comparison to the Santa Ana River water. Although the levels of arsenic were below the then "existing" drinking water maximum contaminant level of 50 µg/L and the then "proposed" maximum contaminant level of 10 µg/L, arsenic represented the majority of risk. Arsenic concentrations in the advanced treated reclaimed water were 60 times lower than the Santa Ana River water and 35 times lower than the imported water levels. The results also showed that the advanced treated reclaimed water was projected to present much less risk that the other waters from bacteria, parasites, and viruses provided that all unit processes in the treatment facility were fully operational and operating properly.

A quantitative relative risk assessment has also been conducted for the Montebello Forebay Groundwater Recharge Project based on chemicals that are currently regulated or under consideration for regulation. Preliminary results are available for the risk assessment (Soller and Nellor, in press). The study has evaluated two control wells that contain little to no reclaimed water and two wells that contain relatively high proportions of reclaimed water (29 and 38 percent). For non-carcinogenic risk, the hazard index for each water matrix was below one, which is considered the threshold for potential health effects. Carcinogenic risks were estimated as the incremental probability of an individual developing cancer over a lifetime as a result of exposure to a potential carcinogen. Probabilistic simulations were conducted to estimate the carcinogenic risk associated with a hypothetical drinking water exposure for the four wells under investigation. The mean risks for the reclaimed water wells ranged from $8 \times e^{-5}$ to $1.9 \times e^{-5}$, and for the control wells from $2.3 \times e^{-5}$ to $3.1 \times e^{-5}$. Arsenic was the greatest contributor to risk; for one of the reclaimed water wells, some samples contained arsenic at concentrations greater than the maximum contaminant level of 10 µg /L. However in terms of contribution to risk, reclaimed water was not the primary source. The average concentration of arsenic in the reclaimed water was substantially lower than the concentrations of arsenic observed in the investigated wells. The source of arsenic is believed to be naturally occurring deposits in the groundwater basin.

Oliveri and Seto (2007) used microbial risk assessment approaches to assess non-potable water reuse applications and develop a matrix of relative microbial risks for a range of different conditions. A summary of the conclusions from this work include:

- The risks associated with full body contact recreation in undiluted effluent are estimated to be five times greater than those associated with landscape irrigation and 10 times greater than those associated with crop irrigation.
- The estimated attributable risks associated with human viruses, *Cryptosporidium parvum* and *Giardia lamblia* are similar for equivalent conditions, and are higher than risks for other pathogens.
- The risks associated with disinfected tertiary effluent are lower than those associated with disinfected secondary effluent by approximately a 0.5 order of magnitude.
- The 90 percent confidence bounds of the risk estimates for pathogens in reclaimed water span approximately three orders of magnitude and point to the need to improve the data for risk assessments, which typically lacks adequate occurrence and exposure information.

A WateReuse Research Foundation research project will be initiated in 2010 that will assess the relative risks of exposure to pharmaceuticals and personal care products present in reclaimed water used for non-potable applications.

8.5. Bio-analytical screening tools

A number of studies have sought to analyze and compare the toxicological properties of reclaimed water to those of drinking water; some of these studies attempted to use the combination of toxicology bioassays and chemical methods to isolate and identify constituents of potential health significance in reclaimed water used for planned indirect potable reuse. A summary of these projects and related studies is presented in Table 24.

Table 24. Summary of bio-analytical screening studies

Project	Types of water studied	Health effects data
Montebello Forebay Groundwater Recharge Study, Los Angeles County, CA (Nellor, et al., 1984)	Disinfected tertiary reclaimed water, storm water, and imported river water used for groundwater replenishment; also recovered groundwater.	The study used the Ames *Salmonella* test and mammalian cell transformation assay. Samples concentrates (10,000 to 20,000 times) were used in Ames test and mammalian cell assays, and subsequent chemical identification was attempted using the Ames assays. Samples were collected from the late 1970s to the early 1980s. The level of mutagenic activity (in decreasing order) was storm runoff > dry weather runoff > reclaimed water > groundwater > imported river water. No relation was observed between percent reclaimed water in wells and observed mutagenicity of residues isolated from wells. The residues did not yield significant cytotoxicity in the mammalian cell assays To facilitate the isolation and identification of the components in sample concentrates, the residues were first fractionated by high performance liquid chromatography, followed by testing of the fractions for mutagens and analysis of the mutagenic fractions by gas chromatography-electron ionization mass spectrometry . Results indicated that mutagenicity generally occurred in the least polar (most hydrophobic) fractions of each sample. In most cases, the sum of TA98 mutagenicity in sample fractions was similar in magnitude to that observed in the whole sample. There was no evidence of synergistic effects in these assays. Analysis by gas chromatography-electron ionization mass spectrometry of mutagenic fractions from 34 samples yielded only four known Ames mutagens in six samples (fluoranthene, benzo(a)pyrene, N-nitrosomorpholine, and N-nitrosopiperidine). However, these compounds were considered to contribute little to the observed overall mutagenicity of the samples. Several unknown compounds detected in the mutagenic fractions could not have caused the mutagenicity in all of the samples,

Project	Types of water studied	Health effects data
		because their frequency of occurrence, distribution in the fractions, and concentrations were not consistent with the bioassay results. Selected sample residues were then evaluated qualitatively by chemical derivatization techniques to determine which classes of compounds might be contributing to the mutagenic activity. Since mutagens are considered to be electrophilic, two nucleophilic reagents were used to selectively remove epoxide and organohalide mutagens from the residues. Analysis of mutagenic residues of groundwater and replenishment water by negative ion chemical ionization gas chromatography-mass spectrometry and Ames assay before and after derivatization supported (but did not unequivocally prove) the role of at least these two classes of electrophiles in the observed mutagenicity. Several samples had more than 100 reactive components, containing chlorine, bromine, iodine, or epoxides, with concentrations at the part-per-trillion level. However, the structures of these compounds could not be determined by negative ion chemical ionization gas chromatography- mass spectrometry, nor were the sources of the compounds identified. Because positive chemical identifications of specific mutagens could not be made and because the estimated concentrations of the components were so low, the biological significance of these materials remained in doubt. Follow-up toxicity testing of reclaimed water residues collected in the mid-1990s (not published) showed no Ames test response, while preserved residues from the earlier testing still showed a response indicating that the character of the reclaimed water has changed over time, perhaps as a result of increased source control activities.
Denver Potable Water Reuse Demonstration Project (Lauer et al., 1996; NRC, 1988)	Advanced treated reclaimed water (ultrafiltration or reverse osmosis) and finished drinking water (current supply). The purpose of the project was to evaluate the feasibility of direct reuse by producing high quality reclaimed water; the project was not implemented.	Organic residue concentrates (150 to 500 times) were used in a 2-year *in vivo* chronic/carcinogenicity study in rats and mice and a reproductive/teratology study in rats. No treatment-related effects were observed.
Tampa Water Resource Recovery Project (CH2M Hill, 1993, Pereira et al., undated; NRC, 1988)	Advanced wastewater effluent (using granular activated carbon and ozone disinfection) and Hillsborough River water using ozone disinfection (current drinking water supply). The proposed	Organic residue concentrates (up to 1,000 times) were used in Ames *Salmonella*, micronucleus, and sister chromatid exchange tests using three dose levels up to the 1,000 time concentrates. No mutagenic activity was observed in any of the samples. *In vivo* testing included mouse skin initiation, strain A mouse lung adenoma, 90-day subchronic assay on mice and rats, and a reproductive study on mice. All tests were

Project	Types of water studied	Health effects data
	project involved augmentation of the Hillsborough River raw water supply; the project was not implemented.	negative, except for some fetal toxicity exhibited in rats, but not mice, for the advanced wastewater sample.
Total Resource Recovery Project, City of San Diego (Western Consortium for Public Health, 1996; NRC, 1988; Erickson, 2004)	Advanced treated reclaimed water (reverse osmosis and granular activated carbon) and San Vicente raw reservoir water (current drinking water supply). This is a proposed surface water augmentation project that would utilize advanced treated reclaimed water to supplement the reservoir water. The project and treatment system are currently being re-evaluated.	Organic residue concentrates (150–600 times) were used in Ames *Salmonella* test, mouse micronucleus, 6-thoguanine resistance, and mammalian cell transformation assays. The Ames test showed some weak mutagenic activity, but reclaimed water was less active than drinking water. The micronucleus test showed positive results only at the high (600 times) doses for both types of water. The 6-thoguanine assay run on whole samples and fractions of each type of water showed no mutagenic effect. The mammalian cell transformation assay, showed a strong response for the reservoir sample, but the single test may not have been significant. *In vivo* fish biomonitoring using fathead minnows (28-day bioaccumulation and swimming tests) showed no positive results. There was greater evidence of bioaccumulation of pesticides in fish exposed to raw water than reclaimed water.
Potomac Estuary Experimental Wastewater Treatment Plant (James M. Montgomery, Inc., 1983; NRC, 1988)	Study of the wastewater-contaminated Potomac River Estuary; 1:1 blend of estuary water and nitrified secondary effluent, advanced treated reclaimed water (filtration and granular activated carbon), and finished drinking waters from three water treatment plants.	Organic residue concentrates (150 times) were used in Ames *Salmonella* and mammalian cell transformation tests. Results showed low levels of mutagenic activity in the Ames test, with advanced treated reclaimed water exhibiting less activity than finished drinking water. The cell-transformation test showed a small number of positive samples with no difference between the advanced treated reclaimed water and finished drinking water.
Windhoek, South Africa – direct reuse (NRC, 1988)	Advanced treated reclaimed water (sand filtration and granular activated carbon). This is a direct reuse project with the reclaimed water added to drinking water supply system. The treatment system has been revised since this work was conducted.	Ames test, urease enzyme activity, and bacterial growth inhibition studies were conducted. *In vivo* tests included water flea lethality and fish biomonitoring (guppy breathing rhythm).
Essex & Suffolk Water Langford Recyckling Scheme, UK (Walker, 2007)	Reclaimed water (secondary treatment, coagulant and polymer addition, sedimentation, nitrification/denitrification in biologically aerated filter, ultraviolet radiation disinfection). This project	Toxicological tests using fish indicated no significant estrogenic effects.

Project	Types of water studied	Health effects data
	now discharges reclaimed water into the River Chelmer, and travels approximately 2.5 miles prior to abstraction and pumping to the Hanningfield drinking water reservoir	
Singapore Water Reclamation Study (Kahn and Roser, 2007)	Advanced treated reclaimed water (microfiltration, reverse osmosis, ultra violet radiation) and untreated reservoir water. The largest amount of Singapore's NEWater is currently used for industrial (semi-conductor manufacturing) and commercial use. A smaller amount is blended with raw water in reservoirs, which is then treated for domestic use.	Japanese medaka fish (Oryzias latipes) testing over a 12-month period with two generations of fish showed no evidence of carcinogenic or estrogenic effects in advanced treated effluent; however, the study was repeated owing to design deficiencies. The repeated fish study was completed in 2003 and confirmed the findings of no estrogenic or carcinogenic effects. Groups of mouse strain (B6C3F1) fed organic concentrates (150 times and 500 times) of advanced treated reclaimed water and untreated reservoir water over 2 years. The results presented to an expert panel indicated that exposure to concentrated advanced treated reclaimed water did not cause any tissue abnormalities or health effects.
Santa Ana River Water Quality Monitoring Study (Deng et al., 2008)	Shallow groundwater adjacent to the Santa Ana River and control water. This is an unplanned indirect potable reuse project where Santa Ana River is diverted for recharge into the Orange County Groundwater Basin. The river base flow is comprised primarily of tertiary-treated effluent.	Approximately 85 percent of the base flow in the Santa Ana River originates from wastewater treatment plants operated by three upstream dischargers. An on-line, flow-through bioassay using Japanese medaka as a means of judging potential public health impacts was employed to evaluate the water quality of the surface water and shallow groundwater originating from the Santa Ana River. Three chronic (3 to4.5 month) exposures using orange-red (outbred, OR) and see-through (color mutant, ST-II) Japanese medaka as bioindicators were conducted to evaluate endocrinologic, reproductive, and morphologic endpoints. No statistically significant differences in gross morphological endpoints, mortality, gender ratios, and vitellogenin induction were observed in fish from the Santa Ana River groundwater compared to the group tested in solute reconstituted reverse osmosis-treated or granular activated carbon treated control waters. Significant differences were observed in egg reproduction and the time to hatch in Santa Ana River groundwater; however, total hatchability was not significantly lower. To evaluate the estrogenic activity of the surface water source of the groundwater, Santa Ana River surface water was evaluated for vitellogenin and gonadal histopathology in juvenile medaka with no effects observed. These results demonstrate that OR Japanese medaka may be a sensitive strain as an on-line monitor to predict potential impacts of water quality, but further studies are needed to elicit causative agents within the water mixture.

Project	Types of water studied	Health effects data
Soil Aquifer Treatment Study (Fox et al., 2006)	Reclaimed water (various treatment facilities), soil aquifer treatment water, storm water.	The study used a variety of analytical methods to characterize and measure chemical estrogenicity: *in vitro* methods (estrogen binding assay, glucocorticoid receptor competitive binding assay, yeast-based reporter gene assay, and MCF-7 cell proliferation assay); *in vivo* fish vitellogenin synthesis assay; enzyme-linked immunosorbent assays; and gas chromatography–mass spectrometry. Procedures were developed to extract estrogenic compounds from solids, liquid/liquid methods for direct extraction from aqueous suspensions such as primary and secondary effluents, and concentration of estrogenic (and other) organics on hydrophobic resins followed by organic fractionation during elution in a solvent (alcohol/water) gradient. Field applications of these techniques were designed to measure estrogenic activity derived from conventional wastewater treatment and from soil aquifer treatment. The stability of estrogenic contaminants removed on soils was investigated by extracting and measuring nonylphenol from infiltration basin soils as well as by measuring total estrogenic activity in soil extracts. The researchers attempted to separate and measure estrogenic and anti-estrogenic activities in wastewater effluent and conducted a multi-laboratory experiment in which a variety of wastewater effluents and effluents spiked with known concentrations of specific estrogenic chemicals were tested for estrogenic activity. Significant variability in reclaimed water estrogenicity was observed in bioassay results. Facilities with the longest hydraulic retention times tended to have the lowest observed levels of estrogenicity. Estrogenicity was efficiently removed during soil aquifer treatment. The study also presented information on the advantages and disadvantages of the bioassay test procedures evaluated.
Toxicological Relevance of Endocrine Disrupting Chemicals and Pharmaceuticals in Drinking Water – Water Research Foundation #3085 (Snyder, 2007; Snyder et al., 2008)	Drinking water (20 facilities), wastewater (4 facilities - raw and reclaimed), and food products.	The researchers used an *in vitro* cellular bioassay (E-screen) with a method reporting limit of 0.16 ηg/L; results were also converted to estradiol equivalents. The results showed that the vast majority of drinking waters were less than the method reporting limit. The level of estrogenicity (in decreasing order) was food and beverage products (particularly soy based products) > raw wastewater > reclaimed water > finished drinking water.

8.6. Toxicological relevance of constituents of emerging concern

A number of studies have or are in the process of developing health information for unregulated constituents of emerging concern in terms of predicted no effect concentrations for relevant toxicological endpoints as presented below. The predicted no effect concentration is the level below which exposure to a substance is not expected to cause adverse effects.

- **Tolerable daily intakes**[29] represent a level of daily intake of a constituent in water that should not result in an adverse health effect from direct exposure in a population, including sensitive population groups, such as pregnant women, children, and people with immune compromised systems, or for sensitive endpoints such as reproductive and developmental toxicity, carcinogenicity, and endocrine-mediated toxicity. Snyder et al. (2008) and Bruce et al. (in press) have developed tolerable daily intakes using different health endpoints with different ranges of uncertainty factors. The endpoints include:
  - Non-carcinogenic effects based on the no observable effect level or lowest observed adverse effect level.

    $$\text{TDI } (\mu\text{g/kg-d}) = \frac{\text{NOAEL or LOAEL (mg/kg-d)}}{\text{UFs}} \times \frac{1000\,\mu\text{g}}{\text{mg}}$$

    Where:

    TDI is the tolerable daily intake;

    NOAEL is the no observable effect level;

    LOAEL is the lowest observed adverse effect level;

    UF is the uncertainty; and

    1,000 is a conversion factor (ηg/μg).
  - Minimum inhibitory concentrations to human gastrointestinal flora.

    $$\text{Upper limit of TDI } (\mu\text{g / kg} - \text{d}) = \frac{\text{MIC}_{50}(\mu\text{g / g}) \times \text{MCC}(\text{g / d})}{\text{FA} \times \text{SF} \times \text{BW}(\text{kg})}$$

    Where:

    TDI is the tolerable daily intake;

    MIC_{50} is the minimum inhibitory concentration of 50 percent of strains of the most sensitive; relevant organism (μg/g, equivalent to μg/mL);

    MCC is the mass of colonic contents (g/day);

    FA is the available fraction of the dose to the gastrointestinal microflora;

    SF is the safety factor; the magnitude depends on the quality and quantity of the microbiological data available; and

[29] Acceptable Daily Intakes and TDIs are often used to represent the same value.

BW is body weight (kg).

- Endocrine-mediated effects in animals or humans, estrogenic, androgenic, or mediated by thyroid hormones (fertility, sexual behavior, ovulation, maintenance of pregnancy, development of specific tissues and organs, growth and viability of offspring, lactation, and maternal behavior) based on no observable effect level or lowest observed adverse effect level for non-carcinogenic effects or tumor incidence data and cancer slope factors for carcinogenic effects.
- Therapeutic dose. This approach assumes that the lower end of a drug's therapeutic range represents a threshold for appreciable biological activity in target populations, and therefore may be considered a threshold for potential adverse effects (a lowest observed adverse effect level).

$$\text{TDI}(\mu\text{g/kg-day}) = \frac{\text{Minimum therapeutic dose } (\mu\text{g/kg-d})}{\text{UFs}}$$

Where:

TDI is the tolerable daily intake; and

UFs are the uncertainty factors.

- Cancer consisting of both genotoxic (gene damage) and non-genotoxic (produces cancer by a mechanism other than gene damage) effects.

$$\text{TDI } (\mu\text{g}/\text{kg}-\text{d}) = \frac{10^{-6}}{\text{SF } (\text{mg}/\text{kg}-\text{d})^{-1}} \times 1000\, \mu\text{g}/\text{mg}$$

Where:

TDI is the tolerable daily intake;

1,000 is a conversion factor (ηg/μg); and

SF is the cancer slope factor.

- **Predicted no effect concentrations**, which represent the concentration in water at or below which no adverse human health effects are expected based on the acceptable daily intake. Schwab et al., 2005 developed predicted no effect concentration based on lowest therapeutic dose and minimum inhibitory concentrations.

$$\text{PNEC}_{\text{DW}} = \frac{1000 \times \text{ADI} \times \text{BW} \times \text{AT}}{\text{IngR}_{\text{DW}} \times \text{EF} \times \text{ED}},$$

Where:

PNEC is the predicted no effect concentration;

ADI is the acceptable daily intake;

1,000 is a conversion factor (ηg/μg);

BW is the child or adult body weight (kg/person);

IngR_{DW} is the child or adult drinking water ingestion rate (L/person-day);

EF is the exposure frequency (days/year); and

ED is the exposure duration (years).

- **Drinking water equivalent levels**, which represent the concentration in water at or below which no adverse human health effects are expected based on the tolerable daily intake (Snyder et al., 2008; Nellor et al., 2009).

$$DWEL\ (ug/L) = \frac{TDI\ (ug/kg-d) \times 70\ kg}{2\ L/d}$$

Where:

DWEL is the drinking water equivalent level; and

TDI is the tolerable daily intake.

- **Recommended drinking water guidelines**, which are similar to drinking water equivalent levels, but consider the relative contribution from water (Environment Protection and Heritage Council et al., 2008).

$$\text{Drinking water guideline } (\mu g/L) = \frac{\text{S-TDI (mg/kg/day)} \times \text{bw (kg)} \times \text{P} \times 10^{-3}}{\text{V (L/day)}}$$

Where:

S-TDI is the surrogate-tolerable daily intake level (which is the lowest dose tested divided by an uncertainty factor of 100 or 1,000);

bw is bodyweight (70kg);

P is the proportion of S-TDI from water, which is 100 percent;

V is the volume of water consumed (2 L/day); and

10^3 is the unit conversion from mg/L to μg/L.

- **Risk metrics** have been developed for some studies to estimate the required water consumption to equal the drinking water equivalent level based on maximum observed concentrations in water (Snyder et al., 2008; Bruce et al., in press).

$$\text{Required water consumption (L/day)} = \frac{\text{DWEL } (\mu g/L) \times 2 \text{ L/d}}{\text{Detected water concentration } (\mu g/L)}$$

Where:

DWEL is the drinking water equivalent level.

A list of these projects, endpoints utilized, and the uncertainty factors applied is shown in Table 25.

Table 25.Toxicological information for Constituents of Emerging Concern

Project	Summary
Human Pharmaceuticals in U.S. Surface Waters: A Human Health Risk Assessment (Schwab et al., 2005)	This study developed TDIs[a] and PNECs[b] for 26 active pharmaceutical ingredients and/or their metabolites, representing 14 different drug classes. The TDIs were primarily based on lowest therapeutic dose with UFs[c] ranging from 22.5 to 500; the TDI for ciprofloxacin was based on the minimum MIC[d] of ciprofloxacin to human intestinal microflora with no additional UF.
Toxicological Relevance of Endocrine Disruptors and Pharmaceuticals in Drinking Water – Water Research Foundation #3085 (Snyder et al., 2008)	This study developed TDIs and DWELs[e] for 16 PPCPs[f] (and 3 metabolites) and 13 EDCs[g]. The candidate list of PPCPs was large (3,000) and winnowed down based on criteria including use, occurrence, available analytical methods, public interest, and representative drug groups. The study looked at non-cancer endpoints with UFs ranging from 300 to 10,000, cancer endpoints, therapeutic dose endpoints, and endocrine effects with UFs ranging from 100 to 5,000; the most sensitive endpoint, including the UF, was selected for derivation of TDIs. Drinking Water Equivalent Levels (DWELs, a similar term for PNEC) were developed based on the TDI and the maximum detected concentration in water from the literature. Risk metrics were developed in terms of the number of 8 ounce glasses of water per day an individual would have to consume to exceed the DWEL.
Australian Guidelines for Water Recycling Augmentation of Drinking Water Supplies (Environment Protection and Heritage Council et al., 2008)[30]	The Guidelines derived TDIs and recommended drinking water guidelines for 87 pharmaceutical agents (pharmaceuticals, cytotoxic drugs, and hormonally active steroids) based on the lowest therapeutic dose adjusted by a UF. A UF of 100 was applied to all pharmaceuticals. An additional UF of 10 was applied to cytotoxic drugs and hormones. The Guidelines also derived recommended drinking water guidelines for 1) Cramer structural chemical classes and classes of toxicity (developmental toxicity, neurotoxicity (cholinesterase inhibitors), and genotoxic carcinogenicity; and 2) Cramer classification for compounds without toxicological information that are not genotoxics, pharmaceuticals or cholinesterase inhibitors.
U.S. Environmental Protection Agency Candidate Contaminant List (U.S. EPA, 2009c)	In 2009, the final Candidate Contaminant List was published, which included 116 contaminants (104 chemicals or chemical groups and 12 microbiological contaminants) that are known or anticipated to occur in public water systems. The list includes chemicals used in commerce, pesticides, waterborne pathogens, disinfection byproducts, and biological toxins. As part of the selection process, Health Relevance Levels (HRLs) were developed for the chemicals. For a carcinogen, the HRL is the one-in-a-million cancer risk expressed as a drinking water concentration. For non-carcinogens, the HRL is equivalent to the lifetime health advisory value. Determining the HRL for chemicals where the Potency value was the NOAEL, LOAEL, or LD50 value from an individual study, required application of an uncertainty factor: 1,000 for the NOAEL; 3,000 for the LOAEL; and 100,000 for the LD50[i].
Toxicological Relevance of Emerging Contaminants for Drinking Water Quality (Schriks et al., 2010)	Derived provisional drinking water guidelines for 50 compounds, 10 of which had statutory drinking water guidelines. For compounds without a statutory drinking water guideline value, TDIs were derived based on NOAELs, LOAELs, benchmark dose levels, maximum tolerated doses or lowest effective safe doses. If toxicity data was only available for inhalation, a route-to-route extrapolation was used. An appropriate safety factor to extrapolate between species (inter-species differences), inter-individual

[30] http://www.ephc.gov.au/sites/default/files/WQ_AGWR_GL__ADWS_Corrected_Final_%20200809.pdf

Project	Summary
	differences (intra-species differences), exposure route/duration and quality of the data was utilized as part of the TDI calculation. DWELs were calculated by multiplying the TDI by a typical average body weight of 70 kg and division by a daily water consumption of 2 L. Finally, to account for the fraction of the TDI allocated to drinking water, the DWEL was multiplied by an allocation factor to give the provisional guideline value. In most cases, when there was insufficient exposure information to derive chemical-specific allocation factors, a default allocation factor of 10% was used.
Tools to Assess and Understand the Relative Risks of Indirect Potable Reuse and Aquifer Storage and Recovery Projects – WateReuse Research Foundation 06-018 (Bruce et al., in press)	This study has developed TDIs and DWELs for 33 PPCPs and 10 EDCs. TDIs were based on the most sensitive endpoint: non-cancer endpoints with UFs ranging from 1,000 for NOAELs[h] and 3,000 for the LOAELs[i,j]; endocrine effects based on NOAELs using a UF of 10,000 and LOAELs using a UF of 30,000; cancer endpoints (10^{-6} slope factor plus lifetime risk for genotoxic compounds with tumor incidence data, maximum tolerated dose from 90-day studies in rodents divided by 740,000 for genotoxic compounds with no tumor incidence data, maximum tolerated dose from 90-day studies in rodents divided by 70,000 for non-genotoxic compounds); the minimum inhibitory concentration (MIC) for ciprofloxacin (with no additional UF); therapeutic dose with a UF of 3,000. DWELs were developed based on the TDI and the maximum detected concentration in water from the literature (if available). Risk metrics were developed in terms of the number of 8-oz. glasses of water per day an individual would have to consume to exceed the DWEL.
Identifying Hormonally Active Compounds, Pharmaceutical Ingredients, and Personal Care Product Ingredients of Most Health Concern From Their Potential Presence in Water Intended for Indirect Potable Reuse – WateReuse Research Foundation, (Snyder et al., in press)	This study consisted of a workshop held in November 2008, which was attended by regulators, scientists, and water industry professionals to discuss alternative methods to efficiently develop regulatory-based human health toxicity criteria for PPCPs and EDCs in wastewater. Case studies of methods for developing toxicity criteria were prepared for a number of PPCPs and EDCs. The 2008 scope of work for the project listed some 22 PPCPs and 15 EDCs to be addressed, some of which were included in Water Research Foundation #3085 and WateReuse Research Foundation 06-018.

a. Tolerable daily intakes (TDIs)
b. Predicted no effect concentrations (PNECs).
c. Uncertainty factors (UFs).
d. Minimum inhibitory concentration (MIC).
e. Drinking water equivalent levels (DWELs).
f. Pharmaceuticals and personal care projects (PPCPs).
g. Endocrine disrupting chemicals (EDCs).
h. No observable adverse effect level (NOAEL).
i. Lowest observable no adverse effect level (LOAEL).
j. The utilization of the default uncertainty factor of 1,000 applied to NOAELs, the uncertainty factor of 3,000 applied to LOAELs, and an additional uncertainty factor of 10 applied to a compound if it is either a non-genotoxic carcinogen or an endocrine disrupting compound was based on recommendations from WRF-05-005.
k. Fifty percent lethal dose (LD50).

9. Ecological issues

The U.S Environmental Protection Agency currently uses a series of guidelines established in 1985 to derive ambient water quality criteria for protection of aquatic life. The guidelines address acute risk (short-term effects such as survival and growth) and chronic risk (longer term effects such as reproduction) for traditional pollutants. However, there are many chemicals of emerging concern, including those that act as endocrine disruptors that alter the normal functions of hormones resulting in a variety of health effects. Endocrine disrupting chemicals can alter hormone levels leading to reproductive effects in aquatic organisms, and evaluating these effects may require testing methodologies not typically available along with endpoints not previously evaluated using the 1985 guidelines. Ecological evaluations are more complex than human health impacts due to the larger number of potential receptor groups, their interactions, and functions within an ecological system (Anderson, 2008). At this time, unequivocal information is currently not available on the overall significance of the effects of endocrine disrupting chemicals present in wastewater discharges. While water reuse involving surface water discharges has the potential to impact ecosystems, it is a broader issue that will ultimately have to be addressed by all wastewater dischargers, regardless of whether reuse is practiced. The primary application of interest for water reuse is reservoir augmentation, although direct application or incidental runoff from landscape irrigation could potentially also be relevant depending on the ecological system and level of exposure. Receptor systems can include phytoplankton, invertebrates, fish, algae, aquatic macrophytes, and amphibians in aquatic systems; and soil bacteria, plants, invertebrates/insects, birds, and mammals in terrestrial systems.

Information in the literature on the effects of chemical exposures to aquatic and terrestrial organisms in terms of growth, survival, and reproduction are expressed in terms of the:

- No Observed Effect Concentration, which is the highest tested concentration at which no statistically significant difference from the control or reference was observed.
- Lowest Observed Effect Concentration, which is the lowest tested concentration at which a statistically significant difference from the control or reference was observed.
- Percent Effect Level, which is the concentration at which a specific percent of the test organisms have been affected (such as 5 percent, 10 percent and 50 percent).

For constituents of emerging concern, information is often presented for biomarkers rather than biological effects, such as vitellogenin levels; or for impacts on individual fish (such as intersex fish). Biomarkers generally provide information on exposure to a substance, but do not necessarily indicate that an adverse outcome has occurred (Ankley et al., 2007). Thus, it is not fully understood if many existing biomarker results can be translated to individual effects and ultimately to effects at the population or community level. Depending on the specific biomarker in question, these outcomes may be related to the presence of contaminants, habitat quality, or the result of natural variations in populations (Dreyer et al., 2006). Reproductive decrease in fish is the most common endpoint used to assess population level impairment by endocrine active substances in treated wastewater (Ankley et al., 2001; Hotchkiss et al., 2008; Ankley et al., 2009). Subsequently, US EPA has recently identified an approach to augment the traditional

1985 water quality criteria development guidelines with new endpoints in aquatic organisms, including fish reproduction that are more sensitive for endocrine active molecules than previously employed for invertebrate reproduction responses (US EPA, 2008). Using these new approaches, the U.S. Environmental Protection Agency is developing recommended water quality criteria for the estrogen 17α−ethynyl estradiol and the antimicrobial triclosan.

Studies of wastewater have shown that it contains a number of potential endocrine disrupting chemicals at concentrations that have the potential to impact aquatic wildlife (Harries et al., 1998; Ternes et al., 2004). These compounds include natural hormones (17*β* −estradiol and estrone) and the more potent synthetic estrogens (17α−ethynyl estradiol) and industrial chemicals with weak estrogenic activity such as nonylphenol and bisphenol (Ying et al., 2002; Manning, 2005). Other studies have recommended predicted no effect concentrations for the protection of freshwater life and marine life from hormones (Young et al., 2002; Caldwell et al., 2008). Goonan (2008) compiled a list of predicted no effect concentrations and lowest tested concentrations at which an effect occurred for 17*β* –estradiol, estrone, 17α−ethynyl estradiol, tributyltin, bisphenol A, nonylphenol and octylphenol, and atrazine.

It is important to note that a project using reclaimed water for surface water augmentation will need to be sensitive to developments in this area and cognizant of mitigation that is available via natural treatment, conventional treatment, or advanced treatment technologies (Ternes et al., 2004). Steroid hormones can be eliminated in common nutrient wastewater treatment (with sludge retention times greater than 15 days) and with advanced treatment technologies (Ternes et al., 2004). It is also important to acknowledge that potential ecological impacts do not transmute to potential human health impacts from ingestion of water.

Information on chemical toxicity relevant to ecological impacts is maintained in a number of databases, such as:

- U.S. Environmental Protection Agency's ECOTOX, AQUIRE, TERRETOX, PHYTOTOX, Duluth Laboratory, and Office of Pollution Prevention High Volume Production databases. This recommendation parallels ongoing efforts by the U.S. Environmental Protection Agency and the U.S. Army Corps of Engineers (Ankley et al., 2009).
- The Human & Environmental Risk Assessment Project for European chemicals.
- The Organization for Economic Co-operation and Development Screening Information Data Set.
- Environment Canada Existing Substances Evaluation Reports.

The Swedish Association of the Pharmaceutical Industry has developed an environmental classification model for pharmaceuticals.[31] It includes information on three levels:

- The basic level gives short information on the environmental risk of the active pharmaceutical substance based on the ratio between the predicted concentration of the

[31] See http://www.fass.se/LIF/produktfakta/fakta_lakare_artikel.jsp?articleID=84645

substance in Swedish water systems (Predicted Environmental Concentration) and the concentration that is predicted to be safe for organisms and plants living in them (Predicted No Effect Concentration). If the concentration in the environment is lower than the concentration that, based on tests, is regarded as safe for organisms (the Predicted Environmental Concentration / Predicted No Effect Concentration is lower than 1), the risk of environmental impact is low or negligible. If, on the other hand, the Predicted Environmental Concentration is higher than the Predicted No Effect Concentration (the ratio Predicted Environmental Concentration / Predicted No Effect Concentration is higher than 1), there is a risk of impact on the environment.

- On the next level, the information on environmental risk is supplemented with information about the characteristics of the substance with regard to degradation and the potential for bioaccumulation of the substance (for example if the substance accumulates in aquatic organisms, thereby gradually increasing in concentration higher up in the food chain). A substance that degrades with difficulty and/or has the capacity to bioaccumulate could mean that exposure increases since the concentration in the environment increases, which in turn enhances the risk over time of environmental impact.
- All background data for the previous assessment of environmental risk, degradability and bioaccumulation are presented, which also details how the assessment was made.

In April 2009, the Southern California Coastal Water Research Project held a workshop to formulate a path forward for integrating science into an effective management strategy for constituents of emerging concern (SCCWRP, 2009). Some of the key outcomes of the workshop included:

- Agreement that the current chemical-specific risk assessment approach is neither feasible nor cost effective for prioritizing and managing the vast majority of constituents of emerging concern. A new paradigm that prioritizes chemicals (or chemical classes) with similar modes/mechanisms of action for further evaluation is needed.
- Owing to the scarcity of data and lack of robust methodologies for measuring most constituents of emerging concern, a flexible, multi-element prioritization framework was recommended to identify those compounds of highest concern. This framework would integrate risk, occurrence, and modeling-based prioritization elements to select the highest priority compounds or surrogates for each specific monitoring application and geographical location. A single master monitoring list of compounds for all applications was believed to be unlikely.
- Interpretation of monitoring data and subsequent decision making should be based on tiered, multiple thresholds. Thresholds associated with no, little, moderate, and high probabilities of impact should be used to trigger risk-appropriate actions aimed at protecting beneficial uses of the resource. In concert with the proposed risk-based prioritization framework, the participants stressed that development of effects-based thresholds should consider mode-of-action, as well as the distribution of dosages that elicit the response of interest. . For example, available human pharmacology and toxicology data appear useful for prioritizing the effects of the most problematic compounds on aquatic life (Berninger and Brooks, 2010).

The Water Environment Research Foundation is sponsoring a study titled "Diagnostic Tools to Evaluate Impacts of Trace Organic Compounds on Aquatic Populations and Communities: Phase I – Prioritization, Development and Testing of Site-Specific Framework (CEC5R08C)" to determine the relationship between exposure to trace organics and adverse impacts to aquatic populations and communities. The primary objectives of this research are to develop a screening tool that the water quality community can use to: 1) assess whether observed site specific impacts on aquatic populations or communities are caused by trace organics, and 2) determine whether exposure concentrations of trace organics are likely to cause aquatic population and/or community effects. The research, which will be completed in 2011, will develop and test:

- A procedure to prioritize which trace organics will be the focus of the research;
- A conceptual framework and diagnostic tools to identify trace organics by source type;
- Exposure-response pathway models for high priority trace organics;
- A relational database of trace organics exposure and effects data;
- A collaboration plan for fostering partnerships among stakeholders; and
- A communication plan to effectively transfer the knowledge gained.

10. Energy and sustainability issues

One of the key values that water reuse offers a community is that of a reliable and locally controlled water supply that is independent of drought, climate change, and other factors that impact most traditional supply sources (Raucher, 2009). It reduces demands on valuable surface and groundwater. Use of reclaimed water can also postpone costly investment for development of new water sources and supplies, and has allowed some communities to continue to grow where the availability of historically used freshwater sources has become extremely limited.

This is a very important inter-relationship between energy and water, where water reuse plays a significant role. First, for some reuse applications that incorporate advanced technologies, that are energy intensive, there is a desire to reduce energy consumption and the carbon footprint of the treatment scheme. Second, increased overall water demands are linked to higher energy production, which provides opportunities for expanded water reuse applications (Raucher, 2009). This area takes into consideration the potential impacts climate change can have on water demand that leads to increased water reclamation, such as augmenting stream flow for habitat protection, providing water for sea water intrusion barriers in the face of sea level rise, and to supplement water as traditional supplies diminish.

The major challenges related to sustainability of wastewater treatment and water reclamation systems are 1) energy self-sufficiency, 2) the utilization of the energy in wastewater for water reclamation, 3) the utilization of external energy inputs, and 4) the application of life cycle assessment (Raucher, 2009).

The California Sustainability Alliance conducted a study to estimate the energy and carbon benefits that could be achieved by accelerating and increasing development and use of reclaimed water in southern California (California Sustainability Alliance, 2008). It evaluated the reclaimed water opportunities for four water agencies: the Inland Empire Utilities Agency and the cities of Ontario, San Diego, and Los Angeles and the amount of additional reclaimed water that could be produced and used if these agencies' reclaimed water development plans could be accelerated by five years, and the potential energy and carbon benefits that could be achieved.

To evaluate energy and carbon benefits, the study used the difference between the energy intensity of reclaimed water and seawater desalination. In addition, the values of avoided electricity and the embedded gas and carbon benefits associated with the electricity consumption that could be circumvented by increasing the use of reclaimed were computed on the same basis used to evaluate the cost-effectiveness of energy efficiency, renewable energy, and other energy programs.

On a statewide basis, the study concluded that every acre-foot of reclaimed water discharged to the ocean or other natural waterway that could have offset use of potable water represented a significant lost opportunity for California. It also recommended that the value of energy and carbon benefits of reclaimed water should be measured on a basis equivalent with other energy efficiency programs in California by using:

- A conservative value of 3,400 kWh/acre-foot and 1.43 CO_2 tons/acre-foot.
- An avoided cost of energy, assuming a levelized price of $0.08/kWh, is $272/acre-foot.

The four agencies studied had about 415,000 acre-feet per year (370 million gallons per day) of tertiary reclaimed water (filtered /disinfected effluent) that could be converted to beneficial use. At an estimated energy benefit of 3,400 kWh/acre-foot, this incremental amount of reclaimed watered represented a potential statewide energy savings of 7 million MWh (7,000 GWh for the five year period; about 1,400 GWh per year). This magnitude of energy savings represented about 16 percent of the state's annual energy efficiency goals. At a conservative value of $0.08/kWh, the five-year electricity benefit of the unused tertiary wastewater was $120 million. If unused secondary treated wastewater was included, the electricity benefit exceeded $500 million. These estimates included the embedded costs of natural gas used to produce the electricity, and an allowance for "externalities" (carbon and other environmental factors).

The study also concluded that significant capital investments would be required to achieve these benefits. In order to use the available reclaimed water, additional facilities (pipelines, reservoirs, pump stations, service laterals) would need to be developed, and sites used for irrigation would have to be retrofitted.

A significant level of effort is being applied to research that is looking at the opportunities and impediments associated with the nexus between the energy and the water sectors. The WateReuse Research Foundation and California Energy Commission are sponsoring a number of projects addressing the following topics:

- How water-intensive energy production methods (such as thermal and biofuel) might provide a valuable opportunity for expanding the market for water reuse applications.
- Forecasting energy demands from the water sector's anticipated future reliance on reuse, desalination, and related water supply approaches and technologies that are relatively energy intensive.
- Examining energy recovery options for water suppliers.

- Exploring how reclaimed water may be productively applied in existing or emerging energy development efforts.
- Evaluating the opportunities for water reuse and desalination utilities to increase energy efficiency, manage peak power demands, and tap into renewable energy supplies to reduce carbon footprints.
- Consider the role of water reuse in planning for and addressing climate change impacts and how climate change may alter the availability and quality of water supplies in the future, and how it may impact the operations and capital programs of water supply and wastewater agencies.

11. Public acceptance/outreach

Public attitudes towards water reuse are critical for the success of a program and vary among the public depending on the water reuse application. Surveys conducted in the 1970's and 1980's and more recently regarding acceptance of various uses of reclaimed water indicated that the public was more willing to consent to direct contact with reclaimed water than drinking it (Bruvold, 1972; Bruvold, 1981; Lohman, 1987; Haddad et al., 2009). Experience and research in the area of public acceptance has clearly shown that public perceptions and opinions can make the difference between the success and failure of a reuse project for both non-potable and potable reuse applications (Metcalf & Eddy, 2007), and it is important to engage the public early in the planning of a project using effective communication and outreach tools.

Potable reuse can often be negatively received by the public leading to unsuccessful implementation. Successful projects have a number of characteristics in common:

- They are designed to improve water quality;
- They augment groundwater supplies or prevent sea water intrusion versus being designed to dispose of wastewater;
- They maintain a historical water quality database and conduct research to support success;
- They are managed by agencies with established experience; and
- These agencies have gained the confidence of regulatory authorities that issue permits.

The WateReuse Research Foundation sponsored a study to examine how people perceive the value of indirect potable reuse, including groundwater recharge, and how the messages and management practices of the sponsoring utility affect these perceptions (WRF, 2004). A second phase of the project developed a set of internet-based tools to help utilities better understand public perceptions of indirect potable reuse, develop a set of best practices, and improve the community dialogue.[32] This body of work identifies 25 best practices, the most "critical" of which are shown in Table 26.

Table 26. Critical best practices for groundwater recharge projects

Practice number	Practice
1	Create and communicate improvement
2	Clearly articulate the problem
4	Evaluate alternatives to potable reuse
7	Understand and avoid environmental justice issues

[32] See http://www.watereuse.org/water-replenish/index.html.

Practice number	Practice
11	Establish the utility as the source of quality
12	Rename the water
13	Communication = collaboration about value
15	Practice good leadership
17	Identify and collaborate with key audiences
18	Embrace potential conflict and opposition
21	Establish relationships with the media

(Source: WRF, 2004)

The WateReuse Research Foundation project also identified the key characteristics of unsuccessful indirect potable reuse projects:

- Inability to address concerns about water quality and health;
- Concerns about a commercial product image;
- The project facilitated growth;
- The project created a political rallying point;
- Concerns regarding environmental justice;
- Cost; and
- Insufficient public input/outreach.

In some cases, the true underlying issue of public concern was not raised (such as growth), but another issue was primarily used as the means to rally public and political opposition (such as health concerns).

The Water Environment Research Foundation funded an interdisciplinary and integrative social science study on public perception and participation on water reuse within the United States (Hartley, 2006). It included case studies, white papers from five different social science disciplines and public health and environmental engineering scientists, and a multi-stakeholder workshop. The case studies included examples of potable and non-potable reuse, with elements of success and failure. The study identified five themes that were critical to building and maintaining public confidence in water resource management and water reuse decision making:

- Managing information for all stakeholders;
- Maintaining individual motivation and demonstrating organizational commitment;
- Promoting communication and public dialog;
- Ensuring a fair and sound decision making process and outcome; and
- Building and maintaining trust.

Millan (2007) advocates that understanding fears and perceptions about reclaimed water use has allowed the industry to better communicate and be responsive when implementing new projects and new uses. Perceptions that need to be considered include the following:

- People do not automatically trust the scientific premise that reclaimed water is safe.
- There is an inherent distrust of government on every level and a public cynicism regarding what scientists claim to be true.
- Because of this, the "yuck" factor of wastewater is not easily overcome.
- Yet, most people view reclaimed water use as an environmentally responsible thing to do.
- There is currently no consistent, nationwide messaging regarding the use of reclaimed water, and thus perception from communities across the country varies greatly.
- The Internet contains a considerable amount of misinformation about water reuse that is readily available, can be taken out of context (and used), and can create fear and misunderstanding of the science related to water reuse.

It is important to acknowledge the difference between "outreach" and "participation" (Metcalf & Eddy, 2007). Outreach is a way of disseminating or collecting information to educate the public; participation implies a means for stakeholders to actively engage in and influence a plan. There are a number of techniques that can be used for outreach and participation, including (Metcalf& Eddy, 2007; Millan (2007):

- One-on-one communications.
- Community relationship management.
- Databases.
- In depth interviews.
- Surveys.
- Open house meetings.
- Workshops.
- Advisory committees/task forces.
- Email broadcasts.
- Twitter.
- Consistent proactive notifications.
- Call centers.
- Project portals.

One example in Texas is the outreach program undertaken by the San Antonio Water System for their water reuse program. This agency is the single largest water purveyor in the San Antonio/Bexar County region and provides water service to more than one million people. Extended drought conditions and continued reliance on a sole source of water supply, the

Edwards Aquifer, created challenges for meeting the City's water supply needs. To meet short-term water needs, the San Antonio Water System decided to pursue an aggressive water conservation program and a water recycling program that would substitute up to 20 percent of the current demand for potable water with reclaimed water. An important aspect of the program was to design and implement a public information and involvement program to inform the citizens of San Antonio about important water issues and involve them in the decision- making process for the development of water conservation and recycling programs. The program:

- Provided full-time on-site public information practitioners and services.
- Conducted focus groups and a public opinion survey.
- Enhanced relationships with local media.
- Worked with the media to enhance favorable coverage of conservation and recycling programs by co-sponsoring contests and special programs on water as well as hosting quarterly educational forums for news reporters.
- Provided briefings on water and reclaimed water programs to the San Antonio City Council, regional water agencies, and state and federal elected officials.
- Conducted public meetings, workshops, and neighborhood events throughout the city to offer citizens an opportunity to provide input to SAWS on water conservation and recycling programs.
- Developed a public outreach plan and assisted with customer marketing for the water reuse program.
- Implemented a proactive speakers bureau to provide presentations to community, civic and business groups.
- Produced informational materials including fact sheets, newsletters, brochures, and videos to support the conservation and reuse programs.

The public information and involvement program effectively assisted the San Antonio Water System with implementing the programs. The San Antonio Express-News issued an editorial in strong support of the cost-effectiveness of water reuse and its benefits to the entire community. The San Antonio Water System approved a plan to deliver over 30 million gallons per day (34,000 acre-feet per year) of reclaimed water to be used for parks, golf courses, industrial users, and stream augmentation.

The WateReuse Research Foundation is sponsoring a number of studies that will provide critical information for future public outreach efforts. The first is "Talking about Water – Vocabulary and Images that Support Informed Decisions about Water Recycling and Desalination." This project is assessing how words, images and concepts influence public perception of reclaimed water. The research will also identify the community's preferred terminology to enable them to understand the different qualities of water available for recycling and feel confident about water recycling. It will also determine if improved knowledge and understanding of water cycle, water science and technology improves acceptance. An outcome of the research will be a glossary (with simple explanations) of preferred terms associated with the different parts of the urban water reuse cycle. This work will be completed in 2010.

The second project is "The Effect of Prior Knowledge of 'Unplanned' Potable Reuse on the Acceptance of 'Planned' Potable Reuse." Often communities considering the use of reclaimed water for indirect potable reuse are unaware of other common water reuse occurrences such as unplanned or incidental reuse that may enhance their familiarity with water reuse. This project, which will be completed in 2012, aims to determine if communities considering the use of reclaimed water for indirect potable reuse would be more accepting of water reuse if they had prior knowledge and understanding of "unplanned" water reuse via discharges of treated wastewater into water supply sources.

12. Multiple barriers for potable reuse

The multiple barrier concept has historically been the cornerstone of the safe drinking water program. The 1996 Safe Drinking Water Act Amendments created a coordinated set of programs and requirements to help water systems make sure they have a safe supply of drinking water. These programs and requirements form a multiple barrier approach complete with technical and managerial barriers that help prevent contamination at the source, enhance treatment, and ensure a safe supply of drinking water for consumers. A successful multiple barrier approach includes barriers between potential threats and the consumer and programs and activities to make sure the barriers are in place and operation. The specific barriers are 1) risk prevention that focuses on the selection and protection of drinking water sources; 2) risk management that focuses on the protection provided by water treatment and system operations; 3) monitoring and compliance to detect and fix problems in the source or distribution system as early as possible; and 4) individual action that focuses on consumer awareness and participation.

For potable reuse, the multiple barrier approach is broadened to include safety measures that go beyond those normally included in conventional water systems to increase overall system reliability (Metcalf & Eddy, 2007). These barriers can include:

- Wastewater treatment;
- Dilution;
- Natural attenuation and time of reaction;
- Storage;
- Retention time underground or in a reservoir;
- Drinking water treatment;
- Raw and treated water monitoring, including monitoring at various locations in the treatment process.

In the multiple barrier approach, individual processes, each capable of some level of contaminant removal, work together to reduce the risk of failure of the overall process. Multiple barriers are frequently somewhat redundant so that a deficiency or excursion of one element does not place the entire system at significant risk.

Drewes and Khan (in press) depict the multiple barrier approach in a framework that consists of six key components.

- A sewage collection program subject to an industrial source control program. For publicly owned treatment plants, this would include conformance with the federal pretreatment standards to prevent pass through of pollutants and interference with wastewater treatment operation, and implementation of federal effluent guidelines and local limits for industries tributary to the wastewater management system. Some source control programs have also developed enhanced pollution prevention elements and chemical inventories.
- Conventional wastewater treatment that allows a facility to meet its waste discharge requirements, including technology and water quality-based standards. Treatment at a minimum removes organic matter, suspended solids, and pathogens. Conventional treatment can be modified to remove nutrients, and this modification is primarily based on meeting the applicable receiving water standards.
- Advanced water treatment processes that provide additional barriers for constituents of concern, such as residual organic chemicals, nutrients, dissolved solids, and pathogens.
- Integration of an environmental buffer or natural treatment system. For example, this could include soil aquifer treatment or river bank filtration for polishing or storage underground or in a reservoir.
- A drinking water treatment plant that treats the augmented source prior to delivery to customers. However, in the United States, for a groundwater system that has been augmented with reclaimed water, treatment prior to delivery may not be required in all cases. Current regulations for groundwater only require disinfection, and it may not be mandated in all cases.
- A monitoring program that evaluates the performance of the framework elements and to ensure the final product water is suitable for consumption.

For direct potable reuse, some barriers such as storage and retention time may not be available. Thus a multiple barrier concept for direct reuse may require additional components such as increased treatment or real-time monitoring.

13. Technology gaps and future needs

To advance water reuse in Texas and around the country, there are a number of key technology gaps and future needs that must be addressed, including the follow key topic areas:

- Understanding the energy/water nexus in terms of the type of treatment needed to meet water quality needs for specific reuse applications, opportunities to design and operate wastewater treatment facilities to maximize water reuse; and the implications of various treatment schemes in terms of energy usage and carbon footprint.
- Identifying the compounds of greatest human health and environmental concern for indirect potable reuse via surface water augmentation as well as for the use of reclaimed

water for environmental enhancement and mitigation, and developing information on the relative risk of using reclaimed water.

- Understanding the role and effectiveness of environmental buffers applied to the use of reclaimed water for augmenting surface water supplies, including residence times (storage), mixing, and contaminant attenuation.
- Evaluating the treatment effectiveness of wetlands when they are used for indirect potable reuse projects and the operational strategies that can be used to enhance wetland performance.
- Developing tools for monitoring water quality, including microbial and chemical indicator and surrogate compounds that are representative of behavior during treatment and can be used to evaluate risk to human and aquatic health; quantitative molecular methods for evaluating the viability and concentration of microorganisms in reclaimed water; evaluating real-time data using online analytical techniques that provide immediate feedback on reclaimed water quality or the effectiveness of treatment processes; bioanalytical tests such as *in vitro* bioassays to address chemicals and chemical mixtures; and more reliable and meaningful analytical methods.
- Developing tools for better defining the costs and social benefits of water reuse projects.
- Developing the science to support the development of or modification to Texas regulations for water reuse.
- Facilitating how utilities can successfully plan and implement reuse projects given the unique water rights and regulatory framework in Texas, including developing strategies for acquiring large volume customers; identifying institutional organizational models that can effectively implement reuse; and developing tools that allow utilities to make informed decisions in the selection of and investment in reuse options.
- Developing a public awareness and outreach strategy and tools that can be used to advance public acceptance of the use of reclaimed water in Texas.
- Developing or adapting models that can be used by Texas utilities to plan and implement new indirect reuse project in conjunction with projected water management activities, including control of nutrients trace organic contaminants, and regulated drinking water contaminants.
- Obtaining funding for water reuse treatment and project infrastructure.

As part of this project (Advancing Water Reuse in Texas), a research needs agenda is being developed to advance the implementation of water reuse projects included in the State Water Plan.

14. Water reuse research

Programs that conduct and promote applied research on water reuse are extremely important to the advancement of reuse technology. By examining the parameters that define a reuse system, efficiency can be increased and reuse opportunities expanded.

14.1. Research foundations

In the United States, there are a number of research foundations that conduct and promote applied research on water reuse. The most prominent of these entities are the WateReuse Research Foundation[33], the Water Research Foundation, and the Water Environment Research Foundation.

The WateReuse Foundation is an educational, nonprofit public benefit corporation that serves as a centralized organization for the water and wastewater community to advance the science of water reuse, recycling, reclamation, and desalination.[34] The WateReuse Foundation's research covers a broad spectrum of issues, including water quality, occurrence and risk of chemical contaminants and microbiological agents, treatment technologies, desalination, public perception, economics, and marketing. The primary sources of funding are subscribers and funding partners, which include the U.S. Department of the Interior's Bureau of Reclamation, the California State Water Resources Control Board, and the Southwest Florida Water Management District. The annual budget is approximately $3.8 million. The WateReuse Foundation's research agenda is updated periodically to reflect emerging research needs based on input from research needs assessment workshops, the results of research projects, and surveys of subscribers. The last research needs workshop was held in December 2009, which will establish research priorities for the next three to five years. The WateReuse Foundation participates in research projects with other foundations and funding partners through its Research Partnership Program.

The Water Research Foundation (formerly the American Water Works Association Research Foundation) is a member-supported, international, nonprofit organization that sponsors research to enable water utilities, public health agencies, and other professionals to provide safe and affordable drinking water to consumers.[35] It provides a centralized, practical research program that focuses on four goal areas: 1) infrastructure; 2) management and customer relations; 3) water quality; and 4) water resources and environmental sustainability. Specific research projects focus on treatment, distribution, resources, monitoring and analysis, management, and health effects. While the primary focus is on drinking water, some Water Research Foundation projects address water reuse or topics that encompass water reuse. The Water Research Foundation is largely funded by subscribers, primarily water utilities, and the U.S. Environmental Protection Agency. Its annual budget is approximately $12 million.

The Water Environment Research Foundation is a member-supported, international, nonprofit organization that sponsors independent scientific research dedicated to wastewater and stormwater issues.[36] The research program focuses on 13 knowledge areas: biosolids; climate change; conveyance systems; decentralized systems; nutrients; operations optimization; pathogens and human health; security and emergency response; stormwater; strategic asset management; trace organics; use attainability analysis; and water reuse. Funding comes from

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[33] In May 2010, the WateReuse Foundation underwent a formal name change to the WateReuse Research Foundation.
[34] See http://www.watereuse.org/foundation.
[35] See http://www.waterresearchfoundation.org/.
[36] See http://www.werf.org//AM/Template.cfm?Section=Home.

subscribers and the U.S. Environmental Protection Agency. The subscribers include wastewater management agencies, stormwater utilities, regulatory agencies, industry, equipment companies, and consultants. The Water Environment Research Foundation spends between $6 and $8 million each year on research priorities set by subscriber volunteers.

A large number of universities conduct research specifically targeted at issues related to the use of reclaimed water, including Arizona State University, the Colorado School of Mines, Texas A&M University, the University of Arizona, the University of California (Berkeley, Davis, and Riverside), the University of Texas, and the University of New South Wales.[37] Other research organizations in the United States and abroad that fund and/or conduct research on water recycling or related issues include:

- Applied R&D Center (Southern Nevada Water Authority)
- National Water Research Institute.
- Global Water Research Coalition.
- EAWAG - Swiss Federal Institute for Aquatic Science and Technology (Switzerland).
- Kiwa (Netherlands).
- PUB (Singapore).
- Suez Environmental - CIRSEE (France).
- Stowa - Foundation for Applied Water Research (Netherlands).
- DVGW TZW- Water Technology Center (Germany).
- UK Water Industry Research (United Kingdom).
- Veolia Water - Anjou Recherche (France).
- Water Quality Research Center (Australia).
- Water Research Commission (South Africa).
- Water Services Association of Australia.

14.2. Texas-based water reuse studies

Some Texas-specific studies have been conducted related to treatment processes and beneficial use of reuse water. The following summarizes several of these projects, but does not represent a complete list of all projects performed in Texas:

Use of reclaimed water for Lake Fort Phantom Hill. In 1988, the City of Abilene initiated a project to identify a system of treatment processes that could be implemented to increase its water supply without detrimental effects on water quality (TWDB and City of Abilene Texas, 1988). The primary objective was to ensure that the discharge of advanced treated reclaimed

[37] Too numerous for all to be named here.

water via a tributary or directly to Lake Fort Phantom Hill (a water supply reservoir), would not cause any adverse effects on the water quality that would alter the beneficial uses of the reservoir, including potable water supply, recreation, fisheries, and irrigation. The study also looked at non-potable water uses that could reduce demands on the potable water system.

One part of the study evaluated the existing water quality of the lake to predict the effects of the introduction of treated effluent on future water quality, including collecting and assessing chemical constituents and specific pathogens and conducting modeling. The project established water quality goals, the level of treatment required and the various treatment process alternatives to meet those goals, and conducted bench-scale testing to support the selection of a treatment process. The project concluded that for reclaimed water flows introduced into Lake Fort Phantom Hill at a rate greater than 3 million gallons per day (3,000 acre-feet per year), the quality of the treated water needed to meet the criteria presented in Table 27.

Table 27. Proposed reclaimed water criteria for Lake Phantom Hill

Constituents	Criteria
BOD[a]	5 mg/L
TSS[b]	5 mg/L
Phosphorus	0.2 mg/L
Ammonia	2 mg/L
Dissolved oxygen	5 mg/L
Turbidity	2 NTU[c]
pH	6.5-8.5
Toxic parameters	Recommended mean contaminant levels for drinking water standards
Microbiological	
Viruses	< 1 PFU[d]
Fecal coliform	<2.2/100 mL

(Source: TWDB and City of Abilene Texas, 1988).

a. Biochemical oxygen demand (BOD).

b. Total suspended solids (TSS).

c. Nephelometric turbidity units (NTU).

d. Plaque forming units (PFU).

The project recommended an "alum with biological phosphorus" treatment process. In addition, it was recommended that the city consider performing pilot evaluations of treatment processes at the water treatment plants. It was also recommended that the city perform ongoing water quality monitoring and conduct a public information and relations campaign. The Texas Water Development Board provided funding for this research project.

Constructed wetlands studies. In 1989, the Tarrant Regional Water District determined that it needed to increase its water supply. After investigating numerous options, the agency elected to pursue two primary options: 1) participate in the construction of a new reservoir in east Texas; and 2) divert water from the effluent-dominated Trinity River into the Richland-Chambers and Cedar Creek reservoirs. Based on water quality studies, it was determined that the Trinity River water should receive additional treatment prior to reservoir diversion. Several treatment options were evaluated and the utilization of constructed wetlands was selected as the candidate treatment process. Tarrant Regional Water District constructed a pilot-scale wetland (about 2.5 acres of water surface) and performed testing for about seven years. Results of the testing showed good removal of target constituents (nutrients, total suspended solids, and biochemical oxygen demand) and supported going forward with constructing a full-scale wetland in phases. Ultimately the wetlands for the Richland-Chambers reservoir will be about 1,800 acres and 1,700 acres for the Cedar Creek reservoir. The combined amount of reclaimed water developed by these wetland projects will be about 195,000 acre-feet per year (174 million gallons per day). This project was primarily funded by Tarrant Regional Water District with partial funding provided by the Texas Water Development Board and the Water Research Foundation. The Tarrant Regional Water District has completed more than three years of operation of the 243-acre field-scale wetland constructed to facilitate further research regarding the treatment expectations and verification of performance capabilities documented during the pilot wetland study, as well as refinement of design criteria for full build-out of the wetlands at the Richland-Chambers Reservoir (Mokry, et al., 2008).

The use of reclaimed water for turf irrigation. This research project was a cooperative effort between El Paso Water Utilities, Texas A&M Agriculture Research Center, and the U.S. Bureau of Reclamation. It surveyed a number of reclaimed water applications, including golf courses, parks, and schools. A primary focus of the research was to assess the soil-salinity status and the effect of using reclaimed water on irrigated vegetation, primarily grasses. The project developed educational material including a video that explains in detail the response of soil and vegetation to the salinity from reclaimed water and provides suggestions for practices to manage the conditions.

Testing integrated membrane bioreactors and reverse osmosis. This project was carried out through a cooperative program between the City of McAllen, Texas, the Texas Water Development Board, the Electric Power Research Institute, the Central and Southwest Energy Services, CH2M Hill, and the U.S. Bureau of Reclamation. It included demonstration-scale testing of an integrated membrane bioreactor and reverse osmosis treatment train to produce reclaimed water from the City of McAllen's municipal wastewater at a quality suitable for use as a new drinking water supply. Testing objectives included demonstrating that: 1) reverse osmosis product water meets all federal primary and state secondary drinking water regulations; 2) membrane bioreactors can be reliably operated using screened, degritted sewage as feedwater, particularly with respect to control of membrane fouling through automatic cleaning; and 3) reverse osmosis (composite membranes) can be reliably operated using membrane bioreactor effluent as feedwater, particularly with respect to membrane fouling. The study also developed estimates of capital and operating costs for an integrated membrane bioreactor and reverse osmosis treatment system.

Developing geospatial data and tools to identify and track industrial water reuse opportunities. The primary objective of this research pilot study was to equip local municipal utilities and industrial facilities of the greater Houston area with practical geospatial data and tools to identify and track industrial water reuse opportunities. The project was comprised of three phases:

- Data acquisition and review including review of regulations and literature, administering a survey, and analyzing the results;
- Design and creation of a comprehensive geographic information system; and

- Development and implementation of a web-enabled reclaimed water management system.

The project developed a web-enabled geographic information system decision support application, which serves as a powerful, cost effective tool for supplying centralized data resources and information to Texas utilities (URS, 2008).

The use of reclaimed water for golf course irrigation. The purpose of this research was to analyze the inherent benefits and potential problems associated with using reclaimed water to irrigate golf courses (Dixon and Ray, 2008). In 2007, a reclaimed water use survey was prepared and sent to United States Golf Association member courses in Texas to evaluate the spatial distribution of golf courses utilizing reclaimed water in Texas. This research also analyzed the regulatory and management issues and considerations identified by Texas golf course superintendents for beneficial use of reclaimed water.

The results of the survey showed that irrigating a golf course with reclaimed water commands more management, regulatory, and maintenance attention than irrigating with potable water. But, with proper implementation and management, reclaimed water was found to be an effective conservation measure as well as an economical, continuous source of irrigation water.

15. Reuse case studies

This section presents nine case studies of water reuse programs in Texas, other portions of the United States, and abroad that embody what are considered to be representative examples of non-potable and potable reuse applications. Information on project costs is presented when it was available.

- El Paso, Texas
- Singapore Public Utilities Board NEWater Project, Republic of Singapore
- Essex and Suffolk Water Langford Recycling Scheme, United Kingdom
- Clayton County, Georgia
- Orange County Water District, California
- West Basin Municipal Water District, California
- Excel Energy Cherokee Station, Denver, Colorado
- Monterey County Water Recycling Project, California
- Irvine Ranch Water District, Irvine, California

15.1. El Paso, Texas

Background. The City of El Paso is located in the Chihuahua Desert in western Texas and has a 2007 population of almost 625,000. Water is scarce, with an average rainfall of eight inches per year and an average evaporation rate of 80 inches per year. El Paso shares groundwater from the Hueco Bolson and the Mesilla Bolson aquifers and surface water from the Rio Grande River with communities in New Mexico and Ciudád Juarez, Mexico. Water from the Rio Grande is available only during the spring, summer, and early fall months and is further limited in years of drought. As a result of long term pumping that began in the early 20th century to sustain increasing growth, groundwater pumping has exceeded the recharge rate and groundwater levels have declined in the Hueco Bolson aquifer.

The current demand in the El Paso Water Utilities service area is about 109,000 acre-feet per year (97 million gallons per day). El Paso Water Utilities is in charge of the operation and management of the city's water, reclaimed water, wastewater, and stormwater systems. El Paso Water Utilities operates two surface water treatment plants, four groundwater arsenic treatment plants, multiple wells, booster stations and reservoirs, four wastewater treatment plants that produce reclaimed water for a variety of uses, and (in a joint project with Fort Bliss), the Kay Bailey Hutchison Desalination Plant, which is a 27.5 million gallon per day (30,800 acre-feet per year) brackish inland groundwater desalination plant.

***Reclaimed water program*.** El Paso began delivering reclaimed water to customers for non-potable reuse applications in 1963. Since that time, the reuse program has been greatly expanded, and about 5 million gallons per day (5,600 acre-feet per year) of reclaimed water from four treatment plants (Fred Hervey Water Reclamation Plant and the Haskell Street, Roberto Bustamante, and Northwest Wastewater Treatment Plants) currently is used for non-potable reuse application, including industrial uses and landscape irrigation at parks, school grounds, golf courses, cemeteries, and other green spaces. Use of reclaimed water for non-potable uses offsets approximately 5% of the total water demand for the City. In addition, 3.1 million gallons per day (3,500 acre-feet per year) is used for in-plant uses and potable reuse via groundwater recharge. An important consideration in the selection of a water reuse scheme was that the municipal wastewater in the northeast area of El Paso is mostly of domestic origin and contains less than 0.1 percent industrial wastes. The almost 7.5 million gallons per day (8,400 acre-feet per year) of reclaimed water used in 2009 was distributed as follows:

- 30 percent for industrial uses;
- 39 percent for irrigation;
- 31 percent for groundwater recharge (injection and percolation); and
- Less than 1 percent for construction and other purposes.

All of the plants provide a minimum of advanced secondary treatment (with filtration) and produce reclaimed water meeting state requirements for Type I reclaimed water use, which is defined as the use of reclaimed water where contact between reclaimed water and humans is likely (see Section 4.2).

Fred Hervey Water Reclamation Plant. The Fred Hervey Water Reclamation Plant was put into service in 1985. It has a design capacity of 10 million gallons per day (11,200 acre-feet per year) and produces reclaimed water for multiple uses, primarily golf course irrigation, industrial cooling water, and groundwater recharge into a potable water supply aquifer. The recharge part of the operation is called the Hueco Bolson Recharge Project. The total capital cost was approximately $33,000,000; funding was provided, in part, by a 65 percent grant from the U.S. Environmental Protection Agency. The remainder of funding was provided through wastewater user rates. Unless otherwise specified in contractual arrangements, the reclaimed water rate in El Paso currently is $1.24/1,000 gallons. The reclamation plant includes the following treatment processes:

- Primary treatment: screening, degritting, and primary clarification.
- Flow equalization.
- Secondary treatment: combines conventional biological treatment with the use of powdered activated carbon with a patented two-stage PACT™ system process. This phase of the treatment process provides organics removal, nitrification, and de-nitrification; methanol is added to the second stage as a carbon source for the denitrifiers.
- High lime treatment (coagulation and clarification) to remove phosphorus and some heavy metals. A pH of at least 11 is achieved to destroy viruses.
- Recarbonation to pH 7.5 by addition of carbon dioxide.
- Sand filtration with traveling-bridge, automatic backwash filters for turbidity and parasite removal.
- Disinfection using ozone.
- Granular activated carbon filtration with traveling-bridge, automatic backwash filters as a polishing process for removal of residual organic compounds and improvement of taste, odor and color.
- Chlorination to produce a residual of 0.25 mg/L to prevent biological growths during storage and recharge.

Figure 4. PACT™ process at Fred Hervey Water Reclamation Plant (Source: El Paso Water Utilities)

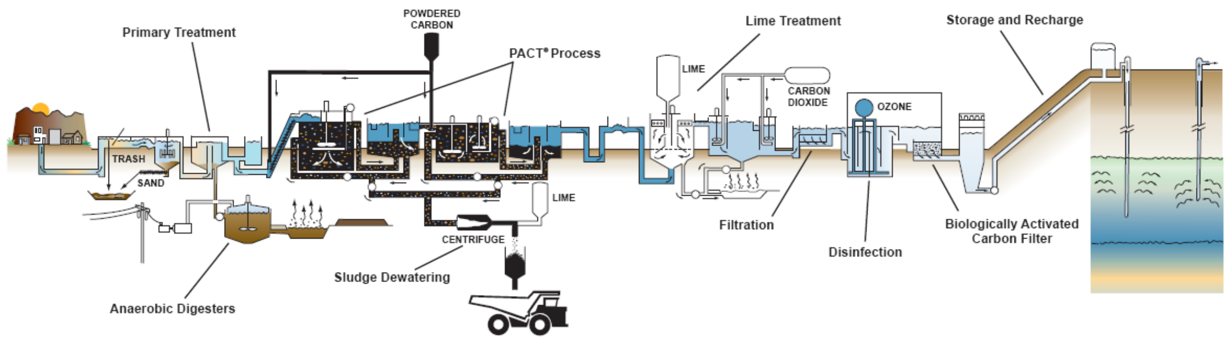

Figure 5. Schematic of Fred Hervey Water Reclamation Plant (Source: El Paso Water Utilities)

The plant is currently being upgraded to meet new permit requirements and to improve reliability. During the upgrade, the plant's capacity will be uprated to 12.2 million gallons per day.

Haskell Street Wastewater Treatment Plant. The Haskell Street Wastewater Treatment Plant was originally constructed in 1923. The plant serves the central part of the city and currently has a treatment capacity of 27.7 million gallons per day. The plant is has an advanced secondary treatment system. Sand filters were added to treat the portion of the effluent used for reuse. The remainder of the flow is discharged to the Rio Grande via a canal to meet contractual return flow requirements with El Paso County Water Improvement District #1.

Figure 6. Haskell Street Wastewater Treatment Plant (Source: El Paso Water Utilities)

In 1999, a $25 million upgrade and renovation introduced several innovative treatment technologies, including energy efficient anoxic treatment basins, biological nitrification, and natural gas fueled air blowers in the aeration process.

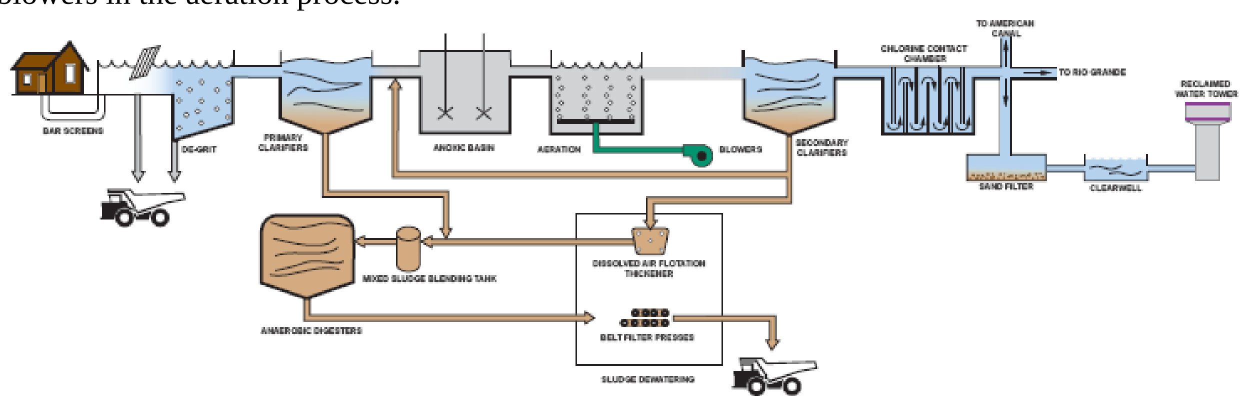

Figure 7. Schematic of Haskell Street Wastewater Treatment Plant (Source: El Paso Water Utilities)

Roberto R. Bustamante Wastewater Treatment Plant. The Roberto Bustamante Wastewater Treatment Plant began serving the east, southeast, and Lower Valley parts of the city in 1991 and has a treatment capacity of 39 million gallons per day. This plant has advanced secondary treatment and utilizes state-of-the-art extended aeration activated sludge processes, biological nitrification, and caustic air scrubbers for odor control. Reclaimed water from the plant is provided to industries located in the Riverside Industrial Park and a cemetery for landscape irrigation.

Figure 8. Robert R. Bustamante Plant (Source: El Paso Water Utilities)

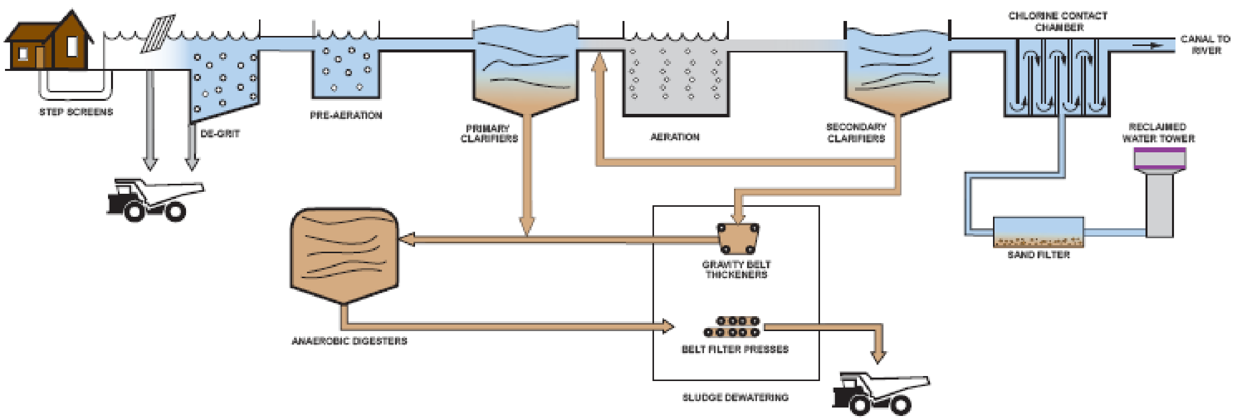

Figure 9: Schematic of Robert R. Bustamante Wastewater Treatment Plant (Source: El Paso Water Utilities)

Northwest Wastewater Treatment Plant. The Northwest Wastewater Treatment Plant has a capacity of 17.5 million gallons per day. The plant also provides advanced secondary treatment, but processes sludge through lime stabilization rather than anaerobic digestion. Other innovative treatment technologies include the use of ultraviolet radiation as a means of disinfection of treated effluent and caustic air scrubbers as a means of controlling odors. Chlorine is applied to the portion of the effluent delivered to the reclaimed water system in order to prevent biological growth in the distribution system.

Figure 10: Reclaimed Water Dispensing Station (Source: El Paso Water Utilties)

Reservoirs are also equipped with recirculating chlorine systems to keep the reclaimed water fresh in the tanks. The Northwest plant also has an automatic reclaimed water dispensing station for transfer of reclaimed water to contractors for construction applications. The Northwest plant serves the greatest number of reclaimed water customers of all the plants, including residential irrigation users.

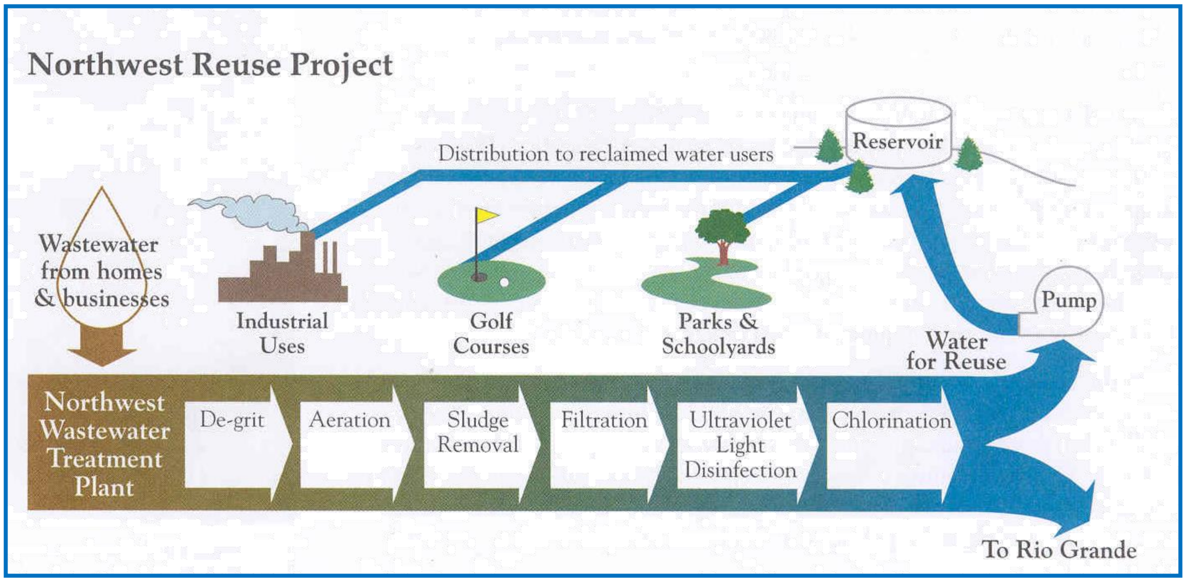

Figure 11: El Paso's Northwest Reuse Project (Source: El Paso Water Utilities)

Hueco Bolson Recharge Project. In 2009, the Fred Hervey Water Reclamation Plant produced about 5.2 million gallons per day (5,800 acre-feet per year) of reclaimed water. Of that total, approximately 1.0 million gallons per day (1,100 acre-feet per year) was sent to 10 injection wells, 1.3 million gallons per day (1,500 acre-feet per year) to an infiltration basin for groundwater recharge, and about 2.9 million gallons per day (3,200 acre-feet per year) was reused for non-potable applications, principally golf course irrigation and industrial cooling water. The surface spreading basin was constructed as a pilot facility in 2000 and has been in operation since 2001 to augment the recharge.

The reclaimed water, which meets both federal primary drinking water standards and Texas Commission on Environmental Quality standards prior to injection, is recharged into the fresh water zone of the aquifer. The injection wells are located from one-half to three- quarters of a mile upgradient from the nearest existing drinking water supply well. This was done to ensure a minimum two-year residence time for the reclaimed water before its withdrawal by any potable water supply wells. The actual retention time underground has been calculated to be more than five years based on simulated groundwater velocity. The extracted groundwater is commingled with other well water and chlorinated prior to distribution as potable water.

Problem encountered. The injection wells have been subject to corrosion of steel well casings and screens in the past. Four of the original 10 wells have been replaced with polyvinyl chloride casings and screens to avoid this problem. In addition, spreading basins have been constructed to supplement the wells.

15.2. Singapore Public Utilities Board NEWater Project, Republic of Singapore

Background. The Republic of Singapore has a population of about 5 million people. Although rainfall averages 98 inches per year, Singapore has limited natural water resources due to its small size of approximately 270 square miles. Singapore obtains approximately 50 percent of its water supply from Malaysia under two bilateral agreements that are due to expire in 2011 and 2061.

To have a diversified, robust and sustainable water supply, Singapore initiated the Four National Taps strategy in the late 1990s, which identified the following four sources of water supply: local catchment water; imported water from Johor, Malaysia; reclaimed water; and desalinated water.

One of the sources, reclaimed water (called NEWater), is the product of a comprehensive and extensive study that was started in 1998. The initial objective of the NEWwater Study was to construct and operate a demonstration scale advanced dual membrane water treatment plant to determine the reliability of membrane technology to purify secondary treated wastewater effluent to a quality that consistently surpasses the World Health Organization drinking water guidelines and the U.S. Environmental Protection Agency's drinking water standards. By achieving that high quality, NEWater could then be supplied to industries, commercial buildings for non-potable use, and for planned indirect potable reuse via discharge to raw water supply reservoirs.

While non-potable reuse has been an important component of Singapore's water resources since the early 1970s when tertiary treated wastewater began to be used for industrial applications, the NEWater Study included evaluation of the use of higher quality water for non-potable applications such as process water at wafer fabrication plants and air conditioning cooling water in commercial buildings.

NEWater Study. The NEWater Study included the following three major areas of investigation:

- Operation of an advanced water treatment demonstration plant using microfiltration , reverse osmosis, and ultraviolet radiation to test the ability of the treatment train to reliably and consistently produce high quality water;
- A Sampling and Monitoring Program that included comprehensive physical, chemical, and microbiological sampling and analysis of water samples; and
- A Health Effects Testing Program to complement the sampling and monitoring study to determine the safety of NEWater. The health effects study involved the toxicological assessment of NEWater against Public Utilities Board source water from Bedok Reservoir.

A 2 million gallon per day (2,200 acre-feet per year) NEWater demonstration plant was built at the Bedok Water Reclamation Plant and placed into operation in 2000. The Bedok Water Reclamation Plant received more than 95 percent of its wastewater from domestic sources. Feed water to the demonstration plant was activated sludge secondary effluent. The advanced water treatment processes included micro-screening (0.3 mm screens), microfiltration (0.2 μm nominal pore size), reverse osmosis with thin-film aromatic polyamide composite membranes configured for 80 to 85 percent recovery in a three-stage array, and ultraviolet radiation with broad-spectrum medium pressure lamps delivering a minimum design total calculated dosage of 60 mJ/cm^2. Chlorine was added before and after microfiltration to control membrane biofouling. One of the objectives of the treatment plant design was to incorporate microfiltration, reverse osmosis, and ultraviolet radiation into the treatment train as multiple barriers for the removal of microbial pathogens and chemical contaminants.

Sampling and monitoring program. An extensive water quality monitoring program was carried out at the demonstration facility. The program included systematic measurement of a suite of physical, microbial, and chemical parameters across the process train to evaluate the suitability of using NEWater as a raw water source for potable use. The U.S. Environmental Protection Agency primary and secondary drinking water standards and World Health Organization water quality guidelines were used as the benchmarks for NEWater quality. More than 50,000 individual physical, microbiological, and chemical water quality analytical results have been determined from multiple monitoring locations across the treatment train. The overall quality of NEWater consistently met the drinking water quality benchmarks. The majority of the measured parameters had values which were lower than the Public Utilities Board potable water.

Health effects studies. A two-year Health Effects Testing Program was initiated in 2000 to evaluate the potential health impact of unidentified and unregulated chemical contaminants in the NEWater. The study involved a comparative toxicological assessment of NEWater with an existing raw water supply from Bedok Reservoir using both rodents (B6C3F1 mice) and fish (medaka). The mouse study was a two-year *in vivo* study, and the fish study was a two-generation study. The findings of the study indicated that NEWater did not have short-term or long-term carcinogenic effects on either the mice or fish and did not have any estrogenic (reproductive or developmental) effects on the fish.

NEWater factories. Singapore's advanced water treatment facilities are called NEWater factories. Currently, there are five NEWater factories in operation, all of which include the same treatment processes as evaluated during the demonstration plant study. The NEWater factories at the Bedok and Kranji Water Reclamation Plants went into service in 2003 and have since been expanded to their current capacities of 18 million gallons per day (20,000 acre-feet per year) and 17 million gallons per day (19,000 acre-feet per year), respectively. A third NEWater factory at the Seletar Water Reclamation Plant was placed in service in 2004 and has a capacity of 5 million gallons per day (5,600 acre-feet per year). The fourth NEWwater factory (Ulu Pandan) has a capacity of 32 million gallons per day (36,000 acre-feet per year) and went into operation in 2007. A fifth facility, the Changi NEWater Factory, is being commissioned in two stages: the first 15 million gallons per day (17,000 acre-feet per year) was commissioned in 2009, with an additional 35 million gallons per day (39,000 acre-feet per year) to be commissioned in 2010.

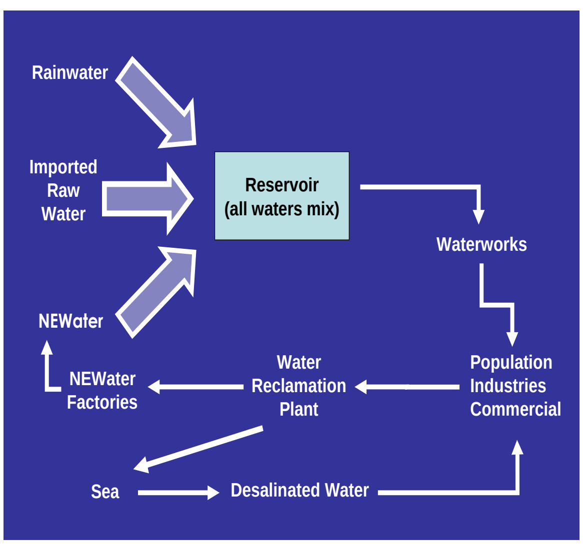

Figure 12. Schematic of NEWater system (Source: Singapore Public Utilities Board)

The NEWater factories all produce high quality product water with turbidity less than 0.5 nephelometric turbidity units; total dissolved solids less than 50 mg/L; and total organic carbon less than 0.5 mg/L. The water meets all U.S. Environmental Protection Agency and World Health Organization drinking water standards and guidelines. Additional constituents monitored include many organic compounds, pesticides, herbicides, endocrine disrupting compounds, pharmaceuticals, and unregulated compounds of concern. None of these constituents have been found in the treated water at health-significant levels.

Most of the reclaimed water from the NEWater Factories is supplied to industries for non-potable reuse. These industries include wafer fabrication, electronics and power generation for process use, as well as commercial and institutional complexes for air conditioning cooling purposes. Less than 10 million gallons per day (11,000 acre-feet per year) of NEWater currently is used for planned indirect potable reuse via discharge to raw water reservoirs, accounting for slightly more than 2 percent of the total raw water supply in the reservoirs. The blended water is subsequently treated in a conventional water treatment plant of coagulation, flocculation, sand filters, ozonation, and disinfection prior to distribution as potable water.

Visitor center. A NEWater Visitor Center was built as the focal point of the Public Utilities Board public education program to build public awareness and acceptance of advanced water treatment technologies. The center is fully integrated with the Bedok NEWater Factory and includes an elevated walkway through the process area and a multi-media interactive exhibition/education area. It includes multimedia displays, videos, interactive computer programs, and guided tours to educate the public, particularly school children, about the importance of water to the community. A small portion of the water produced for potable reuse is bottled and given to visitors and others in Singapore to demonstrate the water's high quality.

Costs and funding. The capital costs for all of the NEWater factories averaged about $2.2 million per million gallons per day capacity. Annual operation and maintenance costs for the water are about $985 per million gallons produced. The Public Utilities Board charges industries and others $2.68/1,000 gallons for NEWater on a full cost recovery approach. This includes the capital cost, production cost, and transmission and distribution cost.

15.3. Essex and Suffolk Water Langford Recycling Scheme, United Kingdom

Background. Britain's Essex and Suffolk Water serves an area where population has increased by more than 18 percent since 1960 to a current population of about 1.75 million. Water supplies in the area are limited, and 50 percent of the drinking water supply is imported from other areas. The National Rivers Authority (predecessor to the Environment Agency) first proposed that Essex and Suffolk Water consider utilizing effluent from the Chelmsford Sewage Treatment Works for potable reuse in the early 1990s that culminated in the Landford Recycling Scheme. Proposed schemes included treatment of the Chelmsford effluent prior to discharge into the River Chelmer and abstraction of the effluent at the end of the pipeline and treating it at Langford prior to discharge into the Hanningfield reservoir.

Preliminary studies. Several studies were undertaken, including: baseline ecology and chemistry assessments of the two potential receiving waters; baseline ecology assessments of the Blackwater estuary; water quality characterizations of the Chelmsford effluent and that of water receiving additional treatment; and the treatability of the water at the Hanningfield Water Treatment Works. Ecology monitoring included gathering baseline data on macrophytes, invertebrates, and fish and bird populations in the River Chelmer, Blackwater estuary, and Hanningfield reservoir. The water quality studies were principally concentrated on establishing baseline levels of nutrients, metals, and organic chemicals in the waters and sediments.

The effluent was tested for the chemical constituents such as heavy metals and selected organic chemicals, while microbial testing included fecal coliforms, salmonella, enteric viruses, and *Cryptosporidium* oocysts. Endocrine disrupting compounds were beginning to be recognized as having adverse effects on aquatic organisms, and studies were conducted to determine the effects of these compounds on fish. Pilot plant data to determine the effectiveness of upgraded treatment at the Hanningfield Water Treatment Works were obtained and evaluated. Treatment processes included two-stage ozonation, chemical coagulation, rapid sand filtration, and granular activated carbon filtration.

Temporary recycling project. The 1995-1997 drought exacerbated water shortages in the region, and the Environment Agency consented to an indirect potable reuse project as an emergency measure. The project involved abstraction of up to 6.6 million gallons per day (7,400 acre-feet per year) of treated wastewater from the effluent pipeline at Langford, treating the water by ultraviolet radiation, and discharging the water to a pipeline that carried river water to the Hanningfield reservoir. The Environment Agency "Consent to Discharge" was for a specified time period: from July 27, 1997 to December 31, 1998. The Environment Agency further stipulated that the previous ecological, chemical, and microbiological studies had to continue and that the reclaimed water must receive an ultraviolet radiation dose of at least 32 mJ/cm^2.

The studies were successful in providing scientific information indicating that the indirect potable reuse project did not needlessly subject the public to any demonstrable adverse health outcomes; however, Essex and Suffolk Water did not develop a public information program to keep the public informed about the project, which initially led to some local opposition to the scheme by local citizens and unfavorable coverage in the media. Opposition to the scheme eventually diminished after a concerted effort by Essex and Suffolk Water to inform the public and others about the project and the study findings. The project operated for the full length of its license and terminated at the end of 1998.

Research on estrogenic effects on fish. The first research efforts to evaluate the effects of steroids (estrone, 17β-estradiol, and 17α-ethinyl estradiol), alkylphenols, and alkylphenol ethoxylates in fish exposed to wastewater were carried out in 1996. The results of that study indicated that, while Chelmsford Sewage Treatment Works effluent contained levels of alkylphenols and alkylphenol ethoxylates that could be expected to result in estrogenic responses in male trout, water treatment processes including ozone and granular activated carbon reduced the levels of alkylphenols and alkylphenol ethoxylates by more than 99 percent during spiking trials. Exposure of trout to a mix of Chelmsford wastewater and river water indicated that the "no observed effect concentration" on the fish occurred at dilutions of 25 percent or less.

Research was continued during the operation of the temporary recycling scheme. During this study, rainbow trout were placed in cages that were fed product water from the Hanningfield Water Treatment Works and monitored for vitellogen to assess the estrogenicity of the water. Water samples from the inlet and outlet of the Hanningfield reservoir, at the fish cages, and before and after ultraviolet radiation disinfection at the reclamation plant were analyzed for the female hormones estrone, 17β-estradiol, and 17α-ethinyl estradiol. The three steroids were below detectable limits in all samples taken at the inlet and outlet of the Hanningfield reservoir and the fish cages. Ultraviolet radiation reduced the concentrations of the steroids, but did not eliminate them, and adult male trout in cages fed with ultraviolet radiation-treated effluent exhibited significant estrogenic response. Further research was conducted on water from a pilot plant in 1999 and indicated that the removal of total steroid estrogens in the product water averaged more than 94 percent after the pilot plant was optimized.

Current project. The project involves intercepting treated wastewater from the Chelmsford Sewage Treatment Works at Brookend that is discharged via an 8.7-mile pipeline into the Blackwater estuary below abstractions of river water for treatment at the water treatment works. The extracted water is treated at Langford to improve its quality and then pumped 1.9 miles for discharge into the River Chelmer.

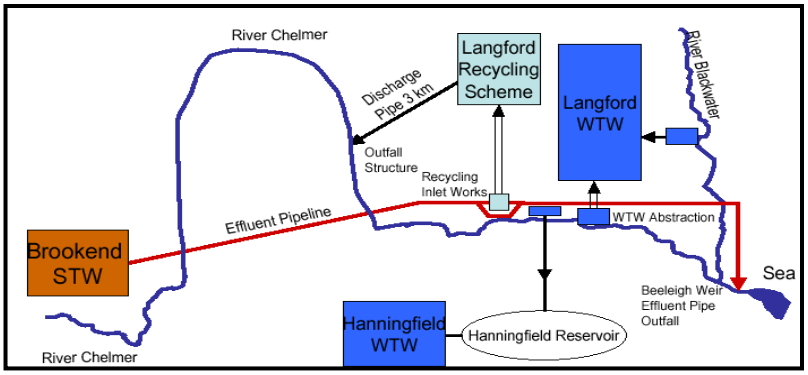

Figure 13. Langford water recycling scheme (Source: Northumbrian Water Limited)

The reclaimed water mixes with the river water and travels approximately 2.5 miles prior to abstraction and pumping to the Hanningfield reservoir. The reclaimed water is diluted 3:1 with river water, on average. The Chelmsford Sewage Treatment Works produces a dry weather flow of about 7.9 million gallons per day (8,800 acre-feet per year) of secondary effluent. The capacity of the Langford plant, which went into operation in 2003, is 10.6 million gallons per day (12,000 acre-feet per year).

The reclaimed water treatment plant at Langford provides the following treatment processes:

- Fine screening;
- Chemical precipitation with ferric sulfate and polyelectrolyte followed by sedimentation;
- Powdered activated carbon;
- Nitrification/denitrification via a biological aerated flooded filter using methane as a supplemental carbon source; and
- Ultraviolet radiation disinfection.

The Hanningfield reservoir has a capacity of approximately 6.9 billion gallons and serves as the source water for the Hanningfield Water Treatment Works. The mixture of reclaimed water and river water receives additional treatment by ozonation and granular activated carbon at the Hanningfield Water Treatment Works prior to distribution as potable water. In 2007, reclaimed water made up 12 percent of the water in the reservoir. Retention time of reclaimed water in reservoir is about 214 days.

The Environment Agency granted the "Discharge Consent and Abstraction License" in April 2000 for an initial time limit of 10 years. The discharge consent includes numerous requirements, including limits on disinfection dose, nitrogen, phosphorus, dissolved oxygen, heavy meals, and selected organic constituents. Microbial monitoring includes total coliforms, fecal coliforms, fecal streptococci, salmonella, viruses, and F-specific bacteriophage. Ecological monitoring in the river and estuary also is required.

15.4. Clayton County, Georgia

Introduction. The Clayton County Water Authority) is recognized for its comprehensive approach to managing the county's limited water resources. Established in 1955, the Clayton County Water Authority initially served approximately 450 customers, but presently provides water, sewer, and stormwater services to more than a quarter of a million people.

Figure 14: Clayton County wetland (Source: Alan Plummer Associates, Inc.)

Located south of Atlanta, Georgia, Clayton County has limited surface and groundwater supplies available and has experienced severe drought conditions at times. The agency's 2000 Master Plan identified constructed wetlands for water reclamation and indirect potable reuse as the preferred method of managing Clayton County's limited water resources. In 2007, during one of the worst droughts in 50 years, the Clayton County Water Authority's reservoirs augmented with reclaimed water, maintained 78 percent of their storage capacity.

Recognizing that wetlands have a significant role within a watershed and the water cycle, the Clayton County Water Authority's wetland systems consist of a series of interconnected, shallow ponds filled with native vegetation. Wastewater is processed in a secondary treatment facility and then discharged into the constructed wetlands, which remove pollutants such as excess nutrients. To demonstrate the value of preserving wetland environments and providing public education relative to natural resource conservation, the Melvin L. Newman Wetlands Center was created and opened in 1995.

Project description. The 4.4 million gallons per day (4,900 acre-feet per year) Panhandle Constructed Wetlands System was brought on line in September 2003. Phase I of the Huie Constructed Wetlands was brought on line in September 2005, providing 3.5 million gallons per day (3,900 acre-feet per year) of treatment capacity. Phase II was brought on line in August 2006, and Phase III was brought on line in 2007. During the drought of 2007, Clayton County Water Authority A was able to recycle over 10 million gallons of reclaimed water per day (11,000 acre-feet per year). Phase IV of the Huie Constructed Wetlands will be brought on line in 2010. Based on the effluent water quality from the W.B. Casey Water Reclamation Facility, the hydraulic loading capacity for the treatment wetlands is 1 million gallons per day (1,100 acre-feet per year) per 15 to 25 acres of wetland based on regulatory permitting requirements.

The Newman Wetlands Center consists of 32 acres and includes a wetlands trail, a 4,888 square foot building complex consisting of a central exhibit/learning lab area, a 50-seat auditorium, offices, restrooms, and a conference facility. Picnic areas are located near the building and can be reserved for groups participating in programs at the Wetlands Center. The wetlands trail is an easy half-mile long walk with benches, covered areas, and a water fountain.

Education and outreach. The Clayton County Water Authority's Newman Wetlands Center is the focal point of community education efforts. Created to demonstrate the importance of preserving wetlands environments and to provide public education, guided group tours are provided by the staff. There have been sightings of over 130 bird species, beaver, river otter, fox, raccoon, muskrat, deer, wild turkey, opossum, mink, and many other species of reptiles, insects, and amphibians. Local schools can enjoy field trips during the year.

Project Benefits. The Clayton County Water Authority draws water from a series of man-made reservoirs and wetlands, which can produce up to 42 million gallons per day (47,000 acre-feet per year) of potable water and can treat up to 38.4 million gallons per day (43,000 acre-feet per year) of wastewater. About 10 million gallons per day (11,000 acre-feet per year) of water are put back into the water supply through the wetland system each day.

One of the major benefits of utilizing constructed wetlands in Clayton County is that it helped the county maintain an abundant water supply during the record-setting drought that began in 2006.

Figure 15: Newman Wetlands Center, Clayton County Wetland (Source: Alan Plummer Associates, Inc.)

Other benefits include cost effectiveness, water supply sustainability, additional wastewater treatment capacity, improved quality of the reclaimed water, as well as reduction of the maintenance and operations burden of spray irrigation land application. Constructed wetlands require less land for treatment than for land application at the forested spray fields, greatly reduce operation and maintenance costs, and utilize natural systems to produce high quality reclaimed water.

The three Clayton County Water Authority's water reclamation facilities that discharge to constructed wetlands were upgraded and expanded to meet the higher levels of pretreatment required. The Shoal Creek plant was upgraded and expanded from 2.1 million gallons per day (2,400 acre-feet per year) to 4.4 million gallons per day (4,900 acre-feet per year), with the effluent being introduced into constructed wetlands. The 3.0 million gallons per day (3,400 acre-feet per year) discharge from these wetlands is captured and pumped to the nearby Clayton County Water Authority Shoal Creek Reservoir, eventually flowing to the J.W. Smith Reservoir to augment potable water supply. The Panhandle Road wetlands treatment system was constructed on a sloping site with 22 wetland cells and three separate flow paths encompassing about 55 wetland acres. The flexibility provided by the design allows for isolating a flow path or wetland cell for maintenance if needed.

A phased implementation plan for the Huie constructed wetlands was developed to optimize the site capacity during wetland construction. The net increase in capacity gained from each wetland phase was utilized for the next phase of construction until site build out was completed. The combined treatment capacity at full build out of the Huie wetlands is 24 million gallons per day (27,000 acre-feet per year) through the constructed wetland treatment systems and 9 million gallons per day (10,000 acre-feet per year) to the remaining forested land application spray fields. Reclaimed water from the Huie wetlands and drainage from the remaining spray fields flow to the Clayton County Water Authority's Blalock Reservoir for indirect potable reuse.

The Constructed Wetlands offer a cost effective, energy efficient alternative with lower operational and maintenance costs. The wetlands also provide a much more sustainable water system that enhances the potable water supply availability to its customers. In addition to increasing the county's water supply, the wetlands area provides wildlife habitat and recreational opportunities.

15.5. Orange County Water District, California

Background. The Orange County Water District in Fountain Valley, California, was formed in 1933 to manage northern Orange County's groundwater supply. More than 250 production wells in Orange County Water District's service area supply about 70 percent of the water demand for a population of 2.3 million residents. The remaining demand is met by imported water from the Colorado River and northern California. Seawater intrusion has been a problem since the 1930s as a consequence of groundwater basin overdraft and was observed as far as 3.5 miles inland from the Pacific Ocean by the 1960s. Further, a 1963 Supreme Court decision limited the amount of water California was guaranteed from the Colorado River.

The Orange County groundwater basin contains an estimated 326 billion gallons of usable water and has an average operating yield of 82 billion gallons/year.   Orange County Water District's inland surface spreading operations recharge an average of 95 percent of this quantity via approximately 1,000 acres of surface water percolation facilities. Historically, imported water from the Colorado River and northern California and water from the Santa Ana River have been the source waters for groundwater recharge in Orange County.

The history of groundwater recharge by Orange County Water District comprised three "eras" that can generally be identified by the reuse facilities in service at the time:

- Water Factory 21 from October 1976 to January 2004;
- Interim Water Factory 21 from June 2004 to August 2006; and
- Groundwater Replenishment System from January 2008 to present.

Water Factory 21. Injection of reclaimed water from Water Factory 21 into the Talbert Gap Seawater Intrusion Barrier began in 1976 via 23 multiple-cased injection wells. Water Factory 21 received activated sludge secondary effluent from the adjacent Orange County Sanitation Districts Plant No. 1. The 15 million gallons per day (17,000 acre-feet per year) Water Factory 21 original processes were lime clarification, recarbonation, ammonia stripping towers, mixed media filtration, granular activated carbon , chlorination, and blending with deep well water.

Reverse osmosis was incorporated into the treatment train (the flow was split 50:50 between granular activated carbon and reverse osmosis) in 1977. Reverse osmosis and granular activated carbon product water were pumped to a blending reservoir, mixed with deep well water, and injected into four aquifers prone to seawater intrusion using the multi-point injection wells. The bulk of the injected water flows inland to augment groundwater used as a potable supply source.

The project included construction of 31 monitoring wells, 5 supplementary deep wells, and 7 extraction wells. The extraction wells, located between the injection wells and the coast, were not been needed to maintain a hydraulic gradient to prevent seawater intrusion. Thirteen additional injection wells were constructed in recent years as part of the Groundwater Replenishment System project.

Interim Water Factory 21. The purpose of Interim Water Factory 21 was to produce up to 5 million gallons per day (5,600 acre-feet per year) of reclaimed water for the Talbert Barrier to prevent seawater intrusion and to serve as a training facility to allow staff to gain experience with the same treatment train as that planned for the larger Groundwater Replenishment System Advanced Water Purification Facility. Utilizing new treatment processes along with modified Water Factory 21 facilities, Interim Water Factory 21 included microfiltration, reverse osmosis, decarbonation, and an advanced oxidation process (addition of hydrogen peroxide prior to ultraviolet radiation) to treat wastewater from the Orange County Sanitation District's Plant No. 1. The reclaimed water was blended with diluent water, chlorinated, and pumped to the Talbert Barrier injection wells.

Groundwater Replenishment System. A recharge project called the Groundwater Replenishment (GWR) System was conceived in the 1990s to replace the Water Factory 21 and provide additional water to recharge the Orange County Groundwater Basin. Detailed design and construction of the Groundwater Replenishment System, a joint project between the Orange County Water District and Orange County Sanitation District, was approved in 1999. The Groundwater Replenishment System consists of three major components: the Advanced Water Purification Facility; the Talbert Gap Seawater Intrusion Barrier; and the Miller and Kraemer spreading basins. The advanced treatment facility began producing reclaimed water in January 2008 for injection at the Talbert Barrier and spreading at Kraemer-Miller Basins.

Figure 16: Orange County Water District, Groundwater Replenishment System Advanced Purification Facility, reverse osmosis units (Source: Dr. James Crook)

The source water for the 70 million gallons per day (78,000 acre-feet per year) advanced treatment facility is either activated sludge secondary effluent or a blend of activated sludge and trickling filter secondary effluent from the adjacent Orange County Sanitation District Plant No. 1, which currently has a rated capacity of 108 million gallons per day (121,000 acre-feet per year). Modifications at Plant No. 1 are in progress that will increase its capacity up to 170 million gallons per day (190,000 acre-feet per year) by 2012. The Groundwater Replenishment System Advanced Water Purification Facility provides further treatment by microfiltration, reverse osmosis, and advanced oxidation; the treated water is stabilized by decarbonation and lime addition. The combination of decarbonation and lime stabilization raises the pH and adds hardness and alkalinity to make the water less corrosive and more stable.

In 2008, the Advanced Water Purification Facility produced 40 million gallons per day (45,000 acre-feet per year) of product water. Current production ranges from 60 million gallons per day (67,000 acre-feet per year) to 65 million gallons per day (73,000 acre-feet per year). Plans are underway to increase the capacity of the Groundwater Replenishment System in phases, with an ultimate build out capacity of 130 million gallons per day (146,000 acre-feet per year). Half of the water produced by the advanced treatment plant is injected into the Talbert Gap Seawater Intrusion Barrier and half is pumped approximately 13 miles through a 78-inch diameter pipeline (gradually reduced to 60 inches) through the Santa Ana River corridor to the Kraemer and Miller Basins in Anaheim, which are deep spreading basins in the Orange County Forebay area. Kraemer Basin covers an area of about 31 acres, has a maximum storage capacity of about 1,040 acre-feet, and has an estimated recharge capacity of 65 million gallons per day (73,000 acre-feet per year). Miller Basin covers an area of approximately 21 acres, has a maximum storage capacity of about 150 acre-feet, and has an estimated recharge capacity of 38 million gallons per day (43,000 acre-feet per year). The nearest extraction well is more than 900 feet from the percolation basin, and the retention time underground prior to extraction exceeds the California Department of Public Health requirement of 6 months.

Extensive monitoring of the Advanced Water Purification Facility has indicated that the product water contains no pathogenic bacteria, viruses, or parasites, and continually meets all drinking water standards. The Advanced Water Purification Facility effectively reduces the concentration of chemical constituents of concern (such as pharmaceuticals, endocrine disrupting compounds, and trihalomethanes) to very low or immeasurable levels. In addition, total dissolved solids are reduced from 1,000 mg/L to 30 mg/L, and total organic carbon is reduced from 11 to 12 mg/L to less than 0.15 mg/L.

Costs and Funding. The capital cost of the Groundwater Replenishment System was more than $480 million, and the annual O&M cost is about $30 million. The Orange County Water District received federal and state grants totaling $92.5 million, an $86 million subsidy for operation and maintenance from Metropolitan Water District of Southern California, and a California Revolving Fund loan of $145 million. Without outside funding, the cost of the product water would be approximately $2.46/1,000 gallons.

Benefits. Some of the important benefits of the Groundwater Replenishment System are as follows:

- Provides a higher quality water than other water sources in Orange County;
- Reduces salinity build up in the groundwater basin;
- Uses approximately 50 percent less energy than needed to import water from northern California;
- Is a reliable, drought-proof source of supply;
- Protects the groundwater basin from seawater intrusion;

- Defers or eliminates the need for a new ocean outfall; and
- Provides needed additional water supply for Orange County.

Green Acres Project. In addition to the Groundwater Replenishment System, Orange County Water District also operates the Green Acres Project, which provides an average of 7.5 million gallons per day (8,400 acre-feet per year) of reclaimed water for landscape irrigation (parks, schools, and golf courses) and industrial purposes such as cooling and process washdown. Reclaimed water is distributed through about 32 miles of pipelines. The reclaimed water receives tertiary treatment (secondary effluent from Orange County Sanitation District's Plant No. 1, filtration, and disinfection) and is distributed for uses in Fountain Valley, Huntington Beach, Costa Mesa, Newport Beach, and Santa Ana. The reclaimed water meets the California Water Recycling Criteria for uses requiring disinfected tertiary treated reclaimed water.

15.6. West Basin Municipal Water District, California

Background. The West Basin Municipal Water District is a public agency that wholesales imported potable water and reclaimed water to local cities, mutual water companies, private companies, and investor-owned utilities. West Basin Municipal Water District's service area encompasses 200 square miles in southwest Los Angeles County, California. The agency provides 80 percent of the potable water used in its service area to more than 850,000 people; the remaining 20 percent is local groundwater pumped by retail water agencies.

Figure 17. Edward C. Little Water Recycling Facility, El Segundo, CA (Source: West Basin Municipal Utility District)

In the early 1990s, about 80 percent of the water used in southern California was imported. West Basin Municipal Water District purchased State Water Project and Colorado River water from the Metropolitan Water District of Southern California for resale to its customers. It was around this time that West Basin Municipal Water District began considering alternative sources of water supply to the region due to the prospect of dwindling supply of imported water caused by environmental concerns and anticipated future allotment cutbacks. In addition, a lack of emergency storage facilities to assure reliable deliveries during droughts made it more imperative for West Basin Municipal Water District to diversify its water supply portfolio. West Basin Municipal Water District pursued water reuse as the most economical choice that would also give the agency the opportunity to treat wastewater to different levels depending on end use. The goals of the recycling program are to reduce dependence on imported water, provide an alternative drought-proof local water source, reduce the volume of treated wastewater discharged to Santa Monica Bay, and prevent further saltwater intrusion of the groundwater basin.

Project Description. The first phase of the project was initiated in 1992 and completed in late 1994. Delivery of reclaimed water from the West Basin Water Recycling Plant began in 1995.

In 2009, an average of 30 million gallons per day (34,000 acre-feet per year) of reclaimed water was used for a variety of uses, including landscape irrigation, industrial cooling and boiler feed water, commercial applications, and groundwater recharge. Secondary effluent from the City of Los Angeles Hyperion Treatment Plant is pumped 5 miles to the West Basin Water Recycling Plant in El Segundo, California, for further treatment prior to reuse. The West Basin Water Recycling Plant produces five different qualities of reclaimed water, all of which meet (or exceed) the treatment and water quality requirements specified in the California Department of Public Health Water Recycling Criteria for the different reclaimed water applications. The quantities of reclaimed water (2009 annual data converted to daily averages), types of treatment, and uses of the water are as follows:

- 3.7 million gallons per day (4,000 acre-feet per year) of filtered disinfected tertiary treated reclaimed water for irrigation. Tertiary treated reclaimed water is used for industrial cooling water and a variety of irrigation uses. The tertiary treatment train at the West Basin Water Recycling Plant consists of coagulant addition using ferric chloride, flocculation basins, anthracite mono-media filters, and disinfection using sodium hypochlorite. The finished water is stored in a 5 million gallon storage reservoir from which it is pumped to a 75-mile long distribution system for industrial and commercial applications and irrigation of parks, golf courses, schoolyards and other landscape areas.
- 7.8 million gallons per day (8,700 acre-feet per year) of nitrified, filtered, and disinfected tertiary treated reclaimed water for production of industrial cooling makeup water. A portion of the tertiary treated water receives additional treatment to remove ammonia, which causes corrosion in industrial cooling towers that have copper-based alloys. Nitrification takes place in biofilters at on-site satellite package plants. Sodium hypochlorite is then added to assure complete destruction of the ammonia and for disinfection purposes.
- 12.5 million gallons per day (14,000 acre-feet per year) of reclaimed water that has undergone secondary treatment, microfiltration, reverse osmosis, and advanced oxidation, and lime stabilization for groundwater recharge. The West Coast Basin Barrier Project, operated by the Los Angeles County Department of Public Works, was constructed in the 1950s and 1960s to inject imported river water into wells along the coast to halt or reduce seawater intrusion into the potable groundwater basins. There are more than 150 injection wells that, in total, inject an average of about 18 million gallons per day (20,000 acre-feet per year) into the aquifers, although as much as 35 million gallons per day (40,000 acre-feet per year) has been injected in some years. Since 1995, the West Coast Basin Municipal Water District has used advanced treated reclaimed water for the barrier project. The reclaimed water is blended with imported river water and pumped to the barrier wells for injection. The reclaimed water meets all treatment and quality requirements specified by the California Department of Public Health. The reject water (concentrate) from all reverse osmosis units is discharged into the Hyperion Treatment Plant's 5-mile secondary effluent outfall pipeline for disposal. The use of advanced treated reclaimed water has been authorized and constructed in phases with modifications made to the treatment process over time:
    - 1995: 5 million gallons per day (5,600 acre-feet per year representing a 50 percent blend reclaimed water);

- 1997: 7.5 million gallons per day (8,400 acre-feet per year representing a 50 percent blend reclaimed water); and
- 2006: 12.5 million gallons per day (14,000 acre-feet per year representing a 75 percent blend reclaimed water) with the ability to go up to 17.5 million gallons per day (19,600 acre-feet per year representing a 100 percent reclaimed water) pending approval by the California Department of Public Health.

- 6.7 million gallons per day (7,500 acre-feet per year) of reclaimed water that has undergone microfiltration, reverse osmosis, and disinfection for production of low-pressure boiler feed water. Reverse osmosis reject water is discharged to the Hyperion Treatment Plant ocean outfall.
- 2.3 million gallons per day (2,600 acre-feet per year) of reclaimed water that has undergone microfiltration, reverse osmosis, disinfection, and second-pass reverse osmosis for production of high-pressure boiler feed water. Reverse osmosis reject water is discharged to the Hyperion Treatment Plant ocean outfall.

Funding: Funding for the initial facilities capital construction costs of about $200 million was obtained from West Basin Municipal Water District water revenue bonds, U.S. Bureau of Reclamation grants, and State of California low interest loans. By 2009, total capital costs (including land) expended for all phases of the project were approximately $500 million. The operating cost of the project was $21.5 million for the fiscal year ending 2009.

West Basin Municipal Water District sells imported water to its customers for $510/acre-foot, while the price of reclaimed water charged to customers varies according to the level of treatment the water receives. Tertiary reclaimed water is sold for 25 to 40 percent less than imported water. Nitrified water is sold for 20 percent less than imported water. Advanced treated reclaimed water is sold for 10 percent less than imported water. Users of single and double-pass reverse osmosis water for low-pressure and high-pressure boiler feed are charged a rate equal to, or slightly higher than, imported water.

15.7. Xcel Energy’s Cherokee Station, Denver, Colorado

Background. As a leading combination electricity and natural gas energy company, Xcel Energy provides energy-related products and services to 3.4 million electricity customers and 1.9 million natural gas customers in eight western and midwestern states. Xcel Energy’s Cherokee Station is located just north of downtown Denver, Colorado. The Cherokee Station is a coal-fired, steam-electric generating station with four operating units that can produce 717 MW and is one of Xcel Energy's largest Colorado power plants in terms of power production capability. The plant also is capable of burning natural gas as fuel.

Xcel Energy has taken steps to reduce the plant's fresh water consumption by using reclaimed water as one of its sources of cooling water. The Cherokee Station is the largest customer of Denver Water's Recycling Plant, using up to 4.6 million gallon per day (5,100 acre-feet per year) of reclaimed water, which reduces the plant's use of fresh water.

Project description. The power plant uses 7.1 million gallon per day (8,000 acre-feet per year) to 8.9 million gallon per day (10,000 acre-feet per year) of water for cooling tower feed, including reclaimed water. Historically, all cooling tower feed water originated from ditch systems that provided raw water to the plant. The Cherokee Station began using reclaimed water in 2004. Today, it brings raw water onto the site and combines reclaimed water and raw water in a large reservoir before feeding the cooling towers. The blend of reclaimed and raw water is also used onsite for ash silo washdown and fire protection.

Figure 18. Cherokee Station (photo courtesy of Excel Energy)

The cooling towers typically run 4 to 5 cycles and bleach is used as a biocide. Blow-down from the cooling towers is treated with lime and ferric chloride to ensure discharge permit compliance before it is discharged into the South Platte River.

Denver Water's Recycling Plant, which is located in close proximity to the Cherokee Station, has a treatment capacity of 30 million gallon per day (33,600 acre-feet per year). In 2009, reclaimed water customers used an average of approximately 5.4 million gallon per day (6,000 acre-feet per year). Treatment at the water recycling plant includes:

- Nitrification with biologically aerated filters;
- Coagulation with aluminum sulfate for phosphorus reduction;
- Flocculation and high rate sedimentation;
- Filtration with deep-bed anthracite filters; and
- Chlorine disinfection with either free chlorine or chloramines depending on season and need.

Many of the treatment targets at the water recycling plant were developed in cooperation with Xcel Energy to ensure that reclaimed water quality would be suitable for cooling tower feed. Typical reclaimed water quality is summarized in Table 28.

Table 28. Denver reclaimed water quality

Water quality parameters	Units	Typical range
Alkalinity, Total as $CaCO_3$[a]	mg/L	50 – 150
Ammonia as N	mg/L	0 – 0.4
Boron	mg/L	0.2 – 0 0.4
Calcium	mg/L	40 – 70
Chloride	mg/L	65 – 170
Chlorine, Total	mg/L	1.5 – 4
Iron	mg/L	0.05 – 0.6
Magnesium	mg/L	5 – 20
Manganese	mg/L	0.003 – 0.08
Nitrate + Nitrite as N	mg/L	5 – 30
Nitrate as N	mg/L	5 – 20

Water quality parameters	Units	Typical range
Nitrite as N	mg/L	0.01 – 0.05
Ortho Phosphorus, Dissolved as P	mg/L	0.04 – 0.3
pH	Standard Units	6 – 8
Phosphorus, Total as P	mg/L	0.04 – 0.4
Potassium	mg/L	10 – 20
Sodium	mg/L	90 – 200
Specific Conductance	µS/cm	360 – 1250
Sulfate	mg/L	80 – 250
Temperature	°C	10 – 30
Total Coliform	MPN/100 mL[b]	<1
Total Kjeldahl Nitrogen	mg/L	0.2 – 2
Total Organic Carbon	mg/L	4 – 8

a. Calcium carbonate ($CaCO_3$).

b. Most probably number (MPN).

Regulatory framework. The Colorado Department of Public Health and Environment regulates reclaimed water under Regulation 84, Reclaimed Water Control Regulation. Reclaimed water used for industrial cooling towers cannot exceed 126 *Escherichia coli* /100 mL as a monthly geometric mean and cannot exceed 235 *Escherichia coli*/100 mL in any sample. The regulations also include a total suspended solids limit of 30 mg/L as a daily maximum. Other regulatory requirements include annual user training, inspections, and user verification of reclaimed water consumption.

Costs and funding. The major components of the capital project to provide reclaimed water to the Cherokee Station included a system development charge (a tap fee), dedicated pump station at the water recycling plant, and a 16-inch service line. Xcel Energy's costs were funded as capital improvements as part of the annual capital budget. The Cherokee Station pays $0.90/1,000 gallons for raw water, and $0.91/1,000 gallons and a $5.58 monthly service charge for reclaimed water.

Benefits. The major benefit of reclaimed water to the power plant is the availability of a new water source and an overall increased water supply. This assures that Xcel Energy will be able to obtain needed water even in dry or drought years.

15.8. Monterey County Water Recycling Project, California

Background. The Salinas Valley is an agricultural region in northern Monterey County, California, where a wide variety of market crops are grown. Heavy agricultural and municipal groundwater demands beginning in the 1940s led to the development of severe groundwater overdrafting of the underlying aquifers, resulting in seawater intrusion from adjacent Monterey Bay. High salt levels in groundwater caused wells near the coast to be abandoned, and agricultural water supply wells and some community drinking water wells were threatened. The Monterey Regional Water Pollution Agency began facilities planning to provide wastewater management services to northern Monterey County, California, in 1975. At that time, water reuse was considered to be an important element in the planning process as a means to reduce groundwater pumping. It is anticipated that the use of reclaimed water for agricultural irrigation will eventually reduce seawater intrusion by 40 to 50 percent.

Agricultural Reuse Demonstration Study. The 11-year Monterey Wastewater Reclamation Study for Agriculture was initiated in 1976. The goal of study was to assess the safety and feasibility of using reclaimed water to irrigate vegetable crops that may be eaten raw. It included a 5-year demonstration project comparing well water with two different reclaimed water tertiary treatment trains. The California State Water Resources Control Board and the U.S. Environmental Protection Agency provided funding for the study, which cost $7 million.

Various crops were irrigated with three types of water: well water, tertiary treated reclaimed water that included chemical coagulation and clarification processes, and tertiary treated reclaimed water using direct filtration. Study results included the following:

- No pathogenic organisms were detected in the reclaimed water or produce;
- Poliovirus seeding tests indicated more than 5 logs removal by the treatment process train;
- Irrigation with reclaimed water did not adversely affect soil permeability;
- Metals were not found to accumulate in the soils or plant tissues;
- Produce yields, quality, and shelf life were as good, and in some cases better, in crops irrigated with reclaimed water; and
- Tertiary treatment using direct filtration was determined to be acceptable for irrigation of food crops eaten raw.

Full-scale facility. Based on the favorable results of the Monterey Wastewater Reclamation Study for Agriculture, a decision was made to design and construct a fullscale facility. Design of the treatment plant facilities, called the Salinas Valley Reclamation Project, was completed in 1994 along with design of the distribution system, which is known as the Castroville Seawater Intrusion Project.

Figure 19. Food crops irrigated with reclaimed water (Source: Monterey Regional Water Pollution Control District)

The 30 million gallon per day (33,600 acre-feet per year) regional wastewater reclamation facility was constructed adjacent to the regional secondary treatment plant to provide tertiary treated reclaimed water for agricultural applications. Tertiary treatment includes flocculation using polyaluminum chloride polymer blend followed by filtration using dual media filters, and disinfection using gaseous chlorine. Diurnal tertiary treatment flow equalization storage is provided. The facility began delivering 20 million gallon per day (23,400 acre-feet per year) of reclaimed water to growers within its service area for food crop irrigation in 1998. The treatment facilities, reclaimed water quality, and distribution system all conform to the requirements specified in the California Water Recycling Criteria for reclaimed water used to irrigate food crops eaten raw.

A Recycled Water Food Safety Study was conducted prior to startup to determine if any viable pathogenic organisms of concern to food safety were present in reclaimed water. Sampling began in 1997 and continues to the present. The study has not detected any *Escherichia coli* 0157:H7, *Salmonella*, helminth ova, *Shigella*, *Legionella*, or culturable natural (*in situ*) viruses. An extremely low number of *Cyclospora* (one instance), *Giardia* with internal structure (one instance), and *Cryptosporidia* (in seven instances) have been detected in the reclaimed water.

The water reclamation facility and distribution system are collectively known as the Monterey County Water Recycling Projects. Reclaimed water is used to irrigate various crops, including lettuce, celery, broccoli, cauliflower, artichokes, and strawberries. During the growing season, supplemental well water is used to meet the total grower demand. The system distributes reclaimed water to 222 parcels of farmland in the 12,000-acre service area.

While there have been no major operational problems related to the distribution system, minor problems include flushing of construction debris from the system, excessive sand in the extracted water of some wells, and a few pipeline breaks. A three-person crew is able to keep the system running on a continuous basis.

The sodium absorption ratio of the reclaimed water is about 4.7, while good quality well water averages 1.7. The combined waters have a sodium absorption ratio slightly above 3.0, which is the maximum level desired by growers. While the Monterey Wastewater Reclamation Study for Agriculture did not indicate any salt buildup during five years of operation with reclaimed water, a multi-year salt monitoring program has found that soil sodium absorption ratios and exchangeable sodium percentages are significantly higher in fields irrigated with reclaimed water, but are within the acceptable range for cool season vegetable production. Efforts currently are underway by Monterey Regional Water Pollution Agency to reduce salt concentration in the wastewater via source control.

Costs and revenues. In order to proceed with the project, a partnership called the Monterey County Water Recycling Projects was formed in 1992 between Monterey Regional Water Pollution Agency and the Monterey County Water Resources Agency. Since many of Monterey Regional Water Pollution Agency customers have no direct benefit from the project, system operation costs are reimbursed by Monterey County Water Resources Agency.

The total capital cost of the Monterey County Water Recycling Projects was approximately $78 million. Low interest loans were obtained from the U.S. Bureau of Reclamation and the State of California. The federal loans, for construction of the treatment facilities and distribution, have 40-year terms, while the state loan has a 20-year term. The total cost to treat and deliver reclaimed water to agricultural areas is estimated to be about $225/acre-foot ($0.90/1,000 gallons) excluding secondary treatment costs, but including both debt service from low interest loans and operation and maintenance costs for the two components (the tertiary treatment facilities and distribution network) of the Monterey County Water Recycling Projects .

The two sources of revenue for the project are land assessments established by Monterey County Water Resources Agency, which is currently $233.41/acre-foot, and a water delivery charge of $0.05/1,000 gallons. The revenue streams provide about $6 million annually and are evaluated and adjusted on an annual basis, as necessary, to cover the operational budget. About \$3.5 million of the operation budget is for direct operating costs with the balance for debt service.

15.9. Irvine Ranch Water District, California

Background. Irvine Ranch Water District was founded in 1961 in the Orange County area of southern California. This semi-arid region receives an average of 12 to 13 inches of rainfall per year. About 40 percent of Irvine Ranch Water District's drinking water is surface water from the Colorado River and from northern California purchased from the Metropolitan Water District of Southern California. The remaining 60 percent is obtained from local wells.

A majority of the property within the district boundaries was owned by The Irvine Company, which began development of the former ranch as a planned community in the early 1960s. The Michelson Water Reclamation Plant became operational in 1967, supplying the community with reclaimed water. Irvine Ranch Water District merged with the Los Alisos Water District in 2000 and began serving additional customers with reclaimed water from the Los Alisos Water Reclamation Plant.

Project description. Irvine Ranch Water District's reclaimed water distribution system reaches most of its 181-square-mile service area, which has a population of 330,000. Irvine Ranch Water District installs reclaimed water lines along with domestic water and sewer lines as new housing or commercial developments are built. When reclaimed water becomes available in previously built areas, the agency works with customers to retrofit their non-potable water systems to use reclaimed water. There are over 4,500 reclaimed water connections, most of which are for landscape irrigation.

The Michelson and Los Alisos water reclamation plants treat wastewater to disinfected tertiary standards as specified in the California Water Recycling Criteria for high level non-potable uses, such as irrigation of residential property. The Michelson Water Reclamation Plant has a capacity of 15 million gallon per day (16,800 acre-feet per year); the Los Alisos Water Reclamation Plant has a capacity of 5.5 million gallon per day (6,200 acre-feet per year). Water is delivered throughout the community through a dual distribution system that includes almost 400 miles of reclaimed water pipelines, 13 storage reservoirs, and 19 pump stations. Three of the reservoirs are open lakes; the others are pre-stressed concrete or steel tanks. Prior to delivery from the open reservoirs to the reclaimed water distribution system, reclaimed water may receive additional treatment via straining, pressure filtration, and/or disinfection. The reclaimed water storage capacity currently is 992 million gallons. Reclaimed water makes up more than 20 percent of Irvine Ranch Water District's total water supply.

The primary use of reclaimed water is landscape irrigation. Eighty percent of all business and public area landscaping in the Irvine Ranch Water District service area is irrigated with reclaimed water. Landscape irrigation uses include parks, school grounds, golf courses, a cemetery, freeway landscapes, city-maintained streetscapes, common areas managed by homeowner associations, and front and backyard residential landscapes. Reclaimed water is also used for food crop irrigation, toilet and urinal flushing in dual-plumbed office buildings, and in commercial office cooling towers.

Because the Irvine Ranch Water District service area is still being developed, there will be a need for additional reclaimed water in the future. Irvine Ranch Water District's master plan calls for the gradual expansion of the Michelson Water Reclamation Plant within its existing boundaries to eventually produce 33 million gallon per day (37,000 acre-feet per year) by 2025. Plans call for the eventual expansion of the Los Alisos plant to 7.8 million gallon per day (8,700 acre-feet per year). In addition, water from the Irvine Desalter, which has received treatment by reverse osmosis, air stripping with activated carbon filters, and disinfection to remove trichloroethylene from a plume of groundwater pollution migrating from a former military base, provide an additional 3.6 million gallons per day (4,000 acre-feet per year) of water to the reclaimed water system.

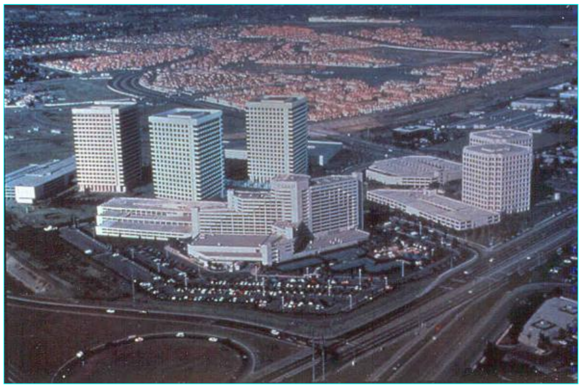

Figure 20. Dual-plumbed office building (Source: Irvine Ranch Water District)

Problems encountered. The major problems encountered by Irvine Ranch Water District are related to salinity and seasonal storage.

With source water (Colorado River) becoming increasingly saline, Irvine Ranch Water District has become increasingly concerned over the addition of more salts into the water reclamation system. Irvine Ranch Water District enacted rules and regulations in the early 1970s to prohibit the use of residential self-regenerating water softeners within Irvine Ranch Water District's boundaries, which helped control salt concentration in the reclaimed water. However, the salinity problem re-emerged in 1997, when court cases brought by the water softener industry against water agencies elsewhere in California overturned such bans. Current California law has been modified to allow local agencies to adopt ordinances to prospectively ban automatic softeners to protect reclaimed water, but Irvine Ranch Water District does not have the statutory authority to ban softeners that were installed post 1997.

Southern California receives most of its rainfall during the winter months. Since landscape irrigation is the main use of reclaimed water, demand fluctuates seasonally. In the winter months, more reclaimed water is produced than can be used. In the hot summer and fall months, the water reclamation plant capacity cannot produce sufficient water to meet demand. Balancing the seasonal storage issue through the use of open lakes is an ongoing challenge. In 2005, Irvine Ranch Water District converted an existing open reservoir that was formerly used for drinking water storage to provide additional seasonal storage of reclaimed water. Irvine Ranch Water District currently is able to meet year-round demand through the use of its numerous storage reservoirs, but will need additional reclaimed water storage to meet expected future demand.

Public outreach. Reclaimed water generally is very well accepted within the Irvine Ranch Water District service area. Because the district has a 35-year track record of successfully and safely providing reclaimed water to the community, it is not met with resistance by the general public. This is due, in part, to an extensive public education and involvement program via brochures, videos, workshops, tours, and other means that has resulted in community acceptance of water reuse as an environmentally sound method for stretching limited water supplies.

Irvine Ranch Water District's public outreach program has included an extensive classroom water education program in local schools for nearly 30 years. The need for water conservation is taught at all grade levels, and the water reuse concept is introduced to students in the fifth grade. In addition, tours of the water reclamation plants and water quality laboratory are regularly held for the general public. Irvine Ranch Water District has found that a well-informed public is less apprehensive about water reuse.

Costs and revenues*.* Irvine Ranch Water District has continued to expand and upgrade its reclaimed water program throughout the years, with most of the capital costs financed via the district's internal funding mechanisms. Infrastructure costs are recovered through a combination of property taxes and connection fees. The base reclaimed water rate is $1.03/100 cubic feet, which is 90 percent of the base domestic water rate. Irvine Ranch Water District uses an ascending block rate structure that severely penalizes excessive water use.

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Appendix A - Glossary

There are a number of common terms and phrases that relate to water reuse issues. In order to provide improved understanding of water reuse, a collection of these terms and phrases is provided below:

Advanced Oxidation: A chemical oxidation process that relies on the hydroxyl radical for the destruction of trace organic constituents found in water.

Advanced Treatment: Treatment used to remove total dissolved solids and or trace constituents for specific reuse applications.

Aquatic Life: Fish, animals, plants, and other organisms occurring in a water body, such as wetlands, rivers, streams, lakes, and ponds.

Aquifer: A geologic formation under the ground that is saturated with groundwater and sufficiently permeable to allow movement of quantities of water to wells and springs.

Aquifer Recharge and Recovery (also called **Aquifer Storage and Recovery**): The use of injection wells to recharge and store water in the ground coupled with recovery wells to extract the water for use.

Attenuation: The collective assemblage of reactions that causes contaminant concentrations to decrease in surface waters or groundwater.

Bioaccumulation: The process whereby a chemical accumulates in aquatic organisms gradually increasing in concentration higher up in the food chain.

Brine: Waste stream containing elevated concentrations of total dissolved solids.

Centralized Treatment System: The collection of wastewater from a large generally urban area using an extensive collection system network for transport to a central location for treatment and reclamation.

Chapter 210 Authorization: Authorization issued by the Texas Commission on Environmental Quality, which allows a wastewater producer to reuse water for specific non-potable purposes.

Chemical of Emerging Concern: Constituents that have been identified in water that include pharmaceuticals, personal care products, and endocrine disrupting chemicals. Many of these constituents are not currently regulated.

Clean Water Act: Federal law that is the cornerstone of surface water quality protection in the United States. The statute employs a variety of regulatory and non-regulatory tools to reduce direct pollutant discharges into waterways, finance municipal wastewater treatment facilities, and manage polluted runoff.

Constructed Wetlands: Wetlands intentionally developed in a non-wetted area to duplicate the processes occurring in natural wetlands, but generally for the purposes of improving water quality with more control.

Conventional Treatment (also called **Conventional Secondary Treatment**): Activated sludge treatment, which is a biological treatment process used for the removal of soluble organic matter and particulates using microorganisms. The microorganisms form flocculant particles that are separated from the water using sedimentation (settling), and the settled material is returned to the biological process or wasted.

Depth Filtration: The removal of particulate matter suspended in liquid by passing the liquid through a granular medium such as sand.

Direct Reuse: The use of reclaimed water for non-potable or potable purposes without first discharging to a water supply source, such as fresh surface or groundwater.

Direct Non-potable Reuse: Treated effluent is piped directly to the reuse site. Water quality is not required to meet strict standards for drinking water. Treatment has removed wastes and pathogens to make it safe for irrigation, maintaining off channel pond levels, and many industrial and commercial applications.

Direct Potable Reuse: The planned introduction of reclaimed water into the potable water supply distribution system downstream of a water treatment plant or into the raw water supply immediately upstream of a water treatment plant.

Disinfection Byproducts: Chemicals that are formed with the residual matter found in treated reclaimed water as a result of the addition of a strong oxidant, such as chlorine or ozone, for the purpose of disinfection.

Dissolved Ions: Negatively charged atoms (anions), such as chloride (Cl^-), or positively charged atoms (cations), such as sodium (Na^+).

Dual Distribution System: The two independent piping networks that supply potable water and reclaimed water.

Endocrine Disrupting Chemicals: Synthetic and natural compounds that mimic, block, stimulate or inhibit natural hormones in the endocrine systems of animals, humans, and aquatic life.

Epidemiology: The study of disease patterns in human populations.

Environmental Buffers: Environmental buffers are elements of planned indirect potable reuse projects that include assimilation/blending of the reclaimed water with the surface water or groundwater that is being augmented, natural attenuation that can occur as reclaimed water percolates through soil (for groundwater recharge) or *in situ*, and time for attenuation to occur as reclaimed water is stored (underground or in surface reservoirs) prior to use.

Eutrophication: The process in which surface waters receive nutrients that stimulate excessive growth of aquatic plants, which accumulate, and from the addition of debris and sediment.

Foliar Damage: Damage to leaves of plants.

Indirect Reuse: The use of reclaimed water for non-potable or potable purposes by discharging to a water supply source, such as fresh surface or groundwater, where it mixes, dilutes, and may be transformed before being removed for reuse.

Indirect Potable Reuse: The planned incorporation of reclaimed water into a raw water supply, such as a water storage reservoir, or a groundwater aquifer, resulting in mixing and assimilation, thus providing an environmental buffer.

***In vitro*:** Biological studies that take place in isolation from a living organism, such as a test tube or Petri dish.

***In vivo*:** Biological studies that take place within a living organism.

Managed Aquifer Recharge: The infiltration or injection of a source water, such as river or lake water, reclaimed water, or urban stormwater, into an aquifer under controlled conditions with the intention of storage and/or treatment of water and in some cases with the intention to augment drinking water.

Maximum Contaminant Level: Enforceable drinking water standards applicable to public water supplies.

Membrane: A device usually made of organic polymer that allows the passage of water and certain constituents, but rejects others above a certain physical size or molecular weight.

Natural Wetlands: Those areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support a prevalence of vegetation. Wetlands include swamps, bogs, marshes, and similar areas.

Nitrification/Denitrification: A biological treatment process used for nitrogen removal that converts ammonia to nitrate, and nitrate to nitrogen gas.

Non-potable Reuse: The planned use of reclaimed water for purposes other than to augment drinking water supplies.

Non-potable Water: Water intended for uses other than human consumption.

Nutrients: The principle nutrients are nitrogen and phosphorus in various forms. When discharged to water, nutrients can stimulate growth of undesirable aquatic life.

Organic Matter: Includes both dissolved and particulate matter, and is principally comprised of proteins, carbohydrates, and fats. Organic compounds that that tend to resist conventional wastewater treatment are often classified as refractory organics.

Pathogens: Microorganisms including bacteria, protozoa, helminthes, and viruses capable of causing disease in animals and humans.

Permeate: The liquid stream that passes through a membrane.

Personal Care Products: Products such as shampoos, hair conditioner, suntan lotion, deodorants, and body lotions.

Potable Water: Water deemed safe for human consumption, food preparation, and drinking.

Potable Reuse: The planned use of reclaimed water to augment drinking water supplies.

Priority Pollutants: The 126 chemical pollutants regulated by the U.S. Environmental Protection Agency. The current list chemicals can be found in Appendix A to Section 40 of the Code of Federal Regulations, Part 423.

Reclaimed Water: Domestic or municipal wastewater which has been treated to a quality suitable for a beneficial use.

Risk: The probability that an organism exposed to a specified hazard will have an adverse response.

Riverbank Filtration: A natural filtration system where the river bottom and bank serve as the interface between surface water and an aquifer being recharged.

Safe Drinking Water Act: The main federal law that ensures the quality of United States drinking water.

Salinity: A parameter referring to the presence of soluble salts in waters, or in soils, usually measured as electrical conductivity.

Salts: Salts are ionic compounds containing the cations sodium, boron, calcium, magnesium, and potassium, and the anions bicarbonate, carbonate, chloride, nitrate, phosphate, sulfate, and fluoride.

Satellite Treatment System: System used for the treatment of wastewater located close to a reuse application. These treatment plants do not generally includes solids processing facilities with solids returned to the collection system.

Soil Aquifer Treatment: The treatment achieved as reclaimed water passes through soil to an aquifer.

Soluble Microbial Products: Organic compounds produced and released as a result of metabolic activity.

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

Use Area: A location with defined boundaries where reclaimed water is used for one or more beneficial purposes, such as a golf course, park, impoundment, or building.

Vadose Zone (also called **Unsaturated** zone): The area between the land surface and the regional water table.

Wastewater: Used water discharged from homes, businesses, industries, and agriculture.

Wastewater Management Systems: The infrastructure for wastewater treatment and disposal including collections systems (sewers), wastewater treatment plants, wastewater discharge facilities, and sludge treatment facilities.

Water Quality Standards: These standards define the goals for a water body by designating its uses (such as recreation, aquatic life, drinking), setting water quality criteria to protect those uses (both numeric and narrative requirements), an anti-degradation policy to maintain and protect existing uses and high quality waters, and general policies addressing implementation issues (such as variances, mixing zones, and low flows).

Water Right: Authorization issued by the Texas Commission on Environmental Quality allowing an entity to transfer, divert and use a specified quantity of water from a surface water source, such as a lake or stream.

Waters of the United States: Navigable waters, including streams, rivers, lakes, creeks, and natural wetlands, as defined in the Clean Water Act.

Appendix B - Summary of CEC Monitoring Recommendations – Recycled Water Science Advisory Panel Final Report June 25, 2010

Compound	Classification	Role	MRL[a] ng/L	MTL[b] ng/L	Monitoring Guidance	Response Guidance
Groundwater Recharge SAT						
17b-estradiol	Steroid Hormone	Health-based Indicator[c]	1	9.0E-01	Tertiary recycled water & groundwater[d] Plant Start-up: Quaterly for 1st year Baseline Monitoring: Twice/year for 3 years	For Indicators: Confer with regulators develop a response plan (investigational only – not for compliance purposes) Goal < 5 times the ratio of MEC/MTL If 25% or less of samples during baseline monitoring > MEC/MTL = 0.1, regulators should consider deleting monitoring requirement for the compound (review MTL before change made) If 1<MEC/MLT< 10: data check, continue to monitor, until 1 year and the MEC/MLT < 1 and preferably is consistently less than 5 times the ratio of MEC/MTL If 10<MEC/MLT< 100: data check, immediate re-sampling and analysis to confirm MEC, continue to monitor, until 1 year and the MEC/MLT< 1 and preferably is consistently less
Triclosan	Antimicrobial	Health-based Indicator	50	350		
Caffeine	Stimulant	Health-based Indicator	50	350		
NDMA (N –nitroso dimethlyamine)	Disinfection byproduct	Health-based Indicator	2	1.0E+01		
Δ Gembribozil	Pharmaceutical	Performance-based Indicator[e]	10	45000	Tertiary recycled water, monitoring well, down gradient potable well Plant Start-up: Quarterly for 1st year Baseline Monitoring: Twice/year for 3 years For surrogates use online devices where feasible	
Δ DEET	Personal Care Product	Performance-based Indicator	10	2500		
Δ Caffeine	Stimulant	Performance-based Indicator	50	350		
Δ Iopromide	Pharmaceutical	Performance-based Indicator	50	7.5E+05		
Δ Sucralose	Food Additive	Performance-based Indicator	100	N/A		
Δ Ammonia	---	Performance-based Surrogate	SM[f]	---		
Δ Nitrate	---	Performance-based Surrogate	SM	---		
Δ Dissolved Organic Carbon (DOC)	---	Performance-based Surrogate	SM	---		
Δ Ultraviolet Absorption (UVA)	---	Performance-based Surrogate	SM	---		

Compound	Classification	Role	MRL[a] ng/L	MTL[b] ng/L	Monitoring Guidance	Response Guidance
						than 5 times the ratio of MEC/MTL If 100<MEC/MLT< 1000: all of the above plus enhance source identification program and monitor closer to the Point of Exposure If MEC/MTL>1000: all of the above plus immediately confer with the CDPH & RWQCBs to determine the required response action; confirm plant corrective actions through additional monitoring that indicates the CEC levels are below at least an MEC/MTL of 100
1,2,3-Trichloropropane	Industrial Chemical	Secondary Monitoring[g]	5	5.0E+00	Secondary/tertiary treated effluent representing the feed water quality to surface spreading Quarterly for 1 year	---
Hydrazine	Industrial Chemical	Secondary Monitoring	1	1.0E+01		
Quinoline	Industrial Chemical	Secondary Monitoring	1	1.0E+01		
Groundwater Recharge Direct Injection						
17b-estradiol	Steroid Hormone	Health-based Indicator	1	9.0E-01	Advanced treated recycled water & groundwater[h] Plant Start-up: Quaterly for 1st year Baseline Monitoring: Twice/year for 3 years	<u>For Indicators</u>: Confer with CDPH & RWQCB to develop a response plan (investigational only – not for compliance purposes) Goal < 5 times the ratio of MEC/MTL If 25% or less of samples during
Triclosan	Antimicrobial	Health-based Indicator	50	350		
Caffeine	Stimulant	Health-based Indicator	50	350		
NDMA (N-nitroso dimethlyamine)	Disinfection Byproduct	Health-based Indicator	2	1.0E+01		
Δ DEET	Personal Care Product	Performance-based Indicator	10	2500	Between secondary and membrane treatment processes;	
Δ Sucralose	Food Additive	Performance-based	100	N/A		

Compound	Classification	Role	MRL[a] ng/L	MTL[b] ng/L	Monitoring Guidance	Response Guidance
		Indicator			between membrane and advanced oxidation treatment; final recycled water prior to injection Plant Start-up: Quarterly for 1st year Baseline Monitoring: Twice/year for 3 years For surrogates use online devices where feasible	baseline monitoring > MEC/MTL = 0.1, CDPH/RWQCB should consider deleting monitoring requirement for the compound (review MTL before change made) If 1<MEC/MLT< 10: data check, continue to monitor, until 1 year and the MEC/MLT < 1 and preferably is consistently less than 5 times the ratio of MEC/MTL If 10<MEC/MLT< 100: data check, immediate re-sampling and analysis to confirm MEC, continue to monitor, until 1 year and the MEC/MLT< 1 and preferably is consistently less than 5 times the ratio of MEC/MTL If 100<MEC/MLT< 1000: all of the above plus enhance source identification program and monitor closer to the Point of Exposure If MEC/MTL>1000: all of the above plus immediately confer with the CDPH & RWQCBs to
Δ NDMA	Disinfection Byproduct	Health-based Indicator	2	1.0E+01		
Δ Caffeine	Stimulant	Performance-based Indicator	50	350		
Δ Conductivity	---	Performance-based Surrogate	SM	---		
Δ DOC	---	Performance-based Surrogate	SM	---		

Compound	Classification	Role	MRL[a] ng/L	MTL[b] ng/L	Monitoring Guidance	Response Guidance
						determine the required response action; confirm plant corrective actions through additional monitoring that indicates the CEC levels are below at least an MEC/MTL of 100
1,2,3-Trichloropropane	Industrial Chemical	Secondary Monitoring	5	5.0E+00	Secondary/tertiary treated effluent representing the feed water quality to surface spreading Quarterly for 1 year	---
Hydrazine	Industrial Chemical	Secondary Monitoring	1	1.0E+01		
Quinoline	Industrial Chemical	Secondary Monitoring	1	1.0E+01		
Landscape Irrigation						
None		Health-based Indicator	---	---	---	---
None		Performance-based Indicator	---	---	---	---
Turbidity	---	Title 22 Surrogate	SM	---	Per permit monitoring program	Per permit monitoring program
Chorine Residual	---	Title 22 Surrogate	SM	---		
Total Coliform	---	Title 22 Surrogate	SM	---		

(Source: adapted from Drewes et al., 2010a)

a. Method Reporting Level (MRL).

b. Monitoring Trigger Level (MTL).

c. Selection as a health-based indicator was based on the ratio of occurrence (MEC)/monitoring trigger level (MTL). To be conservative, data for secondary or tertiary recycled water (90^{th} percentile values) were compared to the MTLs. The MTLs were based on available toxicological information and selected in order of priority: California Department of Public Health (CDPH) derived benchmarks; U.S. Environmental Protection Agency (U.S. EPA) benchmarks; and lowest other available benchmark. If the MEC/MTL > 1, the compound was recommended for monitoring as a health-based indicators. The proposed MEC/MTL ratios should not be used to make predictions about risk.

d. The Panel assumed tertiary effluent was used for groundwater recharge by surface spreading; the groundwater monitoring locations are to be determined on a case-by-case basis by CDPH (downgradient wells, monitoring wells representing the underlying groundwater and/or lysimeters).

e. The intent of the performance-based indicators and surrogates is to quantify the removal differential.

f. Standard Method (SM).

g. U.S.EPA Candidate Contaminant List 3 chemicals with MTLs of less than 500 ng/L and no MECs in recycled water in California.

h. The groundwater monitoring locations are to be determined on a case-by-case basis by CDPH (downgradient wells and monitoring wells representing the underlying groundwater).

APPENDIX C

DRAFT Advancing Water Reuse in Texas
Component B – State of Reuse Technology Report

TWDB staff reviewed the Draft report and provides the following comments:
Responses to comments are shown in italics.

General Comments

1. Photographs of various water reuse facilities have been used in this report. Please ensure that proper approvals have been obtained from the respective facilities to publish the photographs in the report.
Permission has been obtained to publish all figures remaining in the report.

2. Please clearly define the terms water reuse, wastewater reclamation, reclaimed wastewater, and reclaimed water in the introductory sections of the report.
Water reuse has already been defined in Section 2 Introduction ("Water reuse, the practice of taking water that has already been used and using it again for a beneficial purpose…"). We have included the definitions of reclaimed wastewater and reclaimed water in this section.

Specific Comments

Executive summary
Please include the Executive Summary for the report.
We have included the summary in the revised report.

3. Beneficial uses of reclaimed water (Page 4)
The document often refers to potable reuse and non-potable reuse. Please define these terms in the beginning of section 3, where direct and indirect reuses are defined.
We have included the definitions in this section of the revised report.

3.1 Types of uses (Page 4)
Please consider incorporating a table or a chart summarizing different types of beneficial uses of reclaimed water.
We have included a table in this section of the revised report.

3.1.3 Agricultural uses (Page 7)
Please explain in layman's language the relevancy of polynuclear aromatic hydrocarbons, polychlorinated biphenyls, chlorinated benzenes, and phenols.
We have provided this explanation in the revised report.

3.1.7 Potable supply augmentation via indirect potable reuse (Pages 8-11)

a. Please define what an environmental buffer is.

We have provided this information in the revised report.

b. This section focuses on planned indirect potable reuse. As background information, please consider including a discussion of unplanned indirect potable reuse.

We have provided this information in the revised report.

c. This section mentions the creation of salt water intrusion barriers in coastal aquifers as a use of reclaimed water. Please consider revising this section to include inland aquifers as well, which also can experience salt water intrusion issues.

We have revised the report to include barriers for brackish waters.

d. Page 10, last paragraph, 6th line; please add the words "although there are examples of this practice in the state," before the sentence "Texas regulations have not been established for the use of reclaimed water for potable supply."

We have made this change in the revised report.

3.1.8 Direct reuse (Page 11)

a. The paragraph discusses direct potable reuse; therefore, the title of this section should be revised to "Direct potable reuse".

We have made this change in the revised report.

b. Page 11, second paragraph, 3rd and 4th lines; please revise the statement to reflect that the referenced WateReuse California workshop has already occurred.

We have made this change in the report. The work plan stemming from the workshop is not yet available to reference in the report.

4.1 Federal regulations and guidelines (Page 12)

Please describe the key points of EPA's guidelines.

We have made this change in the revised report.

4.1.1 Clean water act (Page 13)

a. Page 14, first paragraph; the value 0.00069 μg/L is inconsistent with the value in the footnote.

The value in the paragraph is based on 10^{-6} risk; the value in the footnote is based on 10^{-5} risk; we have provided additional clarification in the text and footnote.

b. Please define the term "cancer risk 10^{-6}".

We have made this change in the revised report.

c. A statement in the second paragraph mentioned that the criterion for chloroform is reserved. Please explain the use of the term "reserved".

We have provided an explanation in the revised report.

4.2 Texas regulations (Page 18-22)

a. Please consider adding a new section, 4.2.2, "Summary of the Relevance of Existing Laws to Texas" that briefly summarizes or lists the topics previously described such as NDMA, nutrients and TTHM's as they relate to Texas' water reuse future.

Based on the status of Texas water quality regulations and water reuse regulations (particularly the absence of regulations for indirect potable reuse), it would be very speculative to include a discussion on how these topics relate to Texas' water reuse future. We have included them for the purpose of being aware of what's going on in other parts of the country; however, we are not comfortable speculating on just how this will play out in Texas.

b. Page 19, first paragraph; please define Type I and Type II reuse.
   We have made these changes in the revised report.
c. Table 3;
   - Please include a brief explanation why Type II use is listed under Type I use.

   This is an error; it has been revised so that Type II uses are listed under Type I quality since Type I reclaimed water may also be utilized for any of the Type II uses.
   - For fecal coliform 75 CFU/100 mL; footnote g should be changed to footnote h.

   We have made this change to the revised report.
d. Page 20, last paragraph, 3rd line; please verify whether the word 'wastewater' should be replaced with the words 'reclaimed wastewater'.
   We have made this change to the revised report.
e. Page 21, second paragraph; please add a brief introductory explanation addressing why Texas Surface Water Quality Standards are important or relevant to reuse.
   We have made this change to the revised report.
f. Please identify the Texas Surface Water Quality Standards (Title 30, Chapter 307 of the Texas Administrative Code) in the Introduction of Section 4.2.
   We have made this change to the revised report.
g. Page 21, 4th paragraph, last line; please add the words "Texas Surface Water Quality" in front of the word 'standards'.
   We have made this change to the revised report.
h. Page 22, second bullet; please mention the current value for total trihalomethane from which it is being revised to 80 μg/L.
   We have made this change in the revised report.

4.2.1 <u>Comparison of Texas regulations to other state regulations (Page 22-28)</u>

a. Table 4 (Page 23); please consider indenting the subcategories to match EPA 2007, and then relate this table specifically to Texas by adding an asterisk to those uses allowed by Chapter 210 of the TAC. (i.e., irrigation, toilet flushing, fire protection, construction, landscape impoundment, restricted urban agricultural-food crops, agricultural non-food crops, restricted recreational and industrial uses).
   We have revised the table so the unrestricted urban uses are indented as requested and included a footnote to indicate which uses are specifically allowed by Chapter 210 of the TAC.

b. Table 5 (Page 24); in the title of the table, the words 'urban use' should be replaced with the words 'urban reuse'.
   We have made this change in the report.

c. Page 24, last paragraph; the meaning of the word 'narrative' is not clear. Please explain the use of 'narrative' in this context.
We have made this change in the report.
d. Table 6 (Page 25); please spell out the word 'RWC' in the first instance.
We have made this change in the report.
e. Page 28, first bullet; please explain the use of the term 'mandates' in the context; does it refer to legislative mandates?
The Policy is considered to be a regulation - so this is a regulatory mandate to increase the amount of recycled water by specific amounts by specific dates. We have revised the introductory text and bullet to make this clarification.
f. Page 28, fourth bullet; consider replacing the words, 'provide provisions for how to perform' with the words 'guide the performance of'
The Policy actually establishes how to determine compliance with state anti-degradation requirements. We have revised the bullet to make this clarification.

4.3 International guidelines for water reuse (Page 28)

Please consider including information about efforts that the Netherlands has undertaken regarding water reuse. The Netherlands has not only fostered business development that supports new sustainable water technologies, but it also has created a large research center; developed academic programs at all levels of education and stress an integrated approach including innovation and safety.
It is our understanding that this comment was intended to highlight the holistic approach the Netherlands is incorporating into overall water management,[1] and not water reuse per se. Other information in the literature indicates that the Netherlands does not have reuse regulations or guidelines and very little water reuse takes place.[2] Dual distribution systems are not allowed, but projects utilizing wetlands and some reuse of industrial water for industrial processes is occurring.[3] Thus, we do not think information on the Netherlands should be included in this section of the report.

5. Source Control (Page 29)

Footnote 17; please add the word 'water' between the words 'owned' and 'treatment'.
No change is needed. The Clean Water Act uses "publicly owned waste treatment works"; USEPA uses "publicly owned treatment works" in its documents and on its website.

6.1 Constituents of concern (Page 32)

The number of unregulated contaminants (which have yet to be found harmful) is so vast that it can exhaust resources easily. Prioritization of which contaminants need to

[1] TWDB (via USBR) provided this link to the program: http://www.x-flow.com/import/assetmanager/7/12747/Nat%20Geographic_dutchwater.pdf
[2] See http://www.surreycc.gov.uk/sccwebsite/sccwspublications.nsf/591f7dda55aad72a80256c670041a50d/afec3cec70f688a38025731c003f3c9b/$FILE/Further%20Information%201%20Water%20Reuse%20and%20Recycling%20in%20Eureau%20Countries.pdf
[3] See http://www.afs.enea.it/pica/Pubblica/Riuso/Articoli/sdarticle_1.pdf

be studied should occur at some point. Therefore, please consider providing a more clear distinction between which constituents are already regulated versus those that are not regulated.
Information has been included in the introduction to this section that describes the universe of regulated constituents and two prioritization efforts. Often this type of information is used as the basis for identifying contaminants for further study (research and/or monitoring).

6.1.1 Table 7 (Page 33)
Please add a column in the table to discuss the effect of organisms on human health.
Information has been added to the table.

6.1.5 Organic chemicals (Page 36)
a. Please consider providing a summary table to supplement the information provided in this section.
A summary table had been provided.
b. Last two paragraphs of Page 39 discussed various issues of pharmaceutical and personal care products. Please consider moving the contents of these two paragraphs to earlier in the sub-section where pharmaceuticals and their active metabolites are discussed.
We have made this change in the report and have updated some of the research results.

6.2.1 Physical/Chemical treatment mechanisms (Page 40-44)
Table 9, Page 43;

- Please correct the numbering of the footnotes for RO and NF.

We have made this change in the report.

- Footnote f was not used in Table 9. Please remove footnote f.

Footnote f was used for "Photolysis using ultraviolet radiation" under the Target: Trace organics[f] on pg. 42.

- Description of each process in Table 9 focused on water treatment. Please consider expanding the respective description to make them more inclusive of issues pertaining to wastewater treatment/water reuse process.

Actually these all related to wastewater treatment/water reuse processes. The primary source of this information was Metcalf & Eddy, 2007, Water Reuse Issues, Technologies, and Applications.

6.2.2 Biological treatment mechanisms (Page 45)
Page 45, third paragraph; please confirm whether the values from 0.2 to 0.5 mg/L in the 3rd paragraph are correct.
We looked at information from Sedlak et al., 1991 and also looked at Krasner et al., 2008. The range of values for biological nutrient removal is <0.1 to 0.6 mg/L. We have revised the report to include this information.

6.2.4 Disinfection (Page 50)

a. During the discussion of free and combined chlorine, please provide definitions of these two parameters.
This information has been provided in the revised report.
b. Please provide a summary table showing advantages and disadvantages of each type of disinfectant.
This table has been provided in the revised report for UV versus chemical disinfection.
c. The report discussed 'Advanced Oxidation' in detail. However, conventional disinfection has not been discussed elaborately in the report. We recommend dividing 'Disinfection' section into two sub-sections; i) Conventional Disinfection and ii) Advanced Disinfection, and discussing both sub-sections elaborately in the report.
We do not believe Advanced Oxidation is typically selected for disinfection. It is primarily used for removal of residual organics that pass through membranes, yet also provides for substantive disinfection. To ensure that its dual treatment role is emphasized, we prefer to keep it as a separate section and have included information in the introduction about its dual functions.

6.3 Advanced oxidation (Page 52)

a. Please see comment 'c' of 'Disinfection' (section 6.2.4).
Please see response to comment c.
b. A detailed discussion for ozone has been provided. Please consider incorporating similar discussions for hydrogen peroxide and ultraviolet radiation disinfection.
Based on this and other comments about the section, we have revised this section so that it provides a more general discussion of the types of advanced oxidation typically used for reclaimed water.
c. Please provide pro's and con's of each type of advanced oxidation process.
We have included a table in the revised report.

6.3.2 Types of advanced oxidation processes (Page 54)

A significant portion of this section is redundant. Therefore, we recommend merging this section with 'Advanced oxidation' section.
We agree and have revised the section to accommodate this comment.

6.4 Concentrate management (Page 54)

This section appears to be disconnected from the previous sections of the report. Please consider adding a brief introductory explanation on membrane filtration and the importance of concentrate management in membrane filtration process prior to providing detailed technical description of concentrate management.
We have revised the report to provide additional introductory information on membranes and concentrate.

7. Monitoring (Page 60)

a. This section provides an excellent surrogate/indicator framework; however, given the complexity of the issue, please supplement the information by providing a tabular summary for ease of reading.

We believe the framework is depicted in Table 14. However, we have expanded this section of the report to include the monitoring recommendations from the California Recycled Water CEC Science Advisory Panel.

b. Please consider stating that monitoring equipment does not currently exist to satisfy regulators that treatment processes by themselves cannot meet water quality standards all of the time.

We have revised the report to address the status of on-line monitoring equipment.

7.1.1 <u>Surrogate/Indicator frame work (Page 61-62)</u>

Table 14; please define the term "detection ratio".

We have provided a definition in the revised report.

7.2 <u>Bioassays (Page 67)</u>

Please consider providing a more elaborate description of the results of existing bioassay tests.

We have included additional information on the status of bioassays from the California State Water Board Recycled Water CEC Science Advisory Panel final report (June 2010); however, other than the information already provided in the report on bioassays that have been studied, there is no additional data to provide. Further detail on those results would not provide additional elucidation.

8.1 <u>Risk management (Page 68)</u>

Please provide a reference for the definition that is provided in the first paragraph.

We provided a reference in the revised report.

8.3 <u>Epidemiology (Page 70-72)</u>

Table 20; please consider adding the results of the Total Resource Recovery Project to this table.

The results for the project are in the Table on page 71.

8.4 <u>Quantitative relative risk assessments (Page 73)</u>

Please consider revising the description of Oliveri and Seto's work to make it more consistent with the positive results cited in section 8.3. It may be valuable to add qualifying factual information here if it is available.

These are the results directly from Oliveri and Seto's study that looked at the risks related to the use of disinfected tertiary effluent. It is not scientifically correct to compare the results of disparate epidemiology studies to the risk assessment by Oliveri and Seto. Of the epidemiology studies conducted, the only study that looked at a comparable water and that is considered to be representative of conditions applicable in the U.S. is the Health Effects Study, and the morbidity data we used were really very limited – reporting infectious disease in the U.S. is not done consistently nor completely. The Kansas study can't be used for direct comparison – nor can the Windhoek study. We are not sure what is meant by the comment "qualifying factual information." :

9. <u>Ecological issues (Page 83)</u>

This section begins with a statement that ecological evaluations are more complex than human health impacts, yet the report contains much more information on the latter in Section 8. Please consider revising this statement or adding information to clarify the statement.
We have revised this statement to and say that ecological effects are complex yet information is lacking on the overall significance of the effects from wastewater discharges. Thus, at this time we do not believe that there is substantive information to include. The Water Environment Research Foundation is compiling a relational database on ecological effects that will be available next year.

14. <u>Water reuse research (Page 94)</u>
Please include the reference WRF#02-008, "A Reconnaissance-Level Quantitative Comparison of Reclaimed Water, Surface Water and Groundwater". The reference stated that many chemical compounds exist in groundwater and surface water, even prior being under the influence of reclaimed water. A risk probability analysis was also included in the above mentioned reference.
The information provided in this section is about research foundation programs rather than individual research studies as is the case for WRF #02-008. We have not attempted to compile all occurrence data for reclaimed water (or water under the influence of reclaimed water or wastewater) as part of this technical memo. The risk probability analysis for WRF #02-008 was a comparison of water quality data to drinking water regulations and not a risk assessment – thus we elected not to include it as an example in the memo.

15.1 <u>El Paso, Texas reuse studies (Page 100)</u>
a. Third paragraph of Page 100 (Reclaimed water program) indicated that El Paso is currently using reclaimed water from four treatment plants (Northwest, Haskell Street, Roberto Bustamante, and the Fred Hervey) for non-potable reuse. However, only Fred Hervey Water Reclamation Plant is discussed in the report. Please include discussions on the operation and maintenance of Northwest, Haskell Street, Roberto Bustamante wastewater treatment plants.
Discussions on all wastewater treatment plants have been added to this section.
b. Please provide a schematic to explain the process of Fred Hervey Water Reclamation plant.
A schematic has been added.
c. Please provide information on how much of the total demand of EPWU is met by water reuse.
This information has been added to this section.

<u>References (Page 132)</u>
Reference for Wallace and Knight (2006) is missing. Please add the reference.
We have added the reference to the revised report.